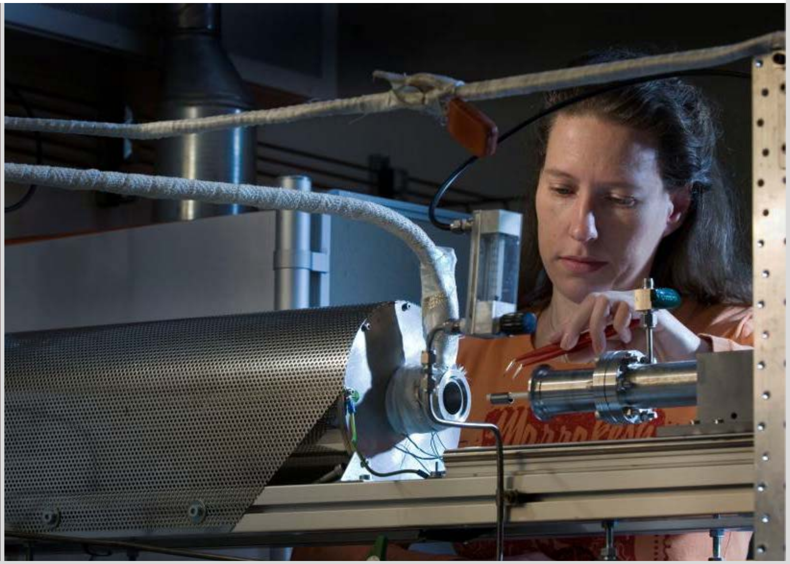
25 years QUENCH program.
Highlights of separate-effects tests

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

25th International QUENCH Workshop, Karlsruhe, 22-24 October 2019

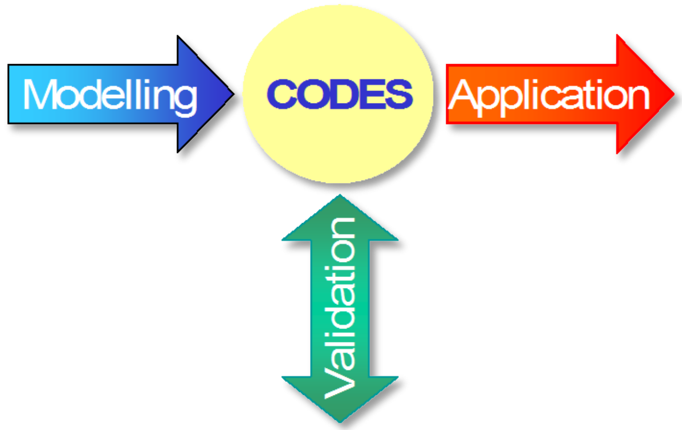
Institute for Applied Materials IAM-AWP & Program NUSAFE

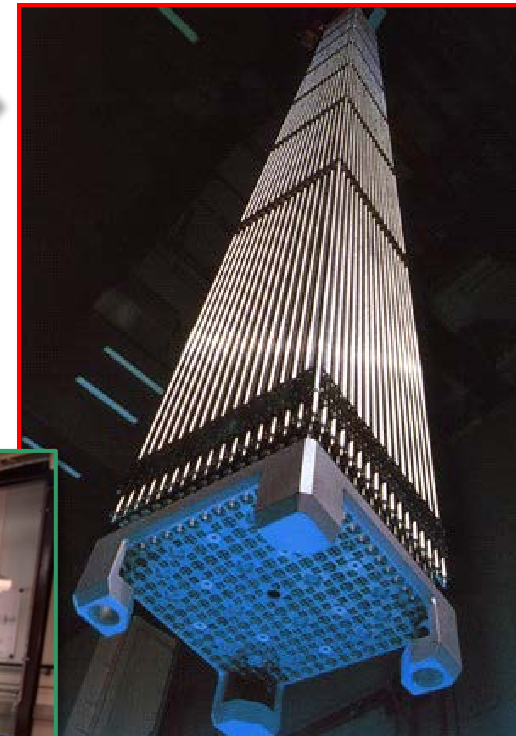


QUENCH program at KIT

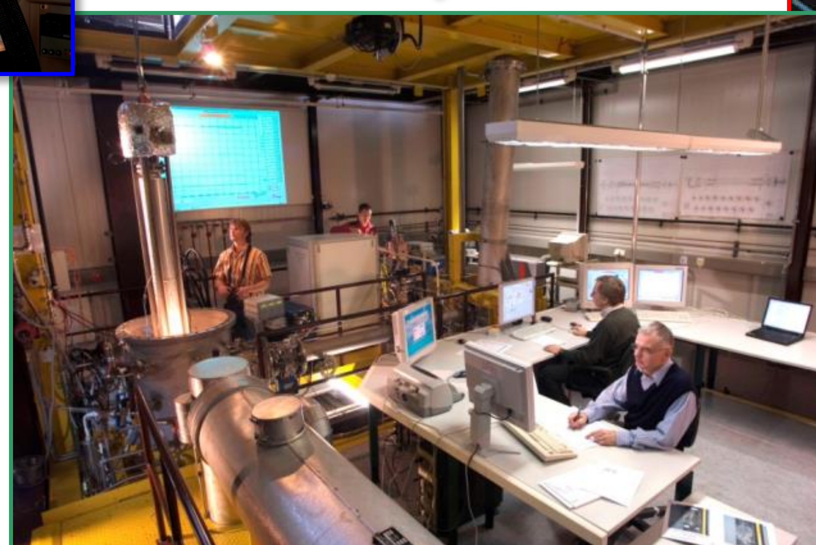
Investigation of hydrogen source term and materials interactions during LOCA and early phase of severe accidents including reflood

Separate-effects tests



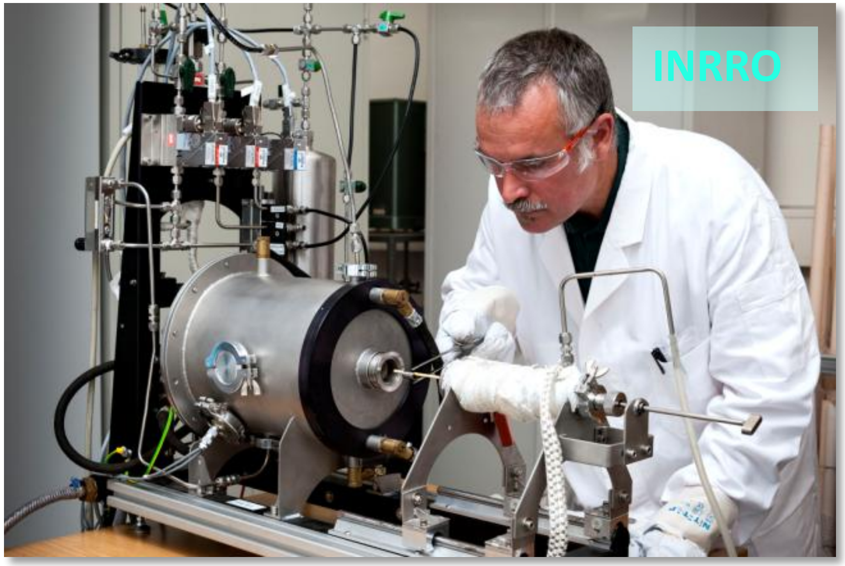


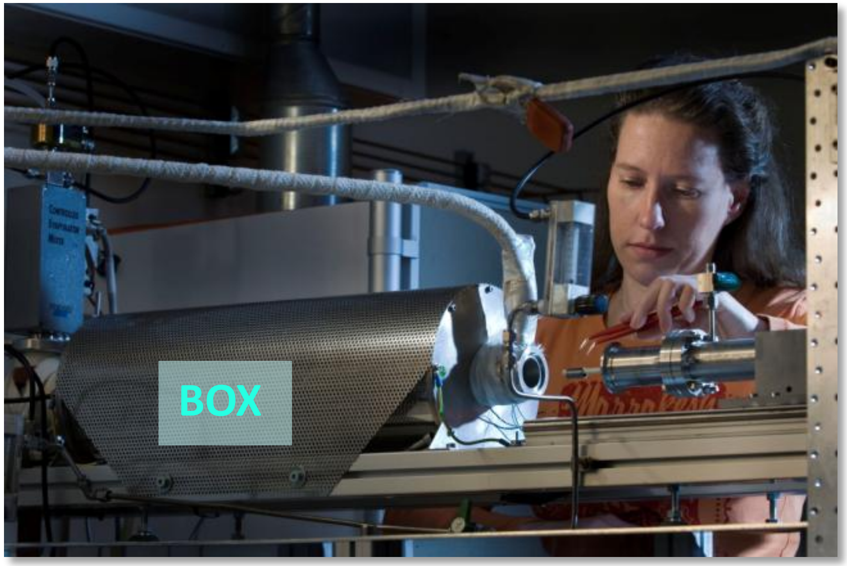
PWR fuel element

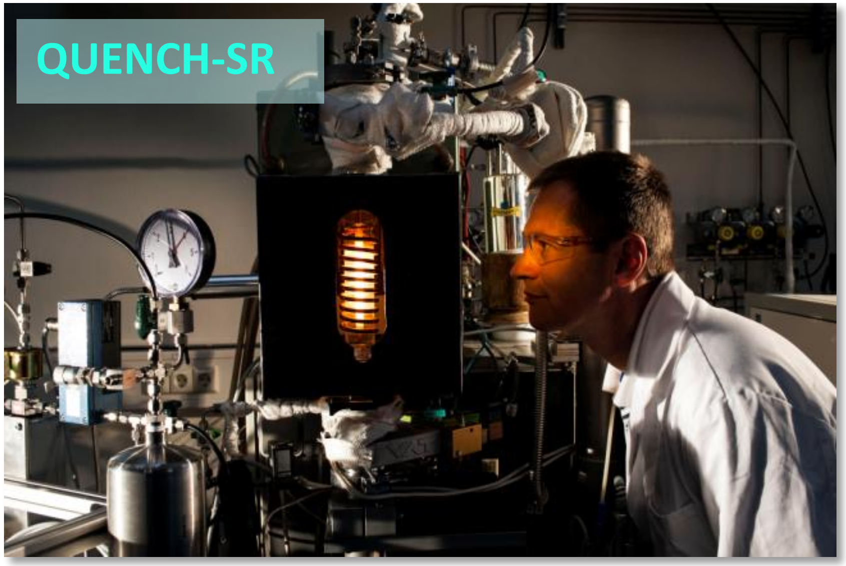


Bundle experiments

QUENCH separate-effects tests: Main setups







Core materials in Light Water Reactors

UO_2(/PuO_2) fuel:	100-200 t
Zry cladding + grid spacers:	20-40 t
Zry canister (BWR):	40 t
Various steels, Inconel:	>500 t (incl. RPV)
B_4C absorber (BWR, VVER, …):	0.3-2 t
AgInCd absorber (PWR):	3-5 t

Environment

- **Water, steam**
- Air
- Nitrogen

(Air, Nitrogen:) After failure of RPV/primary circuit and in spent fuel pool

PWR fuel assembly

BWR control blade

Topics

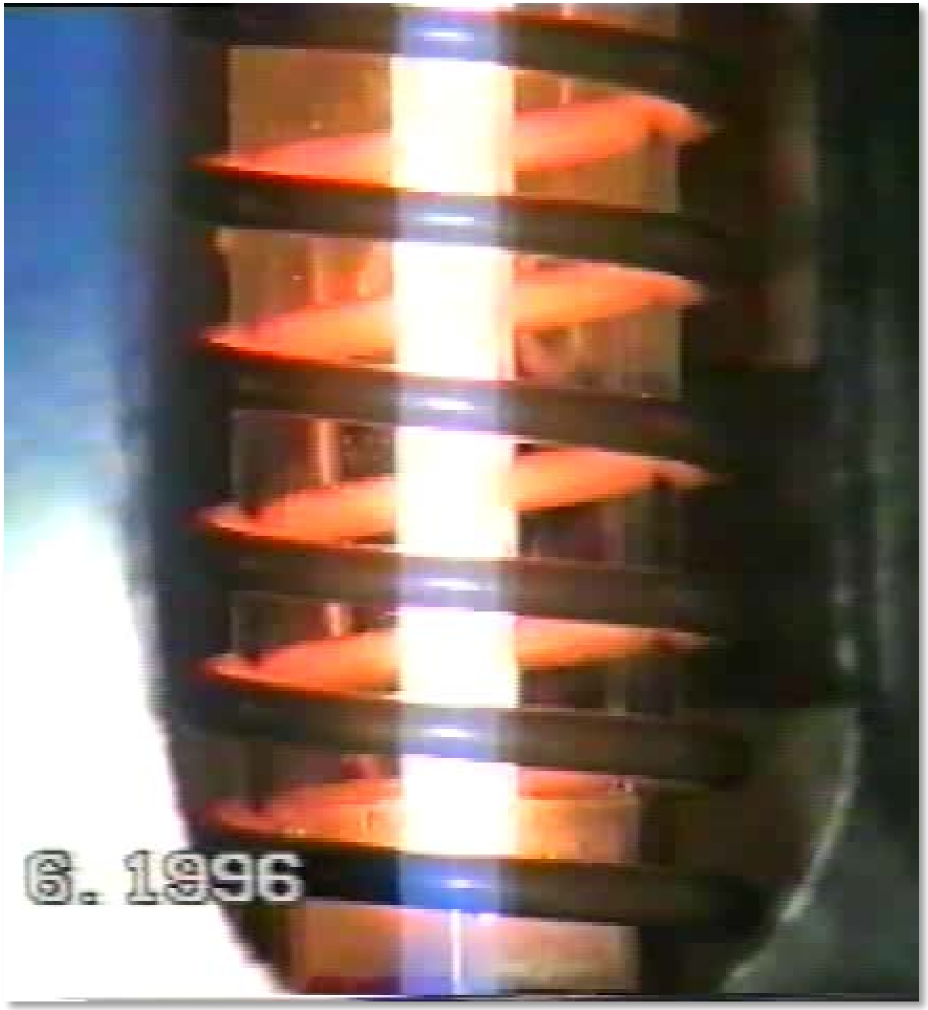
- Generally, high-temperature (> 600°C) oxidation and materials interactions of zirconium alloys (cladding), absorber materials, and structure materials in well-defined atmospheres
- Quenching of pre-oxidized cladding
- Oxide shell failure criterion
- Interaction between Zr melt and ZrO_2 (UO_2) ceramic
- Zr alloy oxidation in steam, oxygen, air, mixtures
- Hydrogen release and absorption
- B_4C absorber rod oxidation degradation
- AgInCd absorber rod failure
- ATF cladding materials
- …

➢ SETs were made mostly in connection with corresponding bundle tests

Early experiments

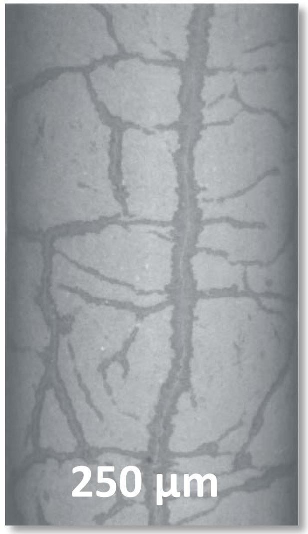
Single-rod QUENCH tests

- 15-cm rods filled with ZrO_2 pellets
- Direct inductive heating
- Video recording
- Mass spectrometer for analysis of hydrogen release
- Parameters:
  - Pre-oxidation 0-350 µm
  - 1000-1600°C at onset of quenching
  - Quenching with hot/cold water or steam
  - Flooding rate 1.5 cm/s

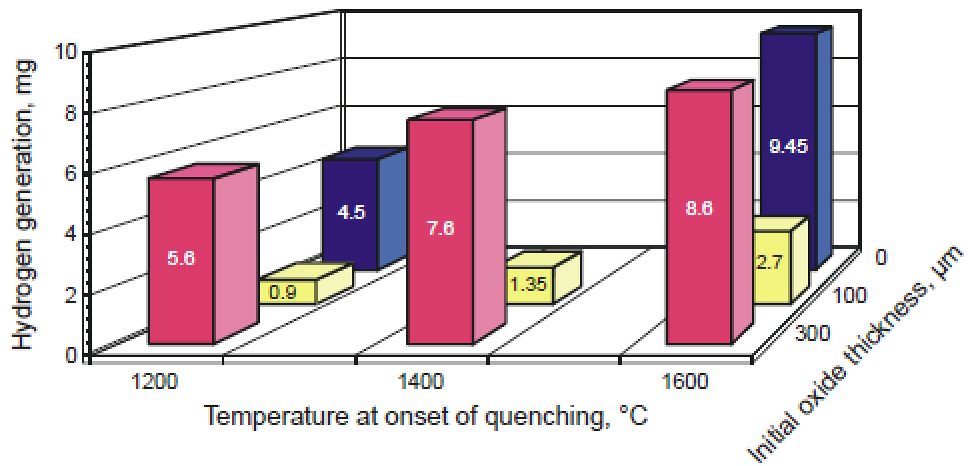


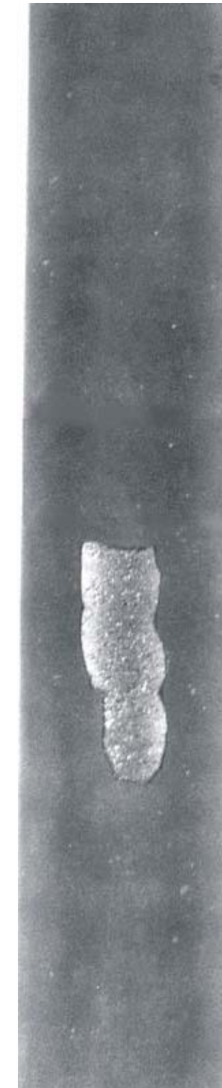
Reflood from 1400°C

Single-rod QUENCH tests – Main results

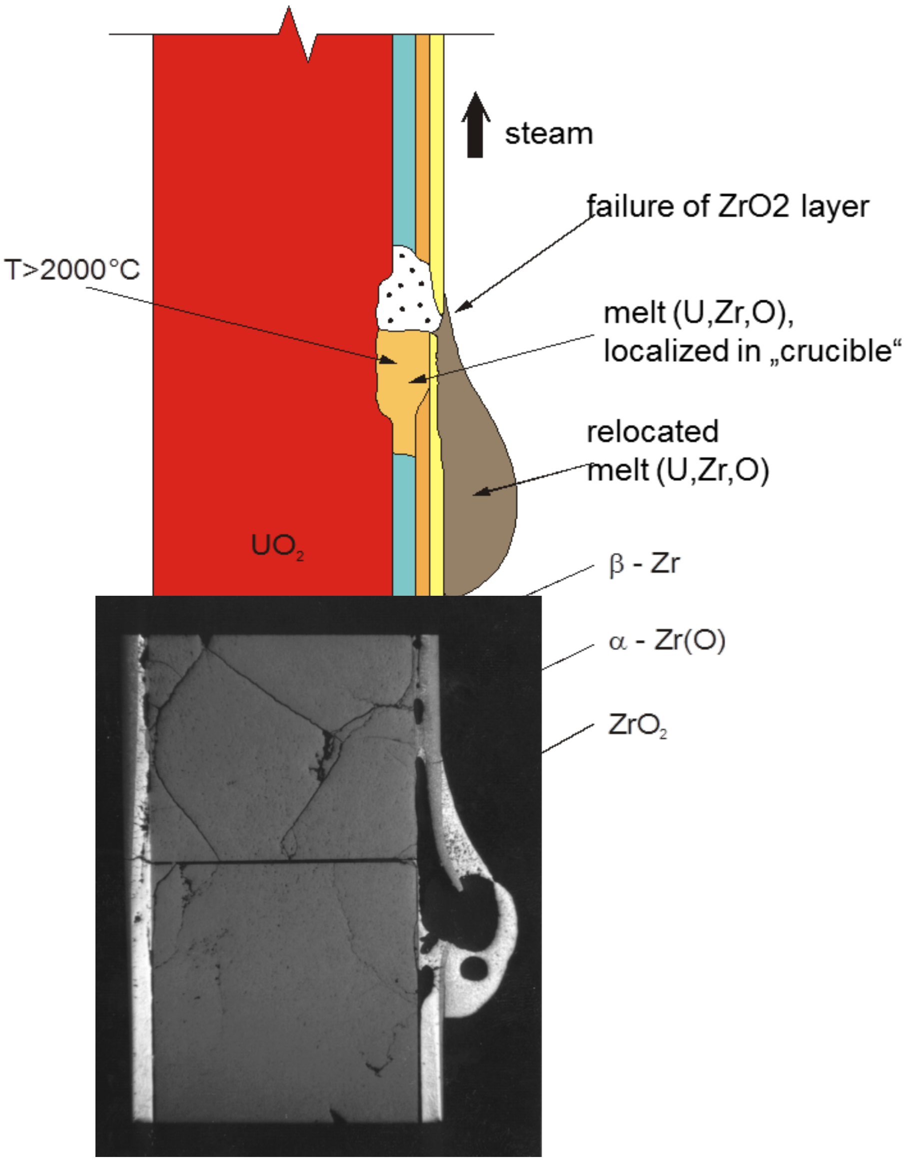


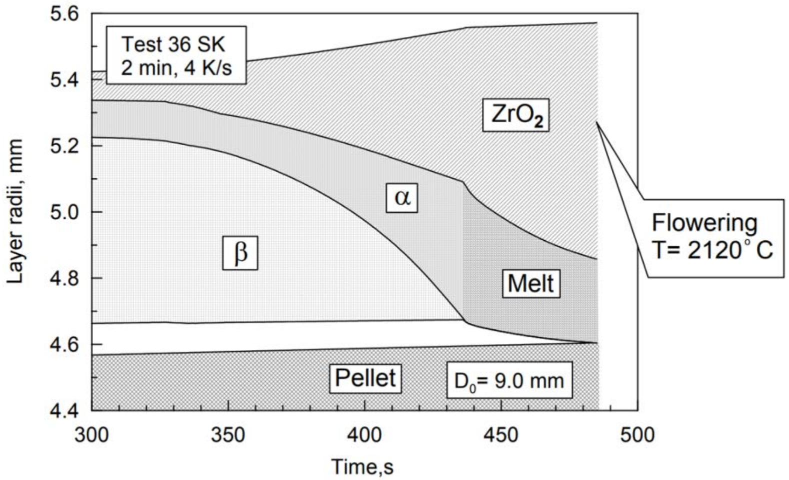
- Through-wall crack for pre-oxidation >200 µm with a density of 0.5 mm/mm^2
- Oxidation of crack surfaces connected with hydrogen absorption by the metal
- Localized spalling of thick oxide scales



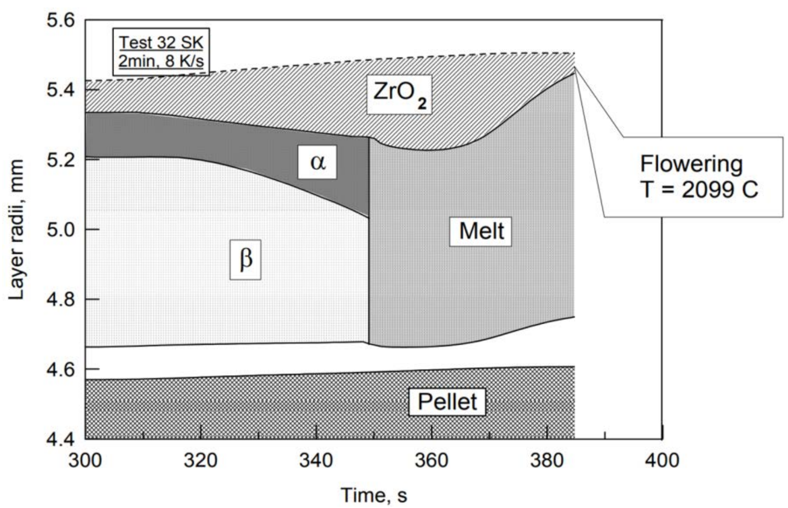


Oxide shell failure





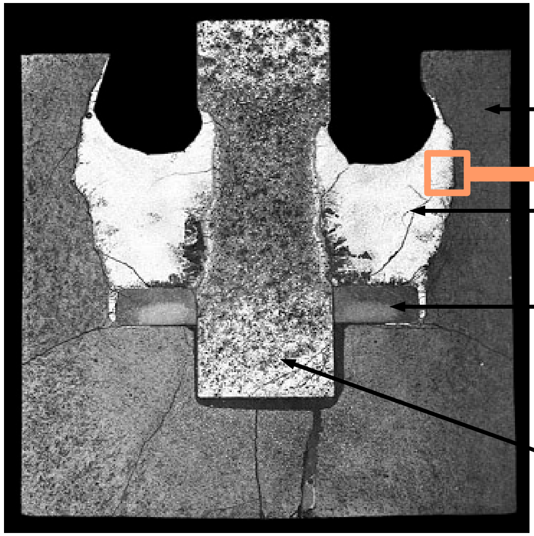
SVECHA simulation: slow heating



SVECHA simulation: rapid heating

UO_2/ZrO_2 dissolution by Zr melt (COLOSS project)

Karlsruhe Institute of Technology

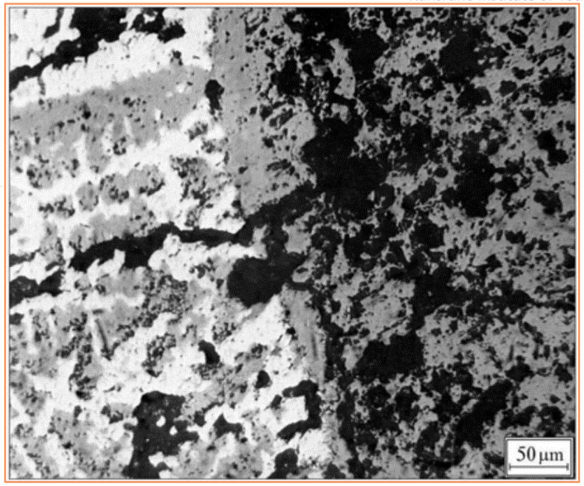


UO_2 crucible

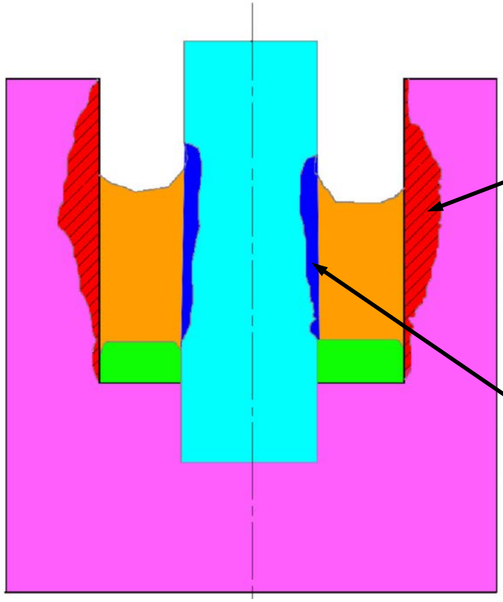
Melt (initially Zry)

Y_2O_3 disc

ZrO_2 rod

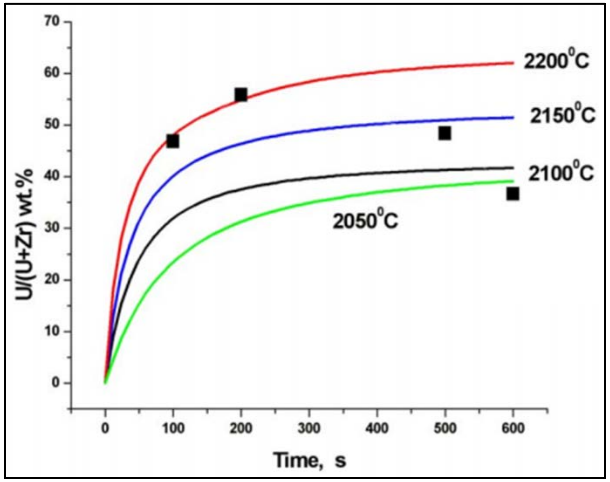


$(U, Zr)O_{2-x}$ precipitates in melt and transition zone between melt and crucible



Dissolved UO_2

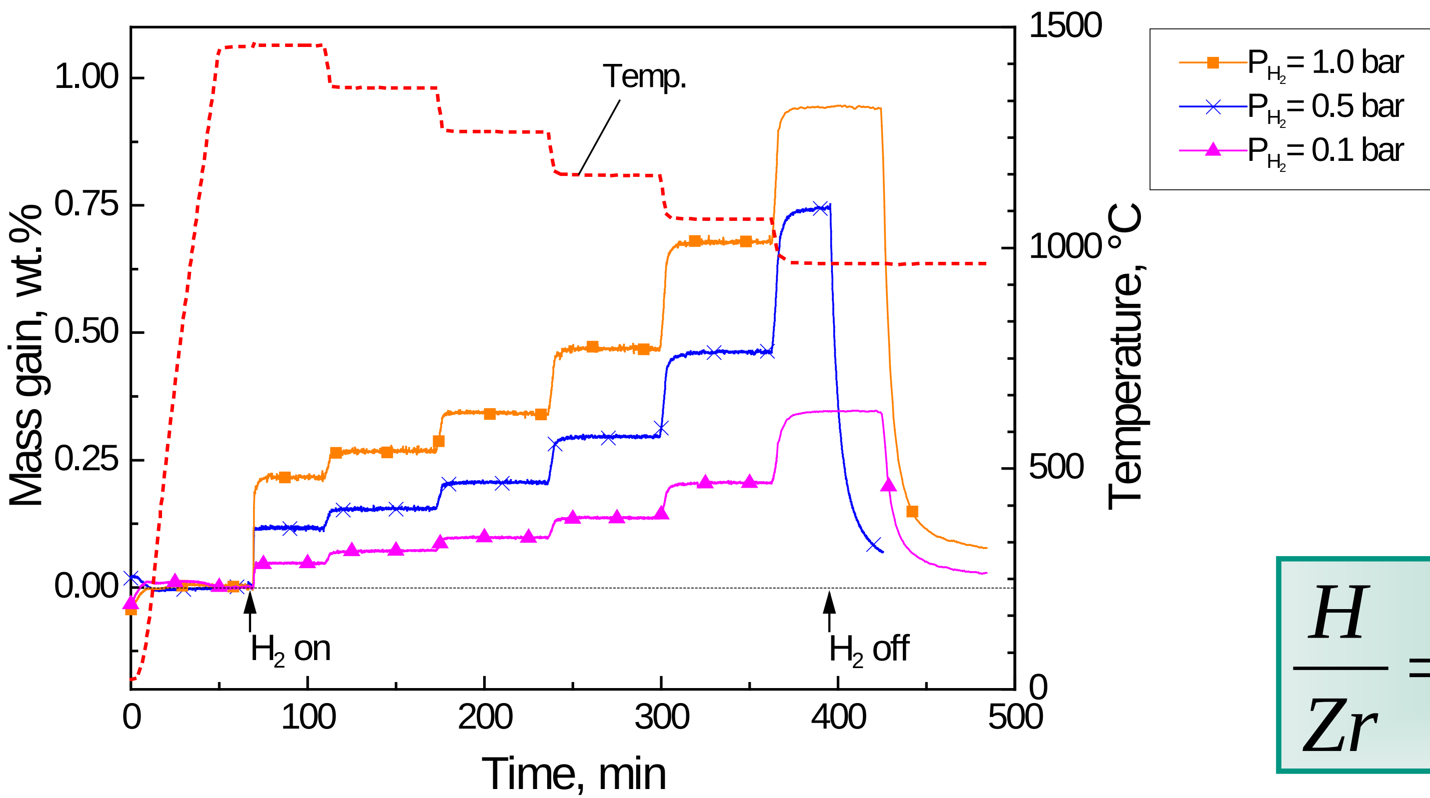
Dissolved ZrO_2



SVECHA simulation: calculated and measured U content in the melt

IAM Institute for Applied Materials

Hydrogen uptake of Zircaloy-4



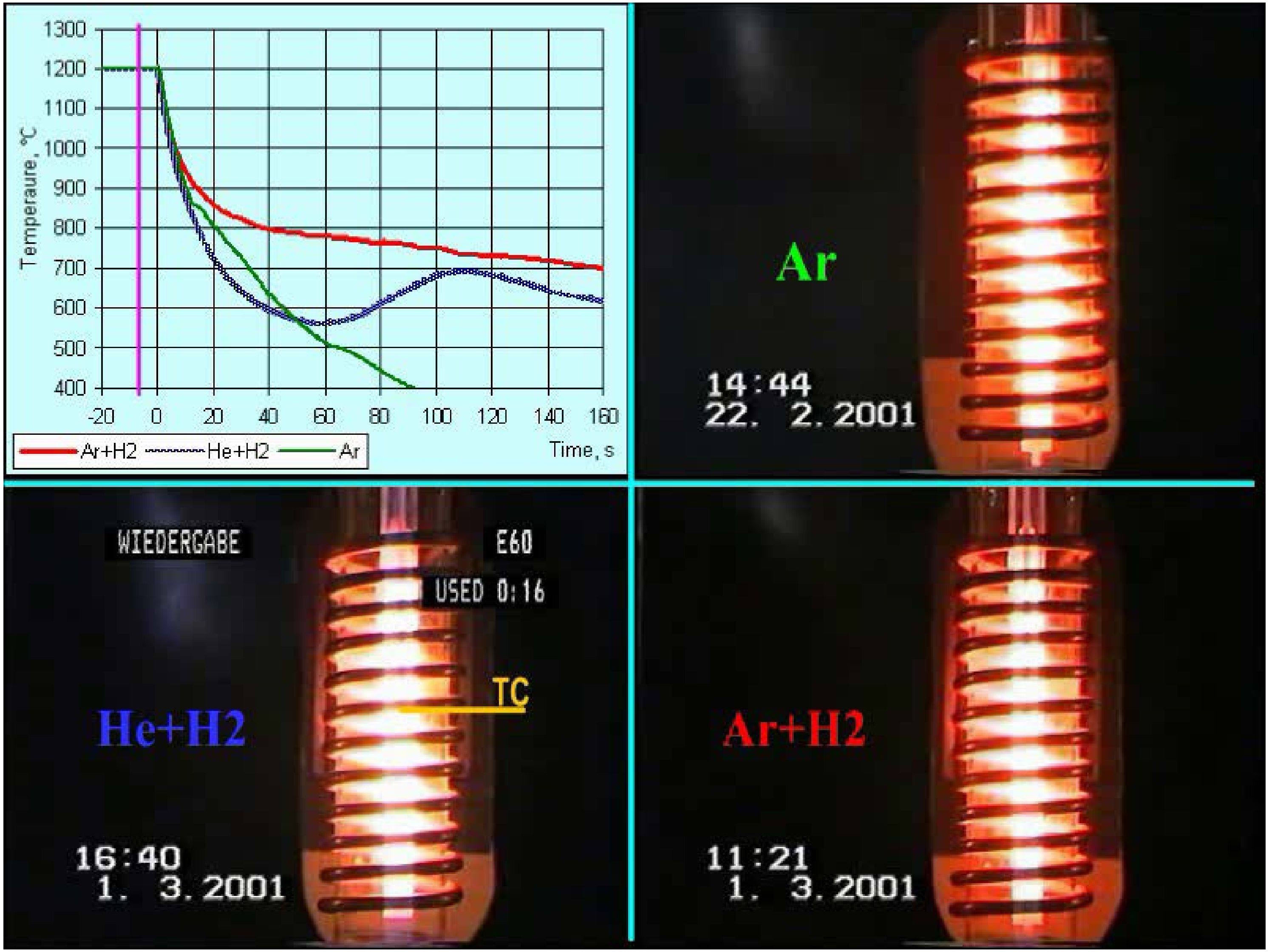
$$\frac{H}{Zr} = k_S \cdot \sqrt{P_{H_2}}$$

Sieverts' law

- Sieverts' law constant determined
- No difference between Zry-4 and M5®
- Reduced H solubility with increasing O content in the metal
- Fast establishment of equilibrium

Exothermal effect of hydrogen uptake

Karlsruhe Institute of Technology



IAM Institute for Applied Materials

Oxidation of zirconium alloys and hydrogen behavior

High-temperature oxidation of zirconium alloys

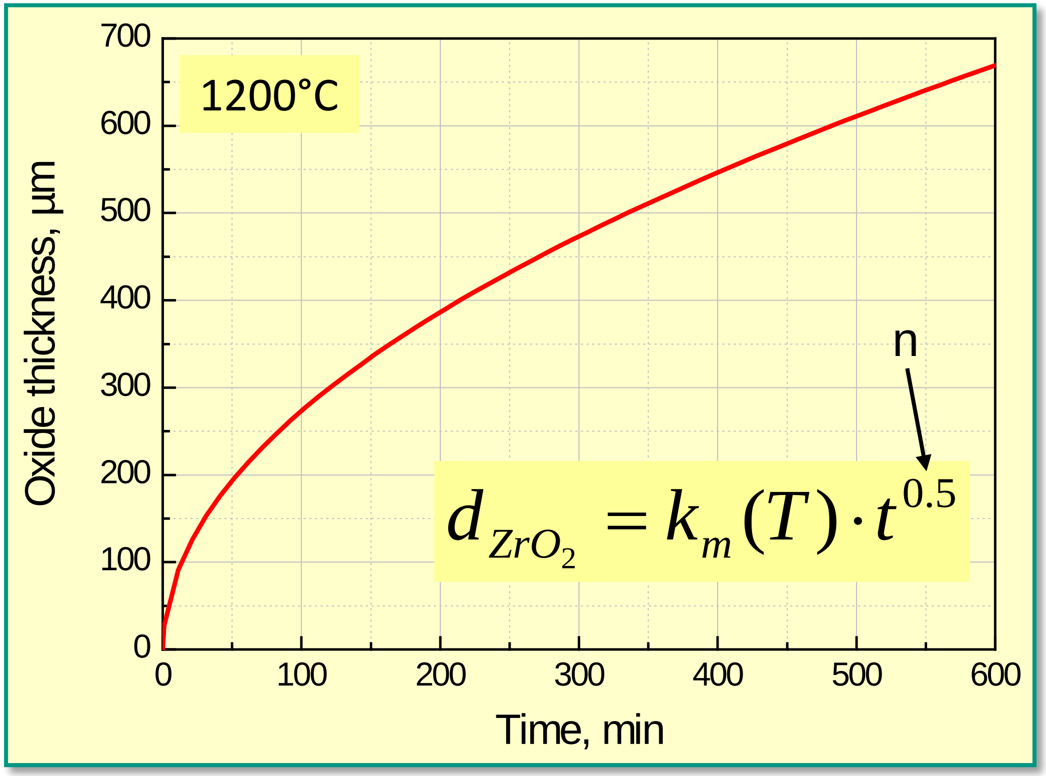
- Most cladding alloys consist of 98-99 wt% zirconium plus some alloying elements (Sn, Nb, Fe, Cr, …)

Element	Zircaloy-4	D4	M5	E110	ZIRLO
Nb	-	-	**1**	**1**	**1**
Sn	**1.5**	**0.5**	0.01	**-**	**1**
Fe	0.2	**0.5**	0.05	0.008	0.11
Cr	0.1	0.2	0.015	0.002	< 0.01

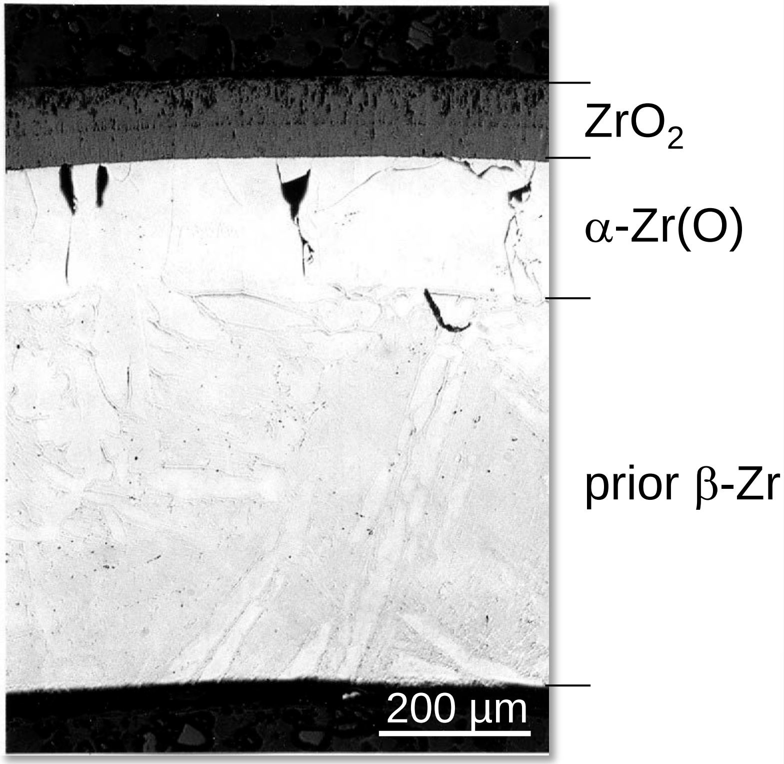
- In steam, oxygen, nitrogen, air, and various mixtures
- Temperature: 600-1600°C

Oxidation in steam (oxygen): Text book knowledge

- Parabolic oxidation correlations determined by the diffusion of oxygen through growing oxide scale



Oxide thickness during oxidation of Zry at 1200°C in steam

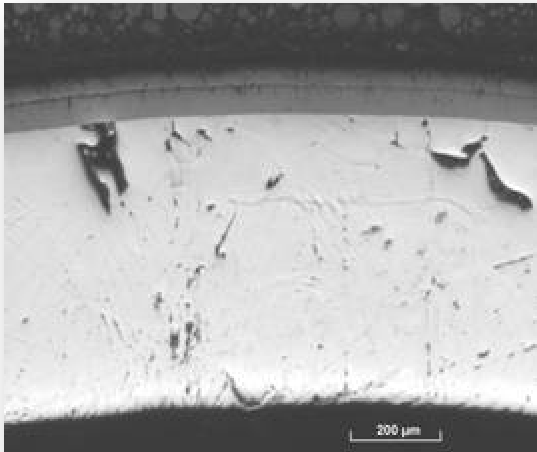


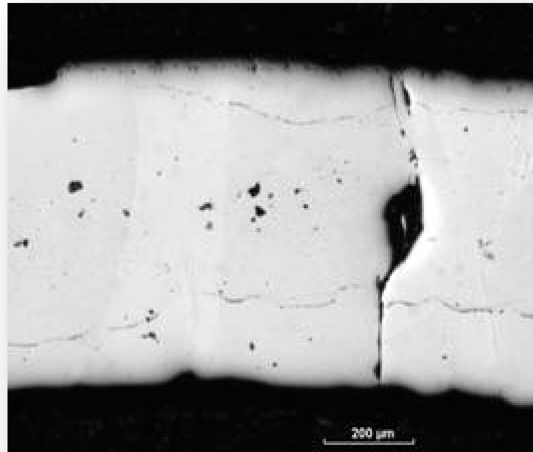
20 min at 1200°C in steam

Deviation from parabolic kinetics

- Starvation conditions at low oxidant flow rates
- Cubic (sub-parabolic) kinetics for $T < 1000°C$ ($n < 0.5$)
- Breakaway ($n \approx 1$ after transition)
- Nitrogen ($n \approx 1$ after transition)

Steam starvation

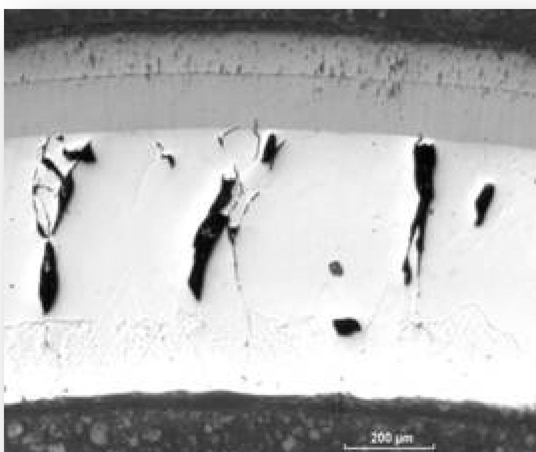


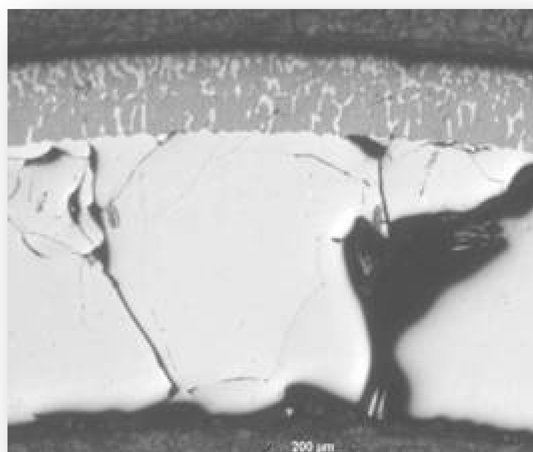


Oxidation

Steam starvation at 1700 K

Dissolution of oxide scale



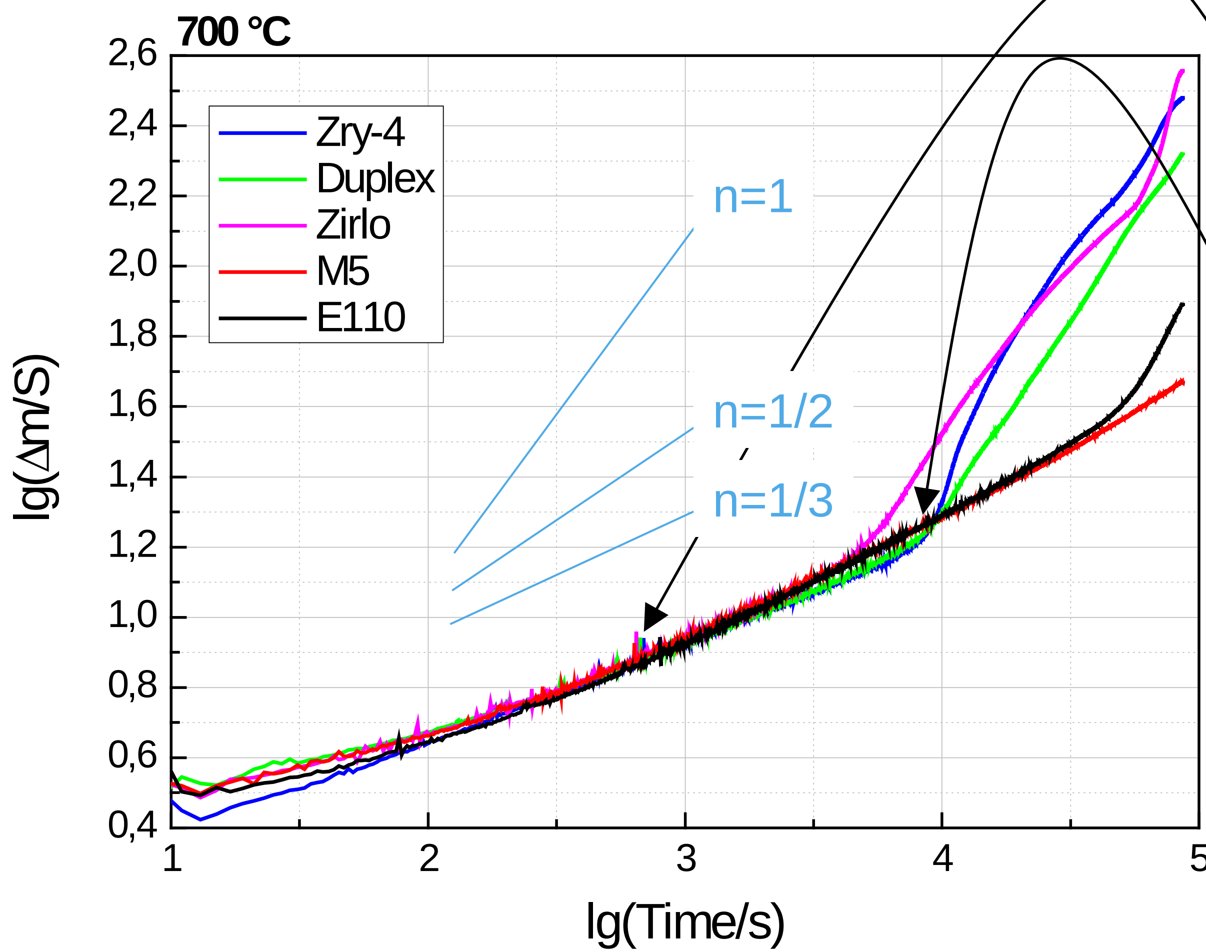


Thinning of oxide scale and precipitation of α-Zr(O) in oxide

- Weakening of protective effect of ZrO_2 oxide layer

Oxidation in steam (oxygen)

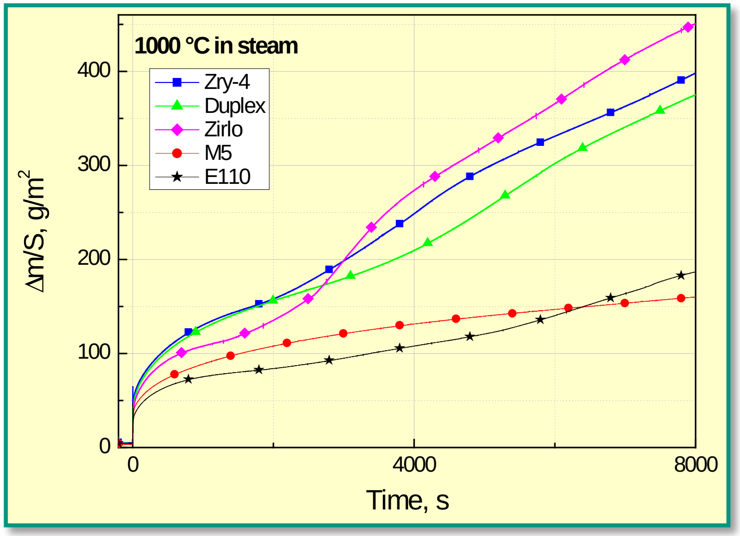
- Deviations from parabolic kinetics at temperatures <1050°C

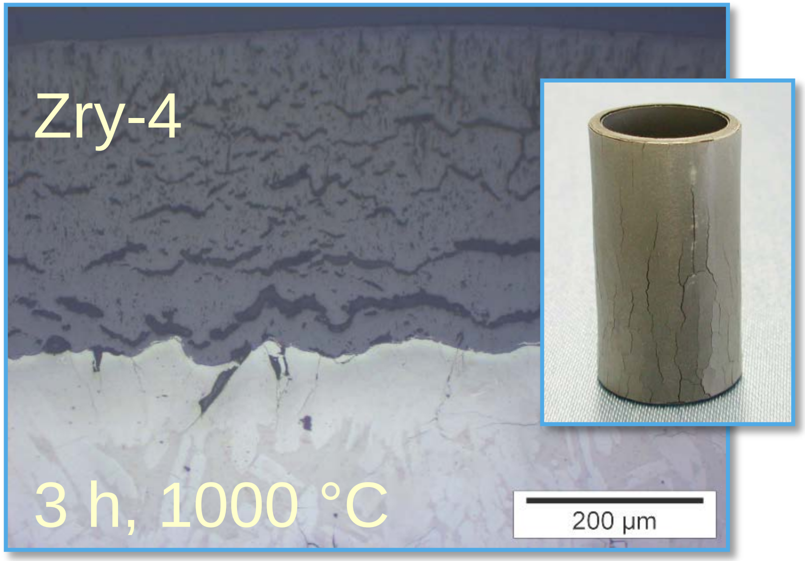


- Sub-parabolic (cubic) kinetics
- Transition from (sub-) parabolic to linear kinetics after critical time / oxide thickness due to breakaway
- Similar kinetics of all alloys before transition, but strongly varying behavior at and after transition

Breakaway oxidation

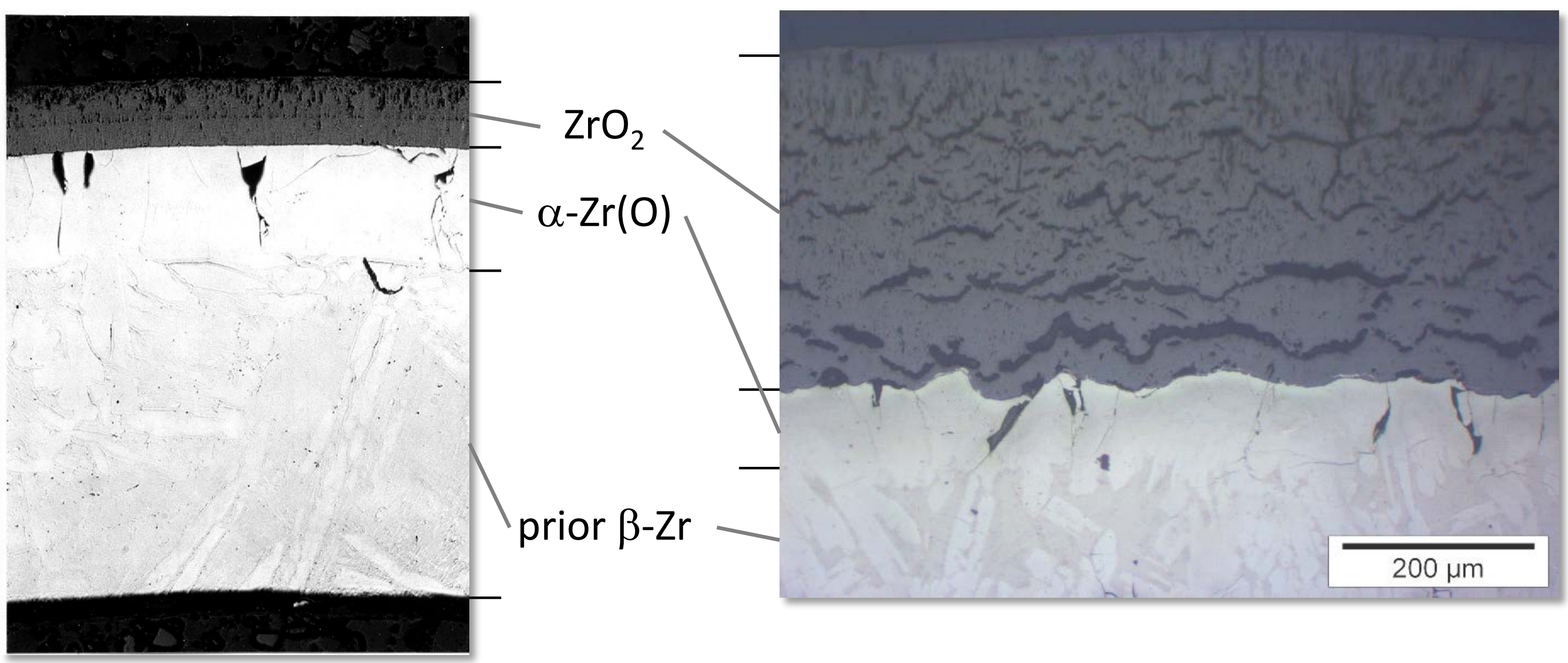
- Loss of protective properties of oxide scale due to its mechanical failure.
- Breakaway is caused by phase transformation from meta-stable tetragonal to monoclinic oxide and corresponding change in density up to ca. 1050°C.
- Critical times and oxide thicknesses for breakaway strongly depend on type of alloy and boundary conditions (30-60 min at 1000°C and 8 h at 600°C).
- During breakaway significant amounts of hydrogen can be absorbed (>40 at.%, 7000 wppm) due to local enrichment of H_2 in pores and cracks near the metal/oxide boundary ("hydrogen pump").





Hydrogen uptake during HT oxidation of Zry in steam

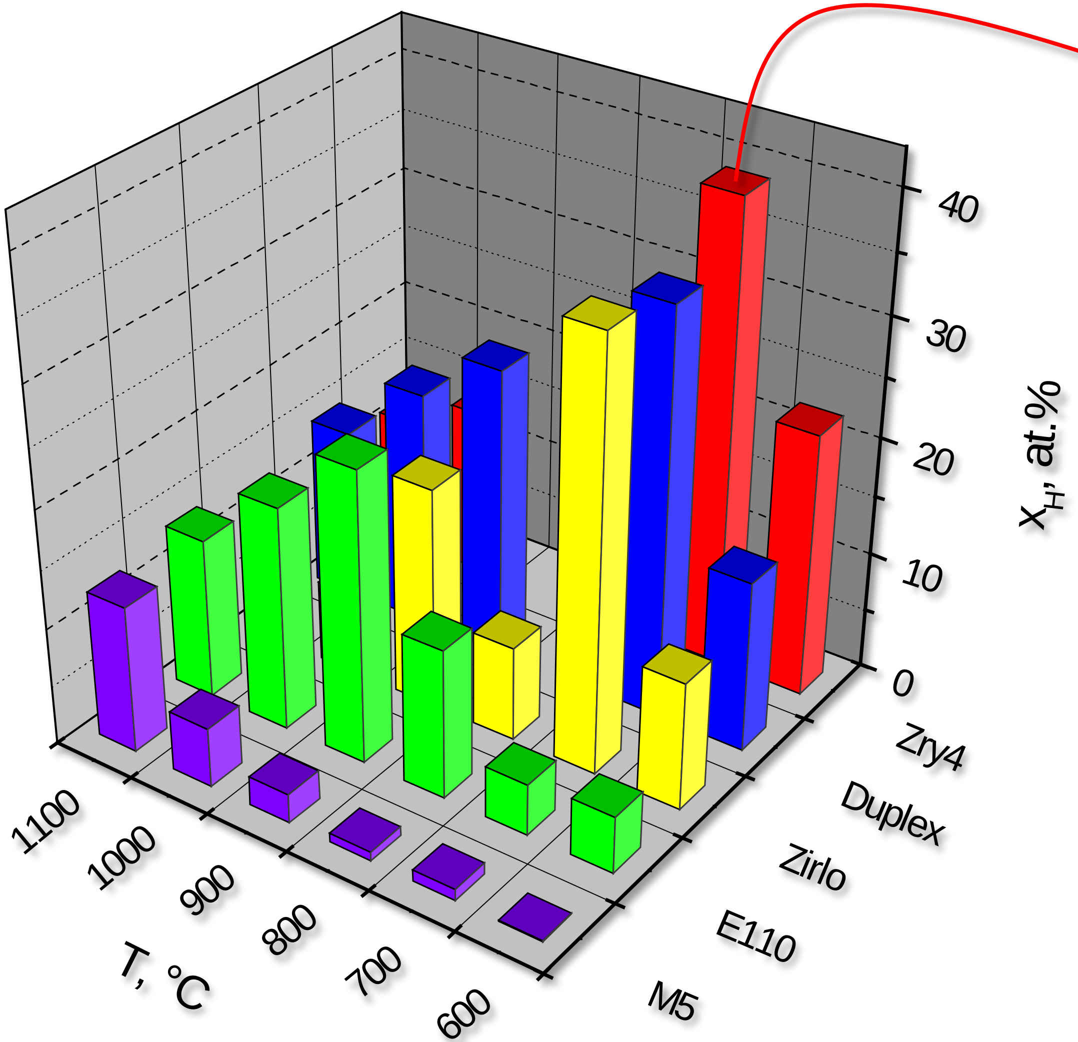
- $Zr + 2H_2O \rightarrow ZrO_2 + 2H_2$
- $H_2(gas) \leftrightarrow 2H(diss)$
- Oxide scale acts as a barrier for uptake and release of hydrogen

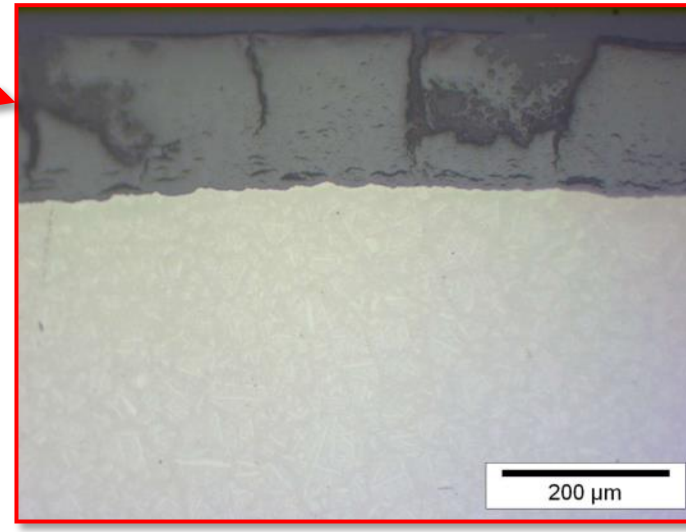


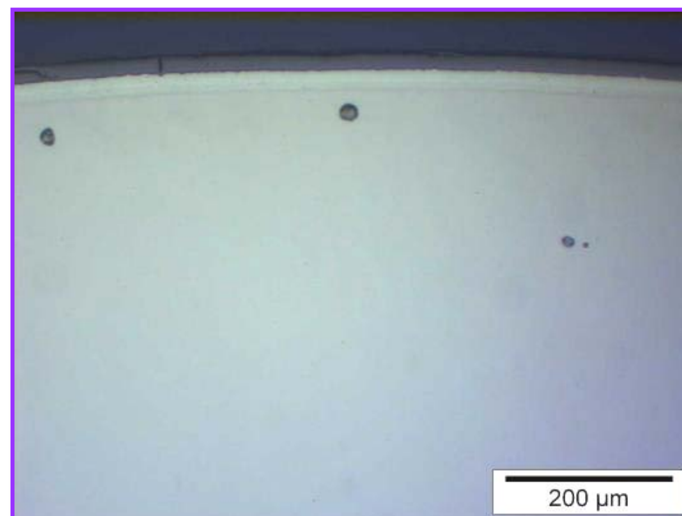
20 min at 1200°C in steam

3h at 1000°C in steam

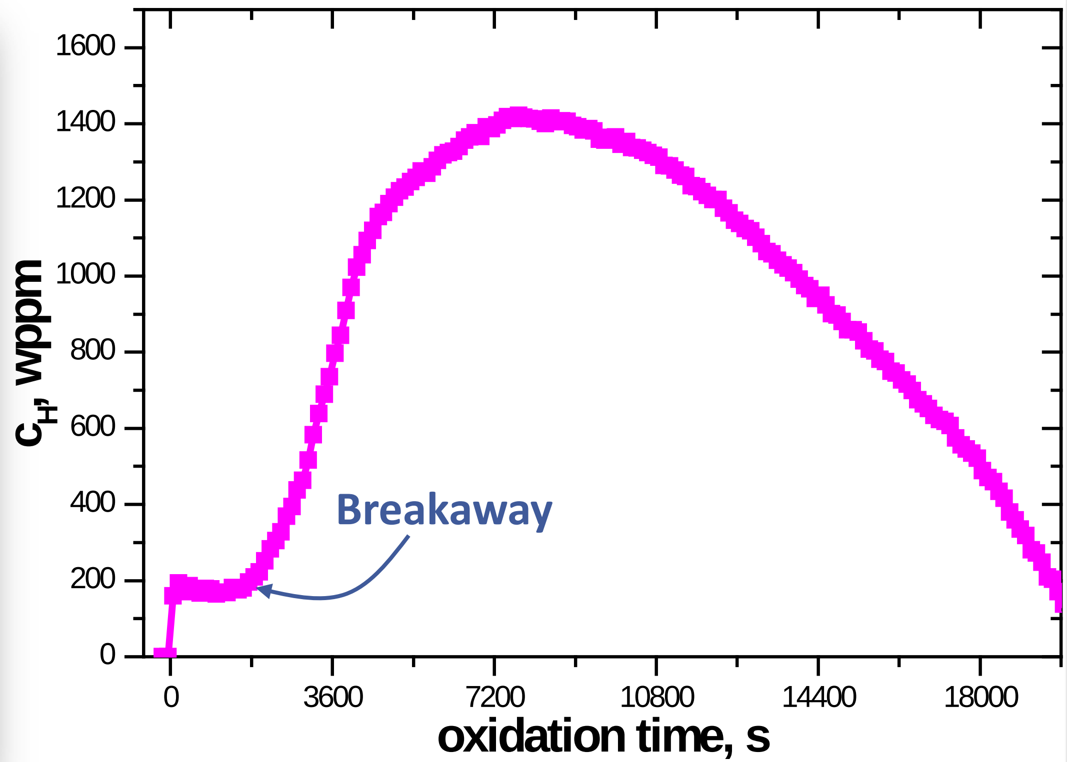
Correlation of H absorption and oxide morphology







In-situ investigation of hydrogen uptake during oxidation of Zry in steam by neutron radiography



Zry-4, 1000°C
30 g/h steam, 30 l/h argon

- Rapid initial hydrogen uptake
- Further strong hydrogen absorption after transition to breakaway

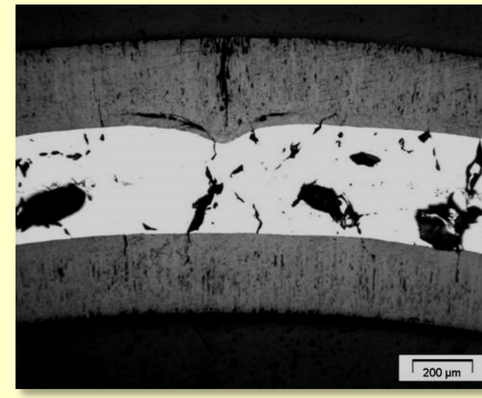
Oxidation in atmospheres containing nitrogen

… under prototypical conditions, including

- Pre-oxidation in steam/O_2
- Tests in mixed air(N_2)-steam atmospheres

1 hour at 1200 °C in

steam | 50/50 steam/air | air



1.5 h steam

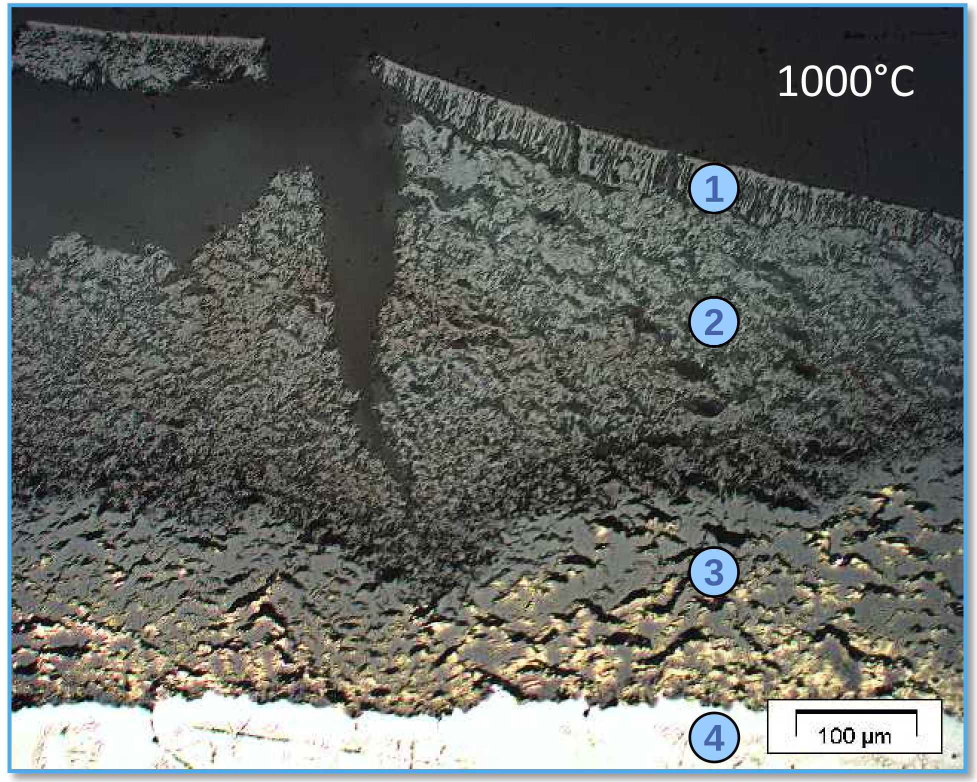
1 h steam/N_2 (50/50)

➡ Loss of barrier effect against FP product release

Mechanism of air oxidation

- Diffusion of air through imperfections in the oxide scale to the metal/oxide interface
- Consumption of oxygen
- Remaining nitrogen reacts with zirconium and forms ZrN
- ZrN is re-oxidized by fresh air with continuing reaction associated with a volume increase by 48%

➡ Formation of porous and non-protective oxide scales



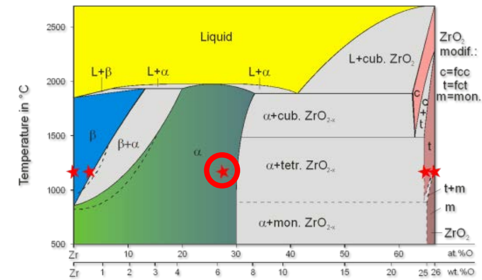
1 – initially formed dense oxide ZrO_2

2 – porous oxide after oxidation of ZrN

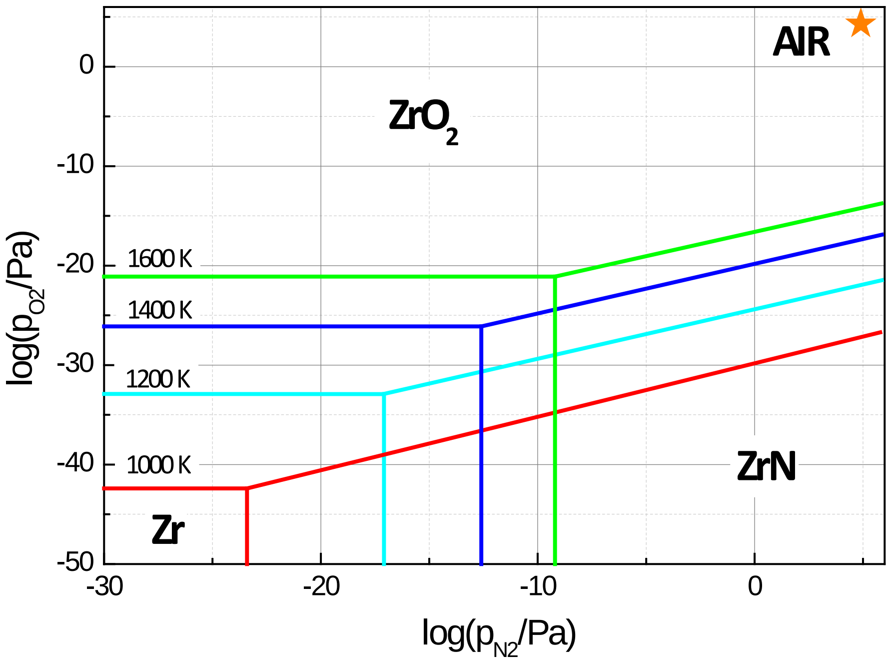
3 – ZrO_2 / ZrN mixture

4 – α-Zr(O)

Mechanism of air oxidation

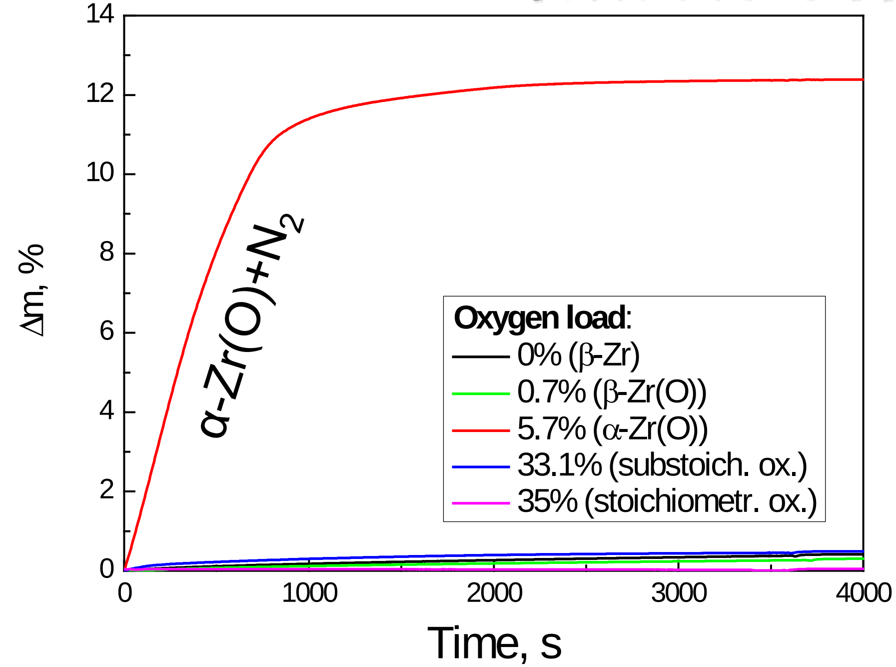


Thermodynamic view



Stability diagram Zr-O-N

Kinetic view



Reaction of ZrO_x with nitrogen (1200°C)

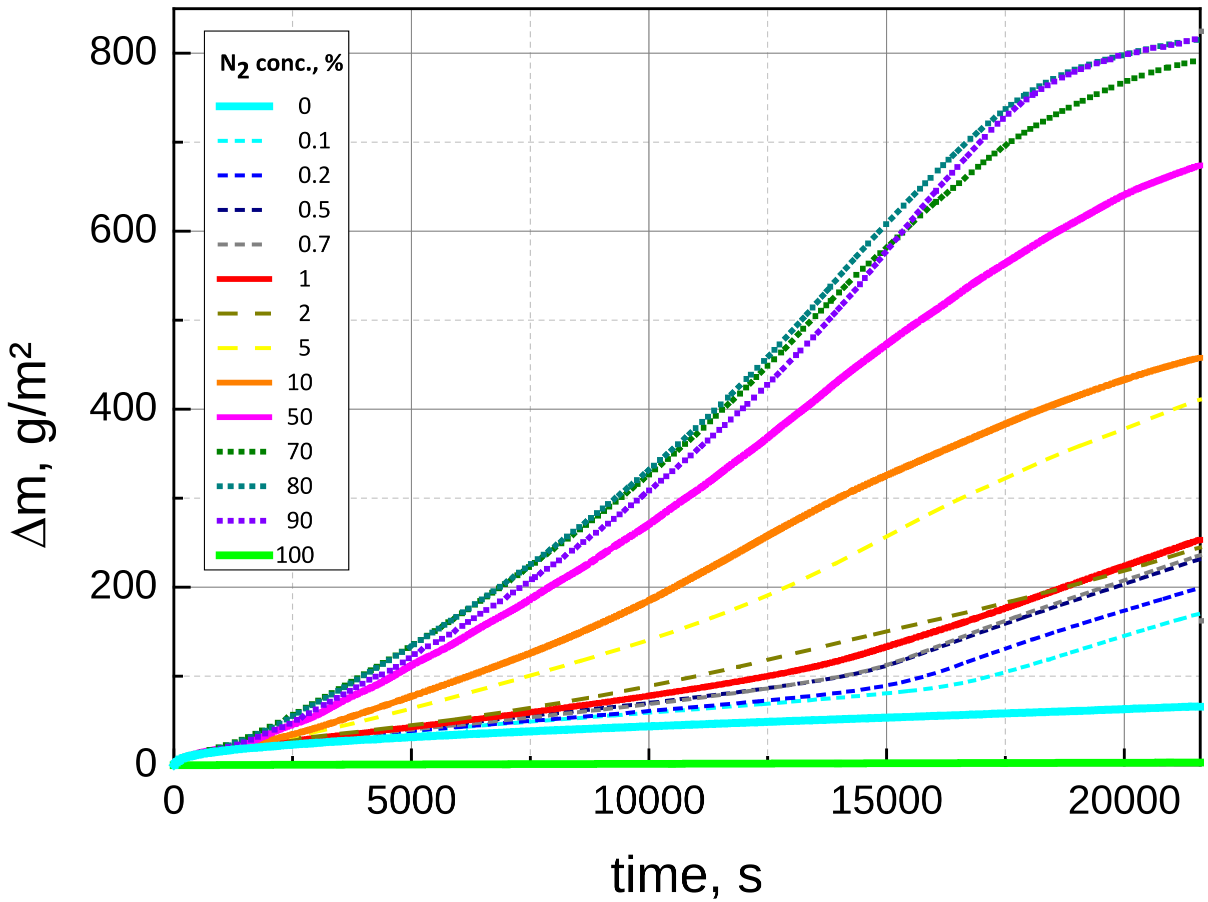
- ZrN only stable at very low oxygen partial pressure (activity)
- Fast reaction of oxygen-stabilized Zr with nitrogen

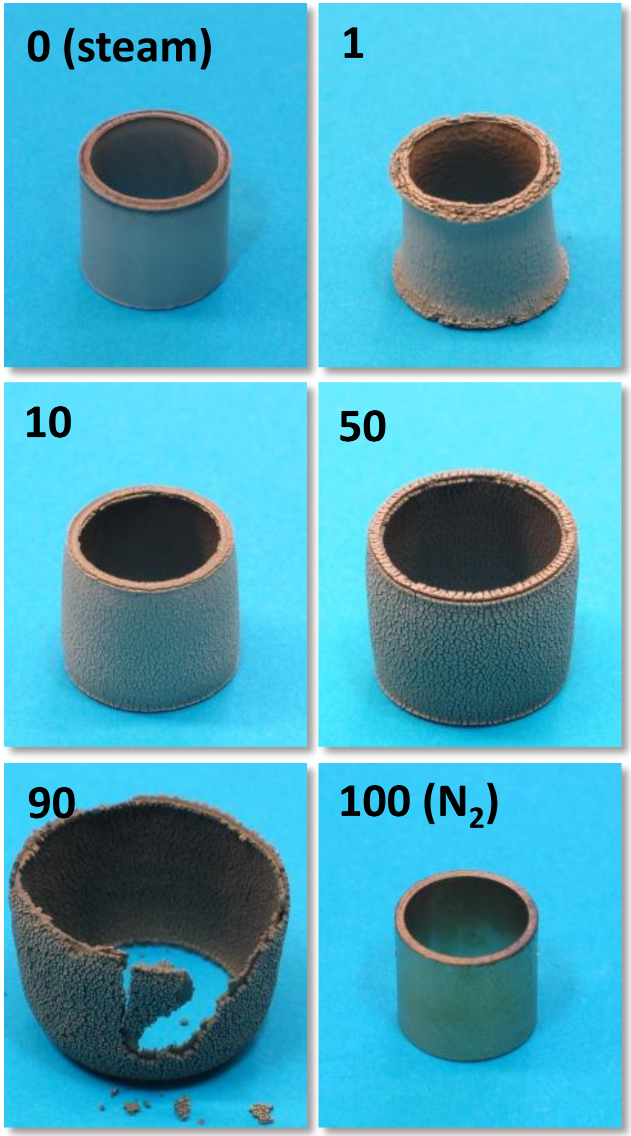
- Both conditions are present locally at the metal-oxide interface

IAM Institute for Applied Materials

Oxidation in mixed steam-nitrogen at 800°C

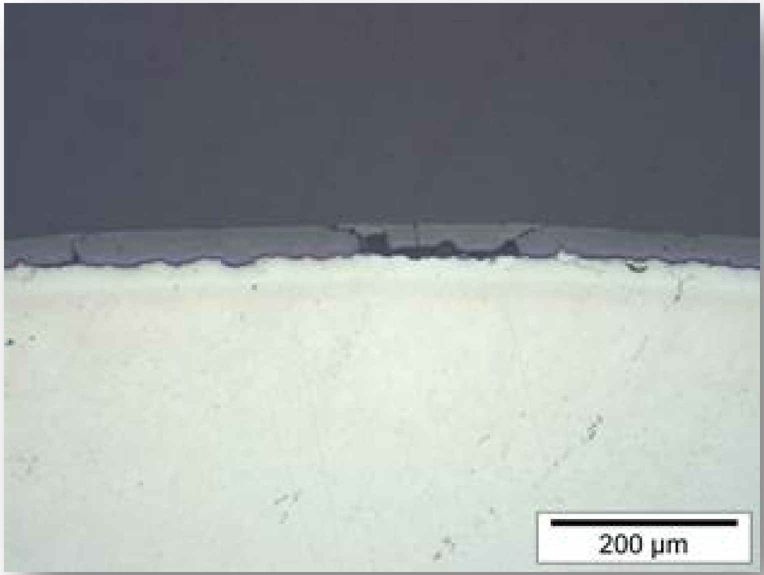
TG results at 800°C, 6 hours



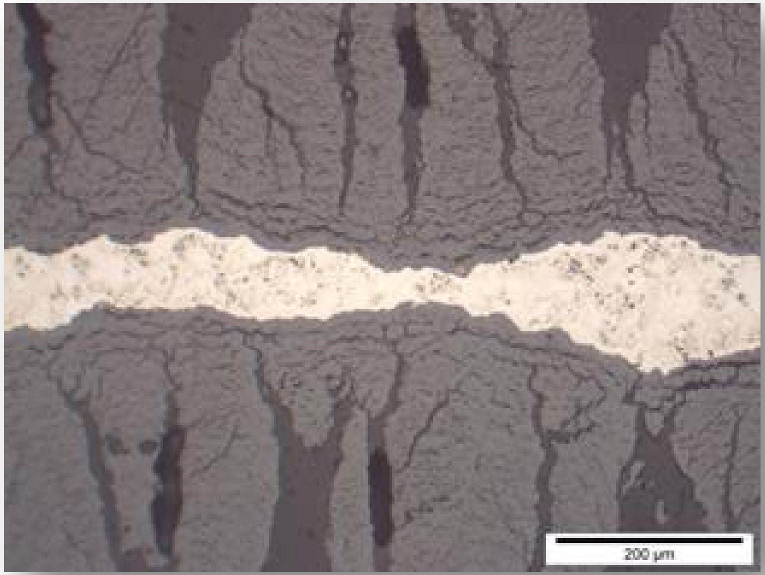


Oxidation in mixed steam-nitrogen at 800°C

6 hour at 800 °C in steam

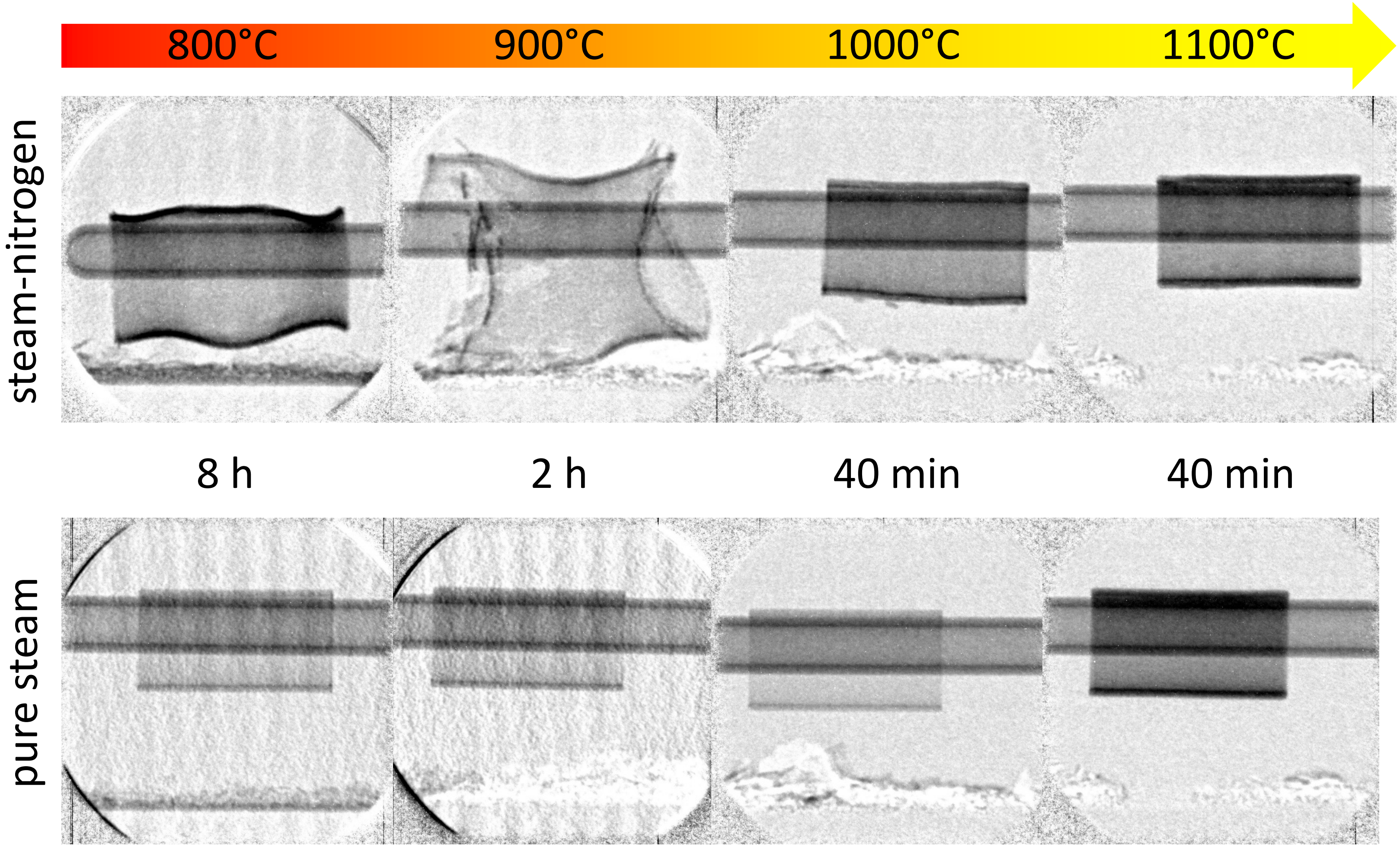


6 hour at 800 °C in 50/50 steam/N_2

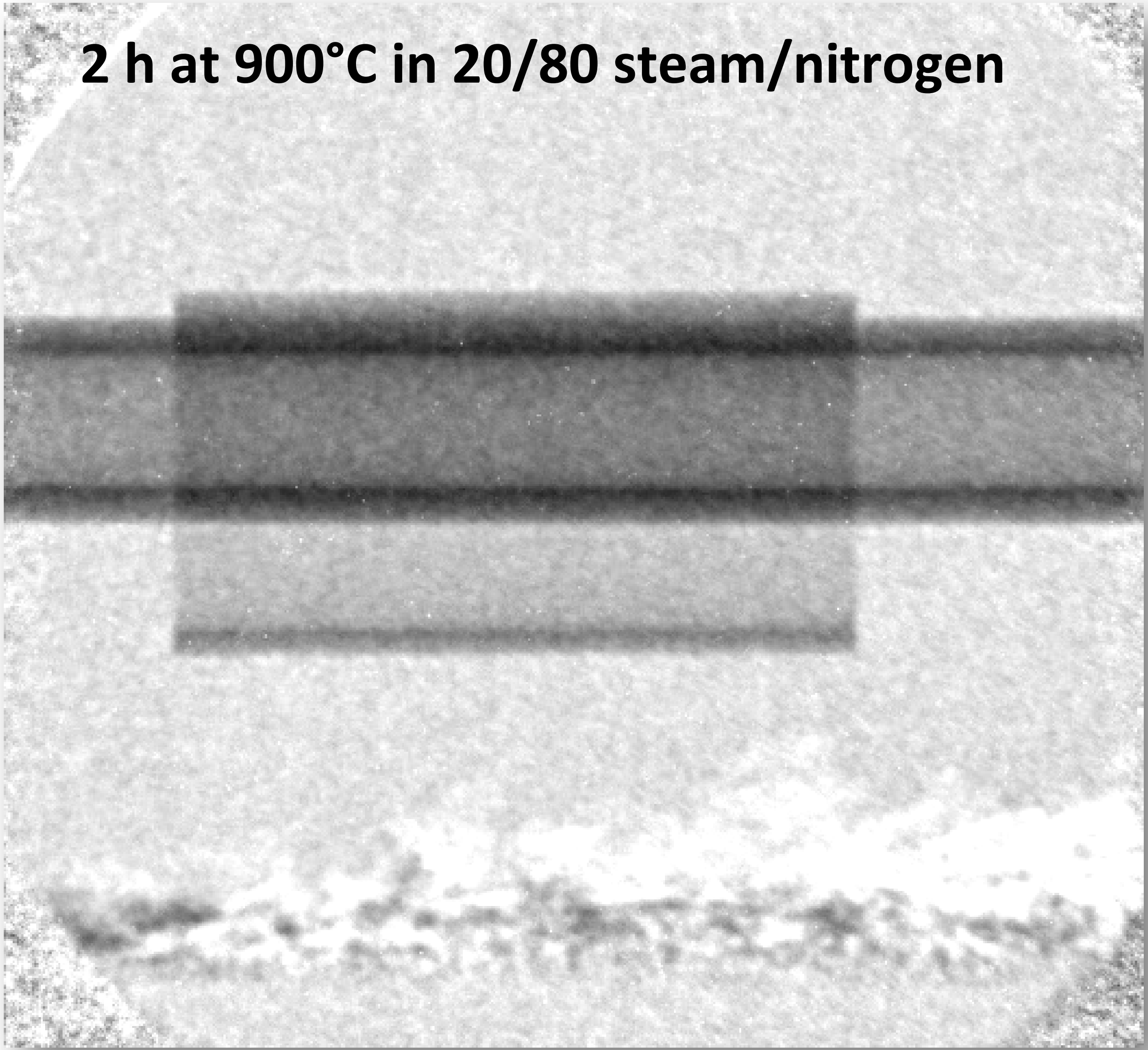


- Strong effect of nitrogen on oxidation and degradation
- Nitrogen acts like a catalyst (NOT like an inert gas)
- Enhanced hydrogen source term by oxidation in mixtures containing nitrogen

In-situ NR of Zircaloy-4 in steam and steam-nitrogen



In-situ NR of Zircaloy-4 in steam-nitrogen

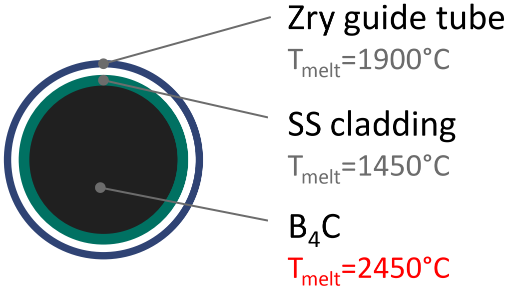


Control rod behavior

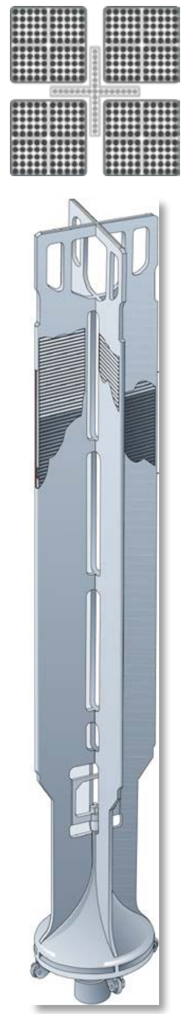
Absorber materials in LWRs

Boron carbide

- Used in boiling water reactors (BWR), VVERs, some pressurized water reactors (PWR)
- Control rods (PWR) or cross-shaped blades (BWR)
- Surrounded by stainless steel (cladding, blades) and Zry (guide tubes, canisters)



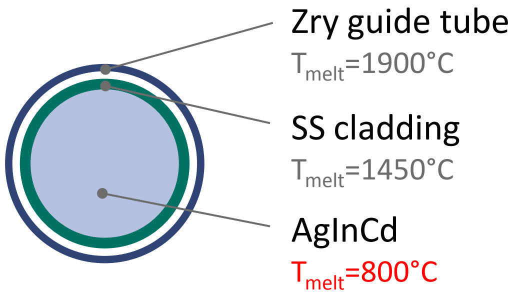
BWR control rod


BWR control blade

AgInCd alloy

- Used in PWRs
- Surrounded by stainless steel cladding and Zry guide tubes
- Rods in Zry guide tubes combined in control rod assemblies


PWR control rod assembly



PWR control rod

Degradation of B_4C control rods (1-pellet)

Post-test appearance and axial cross section of B_4C/SS/Zry specimens after 1 hour isothermal tests at temperatures between 1000 and 1600 °C

1000°C

1200°C

1300°C

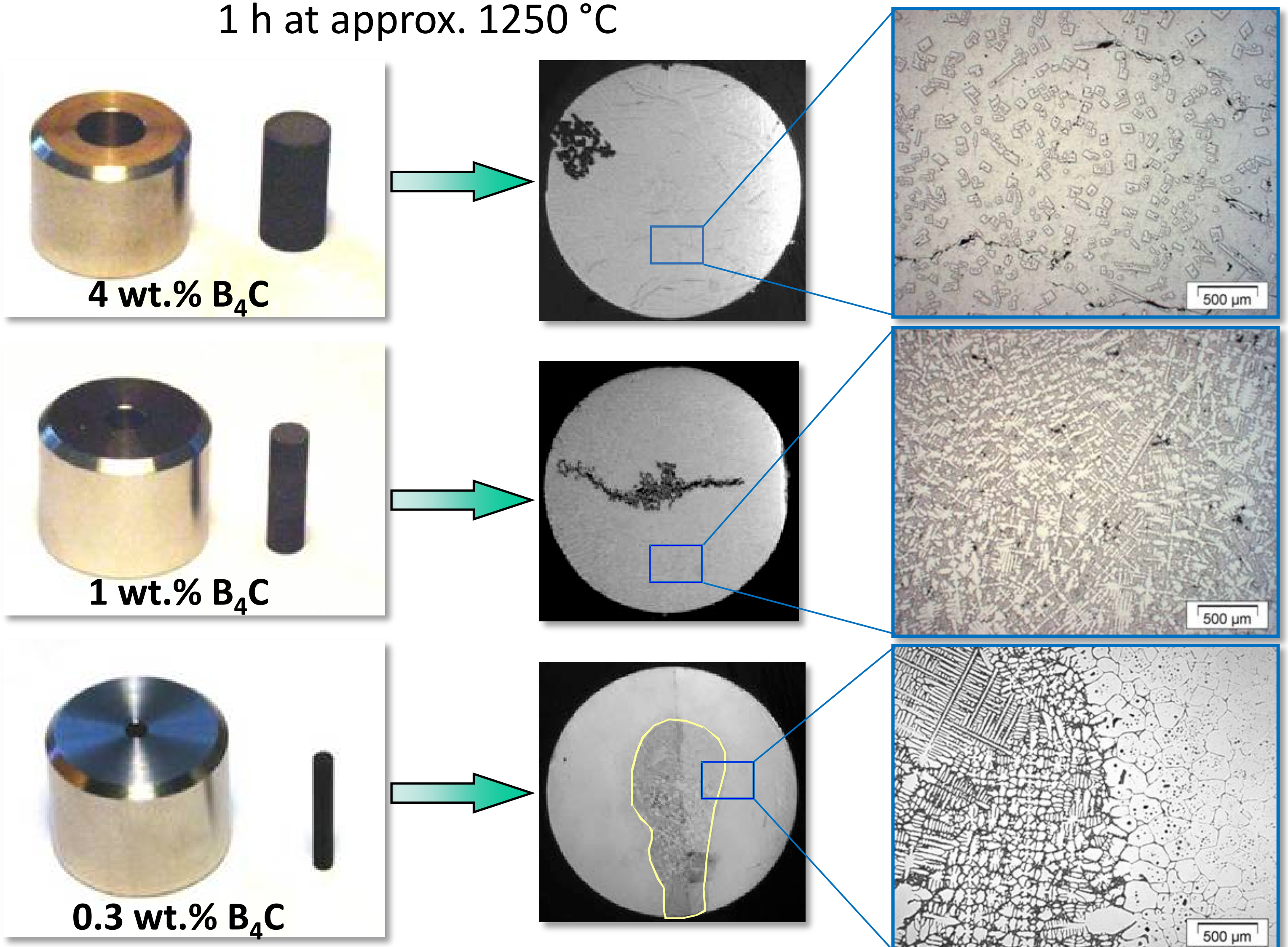
1400°C

1500°C

1600°C

Eutectic interaction of stainless steel with B_4C

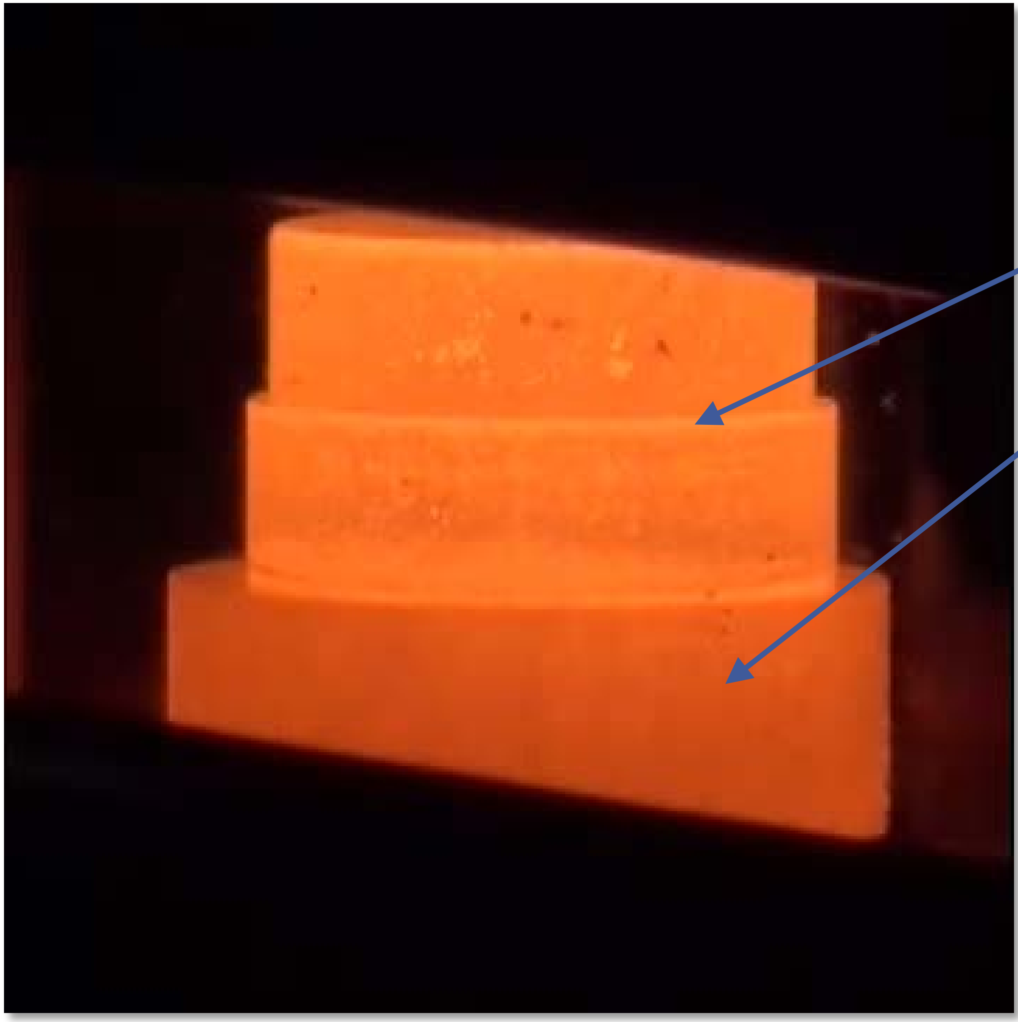
1 h at approx. 1250 °C

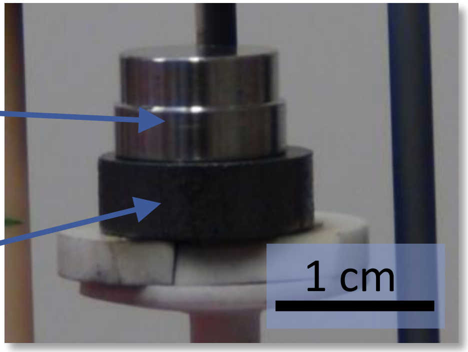


Complete liquefaction of stainless steel

1/3 of SS liquefied

Eutectic interaction of stainless steel with B_4C

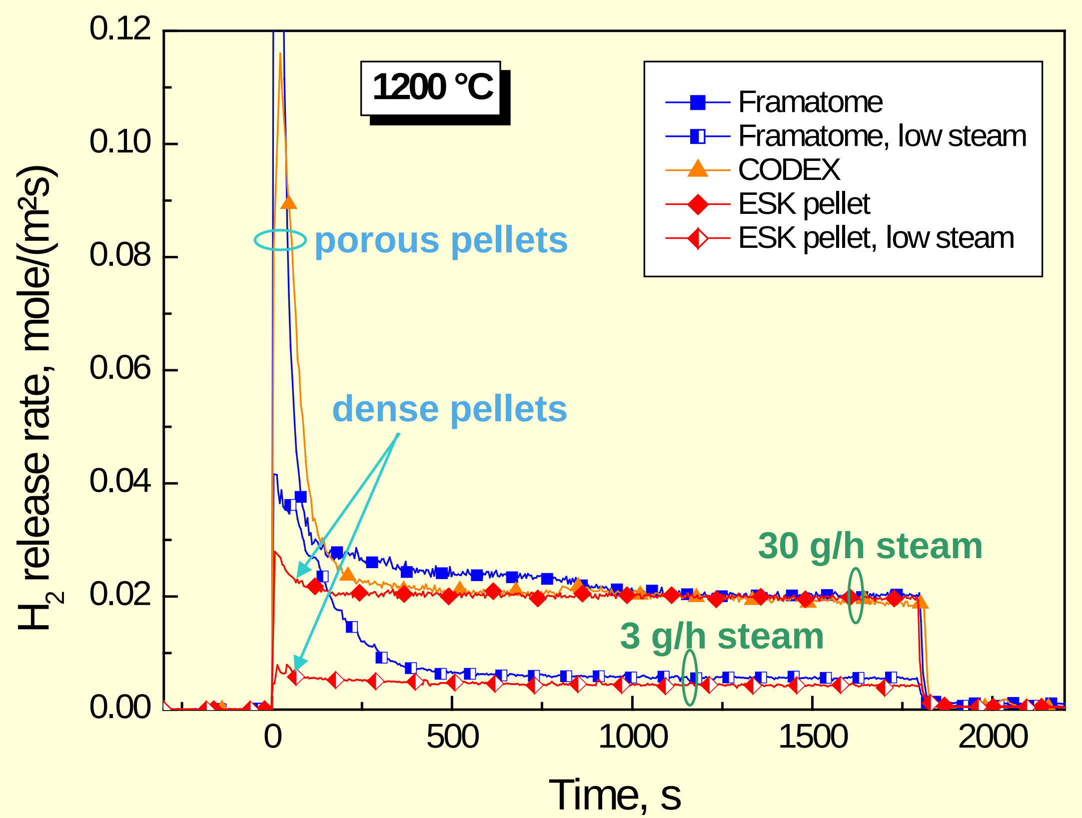




- Rapid and complete melting of SS at 1250°C starting at B_4C/SS interface

Oxidation kinetics of B_4C in steam

Karlsruhe Institute of Technology



- Strongly dependant on B_4C structure and thermo-hydraulic boundary conditions like pressure and flow rate

Institute for Applied Materials

Oxidation of B_4C absorber melts

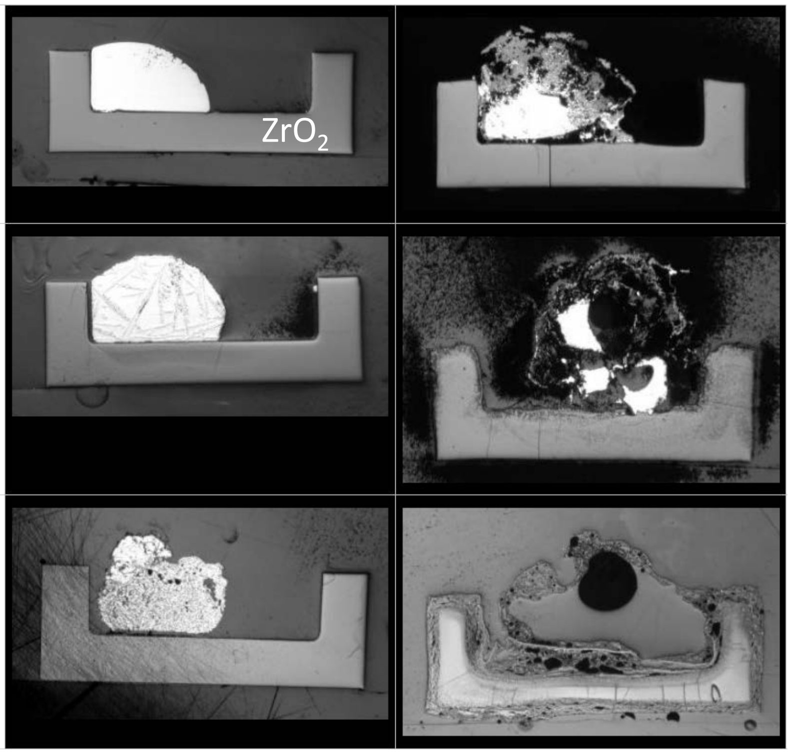
Karlsruhe Institute of Technology

Transient oxidation of B_4C/SS/Zry-4 absorber melts in steam between 800 and 1550 °C

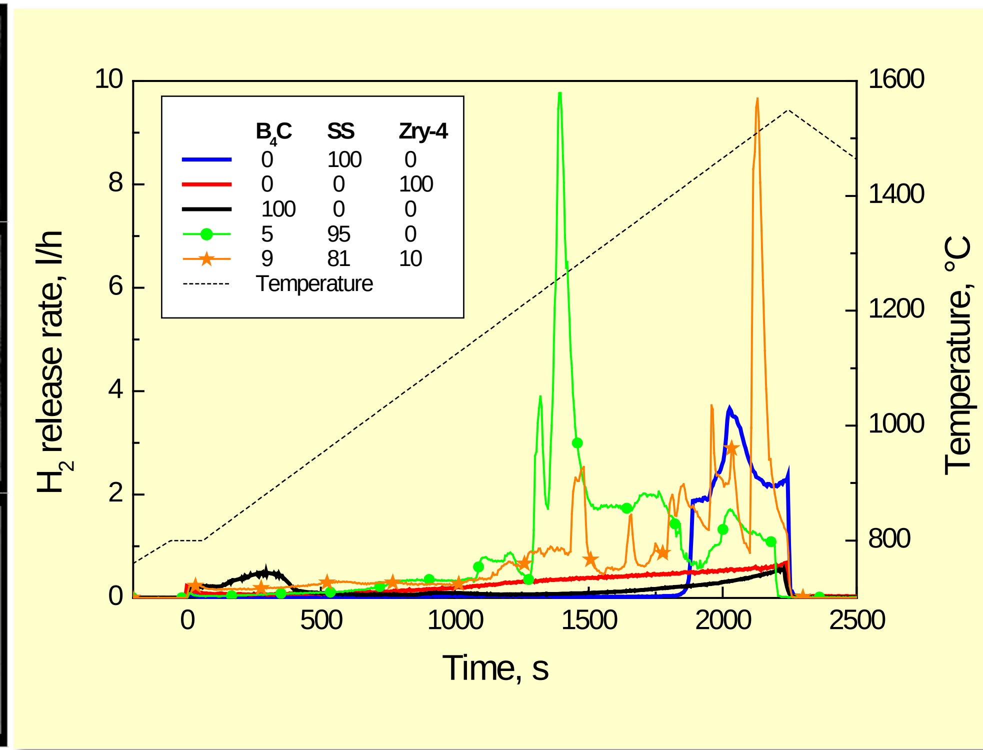
0 B_4C
100 SS
0 Zry

5 B_4C
95 SS
0 Zry

9 B_4C
81 SS
10 Zry



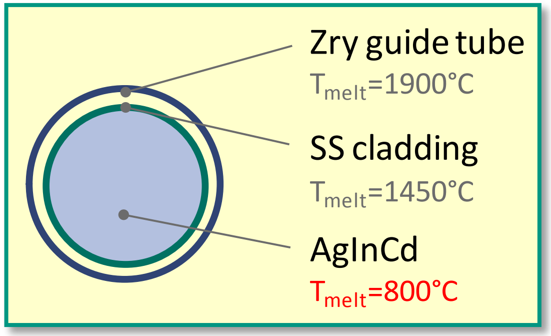
before oxidation | after oxidation



Oxidation rate during reaction of absorber melts and pure CR components in steam

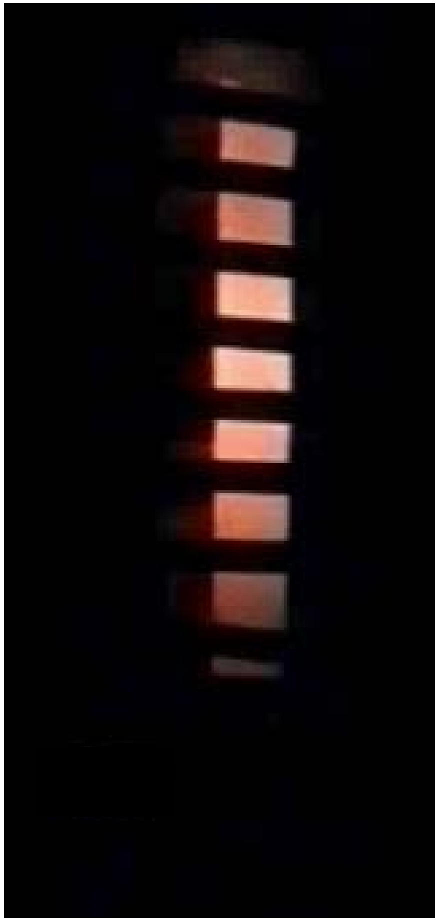
Failure of AgInCd absorber rod

- Ag-In-Cd control rods fail at temperatures above 1200°C due to the eutectic interaction between SS and Zry-4
- Failure is very stochastic (from local to explosive) with the tendency to higher temperatures for symmetric samples and specimens with inner oxidation
- No ballooning of the SS cladding tube was observed before rupture
- Burst release of cadmium vapour is followed by continuous release of indium and silver aerosols and absorber melt

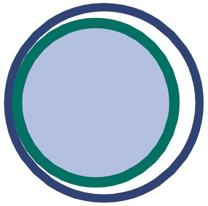


Different failure types of AgInCd absorber rod

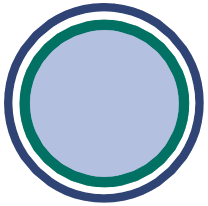
Karlsruhe Institute of Technology



SIC-02 (asym. rod)
Local failure at 1230°C



SIC-05 (symmetric rod)
Global failure at 1350°C



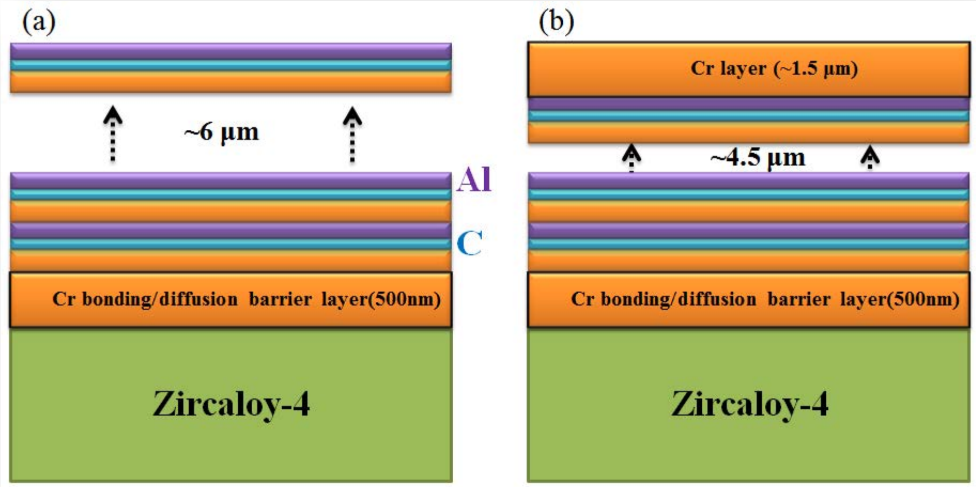
ATF cladding

KIT activities on ATF

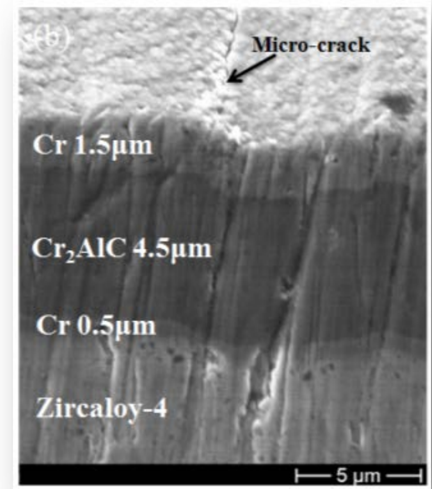
- QUENCH bundle tests with FeCrAl cladding in cooperation with ORNL
- Single-rod oxidation and quench tests with Cr-coated Zr alloy
- Ultra-high temperature oxidation tests with SiC_f-SiC
- Development of MAX phase coatings for Zr alloys

- Participation in various international collaborations on ATF
  - EC IL TROVATORE
  - IAEA ACTOF
  - OECD NEA EGATFL, TOPATF, and QUENCH-ATF (under discussion)
  - Westinghouse CARAT

MAX-phase coated cladding alloys (Cr_2AlC)

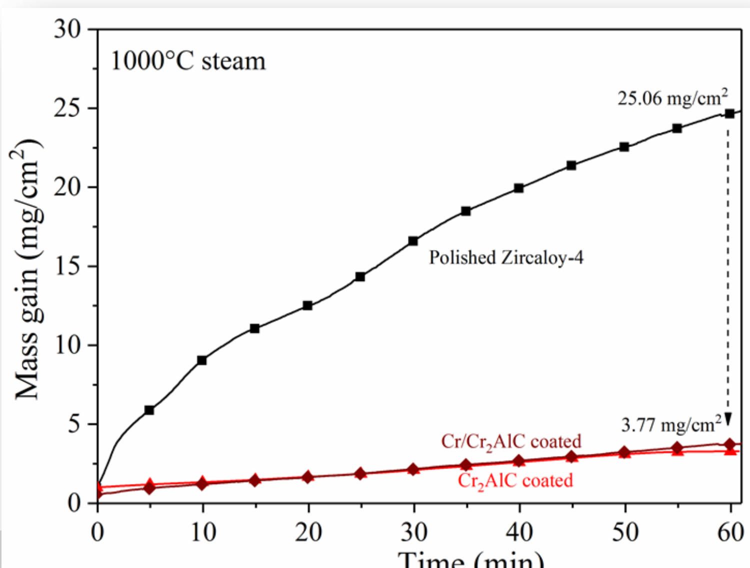


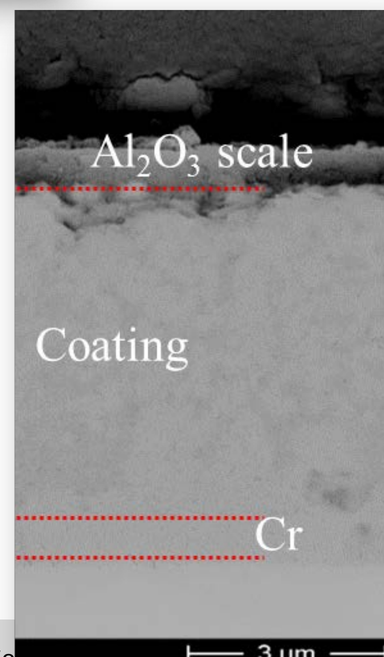
Annealing

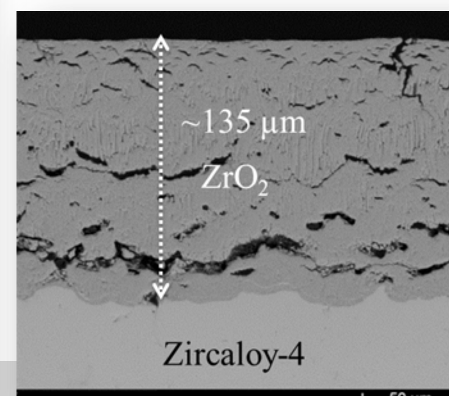


Magnetron sputtered Cr/C/Al nano layers

Pure MAX phase

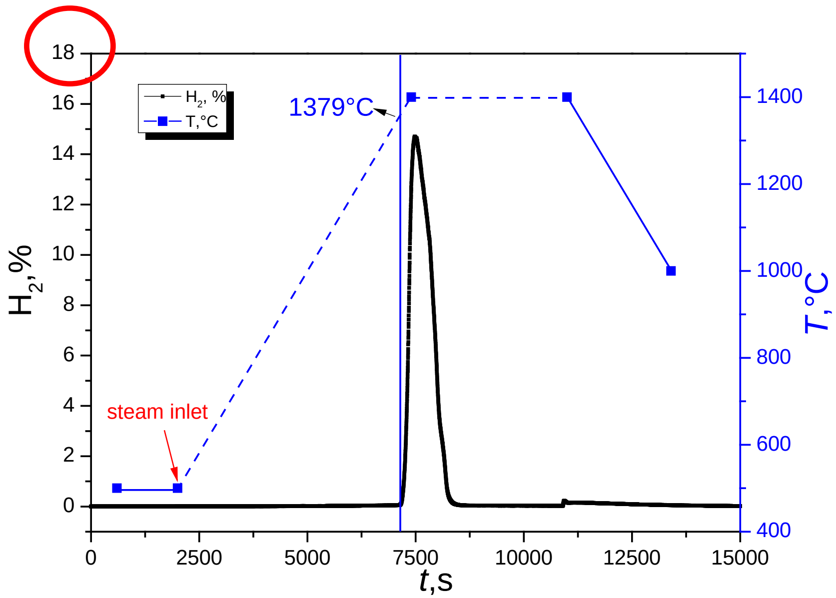




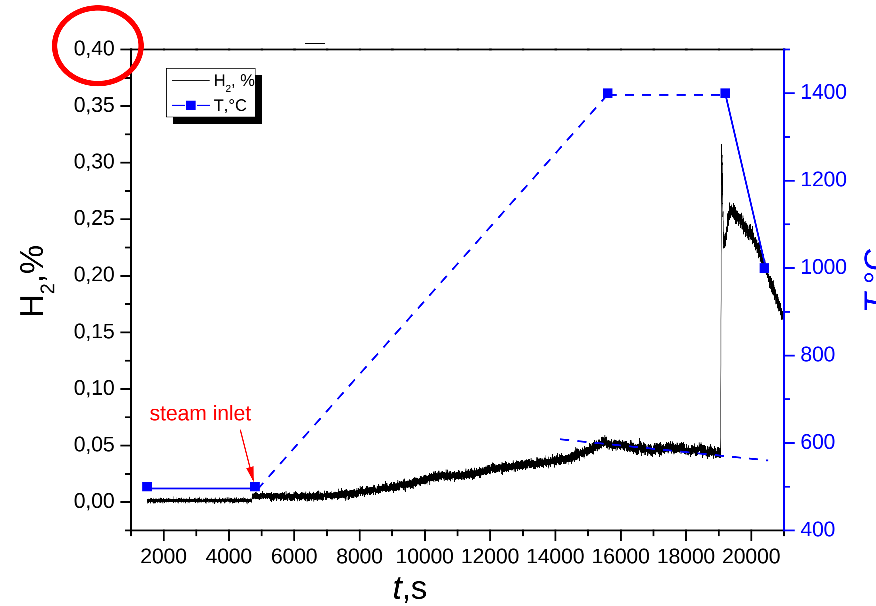


Tang, KIT, PhD 2019

Oxidation of Kanthal-APM (FeCrAl) in steam



Heating with 10 K/min to 1400°C and subsequent isothermal annealing for 1 h in steam

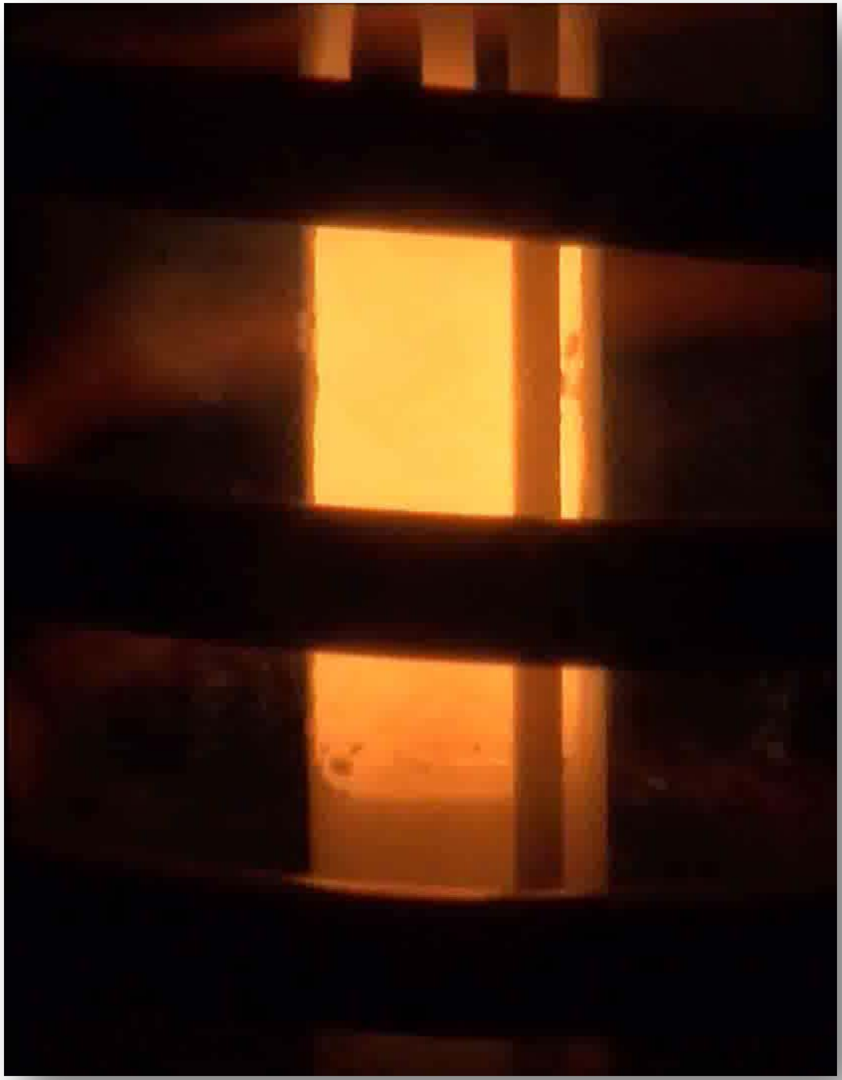


Heating with 5 K/min to 1400°C and subsequent isothermal annealing for 1 h in steam

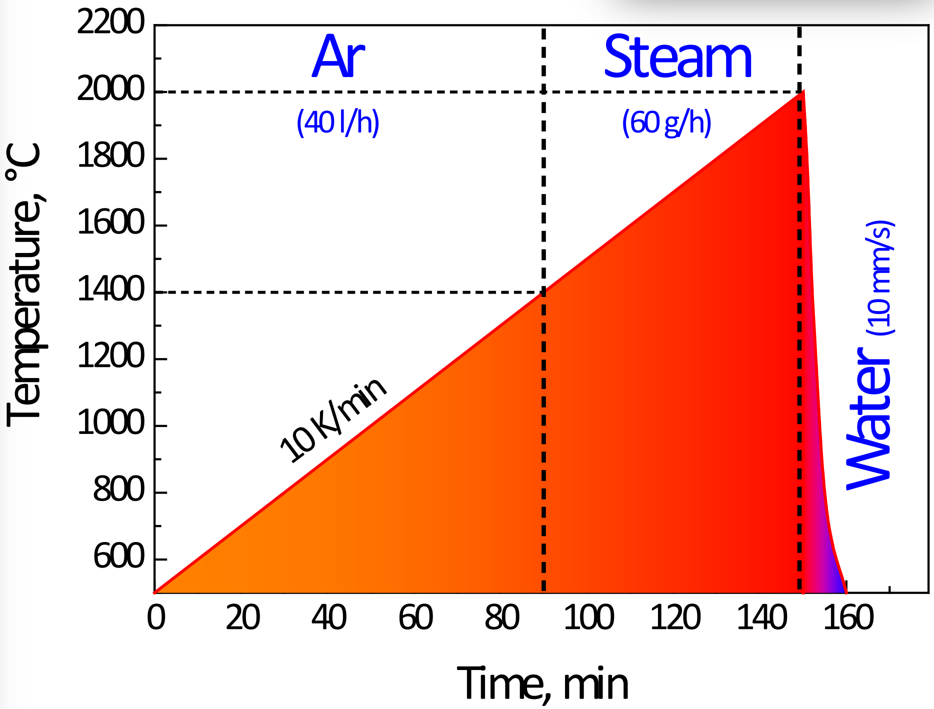
- Formation of a protective alumina scale during slow heatup or pre-oxidation at lower temperatures
- Otherwise, rapid and complete oxidation of the FeCrAl alloy

Tang, JNM 551(2018) 496-507

Steam oxidation of SiC and quench from 2000°C



Post-test appearance of SiC-SiC sample



Test conduct

Avincola, NED 2015
Avincola, KIT, PhD 2016

Takeaways

- Zirconium oxidation at high temperatures is a source of significant release of hydrogen and heat affecting nuclear accident progression.
- Oxidation is not always of parabolic kinetics and may be strongly dependent on experimental boundary conditions.
- Eutectic interactions may lead to melt formation far below the melting points of the individual materials. These melts may slowly relocate and severely oxidize.
- ATF claddings could strongly decrease the risk of temperature escalation and hydrogen detonation during BDB accidents as well as significantly increase the coping time for AMMs.
- Most experimental results were used to improve models, especially in cooperation with IBRAE, GRS, and IRSN as well as internally by H. Steiner and M. Große.

Acknowledgement

- The QUENCH group at KIT for their excellent work and support
- Program NUSAFE at KIT
- Various projects in the 3rd to 7th EU Framework Programs for Research and Innovation
- National and international partners

- You, for your kind attention

Karlsruhe Institute of Technology

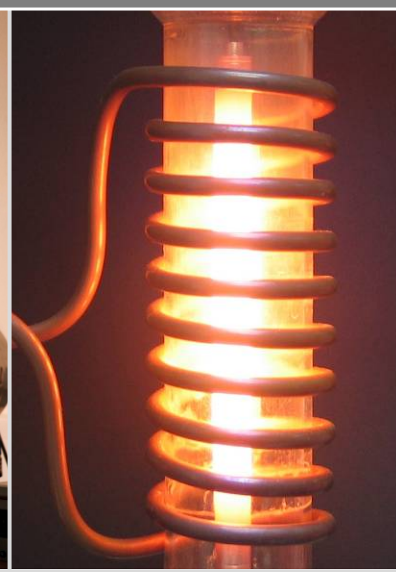
Institute for Applied Materials

25 years QUENCH program
Highlights of separate-effects tests

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

25th International QUENCH Workshop, Karlsruhe, 22-24 October 2019

Institute for Applied Materials IAM-AWP & Program NUSAFE



Key papers: Oxidation of Zr alloys and hydrogen behavior

Karlsruhe Institute of Technology

Grosse, M., Pulvermacher, S., Steinbrück, M., Schillinger, B.
In-situ neutron radiography investigations of the reaction of Zircaloy-4 in steam, nitrogen/steam and air/steam atmospheres
(2018) Physica B: Condensed Matter, 551, pp. 244-248. Cited 2 times.
DOI: 10.1016/j.physb.2018.03.030

Grosse, M., Steinbrueck, M., Schillinger, B., Kaestner, A.
In situ investigations of the hydrogen uptake of zirconium alloys during steam oxidation
(2018) ASTM Special Technical Publication, STP 1597, pp. 1114-1135. Cited 3 times.
DOI: 10.1520/STP159720160041

Steinbrück, M., da Silva, F.O., Grosse, M.
Oxidation of Zircaloy-4 in steam-nitrogen mixtures at 600–1200 °C
(2017) Journal of Nuclear Materials, 490, pp. 226-237. Cited 11 times.
DOI: 10.1016/j.jnucmat.2017.04.034

Stuckert, J., Hózer, Z., Kiselev, A., Steinbrück, M.
Cladding oxidation during air ingress. Part I: Experiments on air ingress
(2016) Annals of Nuclear Energy, 93, pp. 4-17. Cited 9 times.
DOI: 10.1016/j.anucene.2015.12.034

Steinbrück, M., Schaffer, S.
High-Temperature Oxidation of Zircaloy-4 in Oxygen–Nitrogen Mixtures
(2016) Oxidation of Metals, 85 (3-4), pp. 245-262. Cited 23 times.
DOI: 10.1007/s11085-015-9572-1

Steinbrück, M., Grosse, M.
Deviations from parabolic kinetics during oxidation of zirconium alloys
(2015) ASTM Special Technical Publication, STP 1543, pp. 979-1001. Cited 5 times.
DOI: 10.1520/STP154320130022

Key papers: Oxidation of Zr alloys and hydrogen behavior

Karlsruhe Institute of Technology

Pshenichnikov, A., Stuckert, J., Walter, M.
Microstructure and mechanical properties of Zircaloy-4 cladding hydrogenated at temperatures typical for LOCA conditions
(2015) Nuclear Engineering and Design, 283, pp. 33-39. Cited 12 times.
DOI: 10.1016/j.nucengdes.2014.06.022

Steinbrück, M.
High-temperature reaction of oxygen-stabilized α-Zr(O) with nitrogen
(2014) Journal of Nuclear Materials, 447 (1-3), pp. 46-55. Cited 24 times.
DOI: 10.1016/j.jnucmat.2013.12.024

Große, M., Steinbrück, M., Stuckert, J., Kastner, A., Schillinger, B.
Application of neutron radiography to study material processes during hypothetical severe accidents in nuclear reactors
(2012) Journal of Materials Science, 47 (18), pp. 6505-6512. Cited 12 times.
DOI: 10.1007/s10853-011-5553-1

Steinbrück, M., Vér, N., Grosse, M.
Oxidation of advanced zirconium cladding alloys in steam at temperatures in the range of 600-1200 °c
(2011) Oxidation of Metals, 76 (3-4), pp. 215-232. Cited 58 times.
DOI: 10.1007/s11085-011-9249-3

Steinbrück, M., Böttcher, M.
Air oxidation of Zircaloy-4, M5® and ZIRLO™ cladding alloys at high temperatures
(2011) Journal of Nuclear Materials, 414 (2), pp. 276-285. Cited 72 times.
DOI: 10.1016/j.jnucmat.2011.04.012

Steinbrück, M., Große, M., Sepold, L., Stuckert, J.
Synopsis and outcome of the QUENCH experimental program
(2010) Nuclear Engineering and Design, 240 (7), pp. 1714-1727. Cited 84 times.
DOI: 10.1016/j.nucengdes.2010.03.021

Key papers: Oxidation of Zr alloys and hydrogen behavior

Karlsruhe Institute of Technology

Grosse, M.
Comparison of the high-temperature steam oxidation kinetics of advanced cladding materials
(2010) Nuclear Technology, 170 (1), pp. 272-279. Cited 20 times.
DOI: 10.13182/NT10-A9464

Steinbrück, M.
Prototypical experiments relating to air oxidation of Zircaloy-4 at high temperatures
(2009) Journal of Nuclear Materials, 392 (3), pp. 531-544. Cited 79 times.
DOI: 10.1016/j.jnucmat.2009.04.018

Große, M., Lehmann, E., Steinbrück, M., Kühne, G., Stuckert, J.
Influence of oxide layer morphology on hydrogen concentration in tin and niobium containing zirconium alloys after high temperature steam oxidation
(2009) Journal of Nuclear Materials, 385 (2), pp. 339-345. Cited 68 times.

Steinbrück, M.
Oxidation of zirconium alloys in oxygen at high temperatures up to 1600 °c
(2008) Oxidation of Metals, 70 (5-6), pp. 317-329. Cited 35 times.
DOI: 10.1007/s11085-008-9124-z

Grosse, M., Steinbrueck, M., Lehmann, E., Vontobel, P.
Kinetics of hydrogen absorption and release in zirconium alloys during steam oxidation
(2008) Oxidation of Metals, 70 (3-4), pp. 149-162. Cited 39 times.
DOI: 10.1007/s11085-008-9113-2

Steinbrück, M.
Hydrogen absorption by zirconium alloys at high temperatures
(2004) Journal of Nuclear Materials, 334 (1), pp. 58-64. Cited 62 times.
DOI: 10.1016/j.jnucmat.2004.05.007

Institute for Applied Materials

Key papers: Control rod degradation

Karlsruhe Institute of Technology

Kurata, M., Barrachin, M., Haste, T., Steinbrueck, M.
Phenomenology of BWR fuel assembly degradation
(2018) Journal of Nuclear Materials, 500, pp. 119-140. Cited 5 times.
DOI: 10.1016/j.jnucmat.2017.12.004

Steinbrück, M., Stegmaier, U., Grosse, M.
Experiments on silver-indium-cadmium control rod failure during severe nuclear accidents
(2017) Annals of Nuclear Energy, 101, pp. 347-358. Cited 7 times.
DOI: 10.1016/j.anucene.2016.11.039

Steinbrück, M.
Influence of boron carbide on core degradation during severe accidents in LWRs
(2014) Annals of Nuclear Energy, 64, pp. 43-49. Cited 19 times.
DOI: 10.1016/j.anucene.2013.09.027

Steinbrück, M.
Degradation and oxidation of B4C control rod segments at high temperatures
(2010) Journal of Nuclear Materials, 400 (2), pp. 138-150. Cited 32 times.
DOI: 10.1016/j.jnucmat.2010.02.022

Dubourg, R., Austregesilo, H., Bals, C., Barrachin, M., Birchley, J., Haste, T., Lamy, J.S., Lind, T., Maliverney, B., Marchetto, C., Pinter, A., Steinbrück, M., Stuckert, J., Trambauer, K., Vimi, A.
Understanding the behaviour of absorber elements in silver-indium-cadmium control rods during PWR severe accident sequences
(2010) Progress in Nuclear Energy, 52 (1), pp. 97-108. Cited 19 times.
DOI: 10.1016/j.pnucene.2009.09.012

Steinbrück, M.
Oxidation of boron carbide at high temperatures
(2005) Journal of Nuclear Materials, 336 (2-3), pp. 185-193. Cited 53 times.
DOI: 10.1016/j.jnucmat.2004.09.022

Key papers: ATF cladding materials

Karlsruhe Institute of Technology

Steinbrueck, M., Angelici Avincola, V., Markel, I.J., Stegmaier, U., Gerhards, U., Seifert, H.J.
Oxidation of SiC f -SiC CMC cladding tubes for GFR application in impure helium atmosphere and materials interactions with tantalum liner at high temperatures up to 1600°C
(2019) Journal of Nuclear Materials, 517, pp. 337-348.
DOI: 10.1016/j.jnucmat.2019.02.024

Tang, C., Jianu, A., Steinbrueck, M., Grosse, M., Weisenburger, A., Seifert, H.J.
Influence of composition and heating schedules on compatibility of FeCrAl alloys with high-temperature steam
(2018) Journal of Nuclear Materials, 511, pp. 496-507.
DOI: 10.1016/j.jnucmat.2018.09.026

Tang, C., Steinbrueck, M., Stueber, M., Grosse, M., Yu, X., Ulrich, S., Seifert, H.J.
Deposition, characterization and high-temperature steam oxidation behavior of single-phase Ti2AlC-coated Zircaloy-4
(2018) Corrosion Science, 135, pp. 87-98. Cited 7 times.
DOI: 10.1016/j.corsci.2018.02.035

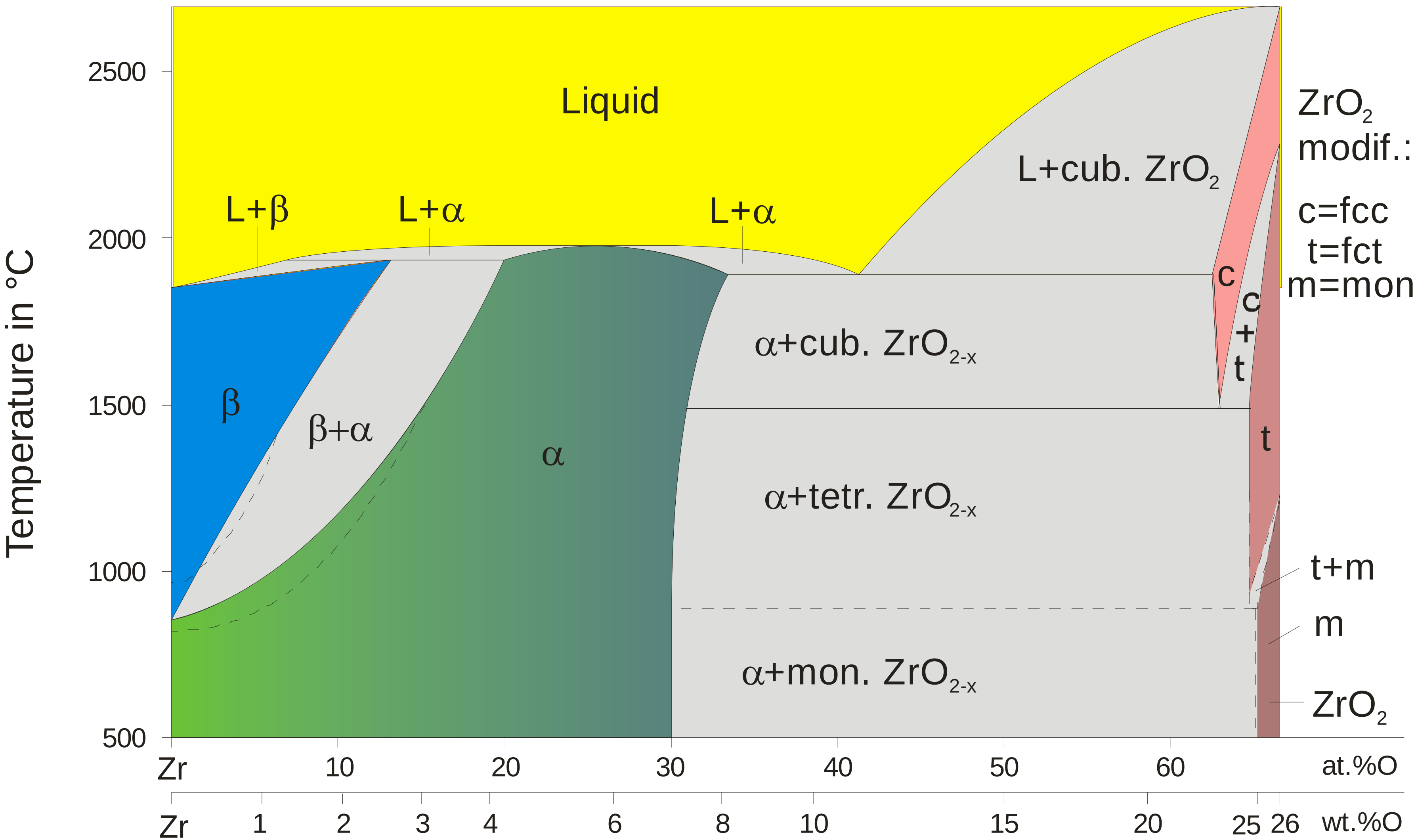
Tang, C., Stueber, M., Seifert, H.J., Steinbrueck, M.
Protective coatings on zirconium-based alloys as accident-Tolerant fuel (ATF) claddings
(2017) Corrosion Reviews, 35 (3), pp. 141-165. Cited 36 times.
DOI: 10.1515/corrrev-2017-0010

Tang, C., Steinbrück, M., Große, M., Bergfeldt, T., Seifert, H.J.
Oxidation behavior of Ti2AlC in the temperature range of 1400 °C–1600 °C in steam
(2017) Journal of Nuclear Materials, 490, pp. 130-142. Cited 8 times.
DOI: 10.1016/j.jnucmat.2017.03.016

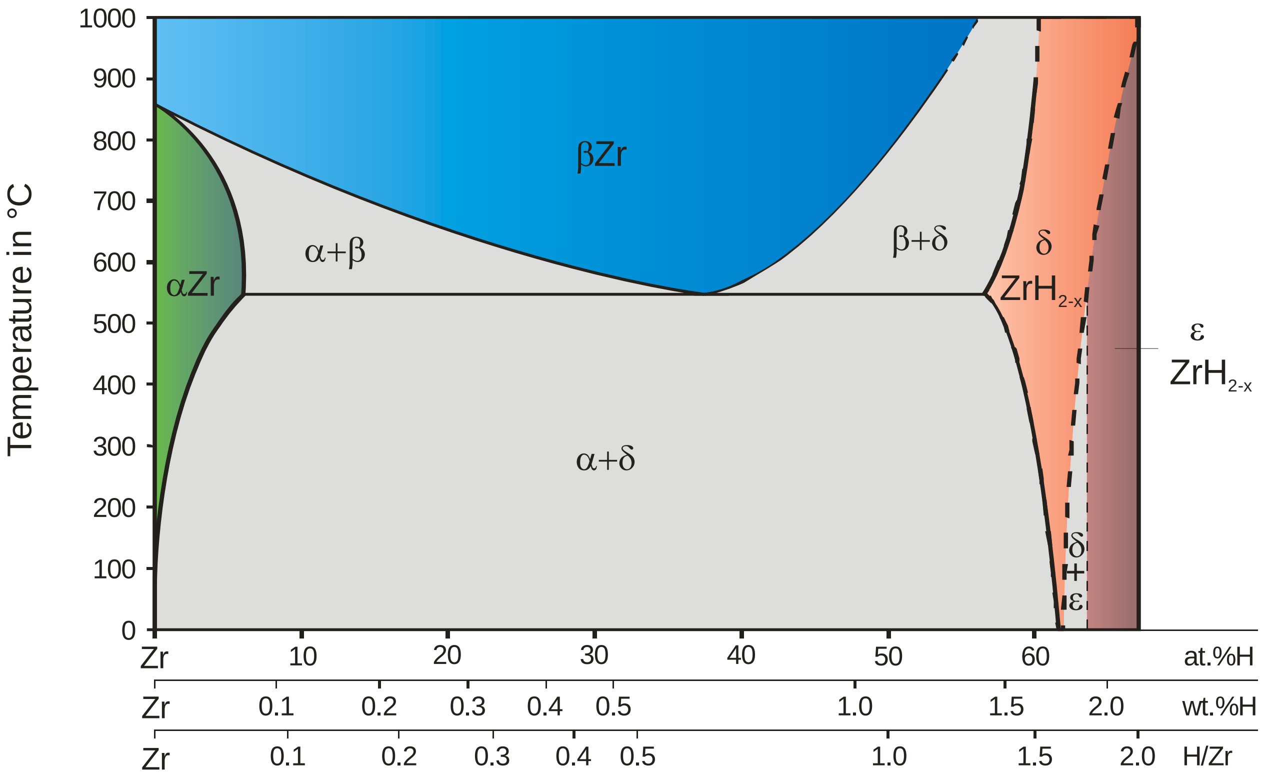
Avincola, V.A., Grosse, M., Stegmaier, U., Steinbrueck, M., Seifert, H.J.
Oxidation at high temperatures in steam atmosphere and quench of silicon carbide composites for nuclear application
(2015) Nuclear Engineering and Design, 295, pp. 468-478. Cited 20 times.
DOI: 10.1016/j.nucengdes.2015.10.002

Institute for Applied Materials

Phase diagram Zr - O



Phase diagram Zr - H



Sieverts' law:

$$\frac{H}{Zr} = k_S \cdot \sqrt{p_{H_2}}$$

with

$$k_S = A \cdot e^{\frac{-B}{RT}}$$