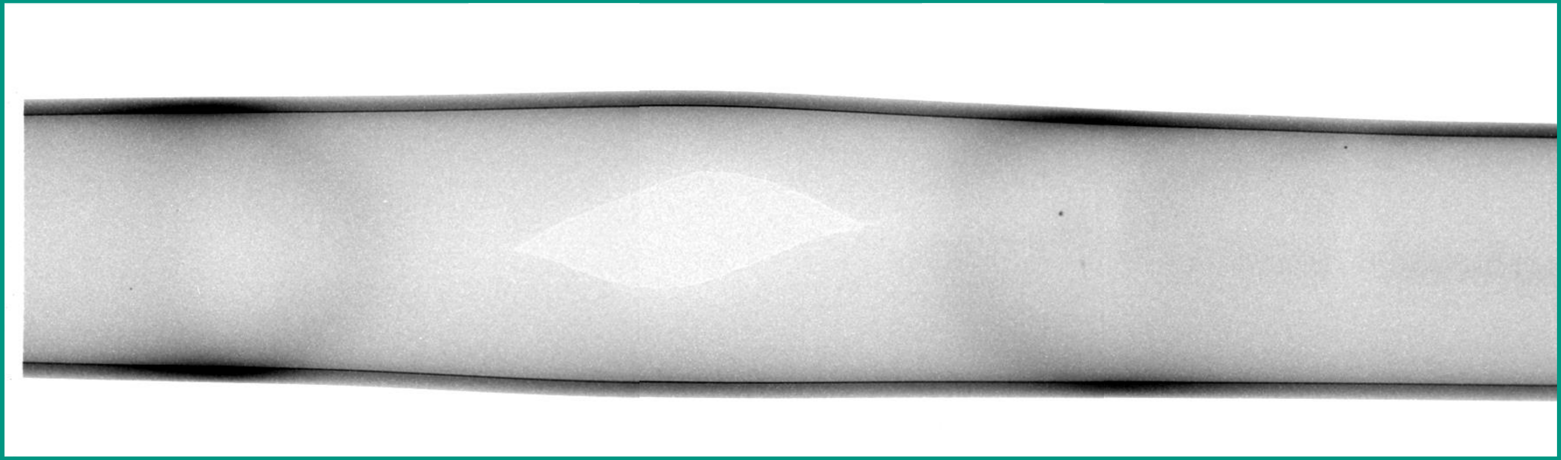
Accident fuel-cladding concepts for light water reactors

M. Grosse

KIT / Institute for Applied Materials / Program NUSAFE



Outline

- Why we need fuel with enhanced accident tolerance?
- Requirements for ATFs
- Which systems are under discussion?
  - Fuel
  - Claddings
- Examples of current research at KIT
  - FeCrAL coatings
  - MAX phase coatings
  - High temperature behavior of SiC
  - Joining of SiC
- Conclusions and Outlook

Why we need fuel with enhanced accident tolerance?

Have we learned enough from former nuclear accidents (TMI, Chernobyl, Fukushima)?

We can divide the external and internal conditions and the reactor behavior into

Do we know what is known and not known?

known known	known unknown
unknown **unknown**	known **unknown**

Conclusion: Be prepared for nuclear accidents!

Defense in depth strategy

Why we need fuel with enhanced accident tolerance?

Defense in depth strategy

- Safe design (cannot be changed for existing reactors)
- Accident training of reactor operators including clear competences
- Additional equipment's for passive safety (water reservoirs for emergency cooling at higher levels than the reactor, hydrogen recombiners)
- Independent devices for emergency measures (Fukushima: all generators fail because of flooding)
- New fuel/clad systems reducing chemical heat release and hydrogen production

Why we need fuel with enhanced accident tolerance?

- Commonly used fuels/claddings made of zirconium alloys behave satisfying at operational conditions.
- Hydrogen enrichments can be formed at design basis accident conditions. They can result in an embrittlement of the claddings and decrease the thermo-shock stability.

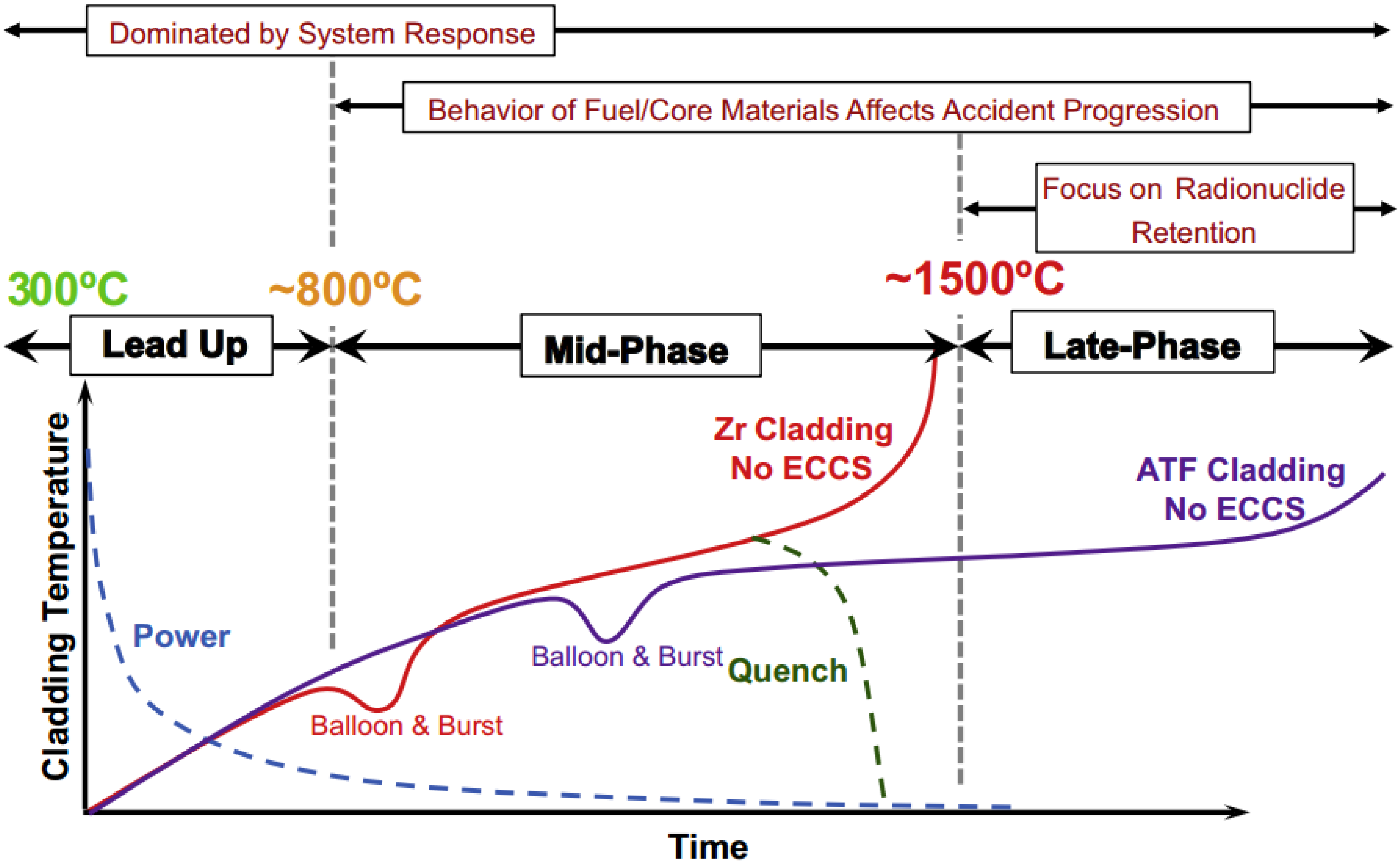
- The behavior of zirconium based alloys is non-satisfying under beyond LOCA conditions as happened in Fukushima.

$$Zr + 2H_2O = ZrO_2 + 4H$$

The reaction is strong exothermic. The hydrogen production caused by the reaction of Zr with steam results in the hydrogen detonation in Fukushima.

- Accident tolerance of nuclear fuels claddings with low oxidation rate until about 1600°C

Why we need fuel with enhanced accident tolerance?



S.J. Zinkle, K.A. Terrani, J.C. Gehin , L.J. Ott , L.L. Snead: “Accident tolerant fuels for LWRs: A perspective “, J. Nucl. Mater. s 448 (2014) 374–379

Requirements for ATFs

- Extending the time to fail for the fuel rods to give the operators more time to initiate measures to terminate the severe accident
- Behavior at operation and design basis accident as good as Zry or better
- Compatible to existing reactors (e.g. neutronics)
- Economics
- Waste management

Which systems are under discussion?

- **Fuel**: Improvement of the thermal conductive reduces the thermal gradients in the fuel, the overheating of the bulk and with it the heat capacity stored in the fuel.
  - Adding of material with high thermal conductivity to UO_2 (e.g. Cu)
  - Change to metallic U, U intermatallic phases (e.g. U_2Si_2), UN

- **Cladding**: new cladding materials with low oxidation rate until about 1600°C
  - *Other metals: Steels (FeCrAL, austenitic steels)*
  - *Compounds Zry-Mo-Zry*
  - *Coated* Zry (Cr or MAX phase coatings)
  - SiC

Which systems are under discussion?

- **Steels:**
  - FeCrAl:
    - + high strength
    - + high corrosion resistance
    - + relative easy to produce claddings
    - - melting point at about 1500°C
    - - strong neutron embrittlement by α´precipitatets
  - Austenitic steels
    - + high corrosion resistance
    - + relative easy to produce claddings
    - - melting point at about 1500°C
    - - strong neutron embrittlement by helium nano-bubbles

Which systems are under discussion?

Coated Zry:

- Cr coatings:
  - + high corrosion resistance
  - + relative easy to produce claddings
  - - Cr_2O_3 becomes volatile at temperatures of about 1350°C

- MAX phases

  M = transition metal, A = A-group element, X = carbon or nitrogen

  e.g. Ti_2AlC

  - + layer structure combines ceramic and metal properties
  - + high corrosion resistance
  - + high melting point
  - - hard to produce
  - - mismatch in the thermal expansion coefficient

General risk: If the coating fails a very strong reaction between the uncovered metallic zirconium and the steam can occur.

Which systems are under discussion?

Karlsruhe Institute of Technology

SiC:

pure SiC

- + high corrosion resistance
- + stable until very high temperatures
- + acceptable neutronic and mechanical properties
- - very difficult to produce
- - high corrosion under operational conditions

Coated SiC or SiC-Zr Duplex

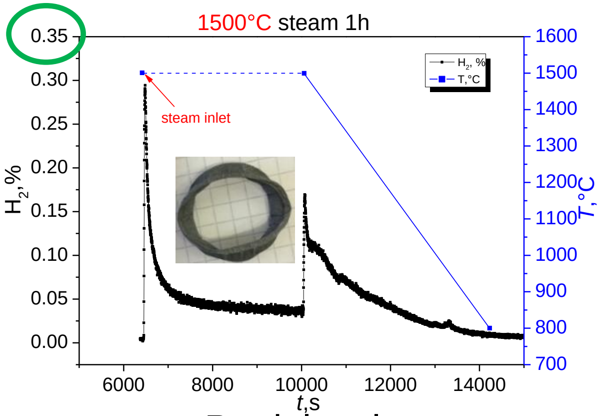
- + good corrosion resistance under all conditions
- + stable until very high temperatures
- + acceptable neutronic and mechanical properties
- - very difficult to produce
- - higher oxidation rate under accident conditions than pure SiC

Examples of current research at KIT

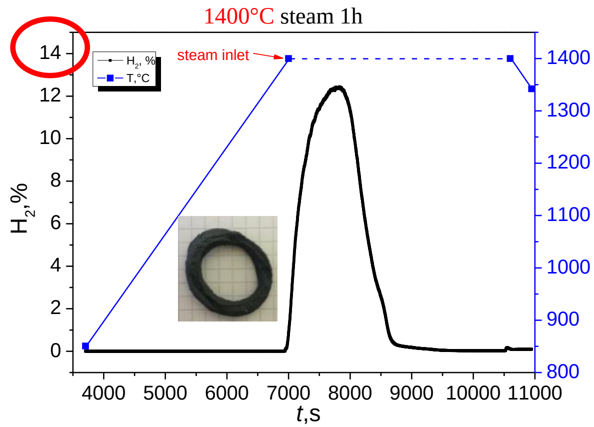
Investigations of FeCrAl

Karlsruhe Institute of Technology

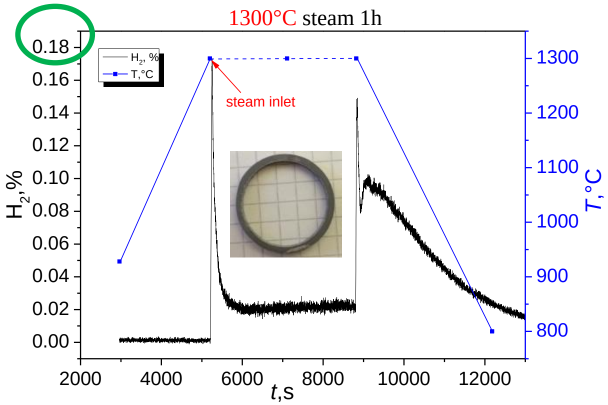
➢ Oxidation of Kanthal APM and D



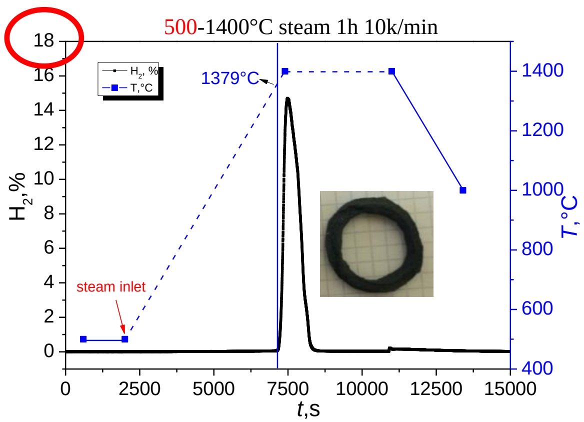
Partial melt
remain protective

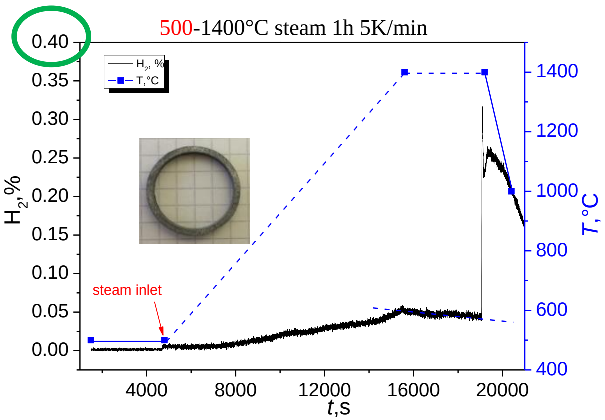


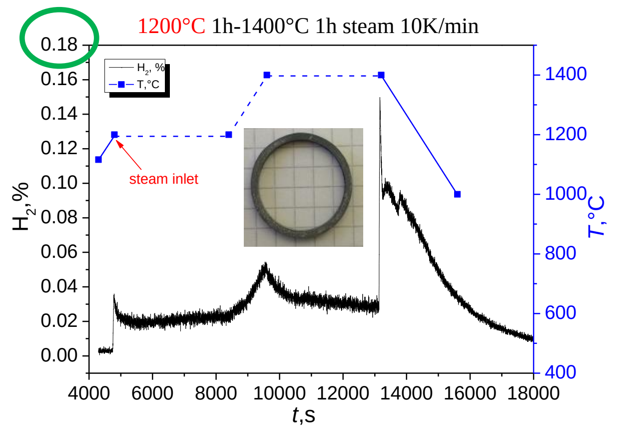
Rapidly and fully oxidized



Protective scale formed







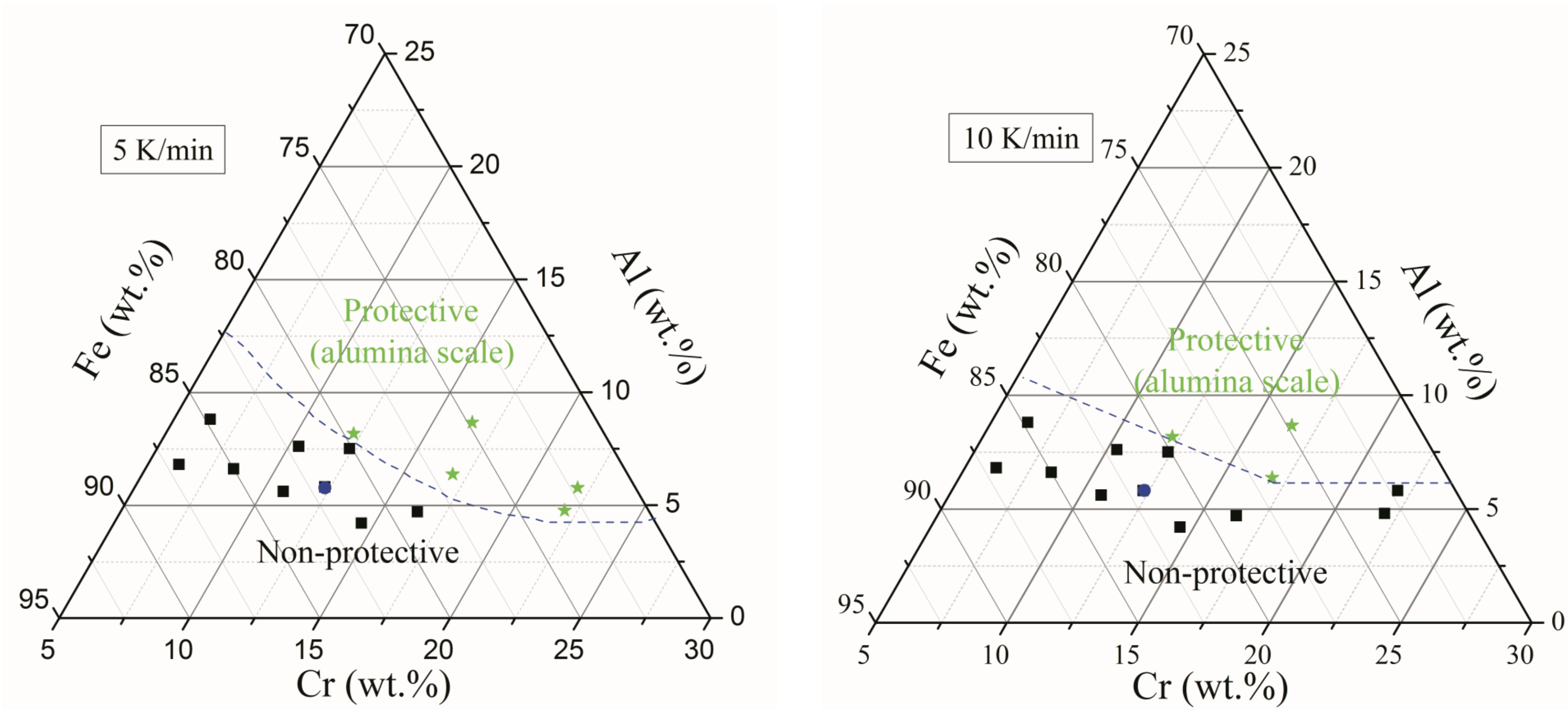
Maximum tolerance temperature
APM: 1379°C, D:1374°C 10 K/min

Protective scale formed when pre-oxidized with heating rate
5 K/min from 500°C or isothermal oxidation at 1200°C for 1 hour

Hydrogen release rates and samples appearance after oxidation of Kanthal APM

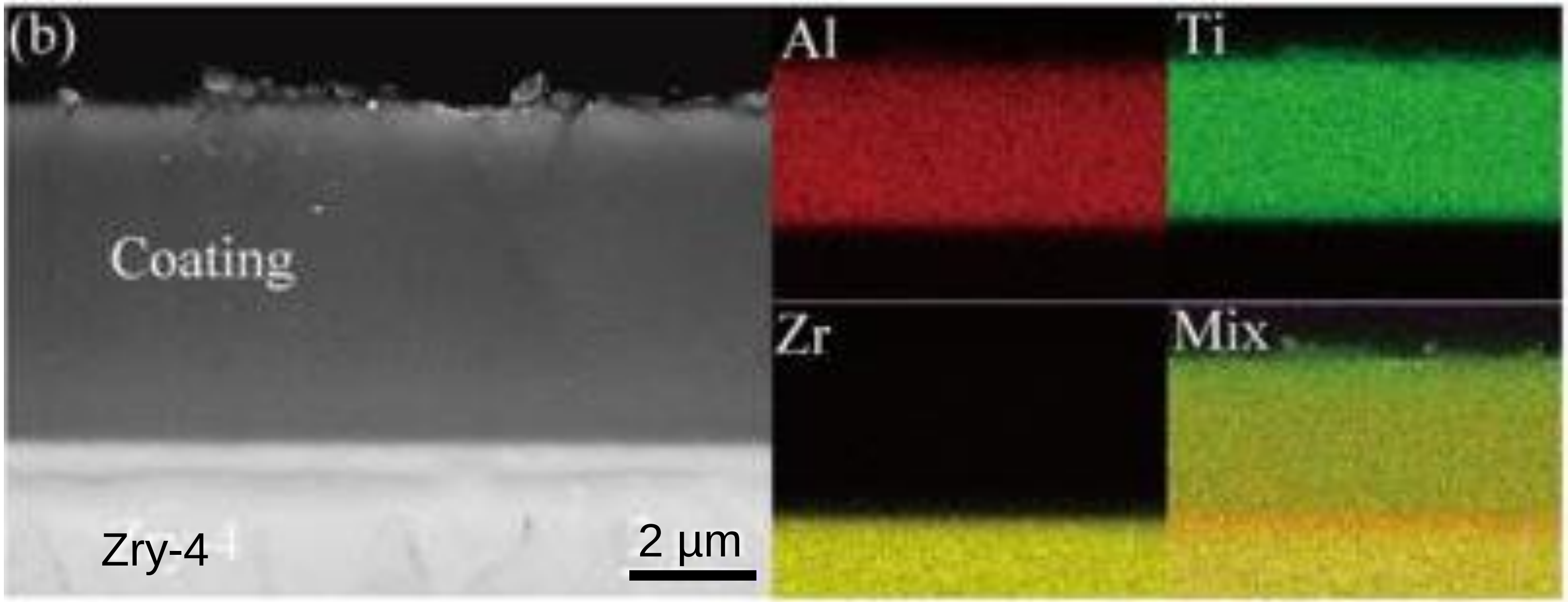
Examples of current research at KIT
Investigations of FeCrAl

➢ **Oxidation of Kanthal APM and D**



Steam compatibility of FeCrAl alloys in ramp test with different heating rates (500-1450°C + 1450°C 1h)

Examples of current research at KIT
Investigations of Ti_2AlC coatings at Zry-4

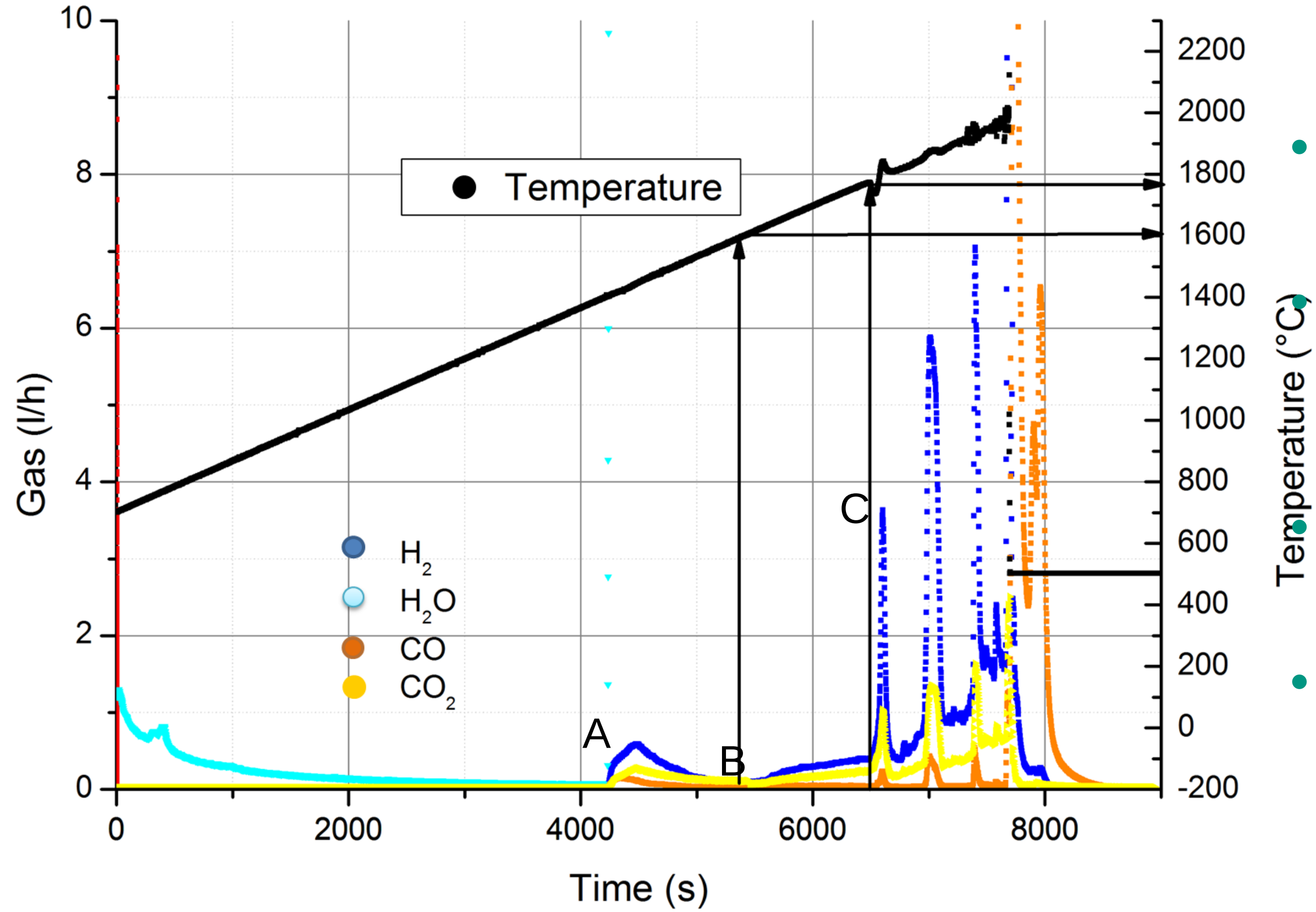


Success in production of a very dense Ti_2AlC coating at Zry-4 by PVD
(Usual plasma-spraying is used resulting in a very porous layer)

Next step: Characterization of the coating behavior at high temperatures

Examples of current research at KIT

High temperature oxidation/quenching of SiC

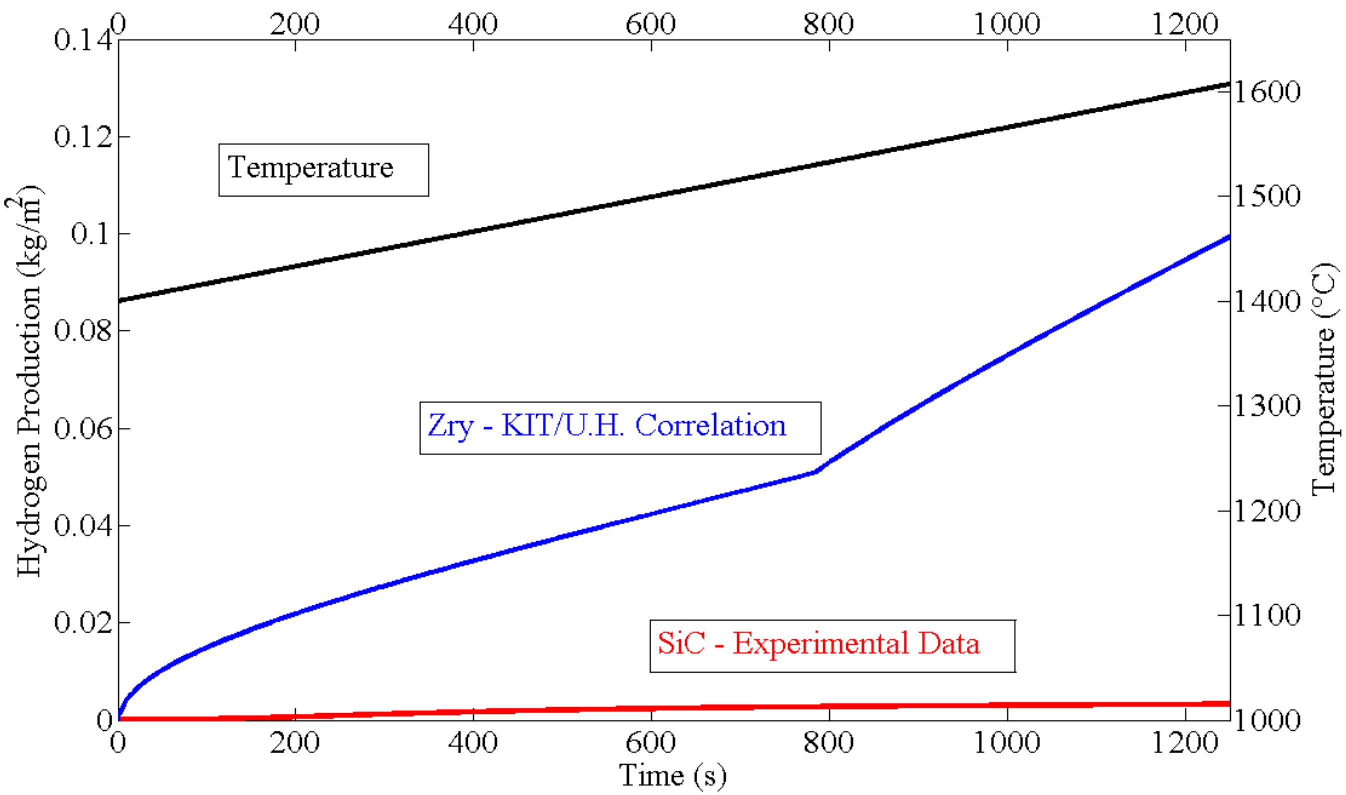


- **A:** steam injection formation of SiO_2
- **B:** start of the phase where the SiO_2 scale is degrading
- **C:** sharp increase of hydrogen production
- **D:** cooling down phase

Experiments: triplex cladding

Examples of current research at KIT

High temperature oxidation/quenching of SiC



Zry-4 would be nearly completely oxidized

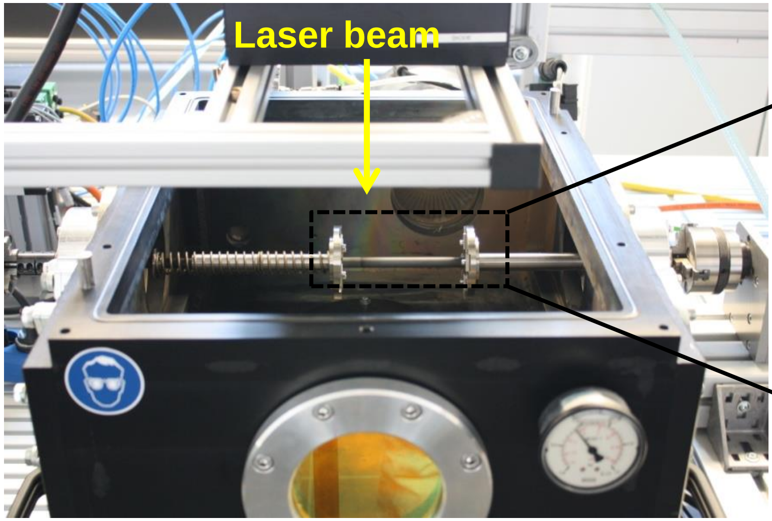
H_2 production:
Zry-4: 99.4 g/m^2
SiC: 3.3 g/m^2
(factor of **30**)

factor **130** in the chemical heat release

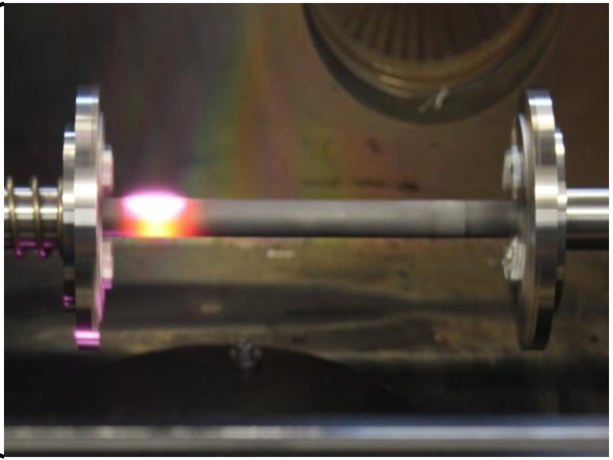
Hydrogen production from SiC during the test compared with Zircaloy H2 production

Examples of current research at KIT

Joining of SiC

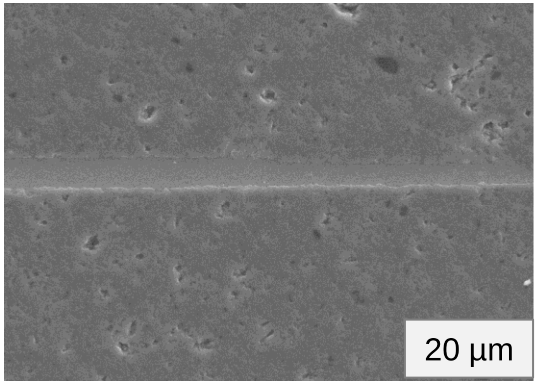


Experimental set-up



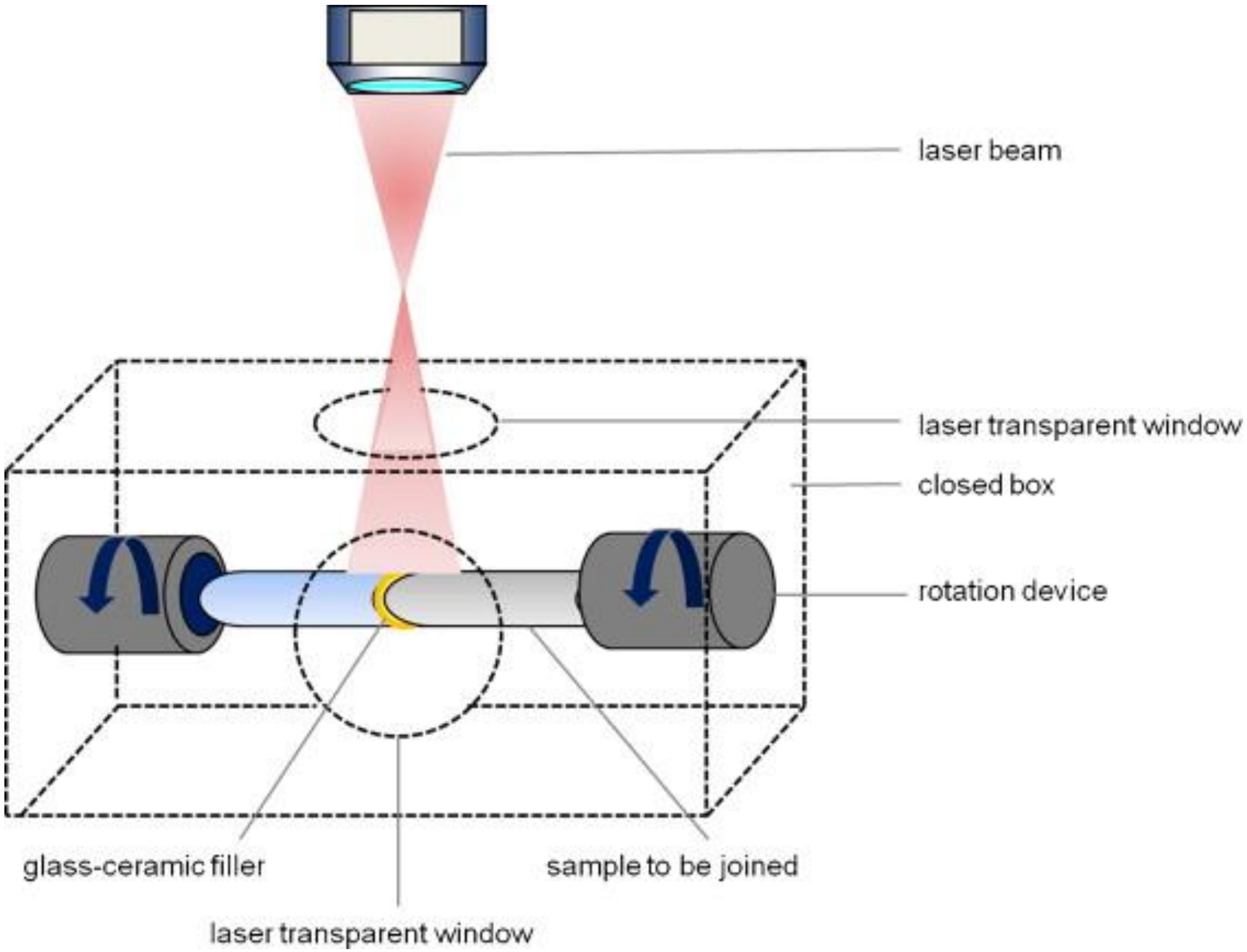
Local heat input

Joined SiC samples



Joined seam with solder Y_2O_3-Al_2O_3-SiO_2

Examples of current research at KIT
Joining of SiC



Cooperations

Karlsruhe Institute of Technology

Summary and Conclusions

- ATF would increase reactor safety significantly.
- A lot of open questions are objective of current investigations of many researchers worldwide
- Common KIT activities comprises:
  - the joining of SiC,
  - the high temperature oxidation and quenching behavior of SiC
  - the production, characterization and testing of coated zirconium alloys
  - Preparation of a severe accident simulation test on fuel rod bundle scale in the QUENCH facility in cooperation with ORNL

KIT team investigating ATF related systems

Prof. H. J. Seifert

Martin Steinbrück

Valentina Angelici Avincola (now at

Chongchong Tang

Sarfraz Ahmed

Ulrike Stegmaier

Petra Severloh

Sven Ulrich

Michael Stüber

Adrian Jianu

Alfons Weisenburger

Thank you for your attention.

Questions?

Conclusions and Outlook

- ATF would increase reactor safety significantly.
- A lot of open questions are objective of current investigations of many researchers worldwide
- Common KIT activities comprises:
  - the joining of SiC,
  - the high temperature oxidation and quenching behavior of SiC
  - the production, characterization and testing of coated zirconium alloys
  - Preparation of The QUENCH-FeCrAl-test (experimental severe accident simulation test on fuel rod bundle scale)

Accident fuel-cladding concepts for light water reactors

M. Grosse

KIT / Institute for Applied Materials / Program NUSAFE