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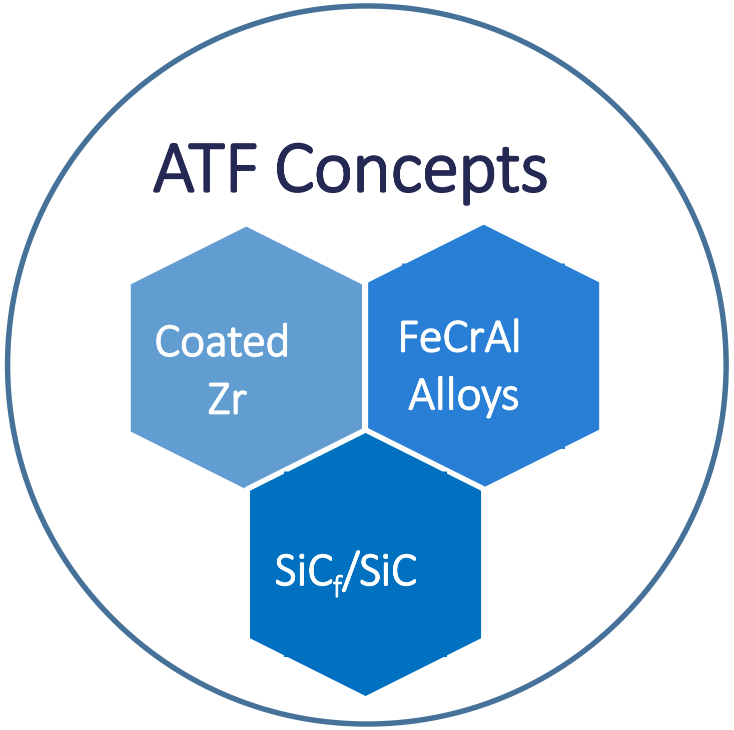
Thermal limits of potential ATF cladding materials

Promising ATF concepts

Various coating systems:
- Metals
- Oxides or silicates
- MAX phases

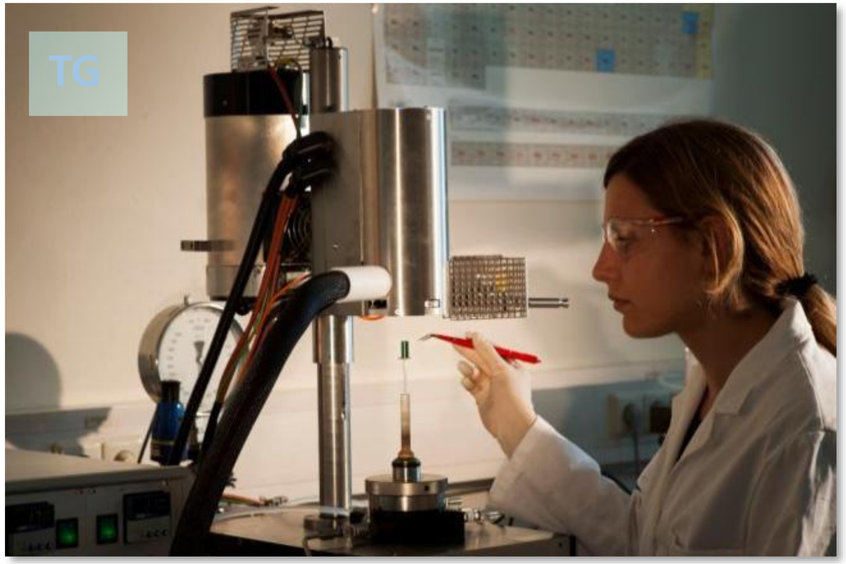
Cr coated Zry is the most promising system

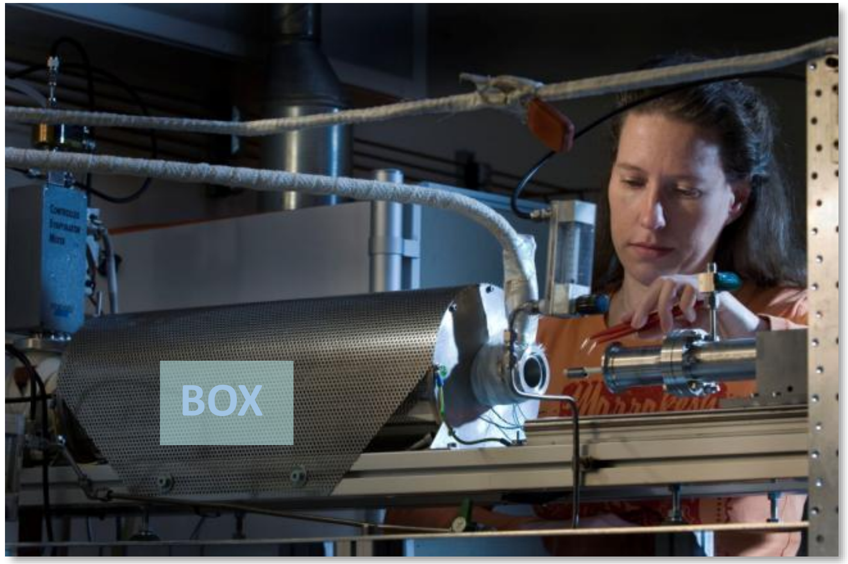


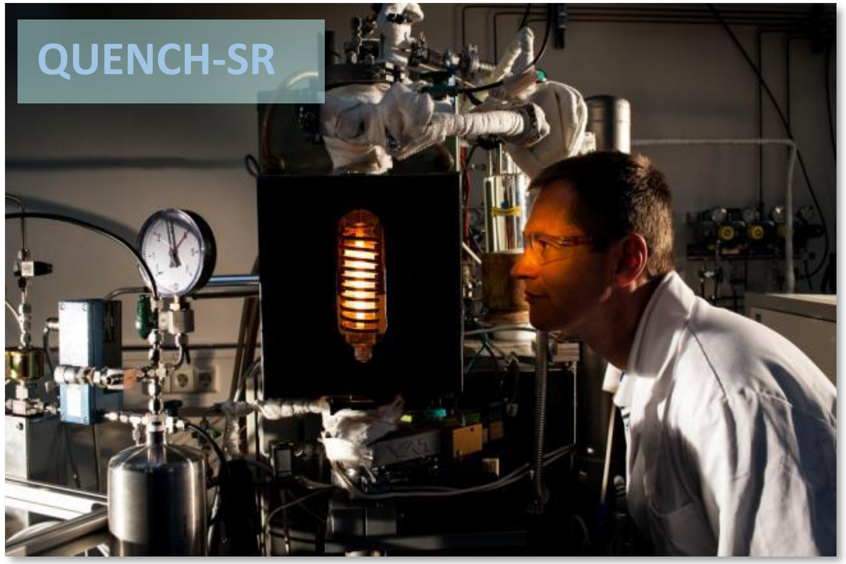
less developed system
best HT properties
issues: - water corrosion
- joining

Cr in FeCrAL is boon and bane at once:
- irradiation induced embrittlement due to the formation of Cr rich α´ precipitates
- Increase of the corrosion and HT oxidation resistance

Several facilities for high and very high temperature tests

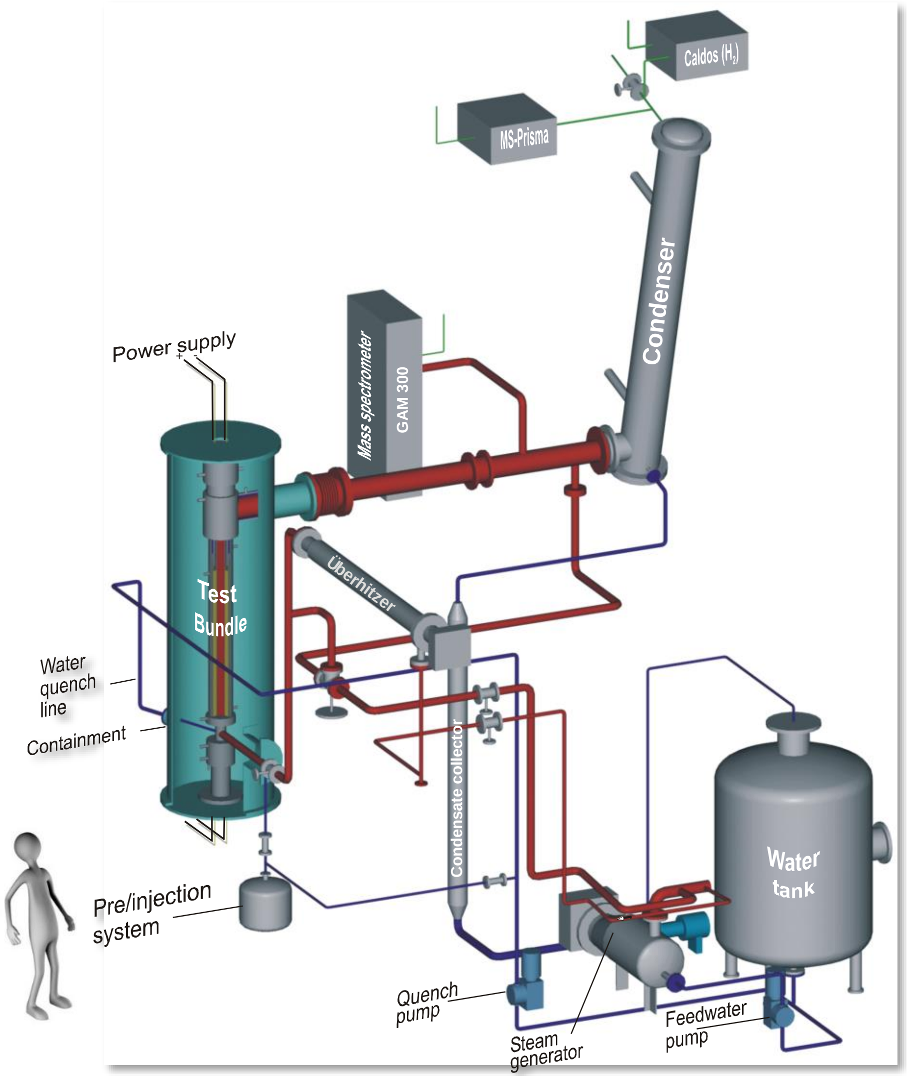


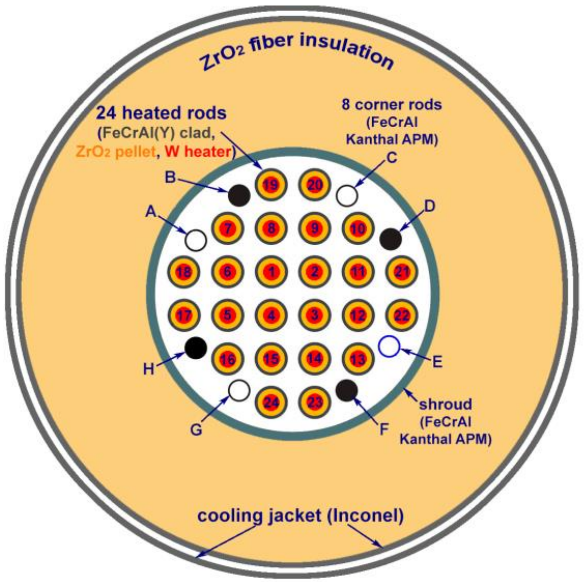


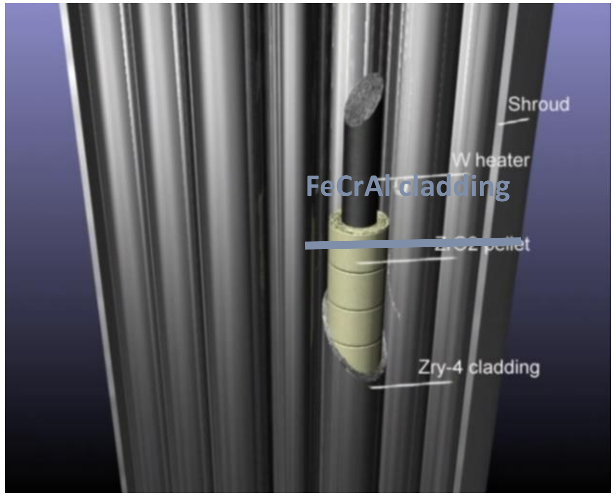


The QUENCH facility for bundle tests

- Bundle with 21 - 32 fuel rod simulators of ~2.5 m length
- Electrically heated: ~2 m;
- Fuel simulator: ZrO_2 pellets
- Quenching from bottom
- Off-gas analysis by mass spectrometer (H_2, steam …)
- Extensive instrumentation for T, p, flow rates, water level, etc. (140 measurement channels)
- corner rods, can be removed during test





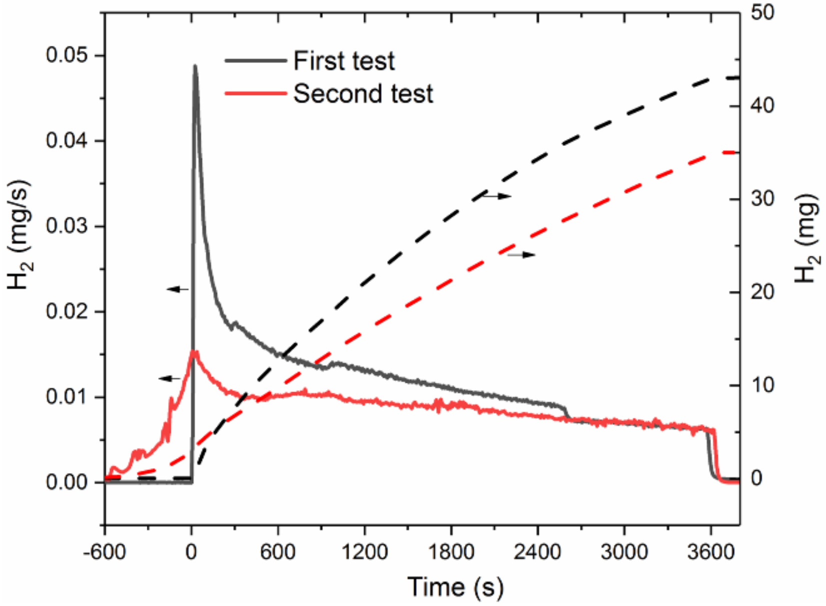


Results — Issues of chromium coatings at Zircaloys — I) bending

Repeated test
Pre-oxidation from 800°C

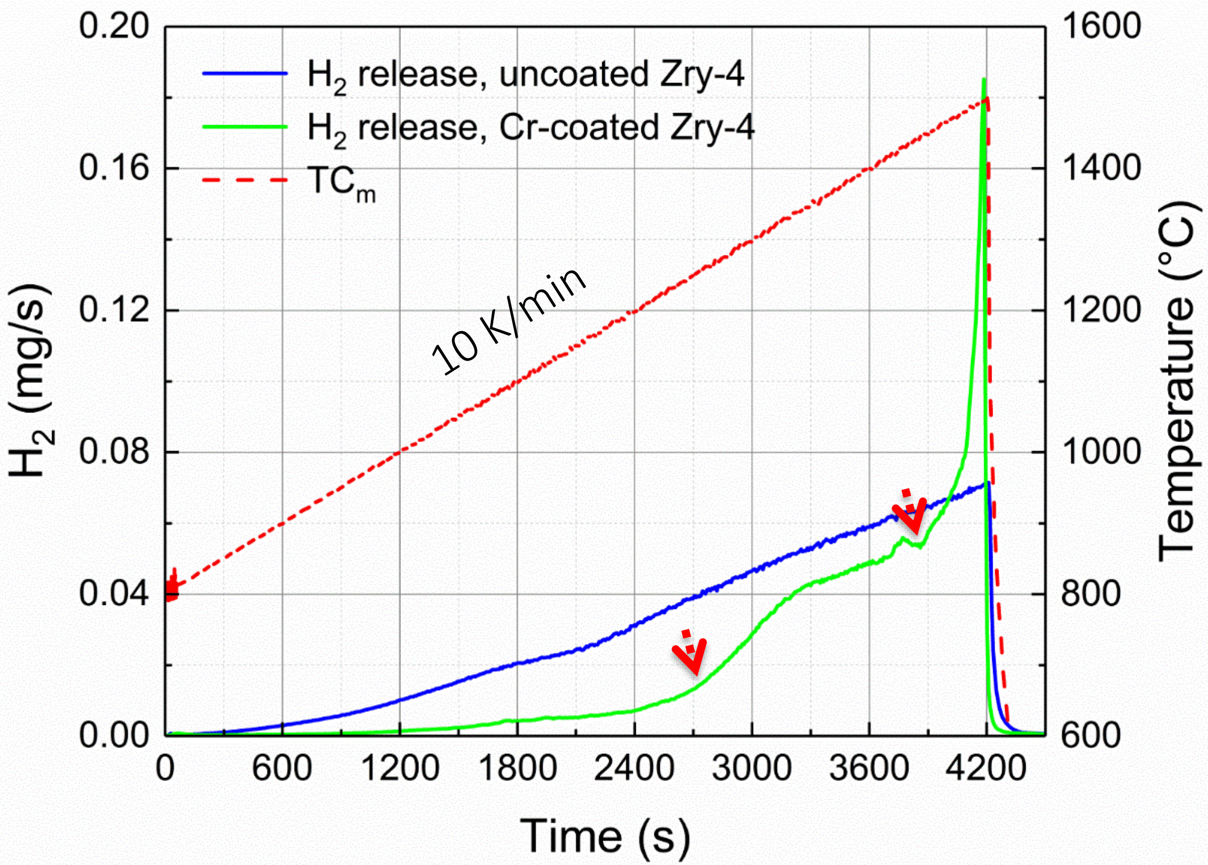
First test

Same level bending



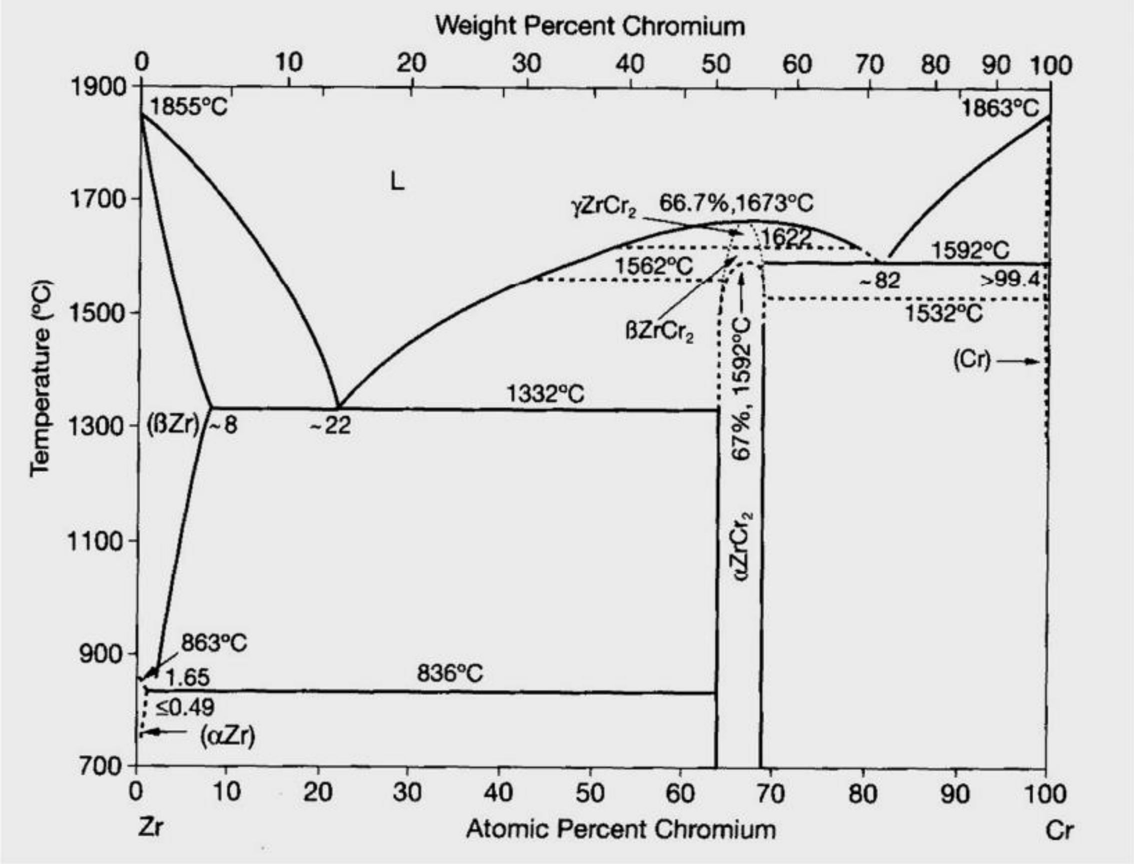
- Bending: High-level of residual stress and stress concentration (inhomogeneity) via cold spraying
- Local variations in the coating thickness

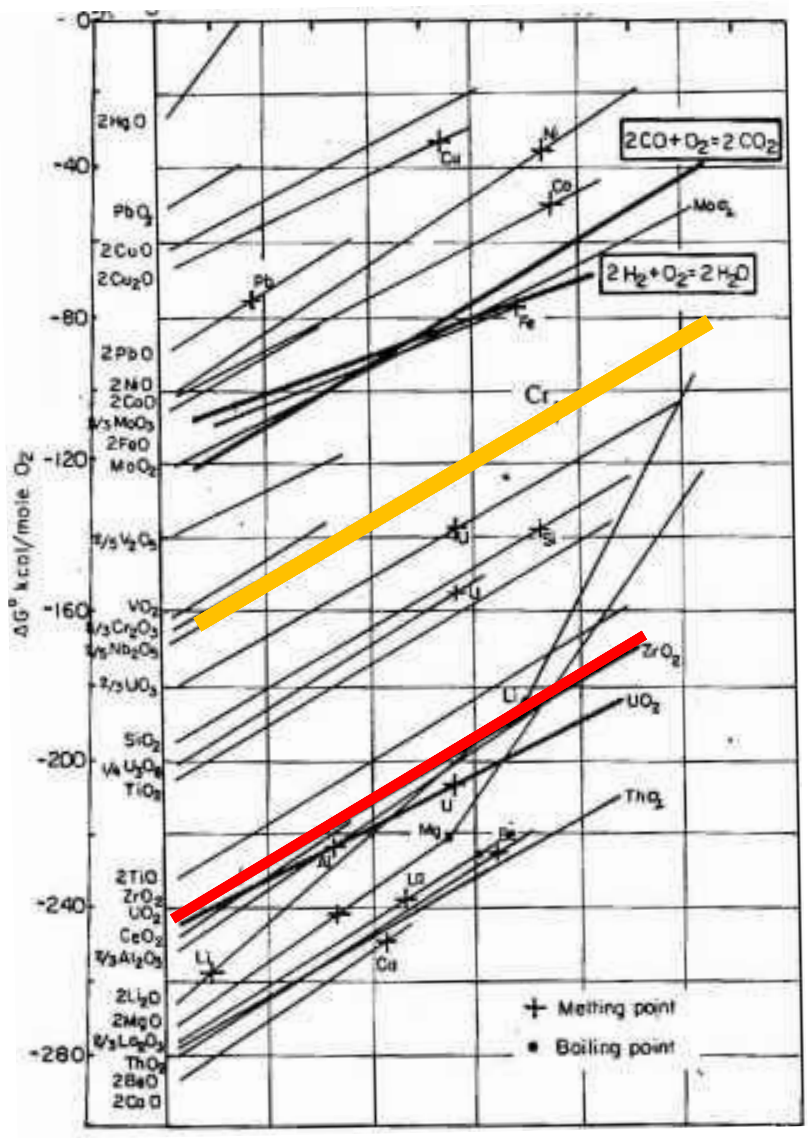
Transient test from 800 to 1500°C



- The hydrogen release rate accelerated at temperature around 1250°C.
- A steeply increased hydrogen release rate above approx. 1410°C, then surpassed that of the uncoated reference Zircaloy-4.

Results Issues of chromium coatings at Zircaly

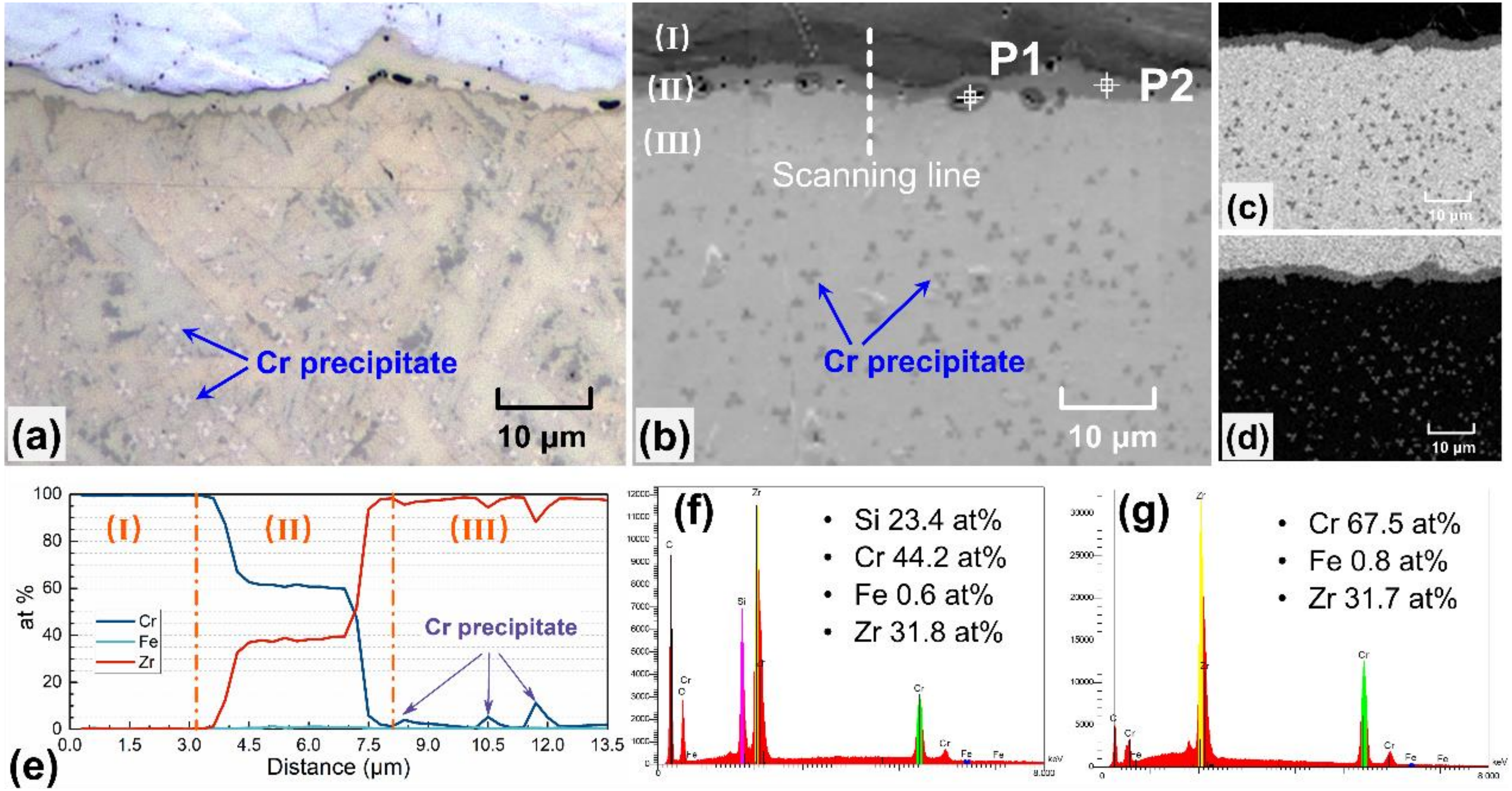




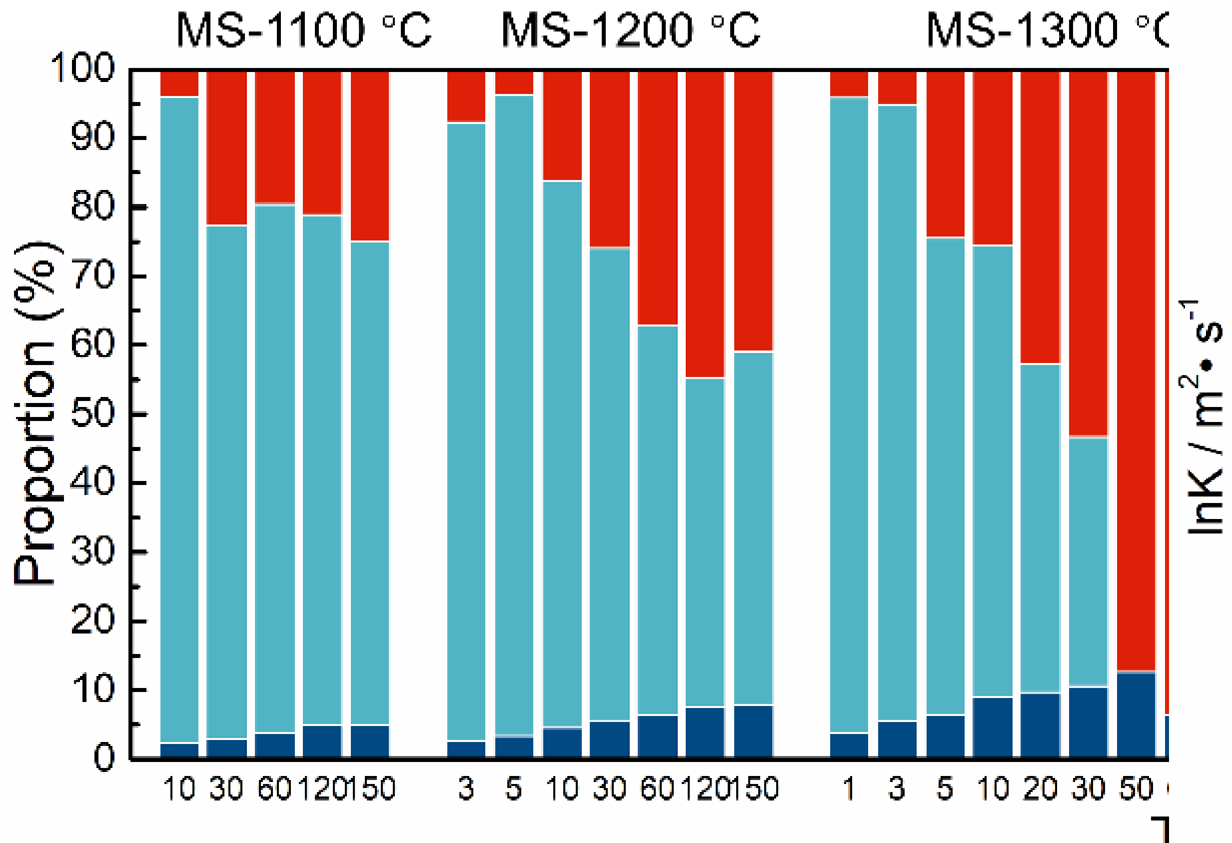
Cr + Zr = $(Zr,Cr)_{melt}$

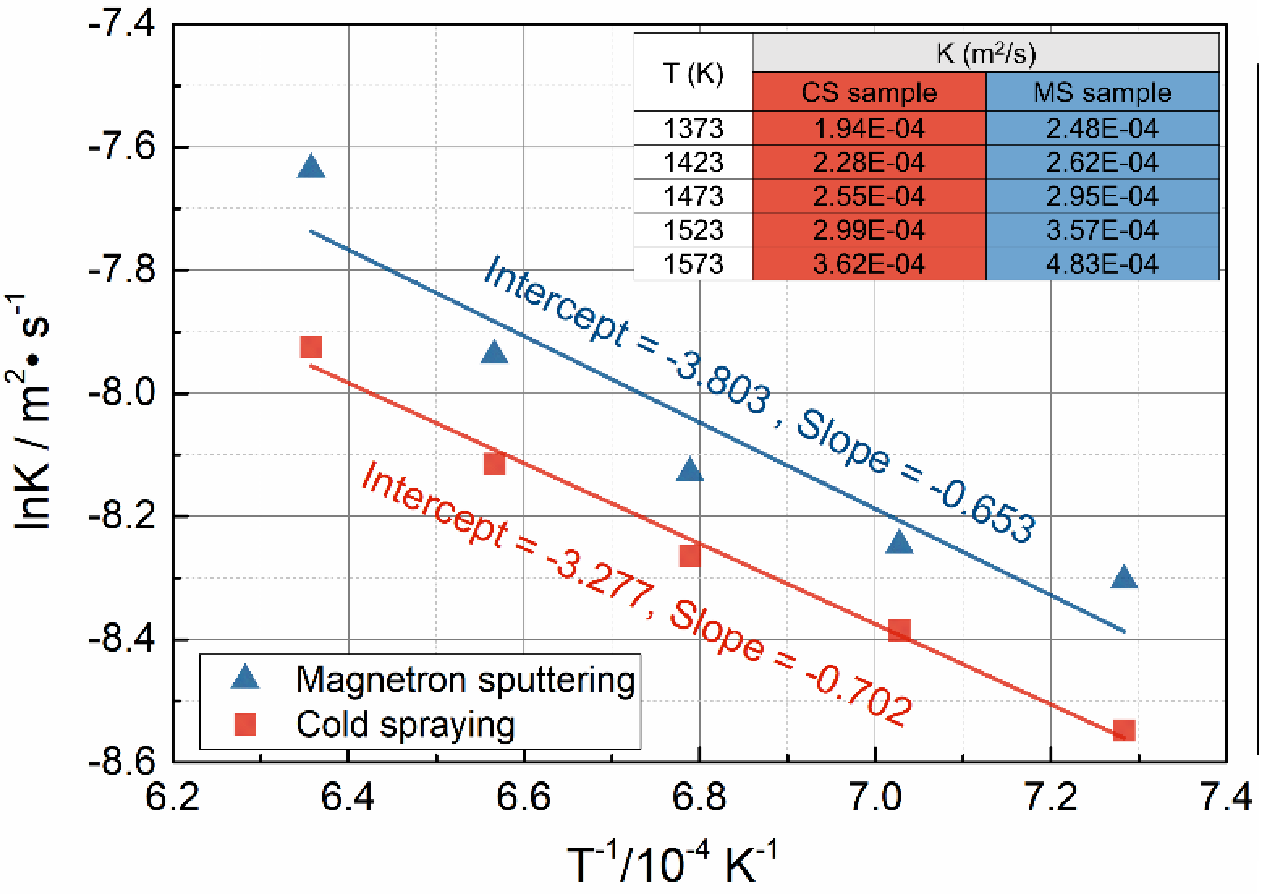
$2\,Cr_2O_3 + 3\,Zr = 3\,ZrO_2 + 4\,Cr$

Results Dissolution of the Cr coating



Results Dissolution of the Cr coating

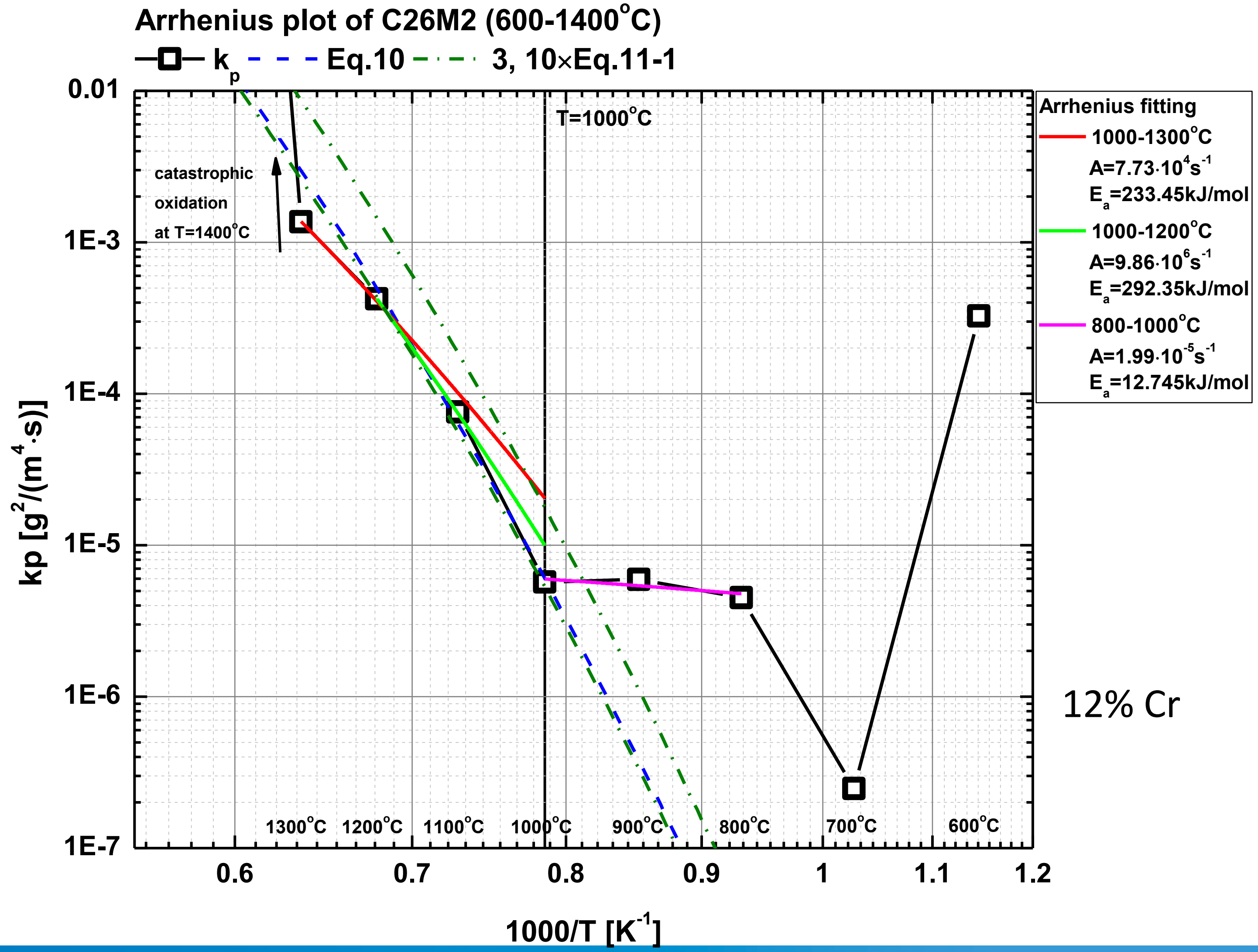




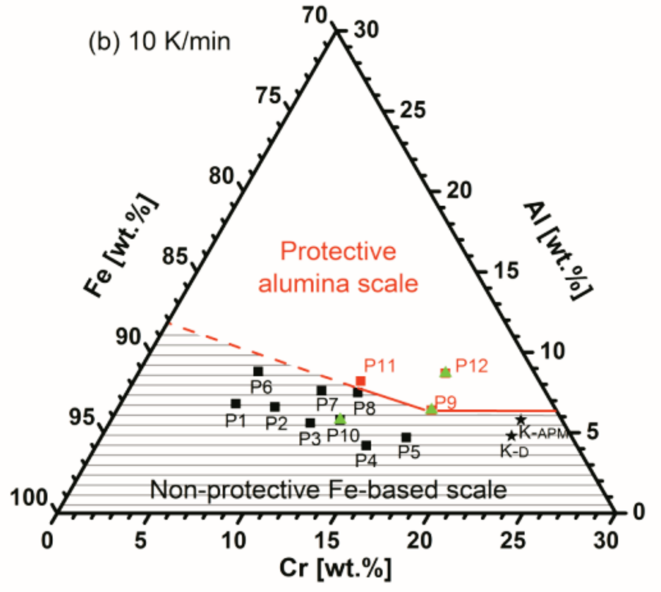
T (K)	K (m²/s)	
	CS sample	MS sample
1373	1.94E-04	2.48E-04
1423	2.28E-04	2.62E-04
1473	2.55E-04	2.95E-04
1523	2.99E-04	3.57E-04
1573	3.62E-04	4.83E-04

MS = Magnetron Sputtering coating thickness ~13 µm
CS = Cold Spraying coating thickness ~31 µm

Results   Issues of FeCrAl   I) kinetic limitations



12% Cr



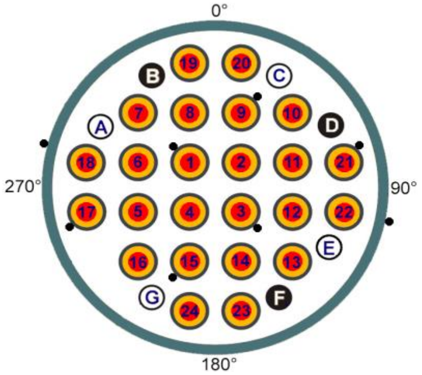
Oxidation behaviour of FeCrAl-based alloys during the transient tests from 500 to 1450°C with subsequent holding 1 h at 1450°C in steam. ■ and ★: alloy specimens showed catastrophic oxidation with non-protective Fe-based oxide scale

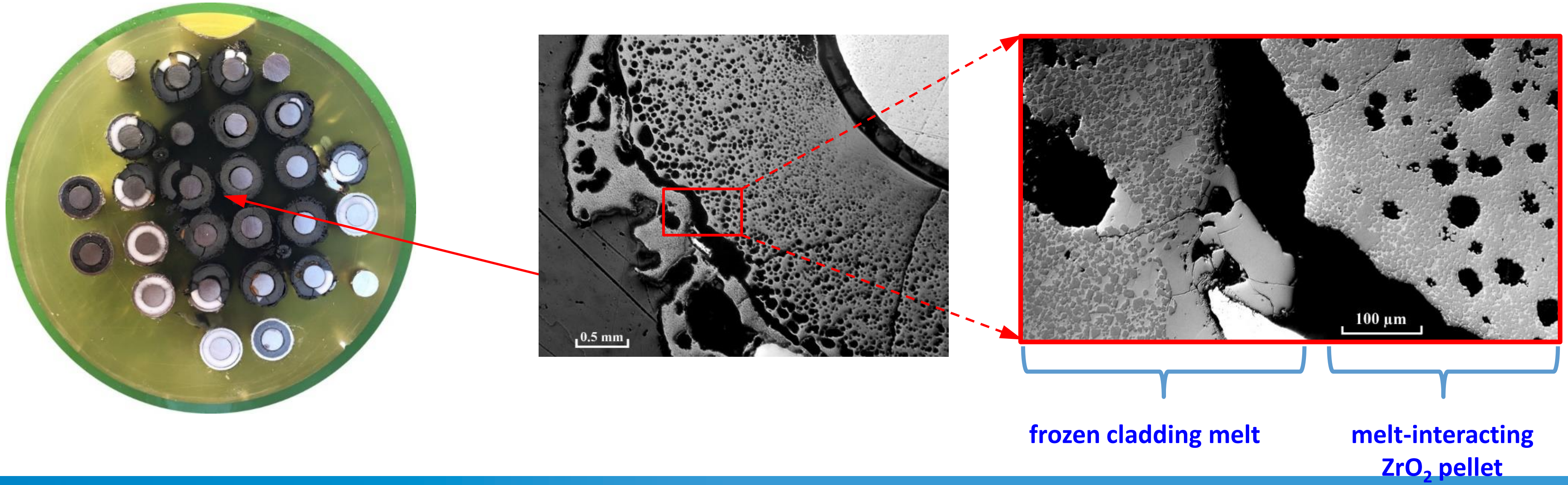
■ and ★: alloy specimens formed protective alumina scale

▲: alloy specimens with Y addition formed protective alumina scale

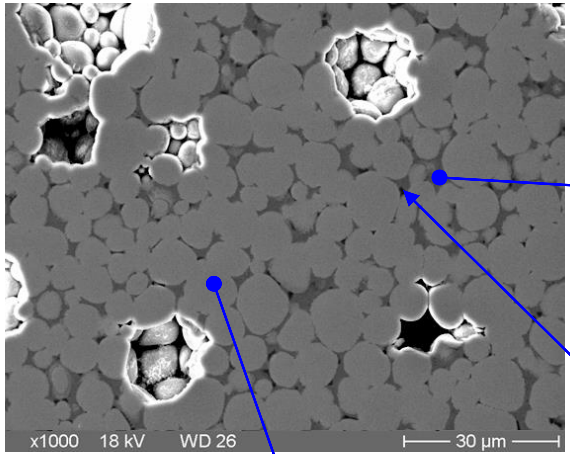
QUENCH-19 test with FeCrAl claddings

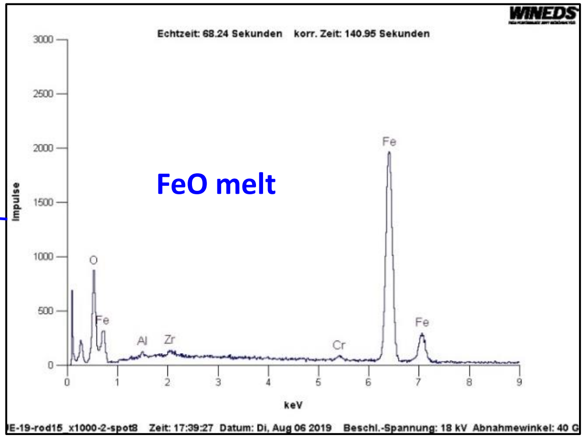
QUENCH-19, 950 mm, rod 2: metallographic investigations, optical observation

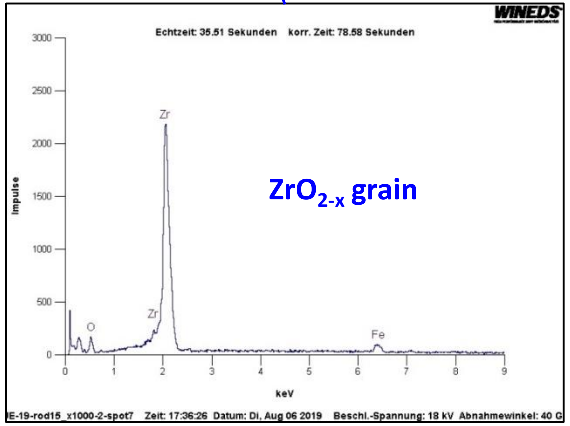


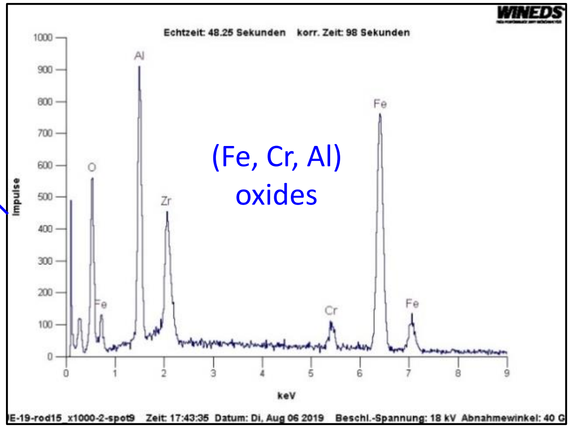


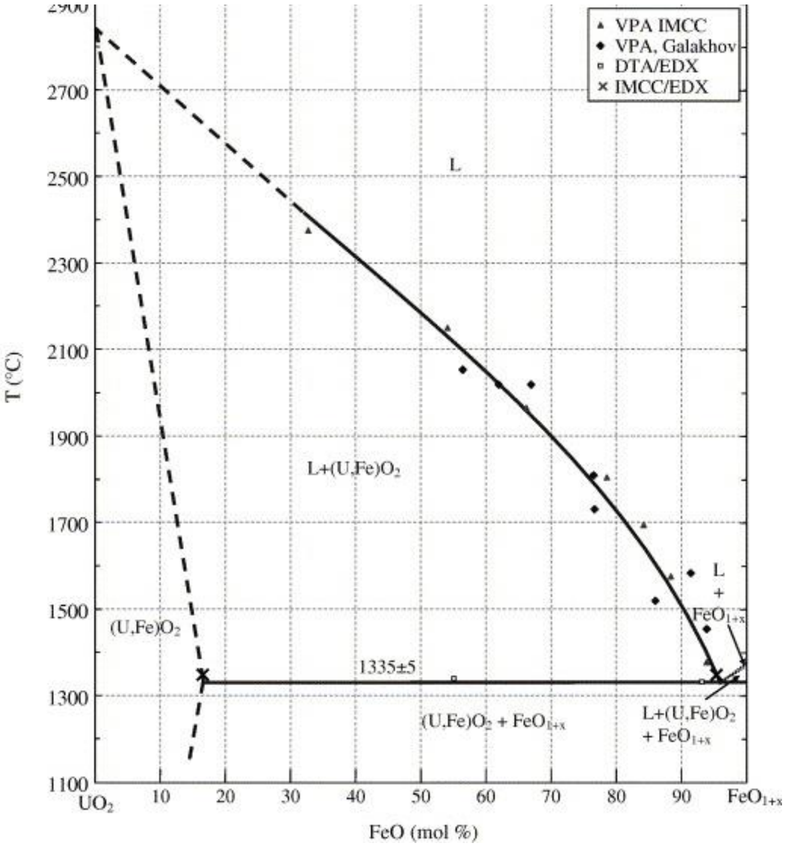
QUENCH-19, 950 mm, rod 2: SEM/EDX analysis of pellet





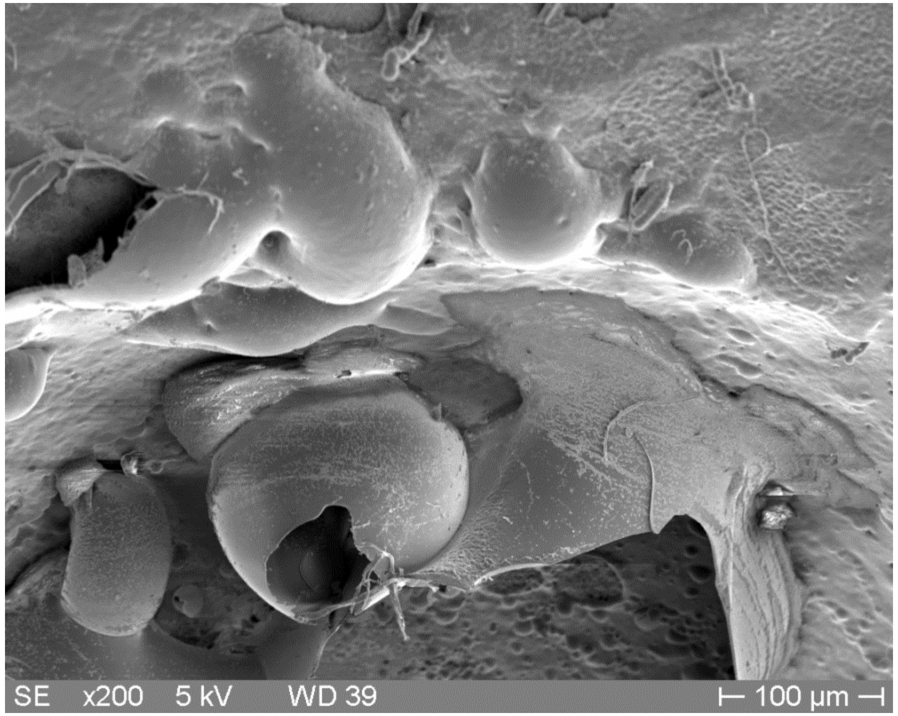




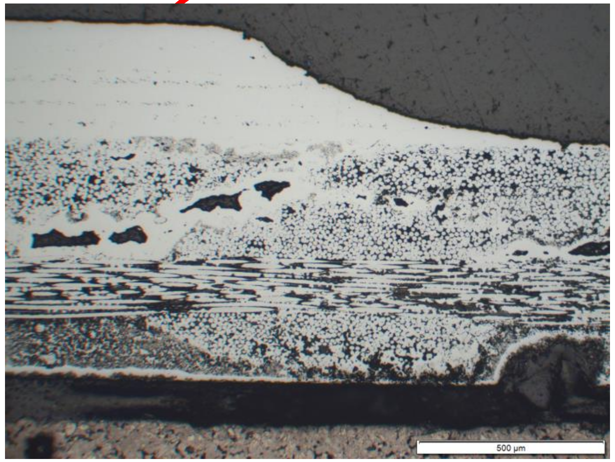


Results Issues of SiC I) accelerated oxidation at T > 1730°C

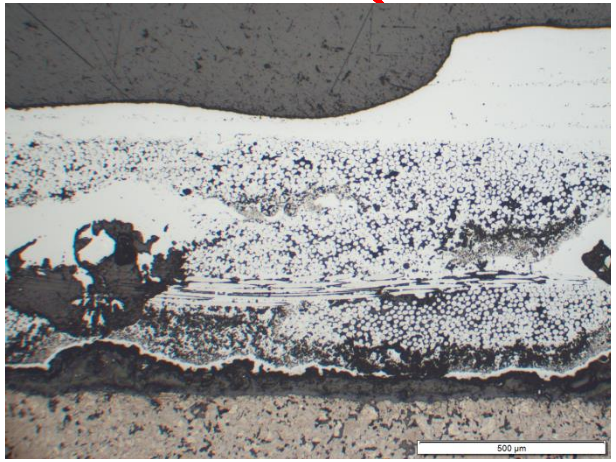
Bubble formation at T > 1713°C (melting point of SiO_2)



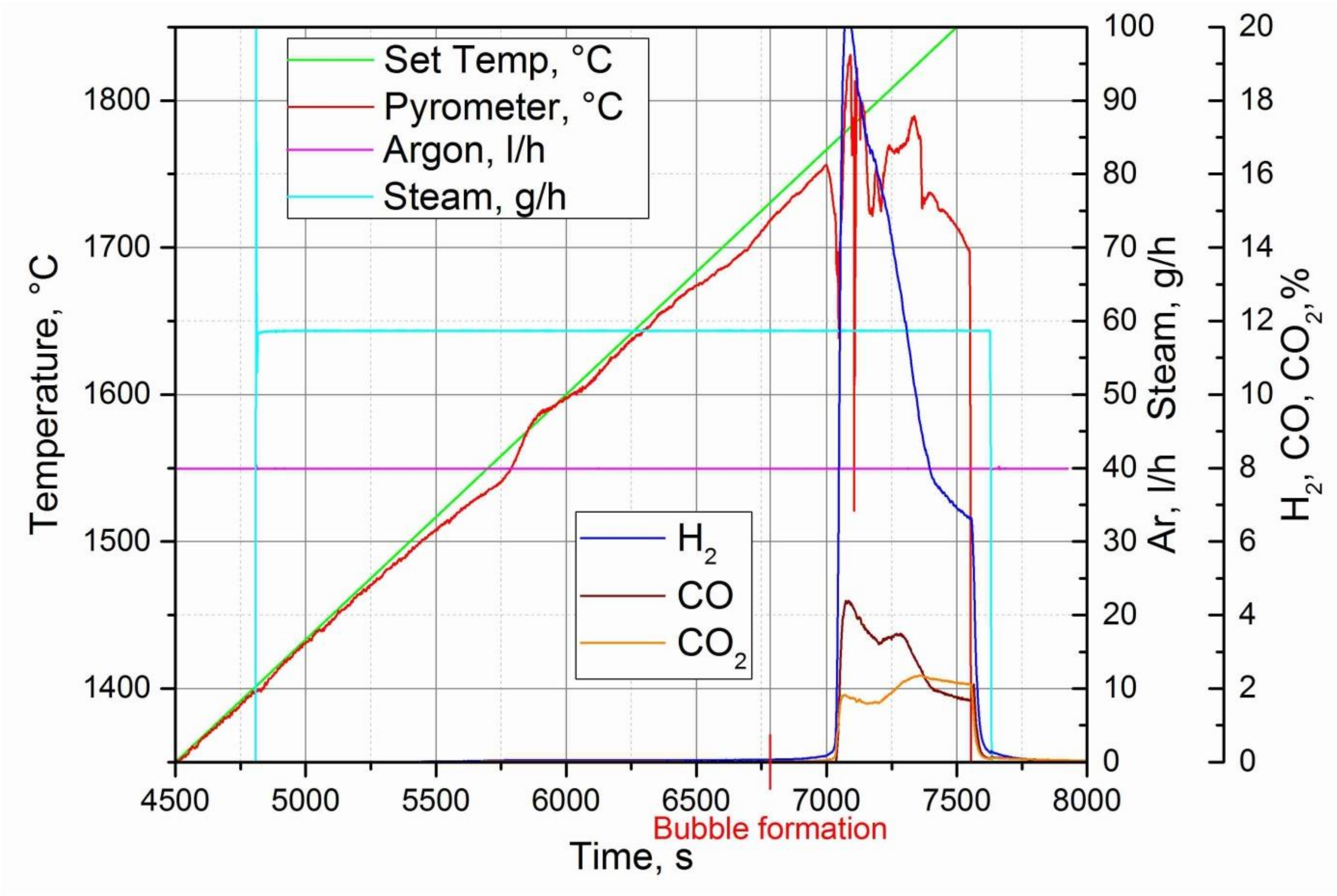
Results Issues of SiC-CMC II) very large reacting surface if steam can penetrate the fibers



Rapid increase of the reacting surface at 1750°C when the monolithic outer layer is consumed.



Results Issues of SiC-CMC II) very large reacting surface if steam can penetrate the fibers



Results   Issues of SiC-CMC   II) very large reacting surface if steam can penetrate the fibers

Summary and Conclusions

- The maximumal temparatures for applications are often less than a-priori expected.
- Cr-coated Zry-4: eutectic interaction between Cr and Zr results in a higher oxidation rate at temperatures above 1330°C. Catastrophic oxidation if the coating fails.
- FeCrAl:
  - Eutectic interaction between molten FeO and UO_2 at 1335°C can results in much earlier core melting.
  - Material performance depends on heating rate. Time is needed to form a protective Al_2O_3 layer. Catastrophic oxidation occurs above 1330°C if no protective Al_2O_3 layer is formed.
- SiC: faster oxidation above the melting temperature of SiO_2 at 1720°C. Catastrophic oxidation occur if the monolithic outer layer fails (even at 1200°C).
- **A lot of work has to be done to achieve accident tolerance. However, it is worth to do this work because the improvement of safety would be great.**

THANK YOU FOR YOUR ATTENTION!

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