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MCCI on LCS concrete with and without rebars

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MOCKA experiments: MCCI by an oxide and metal melt in a stratified configuration

- Initial melt is generated by a thermite reaction : 42 kg **Fe,** overlaid by 68 kg oxide melt (**56 wt.% Al_2O_3, 44 wt.% CaO).**
- 4 kg **Zr** are deposited at the bottom of a cylindrical crucible with **25 cm** inner diameter**.**
- Prototypic heating of both melt phases: **76 %** is deposited in the oxide phase and **24 %** in the metal melt.
- Concrete: **siliceous/LCS.**
- Initial melt temperature ~ **2193 K**.

Types of concrete

Depending on the $SiO_2/CaCO_3$ (silica/limestone) ratio the concrete used in nuclear power plants can be divided into three categories

- siliceous;
- limestone/common sand (LCS);
- pure limestone.
- basaltic concrete is similar to siliceous concrete but with approximately 20 wt.% lower content of SiO_2 and a higher content of Al_2O_3, MgO and Fe_2O_3.
- Concrete fabricated with serpentine aggregates ($(MgO)_6 \bullet (SiO_2)_4 \bullet (H_2O)_4$ with a substantial content of crystal water.

Behaviour of Concrete under Thermal Load

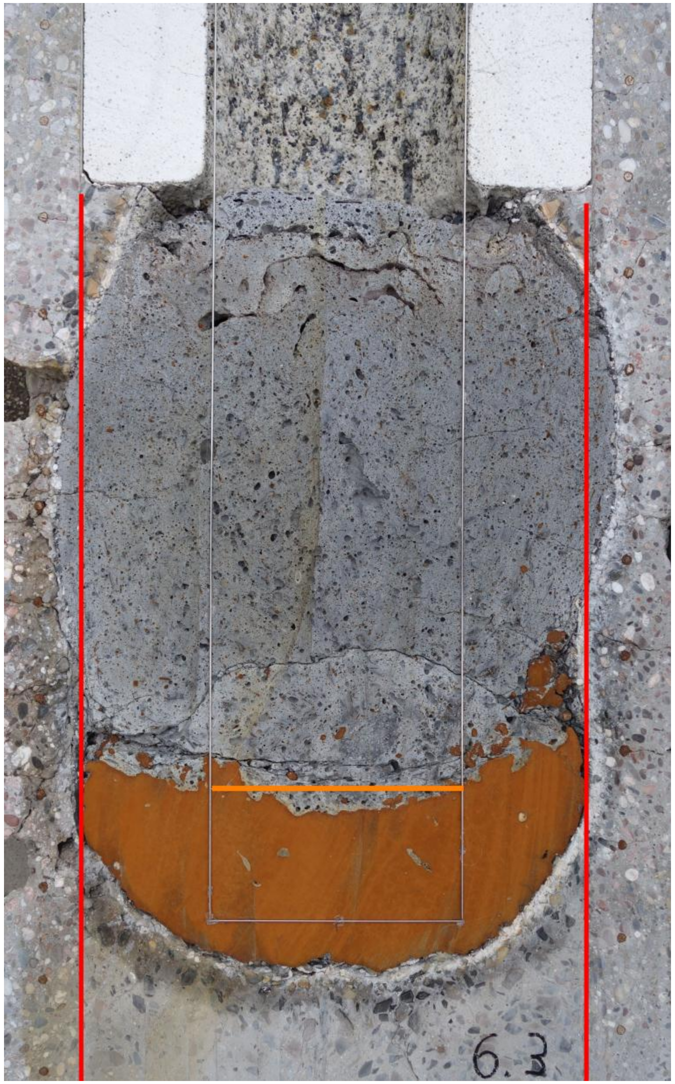
- Decomposition of concrete during heat-up starts with evaporation of physically bound water around 100°C.
- Dehydration of chemically bound water occurs up to 550°C.
- Decarbonation of $CaCO_3$ from the cement and carbonate aggregates occurs from 700 to 900°C.

Consequently, loss of mechanical and thermal strength.

- Liquid phases start to form between 1100-1250 °C.

Fig. 1: Upside down view of the rebar structure.

All experiments on LCS concrete with and without rebars have produced very similar results, but…



$P_{in,\ ox}$ = 454 kW

$E_{er,\ ox}/E_{in,\ ox} \approx 0.47$

Fig. 2:
Left: **MOCKA 6.3** pure concrete.
Right: **MOCKA 7.1** reinforced concrete.

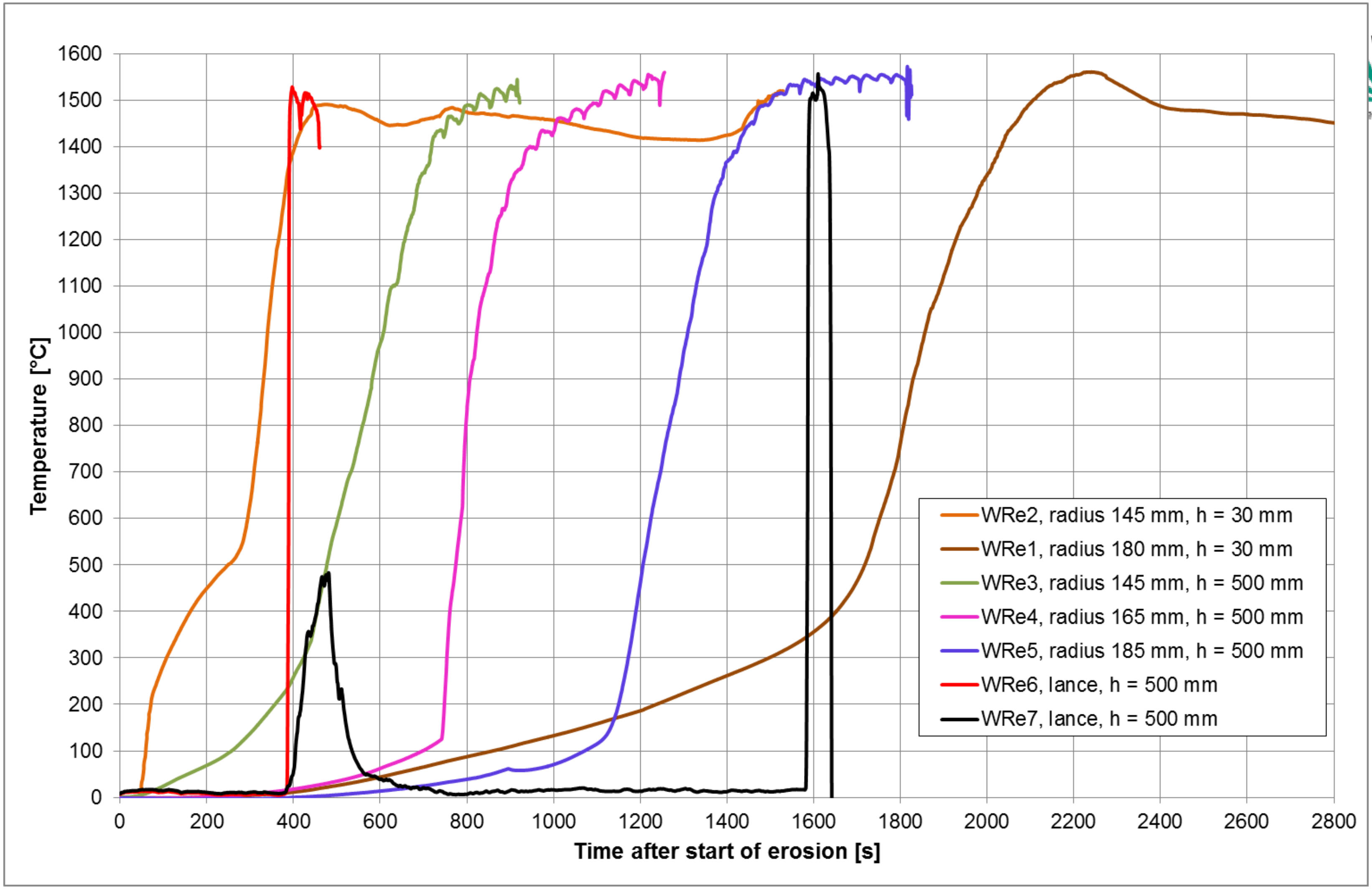


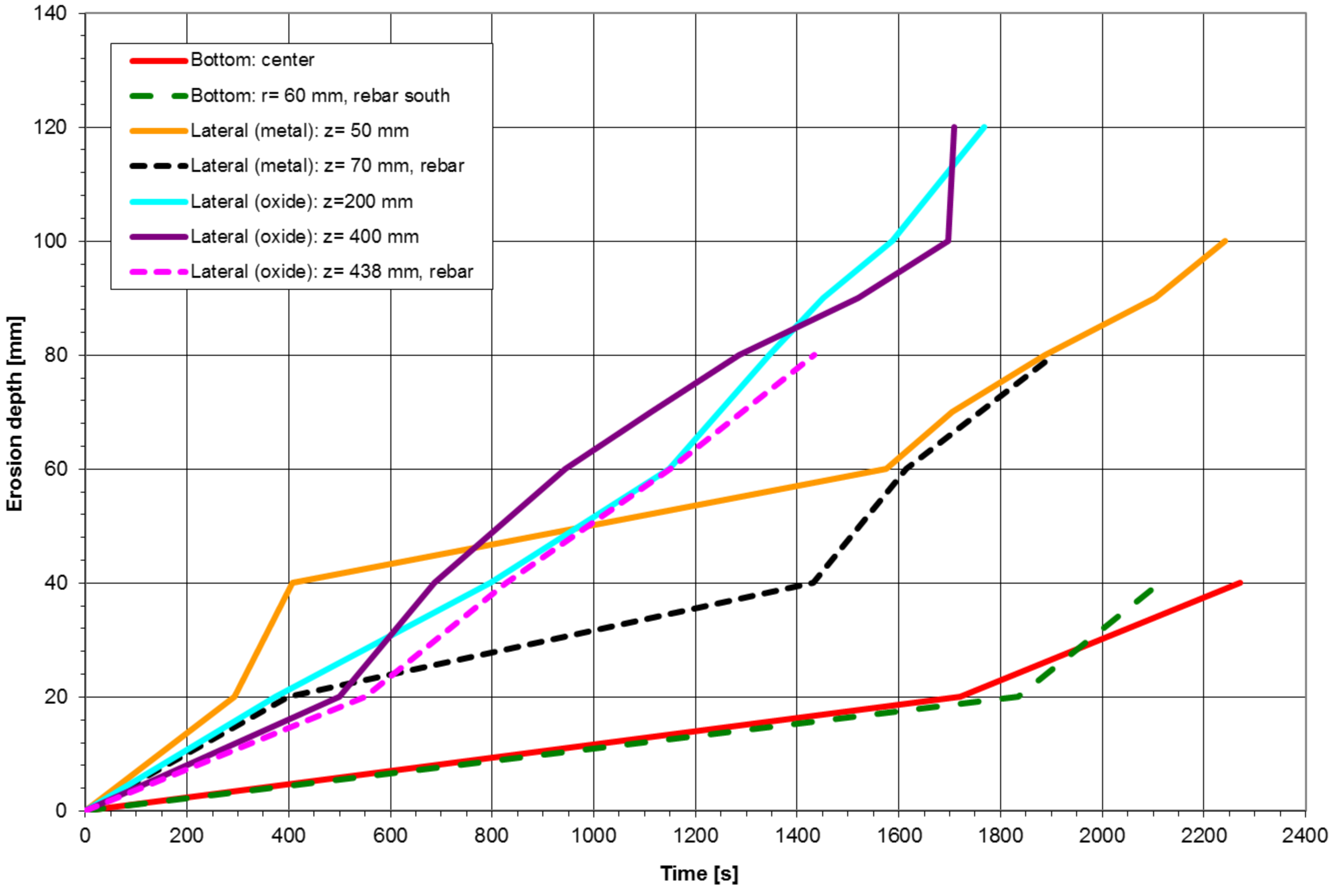
Fig. 3: Melt temperatures in **MOCKA 7.1** (reinforced concrete).

- The rising edges of the oxide melt temperature oscillation correspond with addition of **thermite** and **Zr** to the oxide.

- The mass of the reinforcing steel contained in the eroded concrete by the oxide melt, $f_{rebar}\ m_{er}$, and its enthalpy,

$$f_{rebar}\ m_{er}\ (c_{rebar;\ p}\ (T_{rebar;\ liq} + \Delta T - T_{amb}) + h_{rebar;\ lat}),$$

will be transferred into the metal phase in a stratified melt configuration. This will lead to somewhat lower temperature of the oxide melt.



- Initial metal crust (with estimated **1.6 wt.% Si**), v_{er} = 0,7 mm/min.
- Later pronounced lateral ablation.

$P_{in,\ met}$ = 142 kW

$E_{er,\ met}/E_{in,\ met} \approx 0.34$

Fig. 4: Concrete erosion **MOCKA 7.1** (reinforced concrete).

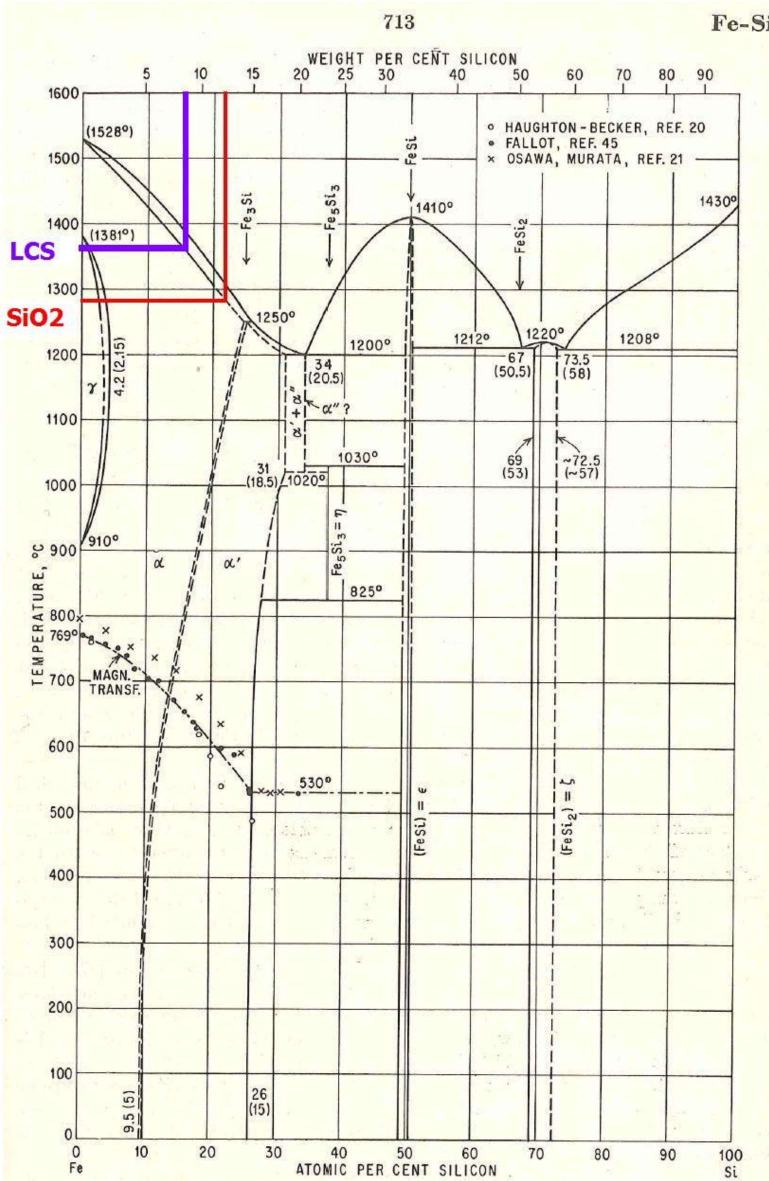


Fig. 394. Fe-Si. (See also Supplement.)

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Si content in the metal melt

Siliceous concrete:

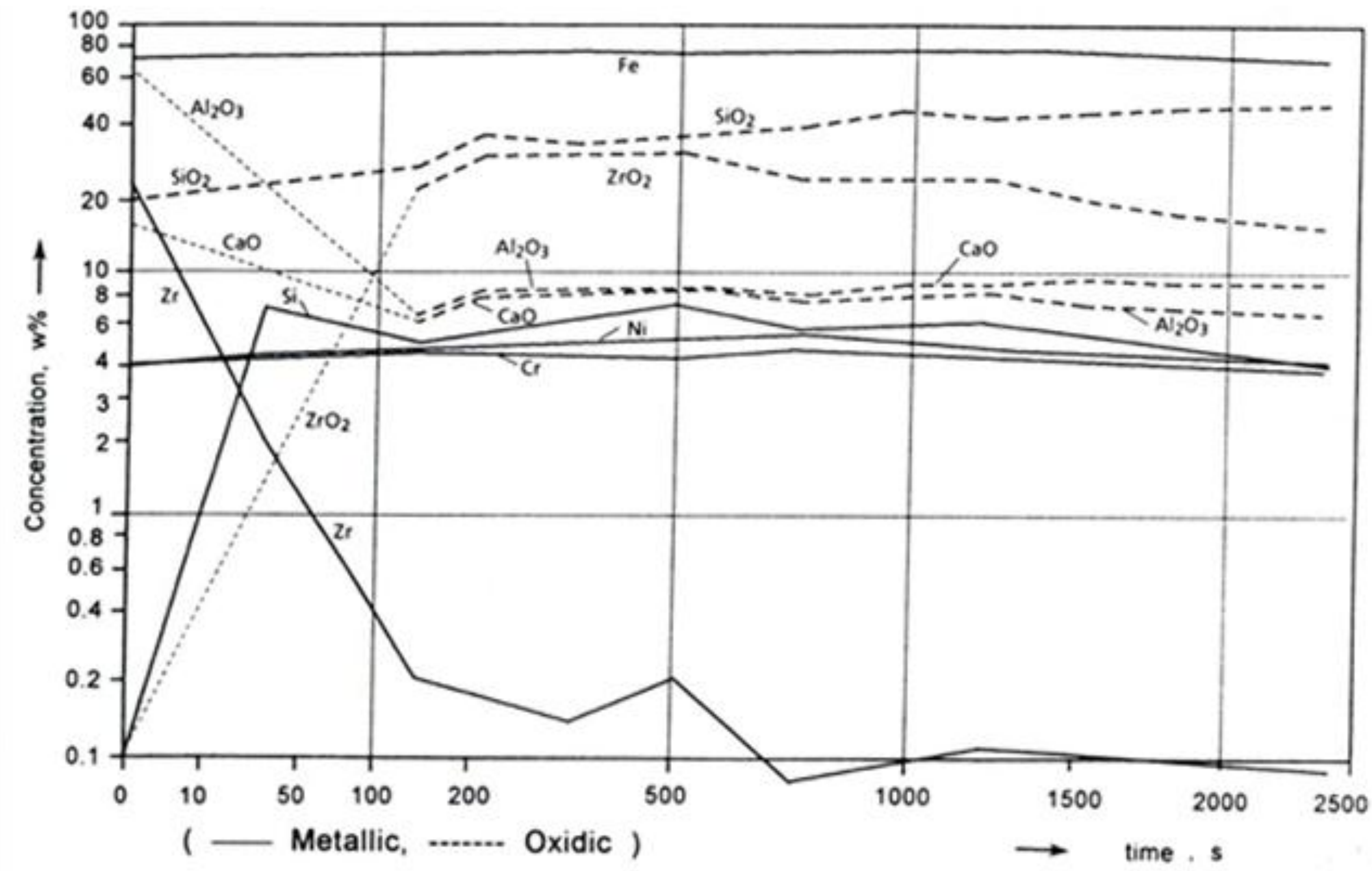
- 13 wt.% (measured)
- 11.3 wt.% (estimated)
- $\rho_{Fe+Si} \sim 5.75 \times 10^3\ kg/m^3$.

- No **iron oxides** are detected in **MOCKA** oxide melts.

LCS concrete:

- 8.3 wt.% (estimated), measurements in progres
- $\rho_{Fe+Si} \sim 6.07 \times 10^3\ kg/m^3$.

- **Slow oxidation of Si (BETA V 5.2)**



Time dependent composition of oxide and metal melts in **BETA V 5.2**.

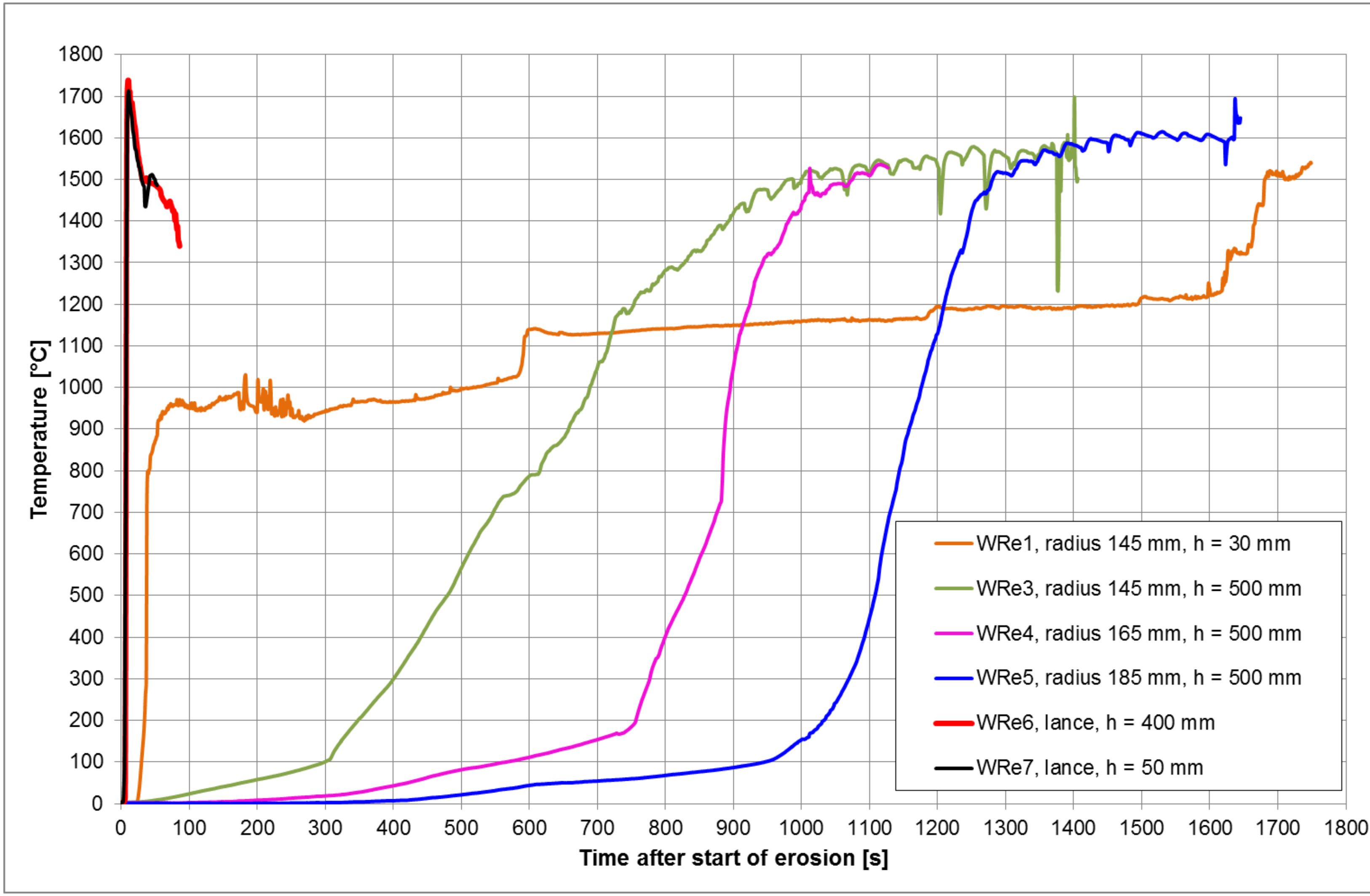
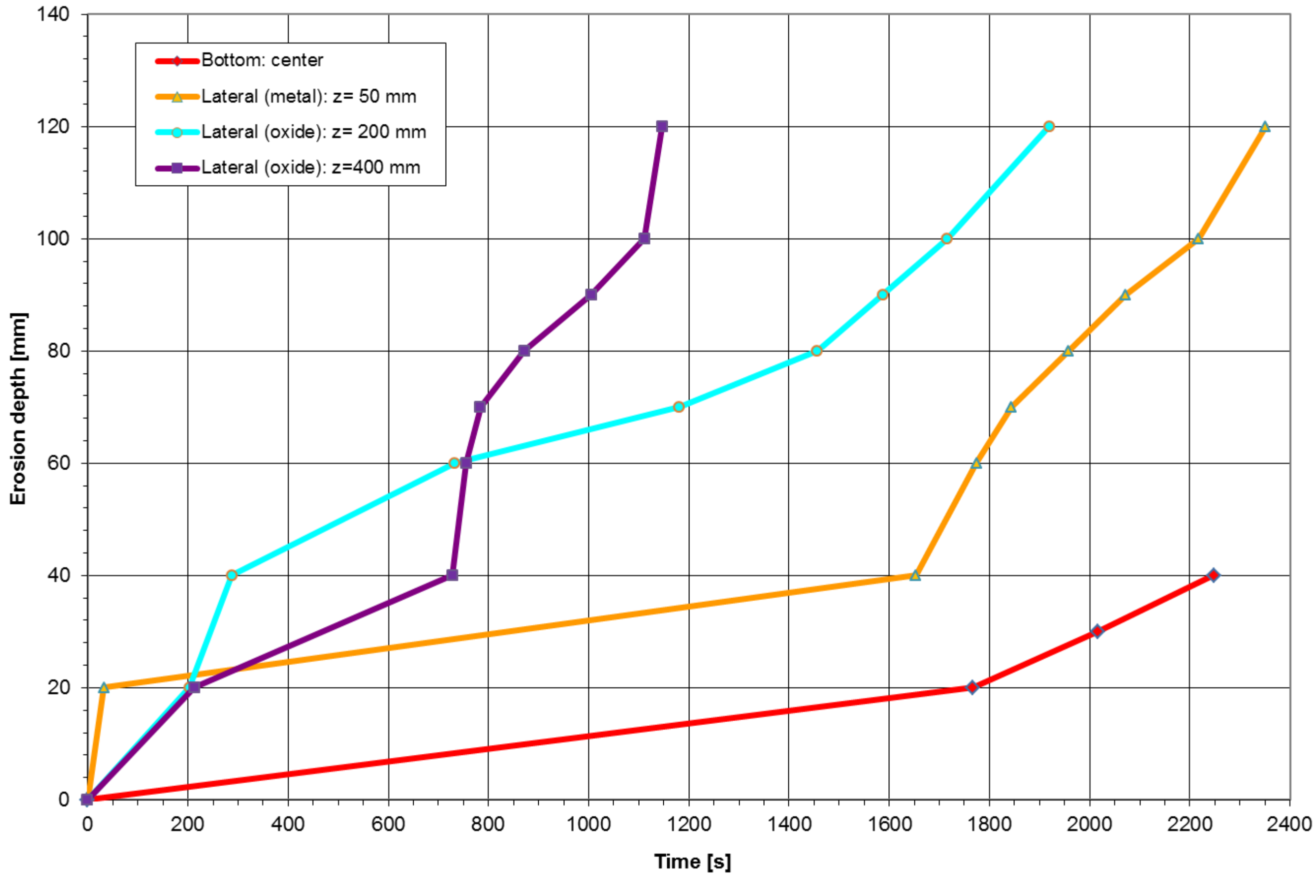


Fig. 5: Melt temperatures **MOCKA 6.3** (pure concrete).



- Initial metal crust with v_{er} = 0,7 mm/min.
- Later pronounced lateral ablation.

$P_{in, met}$ = 142 kW

$E_{er, met}$ /$E_{in, met}$ ≈ 0.39

Fig. 6: Concrete erosion **MOCKA 6.3** (pure concrete).

Initial and boundary conditions

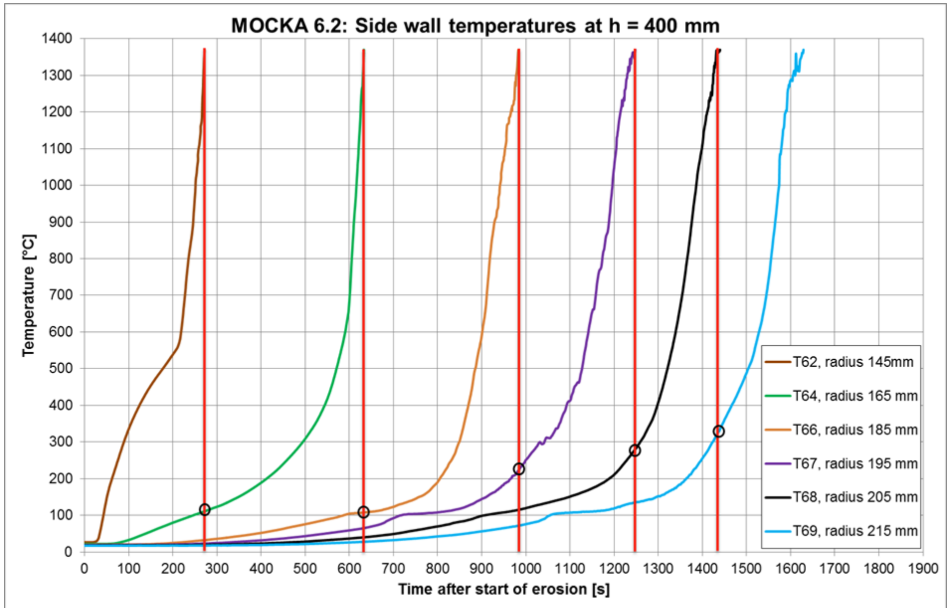
Oxide melt				
	MOCKA 6.3	MOCKA 7.1	CCI-2	CCI-4
Concrete	LCS	LCS + 0.12 wt.% rebar	LCS	LCS
$P_{in,}$ kW	454	454	120	95
E_{er}/E_{in}	0.47	0.47	0.5	0.4
H_{dec} MJ/kg	2.38	2.264	2.38	2.38
$c_{p,\,conc}$ J/kg K	1000	970	1000	1000
T_{int}	T_{dec}	$T_{dec,\,r} = T_{liq,\,r}$	T_{dec}	T_{dec}

- In all experiments under consideration the same quasi-steady-state temperature of the oxide melt, T_{qs} ~ 1560°C, was observed – **but this is not possible if**

$$T_{dec} \approx 1300\ °C \ll T_{liq,\,r} \approx 1526\ °C!$$

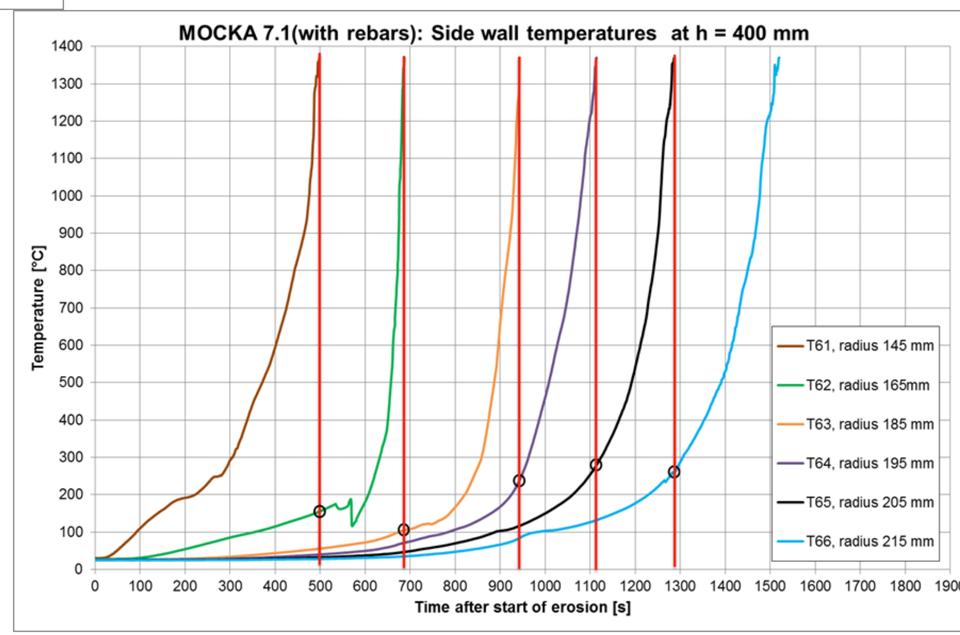
$$T_{qs}\text{-}T_{int} \approx \frac{H_{dec}}{2c_{p,conc}}\left[\sqrt{1-\frac{4c_{p,conc}\left(P_{up}-P_{in}\right)}{\alpha_{ox/conc}\,S_{ox/conc}\,H_{dec}}}-1\right]$$

Heat conduction in concrete without and with rebars



- Based on readings from Type K thermocouples located in the concrete and at the reinforcing bars, it appears that there no enhanced heat transfer in the concrete by heat conduction due to the rebars.

Fig.: Lateral wall heat up 2 cm ahead the moving front of the oxide melt (black circles).



Conclusions

- The findings rise an issue concerning **decomposition temperature** of the concrete.
- There is **no apparent effect of the reinforcement on heat conduction in the concrete**

- Solidus temperature of the initial oxide melt below the contact temperature, therefore, no crust formation (in contrast to **CCI** experiments) after completion of the thermite reaction.
- Initial crust at the metal/concrete interface.

- **Si** enrichment of the metallic melt due to the reduction of the **SiO_2** by **Zr**.

- MCCI on a **LCS concrete: pronounced lateral ablation** by the **metal phase.**
- **Applicability range of the experimental findings? The early phase? The late phase? → Are the models which are validated against the CCI, BETA, MOCKA, VULCANO, ... experiments valid for the whole sequence of the MCCI?**
- **There is <u>no physical reason</u> to assume a <u>long-term</u> 1 to 1 or n to m ratio of the lateral to axial ablation!!!**