Progress in Research and Development of Molten Chloride Technology for Large-Scale Thermal Energy Storage at ≥700°C

Dr. Wenjin Ding[1], Dr. Thomas Bauer[2]

1. Institute of Engineering Thermodynamics, German Aerospace Center (DLR), Stuttgart, Germany
2. Institute of Engineering Thermodynamics, DLR, Cologne, Germany

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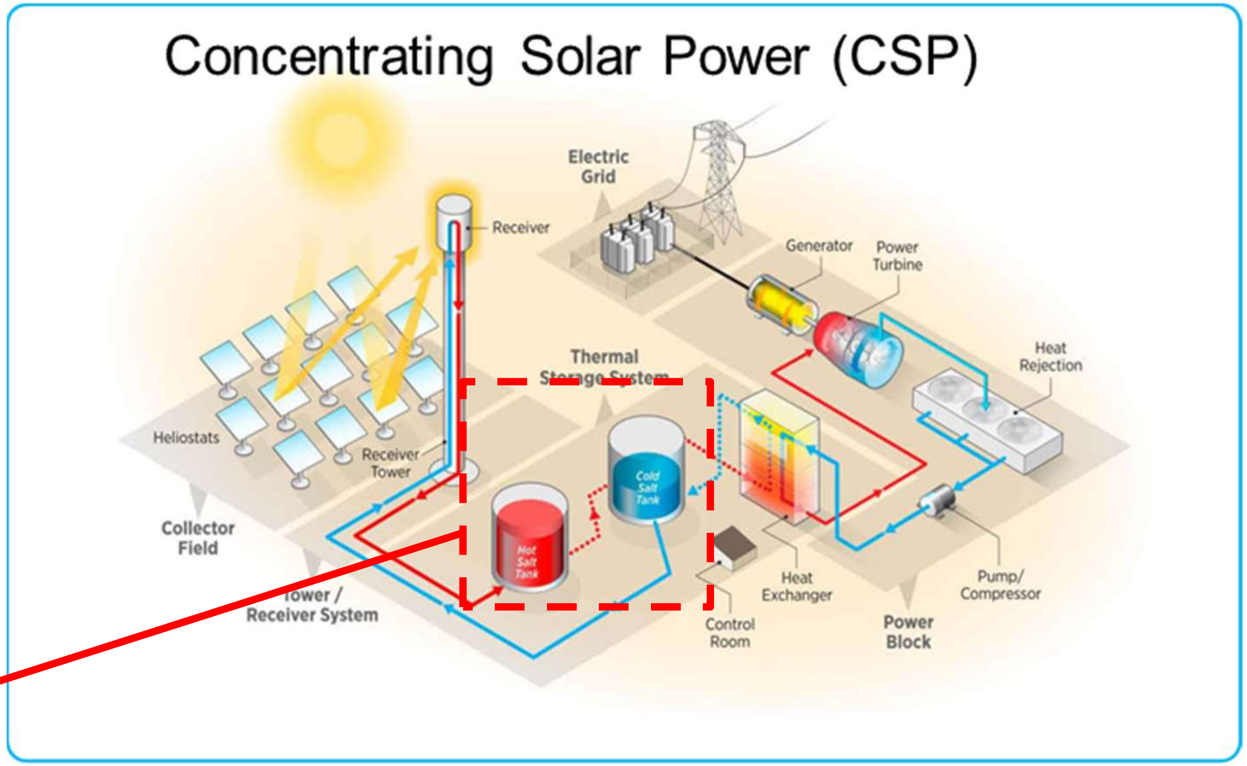
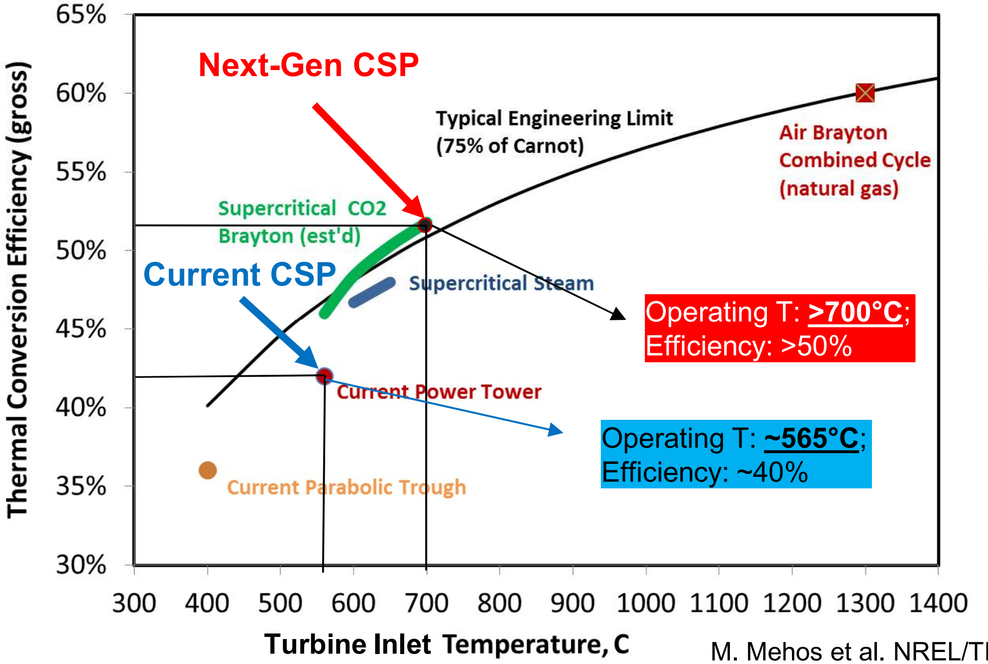
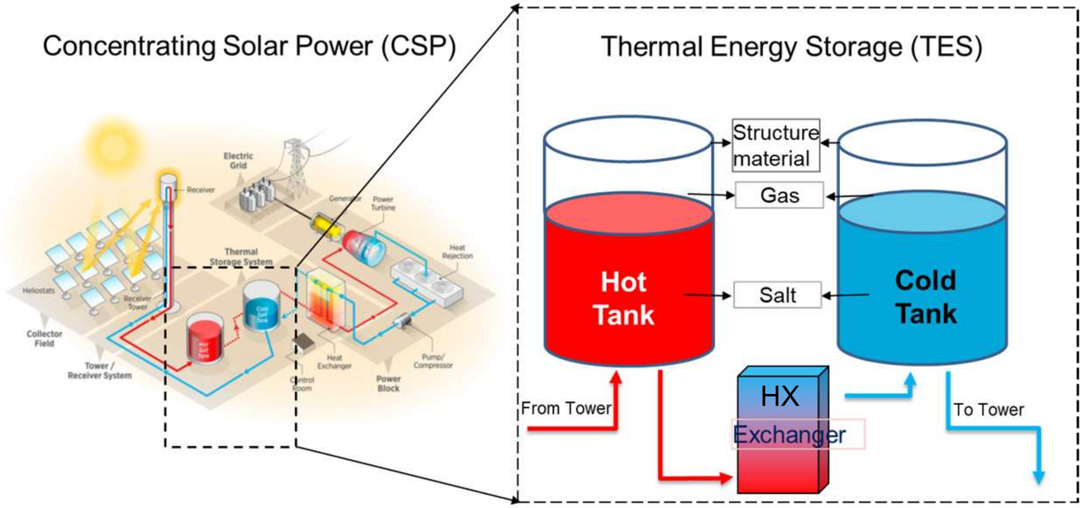
Molten salt TES for CSP



- **>7 GW** CSP, **>60 GWh$_{th}$** molten salt TES in operation
- Molten salt TES (**290-565°C**): **~2.5 GWh$_{th}$** for 10-hour storage of a 100MW$_{el}$ CSP, **~20 000 tons nitrate salts**
- Low CAPEX of molten salt TES: **20-33 \$/kWh$_{th}$**

Molten Chloride TES for Advanced Thermal Power Plants





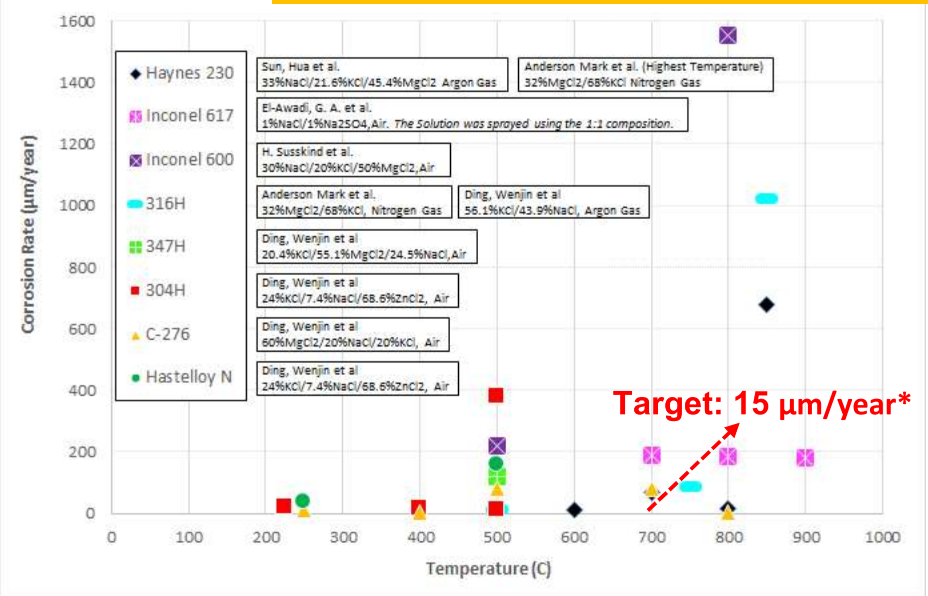
T_{hot} 565°C (Nitrate) → >700°C (Chloride)

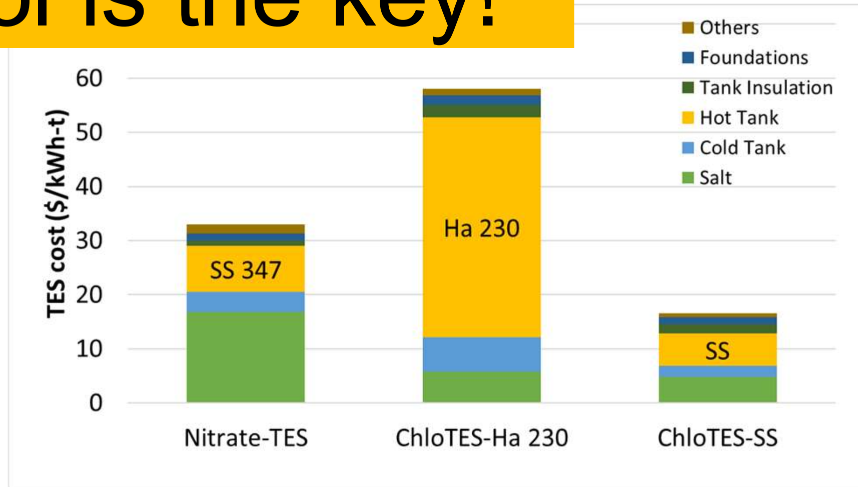
M. Mehos et al. NREL/TP-5500-67464, 2017.
Turchi, Craig. "Concentrating solar power: current cost and future directions." Colorado: National 32 (2017).

- **Next-Gen CSP**: advanced power cycle (e.g., sCO_2 Brayton) with higher efficiency **>50%** → **higher turbine inlet temperature ≥700 °C → higher TES temperature >700 °C**
- **But state-of-the-art commercial Nitrate-TES**: $NaNO_3$-KNO_3 60-40 wt.% (Solar Salt), limited to **565 °C** by thermal decomposition
- **Chloride-TES with operating temperature of >700 °C** with excellent thermal stability of >1000°C

Main Challenges for Next-Gen Chloride-TES

Corrosion control is the key!





Nitrate-TES cost: 20-33 $/kWh$_{th}$
Chloride-TES with Ha 230 hot tank: 58$/kWh$_{th}$
Estimated Chloride-TES with SS hot tank: ~15$/kWh$_{th}$

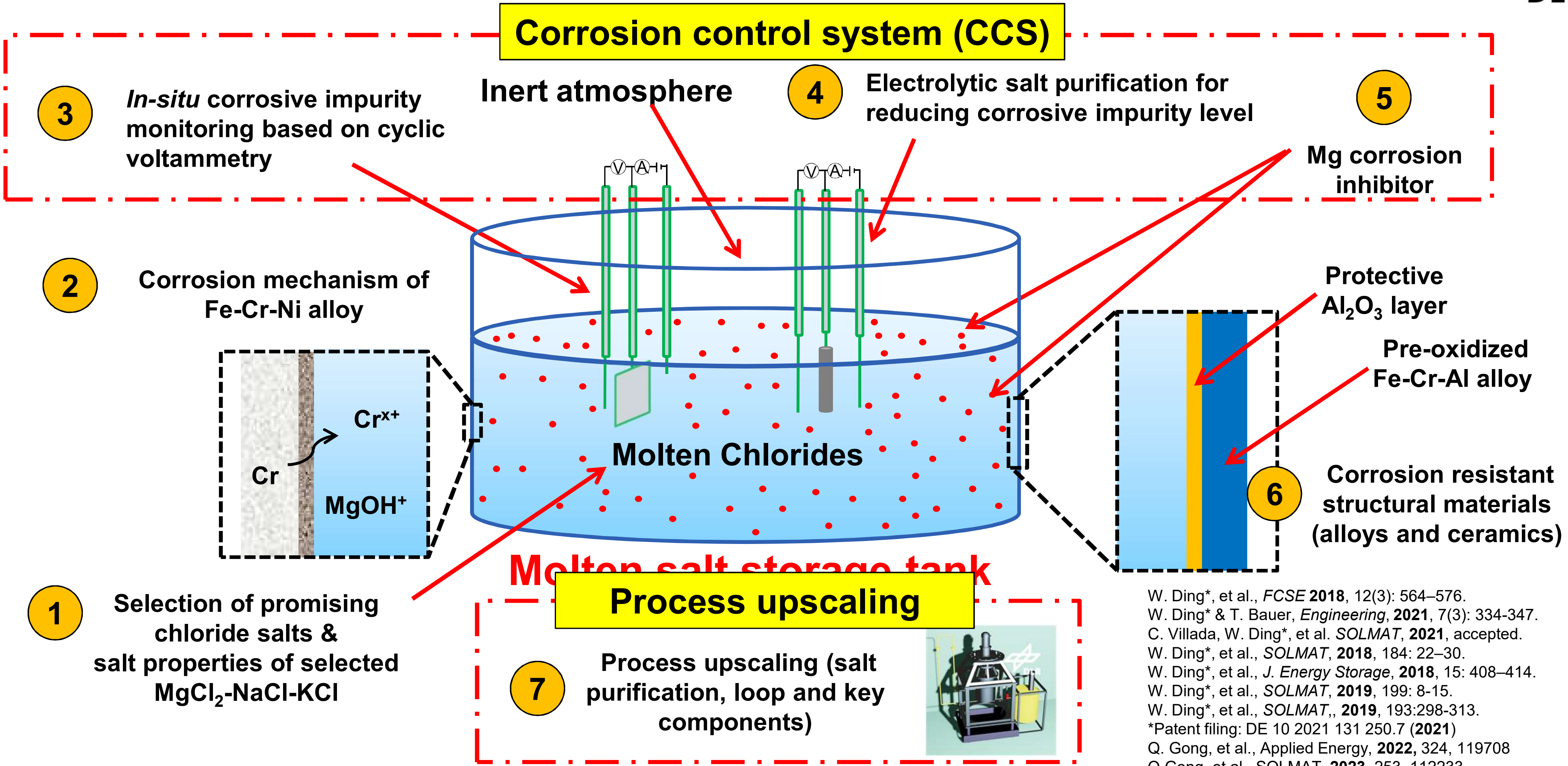
1st challenge: Severe corrosion of molten chlorides

2nd challenge: Affordable structural materials

- **Severe corrosion of alloys in molten chlorides** due to corrosive impurities (e.g., OH^+) formed by hydrolysis
- **Ni-based alloys needed for hot tank** if corrosion control is not achieved → **High TES cost**
- **Fe-based alloys** used for hot tank under successful corrosion control (Chloride **TES-cost ~15$/kWh$_{th}$**)

C. Turchi et al. NREL/TP-5700-79323, 2021. M. Mehos et al. NREL/TP-5500-67464, 2017. *Target of DOE: Garcia-Diaz BL, et al. J.S.C. acad. sci.. 2016; 14(1): 4.

R&D of Chloride-TES at DLR



W. Ding*, et al., *FCSE* **2018**, 12(3): 564–576.
W. Ding* & T. Bauer, *Engineering*, **2021**, 7(3): 334-347.
C. Villada, W. Ding*, et al. *SOLMAT*, **2021**, accepted.
W. Ding*, et al., *SOLMAT*, **2018**, 184: 22–30.
W. Ding*, et al., *J. Energy Storage*, **2018**, 15: 408–414.
W. Ding*, et al., *SOLMAT*, **2019**, 199: 8-15.
W. Ding*, et al., *SOLMAT*,, **2019**, 193:298-313.
*Patent filing: DE 10 2021 131 250.7 (**2021**)
Q. Gong, et al., Applied Energy, **2022,** 324, 119708
Q Gong, et al., SOLMAT, **2023,** 253, 112233

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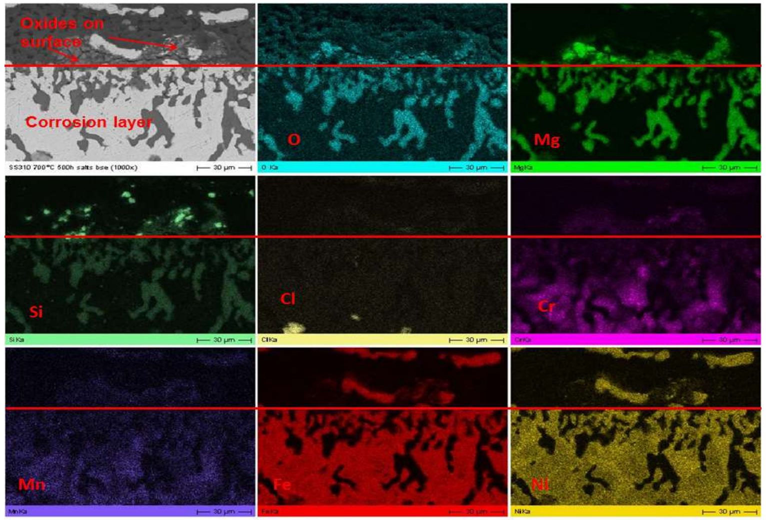
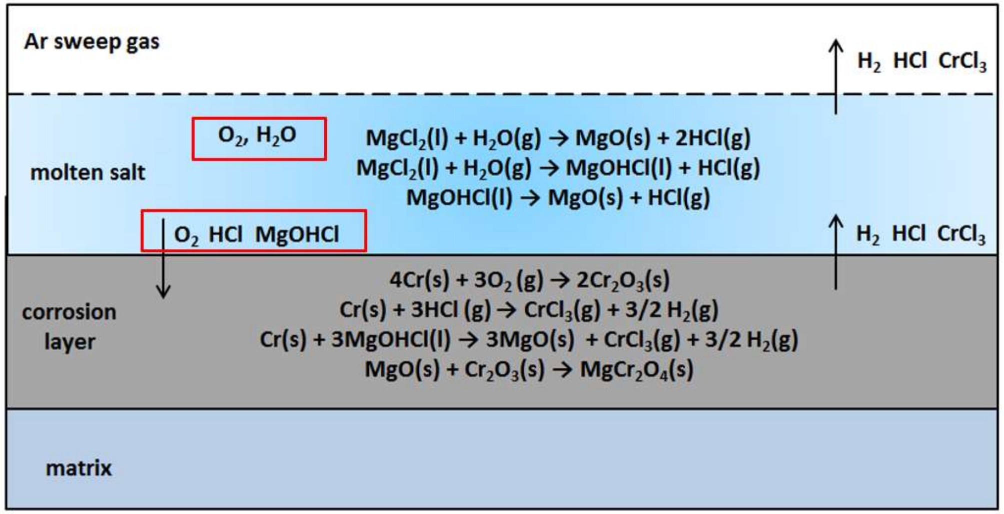
② Proposed Corrosion Mechanism

SS 310 in MgNaK chloride (700°C, 500 h)





- Large amount of Mg and O detected in corrosion layer
- $MgCr_2O_4$ and MgO detected in oxides on surface

Corrosion mechanisms proposed by DLR:

- Cr dissolved preferentially
- Corrosion is driven by impurities mainly **MgOHCl**

- Corrosive impurities: H_2O, O_2, HCl, MgOHCl (high solubility in molten chlorides)
- Corrosion products: $MgCr_2O_4$, MgO, $CrCl_3$
- Corrosion control by controlling concentration of impurities

W. Ding, et al., *SOLMAT*, **2018**, 184: 22–30.

⑤ Mg Corrosion Inhibitor – Breakthrough by DLR

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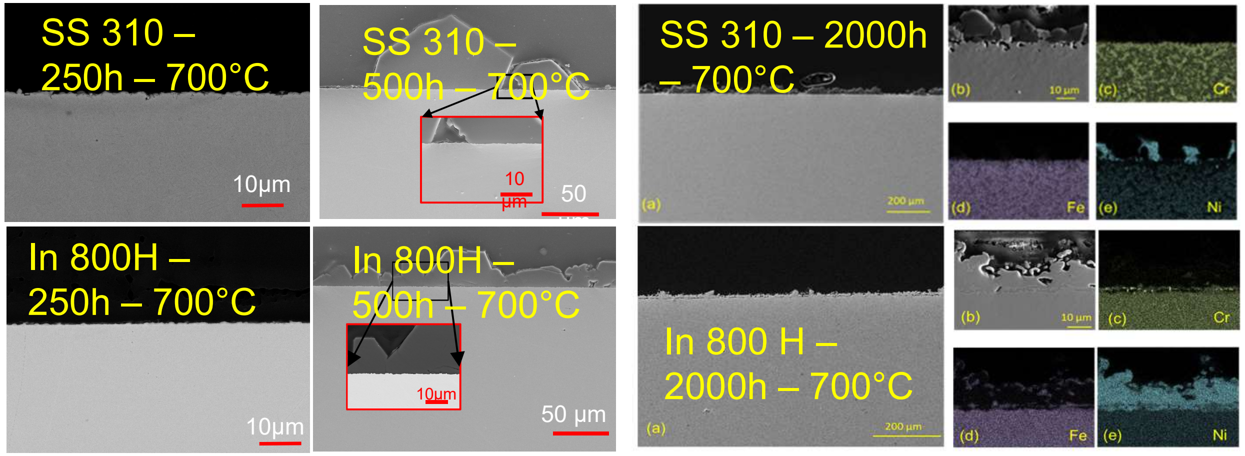
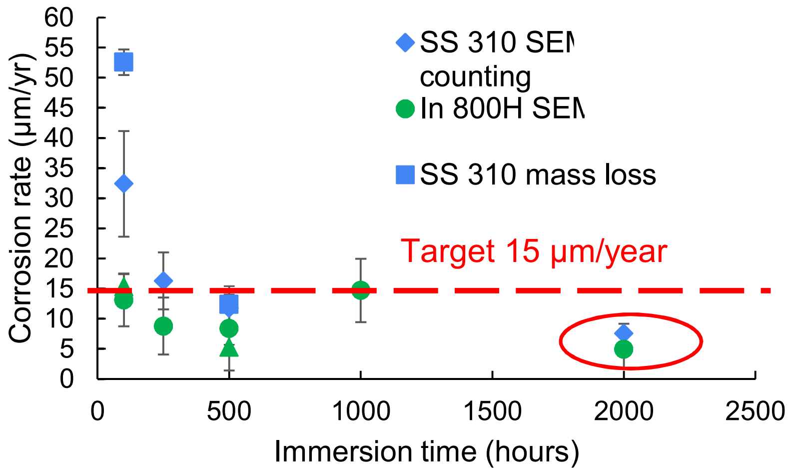




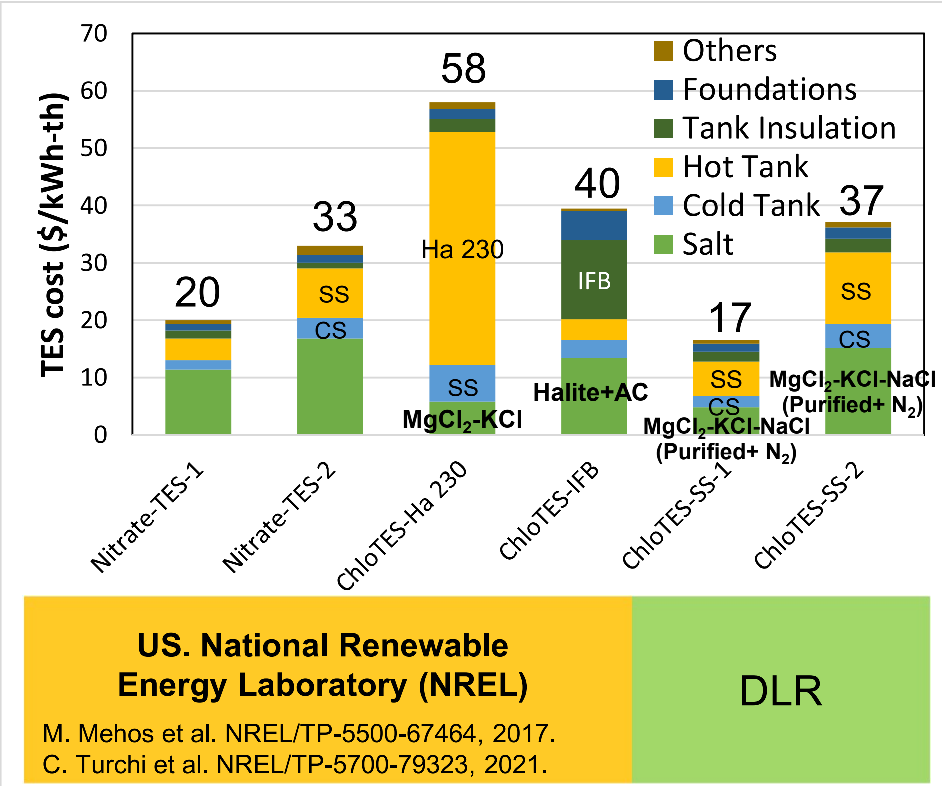
- Salt purified with Mg at 700°C in a patented process*
- **Static immersion tests in purified molten salt at 500-800°C under Ar (up to 2000h)**: Almost no corrosion layers and Cr-depletion of Fe-based steels were observed
- Corrosion rate based on microstructural analysis (SEM) and mass loss: **<15 µm/year for SS 310 and In 800H** at 700°C; **<15 µm/year for P91** at 500°C
- **Breakthrough***: Experimental proof that **Fe-based steels** reach the target of **<15 µm/year** at 500 and 700°C

*Patent: DE 10 2021 131 250.7 (2021)

Q. Gong, T. Bauer, W. Ding, et al., Applied Energy, 324, 119708 (2022)
Q Gong, T Bauer, W Ding, et al., SOLMAT, 253, 112233 (2023)

5 Mg Corrosion Inhibitor –

Competitive low TES-cost based on molten chlorides and Fe-based steels



- Commercial Nitrate-TES cost estimated by NREL: **20 to 33 $/kWh$_{th}$**
- Estimation cost of chloride-TES with insulating fire bricks (IFB) or Ha 230 as hot tank by NREL (corrosion control not achieved): **40 to 58 $/kWh$_{th}$**
- **Competitive low cost of chloride-TES** using Fe-based steels estimated by DLR (corrosion control achieved): **17 to 37 $/kWh$_{th}$**

Ha: Hastelloy for hot tank
SS: stainless steel for hot or cold tank
CS: Carbon steel for cold tank

Q. Gong, W. Ding, et al., Applied Energy (2022)   Q. Gong, PhD thesis, University of Stuttgart, 2023.

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7 Process Upscaling of Chloride-TES

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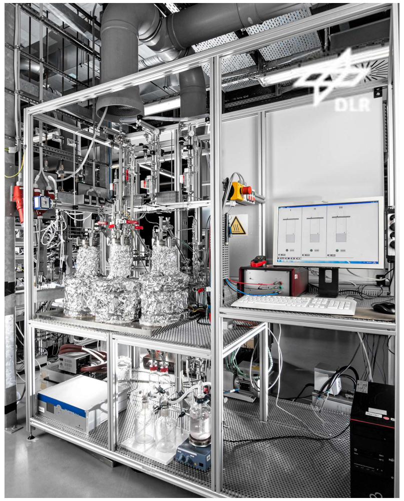
Achieved



Materials research with <1 kg salt: corrosion control, structural materials pre-selection, … (TRL 1-3)

Ongoing

Upscaling with ~100 kg salt: salt purification and corrosion control loop tests, structural materials selection (TRL 4-5)

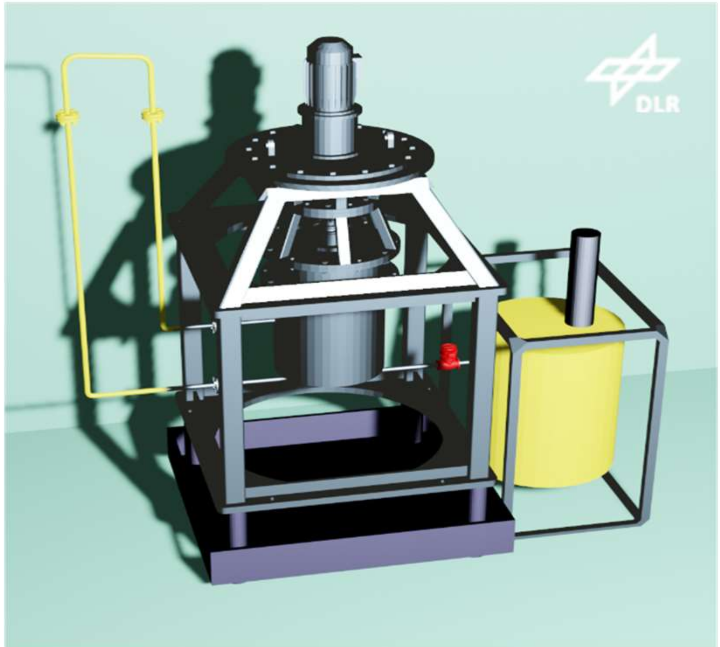
Target

Pilot plant with ~100t salt & component testing (TRL 6-7)

Industry-application (TRL 8-9)

DLR seeks industrial and academic partners for upscaling

Molten Chloride Test Facility (MOCTEF) of DLR



- **Under construction** and will be operated soon

- **Two test units**: one for salt purification, one for pumped loop tests close to conditions in real applications
  - ~100 kg $MgCl_2$-NaCl-KCl is used
  - Conventional stainless steels as structural materials
  - Designed test temperatures >700°C

- **Highlights**: patented corrosion control system, salt and gas phase in-situ analysis, …

Corrosion Test of DMV 310N in Purified Salt at 800 °C

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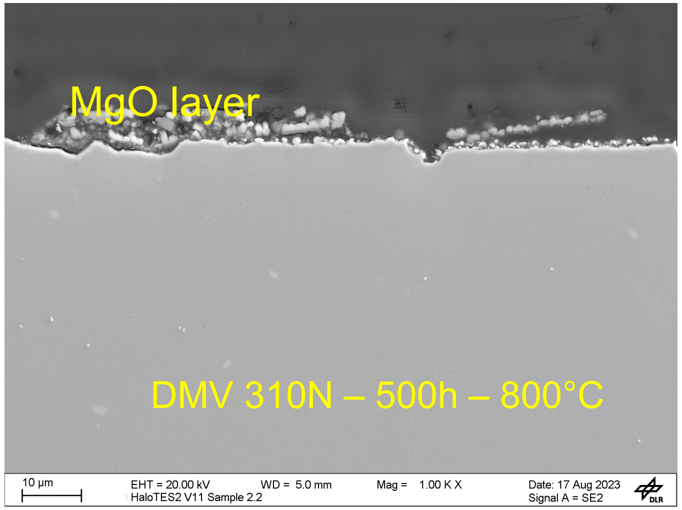

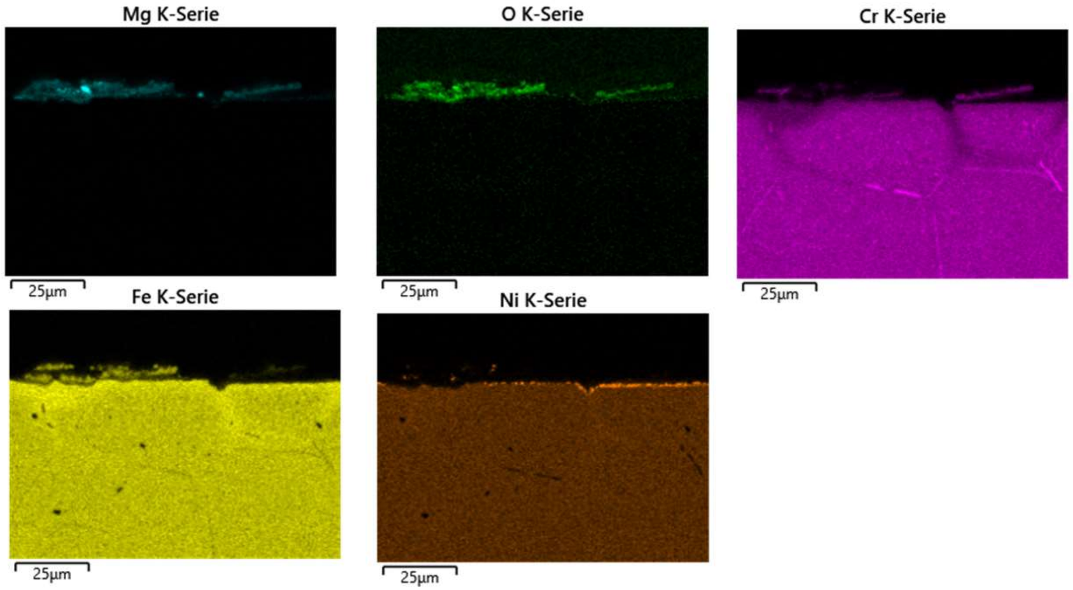

- Pre-test*: 500h static immersion test **at 800°C** in salt purified with MOCTEF salt purification unit
- Corrosion rate (CR) via mass loss: **<50 µm/year**
- Chromium depletion depth **~ 10 µm** (mainly at crystal boundaries)

- 2000h static molten salt immersion and gas tests at 800°C are done and the results (**CR <15 µm/year**) will be published soon, while loop test in MOCTEF at >700°C is planned.

*H Barot, oral presentation in Enerstock Conference 2024, Lyon France, 2024.

Summary

- Molten chloride heat storage and transfer (MOC-HEST) with working temperatures up to 800°C has promising applications in next-gen CSP plants.
- Safe production of CSP plants with molten salt TES under corrosion control is vital.
- Corrosion control technologies in lab-scale have been developed for MOC-HEST.
- Stainless steels (CR<15 μm/year) can be used as the main structural materials in MOC-HEST under corrosion control.
- Process upscaling of MOC-HEST to 100 kg-scale with pumped loop is ongoing.

Thanks for your attention & Welcome to contact us!

Dr. Wenjin Ding: Wenjin.Ding@dlr.de

Dr. Thomas Bauer: Thomas.Bauer@dlr.de

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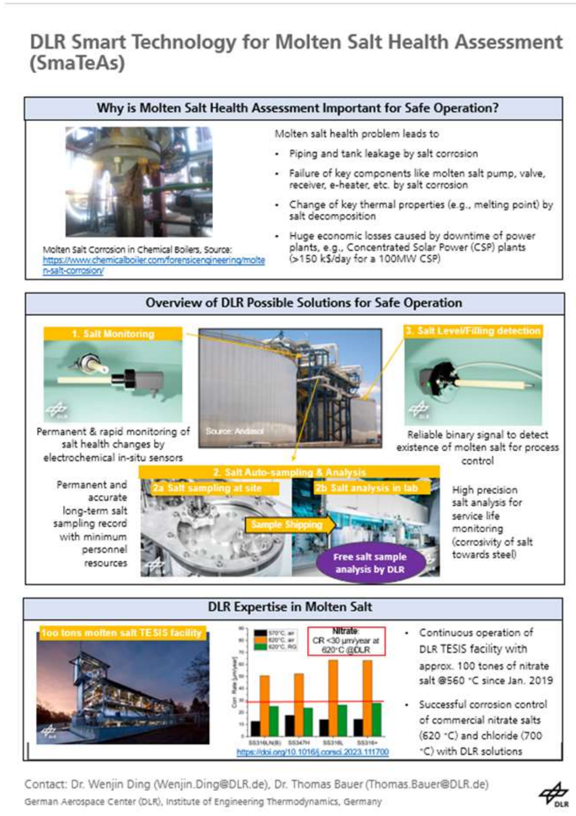

Flyer on DLR molten salt safe operation solutions