European Facility on Molten SALT technologies TO power and energy system applications
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Fast Track School #3

Molten Salt technologies and energy system applications

Evora, 12.-14.11.2024

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Deutsches Zentrum für Luft- und Raumfahrt
German Aerospace Center

Wenjin Ding, Thomas Bauer

Development and potential market launch of new molten salt technologies

Evora, 12.-14.11.2024

Contents

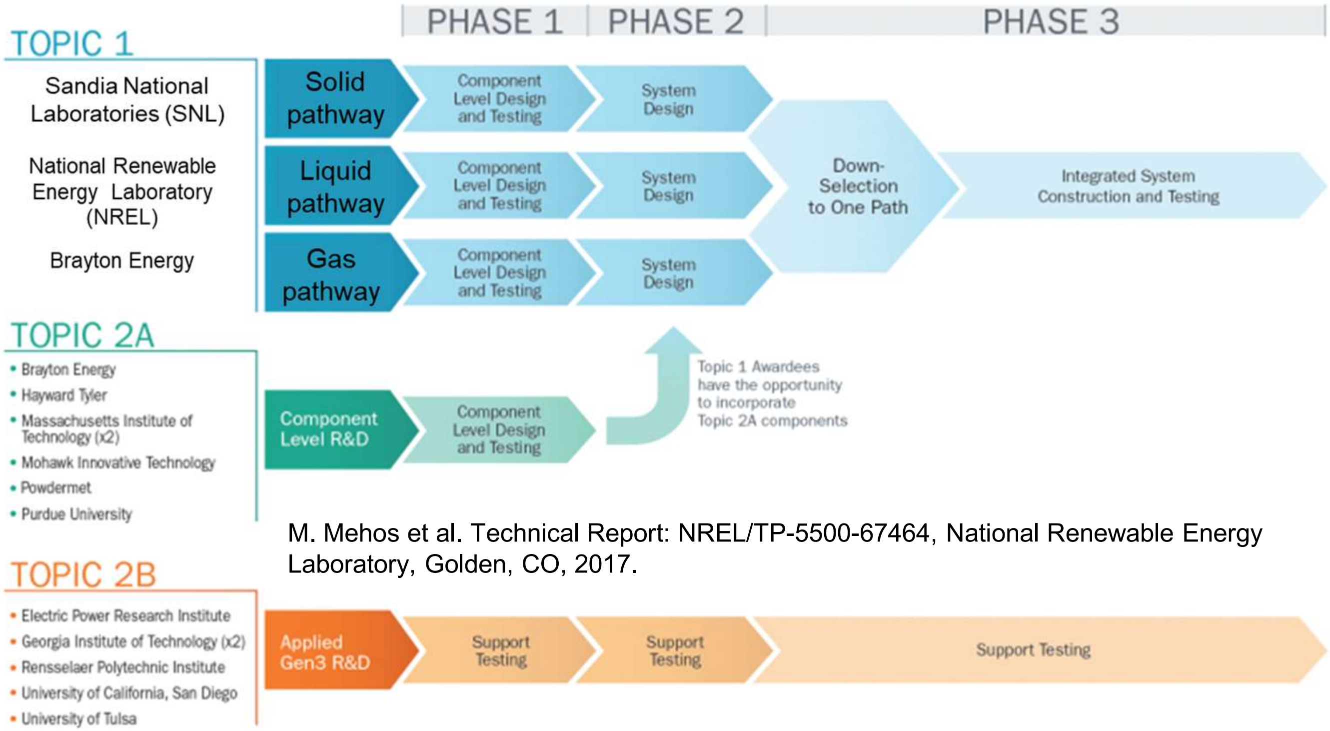
- **Motivation**
- R&D progress in Corrosion Control of Chloride-TES
- R&D progress in Process Upscaling of Chloride-TES
- Potential Market Launch

Applications of Molten Salt Technologies

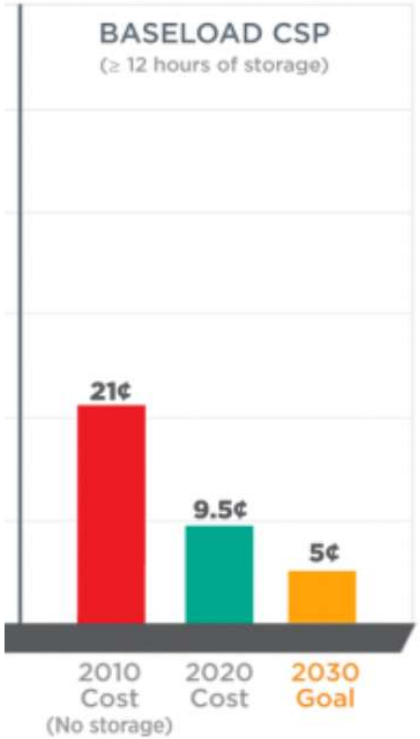
= Commercial applications

= under demonstration

Next-Gen CSP Plants under R&D



M. Mehos et al. Technical Report: NREL/TP-5500-67464, National Renewable Energy Laboratory, Golden, CO, 2017.



Gen3 CSP (Next-Gen CSP) of DOE SunShot 2030 since 2018
Three pathways under R&D:

- Solid pathway
- **Liquid pathway (molten salt/liquid metal)**
- Gas pathway

DOE CSP Target in 2030:

- Low LCOE (≤5 ¢/kWh_e) for baseload CSP (≥12 hours of storage)

2030 CSP Scenarios to Achieve LCOE of 5¢/kWh

Compared to Benchmark 2018, main achievements are required for the target LCOE of 5¢/kWh,

- Higher power-cycle efficiency (≥40%, better ≥50%)
- Lower Power block cost (≤ $900/kW)
- Lower solar field cost (≤ $70/m²)
- Lower thermal energy storage (TES) cost (≤ $15/kWh)

If **higher power-cycle efficiency** is achieved

- Higher costs of power block, solar field and thermal storage are acceptable

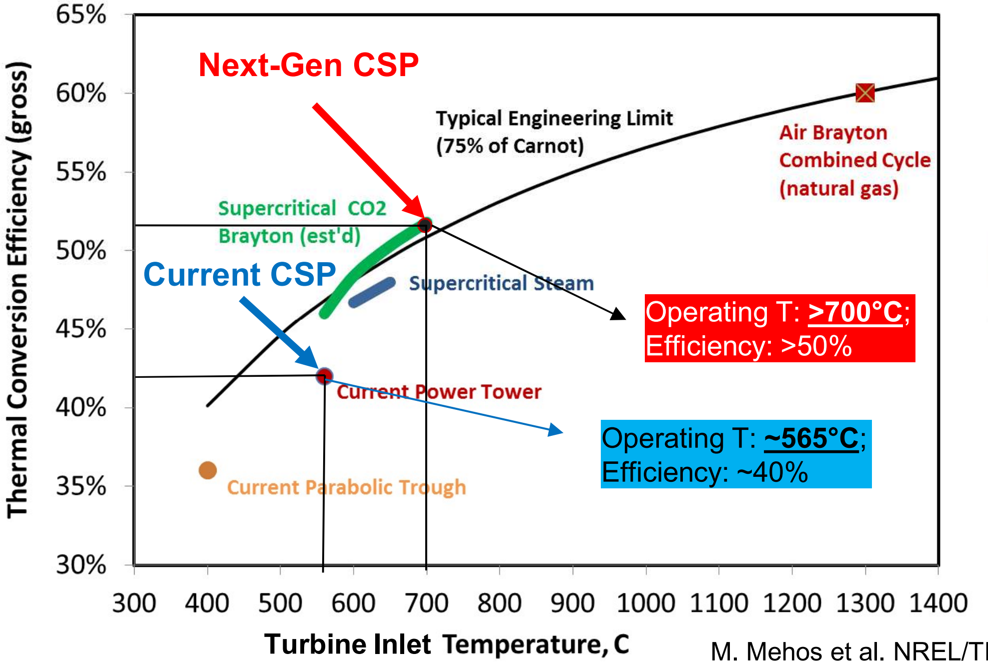
Table IV. Benchmark parameters for a 100 MW CSP system with 14 hours thermal storage.[36]

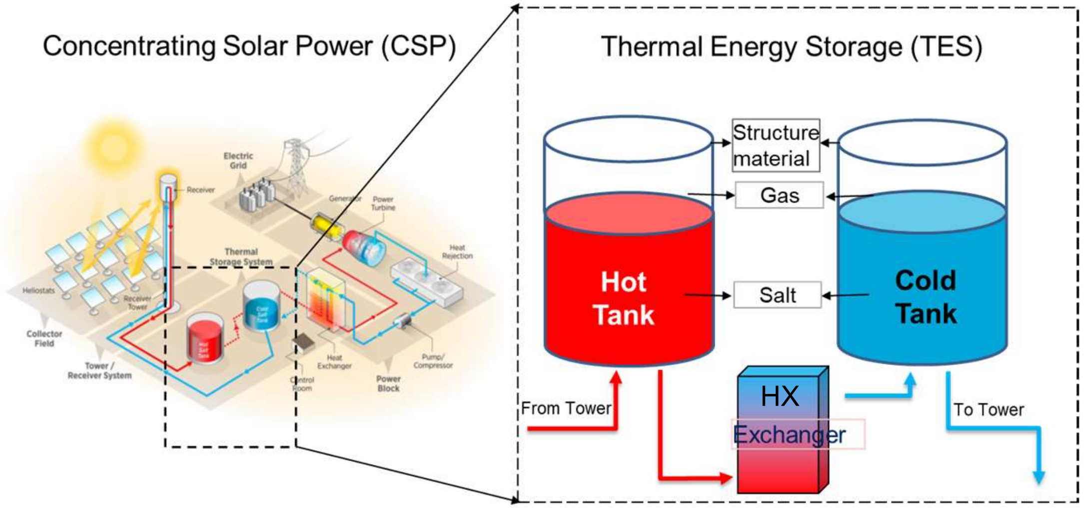
Parameter	2018 Benchmark[37,38]	2030 Low-Cost	2030 Balanced	2030 High-Performance
Net power-cycle efficiency	37%	40%	50%	55%
Rated thermal power	730 $MW_{thermal}$	675 $MW_{thermal}$	540 $MW_{thermal}$	491 $MW_{thermal}$
Power block cost	$1330/$kW_{ac\text{-}gross}$	$700/$kW_{ac\text{-}gross}$	$900/$kW_{ac\text{-}gross}$	$900/$kW_{ac\text{-}gross}$
Solar field cost	$140/$m^2$	$50/$m^2$	$50/$m^2$	$70/$m^2$
Site preparation cost	$16/$m^2$	$10/$m^2$	$10/$m^2$	$10/$m^2$
Tower and receiver cost	$137/$kW_{thermal}$	$100/$kW_{thermal}$	$120/$kW_{thermal}$	$120/$kW_{thermal}$
Thermal storage cost	$22/$kWh_{thermal}$	$10/$kWh_{thermal}$	$15/$kWh_{thermal}$	$15/$kWh_{thermal}$
Levelized O&M cost[39]	$9/$kW_{thermal}$-yr	$6/$kW_{thermal}$-yr	$7/$kW_{thermal}$-yr	$7/$kW_{thermal}$-yr
Levelized capacity factor	68.9%	69.2%	70.7%	71.0%
LCOE (2019 US$)[40]	**9.8¢/kWh**	**5.0¢/kWh**	**5.0¢/kWh**	**5.0¢/kWh**

Target in 2030: LCOE (≤5 ¢/kWh_e) for baseload CSP

https://www.energy.gov/eere/solar/articles/2030-solar-cost-targets

Molten Chloride TES for Advanced Thermal Power Plants





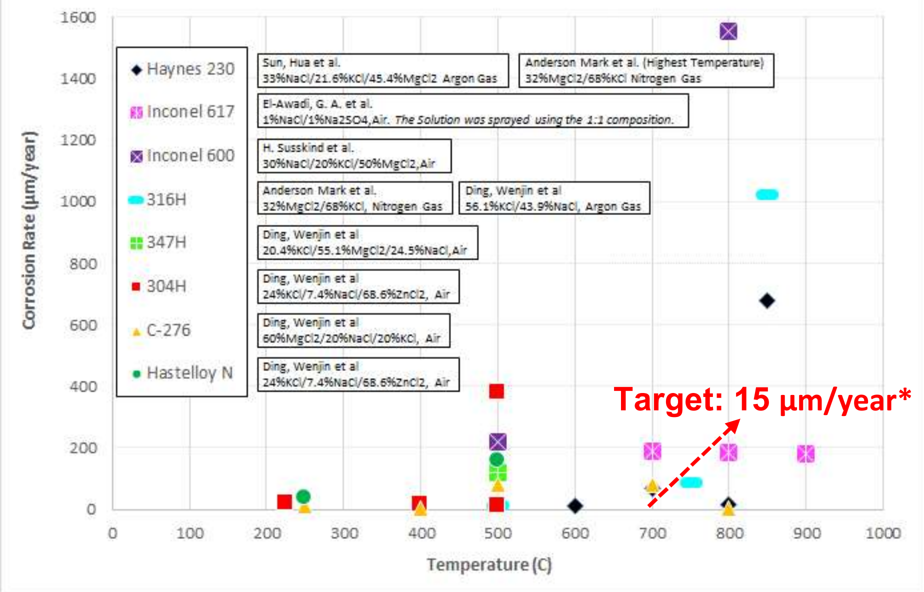
T_{hot} **565°C (Nitrate) → >700°C (Chloride)**

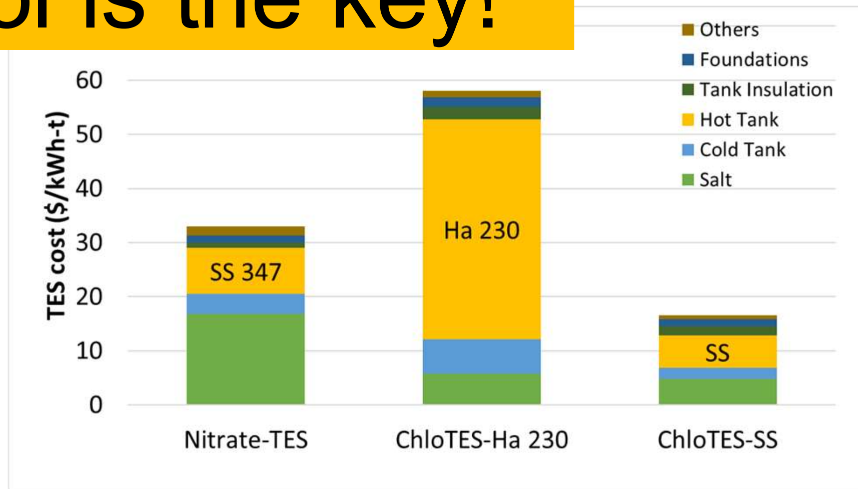
M. Mehos et al. NREL/TP-5500-67464, 2017.
Turchi, Craig. "Concentrating solar power: current cost and future directions." Colorado: National 32 (2017).

- **Advanced thermal power plants (ATPP) like Next-Gen CSP**: advanced power cycle (e.g., sCO_2 Brayton) with higher effic. **>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}$

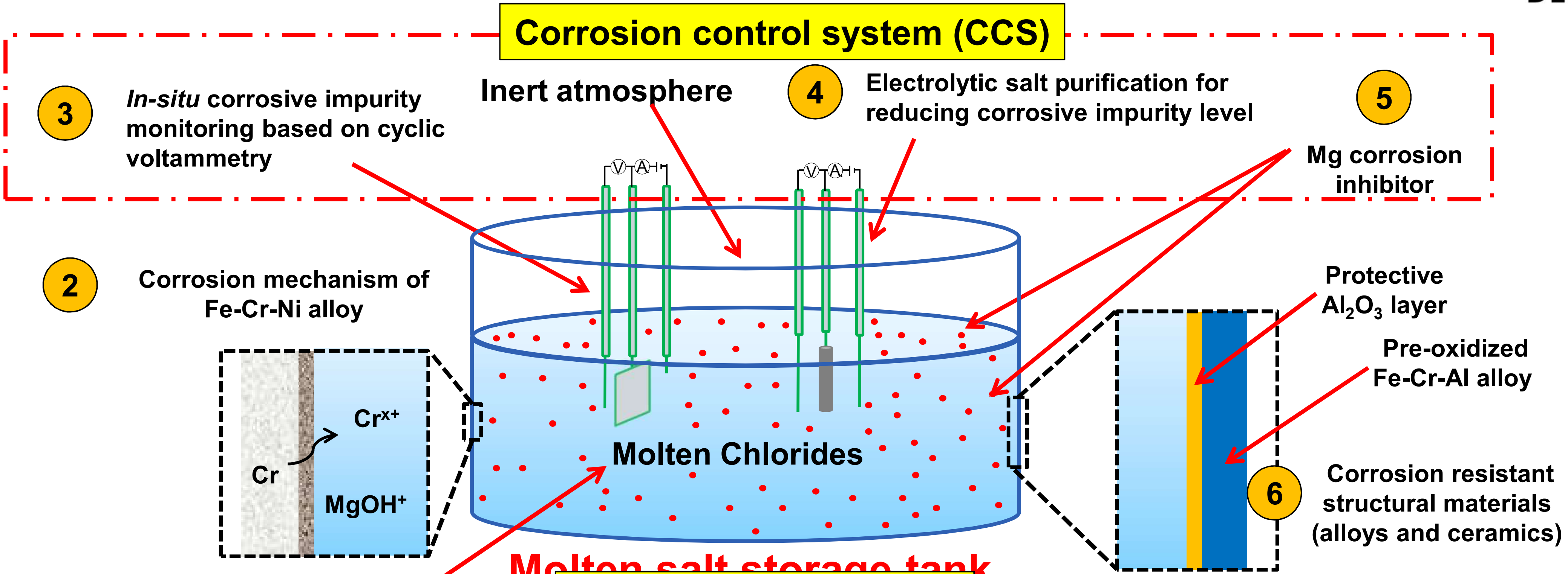
1st challenge: Severe corrosion of molten chlorides

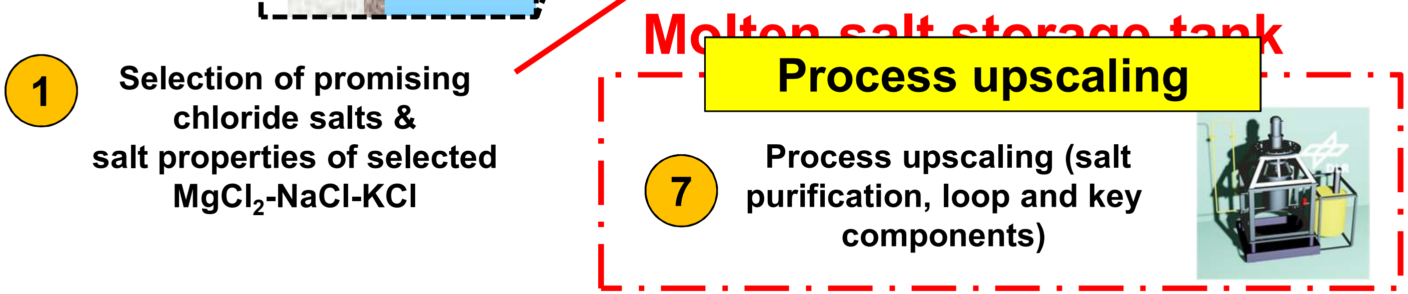
2nd challenge: Affordable structural materials

- **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

R&D of Molten Salt TES at DLR

>10000 ton

100-1000 ton

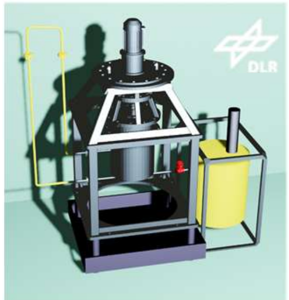
100 kg

10 mg – 1 kg

"... value chain research..."

Material

Process technology (Upscaling)



Component testing & pilot plant

System integration

R&D from material to system level

- Materials: focusing on nitrate/nitrite salts and chloride salts
- Upscaling and component testing: salt purification, corrosion control; Molten salt pump, HX, …
- System: Molten salt TES used in CSP, Carnot battery, …

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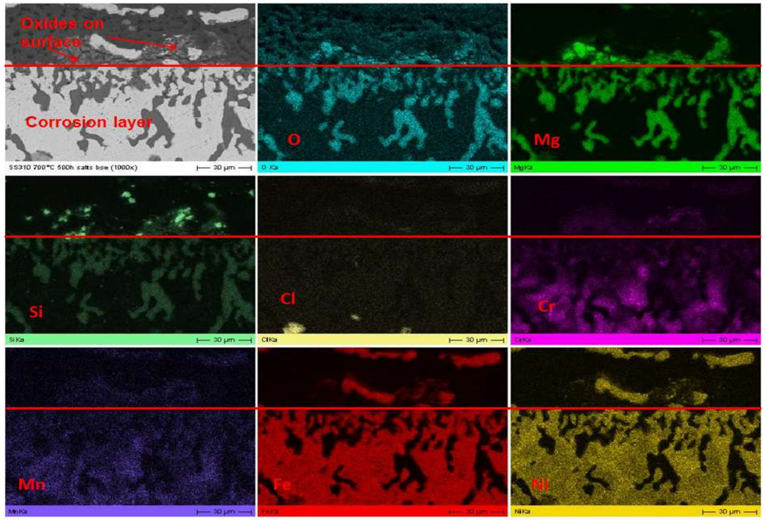
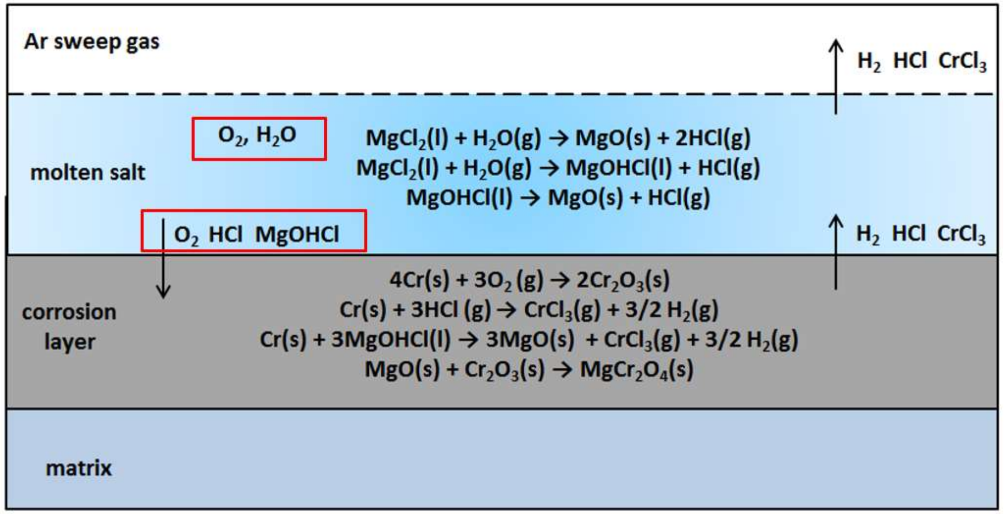
② Proposed Corrosion Mechanism

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:

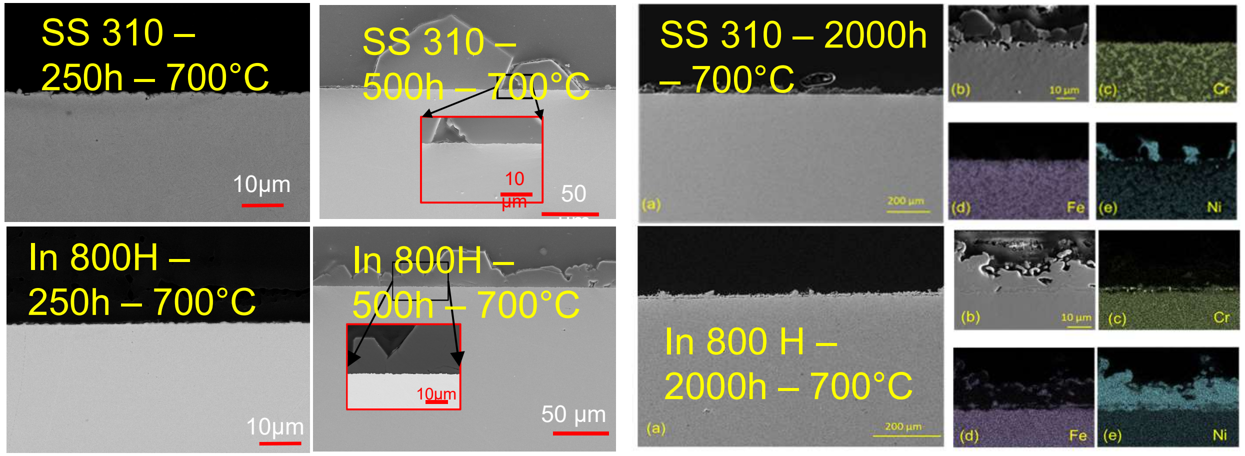
- Cr dissolved preferentially
- Corrosion is driven by impurities mainly **MgOHCl**

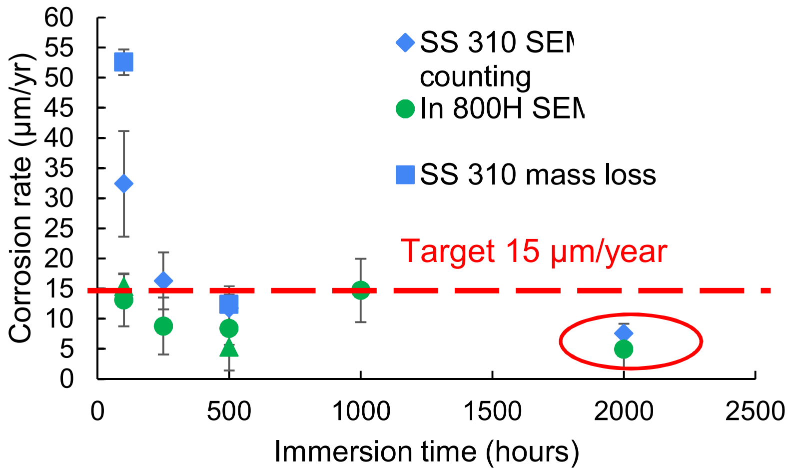
- Corrosive impurities: H_2O, O_2, HCl, MgOHCl (high solubility in molten chlorides)
- Corrosion products: $MgCr_2O_4$, MgO, $CrCl_3$
- Corrosion control by controlling concentration of impurities

Karlsruhe Institute of Technology

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

5 Mg Corrosion Inhibitor – Breakthrough by DLR



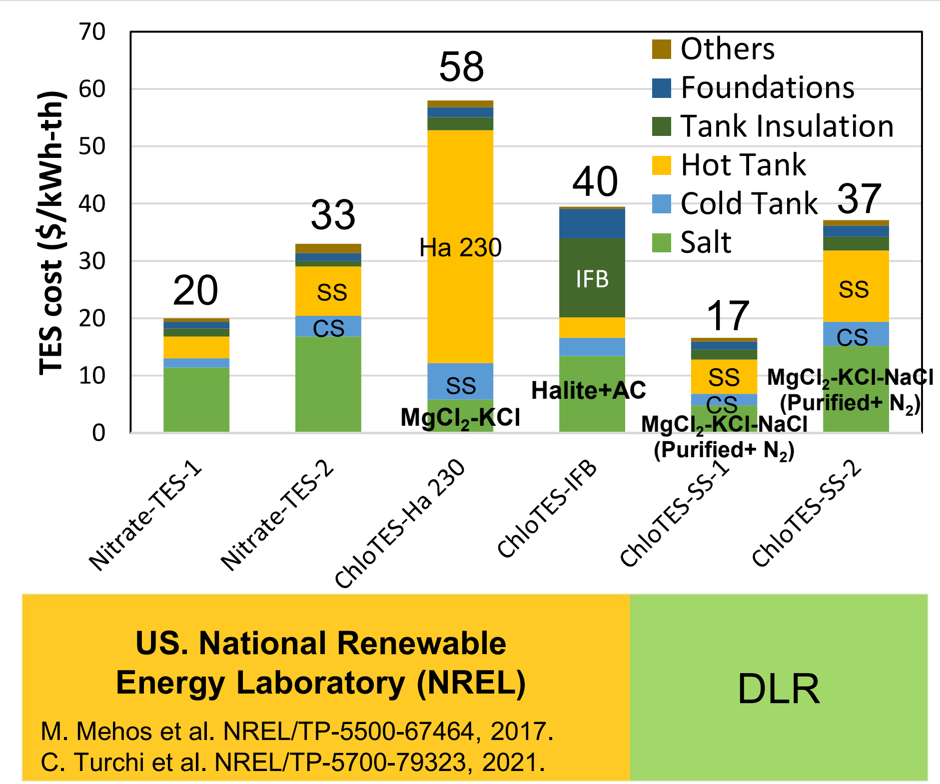


- Salt purified with Mg at 700°C in a patented process*
- **Static immersion tests in purified molten salt at 500-800°C under Ar (up to 2000h)**: Almost no corrosion layers and Cr-depletion of Fe-based steels were observed
- Corrosion rate based on microstructural analysis (SEM) and mass loss: **<15 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 filing: 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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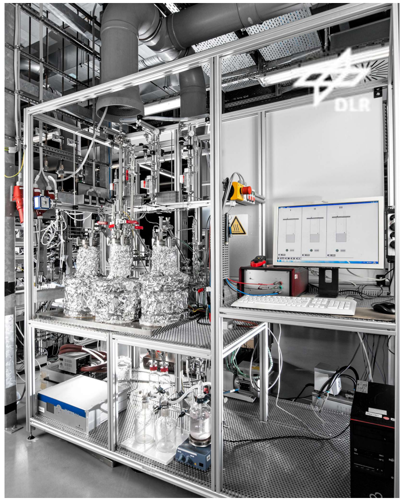
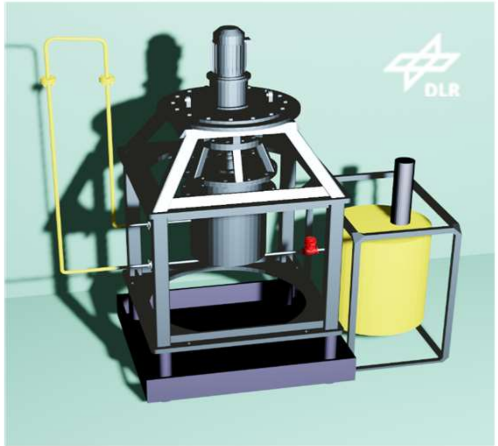
Process Upscaling of Chloride-TES

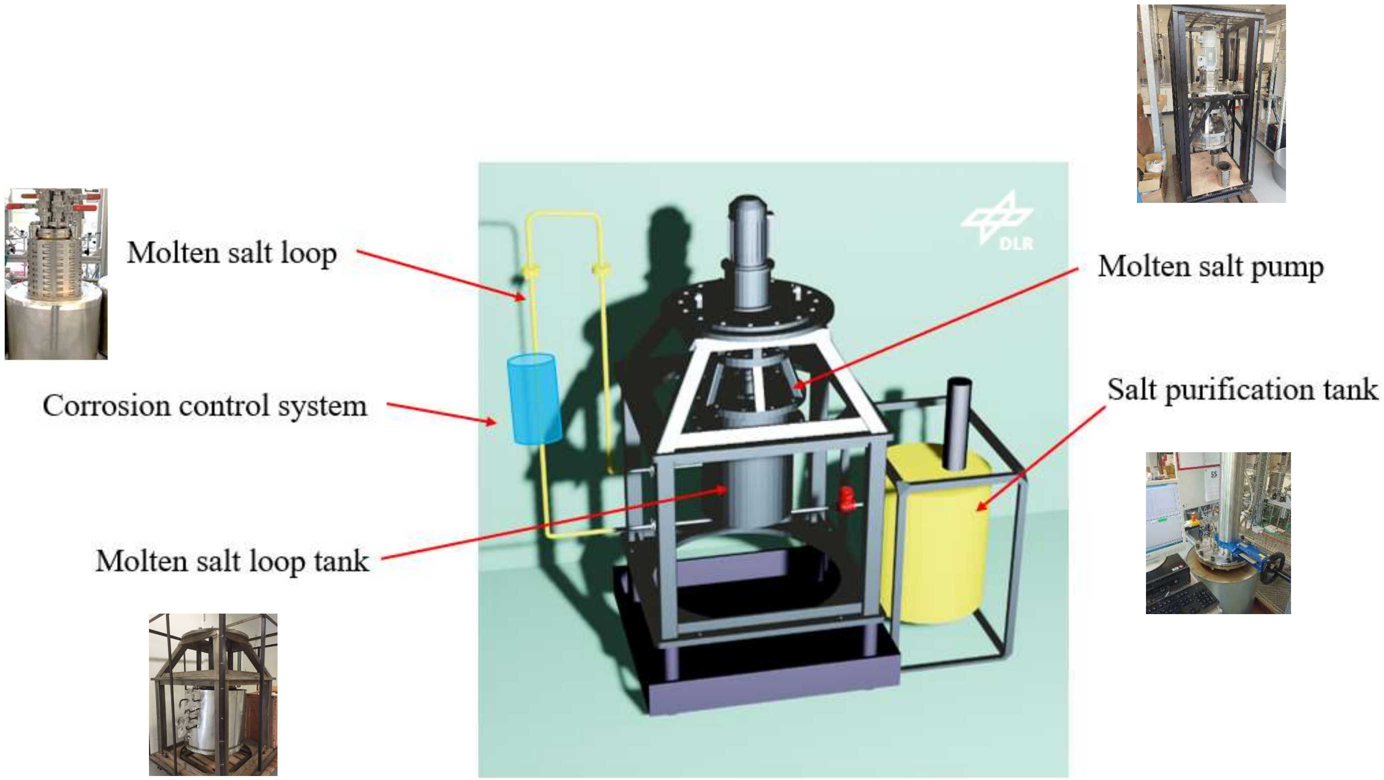
7

DLR

Achieved	Ongoing		Target	
				
Materials research with <1 kg salt: corrosion control, structural materials pre-selection, … (TRL 1-3)	Upscaling with ~100 kg salt: salt purification and corrosion control loop tests, structural materials selection (TRL 4-5)		Pilot plant with ~100t salt & Component testing (TRL 6-7)	Industry-application (TRL 8-9)

DLR seeks industrial partners for upscaling

Molten Chloride Test Facility (MOCTEF) of DLR

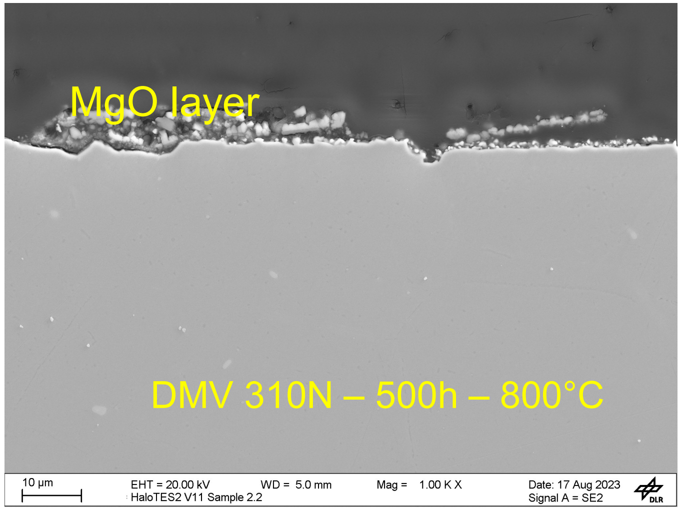


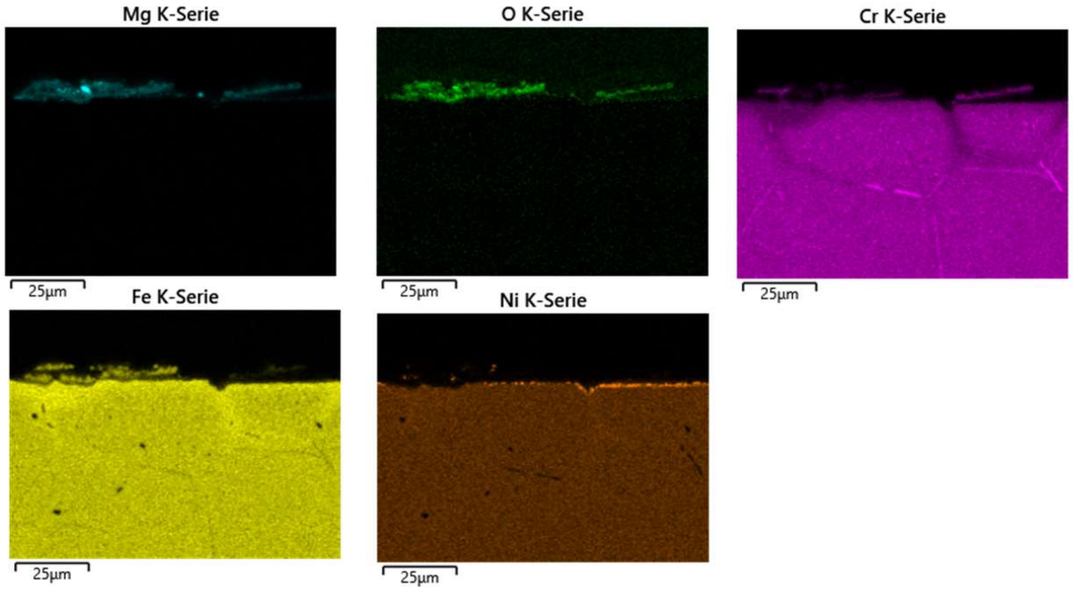
- **Under construction** and will be operation in the starting of 2025

- **Two test units**: one for salt purification, one for loop tests close to conditions in real applications.
  - ~100 kg $MgCl_2$-NaCl-KCl is used
  - 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





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

- 2000h static immersion test at 800°C is ongoing, while loop test in MOCTEF at >700°C is planned.

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

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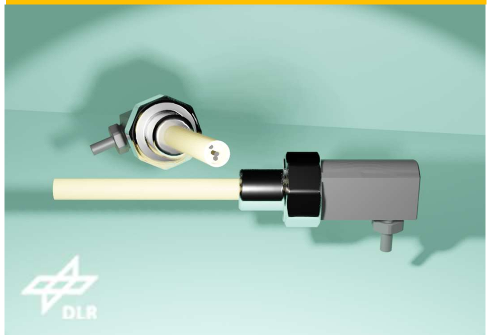
DLR Molten Salt Products/Services for Security Controls

1. Salt Monitoring

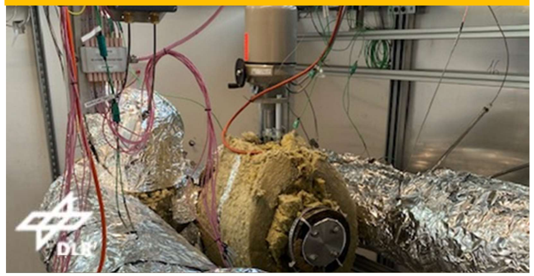


Source: Andasol

3. Salt Level/Filling detection

2. Salt Auto-sampling & Analysis

2a Auto-sampling at site



Sample Shipping

2b Salt analysis in lab

Qualification of Product Developments

All the molten salt products/services

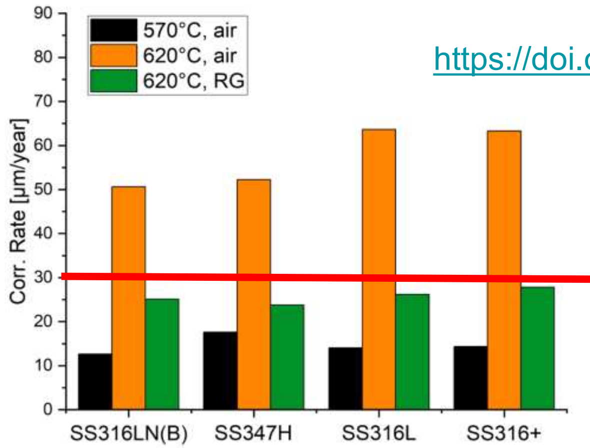
- to be qualified in pumped loop with TESIS or MOCTEF (MOlten Chloride TEst Facility, in building)
- then licensed to industries or distributed via DLR Spin-Offs

Development utilizes experience from continuous operation of the DLR *Test facility for thermal energy storage in molten salts* (TESIS) with approx. 100 tones of nitrate salt since Jan. 2019

Corrosion Control by DLR Molten Salt Products & Services

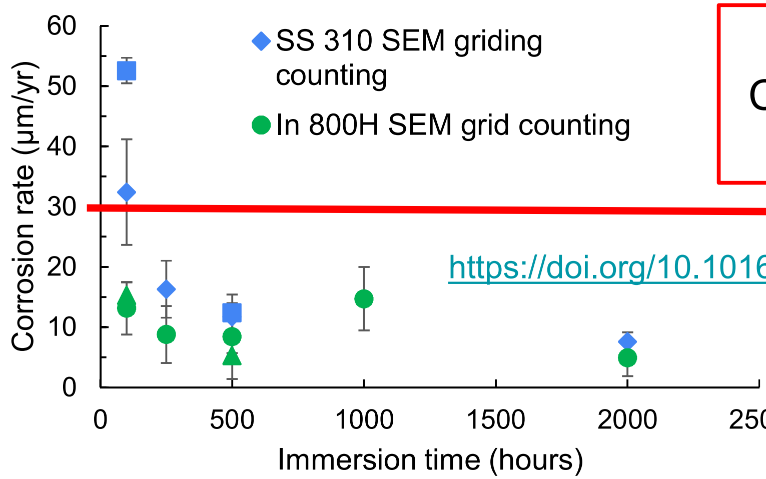
Corrosion control achievements with DLR molten salt products/services

- Corrosion rate (CR) of Fe-based alloys <30 µm/year at extreme high temperatures
- Ensuring safe operation of molten salt systems in designed lifetime



https://doi.org/10.1016/j.corsci.2023.111700

Nitrate:
CR <30 µm/year
at 620°C



Chloride:
CR <30 µm/year
at 700°C

https://doi.org/10.1016/j.apenergy.2022.119708

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German Aerospace Center

Dr. Wenjin Ding, Wenjin.Ding@dlr.de
Dr. Thomas Bauer, Thomas.Bauer@dlr.de

please feel free to contact us for joint developments of sensor technology!

Thank you for your attention!

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