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Liquid metals in concentrating solar power and requirements on structural materials

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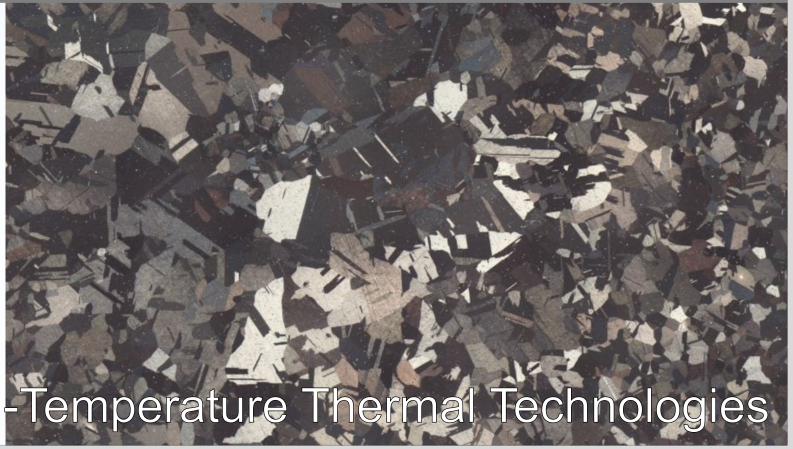
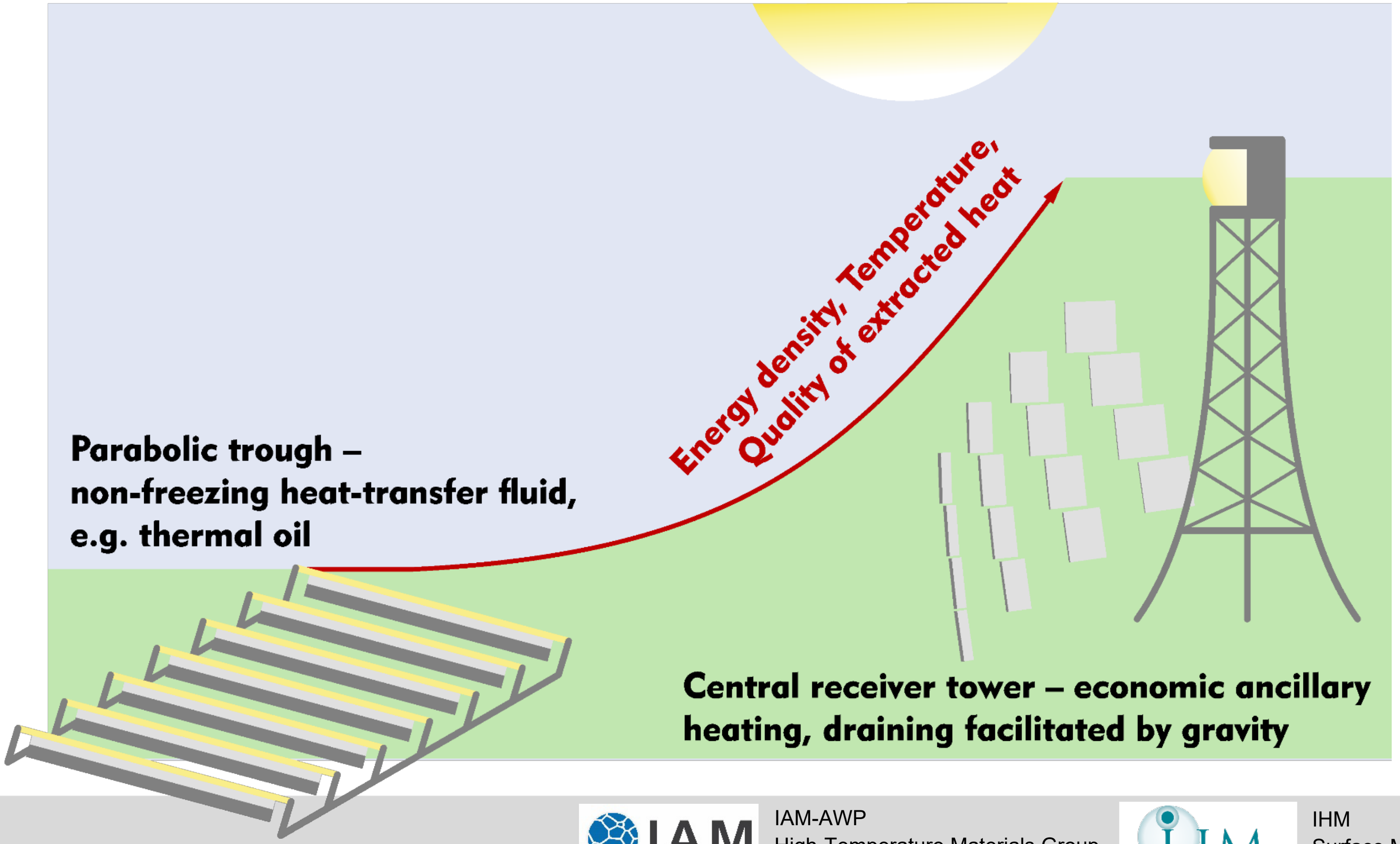


MTET – High-Temperature Thermal Technologies

Evolution in concentrating solar power (CSP)

From trough to tower



- Driven by increase in value of harvested energy.
- Heat-transfer fluid (HTF) imposes technical limits.
- Liquid metals: High boiling point (Na, Pb), relatively low melting point (Na), besides high thermal conductivity.

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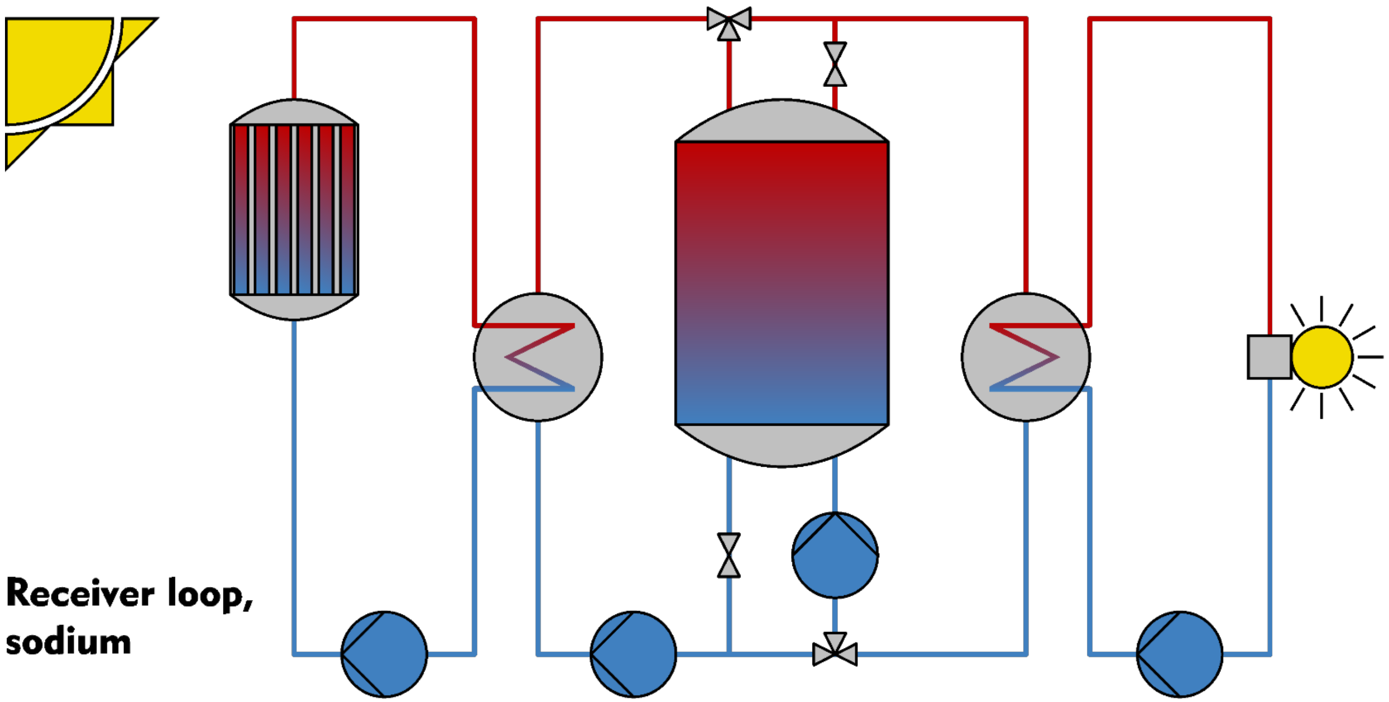
Liquid-metal based CSP

including liquid-metal based thermal energy storage (TES) → Presentation by K. Niedermeier et al., poster by F. Müller-Trefzer et al.



- Stability of liquid phase – Na: 98–881 °C (1000 °C at 3 bar); LBE: 125–1533 °C; Pb: 327–1744 °C.
- Gain in heat-transfer efficiency makes up for relatively high cost of the metals (Na) [1].
- Intermediate TES facilitates avoiding Na and water/steam in one and the same apparatus.

[1] Singer et al., *J. Sol. Energy Eng.* 132 (2010) 41010.

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Load profile for the receiver/receiver loop

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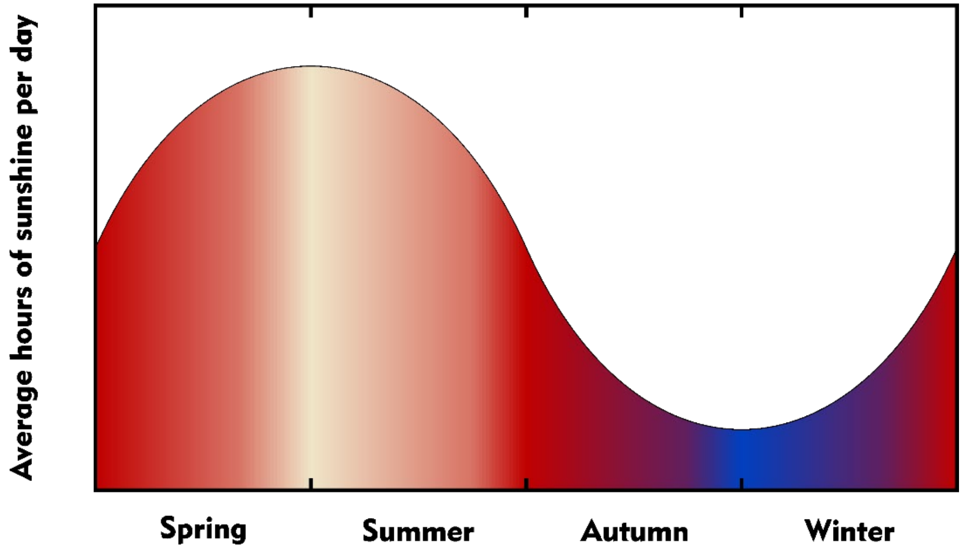
Rough classification, in detail dependent, e.g., on the site of operation.

Thermo-mechanical

- Dominated by thermal stress – compressive on the outer, tensile on the inner surface of tubing heated from outside.
- ~10^4 day/night cycles during 30 years of operation, to be multiplied by average number of shadowing events per day.



Thermochemical

- High-temperature oxidation (air, Pb or LBE).
- Dissolution resulting in corrosion mass transfer (Na, Pb or LBE).
- Other interaction with the liquid metals that potentially degrade mechanical properties.

Compatibility of structural materials and liquid metals

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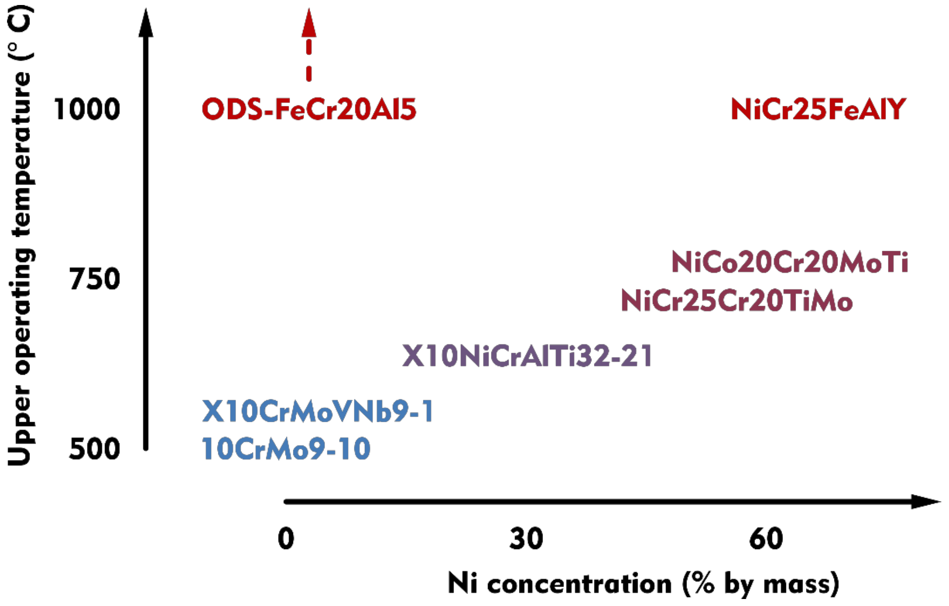
In the realm of steel or nickel-based alloys –
Ni, in general, a harmful element



Na

- Austenitic steels or Ni-based alloys likely to be applicable at up to 750 °C [1].
- Weak performance of Ni-based alloys at 1000 °C [2].

Pb, LBE

- Compatibility to be achieved through alumina formation, i.e. Al addition to the steel.
- Requires a minimum of oxygen dissolved in Pb or LBE [3,4].

[1] Borgstedt and Frees, Mater. Corros. 38 (1987) 732–737.
[2] Borgstedt et al., Mater. Corros. 40 (1989) 525–531.
[3] Chen et al., Corros. Sci. 189 (2021) 109591.
[4] Tsisar et al., Mater. Sci. Forum 1024 (2021) 79–85.

Qualification of structural materials for liquid-metal CSP

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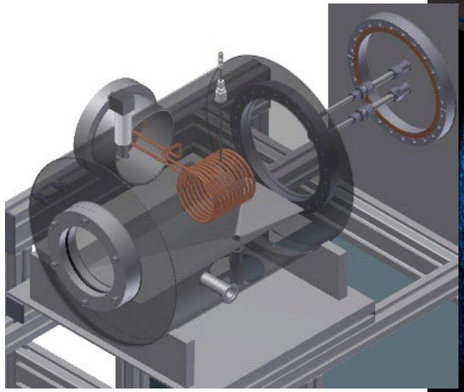
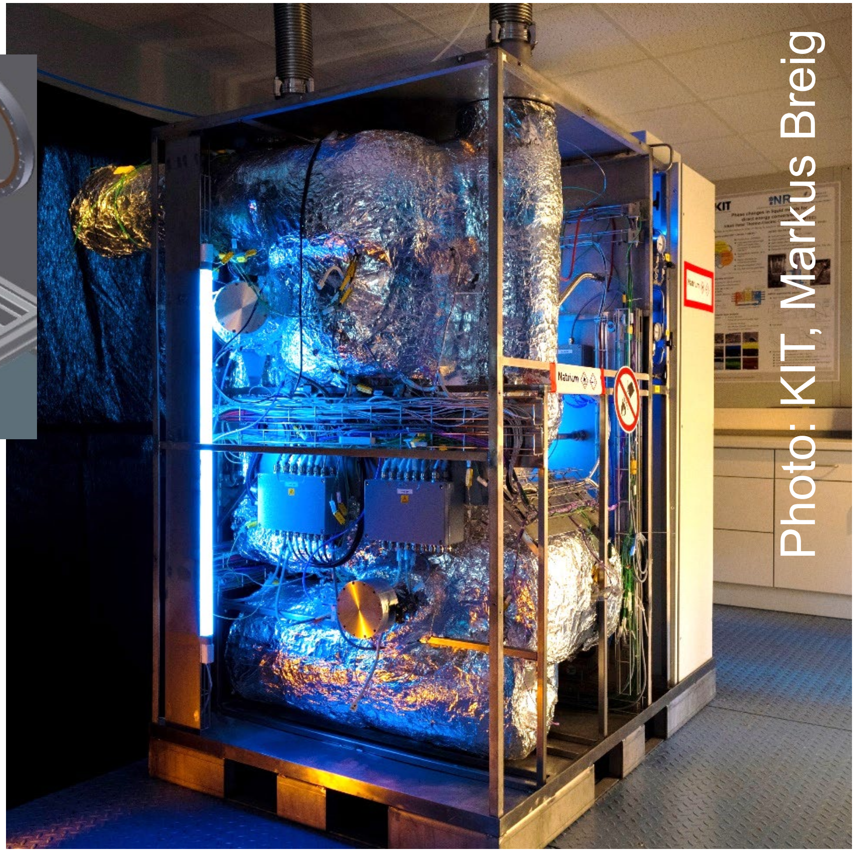
SOLTEC-2 – SOdium Loop to TEst Corrosion and materials (as well as small components)

Operating parameters [1]

- 12 l (9 kg) Na circulating, out of 14 l in total.
- 450 °C in cold leg, up to 720 °C (2.5 bar) in hot leg.
- Mass flow of ~300 kg h^{-1}.
- Test section adaptable to specific qualification test.





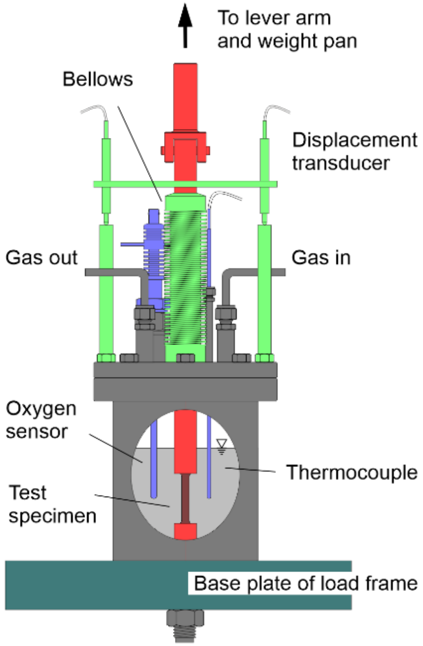
- Facility in operation.
- Successful testing of flow sensors at up to 700 °C.[2,3]
- Material tests in preparation.
- For these tests, additional inductive heating so as to create thermal cycles of duration in the order of seconds.[1]

[1] Onea et al., SolarPACES 2021.
[2] Krauter et al., ASME J. of Nuclear Rad. Sci. (2022) doi:10.1115/1.4062239.
[3] Onea et al., SolarPACES 2022.

Qualification of structural materials for liquid-metal CSP

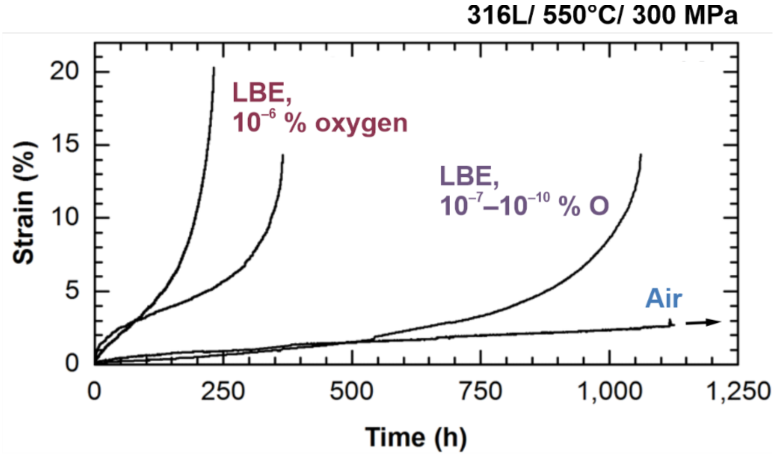
CORTINA – Cyclic mechanical tests (creep fatigue) in static Na with reference to air

- ~750 ml (0.6 kg) Na.
- 550 and 750°C in first and second stage, respectively.
- Preconditioned with regard to dissolved oxygen, oxygen monitoring during the tests.
- ~10^5 load cycles in tensile regime (transients + dwelling), in 1000 h.
- Maximum load adapted to tested class of materials.
- First tests anticipated for end of 2023.



CRISLA – Creep and stress rupture in static Pb or LBE with reference to air

- ~900 ml (9 kg) Pb or LBE.
- Up to 650 °C.
- Oxygen measurement and control via gas/liquid oxygen transfer.



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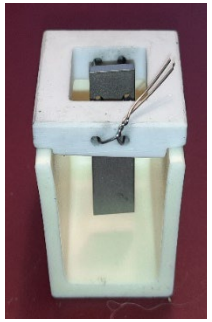
Qualification of structural materials for liquid-metal CSP

Exposure to static liquid metal without mechanical load

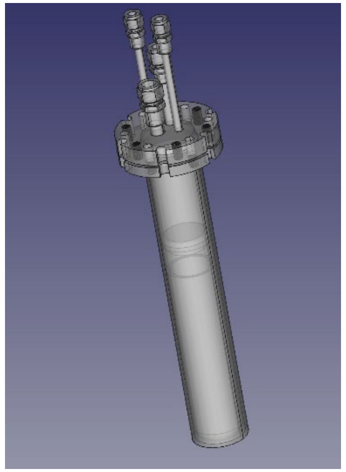
COSTA → Poster by A. Heinzel et al.

- Material sample immersed in 14 ml of liquid metal (Pb/LBE, Na, other), at up to >1000 °C.
- Ceramic crucible serves as a container for the liquid metal.
- Oxygen chemistry influenced by cover gas.
- One of the workhorses of screening materials for liquid-metal applications over the past decades.



Instrumented test capsule

- Several material samples submerged in up to 900 ml liquid metal (in ceramic crucible).
- Monitoring and control of both temperature and oxygen dissolved in the liquid metal.
- Routinely operated with Pb/LBE at up to 650 °C, currently transferred to Na at up to 890 °C.



- As for Na,
  qualification of oxygen sensors,
  investigation of bubble formation at boiling point,
  besides material tests.

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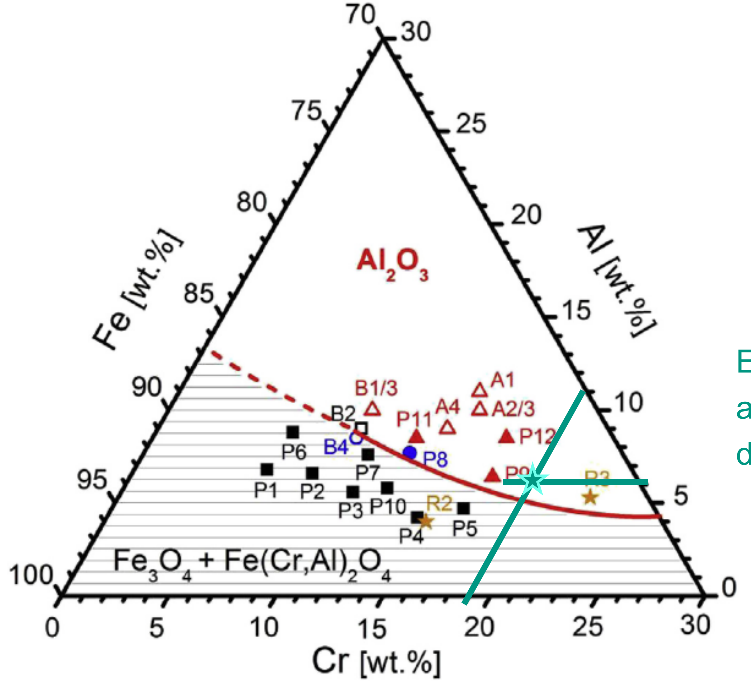
Materials development

Fe –19Cr –6Al-ODS

- Strengthened by dispersed yttria particles (0.5 % by mass), for operation at 1000 °C and above.
- High-temperature oxidation resistance through Cr and especially Al.
- Minimum concentration of Ni, Mn, Co, … that have considerable solubility in liquid metals.
- Formed alumina can be stabilised in Pb/LBE, however, may absorb Na.
- Embrittlement in the presence of liquid metals?

- 10 kg in final stage of fabrication (via powder-metallurgical route).



Expectation as to solid oxide at 400–600 °C, 10^{-6} % oxygen dissolved in liquid Pb [1].

[1] Jianu et al., J. Nucl. Mater. 470 (2016) 68–75.

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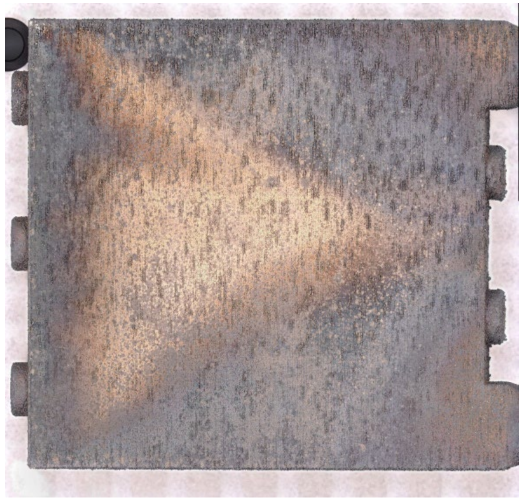
Innovative receiver design

Monolithic receiver requiring a minimum of welding

- Heat extraction from focus point up to 4 MW/m^2, at up to 750 °C.
- Minimum thermo-mechanical stress.
- Drainability as appropriate for operation with Na.

- Monolithic structure through additive manufacturing.
- First test structures produced by selective electron-beam melting at IAM-WK[1].
- Linear and meandering channel, respectively.
- Inconel 718 powder, hot isostatic pressing and further heat treatments after AM.
- In preparation for tests on function.

Linear channel after additive manufacturing.



Meander channel after hot isostatic pressing.

[1] Guth et al., Adv. Eng. Mater. (2023), doi: 10.1002/adem.202300294.

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Summary … conclusions … outlook

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- As for Na (receiver), availability of compatible materials (classic austenitic steels or Ni-based alloys) no obstacle to current establishment of liquid metals in CSP.
- May change for raise in operating temperature to 750 °C and beyond.
- In contact with Pb/LBE (storage), steels generally need protection: Alumina formation and oxygen control.

- End of the long road of (re-)establishing materials testing in Na at KIT almost reached.
- Fe–Cr–Al–Y_2O_3 identified as a promising material for high-temperature CSP and thermal storage using liquid metals—experimental batch will soon be available.
- Potential of additive manufacturing for liquid-metal CSP is being explored.

- Beyond steels or Ni-based alloys?—refractory metals, high entropy alloys, ceramics.


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