SunShot
U.S. Department of Energy

CSP Program Summit 2016

High-Operating-Temperature Heat-Transfer Fluids for Solar Thermal Power Generation (Liquid Metals)

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Outline

- Overview
- Problem Statement
- Value Proposition
- Objectives
- Milestones
- Results
- Path to Market

Overview

- Project Name: High Operating Temperature Heat Transfer Fluids for Solar Thermal Power Generation
- Funding Opportunity: MURI: High Operating Temperature Fluids (DE-FOA-0000567)
- Principle Investigators: Mark Asta, UC Berkeley
  Peter Hosemann, UC Berkeley
  Y. Sungtaek Ju, UCLA
  Jan Schroers, Yale
- Other Contributors: Alan Bolind, UC Berkeley
  Gopinath Warrier, UCLA
- Project Duration: 5 years (10/2012– 12/2017)
- Project Budget: $1,104,727 including cost share, for Phase 3

Problem Statement

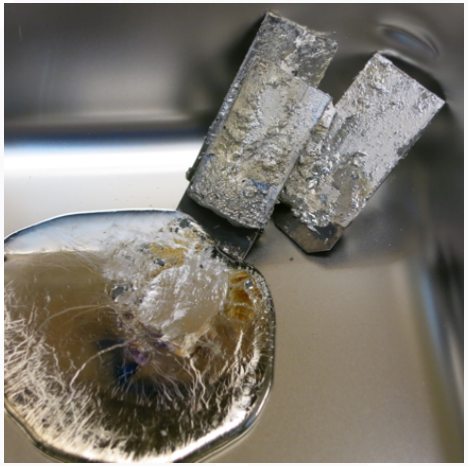
6¢/kWh → Efficiency ≥ 50% (heat to electricity) → Operating Temperature ≥ 650 °C

The problem, then, is…

- to develop a **liquid-metal heat-transfer fluid** for CSP that can operate above 650 °C,

while still satisfying traditional CSP requirements, namely,

- chemical stability,
- low melting temperature,
- existing or potential commercial availability,
- and reasonably slow corrosion of pipes.



Problem Statement

De facto main problem: CORROSION of pipe materials by liquid-metal alloys

The corrosion takes two forms:

1. **Dissolution** of the pipe-material constituent elements
2. **Excessive oxidation** of the pipe material

Fight #1 (dissolution) with slight #2 (oxidation).

Value Proposition

In words…

A liquid-metal heat-transfer fluid that solves the stated problem will enable CSP companies to operate their CSP plants at higher temperatures and thereby achieve greater efficiencies and concomitant lower costs.

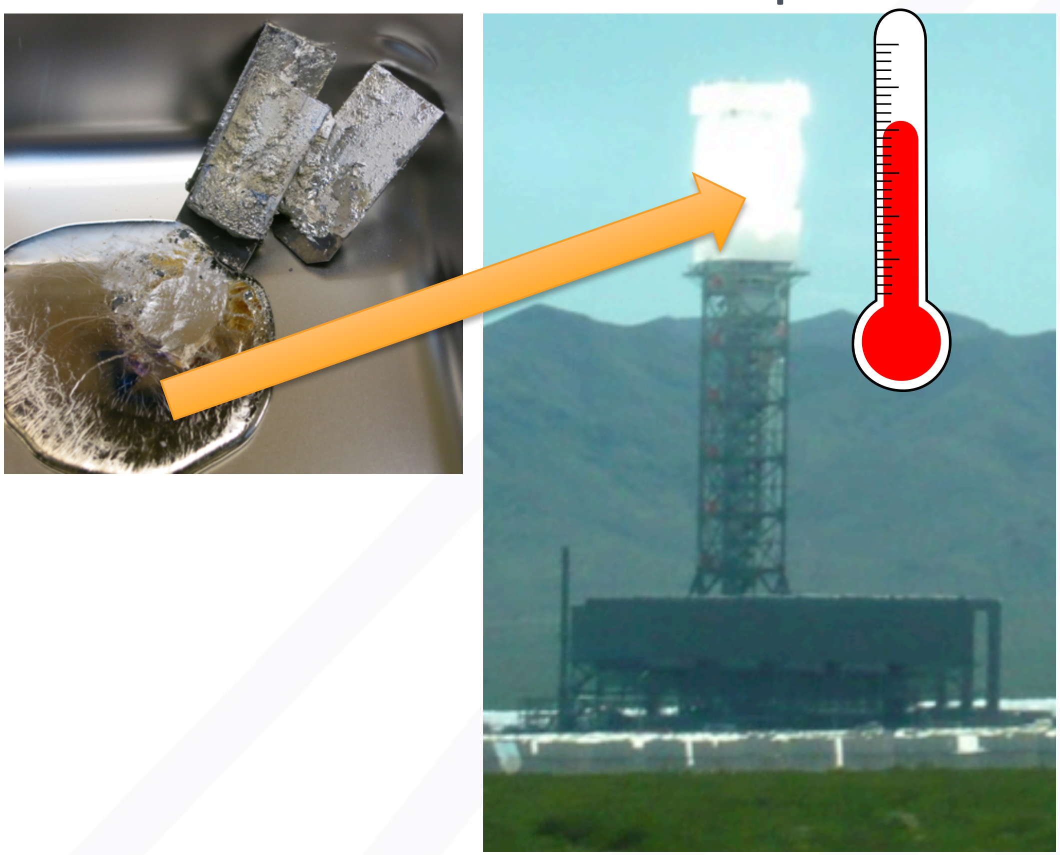
Unlike high-temperature gases that need high pressures for sufficient density, and unlike molten salts that either fail to melt at low temperatures or decompose at high temperatures, liquid metals stay liquid, without excessive pressure, over the temperature range of interest for CSP operations.

Value Proposition

In pictures…

800 °C !!

$\eta > 50\%$!!

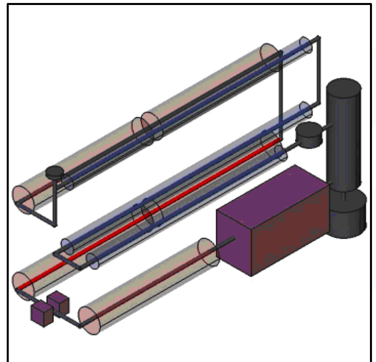


Objectives

UCLA Sungtaek Ju

Objectives of each team member

LM: Liquid Metal
PM: Pipe Material



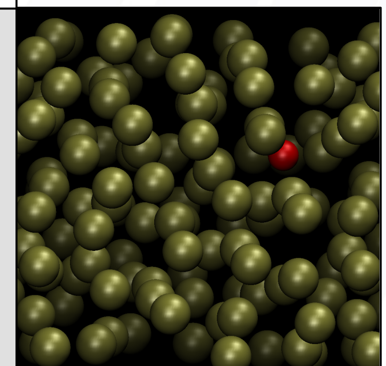
Flowing, loop experiments

- Corrosion testing in flowing LM
- Operational data for a LM loop

Static, autoclave experiments

Cal Peter Hosemann

- Corrosion testing of PM strips in crucibles of LM
- Development of control of oxygen dissolved in LM

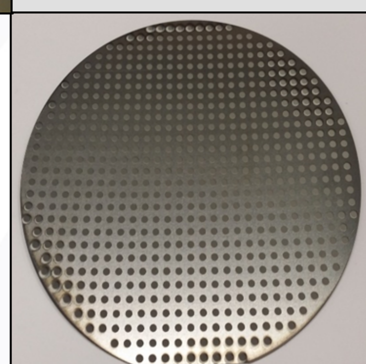


Modeling

Cal Mark Asta

Thermodynamic calculations of…

- Properties of LM
- Protective scales on PM
- Oxygen dissolved in LM



Fast-screening experiments

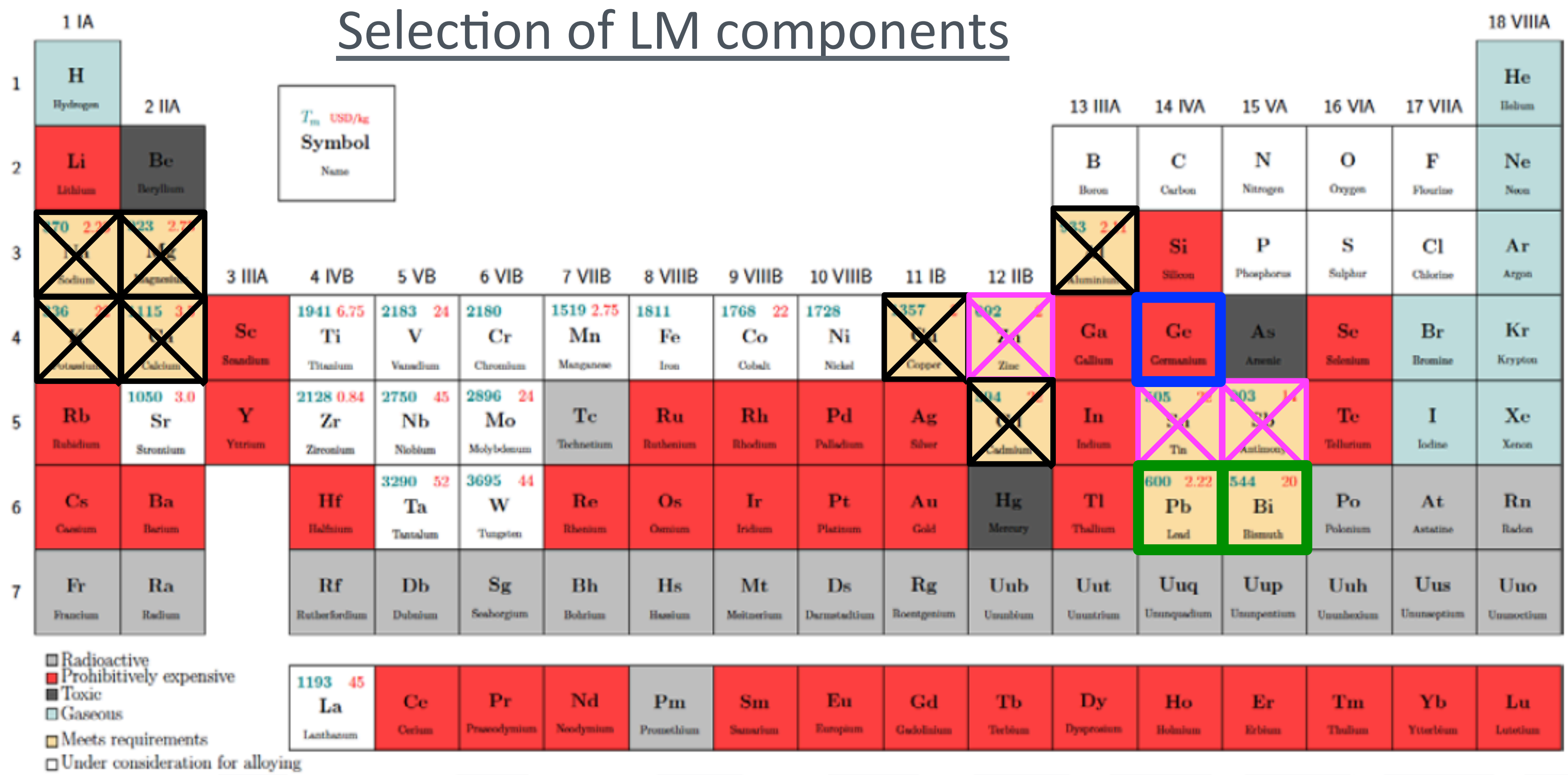
- LM thermophysical properties
- LM/PM corrosion reactions

Jan Schroers

Milestones

- Identified > 50 LM alloys with $T_{melting}$ < 300 °C.
- Established optimal oxygen concentration range; quantified oxide growth and dissolution rates as functions of temperature and oxygen concentration; and identified 1 PM alloy with corrosion < 150 µm/yr
- Calculated free energies of formation of protective oxide and intermetallic scales for LM alloys of LBE + a third additive.
- Quantified LM/PM reaction with additives (e.g., Zn, Sb, Ge), by both fast screening and static corrosion tests.
- Identified the best Pb-Bi alloy composition for LM/PM reaction.
- Conducted tensile testing to show absence of liquid-metal embrittlement.
- Verified the leak-tightness of the flow loop at room temperature.

Results



= rejected after initial screenings

= tested and most acceptable

= rejected after static corrosion testing

= still to be tested, as an additive

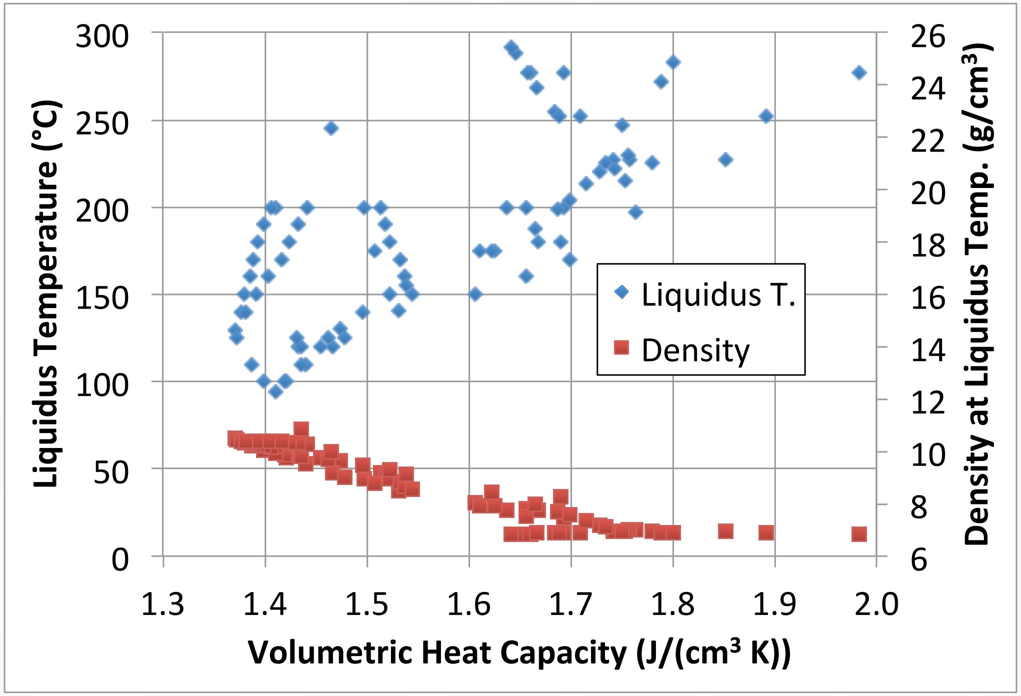
Results

- Lead-Bismuth Eutectic (LBE) is 45% Pb, 55% Bi, by mass.
- This LBE is our default liquid metal of choice, because…
  - it is not too expensive (Pb is very cheap),
  - it is not excessively chemically reactive or toxic,
  - Pb and Bi are the least corrosive of the elements,
  - and the eutectic composition has the lowest melting temperature (125 °C).

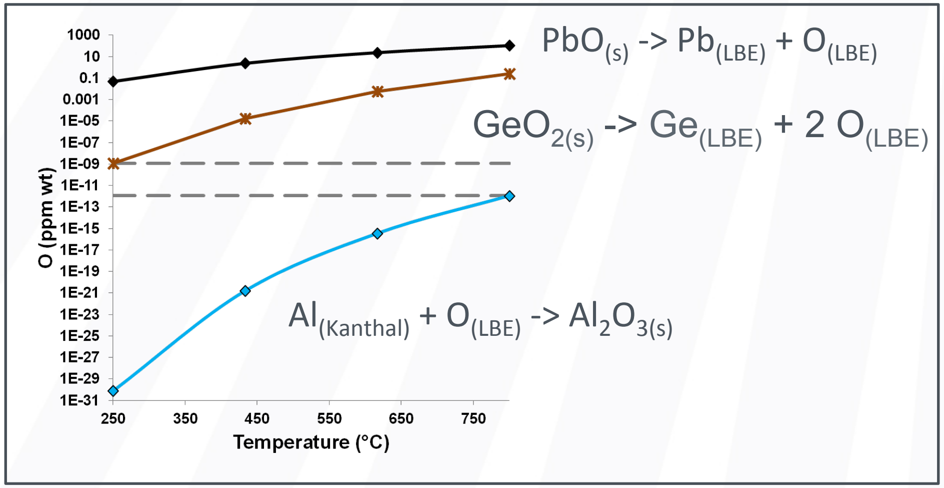
Results

- Examples of calculations

  LM properties

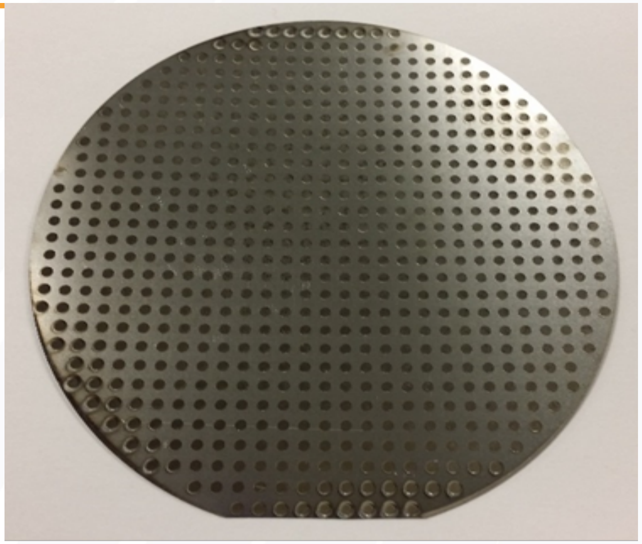


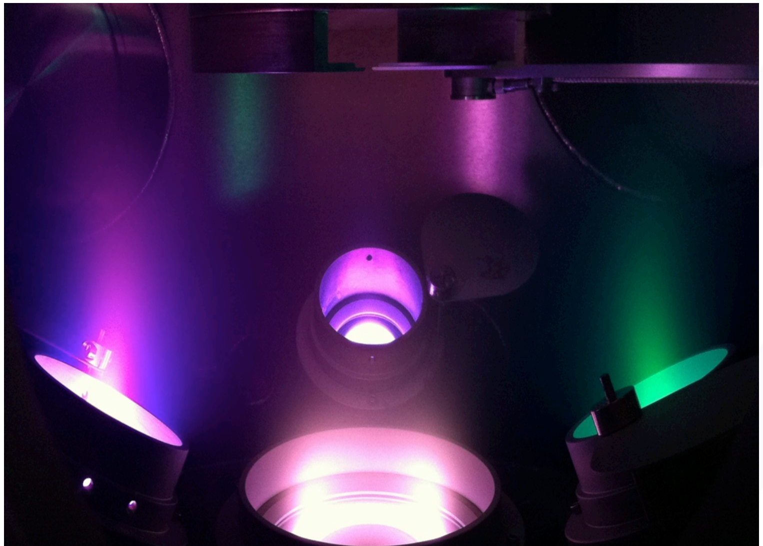
  Window for proper oxygen control



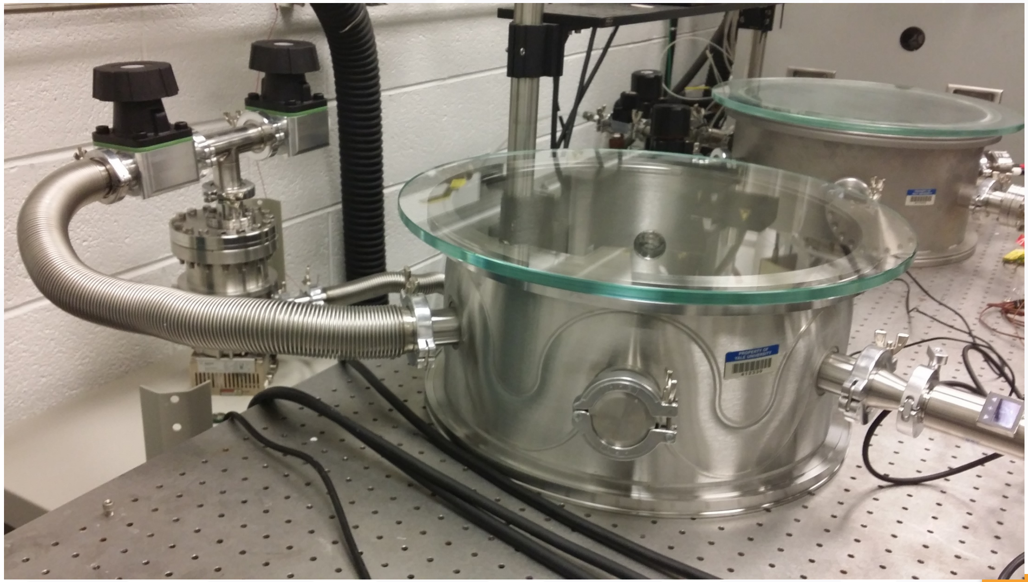
Results

Yale's setup for fast screening:
drops of LM on a PM disk





Ding, S., Y. Liu, Y. Li, Z. Liu, S. Sohn, F. Walker, and J. Schroers, Nature Materials, 13, 494, (2014).



Results

- Example of fast-screening of LM/PM corrosion reactions

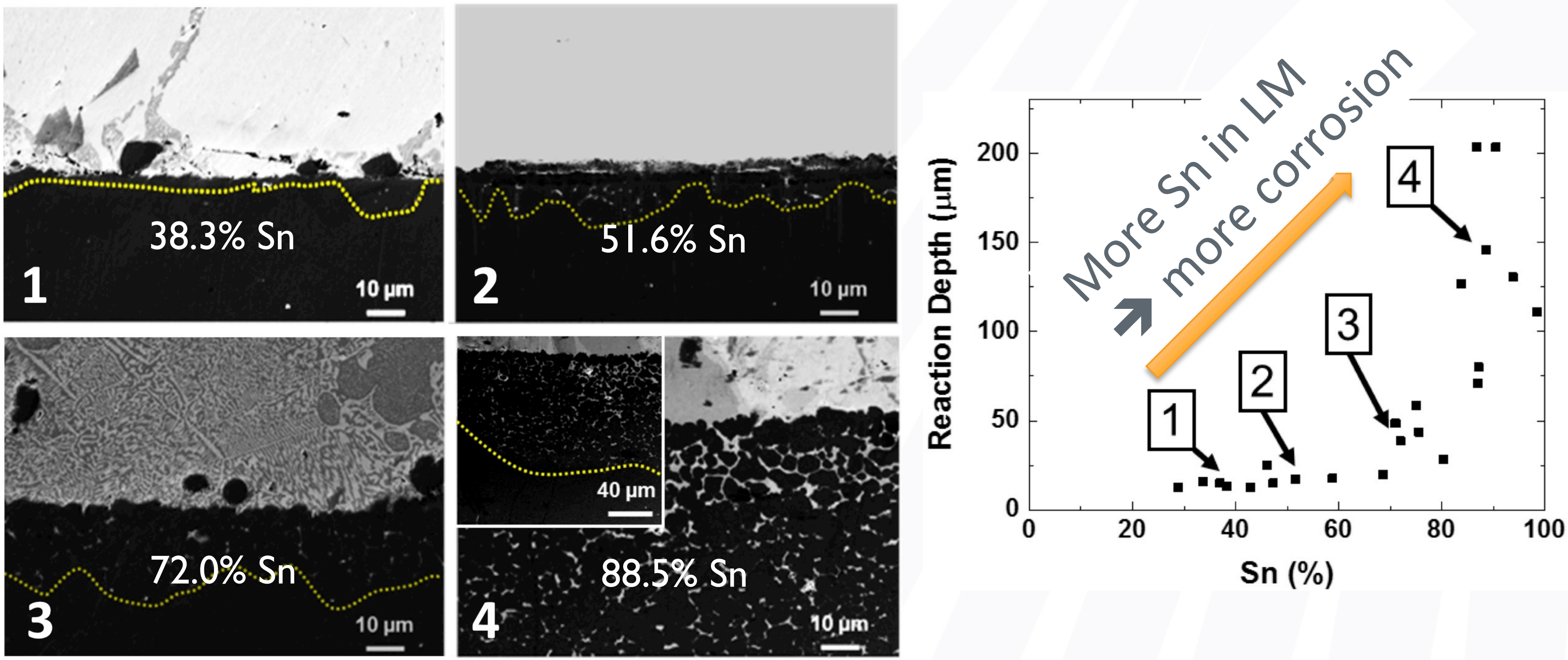
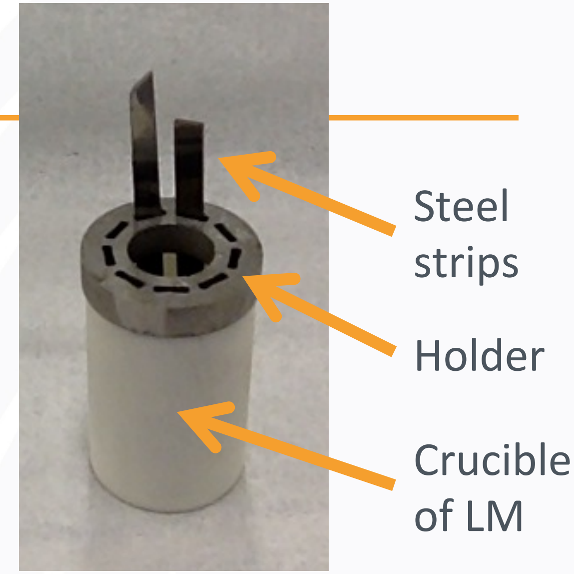


Figure 2.1.2-3: The effect of Sn content on the penetration depth (denoted by the dotted yellow lines) of LM into Kanthal steel PM.

(1) $Bi_{55.4}Sn_{38.3}Zn_{6.3}$ (2) $Bi_{43.3}Sn_{51.6}Zn_{5.1}$ (3) $Bi_{25.1}Sn_{72}Sb_{2.9}$ (4) $Sb_{9.9}Zn_{1.6}Sn_{88.5}$

Results

- Longer-term static corrosion tests
  - Dissolution protection is by aluminum-oxide scales (Al_2O_3).
  - Therefore, we use Kanthal steels because they have 6% Al, by mass.

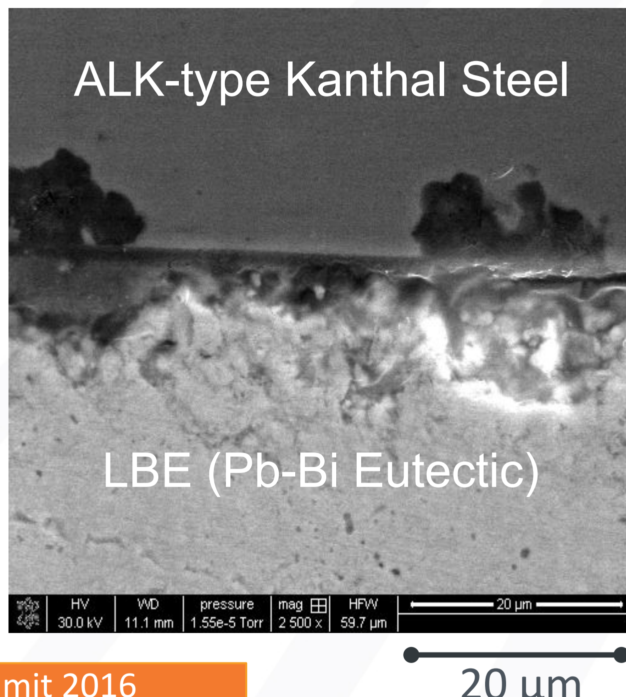


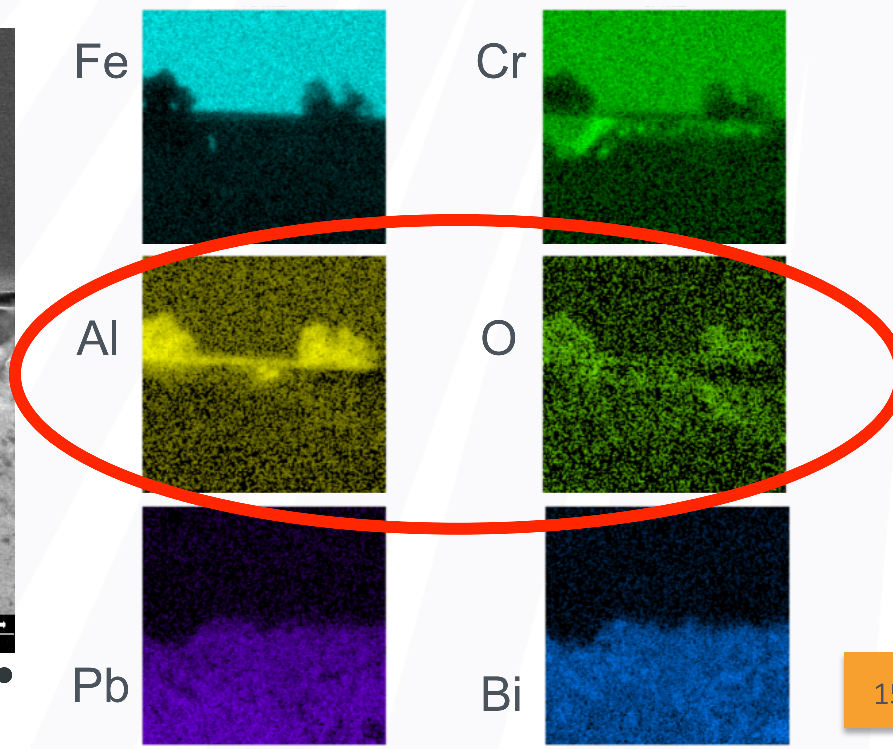
Good Example

1000 hours

700 °C

10^{-6} wt.% dissolved oxygen





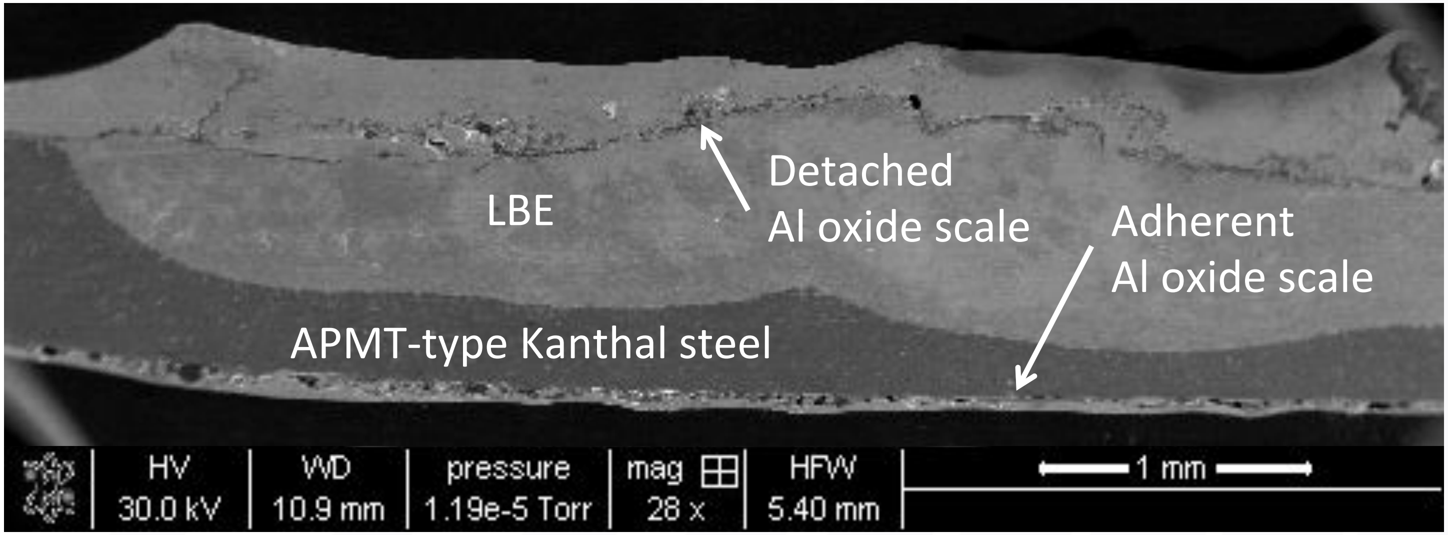
Results

Bad Example

1000 hours

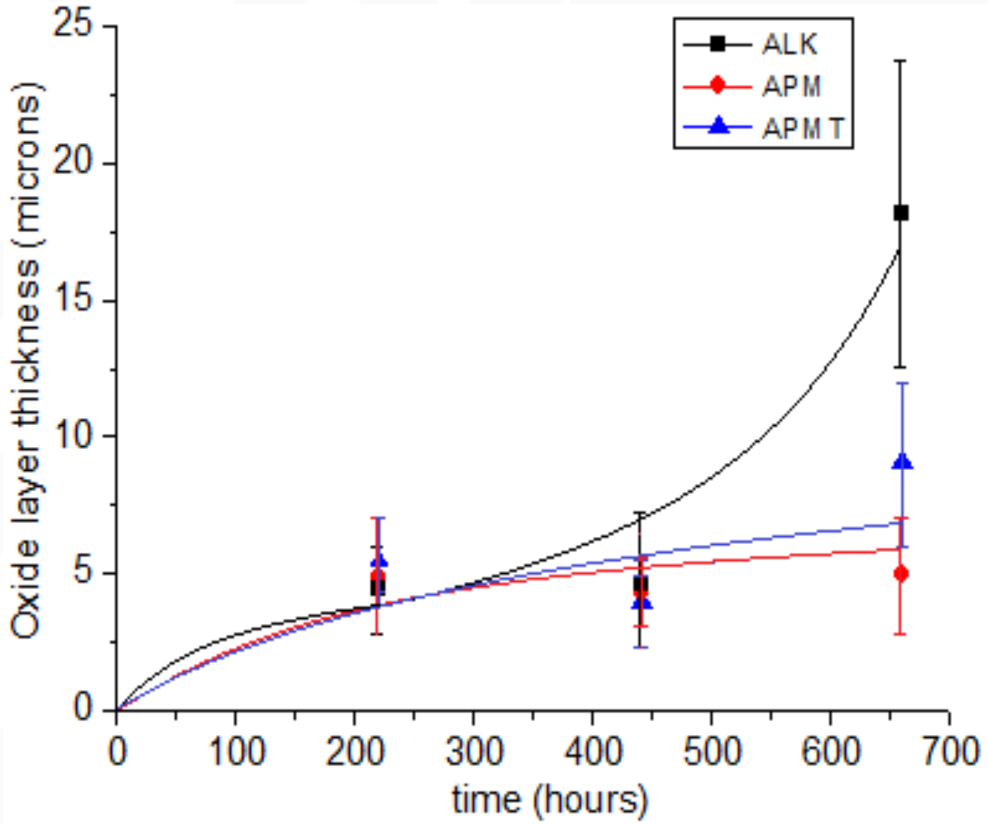
800 °C

10^{-6} wt.% dissolved oxygen



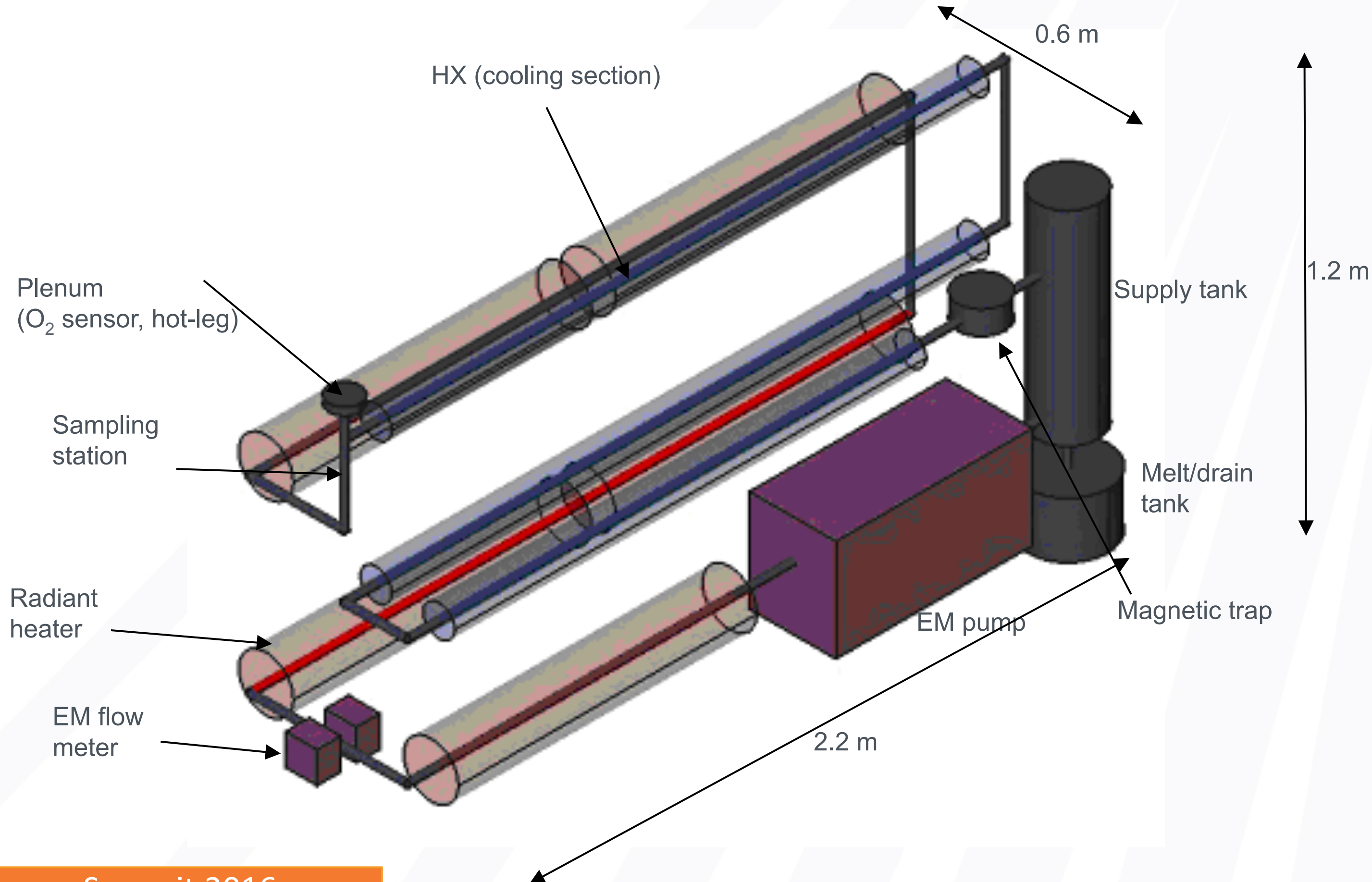
Results

Oxide growth on Fe-Cr-Al ferritic steels (Kanthal) during exposure to static LBE at 700°C with $1\cdot10^{-6}$ wt. % O for up to 660 h



Results

- A forced-convection liquid-metal flow loop has been designed, constructed, and leak tested with gas at room temperature.
- Work is continuing to initiate flow experiments using a liquid metal (LBE).



Path to Market

- This research project → Experimental evidence of LBE as a high-temperature heat-transfer fluid
- Industrial collaboration → Build a scaled test loop with CSP-like configuration, and test over a more exhaustive range of operating parameters
- Industry → Build a prototype CSP plant with liquid metal as the heat-transfer fluid

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