The History of Liquid Metal Batteries

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stationary storage at massive scale:

- point of departure: specifications
- long service lifetime
- safe = fire resistant
- operationally flexible
- super low price point

Research Paradigm Shift:

Cost-informed Discovery

the path forward for storage

- confine chemistry to earth-abundant elements
- ☞ to make it dirt cheap, make it out of dirt!

  preferably local dirt
- and make it easy to manufacture

  ☞ design at the discovery stage

inventing a colossal cheap storage device

☞ pose the right question

- disregard the experts: look outside the field for inspiration
- marvel at the economy of scale of modern electrometallurgy:
  - ☞ aluminium smelter

a modern aluminium smelter

photo credit: “Phase II Makes Alouette the Largest Primary Aluminium Producer in the Americas,” *Light Metal Age*, February 2006.

inventing a colossal cheap storage device

☞ pose the right question

☞ dirt to metal < $1.00 / kg

a modern aluminium smelter

photo credit: “Phase II Makes Alouette the Largest Primary Aluminium Producer in the Americas,” *Light Metal Age*, February 2006.

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Magnesium–Antimony Liquid Metal Battery for Stationary Energy Storage

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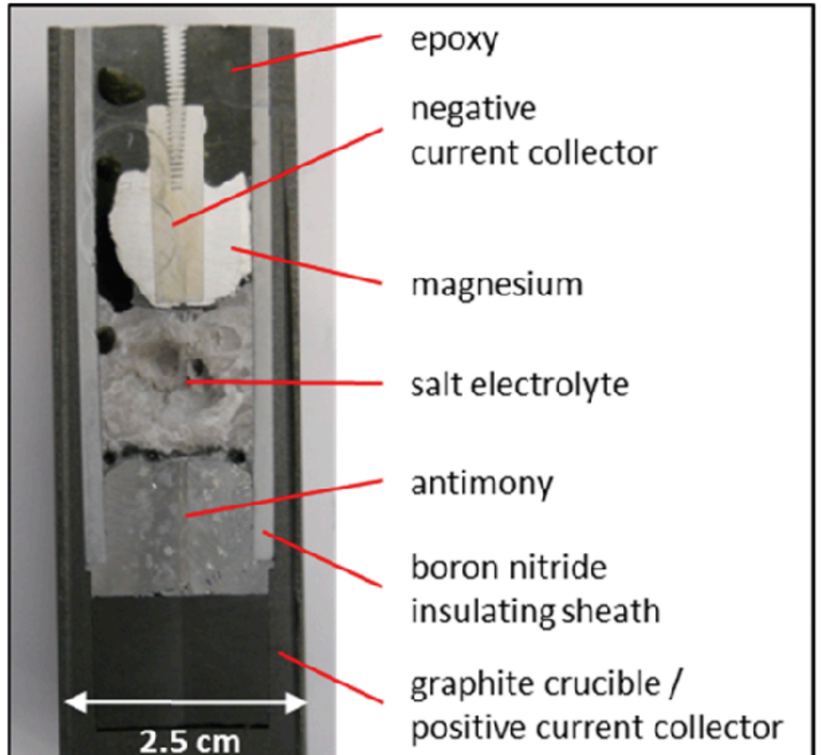
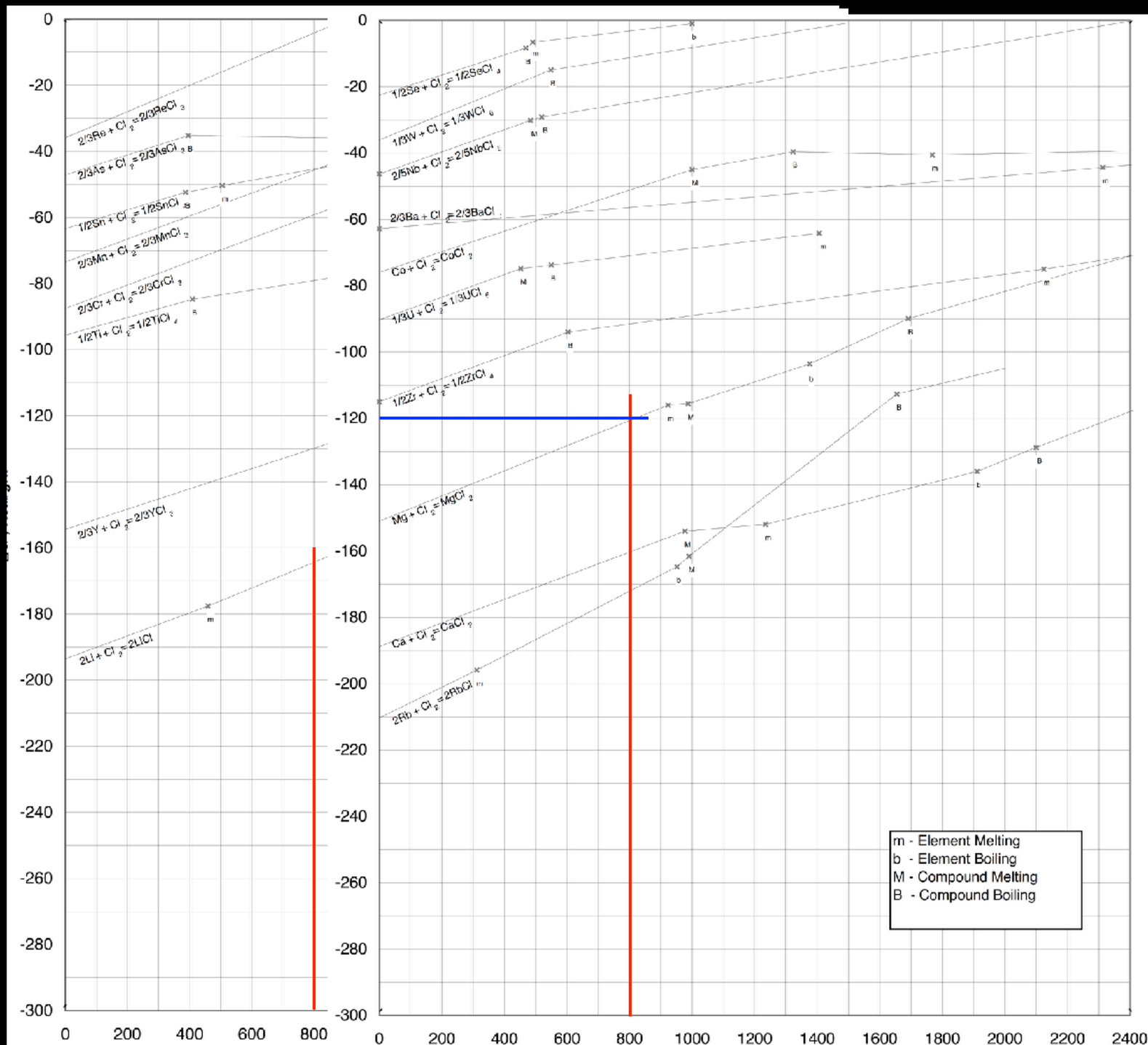
Supporting Information

ABSTRACT: Batteries are an attractive option for grid-scale energy storage applications because of their small footprint and flexible siting. A high-temperature (700 °C) magnesium–antimony (Mg||Sb) liquid metal battery comprising a negative electrode of Mg, a molten salt electrolyte ($MgCl_2$–KCl–NaCl), and a positive electrode of Sb is proposed and characterized. Because of the immiscibility of the contiguous salt and metal phases, they stratify by density into three distinct layers. Cells were cycled at rates ranging from 50 to 200 mA/cm^2 and demonstrated up to 69% DC–DC energy efficiency. The self-segregating nature of the battery components and the use of low-cost materials results in a promising technology for stationary energy storage applications.



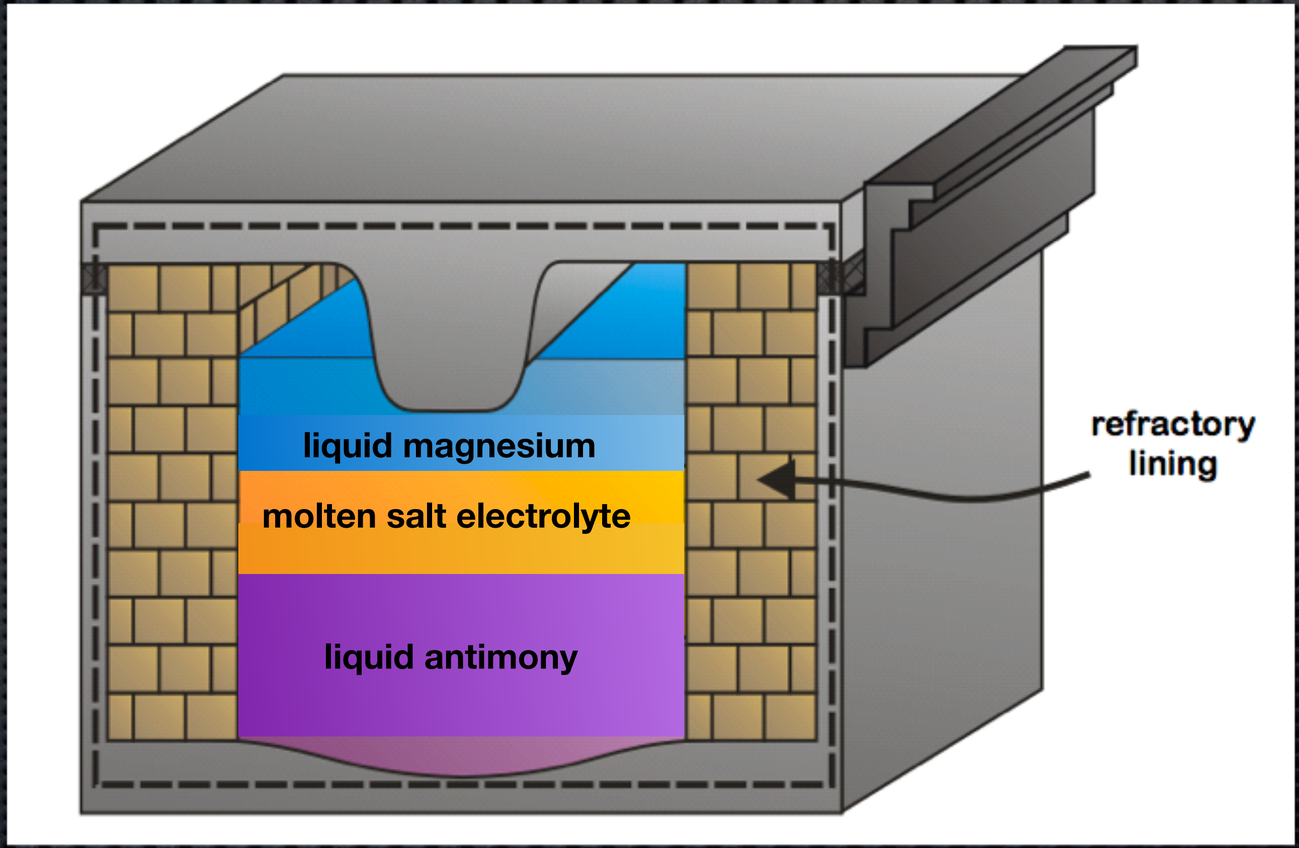
Large-scale energy storage is poised to play a critical role in


2/3Re + Cl2 = 2/3ReCl3
2/3As + Cl2 = 2/3AsCl3
1/2Sn + Cl2 = 1/2SnCl4
2/3Mn + Cl2 = 2/3MnCl2
2/3Cr + Cl2 = 2/3CrCl2
1/2Ti + Cl2 = 1/2TiCl4
2/3Y + Cl2 = 2/3YCl3
2Li + Cl2 = 2LiCl
1/2Se + Cl2 = 1/2SeCl4
1/3W + Cl2 = 1/3WCl6
2/5Nb + Cl2 = 2/5NbCl5
2/3Ba + Cl2 = 2/3BaCl2
Co + Cl2 = CoCl2
1/3U + Cl2 = 1/3UCl6
1/2Zr + Cl2 = 1/2ZrCl4
Mg + Cl2 = MgCl2
Ca + Cl2 = CaCl2
2Rb + Cl2 = 2RbCl
m - Element Melting
b - Element Boiling
M - Compound Melting
B - Compound Boiling

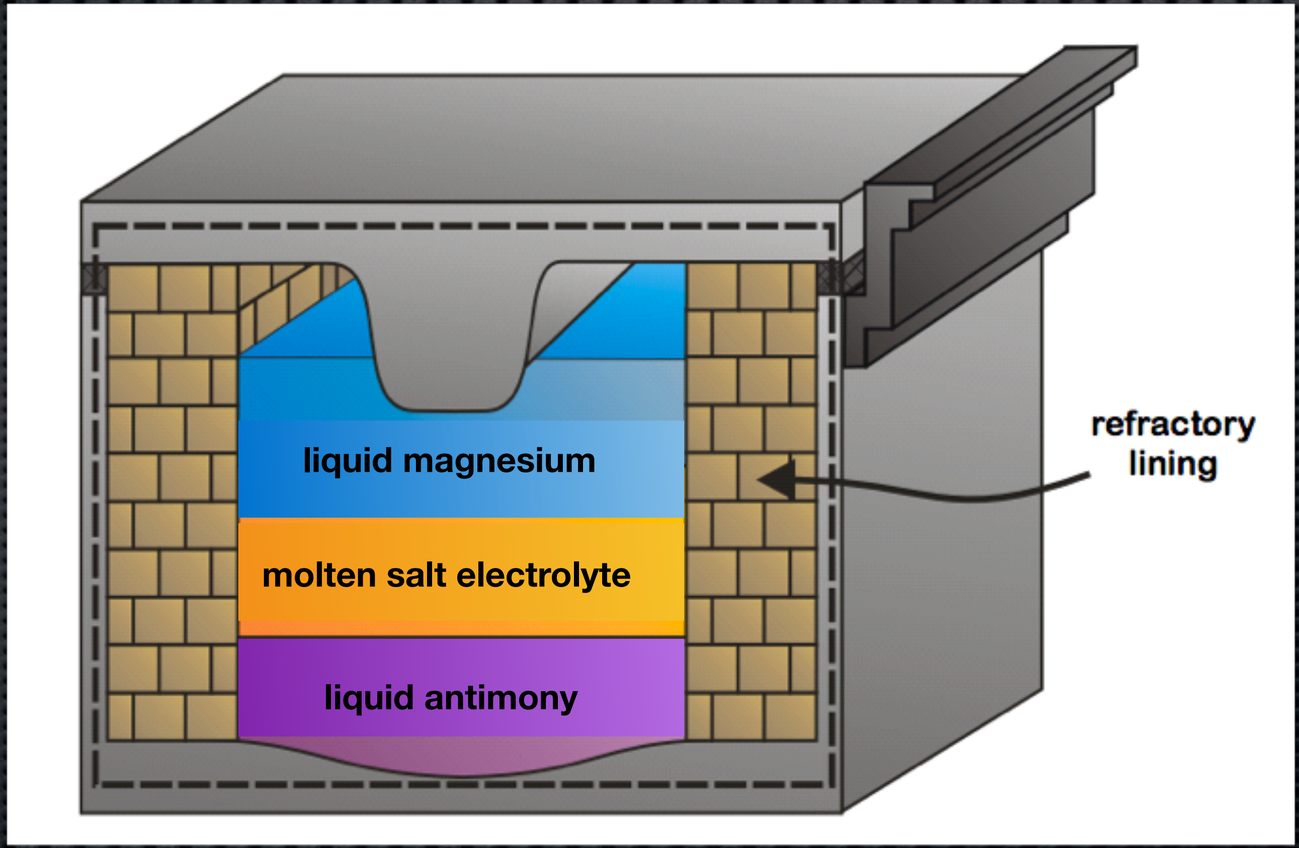
on discharge

$$Mg_{(liquid)} \Rightarrow Mg^{2+} + 2e^-$$

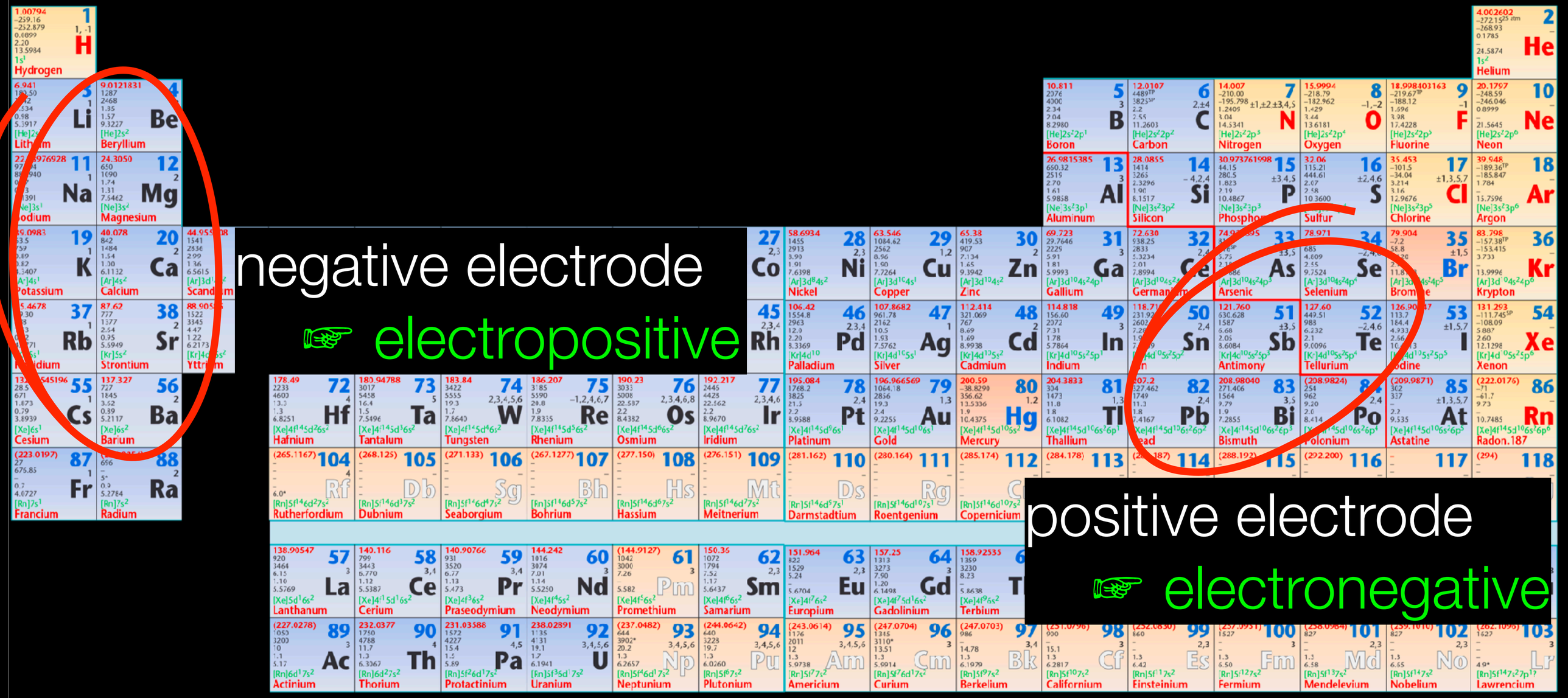
$$Mg^{2+} + 2e^- \Rightarrow Mg_{(liquid\ alloy)}$$



on charge: electrorefine Mg out of Sb



Liquid metal battery: a platform technology



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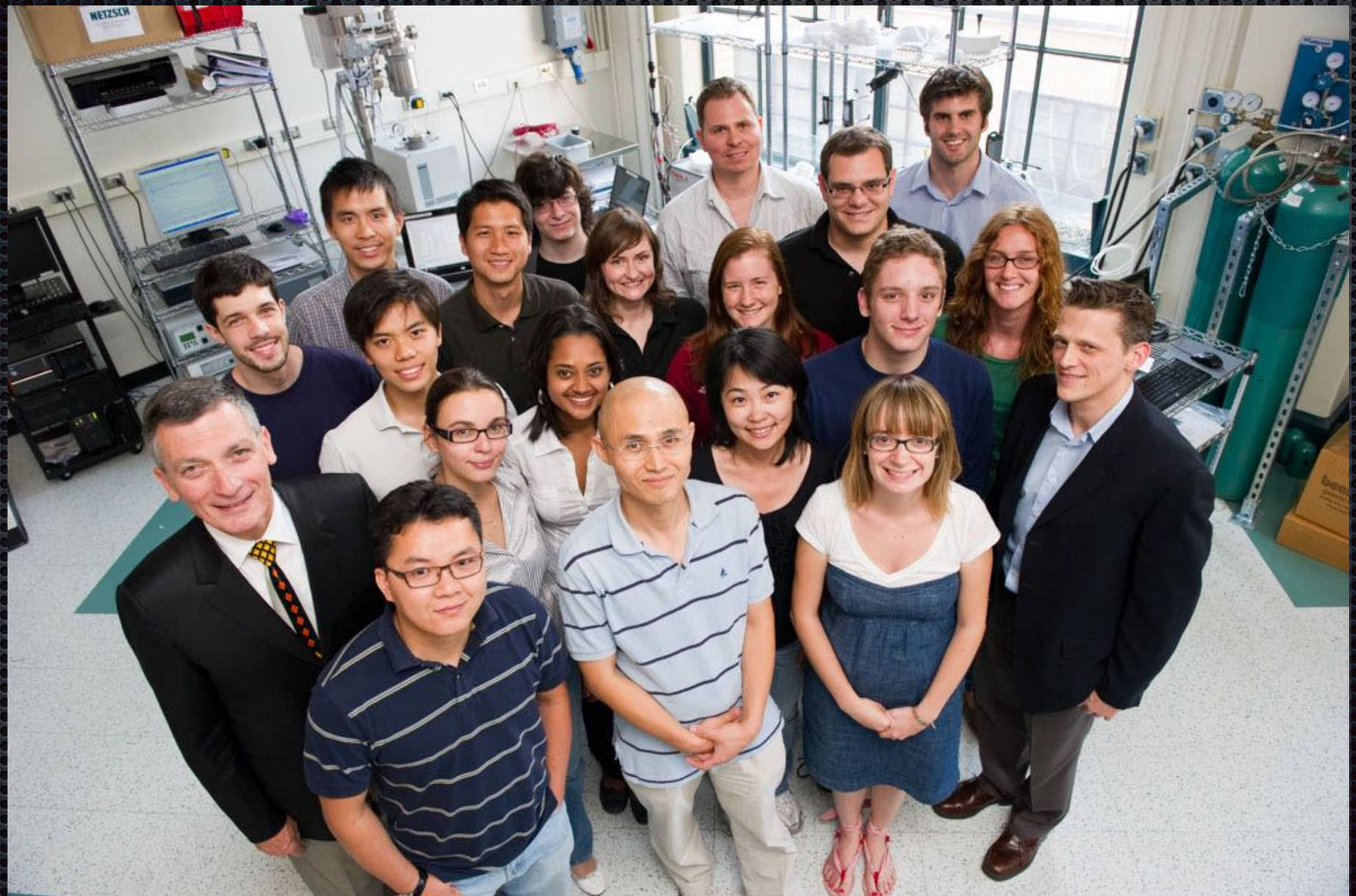
anti-experts, not experts, changing the world



liquid metal battery progress report

- liquid metal battery works:
  - over 1500 cells tested
  - many chemistries: metal alloys & salt solutions
  - < $50/kWh for electrodes + electrolyte

startup time: science in service to society

- Ortiz, Bradwell, Sadoway

- Liquid Metal Battery Corporation established in 2010!

Ambri

new name: CAmbridge

- series A funding from

Bill Gates

Introduction to Solid State Chemistry

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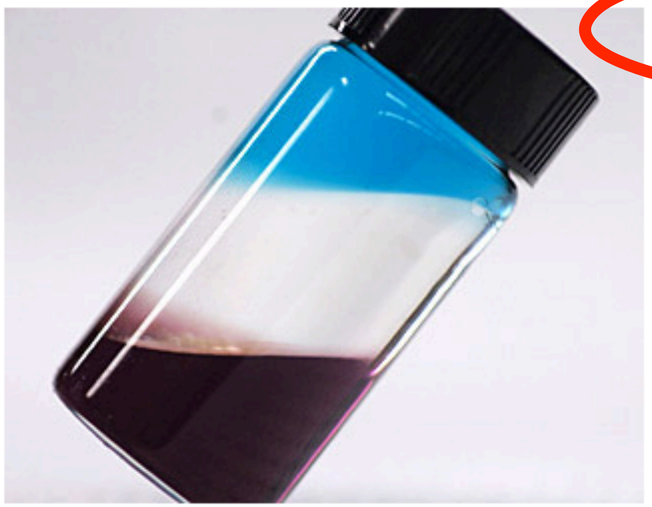

This vial containing three immiscible liquids – that is, liquids that cannot be mixed – demonstrates how the chemical components of a liquid metal battery can self-assemble. When the vial is shaken, the liquids separate after a few seconds. (Photo by Lee Moshurchak, courtesy of Donald Sadoway.)

Instructor(s)
Prof. Donald Sadoway

Level
Undergraduate

Translated Versions
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startup time: science in service to society

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Ambri

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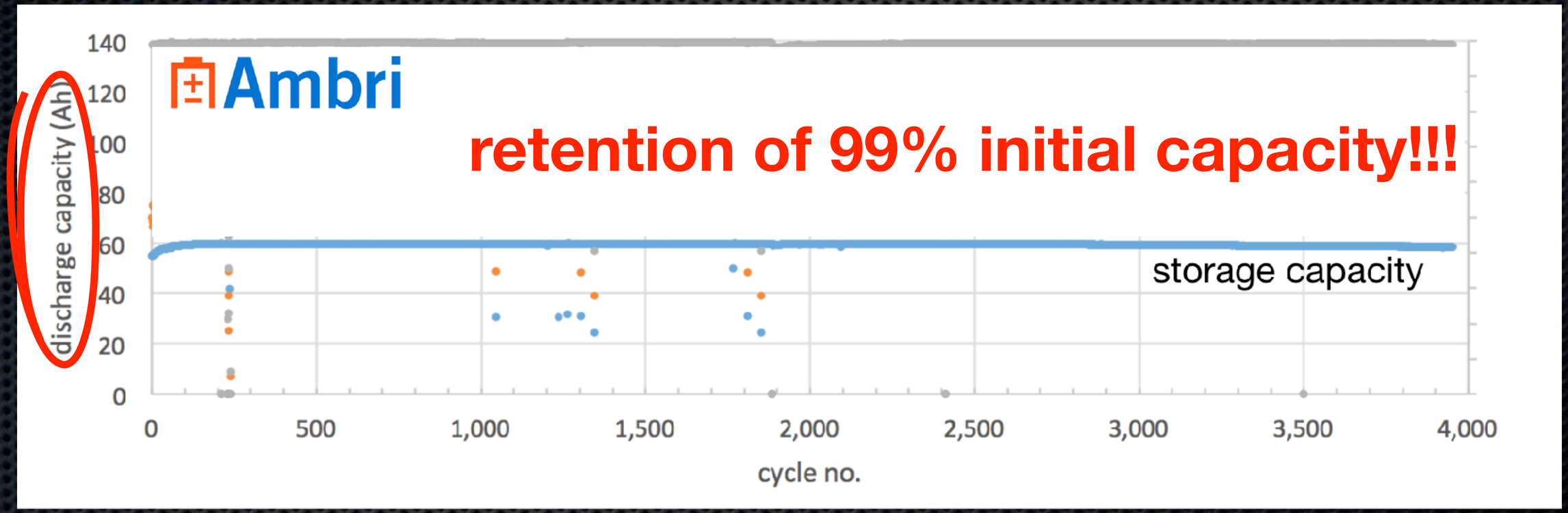
TOTAL

near-zero fade < 0.00009% (Li | Pb-Sb)

- 4.5 years at temperature ☞ 5000 cycles > “13 years”



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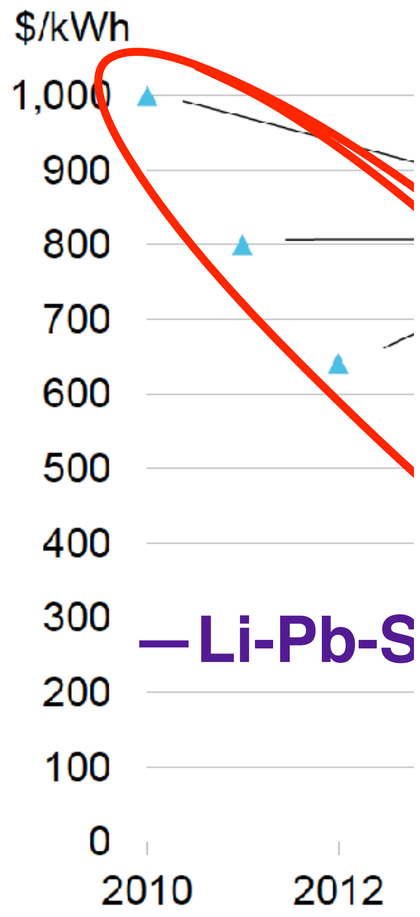

Source: Bloomberg New
Cell costs alone will be l

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Determination and modeling of the thermodynamic properties of liquid calcium–antimony alloys

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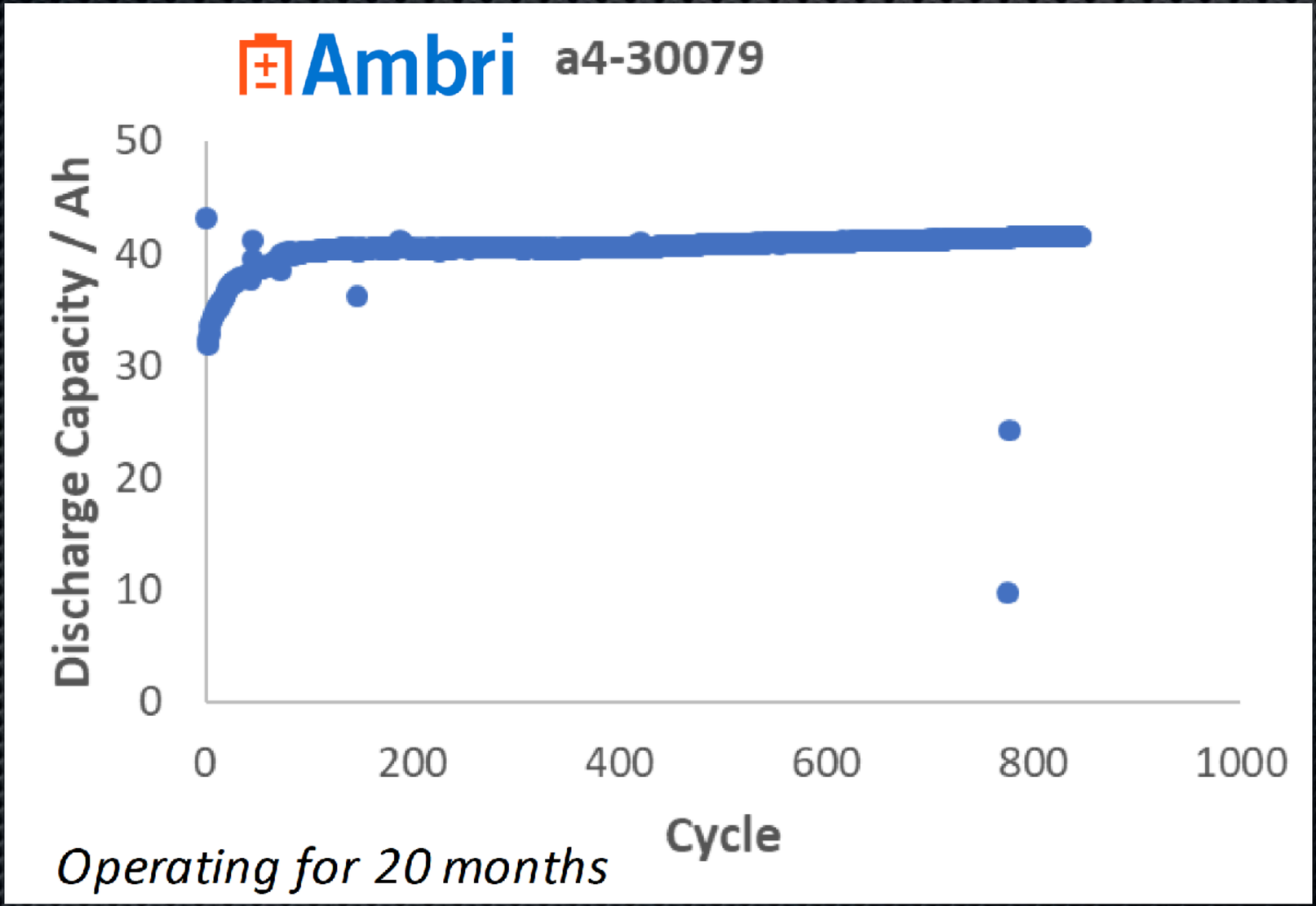
ABSTRACT

The thermodynamic properties of Ca–Sb alloys were determined by emf measurements in a cell configured as Ca(s)|CaF_2|Ca–Sb over the temperature range 550–830 °C. Activity coefficients of Ca and Sb, enthalpy, Gibbs free energy, and entropy of mixing of Ca–Sb alloys were calculated for $x_{Ca} < 0.55$. To explain the connection between short-range order of liquid Ca–Sb alloys and the strong deviation from ideality in the thermodynamic properties, two thermodynamic models were invoked and reconciled: the regular associated solution model, assuming the presence of a $CaSb_2$ associate, and the molecular interaction volume model (MIVM). For the first time, the MIVM was used successfully to model the activity coefficients of a system with high-melting intermetallics, reducing the number of fitting parameters necessary from 5 (regular associated model) to 2 (MIVM). From the interaction parameters optimized by fitting at 800 °C, the activity coefficient of Ca was predicted at 650 °C, with an average error of less than 0.6% in the emf value.

finding puts us on a desirable cost trajectory, this approach may well

$x_{L/Li+Sb+Pb}$ (mol%)

same with other chemistries (Ca | Sb)



Ambri today

- 12 years old! ☞ tough tech, not writing code!!
- Microsoft is the first customer
- expanding manufacturing facilities in Milford, MA
- order book exceeding $500 million
- JVs in India and Saudi Arabia