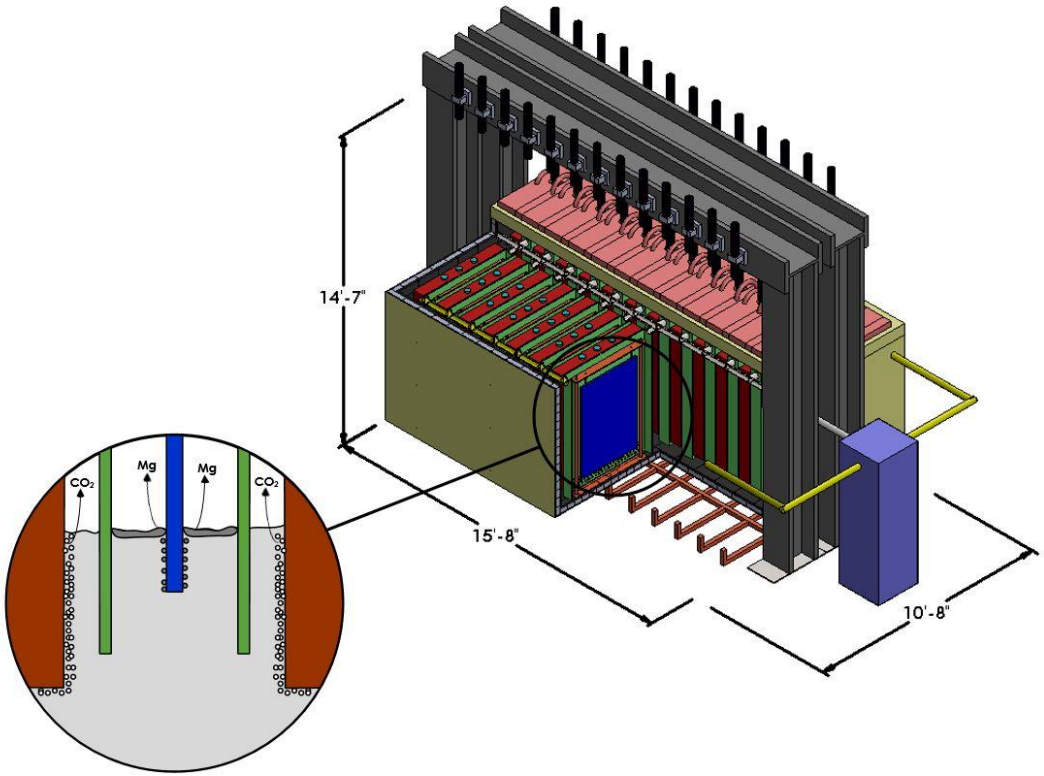
Valparaiso University

August 24 – 25, 2016

Detroit, MI

METALS Annual Meeting



Project Team

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- **Valparaiso University**
  - Robert Palumbo — Mechanical Engineer, Thermal Sciences/Electrochem.
  - Scott Duncan — Mechanical Engineer, Manufacturing/Design
  - Luke Venstrom — Mechanical Engineer, Thermal Sciences
  - Shahin Nudehi — Mechanical Engineer, Numerical Modeling/Intrumentation
  - Daniel Blood — Mechanical Engineer, Manufacturing/Design
  - Jon Schoer — Chemistry
  - Michal Korenko — Molten Salts Electrochemistry
  - Carol Larson — Chemist/Instrument specialist
  - Kristen Blood — Mechanical Engineer
  - Tiffany Lofay — Project Manager
  - Undergraduate Students
- **Partners**

Navigant Consulting	Robert Chiang	MBA
Chrysler FAC	Larry Sak	Materials
Purdue University	Peter Kissinger	Electrochemist
Slovak Academy of Sciences	Frantisek Simko	Molten Salt Chemist
Diver Solar	Richard Diver	Mechanical Engineer

Project Goal & Achievements

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Our Goal:

End the ARPA-E project with an industrial partner ready to scale our cell concept for testing at 1000 A for 1000 hours.

Project Achievements:

1. We developed the requisite engineering science for producing Mg from MgO dissolved in a molten fluoride salt at 1300 K .
2. Achieved current efficiency above 90%
3. Established fundamental transport and kinetic parameters for electrolysis process
4. Expect current densities near 0.75 A-cm^{-2} at 3.1V
5. We combined laboratory-scale cell performance results with an economic analysis that suggests our process is economically viable.

The Process Concept

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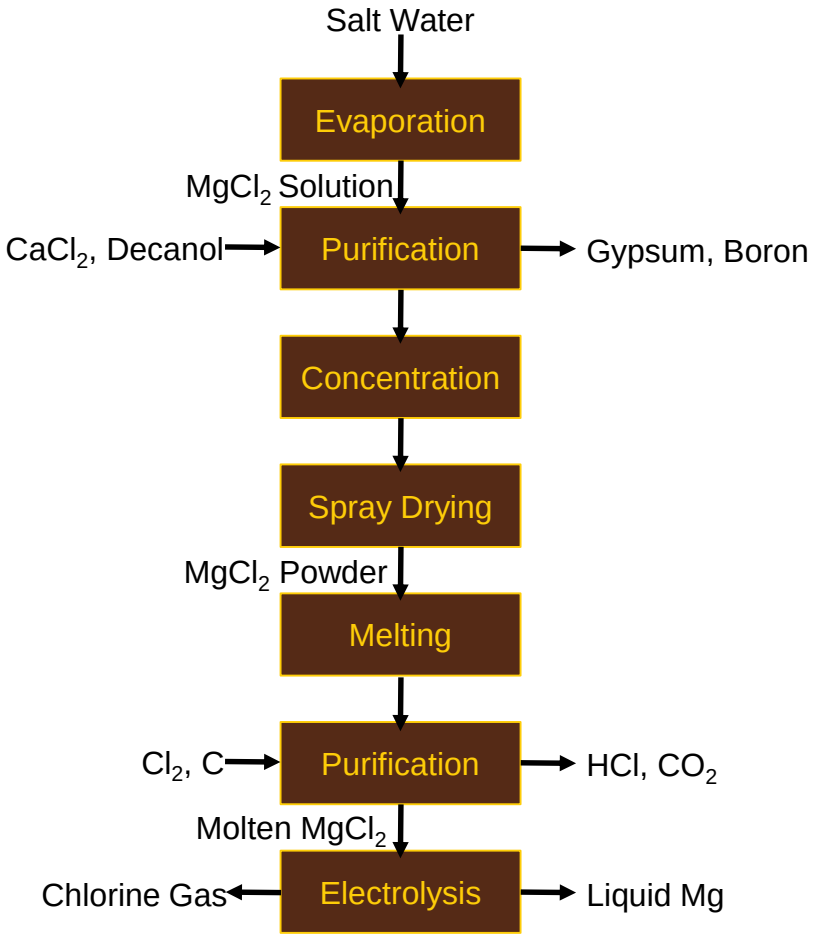
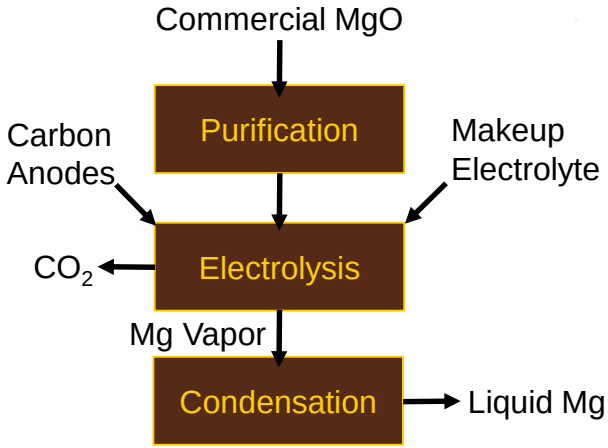
The $MgCl_2$ Approach:
32 kWh/kg



MgO Electrolysis Approach:
25 kWh/kg



MgO Electrolysis eliminates the costly purification of $MgCl_2$ and reduces energy requirements.

Why It Matters

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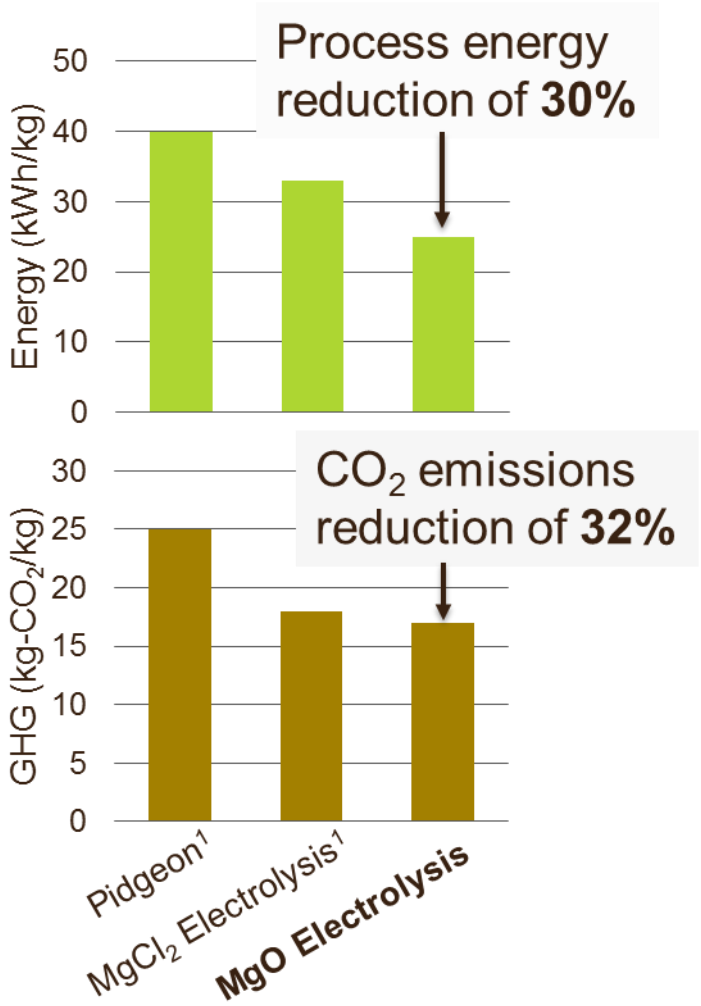

Our MgO electrolysis process leverages the inherent efficiency of electrochemistry to reduce energy intensity, and uses an MgO feedstock to reduce costs.

Estimate from Techno-Econ Analysis

For 17000 ton/year capacity…

Capital: $36M

Operating Cost: $2.20/kg-Mg

U.S. Price: $4.00/kg-Mg

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The 20 A Laboratory Cell

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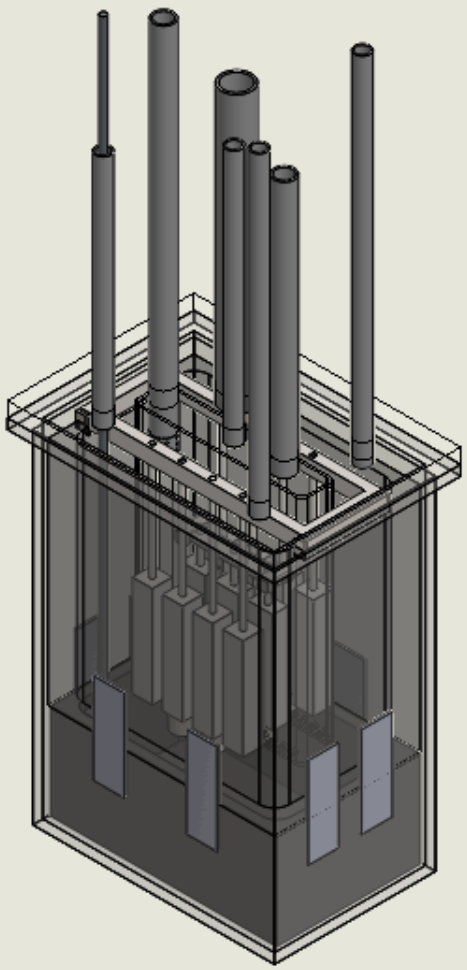

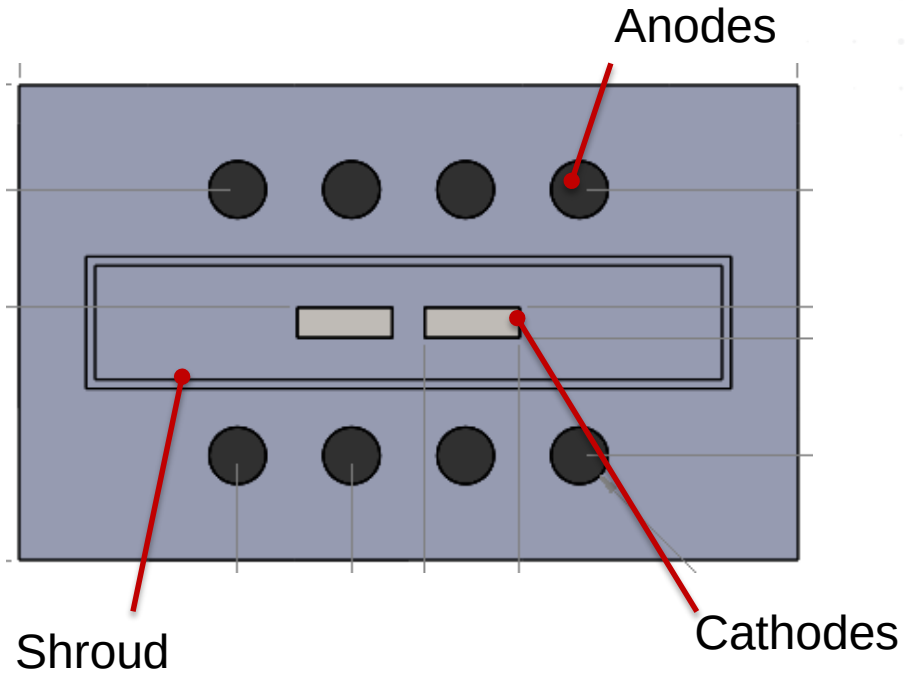
Anodes
Shroud
Cathodes

Cell Performance

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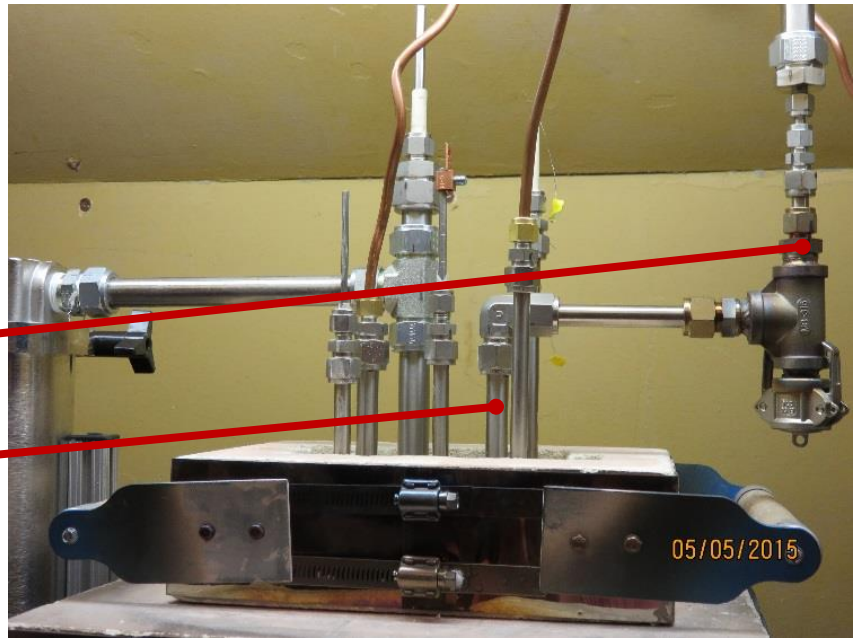
Flash Vaporization for Mg Recovery

80% Current Efficiency based on mass recovered



Cell Performance

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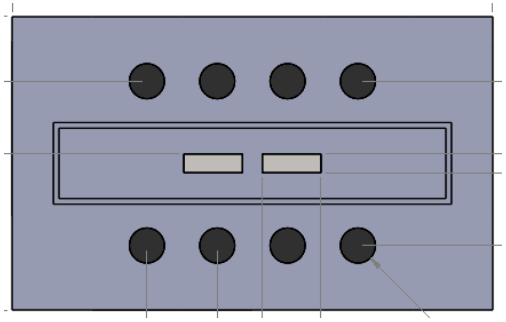

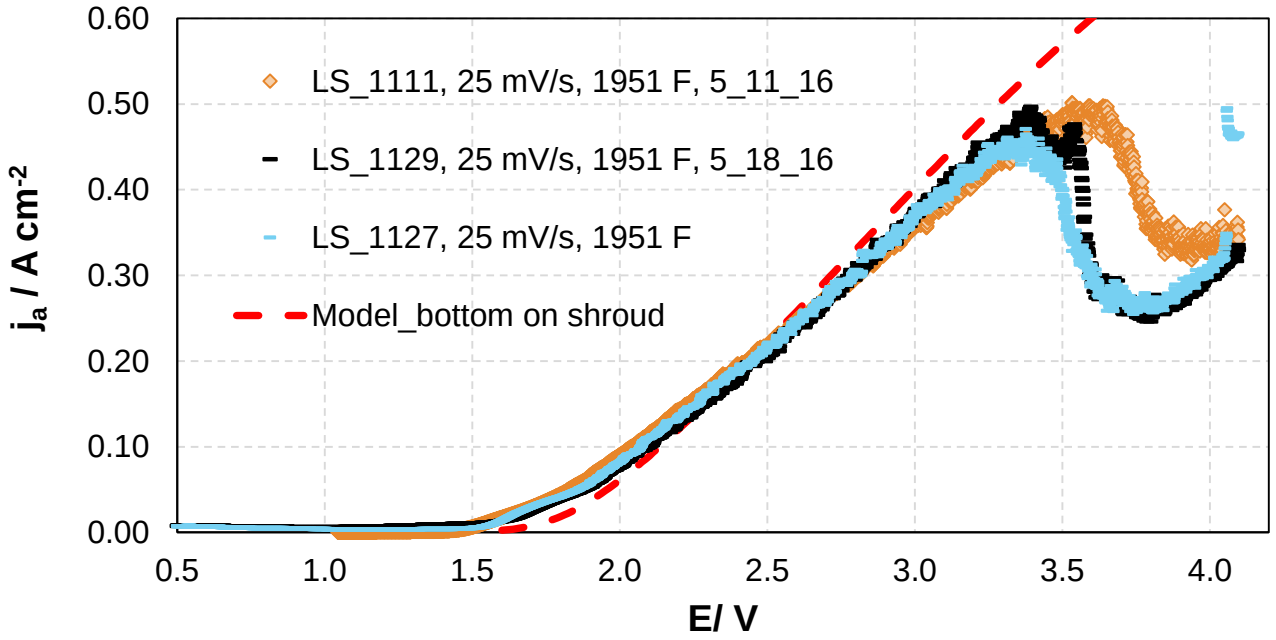

Cell Performance

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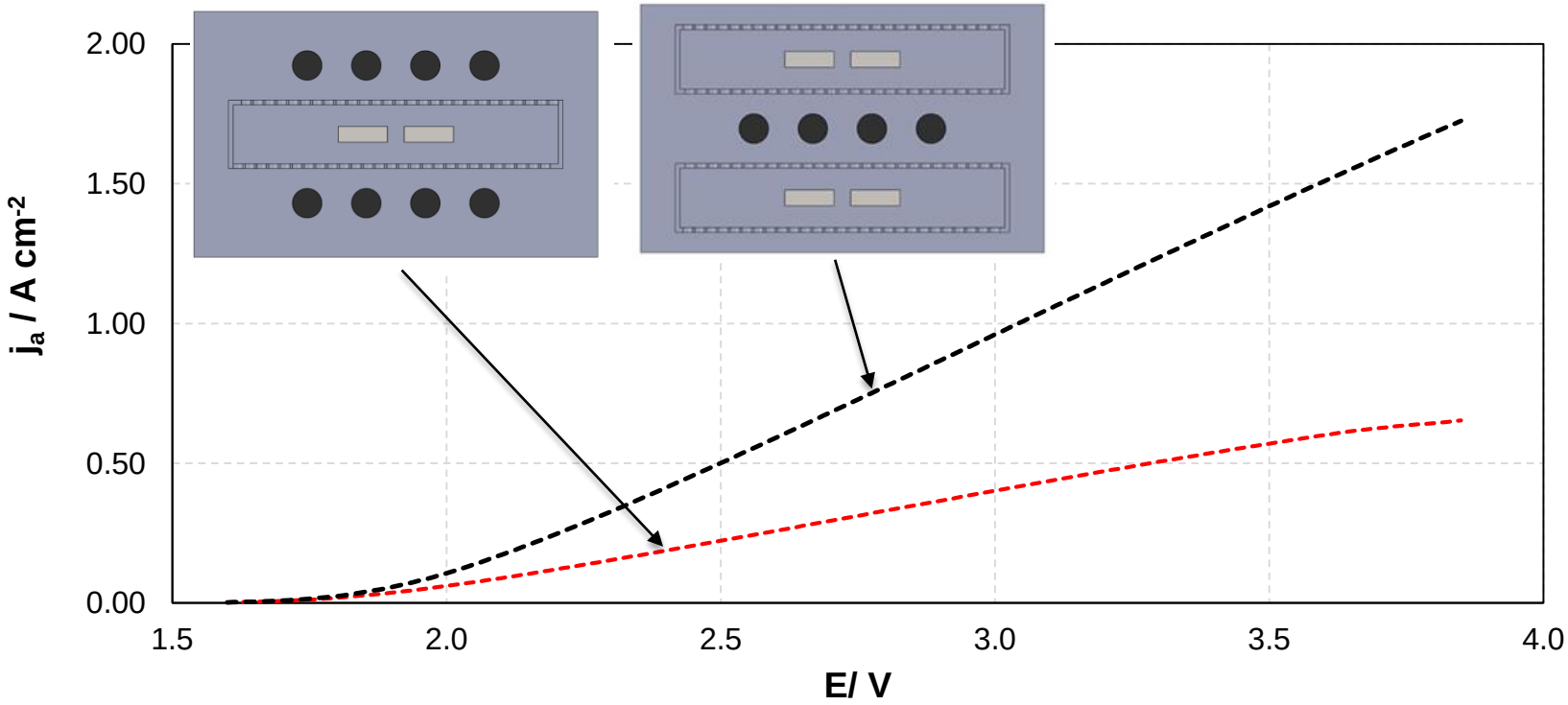
Finite Element Model Estimate of Current Density vs. Cell Voltage for two electrode arrangements



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MgO Solubility

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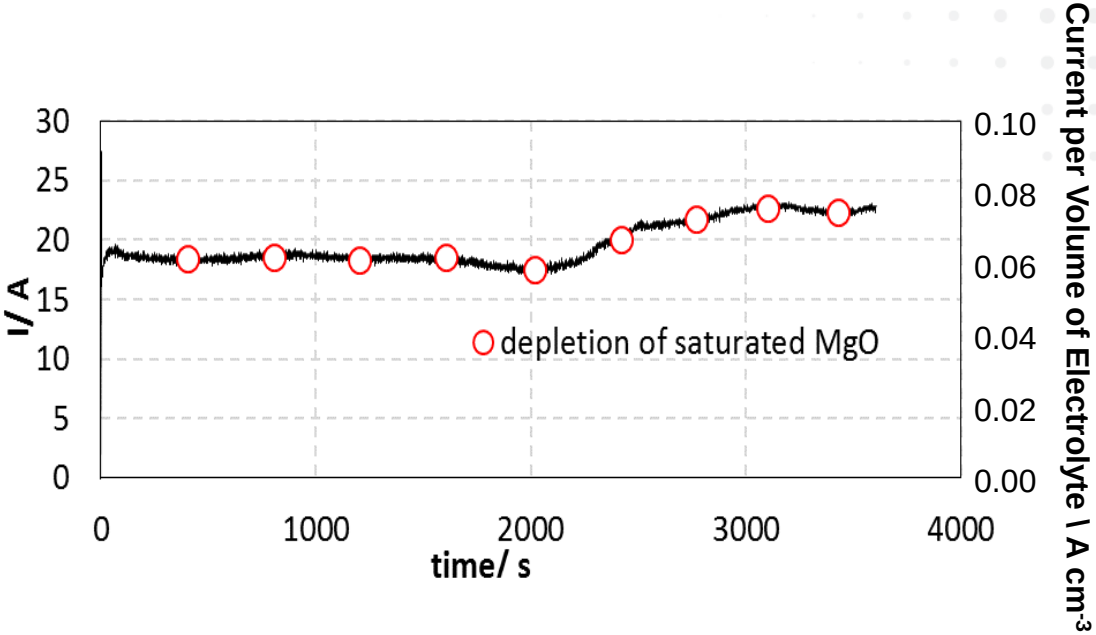
MgO Dissolution Keeps Pace with Current

MgO solubility is 0.3 mol% in our electrolyte

At a cell voltage of 3.4 V

Current density **0.55 - 0.7 A-cm^{-2}**

Current per volume of electrolyte **0.055 - 0.065 A-cm^{-3}**



Value in the $MgCl_2$ electrolysis industry is between 0.008 and 0.005 A-cm^{-3}

Value in aluminum electrolysis industry is between 0.035 and the very best 0.2 A-cm^{-3}

TEA Highlights

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We are targeting the U.S. market, selling Mg at the Tariff price of ~$4.00/kg.

For a 17,000 metric ton facility:

Scenario	Current Density (A/cm^2 at 3.26 V)	Current Efficiency (% $e^- \rightarrow$ Mg)	MgO Cost ($/kg)	Labor Rate ($/h)	Price of Electricity ($/kW-hr)	Capacity Factor (%)	# of Cells	Total Capital Cost ($million)	Operating Cost ($/kg)
Base Case	0.75	90	0.35	56	0.05	90	**18**	**36**	**2.20**

Competitive advantages:

- Feedstock taps into existing dolomite reserves in the U.S. (currently underutilized)
- Minimal processing of feedstock simplifies process
- Mg is produced ready for casting

TEA Highlights

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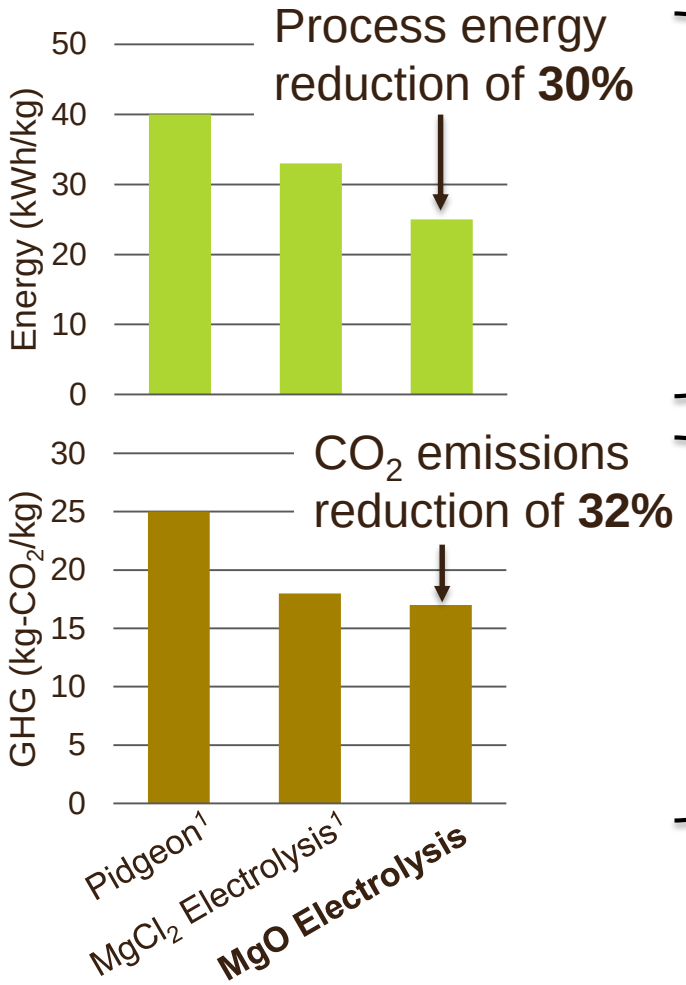
Overall Energy Consumption and Emissions:



- Our process requires **10.8 kWh/kg-Mg**.
- Half of the life-cycle energy requirements at left is for mining and extracting MgO from dolomite.

- Our process is responsible for the emission of **4.4 kg-CO_2/kg-Mg**.
- Most of the CO_2 is released when $MgCO_3$ from dolomite is calcined to MgO and CO_2.

Demo Requirements

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- Demo phase:
  - Demonstration of cell at 1000 A for 1000 hrs.
  - Expected cost: $2-3 million
  - Projected Outcome: Cell performance data that enables extrapolation of cell performance to a 50-100 kA cell

- Partnership needs:
  - An innovator capable of testing an electrolytic cell at 1000 A.
  - A visionary willing to continue to progress MgO electrolysis to the pilot stage

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Summary

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- We have demonstrated that our Mg from MgO electrolysis process is worthy of being scaled to a 1000 A demonstration level.
  - 20 A scale laboratory experiments combined with an economic analysis suggests the process could be industrially viable.
  - Fundamental electrochemistry studies combined with a 3-D finite element model of the cell enables us to extrapolate laboratory scale performance results to the 1000 A scale.

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QUESTIONS?