Scale-Up of Magnesium Production by Fully Stabilized Zirconia Electrolysis

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INFINIUM, Inc.
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Project ID: LM035

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Overview

TIMELINE
Project start date: 10/1/2011
Project end date: 12/31/2015
Percent complete: 83%

BUDGET
Total project funding: $12M
- $6M DoE
- $6.03M INFINIUM

Funding Received in FY14
- $1M DoE
- $1M INFINIUM

Funding for FY15
- $1M DoE
- $1M INFINIUM

BARRIERS
Magnesium supply base:
Inexpensive and clean domestic source of magnesium

PARTNERS
INFINIUM, Inc. – Project Lead
Praxair, Inc.
Kingston Process Metallurgy
Boston University
Exothermics, Inc.
Spartan Light Metal
Cosma International, Automotive Partnerships Canada
MagPro, LLC

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Relevance

Objectives

• Scale up INFINIUM’s primary magnesium production from laboratory demonstration to pre-production pilot plant

• Budget Period 3
  ▪ Achieve industry standard uptime for prototypes
  ▪ Prepare for plant-scale anode manufacturing
  ▪ Produce and test magnesium automotive parts
  ▪ Model full life cycle costs, energy use & emissions

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Increased Energy Security  Reduced Emissions

Reduced Dependence on Foreign Oil

Increased Fuel Efficiency

Lightweight Vehicles

Domestic, Clean, Cost-Effective Magnesium
Phase 1: Alpha Prototype
- Design, build, & test alpha prototype
- Optimize anode design
- Calculate costs, energy use, & emissions
- Produce & test magnesium
- Initiate plant design

Phase 2: Beta Prototype
- Design, build, & test beta prototype
- Achieve prototype-scale anode manufacturing
- Produce magnesium; make & test parts
- Model plant costs, energy use, & emissions

Phase 3: Prototype Operation & Plant Design
- Achieve industry standard uptime for prototypes
- Prepare for plant-scale anode manufacturing
- Produce & test magnesium automotive parts
- Model full lifecycle costs, energy use & emissions
## Approach

<table>
<thead>
<tr>
<th>Phase, Due</th>
<th>Project MILESTONES</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Nov 2012</td>
<td>Conduct electrolysis in alpha</td>
<td>Complete</td>
</tr>
<tr>
<td>1 Nov 2012</td>
<td>Demonstrate stable, $O_2$-producing anode assembly</td>
<td>Complete</td>
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<tr>
<td>1 Nov 2012</td>
<td>Calculate economically viable costs, energy use, &amp; emissions</td>
<td>Complete</td>
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<tr>
<td>1 Nov 2012</td>
<td>Achieve sufficient purity to meet Mg alloy specifications</td>
<td>Complete</td>
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<tr>
<td>1 Nov 2012</td>
<td>Identify potential plant site(s)</td>
<td>Complete</td>
</tr>
<tr>
<td>2 Nov 2013</td>
<td>Conduct electrolysis in beta</td>
<td>Extended to 6/2015</td>
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<tr>
<td>2 Nov 2013</td>
<td>Produce sufficient anode assemblies for prototypes</td>
<td>Complete</td>
</tr>
<tr>
<td>2 Nov 2013</td>
<td>Provide sufficient Mg for tensile testing</td>
<td>Extended to 10/2015</td>
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<tr>
<td>2 Nov 2013</td>
<td>Model plant site</td>
<td>Complete</td>
</tr>
<tr>
<td>3 Nov 2014</td>
<td>Achieve industry uptime standard for prototypes</td>
<td>Extended to 11/2015</td>
</tr>
<tr>
<td>3 Nov 2014</td>
<td>Prepare for plant scale anode manufacturing</td>
<td>Extended to 11/2015</td>
</tr>
<tr>
<td>3 Nov 2014</td>
<td>Produce and test magnesium automotive parts</td>
<td>Extended to 11/2015</td>
</tr>
<tr>
<td>3 Nov 2014</td>
<td>Model full life cycle costs, energy use, and emissions</td>
<td>On Schedule</td>
</tr>
</tbody>
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New Approach

• Shift in project approach: primary production of magnesium for Mg-Nd master alloy
  ▪ Necessary for AE44, WE43, ZEK100, other alloys
  ▪ Can’t be reliably sourced in US today
  ▪ Direct electrolytic primary production from low-cost oxides simplifies alloying
  ▪ Best first-product for INFINIUM Mg
  ▪ Primary magnesium remains on the radar

• New project goal: produce 500 lbs of primary magnesium and Mg-Nd master alloy for WE43 alloy die casting trial (650 lbs total alloy)

• Technical advantage: simpler cell
  ▪ Make liquid Mg-Nd master alloy at cathode
  ▪ Focus on electrolysis cell development: bath, electrodes, etc.
  ▪ No need for simultaneous coupled condenser development

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New Approach

Current Path

Mg-Nd Master Alloy → WE43 Castable Magnesium → [Vehicle Frame]

Possible Future Path

ZEK100 Mg Sheet → [Vehicle Component]
Technical Accomplishments & Progress

Alpha Magnesium Furnace

- Version 2.0 2012: one electrolysis site, continuous condenser with successful pours
- Version 3.0 2013: two electrolysis sites, integrated anode-cathode assembly with hot swapping
- Version 4.0 2014: three ports, longest anode run time

Phase 3
- Achieve industry standard uptime for prototypes
- Prepare for plant scale anode manufacturing
- Produce and test magnesium automotive parts
- Model life cycle costs, energy use, emissions

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Technical Accomplishments & Progress

- Magnesium Master Alloy
  - Finalized master alloy process flow sheet
  - Finalized molten salt bath chemistry after testing four composition classes
  - Demonstrated first alpha-scale master alloy production
  - Preliminary beta-scale design, equipment sizing, 500 lbs production timeline

Phase 3
- Achieve industry standard uptime for prototypes
- Prepare for plant scale anode manufacturing
- Produce and test magnesium automotive parts
- Model life cycle costs, energy use, emissions

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Gamma prototype

- Neodymium production cell for master alloy
- Production of 650 lbs WE43 alloy will require approx. 150 lbs of Nd
  - 50 lbs in process on-site
  - 50 lbs in process off-site
  - 50 lbs in transit

Phase 3
- Achieve industry standard uptime for prototypes
- Prepare for plant scale anode manufacturing
- Produce and test magnesium automotive parts
- Model life cycle costs, energy use, emissions

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Technical Accomplishments & Progress

• Production of larger anode tubes
  ▪ Larger tube diameter facilitates higher oxygen flow rate and larger current collector
  ▪ Cast tubes with 1” and 1.25” outer diameter (cf. older 0.75” tubes)
  ▪ Maintained very low porosity (0.5% cf. best COTS >2%), 100% process yield

Phase 3
• Achieve industry standard uptime for prototypes
• Prepare for plant scale anode manufacture
• Produce and test magnesium automotive parts
• Model life cycle costs, energy use, emissions
Technical Accomplishments & Progress

Phase 3
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Low Silver Infinium Pure Oxygen Anode™

Copper/nickel conductor
Alumina protection Sheath
LSM Ceramic conductor
Oxygen Transfer Membrane Ag Displacement tube (OTM)
Oxygen Exhaust Vent

YSZ Tube insulated from Cathode
Liquid Silver Annular Anode

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High-current anode assembly design optimization

Modeling goals:
- Optimize lead geometry for minimal energy use (resistance & heat)
- Displacing solid design
- Thermal stress, oxygen flow

New model:
- 200-400 A industrial tube design
- Axisymmetric, very fast
- Temperature-dependent properties
- Parameterized geometry

Result: optimal electrical-thermal resistance balance

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Technical Accomplishments & Progress

- Energy balance model
  - Temperature-dependent properties
  - Cell and electrode geometry

Embedded in full cost model

Results: global cost vs.
- Temperature
- Tube material type, thickness, diameter
- Current density
- Anode and current collector geometry

Optimize parameters over entire system

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Response to 2014 Reviewers’ Comments

• Is anode lifetime the rate-limiting step? Anode lifetime is an important factor determining production cost. Anode size is the rate-limitation in terms of kg/hr.

• Extended timeline is delaying return on investment, there are many opportunities for pure Mg. We’ve made great progress on a technology challenge, and will continue to advance it toward timely deployment.

• Can this be integrated with downstream processes e.g. rolling, extrusion? Typically the most practical integration is to transport liquid metal from reduction cells directly to the downstream process.

• How does anode life here compare with other electrolysis processes? Other processes e.g. Hall-Héroult aluminum use a consumable anode with lifetime in hours cf. months for our technology.

• What alloys can be produced by this method? Potentially many others depending on properties.

• Where is this project headed next? Production of 650 lbs WE43 alloy, testing in automotive parts, feasibility study for master alloy production plant.
Collaboration & Coordination w/Other Institutions

- **Kingston Process Metallurgy**: contract R&D including transparent crucible electrolysis, salt recycling
- **Boston University**: contract R&D including current collector, salt-metal interactions, current efficiency improvements
- **Praxair**: process gases, argon recycling R&D, thermal modeling
- **Exothermics**: zirconia production/analysis, current collector R&D
- **Spartan Light Metals**: product testing by die-casting tensile specimens and other parts
- **Vehma**: product testing including die-casting vehicle components and testing those components in vehicle structures
- **MagPro**: large batch alloy melting/blending, other processing
Proposed Future Work

Complete Phase III Tasks

- Conduct electrolysis in reconfigured beta system
- Produce 500 lbs primary Mg from MgO
- Produce 650 lbs WE43 alloy for casting
- Make & test magnesium automotive parts
- Model full lifecycle costs, energy use, & emissions
Summary

- Shift to magnesium-neodymium master alloy
- Extended cell operation time
- New larger higher-current anodes
- Focus on longer term Anode operation

- Larger-scale operation and production in plans for 2014-2015


