Scale-Up of Magnesium Production by INFINIUM 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: 6/30/2016
Percent complete: 95%

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

Funding Received in FY15
- $884,575 DoE
- $884,575 INFINIUM

Funding for FY16
- $251,918 DoE
- $251,918 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 for manufacturing lightweight components that meet VTO targets for significant weight reduction in vehicles

• 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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Approach

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

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## 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>
</tr>
<tr>
<td>1 Nov 2012</td>
<td>Calculate economically viable costs, energy use, &amp; emissions</td>
<td>Complete</td>
</tr>
<tr>
<td>1 Nov 2012</td>
<td>Achieve sufficient purity to meet Mg alloy specifications</td>
<td>Complete</td>
</tr>
<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>Complete</td>
</tr>
<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>Complete</td>
</tr>
<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 6/2016</td>
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<tr>
<td>3 Nov 2014</td>
<td>Prepare for plant scale anode manufacturing</td>
<td>Extended to 6/2016</td>
</tr>
<tr>
<td>3 Nov 2014</td>
<td>Produce and test magnesium automotive parts</td>
<td>Extended to 6/2016</td>
</tr>
<tr>
<td>3 Nov 2014</td>
<td>Model full life cycle costs, energy use, and emissions</td>
<td>Extended to 6/2016</td>
</tr>
</tbody>
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New Approach

- Shift in project approach: primary production of Mg-Nd master alloy directly from MgO and Nd₂O₃
  - Necessary for AE42, AE44, WE43, ZEK100, other alloys
  - Much faster dissolution in Mg than pure rare earth metals
  - 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 AE42 alloy die casting trial (550 lbs total alloy)
- Technical advantage: simpler cell
  - Make liquid 50-50 Mg-Nd master alloy at cathode
  - Focus on electrolysis cell development: bath, electrodes, etc.
  - No need for simultaneous coupled condenser development
New Approach

Current Path

Mg-Nd Master Alloy → AE42 Castable Magnesium → [Component Image]

Possible Future Path

ZEK100 Mg Sheet → [Component Image]
Master Alloy Production Flow Sheet: Today

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

Dioxins, furans

MgO → MgCl₂ → Electrolysis → Mg → Mg-Nd Master Alloy

Nd₂O₃ → Electrolysis → Nd → Mg-Nd Master Alloy

INFINIUM:

MgO → Electrolysis → Mg-Nd Master Alloy

Nd₂O₃ → Electrolysis → Mg-Nd Master Alloy

No PFCs, HF, chlorine, etc.

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Technical Accomplishments & Progress

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

“Delta” Master Alloy Electrolysis Cell
- Version 1.0: one anode-cathode pair, complex liquid metal product partition
- Version 1.1: simplified partition, two large anodes
- More recently: more robust partition, two compact anodes, automated continuous oxide feeder

80 g/hour max rate, runs up to 8 hours unattended
1300+ hours production furnace uptime (and counting)

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Technical Accomplishments & Progress

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

Furnace operator with master alloy product

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Technical Accomplishments & Progress

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

Performance history:
- Delta V1.0: low production, 60-65% CE, anode area up 50% → production rate up 30%
- Delta V1.1: Current efficiency above 90%, 10x production rate increase
- Target Gamma production rate 150 g/hour
  Rapid increase in performance over just 3 months

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“Gamma” Master Alloy Electrolysis Cell

- Repurposed former Nd production cell for MgNd master alloy production scale-up
- Larger anode area, larger cathode
- Production start May 2016

Focus on production, introduce new features only when they are robust on Delta

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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Oxide-to-Metal Life Cycle Metrics

Energy comparison:
- Mg chloride electrolysis: 35 kWh/kg (Das 2011)
- Nd$_2$O$_3$ electrolysis: 8V 80% CE → 5.6 kWh/kg
- 50/50 master alloy today: ~20 kWh/kg (plus alloying furnace hot time)
- INFINIUM direct master alloy: today’s voltage and CE in a self-heated cell → 5.7 kWh/kg (likely 6-7 kWh/kg when scaled up)

Emissions comparison:
- Mg chloride electrolysis: 2.0 kg CO$_2$e/kg Mg (Das 2011)
- Nd$_2$O$_3$ electrolysis: 5.6 kg CO$_2$ + 15-27g CF$_4$ → 103-181 kg CO$_2$e/kg Nd
- 50/50 master alloy today: 52-92 kg CO$_2$e/kg
- INFINIUM direct master alloy: 5.3-6.0 kg CO$_2$e/kg

### Oxide-to-Metal Summary

<table>
<thead>
<tr>
<th></th>
<th>Energy, kWh/kg</th>
<th>Emissions, CO$_2$e/metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pure Mg today</td>
<td>35</td>
<td>2</td>
</tr>
<tr>
<td>Pure Nd today</td>
<td>5.6</td>
<td>5.6</td>
</tr>
<tr>
<td>50-50 Mg-Nd today</td>
<td>20</td>
<td>52-92</td>
</tr>
<tr>
<td>INFINIUM 50-50 Mg-Nd</td>
<td>6-7</td>
<td>5.3-6.0</td>
</tr>
</tbody>
</table>

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

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Magnesium AE42 made with INFINIUM Primary Hardener

AE42
>250lbs

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Response to 2015 Reviewers’ Comments

• How will rare earth element costs be contained?
Rare earth oxide prices are very low today; multiple non-Chinese mines are producing light rare earth oxides including Nd₂O₃, reducing risks

• What other Mg-RE systems can be produced? Mg-Y?
We do not know of any technical barriers to direct reduction of Mg-Y and other Mg-RE master alloys, we will choose master alloy(s) for scale-up according to market forces

• The work plan has been altered significantly from pure Mg to high-price master alloys; is this process viable for large-scale Mg production?
We will produce as much as we profitably can, and will learn about process scaling economics as we produce more master alloy to determine whether it is suitable for pure Mg down the road

• Is the Mg material produced in this project hot-stampable? Are other elevated temperature applications of as-produced alloys planned?
Master alloy itself is not intended for use as-is, but we have heard that Mg-RE alloys produced using this type of master alloy can make warm-formable sheet, and that high-temperature properties are very good

• What approach to optimizing process parameters will be taken?
We will use a comprehensive validated techno-economic model to optimize scale-up design

• Has the team thought about using thermoelectrics to capture spent energy?
We have not investigated this method of reducing energy use, it’s hard to see it being useful with no frozen side-wall (cf. Hall-Héroult Al production)

• How will the project produce large enough quantities of material to address needs in the automotive industry?
As the market develops, we will plan production of more material, including designing and building larger-scale production furnaces

• How will the new alloys that result from this project overcome fundamental limits of this hexagonal close-packed material?
Mg-RE alloys are generally more isotropic than alloys without rare earths; this project’s goal is a low-energy low-emissions domestic technology for Mg-RE master alloy, removing this barrier to high-performance Mg alloys in vehicles

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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
Remaining Challenges and Barriers

Complete Phase III Tasks

• Complete 500 lbs primary Mg production from MgO
• Produce and test parts using INFINIUM Mg-Nd master alloy
• Complete model of full lifecycle costs, energy use, & emissions
Summary

• Successfully executed project pivot to magnesium-neodymium master alloy
• Intermediate scale electrolysis cell performance is excellent
  ▪ Current efficiency above 90% exceeded expectations
• 500 lb production campaign is in progress
Technical Back-Up Slides