Scale-Up of Magnesium Production by INFINIUM Electrolysis

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INFINIUM, Inc.
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Project ID: LM035

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

Relevance

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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

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

Approach

Phase, Due	Project MILESTONES	Status
1 Nov 2012	Conduct electrolysis in alpha	Complete
1 Nov 2012	Demonstrate stable, O_2-producing anode assembly	Complete
1 Nov 2012	Calculate economically viable costs, energy use, & emissions	Complete
1 Nov 2012	Achieve sufficient purity to meet Mg alloy specifications	Complete
1 Nov 2012	Identify potential plant site(s)	Complete
2 Nov 2013	Conduct electrolysis in beta	Complete
2 Nov 2013	Produce sufficient anode assemblies for prototypes	Complete
2 Nov 2013	Provide sufficient Mg for tensile testing	Complete
2 Nov 2013	Model plant site	Complete
3 Nov 2014	Achieve industry uptime standard for prototypes	Extended to 6/2016
3 Nov 2014	Prepare for plant scale anode manufacturing	Extended to 6/2016
3 Nov 2014	Produce and test magnesium automotive parts	Extended to 6/2016
3 Nov 2014	Model full life cycle costs, energy use, and emissions	Extended to 6/2016

New Approach

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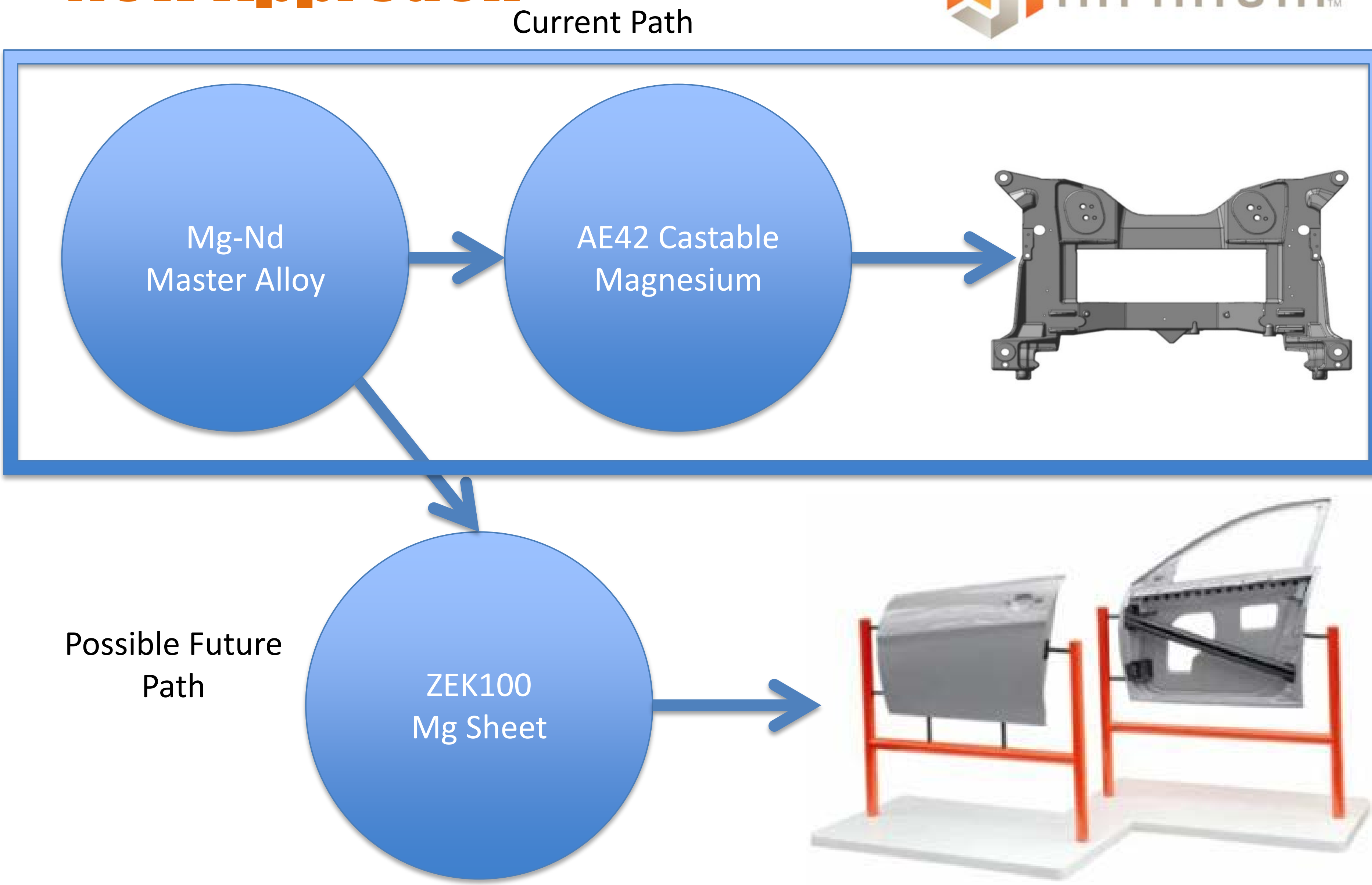
- Shift in project approach: primary production of Mg-Nd master alloy directly from MgO and Nd_2O_3
  - Necessary for AE42, AE44, WE43, ZEK100, other alloys
  - Much faster dissolution in Mg than pure rare earth metals
  - Can't be reliably sourced in US today
  - Direct electrolytic primary production 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

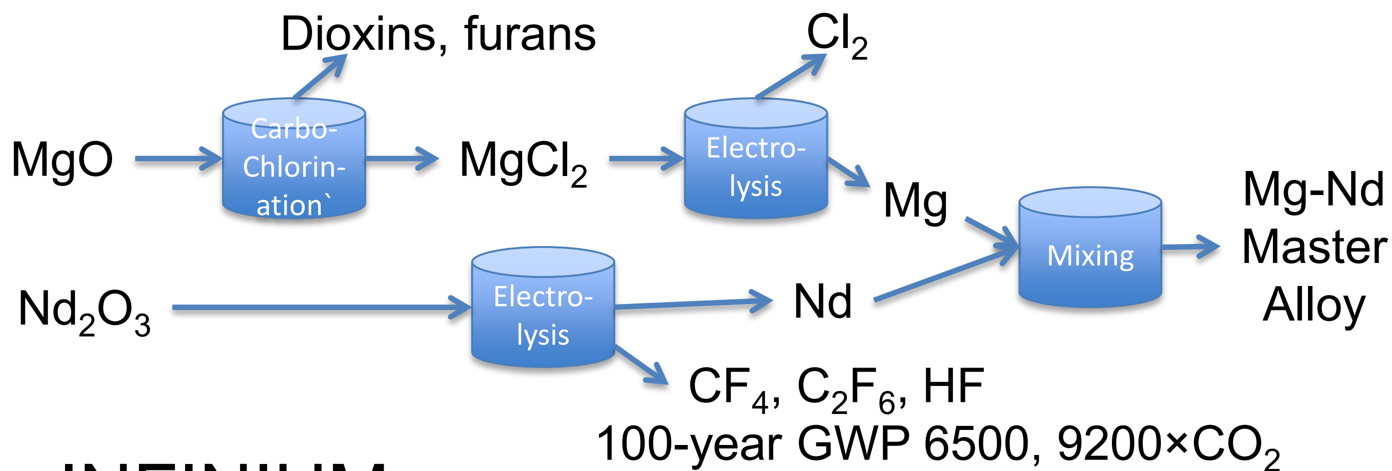
New Approach



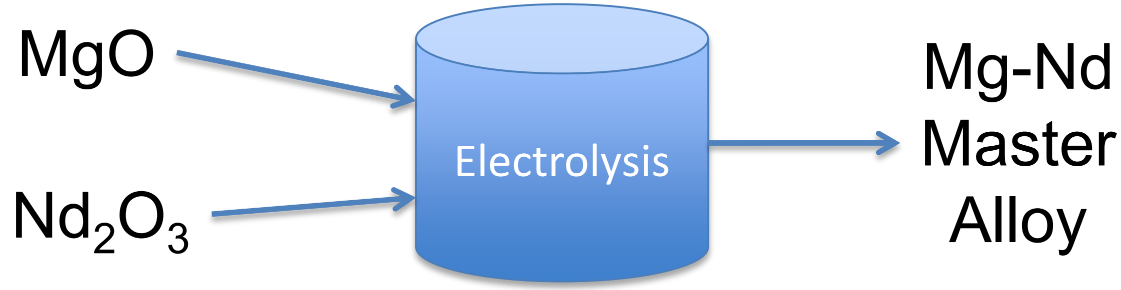
Technical Accomplishments & Progress

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

Master Alloy Production Flow Sheet: Today



INFINIUM:



No PFCs, HF, chlorine, etc.

Technical Accomplishments & Progress

Phase 3

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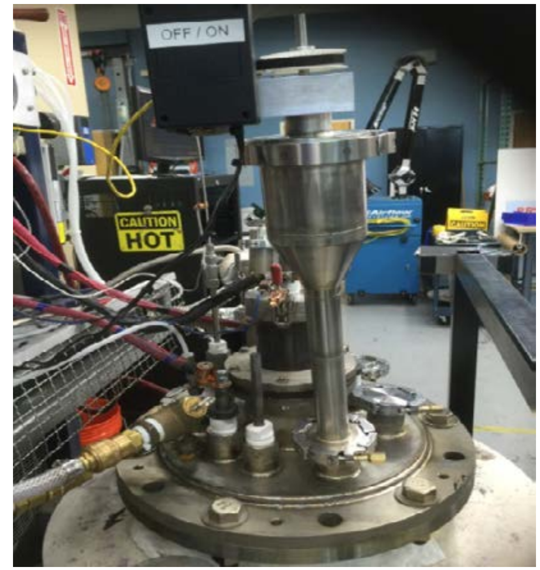

“Delta” Master Alloy Electrolysis Cell

- 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)

Technical Accomplishments & Progress

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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

Technical Accomplishments & Progress

Phase 3
- Achieve industry standard uptime for prototypes
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- **Produce and test magnesium automotive parts**
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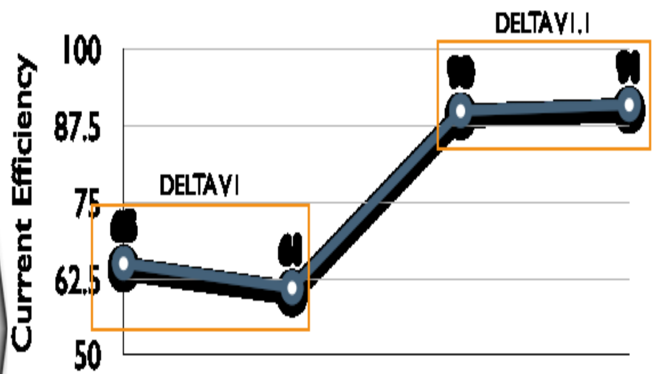
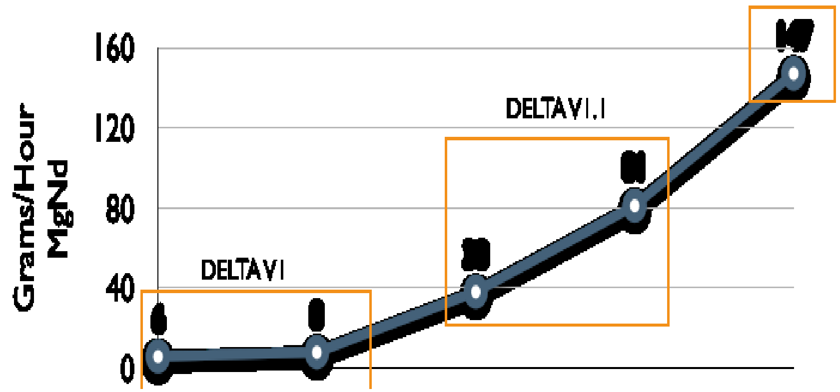
Current Efficiency



Production Rate



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

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

"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

Technical Accomplishments & Progress

INFINIUM™

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**

Oxide-to-Metal Life Cycle Metrics

Energy comparison:
- Mg chloride electrolysis: 35 kWh/kg (Das 2011)
- Nd_2O_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_2e/kg Mg (Das 2011)
- Nd_2O_3 electrolysis: 5.6 kg CO_2 + 15-27g CF_4 → 103-181 kg CO_2e/kg Nd
- 50/50 master alloy today: **52-92 kg CO_2e/kg**
- INFINIUM direct master alloy: **5.3-6.0 kg CO_2e/kg**

Oxide-to-Metal Summary	Energy, kWh/kg	Emissions, CO_2e/metal
Pure Mg today	35	2
Pure Nd today	5.6	5.6
50-50 Mg-Nd today	**20**	**52-92**
INFINIUM 50-50 Mg-Nd	**6-7**	**5.3-6.0**

Magnesium AE42 made with INFINIUM Primary Hardener

AE42
>250lbs

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 Nd_2O_3, 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

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

Publications/ Presentations/Patents

- Guan, X. et al. "Periodic Shorting of SOM Cell to Remove Soluble Magnesium in Molten Flux and Improve Faradaic Efficiency," Metall. Mater. Trans. 45B(6):2138-2144 2014.
- Pal, U., "Green Technology for Metals Production," Presented at TMS Annual Meeting (EPD Distinguished Lecture), March 16, 2015.
- Guan, X. et al., "A Method for Improving Faraday Efficiency of Magnesium Production Employing Solid Oxide Membrane (SOM) Based Electrodes," Presented at TMS Annual Meeting, March 16, 2015.
- Powell, A. et al., "Apparatus and method for condensing metal vapor," China Patent ZL201280043046.0 issued January 6, 2016.
- Powell, A. et al., "Conductor of High Electrical Current at High Temperature in Oxygen and Liquid Metal Environment," U.S. Patent 9,234,288 issued January 12, 2016.