Scale-Up of Magnesium Production by Fully Stabilized Zirconia 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: 11/30/2014
Percent complete: 33%

BUDGET

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

Budget Period 1
- $2,000,000 DoE
- $2,027,924 INFINIUM

Budget Period 2
- $2M DoE
- $2M INFINIUM

BARRIERS

Clean & cost-effective magnesium production

PARTNERS

Praxair, Inc.

Kingston Process Metallurgy

Boston University

Exothermics, Inc.

Spartan Light Metal

Cosma International
Automotive Partnerships Canada

Relevance

OBJECTIVES

- Scale up INFINIUM's primary magnesium production from laboratory demonstration to pre-production pilot plant.
- Budget Period 1
  - Design, build, & test an alpha prototype electrolysis system
  - Optimize zirconia tube composition & structure
  - Calculate costs, energy use, & emissions
  - Produce & test magnesium
  - Identify potential plant sites

Relevance

DOE VTP GOALS

MagGen™ → Domestic, Clean, Cost-Effective Magnesium → Lightweight Vehicles → Increased Fuel Efficiency

Increased Fuel Efficiency → Reduced Emissions

Increased Fuel Efficiency → Reduced Dependence on Foreign Oil → Increased Energy Security

Approach

Phase 1: Alpha Prototype

- Design, build, & test alpha prototype
- Optimize anode design
- Calculate costs, energy use, & emissions
- Produce & test magnesium
- Identify potential plant sites

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
- Select plant site

Phase 3: Prototype Operation & Plant Design

- Develop automated processes for alpha & beta prototypes
- Prepare for plant-scale anode manufacturing
- Produce & test magnesium automotive parts
- Model full lifecycle costs, energy use, & emissions
- Acquire plant site

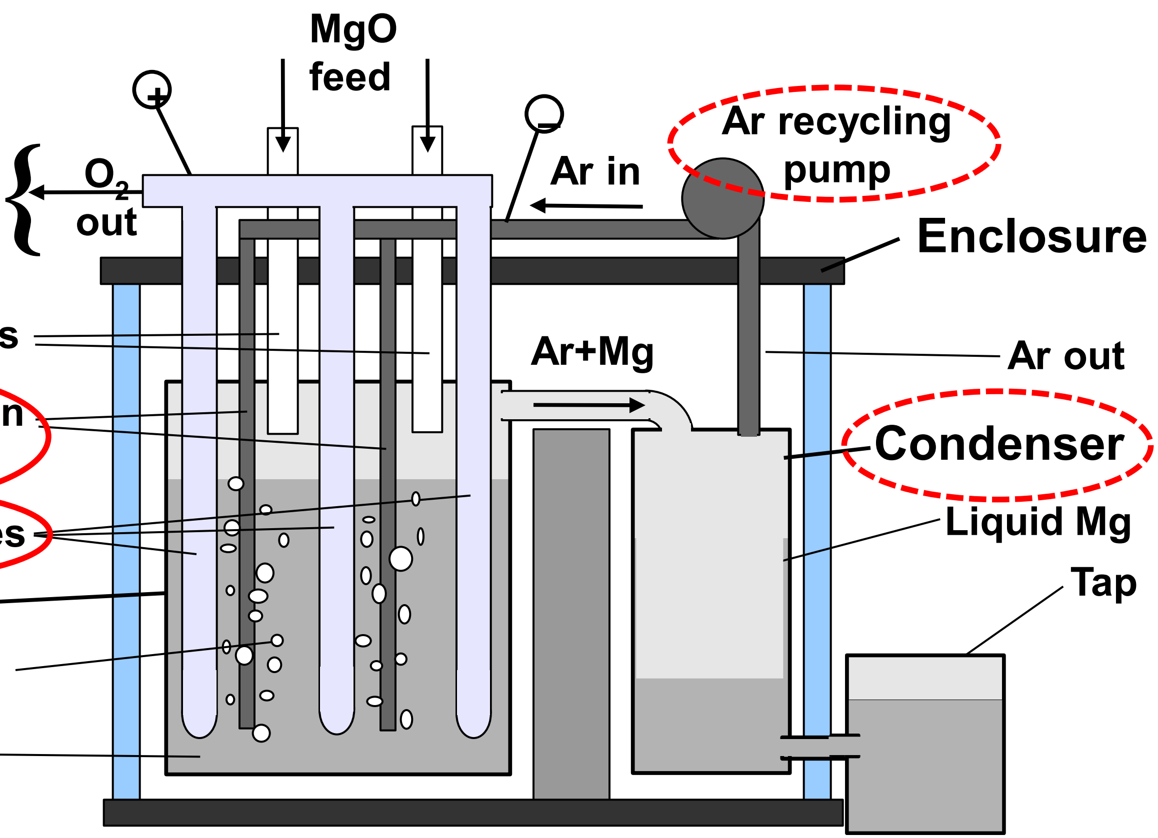
Approach

Due	PHASE 1 MILESTONES	Status
Nov 2012	Conduct electrolysis in alpha	Complete
Nov 2012	Demonstrate stable, O_2-producing anode assembly	Complete
Nov 2012	Calculate economically viable costs, energy use, & emissions	Complete
Nov 2012	Achieve sufficient purity to meet Mg alloy specifications	Complete
Nov 2012	Identify potential plant sites	Complete

Technical Accomplishments & Progress

Phase 1: Alpha

- **Design, build, & test alpha prototype**
- Optimize anode design
- Calculate costs, energy use, emissions
- Produce & test Mg
- Identify potential plant sites



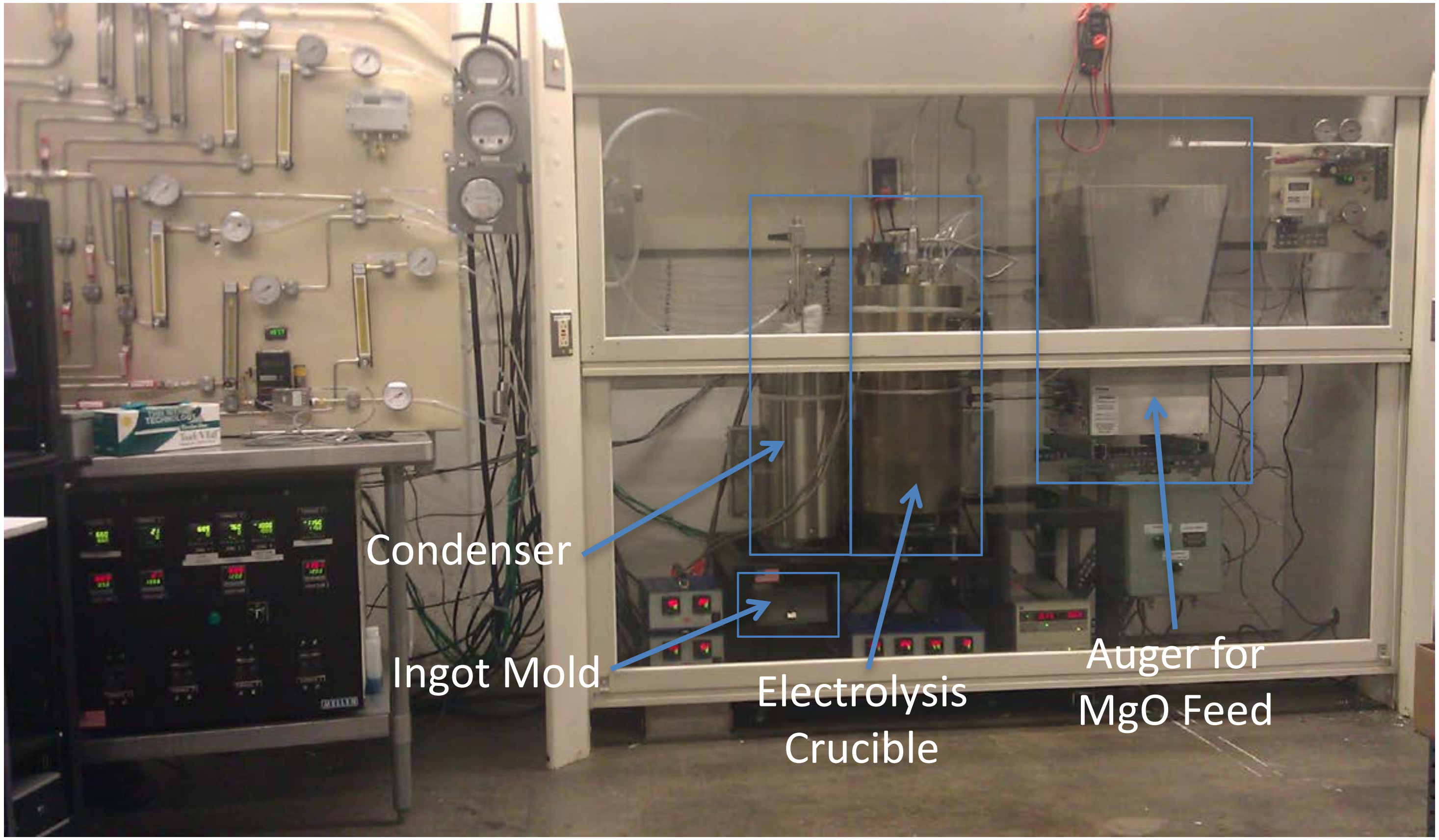
MagGen™ Schematic

Technical Accomplishments & Progress

INFINIUM™

Phase 1: Alpha

- **Design, build, & test alpha prototype**
- Optimize anode design
- Calculate costs, energy use, emissions
- Produce & test Mg
- Identify potential plant sites



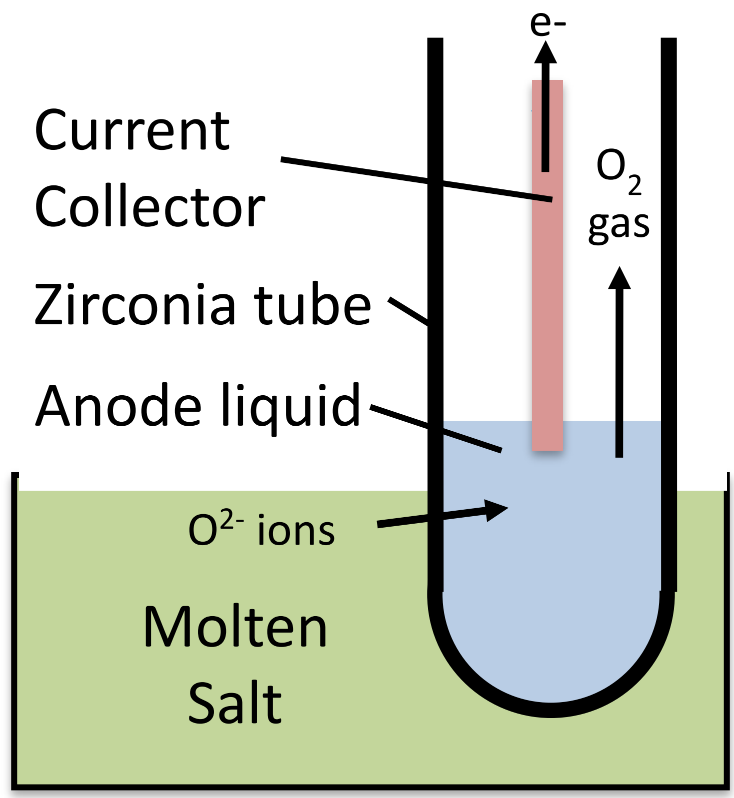
Alpha Prototype

Technical Accomplishments & Progress

Phase 1: Alpha

- Design, build, & test alpha prototype
- **Optimize anode design**
- Calculate costs, energy use, emissions
- Produce & test Mg
- Identify potential plant sites

- Liquid silver anode
  - Simple, robust O_2 generation
- Current collector
  - Metal sealed in sheath
  - LSM, ITO, ZnO:Al, etc. connection
- Zirconia tube
  - Key differentiator



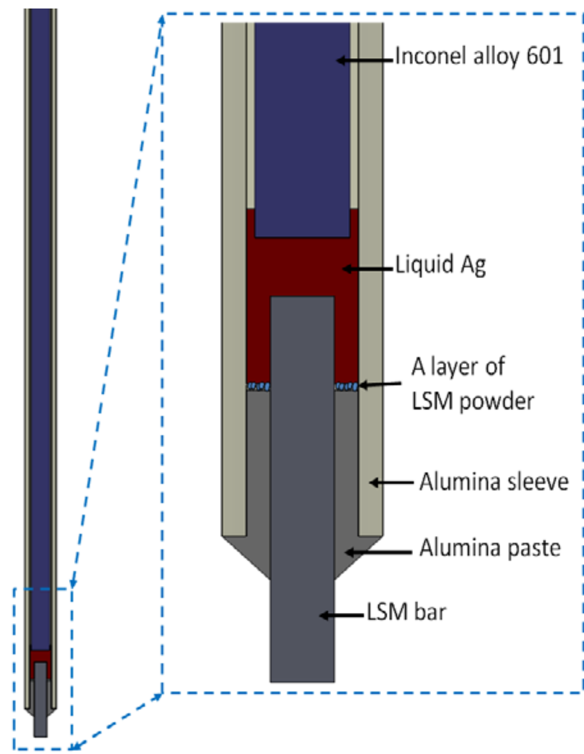
Anode Assembly

Technical Accomplishments & Progress

Phase 1: Alpha

- Design, build, & test alpha prototype
- **Optimize anode design**
- Calculate costs, energy use, emissions
- Produce & test Mg
- Identify potential plant sites

- Design
  - Metal core sealed in alumina sheath
  - LSM, ITO, ZnO:Al, etc. connection
- Performance
  - 0.1 Ω resistance
  - Stable over 30 hours runtime



Developed in collaboration with Boston University

Current Collector

Technical Accomplishments & Progress

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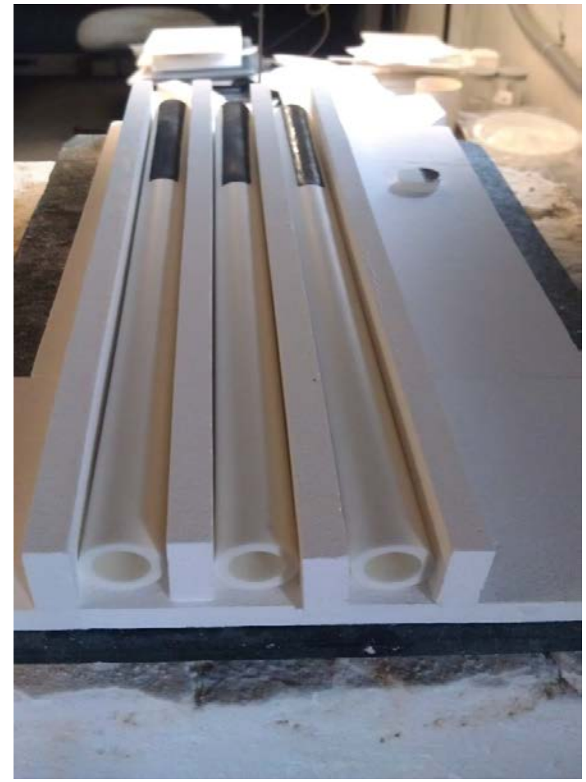
Phase 1: Alpha

- Design, build, & test alpha prototype
- **Optimize anode design**
- Calculate costs, energy use, emissions
- Produce & test Mg
- Initiate plant design

- Best COTS tubes
  - 6YSZ
  - 96-97% dense
- Custom Tosoh tubes
  - 8YSZ, 10YSZ
  - **99.5%** dense
- INFINIUM powders
  - YSZ, CSZ, MSZ



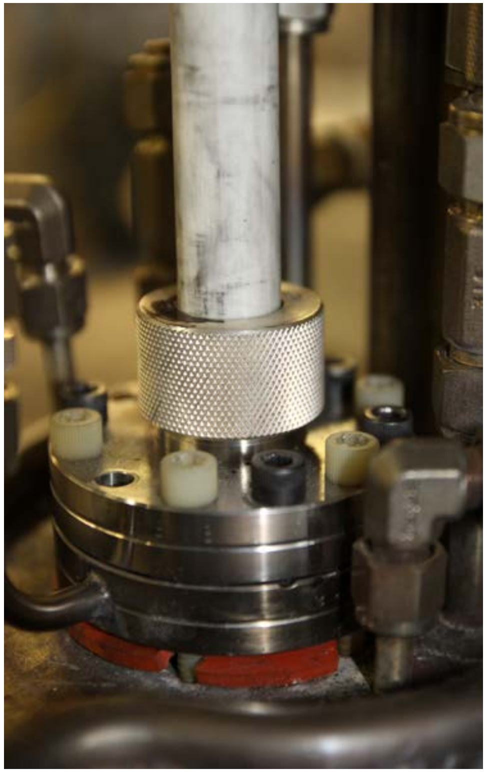
Custom Tube Production

Technical Accomplishments & Progress

INFINIUM™

Phase 1: Alpha
- Design, build, & test alpha prototype
- **Optimize anode design**
- Calculate costs, energy use, emissions
- Produce & test Mg
- Initiate plant design

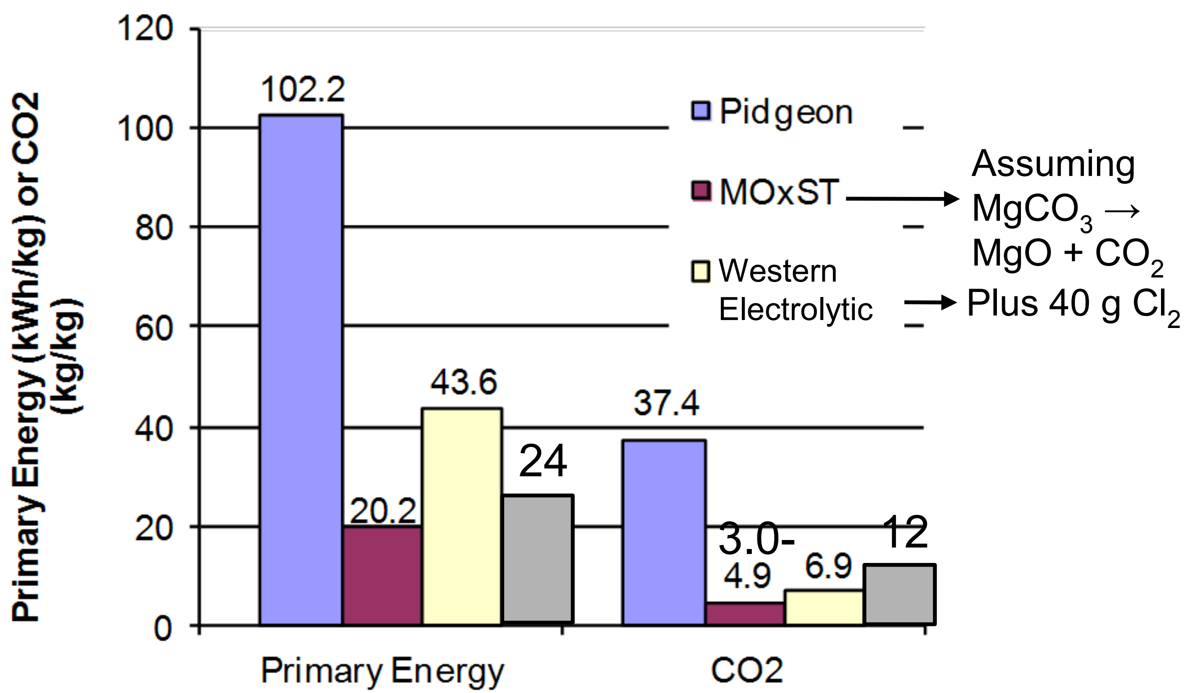
- Integrates argon bubble curtain
- Low cathode current density
- Oxide ion mass transfer to anode
- Makes an easy hot swappable component



INTEGRATED ANODE-CATHODE

Technical Accomplishments & Progress

Phase 1: Alpha
- Design, build, & test alpha prototype
- Optimize anode design
- **Calculate costs, energy use, emissions**
- Produce & test Mg
- Initiate plant design



Compare: Aluminum 24 kWh/kg, 12 kg CO_2e/kg Al

Source: Sujit Das (ORNL): [DOE Lightweight Materials Annual Merit Review 2011]

Industrial Energy Use & GHG Emissions

Technical Accomplishments & Progress

INFINIUM™

Phase 1: Alpha

- Design, build, & test alpha prototype
- Optimize anode design
- Calculate costs, energy use, emissions
- **Produce & test Mg**
- Identify potential plant sites

Element	Percent	Element	Percent
Mg	99.95	V	0.0005
Fe	0.033	W	0.0005
Cu	0.007	Ce	0.0005
Mn	0.0041	Th	0.0005
Na	0.0022	B	0.0005
Al	0.0016	Pb	0.0003
K	0.0014	Ni	0.0003
Si	0.001	Cd	0.0001
Sn	0.0005	Co	0.0001
Mo	0.0005	Cr	0.0001
N	0.0005	Ca	0.0001
P	0.0005	Zn	0.0001
Ti	0.0005		

Mg Composition

- 99.95% Pure Magnesium from INFINIUM MagGen™

Collaboration & Coordination w/ Other Institutions

INFINIUM™

BUDGET PERIOD 1 & 2

- Kingston Process Metallurgy
  - Transparent crucible electrolysis
  - Salt recycling
- Boston University
  - Current collector
  - Salt-metal interactions
  - Current efficiency improvements
- Praxair
  - Process gases
  - Argon recycling
- Exothermics
  - Materials expertise & testing

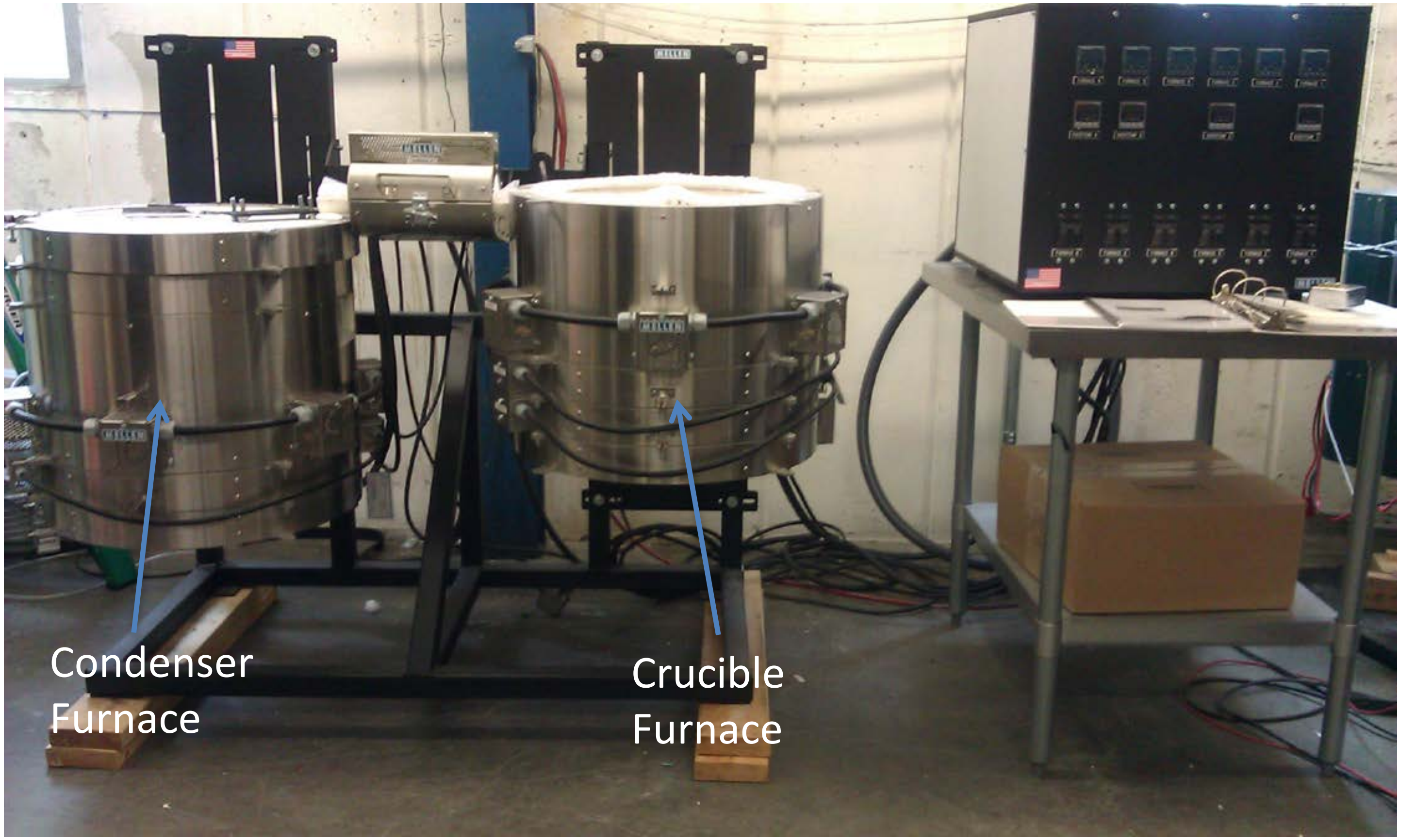
BUDGET PERIOD 2 & 3

- Spartan Light Metals
  - Mg product testing
- Vehma
  - Mg vehicle component testing

Proposed Future Work

Due	PHASE 2 & 3 MILESTONES	Status
Nov 2013	Conduct electrolysis in beta	On Schedule
Nov 2013	Produce sufficient anode assemblies for prototypes	On Schedule
Nov 2013	Provide sufficient Mg for tensile testing	On Schedule
Nov 2013	Select plant site	On Schedule
Nov 2014	Achieve industry uptime standard for prototypes	On Schedule
Nov 2014	Demonstrate scalable anode assembly manufacturing	On Schedule
Nov 2014	Demonstrate satisfactory Mg performance in automotive parts	On Schedule
Nov 2014	Acquire plant site	On Schedule

Proposed Future Work



Beta Prototype

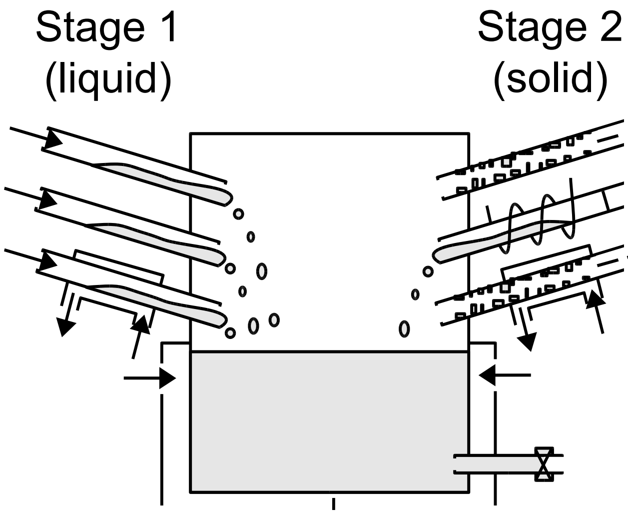
Summary

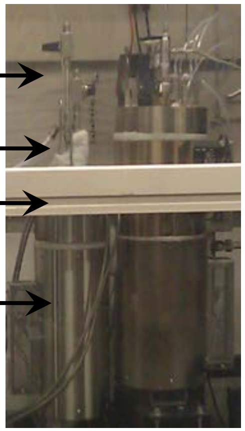
- Alpha furnace online & producing Mg
- In-house zirconia tubes optimize structure, composition, & cost
- Lowest energy use & GHG emissions
- Mg meets alloying purity standards
- Plant sites near Niagara Falls
  - Low cost electricity
  - Ship & rail lines access

Technical Back-Up Slides

Two-Stage Condenser

- Condense liquid first, then solid
- Drive solid into liquid to melt it
  - Melt it
  - Mechanically drive it
  - Cool it
- Submerged bubbler variation





Mg Condenser Constraint

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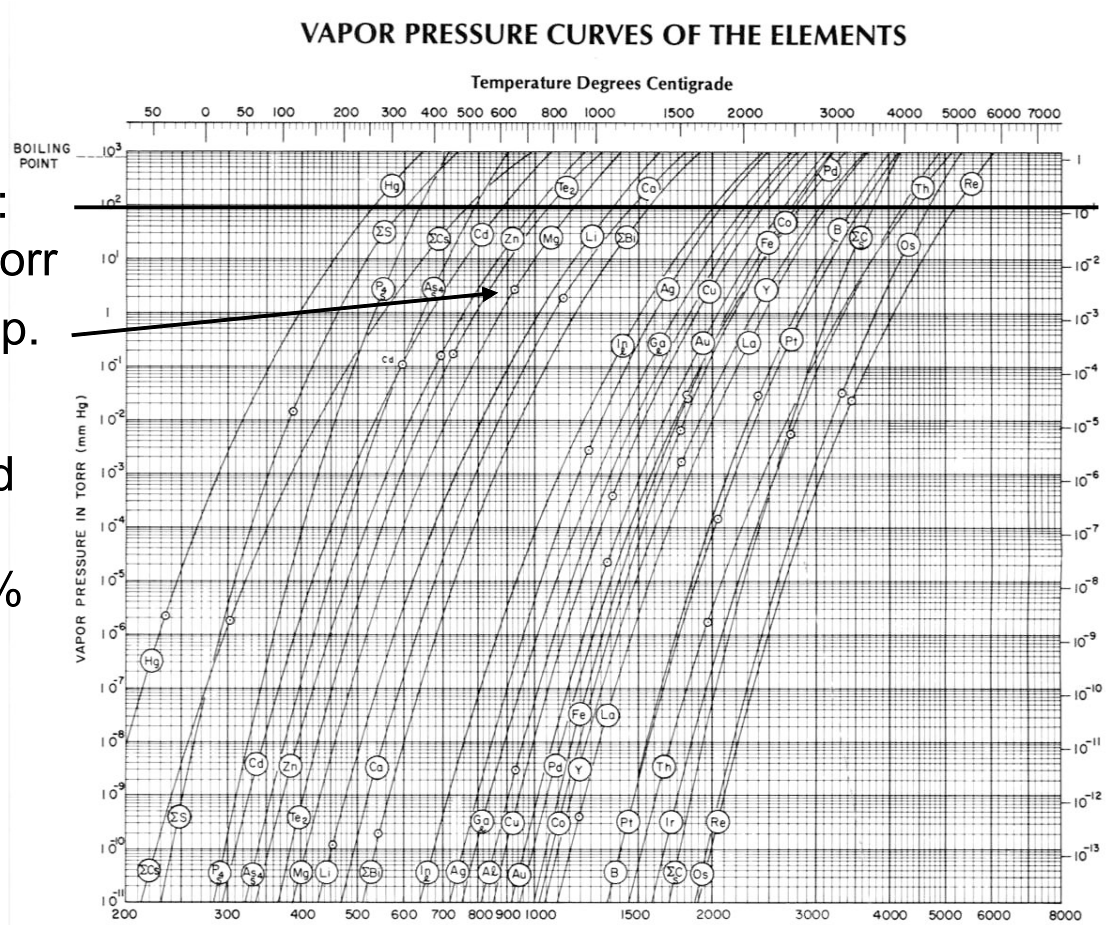
Zirconia Compatibility: $P_{v,max}$ = 100 torr

Mg: p_v at m.p. is 3 torr!

Perfect liquid condenser captures 97%



Argon Recycling

- Important to reduce cost of Argon
  - Test results show very pure Argon for recycling
- Simple pump e.g. regenerative blower
- Highly-reactive magnesium in condenser removes nearly everything: O, N, Cl, F
  - Very few gases build up: H_2, S_2, maybe entrained Mg
- Chemical trap e.g. steelmaking slag particle bed

$$Fe_2O_3 + CaO + H_2 \rightarrow 2FeO + Ca(OH)_2$$

$$3Fe_2O_3 + CaO + \frac{1}{2}S_2 \rightarrow 6FeO + CaSO_4$$

$$Fe_2O_3 + Mg \rightarrow 2FeO + MgO$$