Advanced Thermo/Electrochemical Metals Extraction (A-TEME)

An ARPA-E Thematic Workshop

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Marriot Crystal Gateway
Arlington, VA
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ARPA-E Mission

Enhance the economic and energy security of the U.S.

Ensure U.S. technological lead in developing and deploying advanced energy technologies
Why Are We Here Today?

**A-TEME Mission:**
Enable the development of transformative light metal (Al, Mg, Ti) processing technologies that significantly reduce the energy requirement to extract primary metal from ore, reduce emissions associated with primary light metal extraction, and increase the supply of high grade recycled light metal.

**Expected Program Outcomes:**

1. Energy savings on metals manufacturing of 0.6 Quad/yr
2. Life-cycle energy savings from vehicle light-weighting of a 2 Quad/yr
3. Emissions reduction of 250 Million Tons of CO2/yr
4. Reduced cost light metals to enable advanced energy technologies
5. Renaissance of U.S. light metal manufacturing
ENERGY AND EMISSIONS IMPACT FROM LIGHT METAL EXTRACTION
# Global Metal Production and Associated Energy Consumption

<table>
<thead>
<tr>
<th>Metal</th>
<th>Annual World Production</th>
<th>Total Energy Consumed</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Millions of tons</td>
<td>Quadrillion BTU</td>
</tr>
<tr>
<td>Fe</td>
<td>943&lt;sup&gt;1&lt;/sup&gt;</td>
<td>11.6</td>
</tr>
<tr>
<td>Al</td>
<td>44.0&lt;sup&gt;3&lt;/sup&gt;</td>
<td>8.2</td>
</tr>
<tr>
<td>Cu</td>
<td>16&lt;sup&gt;4&lt;/sup&gt;</td>
<td>0.7</td>
</tr>
<tr>
<td>Mg</td>
<td>0.77&lt;sup&gt;2&lt;/sup&gt;</td>
<td>0.2</td>
</tr>
<tr>
<td>Ti</td>
<td>0.15&lt;sup&gt;5&lt;/sup&gt;</td>
<td>0.09</td>
</tr>
</tbody>
</table>

 TOTAL = 21 quads

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1) Bureau of International Recycling, Ferrous Division – 2011 data (crude – recycled)
2) Index Mundi – Magnesium 2011 data
3) World Aluminum – 2011 data
4) Oracle Mining Group, Copper – 2011 data
Energy Consumption and Emissions Associated with Metal Extraction

Opportunities for arpa-e disruptive technology development

<table>
<thead>
<tr>
<th>Metal</th>
<th>Theoretical Minimum (ΔG)</th>
<th>Current Process</th>
<th>Global warming potential</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe</td>
<td>6</td>
<td>23</td>
<td>5</td>
</tr>
<tr>
<td>Cu</td>
<td>33</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Zn</td>
<td>36</td>
<td>27</td>
<td>21</td>
</tr>
<tr>
<td>Al</td>
<td>211</td>
<td>211</td>
<td>211</td>
</tr>
<tr>
<td>Mg</td>
<td>366</td>
<td>361</td>
<td>361</td>
</tr>
<tr>
<td>Ti</td>
<td>17</td>
<td>17</td>
<td>17</td>
</tr>
</tbody>
</table>

Energy [MJ/kg]

Global warming potential [kg CO2e/kg]
US Primary Aluminum Production in Million Tons/Year

- Declining production and market share

US only 4.7% of market in 2011
US Primary Magnesium and Titanium Sponge Production

US vs Global Magnesium Production in Thousand Tons/Year

US Magnesium

Global Magnesium

RISK

US only 5.6% of market in 2011

US vs Global Titanium Production in Thousand Tons/Year

US Titanium/sponge*

Global Titanium

RISK

US only 8.7% of market in 2011
Summary of Energy and Emissions Impact from Light Metal Extraction

● Global market for metal extraction results in 21 Quad/yr energy consumption

● U.S. market share for primary light metal (Al, Mg, Ti) production is alarmingly low

● Light metal production has high specific energy consumption (MJ/kg)

● U.S. light metal manufacturers can gain technological edge through reduced energy requirement for production

● If U.S. manufacturers could capture 15% of light metal market at current demand, the result is an energy impact of 1.3 Quad/yr and emissions impact of 151 Million Tons CO2
Example Impact: ENERGY IMPACT FROM VEHICLE LIGHTWEIGHTING
The 2016 and 2025 CAFE standards set aggressive targets for vehicle fuel consumption.

![Graph showing historical fuel economy values, 2016 CAFE fuel standard, and 2025 CAFE fuel standard. The graph indicates a significant increase in fuel economy targets from historical values (28.8 MPG in 2005) to 54.6 MPG by 2025.](image-url)
Scenarios for Meeting the 2025 CAFE Standards – ALL Involve Significant Weight Reduction (MIT Study)

Scenarios for meeting CAFE (55mpg) in 2025

<table>
<thead>
<tr>
<th>Material</th>
<th>Strength to weight ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>0.04 – 0.06</td>
</tr>
<tr>
<td>Al</td>
<td>0.11</td>
</tr>
<tr>
<td>Mg</td>
<td>0.13</td>
</tr>
<tr>
<td>Ti</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Light metals have higher strength to weight ratio

Adapted from “Factor of Two: Halving the Fuel Consumption of New U.S. Automobiles by 2035”
MIT Publication No. LFEE 2007-04 RP
Iron and steel usage on the decline

Material composition of the average automobile in the US

Average material composition %

100% 90% 80% 70% 60% 50% 40% 30% 20% 10% 0%


- Other
- Plastics
- Light metal
- Iron & Steel
Potential Fuel Energy Savings from Automobile Lightweighting

Embedded energy in metal due to extraction not included in analysis below

<table>
<thead>
<tr>
<th>Material</th>
<th>Mass savings (% of vehicle)</th>
<th>Annual fuel savings (L/vehicle/yr)</th>
<th>Total energy savings (Q/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>33%</td>
<td>328</td>
<td>2.58</td>
</tr>
<tr>
<td>Mg</td>
<td>41%</td>
<td>407</td>
<td>3.21</td>
</tr>
<tr>
<td>Ti</td>
<td>19%</td>
<td>188</td>
<td>1.48</td>
</tr>
</tbody>
</table>

Assumptions:
• 0.0036L/km fuel reduction per 100 kg reduced vehicle mass
• 20,000km traveled/car/yr (~12,500 mi)
• 239 million cars on the road (US 2012)
• 35MJ/L energy content of gasoline
• All steel replaced by light metal (equal bending stiffness/strength basis)
Potential Fuel Energy Savings from Automobile Lightweighting

- In order to gain an efficiency benefit by lightweighting, embedded energy content in light metals must be reduced.

<table>
<thead>
<tr>
<th>Material</th>
<th>Total Lightweighting energy savings (Q/yr)</th>
<th>Embedded energy (Q/yr)</th>
<th>Net energy saved (Q/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Al</td>
<td>2.58</td>
<td>2.1</td>
<td>0.48</td>
</tr>
<tr>
<td>Mg</td>
<td>3.21</td>
<td>2.7</td>
<td>0.51</td>
</tr>
<tr>
<td>Ti</td>
<td>1.48</td>
<td>5.1</td>
<td>-3.62</td>
</tr>
</tbody>
</table>

Assumptions:
- 10 yr lifetime of vehicle
- Entire fleet of vehicles replaced with light metal
Potential Fuel Energy Savings from Automobile Lightweighting

Would take ~5 years and >50,000 miles to break even with steel based vehicles

Assumption: 12,500 mi/yr
Summary of Energy and Emissions Impact from Light Metal Extraction

● Potential energy savings from vehicle lightweighting is approximately 3 Quad/yr

● Corresponding emissions reduction is 200 million tons/yr

● Lightweighting energy savings can only be achieved by reducing the embedded energy in light metal extraction

● A trend toward vehicle lightweighting has already begun; an opportunity exists to address the metal embedded energy.
SOME ECONOMIC CONSIDERATIONS FOR LIGHT METALS MANUFACTURING
Impact of Reduced Energy on Aluminum Cost

Sample cost breakdown for primary Al production*

- Energy: 24%
- Alumina: 30%
- Anodes: 15%
- Chemicals: 10%
- Other: 13%
- Labor/admin: 8%

*Values vary depending on region, current energy prices, etc. (especially for energy and anodes)

Source: Metal Miner, Carbon Trust, ORNL
Points of Interest on Aluminum Smelting

- Aluminum smelting is only done where inexpensive electricity is available; <3 cents/kW-hr
- Aluminum smelters enjoy hydroelectric power
- Domestic smelters are not economically viable with rising electrical costs
Pacific Northwest Smelters Face Economic Crisis

If we load electric vehicles onto the grid, electricity cost rises and domestic aluminum smelting is not economically viable.

Electric vehicles are coming!

Affordable Electricity Price Limits of Al Smelters at $1500/ton Al price

Forecasting Electricity Demand of the Region’s Aluminum Plants, DSI, 2005
Aluminum Demand

Demand growth for both primary and scrap re-used Al for vehicle light weighting

Vehicle parts where Aluminum will continue to penetrate
Magnesium Demand

- Magnesium demand is on the rise; U.S. is losing market share

The U.S. Automotive Materials Partnership sees the potential of magnesium content per vehicle increasing by an order of magnitude from 5 kg today to 160 kg by 2020.

Only 1 Mg production plant left in US (Utah)
Boeing 787 and 777 lightweight aircraft require 80 and 50 metric tons of titanium per airplane, respectively (enabler of carbon fiber)

Boeing projects 34,000 new airplanes to be built between 2012-2031

2.2 million tons required to meet demand or 116 thousand tons/yr
Precedent for revival in U.S. Metals Manufacturing: STEEL

Technology transition to energy efficient ‘mini mills’ (EAF)

Inefficient OHF

Today - EAF produce 64% of crude steel
Small Modular Infrastructure: the business case for scaling down.

Eric Dahlgren, Klaus S. Lackner
School of Engineering and Applied Science, Columbia University
Caner Gocmen, Garrett van Ryzin
Graduate School of Business, Columbia University

- Small scale allows more rapid adoption of new technology to give a competitive edge
- Adoption of automated systems can neutralize economies of scale
- Small scale allows manufacturer to more easily tailor product to customer needs
Small Modular Infrastructure: *the business case for scaling down.*

**Arbitrage ~ manufacture @ off peak hours & sell power at peak hours**

**Geographic Advantage ~ cheap electricity resources**

Utility (ComEd) hourly prices, Northeastern Illinois during summer

**Industrial rates by states in cents/kWh during summer**

- 4.1 - 5.0
- 5.1 - 6.0
- 6.1 - 7.0
- 7.1 - 8.0
- >8.1
U.S. Light Metal Manufacturers Need a Technological Edge

Ideal transformative new technology will:

1) Significantly reduce energy requirements and emissions for primary light metals extraction

2) Enable continuous processing that is amenable to significant automation

3) Tolerate interruptions in power or energy source for sustained periods

4) Amenable to thermal recovery and power production
**ARPA-E Programs and Projects**

1. **Impact**
   - Aimed at ARPA-E mission areas
   - Shows a credible path to market
   - Has a large practical application

2. **Transform**
   - Challenges what is possible
   - Disrupts existing learning curves
   - Can leap beyond today’s technologies

3. **Bridge**
   - Translates science into breakthrough technology
   - The path lacks technical or financial resources
   - Catalyzes new interest and investment

4. **Team**
   - Comprised of best-in-class people
   - Brings skills from different disciplines
   - Focuses on translation of technologies to the market
ARPA-E not seeking incremental improvement; radically different innovations sought

Traditional R&D path: improvements in cost/energy intensive processes

**ARPA-E Example Path**: Entirely new processes to enable a large leap forward in performance
Workshop Breakout Sessions

Breakout Session I: Technology paths that enable program goals
1) Electrochemistry
2) Thermochemistry
3) Renewable Energy
4) Heat Recuperation and Power Generation
5) Recycling and Innovative Technologies

Breakout Session II: Setting program performance targets
1) Aluminum
3) Magnesium
2) Titanium
Benchmarking Performance Targets

ARPA-E Energy Targets

- Theoretical Minimum MJ/kg
- Breakeven substitution of steel for lightweighting MJ/kg
- ARPA-E target for primary production MJ/kg
Benchmarking Performance Targets

ARPA-E Cost Target

DARPA Titanium Initiative

Metal Production Cost $/kg

Past Cost Targets $/kg

ARPA-E cost target $/kg

Breakeven substitution of Steel for lightweighting $/kg
Thank You for Your Participation in Today’s Workshop!