Making Magnesium a More Cost & Environmentally Competitive Light-Weighting Option

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Douglas Reeson

Presented at 9th International Conference on Magnesium Alloys & Applications (July 8 - 12, 2012)
Light Materials… play increasingly important role in transportation

- **Tighter Fuel Standards**… USA: 6.5 liters /100 km by 2014 decreasing to 4.3 by 2025
- **Electric Vehicles**… need light weight for improved range & performance

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**Weight Savings**… key part of automotive strategy going forward

![Graph showing weight savings] Source Audi

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Weight Saving With Magnesium

- Highest Strength to Weight Ratio
- Highest Stiffness to Weight Ratio
- Best Machining Properties of ALL Metals
- Excellent Vibration Damping
- High Dent Resistance

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Magnesium... largely single part substitution

USAMP 2004 Study

Exhibit 3.2.2.
Magnesium Components Used in Vehicles (lb.)

<table>
<thead>
<tr>
<th>Original Material</th>
<th>Mg Weight</th>
<th>Weight Saved</th>
</tr>
</thead>
<tbody>
<tr>
<td>CHASSIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4 Wheels</td>
<td>65</td>
<td>39</td>
</tr>
<tr>
<td>1A Frame Cross Member</td>
<td>20</td>
<td>10</td>
</tr>
<tr>
<td>Engine Cradle</td>
<td>34.8</td>
<td>23.7</td>
</tr>
<tr>
<td>Fuel Tank Barrier</td>
<td>8.7</td>
<td>5</td>
</tr>
<tr>
<td>Brackets - Adjustable Pedal</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Brake/Accelerator</td>
<td>2.5</td>
<td>2</td>
</tr>
<tr>
<td>Steering - Wheel</td>
<td>2.5</td>
<td>1.5</td>
</tr>
<tr>
<td>Columns</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Column Brackets</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>ABS Mounting Bracket</td>
<td>1.3</td>
<td>0.9</td>
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<tr>
<td>INTERIOR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Seats - Frame</td>
<td>44</td>
<td>16</td>
</tr>
<tr>
<td>Stanchions (6)</td>
<td>34</td>
<td>13</td>
</tr>
<tr>
<td>NP - X-car beam</td>
<td>24</td>
<td>13</td>
</tr>
<tr>
<td>Knee Bolster</td>
<td>1</td>
<td>6</td>
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<tr>
<td>Console</td>
<td>1</td>
<td>3</td>
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<tr>
<td>Brackets</td>
<td>1</td>
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<tr>
<td>Glove Box Door</td>
<td>1</td>
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<tr>
<td>POWERTRAIN</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Engine Block 1.6</td>
<td>56</td>
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<tr>
<td>Engine Block 1.4</td>
<td>44</td>
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<tr>
<td>Automatic Transm</td>
<td>42</td>
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<tr>
<td>Intake Manifold</td>
<td>22</td>
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<tr>
<td>Transfer Case</td>
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<tr>
<td>Clutch Housing</td>
<td>14</td>
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<tr>
<td>Oil Pan</td>
<td>9</td>
<td></td>
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<tr>
<td>Engine Mounting Brackets</td>
<td>6</td>
<td></td>
</tr>
<tr>
<td>Alternator Bracket</td>
<td>5</td>
<td></td>
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<tr>
<td>Carb Cover (5)</td>
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<tr>
<td>Cylinder Head Cover</td>
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<tr>
<td>Air Intake Housing</td>
<td>6</td>
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<tr>
<td>Oil Pump Housing</td>
<td>3</td>
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<tr>
<td>Power Steering Pump Bracket</td>
<td>1.3</td>
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<tr>
<td>BODY STRUCTURE</td>
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<tr>
<td>Door Inner Panels (4)</td>
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<tr>
<td>Radiator Support/GOR</td>
<td>32</td>
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<tr>
<td>Front of Dash Structure</td>
<td>40</td>
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<tr>
<td>LR gate Taper</td>
<td>72</td>
<td></td>
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<tr>
<td>Windshield Surround (Frame)</td>
<td>22</td>
<td></td>
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<tr>
<td>Targa Roof Frame Opening</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Wiper Motor/support Assembly</td>
<td>3.5</td>
<td></td>
</tr>
<tr>
<td>Mirror Housing</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Headlight Retainer</td>
<td>1.3</td>
<td></td>
</tr>
<tr>
<td>TOTAL</td>
<td>662</td>
<td></td>
</tr>
</tbody>
</table>

~ 50 different parts
~ 155 major platforms
~ Totaling 380 lbs (173 kg)
~ Ave. car only 5-6 kg Mg

“Single Part Substitution”... limited impact on “Big Picture” Weight Saving Needed in Future (> ~ 100 kg)
Single Part Substitution… falls short of maximum weight savings potential

- Mg parts typically installed by “Substitution”… replace Steel or Aluminum part(s) with a single Mg die cast part

- Impact on “Big Picture” Vehicle Weight Savings is Limited…
  - Single Part Substitution Weight Savings… targeted to specific location & part with few secondary weight savings
  - Mg Use Limited… averages only about 5 - 7 kg per vehicle

Baseline: 2009 Ford F150
USAMP Big Picture …
~155kg Mg parts can provide ~ 222 kg Primary & Secondary Weight Savings (~15% Wt Reduction)

“Big Picture” Mg Wt Saving... requires Multi Material Assemblies
✓ ~ 45% weight saving compared to high performance steel baseline
✓ ~ 60% reduction in number of component parts
✓ ~ 25% weight saving compared to similar Al structure

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USAMP... undertaken 3 Phase DEMO Project
• 5 yr project (executed in 3 parts 603, 604, 904)
• $9.2M budget
• 59 international partners

USAMP Project Demonstrated
MAGNESIUM Enabling Technologies

- ✔ Crashworthiness
- ✔ Noise & Vibration
- ✔ Fatigue & Durability
- ✔ Corrosion & Surface Finish
- ✔ Hi Quality Casting & Forming Technology
- ✔ Welding & Joining Technology
- ✔ New Alloys

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MAGNESIUM… requirements to seize the “Big Picture” Weight Savings

☑️ CAPABILITY FOR AUTO… Mg assemblies can satisfy automotive requirements
  ✓ Crashworthiness
  ✓ Noise, Vibration & Harshness
  ✓ Fatigue
  ✓ Durability & Corrosion Resistance
  ✓ Joining & Fabrication

☑️ SIGNIFICANT WEIGHT SAVINGS & DESIGN SIMPLICITY…
  Mg Assemblies… significant weight savings over Steel (~50%) & Al (~25%)
  Design Simplicity… significant reduction in number of parts

☑️ SIGNIFICANT ALLOYING & PROCESSING R&D UNDERWAY… as reported
  ✓ Corrosion Resistance… Hi Purity alloys, Coatings & Galvanic resistant designs
  ✓ Hi Temp Creep & Flammability Resistant Alloys… RE, Ca, Sr, Sn, Y, CaO
  ✓ Joining Technologies… TIG & Laser welding, adhesives & mechanical fastener
  ✓ Mg Sheet… improved conventional slab & twin roll processing methods for high strength & elongation sheet alloys
  ✓ Formability… improved room temperature sheet formability & laser hemming

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Magnesium industry undergone TWO competitive paradigm shifts

Before ~ 1990 China Produced No Magnesium... Dow, Norsk Hydro, US Mag, Northwest Alloys (Alcoa) & Pechiney dominated production

- Price Mg > 1.50 times Price Al

“First Paradigm Shift” began in ~ 1990... led by lower labor costs in China. Rapidly declining prices & relocation of production base from the West to China

- Price Mg < Price Al

Today China is producing > ~80% of world’s Mg...
Dead Sea (Israel), US Mag, RIMA (Brazil) & few former Soviet based plants are only remaining western producers

REMAINING SUCCESS FACTORS for MAGNESIUM

Needs to be Competitive with Other Light Weight Materials particularly Aluminum

- Price ... Price Competitiveness requires Operating Cost Competitiveness
- Environmental... Life Cycle Competitiveness

Magnesium... alloying & downstream
R&D impressive BUT competitiveness will be deciding factor determining Mg demand

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Magnesium Production...
USGS Data +6.9% CAGR (1994 – 2011)

N. America

Europe

CIS

China

1994
267,000 MT

2011 (est)
825,000 MT

59%

15%

18%

4%

6%

3%

7%

4%

2%
Concentrated Chinese Mg Production... dramatic & fundamental impact on market dynamics

- China shifting to a deregulated free market economy...
  fundamental upwards shift in energy, materials & labor costs

<table>
<thead>
<tr>
<th>Commodity</th>
<th>% Increase (2005-2011)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal Coal</td>
<td>~ 450%</td>
</tr>
<tr>
<td>Electricity</td>
<td>~100%</td>
</tr>
<tr>
<td>Ferrosilicon</td>
<td>~ 60%</td>
</tr>
<tr>
<td>Labor Hourly Rate</td>
<td>&gt; 250 – 350%</td>
</tr>
</tbody>
</table>

Based on Published Data

Chinese Mg Production Costs ... have risen sharply since 2005

Between 2005 to 2011
Cost of Mg Ingot “Delivered” to EU & NA Markets
Has Essentially Doubled

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Today’s Higher Magnesium Prices

... reflect fundamentally higher Chinese production & transportation costs

- Chinese Magnesium
  - Prices just above “Cash Costs”
  - Margins are Very Low

First Paradigm Shift

Second Paradigm Shift

Published Free Market Year End Mg Price Landed in West

~ Cost of Chinese Mg FOB EU & NA Port

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Magnesium’s Competitive Position vis-à-vis Aluminum

Non Structural Parts – Straight Density based Substitution

Structural Parts Increased Thickness – Mechanical Property based Substitution

Mg to Al Competitive Price Point

% Weight Savings with Mg

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Free Market Mg Competitive Position

... deteriorated compared to aluminum & growth has suffered

1st Paradigm Shift...
High Growth  CAGR (2000-2007): 10.7%

2nd Paradigm Shift...
Low Growth  CAGR (2007-2011): 1%

Based on Year End Prices
- Free Market Mg landed in West
- LME Al Price

Competitive Point...
Al/Mg Density

Better Competitive Point
What Can Mg Free Markets Expect?  Given Concentrated Chinese Production

Future Magnesium Pricing???

- **Chinese Inflation Upward Pressures**
  Increasing prices for coal, electricity, oil & labor

- **Mg Margins are Low**
  Mg Price expected to move in step with Chinese inflation

- **Mg to Al Price Ratio**
  "could be under increasing Upwards Pressure as production base for Al much more diverse than for Mg"

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**Free Market Year End Mg Price**

- **Mg Year-end Price US$/MT**
  - '96, '97, '98, '99, '00, '01, '02, '03, '04, '05, '06, '07, '08, '09, '10, '11

- **Cost of Chinese Mg FOB EU & NA Port**
USA Magnesium’s Competitive Position… even worse vis-à-vis aluminum

Based on Year End Prices
- Published Free Market & US Mg Prices
- LME Al Price

Mg Increasingly Less Competitive … When Auto Increasingly Looking for Light Weight Solutions
Mg Environmental Competitiveness...

- China ~ 80% world’s Magnesium.... 1940 vintage Pidgeon Process

- Chinese Pidgeon Process is Labor & Energy Intensive...
  - FeSi (50% of Mg Cost)… electricity generated from coal
  - Mg Production… uses coal or coal gas

<table>
<thead>
<tr>
<th>Production</th>
<th>Process (Location)</th>
<th>GWP Kg CO2/kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>China – Coal</td>
<td>43.3</td>
</tr>
<tr>
<td></td>
<td>China – COG (IMA)</td>
<td>26.2</td>
</tr>
<tr>
<td>Aluminum</td>
<td>Average</td>
<td>12.7</td>
</tr>
<tr>
<td></td>
<td>North America</td>
<td>9.8</td>
</tr>
<tr>
<td></td>
<td>Europe</td>
<td>11.0</td>
</tr>
<tr>
<td></td>
<td>China</td>
<td>24.7</td>
</tr>
</tbody>
</table>
MAGNESIUM KEY SUCCESS FACTORS… to Seize Auto Opportunity

- PROVEN CAPABILITY FOR AUTO… as verified by USAMP study,
  - Crashworthiness
  - Noise, Vibration & Harshness
  - Fatigue
  - Durability & Corrosion
  - Joining & Fabrication

- SIGNIFICANT WEIGHT SAVINGS & DESIGN SIMPLICITY
- SIGNIFICANT ALLOYING & SHEET PROCESSING R&D BREAKTHROUGHS

??? REMAINING SUCCESS FACTORS… require new production technology that is competitive with other Light Weight Materials particularly with Aluminum
  ? Price … Impacts on Price of increasing operating costs
  ? Environmental… Life Cycle Competitiveness

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Gossan Resources Magnesium Project... 1st Advantage is Location & High Quality Ore Reserves

- **Strategic Manitoba Location**… mid-continent trade corridor with excellent access to NAFTA & EU
- **Extensive high purity Dolomite & Quartz reserves**… for Mg & FeSi Production
- **Measured Dolomite resource**… ~100,000 MT Mg metal per year for 30 years

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Gossan’s Magnesium Project…

2nd Advantage is Electricity

Manitoba…
Among World’s Lowest, Most Stable Pricing & Cleanest Electricity

US Cents per kWh

100% Hydro

Manitoba, Quebec, Utah, Nevada, Korea, China, France

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Develop Breakthrough Magnesium Technology…
a novel Thermal Process has been developed on basis of extensive Mg process & technology experience

Breakthrough Technology… targets major issues with EXISTING Magnesium Thermal Processes

► **Poor FeSi & Dolomite Utilization Efficiencies**… target improved raw material efficiencies to lower material costs, reduce by-product waste & lower energy

► **Costly & Complex Process**… target elimination of vacuum & large number of small scale high Ni alloy retorts to reduce cost of consumables, maintenance & labor

► **Solid Mg Condensation**… target molten Mg condensation to reduce energy, improve % yield & increase productivity

► **High GHG Emissions**… target improved life cycle attractiveness to be competitive with other materials especially Aluminum

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Gossan’s Magnesium Project...
3rd Advantage Breakthrough Technology

EXECUTION PLAN

Develop Breakthrough Process Concept
- Increase raw materials utilization efficiency
  - Reduce energy consumption
- Minimize labor & process complexities
  - Increase %yield & recoveries
  - Continuous Process
- Competitive cost & environmentally with Al

Confirm Process Fundamentals Correct
- Thermodynamics
  - Kinetics

Experimental Confirmation
- Bench Scale Testing... confirm modeling
- Larger Scale Testing... material flow

Pilot Scale Demonstration

STATUS

☑️ Breakthrough process conceived...
signed contracted Gossan 2007

☑️ Detailed Cost Modeling indicated
  - 25 – 30% advantage... over Chinese Mg cost
  - Cost... within 1.3 Mg to Al
    “Competitive Cost Ratio Target”

☑️ FactSage Thermodynamic Modeling...
  Prof Pelton Ecole Polytechnique Montreal
  Confirmed fundamentally sound

☑️ Bench Scale Trials... Process Research ORTECH
  Test & Modeling results agree
  Larger Scale Tests underway

Planning 5,000 MT semi-commercial facility

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### Reduction of Calcined Dolomite to Produce Magnesium Vapor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Measure</th>
<th>Experimental Mass Balance</th>
<th>Thermodynamic FACT Model</th>
<th>Delta %</th>
</tr>
</thead>
<tbody>
<tr>
<td>FeSi Balance</td>
<td>Weight Consumed by reaction</td>
<td>25.0</td>
<td>25.3</td>
<td>1.2%</td>
</tr>
<tr>
<td>By-Product Balance</td>
<td>Weight Produced by reaction</td>
<td>131.3</td>
<td>130.1</td>
<td>0.9%</td>
</tr>
<tr>
<td></td>
<td>Molar CaO/ SiO2</td>
<td>1.98</td>
<td>2.04</td>
<td>2.9%</td>
</tr>
<tr>
<td>Mg Balance</td>
<td>Weight Produced by reaction</td>
<td>34.0</td>
<td>33.8</td>
<td>0.6%</td>
</tr>
<tr>
<td>Efficiency Factors</td>
<td>Mg Produced per Si Consumed</td>
<td>1.63</td>
<td>1.63</td>
<td>0.0%</td>
</tr>
<tr>
<td></td>
<td>% Si Efficiency</td>
<td>94.4%</td>
<td>94.2%</td>
<td>0.2%</td>
</tr>
<tr>
<td></td>
<td>% Mg Recovery</td>
<td>92.9%</td>
<td>92.3%</td>
<td>0.6%</td>
</tr>
</tbody>
</table>

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**Method Patent Filed...**

1st US Provisional patent filed June 2011
2nd US Provisional patent filed April 2012

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# Comparison of Mg Processes

<table>
<thead>
<tr>
<th>Process Comparison to produce 1 kg Mg ingot</th>
<th>Pidgeon Process CHINA</th>
<th>GOSSAN CANADA</th>
</tr>
</thead>
<tbody>
<tr>
<td>World Magnesium Production</td>
<td>~ 80%</td>
<td>NA</td>
</tr>
<tr>
<td>Process Dynamics</td>
<td>Solid State</td>
<td>Molten State</td>
</tr>
<tr>
<td>Reduction Reactor Pressure</td>
<td>Vacuum</td>
<td>Atmospheric</td>
</tr>
<tr>
<td>Mg Recovery – from calcined ore</td>
<td>~ 74.0%</td>
<td>90.4%</td>
</tr>
<tr>
<td>Silicon Efficiency</td>
<td>~ 64.8%</td>
<td>91.9%</td>
</tr>
<tr>
<td>Production Cost Ratio</td>
<td>1.00</td>
<td>0.70 – 0.75</td>
</tr>
<tr>
<td>GHG – kg CO2 per kg Mg</td>
<td>26.2 ** - 43.3 *</td>
<td>9.1 **</td>
</tr>
<tr>
<td>LCA – breakeven, thousand km</td>
<td>171.6 – 275.6 ***</td>
<td>69.5***</td>
</tr>
</tbody>
</table>

- ** IMA with COG (2012)
- *** Based on 222 kg weight saving from 154 kg Mg following method of F.D’Errico et al. JOM, Vol. 61, No.4, 2009

**Magnesium Very Competitive with Aluminum**

**LCA Breakeven 69,500 km**

Reduces Emissions ~7% Over 200,000 km car life

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## Gossan Magnesium Project…
### Next Steps & Timelines

<table>
<thead>
<tr>
<th></th>
<th>2012</th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017+</th>
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</thead>
<tbody>
<tr>
<td>Large Scale Testing</td>
<td></td>
<td></td>
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<tr>
<td>Financing or JV Partnership</td>
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<tr>
<td>Initial Permitting</td>
<td></td>
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<tr>
<td>Pilot Design, Construction &amp; Commissioning (5,000 tpa)</td>
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<tr>
<td>Pilot Demonstration Plant (operation, customer development)</td>
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<tr>
<td>Final Permitting</td>
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<tr>
<td>Final Engineering &amp; Construction</td>
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<tr>
<td>Full Scale Production</td>
<td></td>
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</tbody>
</table>

Preliminary estimate subject to commercialization of the Zuliani process, financing, permitting and other risks

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Summary

Recent R&D... confirms Mg can be significant player in lightweight vehicles
  ✓ Addresses Technical Capabilities for Auto
  ✓ Confirms Significant Weight Savings & Reduction Number of Parts
  ✓ Alloing & Downstream Process Breakthroughs

Mg production dominated by China (~80%)
  ? Production Cost & “Mg to Al” Price Ratio
  ? Mg Prices Ongoing Upward Pressure
  ? “Mg to Al” Price Ratio Upward Pressure
  ? Environmental GWP & LCA

Gossan’s Breakthrough Magnesium Technology
  ✓ Significant Improved Process Efficiencies... production cost 25 - 30% less
    than China & within target 1.3 Mg/Al competitive production cost ratio
  ✓ Environmentally Competitive... favorable GWP & LCA compared to Al
  ✓ Gossan Resources Mg Project... favorable western location, high quality
    dolomite resource & exceptionally low and stable electricity rates

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