Making Magnesium a More Cost and Environmentally Competitive Option

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Abstract

As the world's lightest structural metal, the growth potential for magnesium is unprecedented in view of the accelerating demand for light-weighting in transportation and for portable devices.

To seize this opportunity, magnesium must become cost and environmentally competitive with other lightweight materials, particularly aluminum. In view of its weight saving advantage, magnesium's cost competitive position improves dramatically if its production cost is maintained at less than about 1.3 times aluminum's production cost. Future growth also requires environmental competitiveness; magnesium producers need to utilize process technology that provides a much more attractive life cycle assessment than is currently achieved.

This paper provides an update of the Zuliani Process currently being developed by Gossan Resources for its magnesium production project in Manitoba Canada. Process efficiencies, Greenhouse Gas emissions (GHG) and Life Cycle Analysis (LCA) as determined from thermodynamic modeling and experimental testing are compared to existing processes. Based on the results, Gossan is confident that its magnesium project will realize the operating cost and environment objectives needed to significantly enhance magnesium's competitive position.

Introduction

Reducing weight especially in the front end has traditionally been used to improve vehicle handling, acceleration and braking distance. However, weight reduction is an important factor in lowering fuel consumption (Figure 1) as well as in extending the range of electric vehicles. As such, weight saving can be expected to become an increasingly important design factor as manufacturers respond to tighter fuel standards such as the 54.4mpg fleet average fuel economy proposed in the 2025 CAFE Standards. For example, Ford has reportedly developed a plan to use over 113 kg of Mg in future vehicles **[1].**

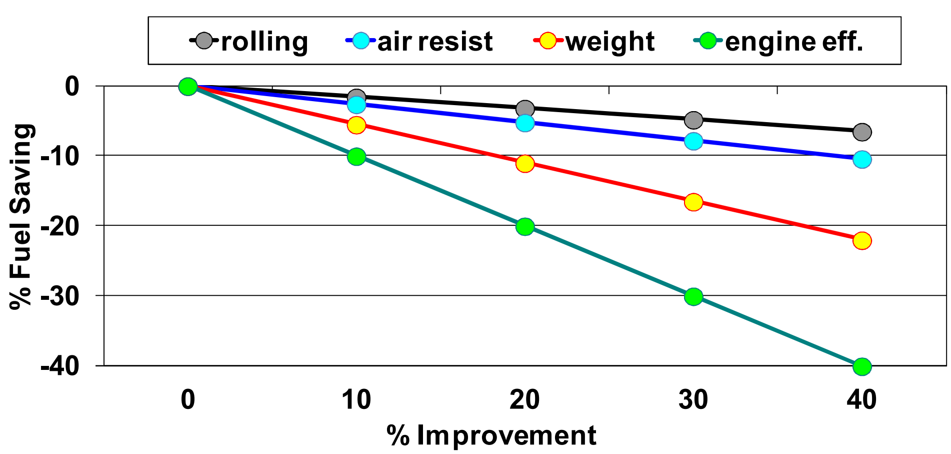

Figure 1: Relative effects of rolling resistance, air resistance, engine efficiency & weight on fuel savings [2].

Weight savings are achieved in two ways; primary reduction from substituting heavier materials with lighter ones such as replacing steel and aluminum with magnesium, and, secondary savings available in the chassis, powertrain and suspension resulting from the primary weight reduction. Proportionately, secondary weight savings will increase if there is a major light-weighting redesign resulting from a large primary saving. For example, USAMP in a recently published study Magnesium Vision 2020 estimated that total weight savings of 227 kg could be achieved from a secondary weight savings of 95.5 kg resulting from a major redesign that would enable 227 kg of steel and 59 kg of Al to be substituted by 154.5 kg of Mg **[3]**. USAMP predicts reduced weight by ~15% and fuel consumption by over 8%.

Depending on the structural requirements, magnesium parts can provide weight savings of between about 50-75% over conventional steel, 40-50% over higher strength "light steel" and 20-34% over aluminum. Magnesium alloys also demonstrate excellent strength, stiffness, castability, machinability and dent resistance. For transportation, sporting goods and portable equipment design engineers, magnesium has the potential to be an extremely attractive ultra-light material that exhibits the highest strength and the highest stiffness per unit weight together with enhanced casting and fabrication characteristics.

To seize this growth opportunity, magnesium must be cost and environmentally competitive with other lightweight material options, particularly aluminum. In view of its weight saving advantage, magnesium's cost competitive position improves dramatically if it's per unit weight production cost is maintained at less than about 1.3 times the production cost of aluminum (Figure 2). Long-term future growth also requires environmental competitiveness; magnesium producers need to utilize process technology with a much more environmentally attractive life cycle assessment than is currently achieved.

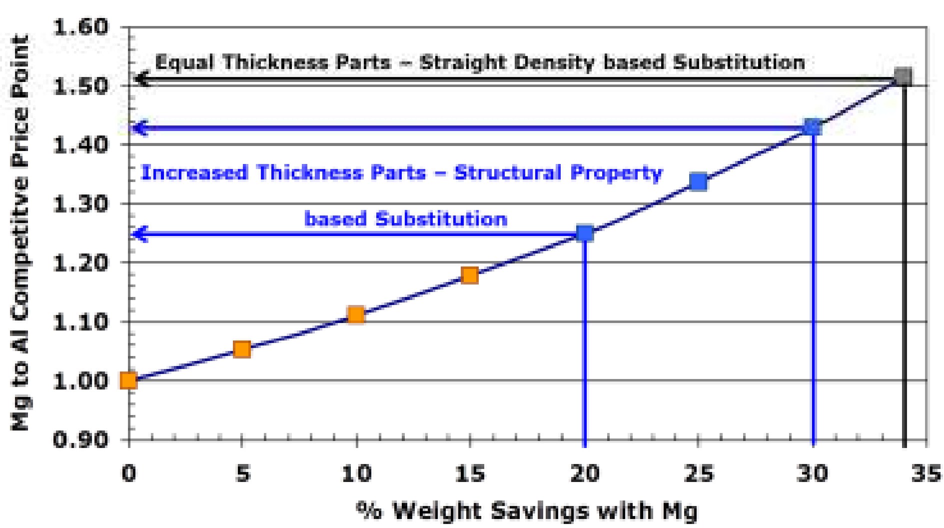

Figure 2: Effect of % Weight Savings on the Mg to Al Competitive Price Point

Two Fundamental Paradigm Shifts Affect Magnesium Production Cost & Pricing

The magnesium industry has undergone two major paradigm shifts over the last two decades. The first paradigm shift started about 1990 when China began to produce magnesium metal employing 1940's thermal reduction technology originally developed in Canada by Dr. Lloyd Pidgeon **[4].** The low CapEx, raw material, energy & labor intensive *Pidgeon Process* was ideally suited to late 20th century China with low labor costs and lax environmental regulations.

The net result of this development was an exponential growth in Chinese production, and correspondingly, a dramatic decline in magnesium market prices which had been previously averaging between US $3,100-$3,800 per tonne. By 1996, prices had fallen sharply to $2,500 per tonne and continued to decline to less than $2,000 by the turn of the century. The resulting dramatic price shock eventually led to the shuttering of many western magnesium facilities including Dow, Norsk Hydro, Pechiney, Alcoa and Timminco. Today, ~80% of the world's magnesium is produced in China with over 95% of producers using the Pidgeon Process **[5]**.

The second major paradigm shift started in about 2007. China's rapid industrialization and move towards a freer economy combined with rapidly accelerating inflation and a sharp spike in world oil prices resulted in a dramatic and fundamental step change in Chinese magnesium production and delivery costs. The result was a sharp escalation in energy, labor and raw material costs used in magnesium production (Table 1). As early as 2007, industry observers had concluded that "the days of exceptionally low magnesium prices were indeed coming to an end" **[6].**

Table 1: Raw materials, energy & labor costs in China (2005 to 2011) – taken from various published sources

Commodity	**% Increase (2005 - 2011)**
Thermal Coal	~ 450%
Electricity	~100%
Ferrosilicon	~ 60%
Labor Hourly Rate	> 250 – 350%

Chinese inflation has had a dramatic impact on magnesium production cost and market pricing. Since 2005 the direct cost of producing magnesium in China and landing it in western markets has increased by between 1.7-1.9 times from ~US $1485 per tonne to between US $2530-$2830 by the end of 2011. Because Chinese producers tend to price marginally above "cash cost", magnesium's free market "floor price" has correspondingly increased by about 1.7 times over the same period from about US $1,800 per tonne in the mid-2000's to just over US $3,000 per tonne by the end of 2011.

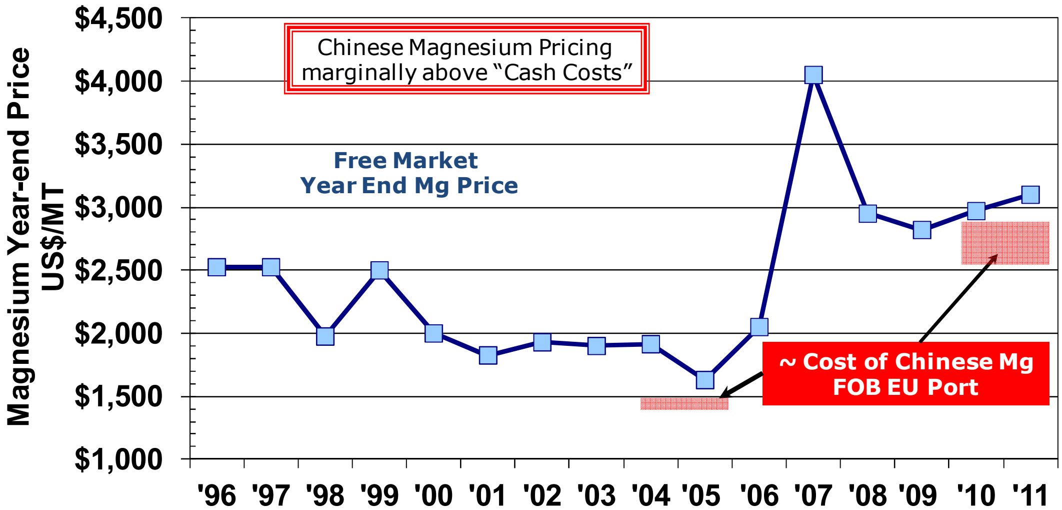

Figure 3: Trends in Free Market Mg Price

Future Economic Prospects for Magnesium

After about 10 years of low and stable prices, magnesium customers suddenly experienced a sharp price spike in 2008 which has subsequently leveled out at a new "floor" price that is ~1.7x pre-2008 levels.

Most importantly, the sharp price swings have affected magnesium's competitive position vis-à-vis aluminum (Figure 4). Up to about 2007, the Mg to Al price ratio was very favorable leading to unprecedented growth in Mg demand – from 2000 to 2007 production grew from about 400,000 tpa to almost 600,000 tpa on the strength of competitive pricing stemming from the low operating cost structure in China. However, the recent sharp rise in Chinese production costs and the corresponding price increases have significantly diminished magnesium's competitive position with aluminum. The net result is that growth in magnesium production and demand has been significantly curtailed in recent years.

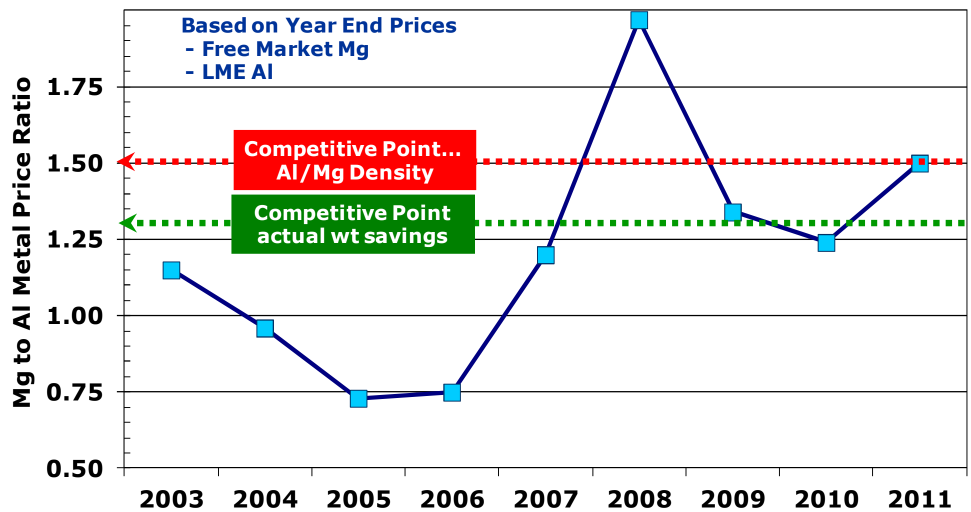

Figure 4: Recent Trends in Mg to Al Price

Looking forward; since ferro-silicon (FeSi) represents almost 50% of Pidgeon Process magnesium production cost, the Chinese magnesium price has typically trended between 2 - 2.5 times the Chinese FeSi price. Hence, projections for FeSi demand and pricing can be expected to largely determine magnesium's future production cost and pricing dynamics.

The vast majority of the world's FeSi is produced in China. FeSi is a major alloying element used in the production of steel hence FeSi demand is fundamentally tied to the demand for steel. Between 2001 and 2010 world steel production grew from about 850 million tonnes to 1,417 million tonnes with Chinese steel production increasing over the same period from 152 million tonnes to 627 million tonnes **[7].**

According to a recent CRU publication **[8],** the current economic slowdown in China is expected to result in a slight pause in steel demand until about Q2 2012 at which point Chinese domestic steel demand will continue to grow. CRU is forecasting that from 2010 - 2015, Chinese steel demand will grow at near GDP levels of about 6 - 7% per annum. Hence, domestic Chinese FeSi demand can also be expected to grow at a similar 6 - 7% per annum.

Electricity is the major cost component impacting on the Chinese FeSi price. Based on a recent EU Commission Study **[9],** assuming a conservative average Chinese GDP growth going forward of about 6.5%, demand for electricity is expected to increase annually by about 7.2% which in turn will impact significantly on the demand for coal. The EU commission projects that by 2025, China will consume over 6 billion tonnes of coal annually or nearly 3 times the 2005 consumption. Importantly, coal is the primary energy source for Chinese Pidgeon Process magnesium production.

Given the expected annual growth rates of between 6-7% for steel, FeSi, and electricity together with the rapidly accelerating demand for coal, once the current economic slowdown in western markets diminishes, inflationary pressures in China can be expected to resume for the foreseeable future. Even though the current slowdown has resulted in a slowing in Chinese growth and a corresponding pause in magnesium price pressure, magnesium production costs and market prices are likely to feel significant upward pressure once Chinese energy, raw material and labor costs continue to increase. Because Chinese profit margins on magnesium are far too low to absorb any significant increase in production costs, western consumers should expect magnesium prices to continue upwards on a parallel path with the Chinese energy, materials and labor cost inflation rate.

Most importantly for magnesium, with about 80% of the world's production being concentrated in China having production cost and pricing pressures, that are not largely shared by the world's more diversified aluminum production base, there is a significant risk going forward that continued upward pressure on magnesium prices arising from increasing FeSi, labor and energy costs in China will lead to an increasingly uncompetitive position vis-à-vis aluminum.

Magnesium's Life Cycle Analysis (LCA)

In order to seize the lightweight opportunity, magnesium must not only be cost competitive but going forward, it must also be environmentally competitive. Table 2 provides a summary of the Global Warming Potential (GWP) which represents a summation of the "direct plus indirect" kg CO_2 for various processes/plants. For comparison purposes, the world average GWP for aluminum ingot is 12.7 kg CO_2 per kg **[10]** but it is highly regionally dependent; 9.8 in North America, 11.0 in Europe and 24.7 in China.

Table 2: GWP for Mg ingot produced with various processes [12] **indicates plants not in operation today

Magnesium Production Process (Location)		GWP
Thermal	Bolzano (Brazil)	13.8
	Magnetherm (France)**	17.6
	Pidgeon (China)	43.3
Electrolytic	Norsk Hydro (Canada)**	16.1
	AM (Australia)**	27.9

Because Chinese producers supply ~80% of the world's magnesium with the Pidgeon Process, the GWP for the vast majority of magnesium applications is 43.3 kg CO_2. per kg Mg ingot.

It should be noted that RIMA Brazil (Bolzano Process) accounts for about 3% of the world Mg production [**11**]. While the Bolzano and Pidgeon processes use different furnace configurations, both involve solid state reduction of calcined dolomite by FeSi under vacuum to produce a solid, crude Mg condensate that needs to be melted prior to refining and ingot casting. As shown in Table 4, both the Pidgeon and Bolzano processes have essentially the same raw materials utilization efficiencies. Hence, the environmental benefits reported in Table 2 cannot be attributed to improved process efficiencies but instead are primarily due to RIMA's specific locational situation involving the use of hydroelectricity and charcoal produced from renewable eucalyptus trees grown in Brazil which provides a net GHG biofuel credit for the production of Mg and FeSi.

Given the dominance of Chinese magnesium, produced essentially with the Pidgeon Process, and that its GWP is 3.4 times higher than the average for Al ingot production, the LCA for magnesium in automotive applications does not appear to be very favorable. For example, D'Errico et al. **[12, 13]** reported that the LCA for 100 kg weight savings from the replacement of steel with 42 kg of magnesium components made from Chinese magnesium ingot indicated a typical vehicle would have to travel a distance that is 1.45 times farther than the vehicles expected lifetime distance before the CO_2 emissions "saved from its reduced weight" would breakeven with the additional CO_2 "generated from the production of the Mg components".

Gossan Resources Breakthrough Magnesium Project

Gossan Resources Ltd a Canadian public company (TSX Venture – GSS) is developing a new breakthrough thermal magnesium process for use in its project to produce magnesium metal from its extensive, high quality dolomite resource located in Manitoba Canada **[14]**. The project will make use of stable and low priced hydroelectricity **[15]** and natural gas both of which are abundantly available in Manitoba

The ZULIANI PROCESS (the PROCESS") utilizes electricity to produce magnesium metal from calcined dolomite and FeSi. It has been designed to address the main constraints that have unfavorably impacted operating cost, productivity and GHG emissions with all known thermal magnesium processes:

- To maintain sustainable profitability by realizing a 20-30% direct production cost advantage of over existing magnesium producers in China;
- To spur market growth by realizing a direct production cost that will be cost competitive with aluminum. The target competitive magnesium production cost should range between ~ \$1,950 - \$2,340 per tonne (~1.3 x Al cost) **[14]**;
- To achieve a Life Cycle Assessment competitive with aluminum.

Process Efficiency - To date, independent thermodynamic modeling and bench scale experimentation have been conducted to verify the chemical and raw materials utilization efficiencies of the PROCESS.

In 2007 Dr. Arthur Pelton, of THERMFACT Ltd. and a Professor at Ecole Polytechnique in Montreal, Quebec was contracted to develop a thermodynamic model of the PROCESS using the FactSage integrated thermodynamic databank system which calculates the conditions for multiphase, multi-component equilibria in complex gas-slag-metal systems.

Following Dr. Pelton's successful modeling work, Gossan retained Process Research ORTECH Inc. (ORTECH) of Mississauga, Canada, an independent pilot lab with recognized metallurgical expertise to conduct bench scale testing of the PROCESS to extract magnesium metal from dolomite and confirm process thermodynamics and kinetics. The ORTECH bench scale tests were carried out in three phases with final results reported in September 2011.

The following was concluded based on a comparison between Dr. Pelton's thermodynamic modeling and a mass balance derived from ORTECH's bench scale experiments – see Table 3:

1: The PROCESS produces magnesium metal vapor at 1 atmosphere in the desired temperature range. Atmospheric production will avoid the need for using costly and complex vacuum systems and is an important prerequisite for molten magnesium condensation.

2: The efficiency and chemical effects of varying FeSi grade in the range between 30-75% were consistent with that previously predicted by Dr. Pelton's FactSage thermodynamic model.

3: There is exceptional agreement between the experimental mass balance developed using the measured initial raw material chemistry, measured raw material weights and measured final slag weight and chemistry as determined in the ORTECH tests and Dr. Pelton's thermodynamic model. In a subsequent independent analysis of the results, Dr. Pelton reviewed and verified that there is excellent agreement between the ORTECH experimental mass balance and the FactSage thermodynamic modeling predictions. This excellent agreement indicates that the high efficiencies predicted by the thermodynamic model are confirmed by actual experimentation.

Table 3: Comparison between Bench Scale Mass Balance Results & FactSage Thermodynamic Modeling Predictions to produce 1 kg magnesium vapor

Process Efficiency Factors	ZULIANI PROCESS		At 100% Efficiency
	FactSage Model	Experiment Mass Balance	
kg Si per kg Mg vapor	0.6135	0.6124	0.5780
kg Dolime per kg Mg vapor	4.444	4.405	4.098
kg By-product per kg Mg vapor	3.851	3.862	3.571
Mg Vapor Recovery	92.3%	92.9%	100.0%
Si Utilization Efficiency	94.2%	94.4%	100.0%

As shown in Table 4, the results confirm significant efficiency improvements when compared to other thermal production methods currently in commercial use.

Table 4: Thermal Process Efficiency Factors to produce 1 kg magnesium Ingot

THERMAL PROCESS Efficiency Comparison	@ 100% Eff	Pidgeon CHINA	Bolzano BRAZIL	Zuliani CANADA
PROCESS DYNAMICS	-	Solid State	Solid State	Molten State
Energy Source	-	Coal	Hydro & Charcoal	Hydro & Nat Gas
Reaction temperature, °C	-	1200	1200	1600
Mg vapor pressures, atm	-	0.045	0.045	$\geq$ 1
Vacuum	-	Yes	Yes	No
Mg condensate	-	solid	solid	molten
EFFICIENCY FACTORS				
Kg Si used per kg Mg ingot	0.578	0.89	0.81	0.63
Kg dolime used per kg Mg ingot	4.13	5.36	5.84	4.55
Kg by-product per kg Mg ingot	3.9	5.5	5.9	4.4
% Mg Recovery (Dolime to Ingot)	100%	77.1%	71.4%	90.7%
% Si Efficiency	100%	64.9%	71.4%	91.8%

Environmental Considerations – ORTECH was also contracted to carry out an independent environmental assessment of the PROCESS to determine the GWP and LCA implications. A detailed mass and energy balance method was developed to calculate the GWP associated with magnesium production. As a methodology check, ORTECH determined that the GWP for Chinese magnesium produced using the Pidgeon Process is 42.0 kg CO_2 per kg Mg ingot which compares very favorably with previously published GWP of 43.3 **[5]**.

Using similar heat and mass balance methodology for FeSi and magnesium produced with the highly efficient PROCESS in Manitoba using hydroelectricity and natural gas for calcining dolomite, the GWP of Gossan magnesium (direct & indirect emissions) has been determined as 9.1 kg CO_2 per kg Mg ingot which is 28% less than the 12.7 GWP for average aluminum ingot production and 78% less than the GWP for Chinese Mg ingot.

Using the LCA approach together with the more efficient magnesium component manufacturing methods described by D'Errico **[12,13]**, a lightweight USAMP vehicle design**[3]** that replaces 381 kg of iron, steel and aluminum with 154 kg of Mg components made from Gossan magnesium ingot would begin to generate net GHG savings after a travel distance of only 69,500 km. This compares to a breakeven distance of 275,600 km before a net CO_2 benefit starts if Chinese magnesium ingot were employed - the vehicle CO_2 savings from a weight savings of 227 kg would be 2.46 kg CO_2 per 100 km travelled. The kg of CO_2 generated from the production of 154 kg of parts from Gossan magnesium would be 1,709 kg versus 6,776 kg from Chinese magnesium.

Such performance is clearly advantageous compared to Chinese magnesium however most importantly it would place Gossan's magnesium ingot in a much more favorable environmental position vis-à-vis aluminum which has a somewhat higher GWP and provides on average between 20-30% less weight savings than magnesium.

Economic Considerations - On the basis of the modeling and experimental work carried out to date, a continuous process route and flow sheet has been established for the continuous production of molten magnesium metal. This process route has been examined independently and favorably reviewed by a third party metallurgical company with direct expertise in magnesium production. A US Provisional method patent has also been filed in June, 2011.

A detailed direct cost model has been developed and indicates that with the exceptional raw materials efficiency and the use of stable and low priced hydroelectricity in Manitoba, Gossan's direct operating cost to produce magnesium metal is projected to be significantly below (20-30%) of the cost to deliver Chinese magnesium into western markets.

Most importantly, the direct cost also appears to be well within the target range set out to be competitive with aluminum thereby enabling magnesium to remain in a highly competitive position even when market conditions fluctuate.

Summary & Next Steps

The fundamental thermodynamic and kinetic aspects of the Zuliani Process have been confirmed by the modeling and experimental work conducted to date. The next step which is now underway is to undertake larger scale experimentation needed to support the design of the continuous reactor specifically to verify molten bath mass flow characteristics and to confirm the efficiency of the molten magnesium condenser. The results from this next phase of work will enable detailed design engineering and will support financing for the first commercial stage which is envisioned to be a 5,000 tonne pilot/demonstration scale plant.

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