



Reductant Considerations in Thermal Pathways to Primary Magnesium Metal Production: A Case for Aluminothermic Reduction

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Abstract

Thermal routes to produce primary magnesium metal are generally demarcated with lower capital costs. However, the range of operational costs are high depending on reduction reactor efficiencies and configuration, labor intensity, and the cost of reductant. Choosing a reductant material can be a challenge in terms of logistics, supply security, cost, and technical performance. Presented is an assessment of possible reductant materials and the interplay between heat of reaction, reactor and condenser design, byproducts, and the behavior and role of impurities. On one end of the reductant spectrum is the reaction of carbon and magnesia, generating exclusively a byproduct gas, along with the product magnesium metal, and virtually no solid residue. Conversely, the reaction between calcined dolomite and ferrosilicon generates virtually no byproduct gas and nearly $6\times$ more mass of calcium silicates than magnesium metal. These chemistries share engineering challenges that center on the method of recovery products.

Keywords

Magnesium • Pyrometallurgy • Process technology • Primary production • Aluminothermic reduction • Techno-economics

Extended Abstract

Thermal production routes to produce primary magnesium metal are generally demarcated with lower capital costs over electrolytic processes. However, the range of operational

costs are high depending on reduction reactor efficiencies and configuration, labor intensity, and the cost of reductant. Choosing a reductant material can be a challenge in terms of logistics, supply security, cost, and technical performance. For silicothermic reduction chemistry, three different reactor configurations have been commercialized: Pidgeon, Bolzano, and Magnetherm. While the theoretical energy required to drive the reaction are all about the same, depending on reactor temperature, the reactor configurations and heating methods give rise to large variation in applied energy consumption, as reported in Table 1.

In addition to ferrosilicon, other reductants have been explored including carbon, aluminum, carbides, and metal alloys containing combinations of calcium, silicon, and/or aluminum. On one end of the spectrum is the reaction of carbon and magnesia, which generates the byproduct gas carbon monoxide along with the product magnesium metal and virtually no solid residue. Conversely, the reaction between calcined dolomite and ferrosilicon generates virtually no byproduct gas and nearly six times more mass of calcium silicate than magnesium metal. This solid byproduct is practically valueless in industrial markets.

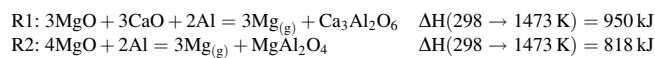
Use of aluminum metal, when used with calcined dolomite, produces a calcium aluminate solid byproduct, a value-add output (Reaction 1). Similarly, when reacted with magnesia, the byproduct is magnesium aluminate spinel, a high-value refractory (Reaction 2). Laboratory experiments confirm the formation of spinel and high conversion of MgO at relatively low reduction temperatures in the range of 1273–1473 K. Total gross energy consumption for an MgO-to-ingot process was calculated to be 8.8 kWh/kgMg. For all unit operations, electrified equipment is used or assumed. Since there no direct emissions from the process, all indirect emissions are related to the source of power. In the USA, the national average of the electrical grid is 0.418 kgCO_{2eq}/kWh, which results in estimated process emissions of 3.7 kgCO_{2eq}/kgMg with no direct greenhouse gas emissions.

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Table 1 Comparison of theoretical and apparent energy consumption for various reduction chemistries to produce magnesium metal

Reduction chemistry	Nominal operating temp (K)	Theoretical minimum energy (kWh/kgMg)	Reported energy consumption (kWh/kgMg)	GHG impact (kgCO ₂ /kgMg)	Source
Silicothermic					
<i>Pidgeon</i>	1473	4.26	13.3–14.8	21.8–25.3	[1, 2]
<i>Bolzano</i>	1473	4.26	7.0–7.3	10.1	[3]
<i>Magnetherm</i>	1873	4.77	~16	NR	[4]
Carbothermic	2073	8.39	10–12	0.7–12.6	[5]
Electrolysis	973	7.32	12–19	6–19	[3, 6]
Other			No commercial operations		[7]
Aluminothermic					
<i>Al</i>	1473	3.12			
<i>CaC₂</i>	1473	4.17			
<i>SiC</i>	1773	6.20			
<i>Ca–Si [1:3] Alloy</i>	1473	3.88			
<i>Al–Si [1:1] Alloy</i>	1473	3.88			

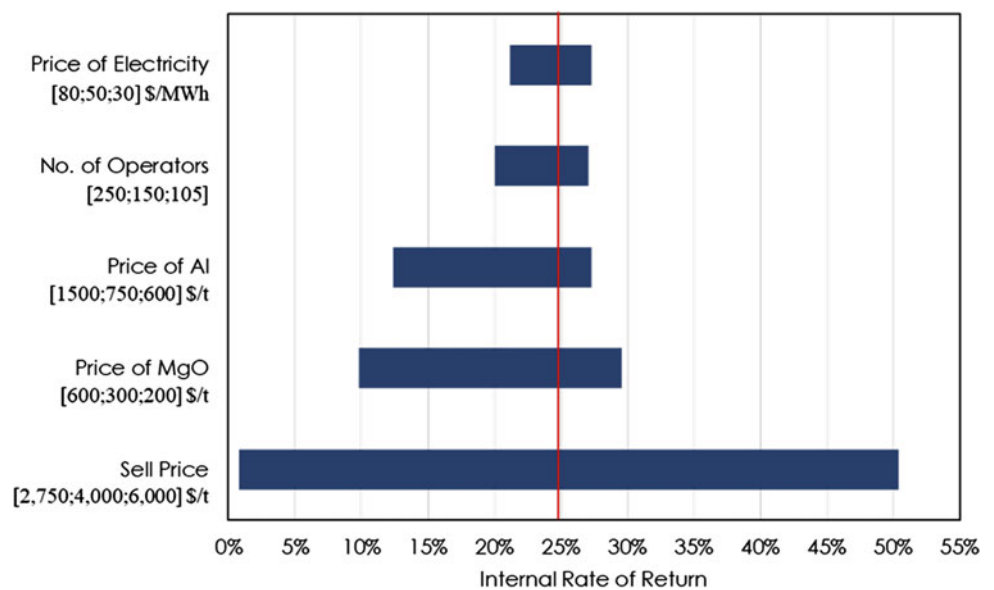
GHG impact for the overall cradle-to-gate process is also reported for commercialized processes



Using laboratory and pilot data, a discounted cash flow techno-economic model revealed a base-case capital intensity of \$3120 per ton-capacity of magnesium metal produced for the MgO-to-ingot process boundary. Mining, transportation, and calcination were not included. The value-add spinel serves to offset the relatively high cost of aluminum scrap, whose normalized cost is on par with ferrosilicon, \$550–1300/tMg. However, without the solid byproduct revenue stream, a commercial plant on the order of 50,000

tpy results in a 24.9% internal rate of return and a \$163.7 million net present value using a 12% discount rate and a sell price of \$4.00/kgMg. Sensitivity analyses, Fig. 1, revealed that the sell price of magnesium was the most significant factor affecting economic metrics along with the prices of aluminum and MgO.

The use of aluminum as a reductant material was shown to be effective with the benefit of a value-add byproduct. The volatility of pricing over the past several years implies some degree of uncertainty in economic forecasting which increases the incentive to implement a production process with more than one revenue stream.

Fig. 1 Sensitivity analysis for selected factors on IRR

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