Mintek Thermal Magnesium Process: Status and Prospective

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Abstract

During the last decade, the magnesium industry has undergone drastic changes including China's dominance of primary magnesium production and its entry into the die-casting alloy industry. Metal prices declined steadily with the expansion of Pidgeon plants in China, forcing most of the Western world producers to close down, in addition to the abandonment of several new magnesium projects. The depressed prices continued until the middle of 2005. Since then, they have been increasing sharply, reaching record high in June 2008. In spite of the high prices and China's dominance, world-wide demand for primary magnesium has been gaining momentum.
The techno-economics of the Mintek Thermal Magnesium Process (MTMP) has been revisited and at current market conditions, and for operation in South Africa, it competes favourably with China's Pidgeon plants. Ideally, the process should be operated for at least 12 months at an intermediate scale (5000 t Mg/annum) before implementing this new technology at a fully commercial scale (25kt Mg/annum).

Introduction

Primary magnesium production is largely dominated by China where about 77 per cent of the world throughput is produced in relatively small Pidgeon plants [(1-3)] with capacities of 5-20kt/annum. The closure of major plants (Magnetherm and Electrolytic) and cancelling of various magnesium projects can be directly related to the rapid expansion of the Chinese magnesium industry over the last 10 years, or so. This rapid expansion lead to very low magnesium prices due to certain market factors which are specific to the Chinese economic conditions. These factors include very low labour costs, in-expensive energy and coal prices, and less onerous environmental, safety, and health laws.
Recently, the Pidgeon plants in China have been undergoing certain changes including; closure of smaller facilities (≤2000 t/a), stricter environmental, health and safety regulations, and technical improvements intended to increase the overall efficiency. The improvements include; capacity expansion, installation of vertical retorts, use of coke-oven gas or coal-water gas mixture, instead of direct combustion of coal, to provide energy for the reduction and refining furnaces, etc [(4, 5)]. In spite of these improvements, it is seriously doubtful that the Pidgeon process can be economically viable in the Western world, even at the latest magnesium prices.
The Mintek Thermal Magnesium Process, MTMP, offers an alternative to the Pidgeon process in the Western world, and could compete effectively with the Chinese producers in terms of cash operating costs. Ideally, the process should be operated at an intermediate scale (5000t Mg/annum from a single furnace) in order to confirm the operational and metallurgical data obtained during the pilot trials and thus to minimize the risks of scaling up to the full commercial scale of a 25-35 MW furnace. The rationale behind the demonstration plant are briefly discussed in this paper, along with the recent trends associated with the magnesium market.

Status of the MTMP

The MTMP is based on silico-thermic reduction of calcined dolomite (dolime) in a DC open arc furnace at atmospheric pressure. It was first developed in the mid 1980's at the 100kW scale of operation [6, 7]. Pilot plant trials were carried out in the period 2000-2004 [8-16]. These trials were conducted at 750-850 kW scale (80-100kg Mg/h). The trials were concluded with a successful campaign towards the end of 2004, where the pilot plant was operated for over 52 hours of feeding on a continuous basis, achieving high condensation rates and very good magnesium extraction (in contrast, the cycle time of the Pidgeon process is between 10-20 hours, while that of Magnetherm is 10-12 hours). A scoping study was then undertaken jointly by Anglo American Corporation (AAC) and Mintek to thoroughly analyse and evaluate the metallurgical and operational data collected throughout the trials. The study concluded that certain aspects of the process could not be proven at the pilot scale, and therefore an intermediate stage (demonstration plant) should be built first. These aspects include the condenser liquid metal cooling circuit, specific condensation area, and scalability to a commercial size of 25-35 MW.

The size of the pilot condenser, and hence its surface area, was largely dictated by its in-and-outlets and by the stirrer assembly. As a result, its surface area was relatively large resulting in large energy losses to the surroundings. The pilot condenser therefore, required external (gas) heating as a means of maintaining its temperature at about 700°C. Industrially, the energy of condensation needs to be extracted from the condenser very quickly in order to achieve high condensation rate. Energy removal should also take place while maintaining the condensing surface at an appropriate temperature range. This is envisaged to be accomplished by using liquid metal cooling circuit (such as tin, lead, etc).

The demonstration plant should be capable of achieving a specific condensation rate of 80kg Mg/h/m^2, and higher, in order to limit the size of the commercial condenser to less than 3 meters in diameter (25 MW plants). This condensation rate could not be approached in the pilot condenser as a result of its large surface area, where an average rate of 30-40 kg Mg/h/m^2 was obtained. Commercially, the target condensation rate is expected to be at least 100kg Mg/h/m^2.

Another aspect that calls for a demonstration plant is the scalability to a commercial size. In particular, scalability of certain condenser components, such as the ducting between the furnace and condenser, the stirrer assembly, and the mechanical cleaning devices of the condenser inlets and outlets, and their mechanical and operational performance, are very important so that the demonstration plant can be operated on a more continuous basis. This is to ensure that steady operation is realized for relatively long period of time with an overall availability of 80%, and more.

The target availability is crucial in order to allow the generation of reliable metallurgical and operational data required to design and build the commercial plant. High availability could also allow the optimization of feed recipe, slag granulation, and testing of various dolomite resources and qualities.

The feed recipe employed during the pilot plant trials was based on the Magnetherm process and aimed at 10-12% Al_2O_3 in the slag for ease of tapping the furnace at moderate temperatures. This Al_2O_3 slag content required between 5-6% Al addition (mass percent of the dolime feed). However, it is possible to carry out magnesium extraction with ferrosilicon as the only reducing agent [11], depending on the relative costs of aluminium, FeSi, and magnesium.

Slag granulation may offer the opportunity to investigate its suitability as a cement additive. If successful, the slag could contribute to the overall economics of a commercial installation.

Two large dolomite deposits that are believed to be suitable for magnesium production exist in the Western Cape. The estimated reserves are 25 million tons at Vredendal and 60 million tons at Bridgetown. However, several other deposits are located in Gauteng area, but are thought to be of inferior quality. The demonstration plant can offer an opportunity to test such deposits, and to determine the sensitivity of the process to changes in the quality of dolomite.

The above considerations lead to the conclusion that a 5MW plant should be built in order to adequately demonstrate the process, in addition to the costs associated with the design, construction, and operation of the plant.

Market Aspects

Uses. The major uses of magnesium are: die-casting alloys production, aluminium alloying additions, steel de-sulphurisation, and titanium sponge production (4, 17, 18). The low density of magnesium and its excellent die-casting characteristics make it very attractive for the manufacture of automotive components that have been traditionally made using aluminium alloys. The drive here is to reduce the weight of the vehicles, and thus to improve fuel efficiency and decrease CO_2 emissions.

Since the mid 1990's, the annual growth in the usage of die-cast automotive parts has averaged 10-15% in the Western world, while that in China is said to be much higher, particularly over the last 4-5 years (4). The die-casting alloys market is currently the largest single user of magnesium (Figure 1), with China being the biggest consumer. Its die-casting industry has been growing at more than 50% annually for the past 5 years, reaching over 90 kt in 2007.

Magnesium usage in the aluminium industry is the second largest consumer of the metal. It is usually added in small proportions (typically ≤1%, but Al-alloys containing up to 10.6% Mg are also produced) in order to obtain a strong alloy with good corrosion-resistance properties. Magnesium-containing aluminium alloys are used in packaging, transports and construction, with annual consumption of 140, 80, and 40 kt, respectively (2006).

Magnesium has a unique affinity to sulphur, and when mixed with lime, its efficiency in capturing the sulphur content of molten steel is significantly improved. With steel production increasing by about 8% annually, demand for magnesium by this sector could grow by 6-7%.

The fourth largest use of the metal is in titanium sponge production. The ratio of magnesium required to titanium is approximately 1:1. However, the magnesium chloride produced in the Kroll process is partially recycled back to magnesium metal. Although the demand for titanium has been growing rapidly, and is expected to grow by 7% to the year 2012, recycling of $MgC1_2$ and the potential development of direct and continuous reduction process of titanium dioxide, magnesium growth in this sector may not exceed 2%. Other uses of magnesium include cathodic protection, nodulizer in ductile cast iron, batteries and certain chemicals.

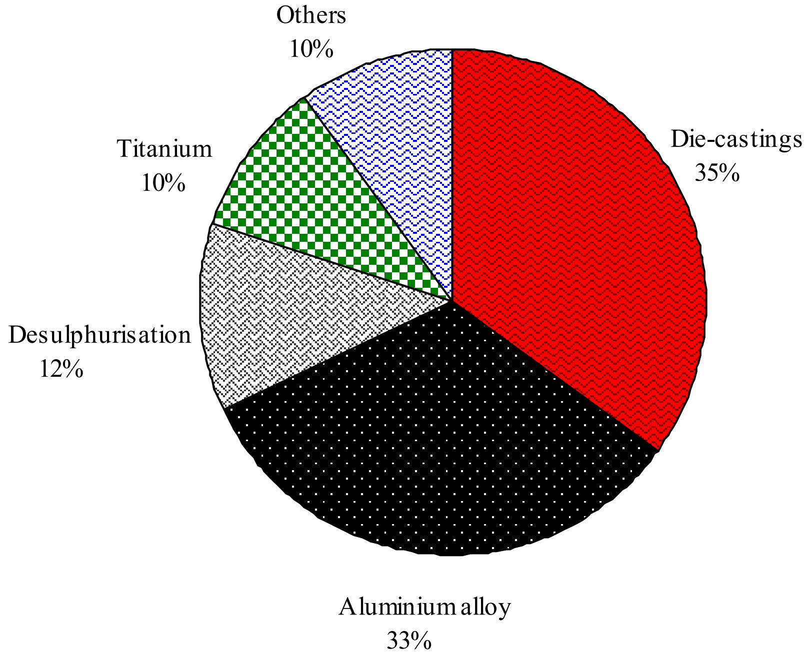

Figure 1. Magnesium consumption by sector (2006).

Production. In spite of the closure of several major plants over the last eight years, primary magnesium production has been growing steadily since 2002 as a result of the rapidly expanding Pidgeon plants in China, where its throughput of the metal represented about 77% of the total production in 2007 (Figure 2). Outside China, the main Western producing countries are the USA and Israel. Russia, Khazakhstan, and Ukraine produced about 110 kt in 2007, mostly to service their titanium production. Recycling of the metal added about 140kt during last year [(4)].

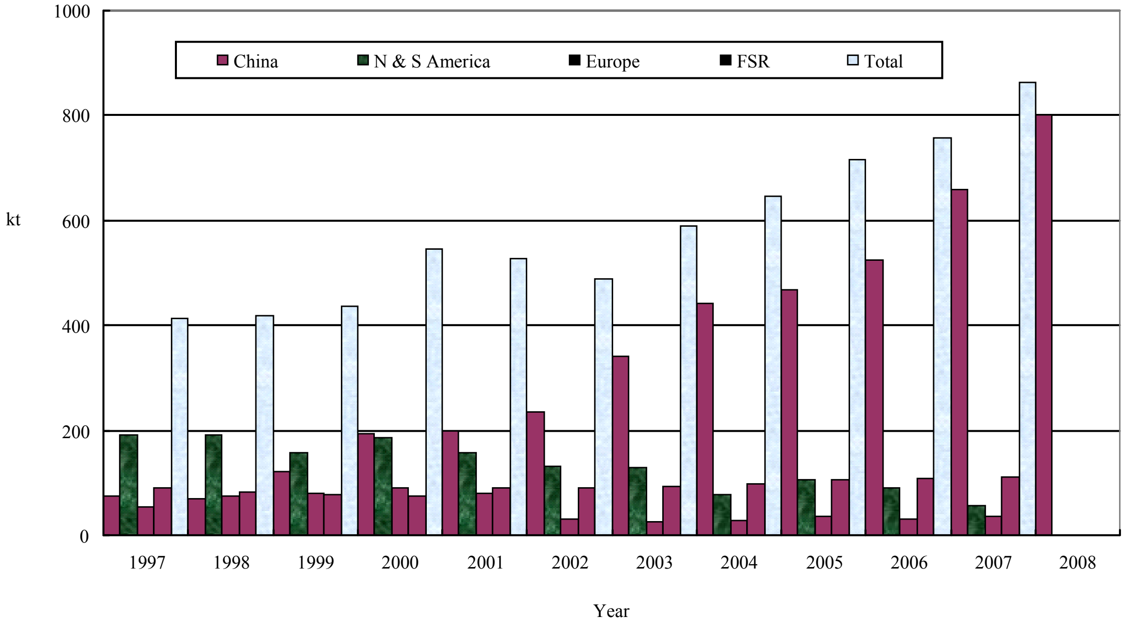

Figure 2. Magnesium production by region/country.

Demand. In addition to its dominance in primary metal production, China is expanding its die-casting alloys sector at more than 50% annually since 2002, as well as other areas, making it the largest single consumer of the metal (Figure 3). In 2006, die-casting accounted for more than 35% of magnesium consumption, as compared to about 15% in the early 1990's. This field of application is the largest growing area and is predicted to show a 10% annual growth for the next three to four years [(4)].

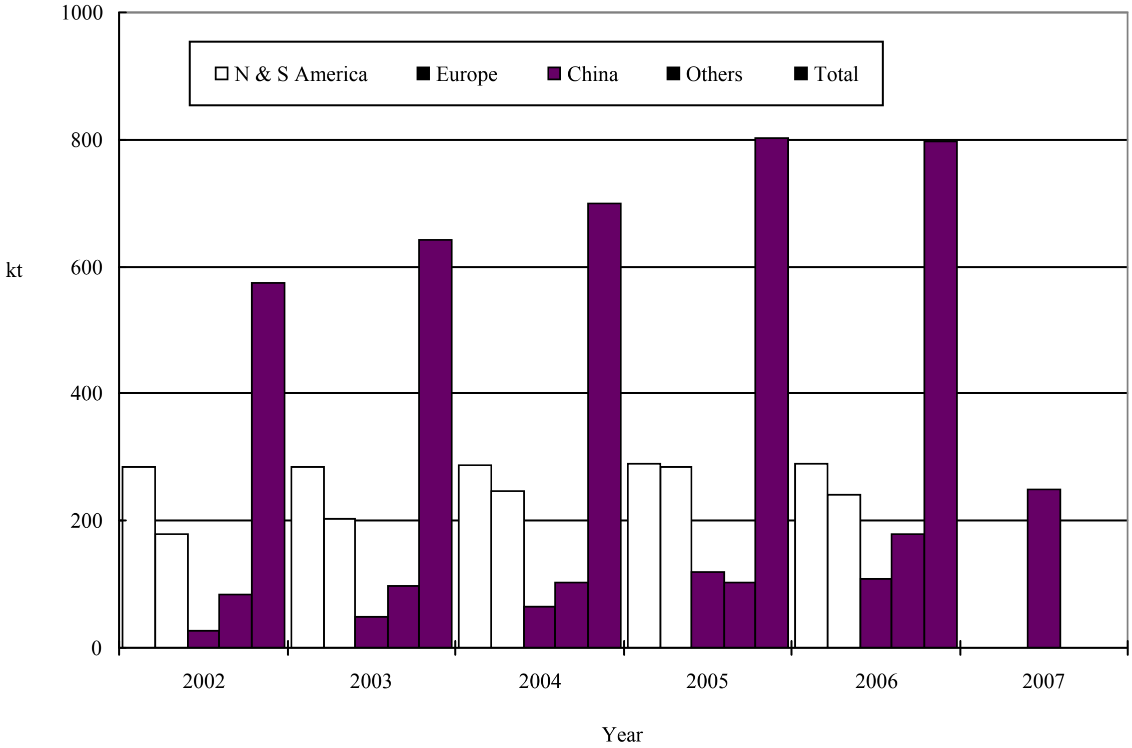

Figure 3. Magnesium consumption by region/country.

Capacity. In 2007, world-wide primary magnesium capacity was estimated at about 1100 kt/year (Figure 4), with China accounting for more than 75% of the total. In addition, Chinese producers are believed to be expanding their capacity by over 210 kt/year. The additional capacity is expected to come on-line in 2008/2009 [(4)].
It is interesting to note that Alcoa is evaluating restarting their magnesium plant. The plant had a capacity of about 35 kt/year before it was shut down in 2001 [(19)]. Also, Silmag announced their intention to operate the Norks Hydro plant in Norway to produce 35 kt/year, with production being scheduled to begin in 2011 [(5)]. Other major magnesium projects being considered could add about 270 kt/annum of extra capacity world-wide, which could bring the total capacity to almost 1.5 Mt/y by 2015.

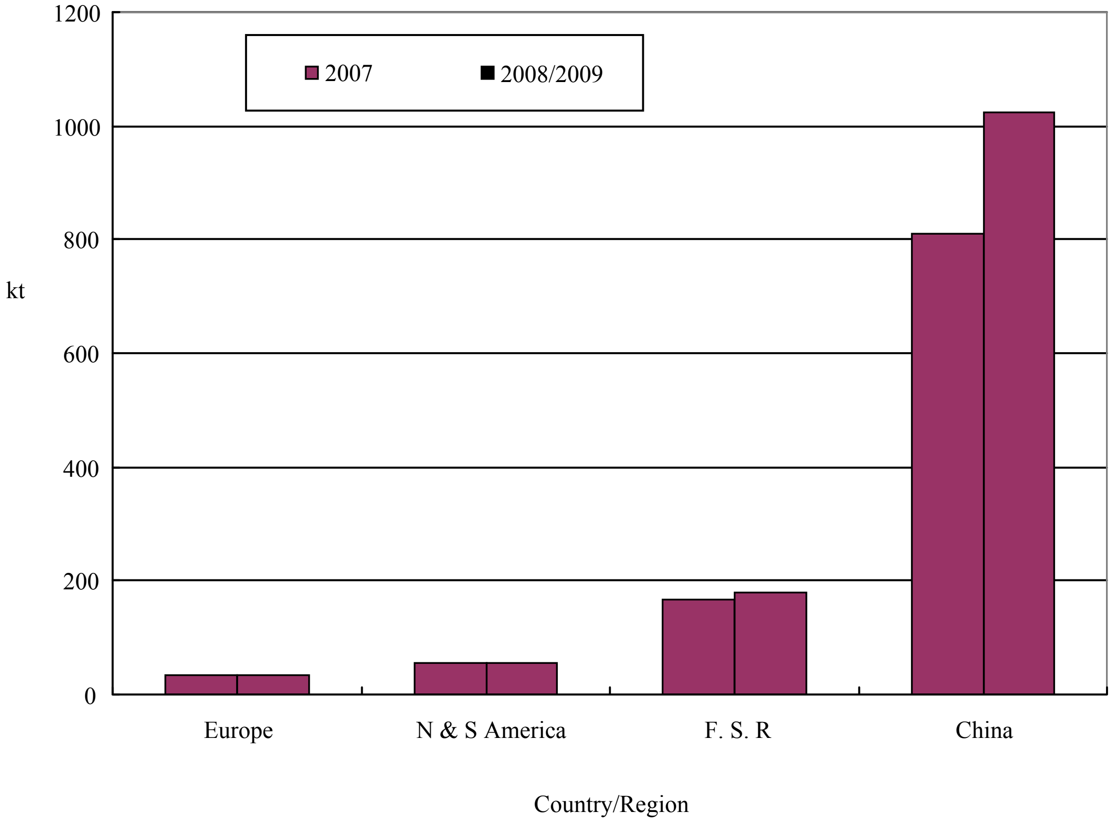

Figure 4. Production capacity of magnesium (Source: Platts metal week).

Prices. The planned capacity expansion is not surprising given the strong demand for the metal and more importantly its current prices (Figure 5). Since 2002, the prices have been increasing steadily. In particular, in the last two years, magnesium prices have more than tripled, reaching a record high of over US$ 6000/ton in June of this year [20].

Several factors might be playing a role here, including the boom in commodity prices as a whole, rising costs of ferrosilicon, electrical energy and coal, stricter environmental regulations, and, mostly likely, increasing labour costs in China in recent years.

It is believed that Alcoa's decision to study starting up their plant and the planned production of magnesium by Silmag at the former Norsk Hydro plant are partly influenced by these prices. Notice that the ferrosilicon prices have shown similar trends to those of magnesium in the period 2000 to 2008.

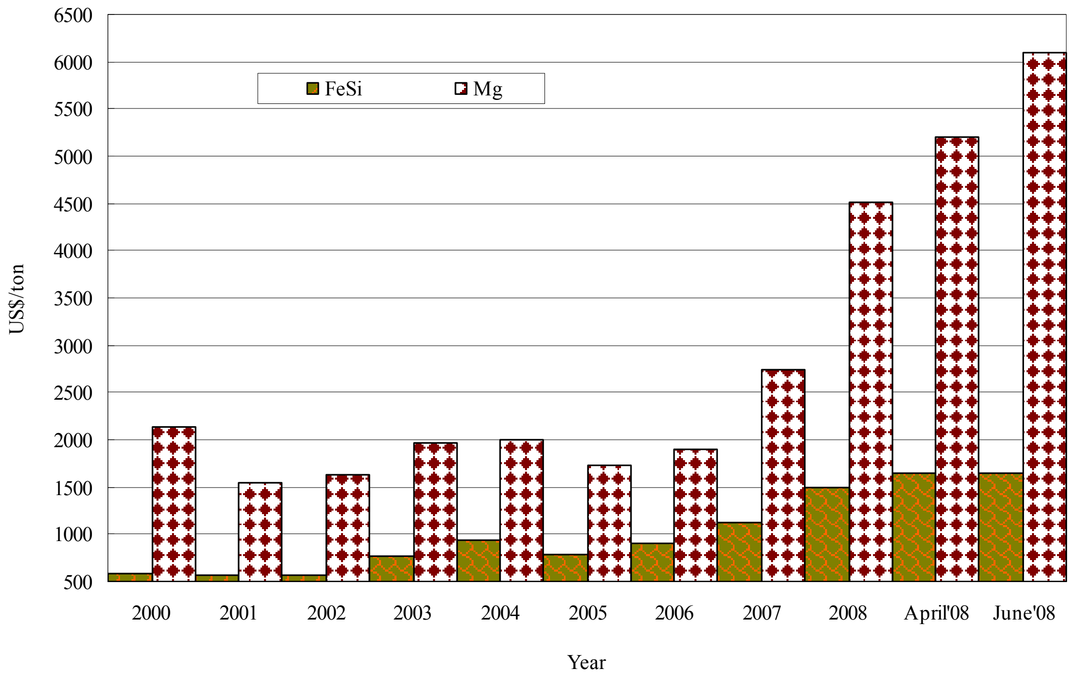

Figure 5. Historical prices of magnesium and ferrosilicon (Source: Metal Bulletin).

Economics of the MTMP

Background

While the economic analysis must be regarded as being of a conceptual level, care was taken to produce as realistic an answer as possible given the level to which the pilot plant results were obtained and the potential accuracy of the capital and operating costs.

In terms of capital, three of the four major unit operations were specified in as much detail as possible. An international technology vendor provided a budget estimate for the dolomite calcining kiln. The furnace plant cost was based on a recent estimate by a large contracting engineering company and the capacity factored to the appropriate power rating. Finally, the magnesium refinery and casting section was costed by another engineering contractor that had previously done a detailed design for a similar facility. In the latter instance, the cost was escalated to Q2/3, 2008, a process that may have introduced some uncertainty. Of late, the process of escalating historical cost data has been fraught with problems due to individual cost indices not keeping pace with real changes in the industry.

The operating cost predictions are believed to be of a higher level of accuracy but unit prices carry distinct uncertainties. This observation is especially true of ferrosilicon. Likewise, the magnesium selling price has increased dramatically and any long term prediction is unlikely to have any realism. However our best attempts were made to predict these prices.

Capital cost

Table 1 reflects the total fixed capital in Q2/3, 2008 terms. The site chosen was the Western Cape area of South Africa where a good grade of dolomite is available. As far as is known, no suitable dolomite exists in other parts of the country. Transport of this material, at least over any significant distances, would deleteriously affect the economics. Each important section of the plant was considered and the individual costs include allowances for EPCM and contingency, each at 20%. Building costs are not shown separately but included with the appropriate line items

Table 1. Fixed capital Costs

ITEM	COST [R, million]
Site development/civils	160
Dolomite/coal sizing and handling	215
Calciner	965
DC furnaces with condensers	1 480
Off-gas handling	75
Magnesium refinery/caster	550
Cooling water plant	40
Utilities	130
Slag handling/effluent treatment	40
Electrical supply [excludes furnace power systems]	210
Instrumentation and controls	40
Infrastructure	50
Owners cost	60
TOTAL	4 015

Note: The costs relate purely to a battery limits plant without any infrastructure outside the boundary fence. For convenience, a capital cost of R4 billion was used for the economic analysis.

Operating Costs

Two important cost/revenue components are the price of ferrosilicon and the selling price of magnesium ingot. These will be discussed later but it is important to stress that they are based in dollar terms. An exchange rate of USD 1.00 = R8.00 is assumed.

Table 2. Variable Costs

ITEM	UNIT	COST PER UNIT [R]	UNITS/t Mg	R/t Mg	Note
Dolomite	t	140	12.2	1 713	
Ferrosilicon	t	17 593	0.96	16 914	1
Coal	t	575	1.5	884	2
Electrodes	kg	25	10	250	
Fluxes, etc.	R	1	230	230	
Effluents/environmental	R	1	375	473	3
Electricity	MWh	210	9.1	1 911	4
Argon	kg	4	116	466	
LPG	GJ	80	6	480	5
Water	kl	4	92	368	
TOTAL				23688	6

Notes:
[1] Priced at US$1.33/lb of contained Si
[2] The calcining operation is based on coal as the fuel for the kiln
[3] The principal waste that requires treatment is the sludge from the condenser and the Mg refinery
[4] The Eskom Megaflex tariff was used and a factor added for penalties. It will be appreciated that the supply and cost of electricity in South Africa are subject to significant uncertainties

[5] As natural gas is not available, it was assumed that LPG will be used in the Mg refinery
[6] The total was calculated after rounding

Table 3. Fixed Costs

ITEM	COST [R'000/a]
Labour	45 000
Maintenance [4% of fixed capital per annum]	160 000
Insurance [0.75% of fixed investment]	30 000
Overheads [5% labour + maintenance]	10 250
TOTAL	245 250

Revenue

The ex-works seling price of magnesium ingot was taken as US$2.50/lb [equivalent to US$5 512/t] which, at 70 000 t/a, yields an annual revenue of about R3.1 billion.

Economic Analysis

A discounted cash flow analysis was done over a production life of 25 years. The basis for the study is listed below:

- Fixed capital outlay over 3 pre-production years , the cash flow pattern being 10% of the total in Year -2, 30% in Year -1 and 60% in Year 0.
- Production commencing in Year 1 at 60% of design capacity, 80% in Year 2 and full capacity [70 kt Mg] in Year 3 and onwards.
- Working capital provided at 4 weeks of raw materials, products and creditors, 6 weeks of maintenance materials and 8 weeks of debtors. The latter is to cover export of the Mg produced.
- Depreciation for tax purposes at 5% per annum for plant buildings and 20% per annum for productive plant. Of the total capital, 10% was assigned to buildings and 80% to productive plant.
- Tax rate of 28%. Losses in the early years were rolled over.
- Real IRR and NPV values calculated, i.e., no escalation included with all monetary values in Q2/3, 2008 ZAR. Capital funding on a full equity basis.

Table 4 Operating Income Statement

	R'000
FIXED CAPITAL	4 000 000
WORKING CAPITAL	588 099
	R'000/a
REVENUE	3 086 440
COSTS	
Variable	1 658 131
Fixed	245 250
TOTAL	1 903 381
GROSS PROFIT	1 183 059
IRR (%)	18

NPV (15% discount rate) (R'000)	638 849

A sensitivity analysis revealed that the project is marginally sensitive to changes in capital cost but more so to operating cost and magnesium selling price. If opex is increased by 10%, the IRR reduces to 15%. At selling price decreases of 10 and 20%, the IRR numbers are 13% and 8% respectively. One mitigating factor is that changes to Mg selling price and ferrosilicon price follow a pattern that, however is neither exact nor rigid. Allowing for lags and leads, this means that a reduction in selling price is accompanied by a roughly proportional decrease in the cost of the reductant.

Comparison of Technologies

Background

The recent increase in the selling price of magnesium has generated keen interest in manufacture outside of China. There is speculation that the Northwest Alloys plant and that of Norsk (in Norway) could be re-started. Given the shortcomings of the Magnetherm process and the high capital outlay of an Electrolytic plant, these recent developments may offer an opportunity for MTMP magnesium plant to be installed in South Africa in the future. It is necessary therefore, to review the different technologies in order to determine if any one has a material economic advantage.

A comparison of 3 processes was done at no better than an indicative level (Tables 5-7). Any studies of a more accurate nature would require a significant engineering input to obtain capital and operating costs. Historical data were revised and benchmarked against the latest estimates for the MTMP process. The salient aspects of the two competing technologies are as follows:

- Fused salt electrowinning [FSEW]: The process is not well suited to South Africa because suitable magnesite is not available. Thus, the economics were based on the importation of magnesite. This, however, did permit a reasonably favourable location to be chosen, viz. on the east coast of the country where chlorakali products and natural gas are potentially available.
- Pidgeon process: This, styled on current Chinese plants, must be situated in the West Cape so as to be near good dolomite resources.

Capital Costs:

Total fixed capital outlays are given in Table 5. A Pidgeon plant could cost about 40% of that of an MTMP facility, while that based on the Electrolytic process may be twice as expensive.

Table 5. Order of Magnitude Capital Costs

	MTMP	FSEW	Pidgeon
Rand million	4 000	7 800	2 400
$/lb Mg	3.24	6.32	1.94
$/t Mg	7 100	13 900	4 300

Notes:

[1] For the FSEW a capital of $9 000/annual ton Mg was the basis. This dated to about 2005 and was escalated to present day SA conditions

[2] In the authors' opinions there is no possibility of achieving a figure of $1 000/annual ton of Mg for a Pidgeon plant. We judged certain items of the plant to be almost identical with the MTMP facility.

These are listed below and represent about 47% of the MTMP capital cost. For the rest, earlier estimates were used and appropriately escalated. Even 3-4 years ago one of the author's formed an opinion that the Chinese capital figure was an artificial one that bore no resemblance to reality, at least outside China. The identical areas are:

- Site development
- Material handling
- Calcining
- Mg refining and casting

Variable costs

The variable costs of an MTMP plant are intermediate to those of an FSEW and Pidgeon, where the latter is significantly high at about US$1.81/lb Mg ingot.

Table 6. Variable Costs

Item	R/t Mg			Note
	MTMP	FSEW	Pidgeon	
Dolomite	1 713		1 680	
Magnesite		3 000		1
Ferrosilicon	16 914		19 704	2
Coal	884		9 250	3
Hydrogen chloride		1 125		
Hydrogen		2 500		
Other	1 786	4 950	650	4
Electricity	1 911	4 200	250	
Gas	480	2 592	480	5
TOTAL	23 688 (1.34)	18 367 (1.04)	32 013 (1.81)	6

Notes:
[1] Taken as 4 t/t Mg @ R750/t
[2] According to published data a Pidgeon plant is less efficient in consuming ferrosilicon
[3] Published information points to Chinese plant using anthracite for both reduction and energy
[4] The FSEW estimate includes expenditure on electrodes, environmental and utilities
[5] The presumption is that an east coast plant will be able to procure natural gas at R48/GJ
[6] Figures in parenthesis are US$/lb

Fixed Costs

The fixed cost component derived for the FSEW process is 300 and 80% higher than those pertinent to the Pidgeon and MTMP cases, respectively. This is largely due to the capital costs presented earlier.

Table 7. Fixed Costs

Item	R million/a			Note
	MTMP	FSEW	Pidgeon	
Labour	45	45	55	1
Maintenance	160	312	72	2
Insurance [0.75% of capital]	30	58	18	
Overhead [5% of labour/maint]	10	18	6	
TOTAL	245	433	151	
$/lb Mg	0.20	0.36	0.12	

Notes:
[1] While the Pidgeon process uses far more people than the other two, the majority are unskilled labour. This was taken into account in arriving at the costs but, in the absence of a detailed staffing

schedule, the estimate must be regarded as having a high level of uncertainty. Intuitively the feeling is that the total cost is understated.
[2] For the MTMP and FSEW plants maintenance was calculate at 4% of fixed capital annually. In the case of Pidgeon, this was reduced to 3% due to the reactors being relatively unsophisticated. Again, a Pidgeon plant has multiple reactors which may partially offset this advantage,

Economic analysis

Applying the same parameters as was done for the MTMP, the comparative returns for the three processes are as shown in Table 8. The IRR for the MTMP case is only marginally higher than that of a Pidgeon plant, but it is about 65% higher than that of the FSEW process. Overall, the analysis tends to indicate that the MTMP offers better economic returns.

Table 8. Economic Returns

	MTMP	FSEW	Pidgeon
IRR (%)	18	11	16
NPV (R'M)	639	-149	154

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