PILOT PLANT DEMONSTRATION OF THE MINTEK THERMAL MAGNESIUM PROCESS

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ABSTRACT

Successful demonstration of The Mintek Thermal Magnesium Process (MTMP) was achieved in November 2004 at the pilot-scale. About 30 tons of magnesium producing recipe was smelted in the DC arc furnace over a continuous operation of 8-days. Twenty-two furnace batching-tapping operations were carried out at a feed rate of 525kg/h and a smelting temperature of 1600-1700^{0}C. The MgO content in the produced slag was as low as 6.7%, and averaged 9.2% MgO, resulting in an overall magnesium extraction of 77%, which reached 87% during good operating periods. Magnesium vapour was extracted at a rate of 70-85kg/h and was delivered to the condenser that was operated at 680-720^{0}C. The magnesium was captured in the condenser crucible in a liquid state, allowing its prompt tapping. More than 3500kg of crude metal were produced over 15 on-line metal tapping operations. On average, a condensation efficiency of 85% was achieved during the entire testwork, which peaked at 87% during steady operations. The quality of the crude metal was similar to, if not better than, that of the Magnetherm's crude magnesium. A pre-feasibility study has indicated that the MTMP has the potential for lower capital and operating costs as compared to the electrolytic process, and therefore Mintek and its consortium partners are exploring opportunities for a commercial production facility.

INTRODUCTION

Since early 1990's, a large number of Pidgeon plants [1] have been built in China, where the annual magnesium production has reached more than 400kt, or about 70% of total 2004 world production [2,3]. The Pidgeon process, invented first in Canada in the 1940's, is a labour intensive batch process, and is usually operated at 0.001atm and lower. It relies on solid state reduction of calcined dolomite (dolime) in the presence of ferrosilicon at temperatures of about 1150^0C. A semi-continuous scaled-up version of the Pidgeon process was developed in France in the 1960's. It is commonly known as the Magnetherm process [4,5] and relies on AC submerged arc smelting of calcined dolomite in the presence of ferrosilicon and aluminium. It is carried out at low pressures (0.05-0.10atm) and at 1550-1600^0C.

During the 1980's, Mintek began small-scale testwork in order to develop a more continuous thermal process for magnesium production [6,7]. The process is referred to as Mintek Thermal Magnesium Process, or MTMP, and is based on atmospheric magnesium extraction from dolime and/or magnesia in a DC open arc furnace. The reaction is carried out at temperatures of 1700-1750 ^{0}C, using ferrosilicon, and if required aluminium, as the reducing agent [8-13]. The volatilised magnesium is captured in a condenser assembly as liquid, also at atmospheric pressure, allowing its prompt tapping and thus maintaining a continuous operation.

Since the year 2000, extensive development testwork has been carried out on a 100kg/h magnesium MTMP pilot plant. During the first nine runs (campaigns), a prototype Magnetherm condenser was used, which allowed the attainment of good condensation efficiency (up to 80% in Run 9). However, prompt tapping of the condensed metal was difficult, and thus most of the runs were terminated prematurely. After Run 9, it was concluded therefore that a radically new condenser design was required. The novel condenser was built and commissioned in June-October 2004. This was followed by an 8-day continuous campaign (Run 10) in November 2004.

This paper gives a brief description of the MTMP pilot plant, the operating strategy, and certain metallurgical and operational data obtained during Run 10. A brief economic analysis of an MTMP magnesium plant is also presented and compared with the electrolytic process.

PILOT PLANT DESCRIPTION

A schematic of the 100kg/h magnesium pilot plant is shown in Figure 1. The equipment consists of a 1.5 MW (10kA) power supply, a DC arc furnace, a raw material feed system, a magnesium condenser, a combustion chamber, a gas-cleaning system, and certain other ancillary equipment. The airtight feed system consists of three surge bins (upper bins) and three weigh bins (lower bins), varying in size from 60 *l* to 550 *l*. Each pair of upper/lower bins is dedicated to deliver a specific raw material to the furnace. The feed system is designed to feed 250 to 500 kg/h hot dolime (at up to 900°C), 40 to 80 kg/h ferrosilicon, and 15 to 60 kg/h aluminium to produce 50 to 100 kg/h magnesium vapour. The upper bins are provided with argon and vacuum lines for purging, after

charging batches of raw materials to them. Airtight valves are positioned between each pair of bins. Vibratory feeders are used to charge the ferrosilicon and aluminium, while a rotary feeder is employed to feed the dolime into the furnace.

The furnace consists of a refractory-lined cylindrical shell and a conical roof. The furnace has an internal diameter, at the slag level, of about 1200 mm, and a shell diameter of 1900 mm. The hearth area is lined with carbon blocks, while magnesia-based refractories are used for the hot face, above the slag level (due to the erosion of the side wall refractory, neutral slag recipe was employed to warm-up the furnace and to form a freeze lining, as will be discussed later) . The anode connection consists of two graphite rods, cemented into the carbon hearth-blocks. The graphite rods are further linked to the anode cables via water-cooled copper pins. The furnace shell is equipped with water spray cooling. Water-cooled panels are used at the conical roof, which is lined with alumina castable. The roof contains a central entry port for the graphite electrode, an off-gas duct, and a feed port. The electrode seal consists of a flexible stainless-steel bellow. The off-gas port contains vermiculite based bricks, behind the alumina hot-face castable.
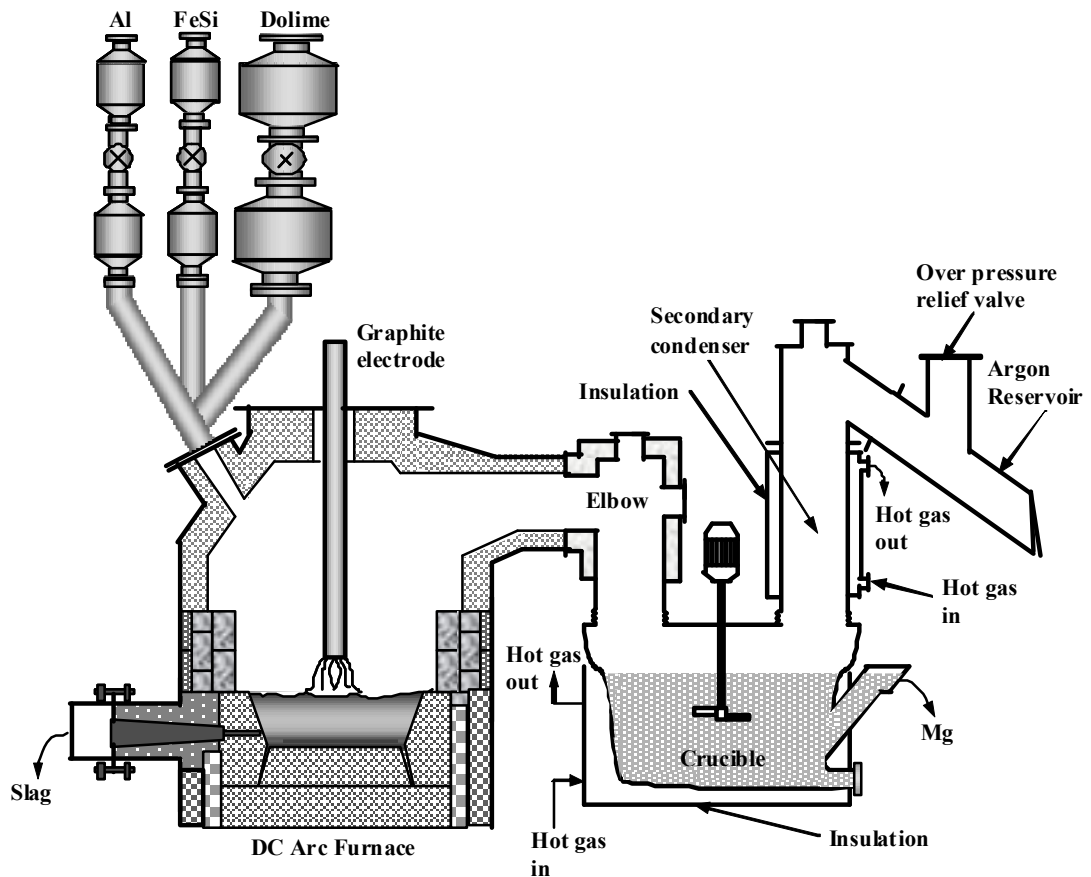

Figure 1 - Lay out of the MTMP pilot plant

A radically new condenser was designed based on certain principles in order to allow continuous (semi-continuous) operation of the facility for extended period of time.

It allows the removal of the condensed magnesium along with any oxides that might be present. Flow restrictions and blockages in the condenser system are also dealt with on-line without interrupting magnesium production.

The new condenser set-up includes an elbow section, a crucible, a secondary condenser, a stirrer, and plungers for the clearing of blockages. The top section of the condenser (elbow) incorporates a thermally insulating refractory material, between concentric 3Cr12 stainless steel sleeves (ferritic steel developed by Southern Africa Stainless Steel Development Association, SASSDA), with an inner diameter of 400mm. The elbow forms the connection between the furnace and the condenser crucible. The condenser crucible consists of a cylindrical steel shell, a dished bottom, and a flat top plate. The crucible is 1.2 m in diameter, 1.3 m high, and is made of 28 mm thick 3CR12 steel plate. The top section is widened to fit the inlet and outlet into a relatively small diameter crucible. The crucible contains an underflow/overflow arrangement, consisting of an inclined spout and an overflow box, in order to remove magnesium under sealed conditions.

During operation the magnesium level is kept between the bottom and the middle of the overflow box, for effective operation of the condenser. The impeller of the stirrer is engineered to create a vortex in order to pull in oxides and magnesium vapour. The condenser crucible contains three baffles to break up the centrifugal motion that is induced by the stirrer, and to enhance mixing.

A secondary condenser is connected behind the crucible and consists of a cylindrical 3CR12 steel pipe, 400mm in diameter, and 1.7 m long. The surface area of the secondary condenser is designed such that it is sufficient to condense all the magnesium vapour produced in the furnace.

The condenser system also includes two propane burners for preheating of the condenser crucible and the secondary condenser, and for maintaining the condenser temperature at 650°C to 750°C during magnesium production.

Three hydraulic plungers are included for the on-line cleaning of blockages in the crossover duct between the furnace and the condenser, in the elbow, and in the secondary condenser.

The off-gas system consists of an argon reservoir (mild steel, 350mm diameter), equipped with a flap valve arrangement devised to prevent a large amount of air from entering the condenser via the combustion chamber, and a pressure release disc. The combustion chamber is refractory lined and equipped with a pilot burner to oxidize any uncondensed magnesium, carbon monoxide and hydrogen. The reverse-pulse bag-filter is intended to separate the oxidized magnesium from the off-gas, and to vent only clean air and argon to the atmosphere. Auxiliary equipment included a condenser cleaning station, drill machine-mud gun assembly for slag tapping, etc.

RAW MATERIALS

The magnesium generating charges consisted of calcined dolomite (dolime), ferrosilicon, and aluminium. Dolomite from the Vredendal deposit (Western Cape), calcined at Vereeniging Refractories, (Verref, a South African refractory producer) was the source of magnesium. The dolime (Verref grade RS57, Table 1) with a size range of

6 to 20mm was supplied in 500kg bulk bags, wrapped with vacuum-sealed plastic liners to prevent absorption of moisture and carbon dioxide during transport and storage. Lumpy ferrosilicon (6-12mm) from Rand Carbide and aluminium pellets (5-15mm) from Zimalco (a member of the Zimco Aluminium Group), were used as reducing agents. The average chemical analyses of ferrosilicon and aluminium appear in Table 2. Carbon, LOI (loss on ignition), moisture, and BET (specific surface area) analyses of dolime are given in Table 3. Magnesium ingots, acquired from Metallurg SA (a South African Metal trader) were used as a metal heel in the condenser crucible Table 2).

Table 1 - Analyses of dolime, mass per cent

Component	Dolime
MgO	37.49
Al_2O_3	1.34
SiO_2	3.33
CaO	55.60
Fe_2O_3	1.55

Table 2 – Analyses of ferrosilicon, aluminium and magnesium, mass per cent

Element	FeSi	Al	Mg-heel
Mg	0.00	0.0025	99.50
Al	0.74	99.8	0.0064
Si	76.7	0.06	0.0130
Mn	0.13	0.0025	0.0160
Fe	21.9	0.15	0.0051
Ni	0.02	0.01	0.001

Table 3 - Mass per cent carbon, LOI, and moisture in dolime and BET results

Carbon	LOI	Moisture	BET, m^2/g
0.035-0.082	0.02-0.05	<0.10	0.018-0.030

OPERATIONAL AND METALLURGICAL RESULTS

Kiln and Furnace

The dolime was heated up in an electrically operated kiln. The kiln temperature was between 1000-1100^{0}C, and was rotated at 3.0-3.5rpm. The feed rate was varied in order to match the furnace requirements and ranged from 250-400kg/h. The heated dolime was collected in refractory-lined transfer bins and then discharged into the furnace feed system. Temperatures taken in the dolime upper hopper indicated a dolime temperature of 550-630^{0}C, as compared to 640-750^{0}C measured at the kiln discharge.

The furnace total feed rate averaged about 525kg/h (10.7%FeSi, 5.5% Al, the balance being dolime) and the feed duration was about 2.5 hours, giving a batch size of

1300kg. The feed recipe was selected based on the relative ease of tapping of the resulting slag at the temperatures employed. Commercially, the recipe will be largely dictated by the overall economics of the process. About 30 tons of magnesium producing recipe was processed over 22 feeding-tapping operations, where 24 tons of slag was produced. The furnace energy losses averaged about 360kW. The operating power was about 780kW, on average, and varied between 680 and 870kW, depending on the feed rate, furnace energy losses, and the dolime temperature, as measured in its weigh bin. An operating voltage of 180-200V was employed during the smelting period. The power-voltage operating ranges resulted in an arc length of 100-250mm (shorter arc at the end of the batch where the slag depth was 430-460mm, longer arc at the beginning of the feeding period where the slag depth was 80-150mm).

Slag tapping was carried out by drilling through the tap-hole, followed by oxygen lancing, when required. This practice introduced some oxygen into the furnace and condenser, and resulted in at least partial oxidation of residual magnesium vapour in the system, and possibly some of the condensed metal inside the condenser assembly.

The slag tapping temperature throughout most of the testwork was relatively low (Figure 2) and averaged about 1615^0C. Due to the severity of the furnace refractory erosion, particularly the sidewall bricks, no serious attempt was made to control the slag temperature at the target value of $1700-1750^0$C, i.e., by increasing the power set-point. The relatively low furnace operating temperature contributed to high MgO content in the slag (Figure 2), which averaged about 9.2 %. Other factors that may have influenced the slag MgO analysis included:

1. Carry-over of the neutral slag recipe where the MgO analysis was 18-21% (Table 4). In addition to heating up the furnace to the desired temperature, this slag recipe was intended to form a freeze lining on the furnace sidewall. However, interactions with the magnesium producing recipe and with the resulting slag lead to the remelting of the freeze lining and thus to the relatively high MgO in the tapped slag.

2. The furnace roof refractory (castable alumina) was partially replaced by a layer rich in MgO, as established during the dig-out. The surface of this layer was fairly loose, and a proportion of it could have fallen onto the slag bath during the testwork, adding to the slag MgO content, as well as to that of alumina (Table 5). The MgO-rich layer is believed to have formed by the reaction between the magnesium vapour and the roof refractory according to:

$$3 \text{ Mg}_{(v)} + \text{Al}_2\text{O}_3 = 3 \text{ MgO} + 2\text{Al} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \ldots.(1)$$

Reaction of magnesium vapour with air (due to small leaks) and oxygen during lancing could have contributed to the formation of such layer.

3. Chemical dissolution and thermal erosion of the MgO-based refractory bricks (on the upper sidewalls of the furnace shell) might have affected the MgO analysis in the tapped slag.

4. Others including relatively high levels of Fe_2O_3, SiO_2 and Al_2O_3 in the dolime, ineffective bath mixing (agitation was due to only arc-induced stirring), and insufficient retention time.
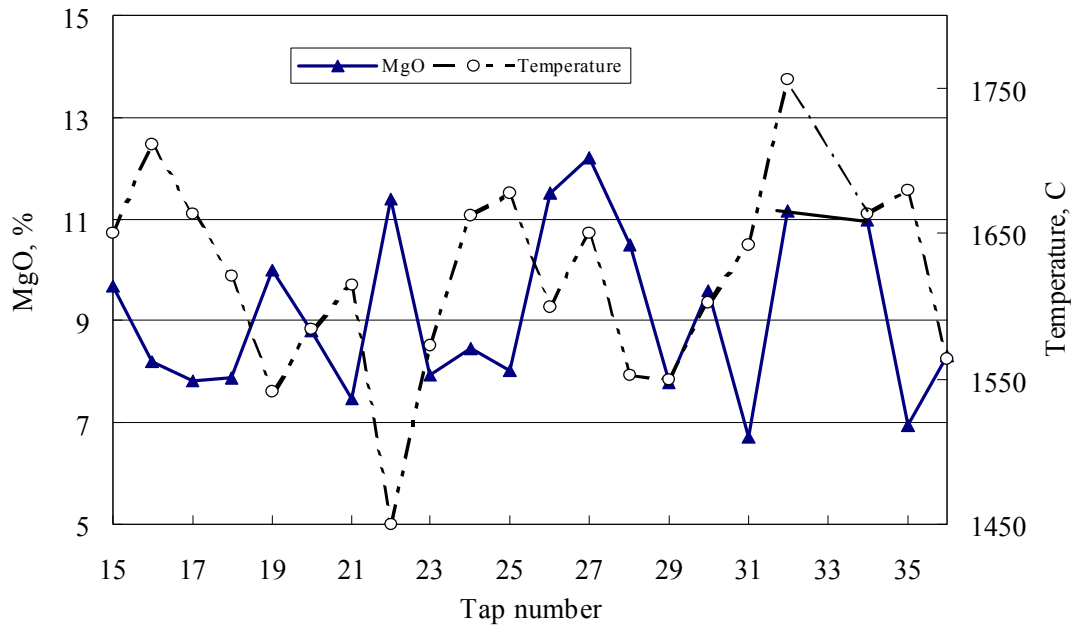
Figure 2 - MgO content in the tapped slag (mass per cent) and tapping temperatures

Table 4 - Average chemical analyses of the neutral slag*, mass per cent

MgO	Al$_2$O$_3$	CaO	SiO$_2$	FeO
19.2	10.4	31.1	39.6	0.4

*Neutral slag recipe consisted of alumina, silica, and calcined dolomite

It appears that the magnesium extraction, and hence its extraction rate, was also limited by the batch duration (2.5-3.0 hours). This was evident upon furnace tapping as white fume (MgO) continued to escape from the slag-filled ladles for several minutes. In addition, small globules of residual ferrosilicon (0.1-2.0mm in diameter) were present in most slag taps. Chemical analysis of these globules indicated a silicon content of up to 37% by mass, suggesting that these globules were only partially reacted. In comparison, the tapped residual FeSi analysed 25.5% Si, on average (Table 6).

Table 5 - Chemical analyses of the tapped slag, mass per cent

	MgO	Al$_2$O$_3$	CaO	SiO$_2$	FeO
Average	9.18	14.33	52.43	21.24	2.70
Minimum	6.71	11.9	45.70	12.60	0.38
Maximum	12.20	16.1	58.90	29.80	6.69

Table 6 - Chemical analyses of residual ferrosilicon, mass per cent

	Si	Fe
Average	25.5	70.7
Globules	36.7	50.9

Balance: Cr, Mn, Ti, C, etc.

The degree of magnesium extraction was determined based on the actual masses and analyses of the feed materials and the slag. The calculated values varied from tap to tap and ranged from 63 to 87%, with an average of 77% over the entire campaign. Based on the original furnace internal diameter, the magnesium extraction rate was between 70 and 85kg/h/m^2. During previous testwork, steady improvement in magnesium extraction was attained. As shown in Table 7, the extraction increased from 66% in Run 5 to 87% in Run 9, where the MgO analysis in the tapped slag dropped from 13.5% to about 6.4%.

It is believed that magnesium extraction can be optimised by, among other factors, good control of the slag temperature, which can be achieved, in part, by continuous slag tapping and improved overall plant availability.

Table 7. MgO content in the slag, extraction, and condensation efficiency, Runs 5-10

Run No.	5	6	7	8	9	10
MgO, %	13.5	7.7	6.4	7.4	6.4	6.7
Extraction, %	66	80	83	80	87	87
Condenser efficiency, %	45	53	38	65	80	85

Condenser

At the start of the testwork, the condenser crucible was charged with about 1100kg of magnesium ingots, heated up and melted, and then maintained at the operating temperatures of 680-720 ^{0}C, as measured inside the crucible (Figure 3). The stirrer speed was kept at a narrow range of 60-70rpm throughout most of the testwork. The condensed magnesium was periodically removed from the crucible every 3-4 hours of furnace "feed on" time, or as required. Fifteen magnesium taps were carried out on-line, each averaging about 230kg of crude metal. In certain occasions, metal tapping was undertaken immediately after detecting a gradual increase in the system pressure that could not be overcome by operating the mechanical plungers. Doing so assisted in eliminating the pressure build-up and in maintaining a slightly negative pressure throughout the facility (-10mm H$_2$O).

Magnesium condensation took place in the elbow compartment, and more importantly inside the crucible itself. This was evident from the rapid response of the thermocouple located at the crucible roof as soon as the furnace feed was switched on/off. It is also believed that condensation took place on the metal surface, where the crucible inside temperatures tended to increase by 5-15^{0}C while feeding a given batch. The fact that the crucible upper thermocouple reading was almost always higher than that of the middle one (by a few degrees) supports such conclusion (Figure 3).

It was also possible that the stirrer contributed to the condensation process by creating a central vortex that pulled in the magnesium vapour. Such action provided better liquid-gas contact, which in turn enhanced both mass and energy transfer rates, thus aiding the condensation process. Any fog or mist of magnesium could have also been pulled into the magnesium bath by the stirrer action. The agitation of the magnesium bath tended to create a more uniform temperature profile within the crucible as seen by the inside temperatures, as well as those of the side-walls of the crucible. This

is related to the effective dissipation of the energy of condensation (taking place at the metal surface) into the molten bath and eventually through the crucible side-walls.

Although the secondary condenser was designed to allow all the magnesium vapour to be condensed there, very little condensation took place at its surface. This was evident from the lack of response of the thermocouples located at its exterior surface. In addition, there was insignificant amount of metallic magnesium present in this compartment when the facility was disassembled after the conclusion of the testwork.

One of the basic requirements of the condenser design was to be able to tolerate 5-10% solids in the magnesium bath (mostly oxides and nitrides of magnesium, and smaller amounts of CaO, SiO_2, Al_2O_3, C, etc). This was largely achieved by good control of the magnesium level within the crucible (within ±100mm of the target level) and the design and operation of the stirrer assembly. The stirrer speed (60-70rpm) proved to be effective in maintaining a suspension of oxides in liquid magnesium. The suspension was periodically tapped from the crucible without any major difficulty. Doing so prevented any accumulation of the solids inside the condenser, either on top of the metal surface or on the bottom of the crucible. This allowed the facility to be operated for long period without the need to disconnect the condenser for cleaning, as practised in the Magnetherm process. Notice that co-melting of the crude metal with fused $MgCl_2$-KCl indicated that the tapped magnesium contained between 3 and 8% solids.
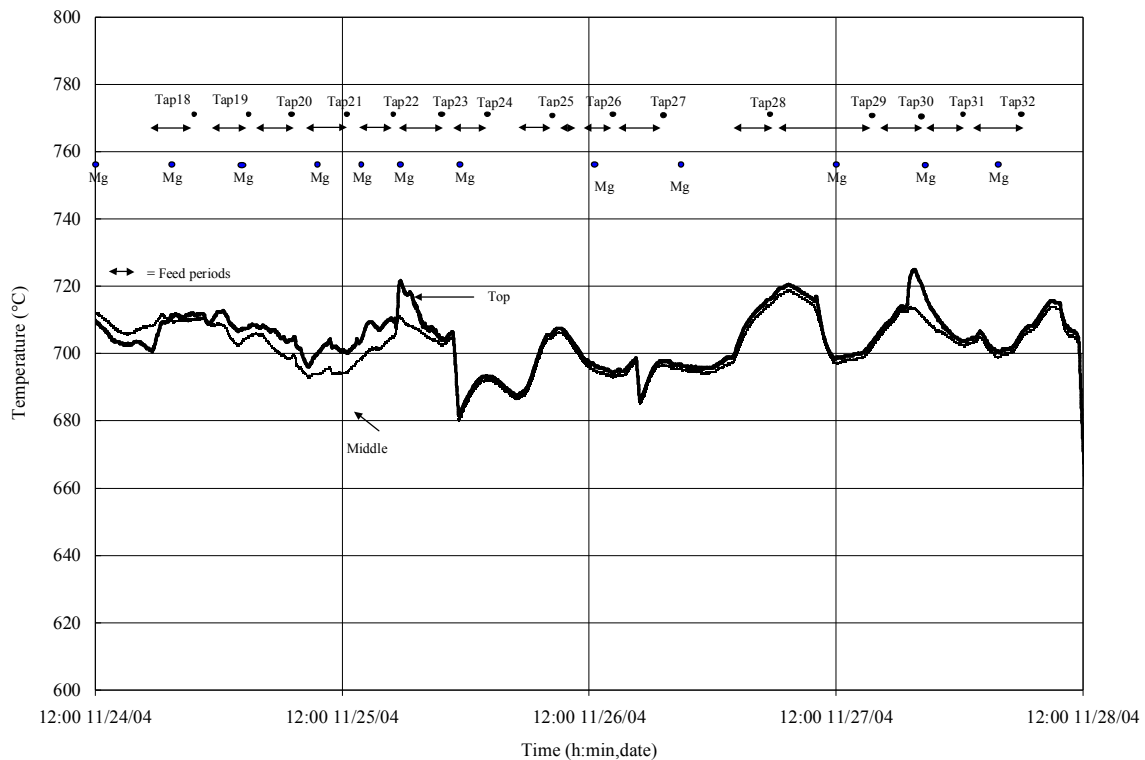

Figure 3 - Condenser crucible inside temperatures, Taps 18-32

Bath stirring and maintaining an oxide-magnesium suspension poses potential challenges, though. Agitation of the bath at the operating temperatures of 700-750^{0}C, may enhance the reactions between liquid magnesium and certain metal oxides, such as Al_2O_3, SiO_2, FeO, etc. The crude metal quality therefore might be negatively affected and thus flux requirements in the refining stage could be higher. This could become a significant factor when severe dusting from the furnace is experienced and/or when the arc-side reactions become excessive, particularly during periods where the furnace feed is interrupted for relatively long periods.

Another potential challenge of bath agitation is that the tapped magnesium would be dirty in the sense that it is well mixed with the oxides/solids, which has a negative impact on the refining operation. However, proper design of an industrial facility might overcome such problem. It might be possible to directly tap the suspension into a stirred ladle where certain fluxes could be added in controlled amounts in order to promptly remove the solid inclusions.

In total, 3500kg of crude magnesium was produced. Chemical analyses of the metal are shown in Table 8, along with those of the ASTM standards for grade 9980 and the Magnetherm crude metal [14]. The levels of iron and silicon are relatively high compared to those obtained in earlier campaigns [15]. This is believed to be due to the repair work carried out inside the crucible just before the current testwork that left welding debris inside the crucible. In order to carry out the work safely, the crucible base was covered with a layer of silica sand. Although the crucible was cleaned prior to commencing with Run 10, it is possible that some silica and welding debris was left behind and thus contaminated the condensed metal. This conclusion is supported by the chemical analyses of later metal taps that showed significantly lower iron and silicon contents. In spite of this, the MTMP crude magnesium is of a similar quality to, if not better than, that of the Magnetherm product. Co-melting with M130 fluxing agent (fused magnesium and potassium chlorides), resulted in the removal of more than 90% of the contained calcium and significant proportions of the silicon and iron contents [16].

Table 8 - Chemical analyses of the MTMP magnesium, mass per cent.

	Al	Si	Ca	Fe	Mn
Crude Mg	0.003-0.045	0.100-0.290	0.030-0.240	0.002-0.240	0.011-0.065
Magnetherm	0.08-0.11	0.11-0.30	0.85-1.20	NA	NA
ASTM B92	0.05	0.05	0.05	0.05	0.10

NA: Not Available

The magnesium condensation efficiency was calculated at 85% for the entire test duration, and is believed to have reached 87% during good and steady periods of operations (furnace Taps 18-32). In addition to air ingress and oxygen lancing, factors that could have negatively influenced the condenser efficiency, and most likely the crude metal quality, included:

1. Operating the furnace without feed for relatively long time in several occasions (to un-block the magnesium tapping spout and launder, for example).

2. Significant air ingress while attempting to clear a feed-port blockage that occurred in Tap 32, while adding electrode sections, and during slag tapping operations. The influence of argon flow rate (50-75 l/min) on the condenser efficiency could not be quantified at this stage.

The feed port blockage occurred at the end of Tap 32. After clearing the blockage, feeding of magnesium producing recipe commenced, where three additional magnesium metal taps were performed. Electrode addition/slipping (performed in three occasions during the test duration) did not appear to have affected the metal condensation and tapping. This was significant in the sense that, even after a major interruption in the furnace feed and opening a port for relatively long periods, there was no need to dismantle the condenser for cleaning, as practised in the industry.

The performance of the novel condenser during Run 10 was a remarkable improvement over what was achieved in earlier runs (Table7) where a Magnetherm pilot condenser was used. Its efficiency, at the pilot scale, is not significantly different than that obtained in the Magnetherm condenser, which is believed to be between 90 and 92%.

Other results

It is interesting to note that silicon utilisation (proportion of the silicon metal in the feed that reacted to produce magnesium vapour) was between 84 and 88%. The lower value was derived from the slag mass and its average SiO_2 content, while the higher figure was based on the Si-content in the tapped residual FeSi and assuming that all the iron in the feed reported to the residual FeSi. In addition, the electrode consumption was determined at 0.89kg/MWh. Note that a 200mm diameter graphite electrode was used, and the electrical current density averaged 13.7 A/cm^2 during the campaign. This electrode consumption value is relatively low and could contribute towards improving the overall plant availability in a commercial installation, as electrode addition would be less frequent. In addition, the usage of special magnesium coalescing agents (AlF_3, for example) in the refining stage could be significantly reduced, as less carbon would be present in the crude metal.

ECONOMIC ASSESSMENT OF THE MTMP PROCESS

An economic analysis was performed for a 40kt Mg ingot/annum based on the MTMP technology as opposed to an electrolytic plant, both plants being located in Canada (Table 9). The results indicate that the capital costs of an MTMP plant could be less than 50% of those of the electrolytic process. In addition, The MTMP plant could realise about 20% reduction in the cash operating costs when compared to the electrolytic case.

For a 72kt MTMP magnesium plant located in South Africa, the financial analysis shows a capital cost of about US $4250/ton Mg and a cash operating costs of between US $0.76 and $0.82/lb. Two major assumptions were made in deriving the financial data for the MTMP plant. The first is related to the overall plant availability (utilisation) which was taken to be 82%. This is a conservative estimate, and is largely based on the plant

utilisation of the semi-batch Magnetherm process. Atmospheric operation of the plant, coupled with continuous slag (and possibly metal) tapping, should lead to significant improvement in the plant utilisation, where a plant availability of 90% is believed to be achievable. A second conservative assumption made was that the magnesium condensation efficiency was only 90% and that the improved design and operation of the condenser do not have major influence on the crude metal quality and on the condensation efficiency.

The favourable economic potential of the MTMP technology has lead Mintek and its consortium partners (Anglo American Corporation and Eskom Enterprises) to pursue a full-scale feasibility study for a 3kt Mg/annum demonstration plant as a first step towards installing a 72kt/a industrial facility.

Table 9 - Capital and operating costs of the MTMP versus those of the Electrolytic process.

	Electrolytic[1]	MTMP[1]	MTMP[2]
Capital Costs, US $/T Mg Ingot	8000	3800	4250[3]
Cash operating Costs, US $/lb	1.10	0.89	0.76-0.82

1: Plant located in Canada-40kt/annum
2: Plant Located in South Africa-40kt/annum
3: Includes 25% contingency-72kt/annum

CONCLUSIONS

The research and development work on the Mintek Thermal Magnesium Process was successfully concluded in November 2004. A novel condenser design was employed during the campaign that allowed the continuous operation of the facility for 8-days where about 30 tons of feed materials were smelted in the dc furnace, producing 3500 kg of crude magnesium.

Preliminary techno-economic evaluation of the MTMP technology has shown that it has much lower capital costs and very similar, if not lower, operating costs when compared to the electrolytic process.

ACKNOWLEDGEMENTS

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