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Pyrometallurgy at Mintek

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Keywords: Pyrometallurgy, Mintek, DC arc furnace, plasma, smelting, chromite, ilmenite, cobalt, slag, zinc fuming, dust, magnesium, laterite, ferronickel, arc modelling, Pyrosim, thermodynamics

Abstract – The Pyrometallurgy discipline at Mintek was initiated in the early 1970s, to support a growing ferroalloy industry in South Africa. In addition to a range of pyrometallurgical options, Mintek specialises in DC arc furnace technology and has pilot plant facilities up to 5.6 MVA, as well as a strong base in process and arc modelling. Industrial processes have been developed for ferrochromium production, ilmenite smelting, and cobalt recovery from slag. Recent work has been done on such processes as the production of ferronickel from laterite ores, the fuming and condensation of magnesium, and the recovery of platinum group metals from 'difficult' feedstocks.

INTRODUCTION

Mintek's mission is focused on research and development and technology transfer in the field of minerals and mineral products, as well as ensuring that the science and technology base of South Africa is healthy and capable of renewal. Mintek is structured as a statutory Science Council, with the chairman of the board reporting to the Minister of Minerals and Energy. Essentially, this means that Mintek is wholly owned by the South African government. Mintek is managed by a President, supported by four General Managers. Mintek has substantial capabilities in all metallurgical disciplines. The technical divisions at Mintek include Advanced Materials, Analytical Science, Biotechnology, Engineering Services, Hydrometallurgy, High Temperature Technology, Measurement and Control, Mineralogy, Minerals Processing, and Pyrometallurgy.

Mintek currently has a permanent staff of about 500 people, including about 230 professionals with tertiary education. There are about 150 outsourced positions, mostly in support functions. In the past decade, Mintek has undergone a radical change in the source of its funding. In 1995, funding from the government was about twice that from the commercial sector. By 2005, the picture had reversed, with commercial income being twice that received from the government. Mintek's turnover in 2005/6 was about R270m. Of this, R90m was provided by the state science vote, R12m from competitive government grants, and R168m from the sale of products, intellectual property, and services. It is worth noting that Mintek's turnover has approximately doubled in the past five years.

A BRIEF HISTORY OF MINTEK

Mintek is 72 years old in 2006, having started life as the Minerals Research Laboratory[1] (as a joint venture between the state's Mines Department and the University of the Witwatersrand) in July 1934. Since it began, it has also been known as the Government Metallurgical Laboratory (from 1944), the National Institute for Metallurgy (NIM) (from 1966), and the Council for Mineral Technology (from 1981). The name Mintek was formally adopted in 1981 as an abbreviated title, and later became the official name of the organization. An initiative known as 'framework autonomy' was introduced in 1989, and had a considerable impact on all the science councils. This freed Mintek from the constraints of the civil service, and allowed for operation within a more commercial, client-orientated mode, paying more market-related salaries (limited mainly by the ability to generate funds). As a result, the science councils had a lot more freedom to act independently and take commercial decisions. This process was accelerated in 1994, when the science councils were encouraged to use their Science Vote funds to follow the interests of the State, but to act commercially with the rest.

Originally housed at the University of the Witwatersrand, then from 1946 located in a building in Yale Road, Milner Park, adjacent to Wits University, Mintek moved to its current 23-hectare site in Randburg in 1976.

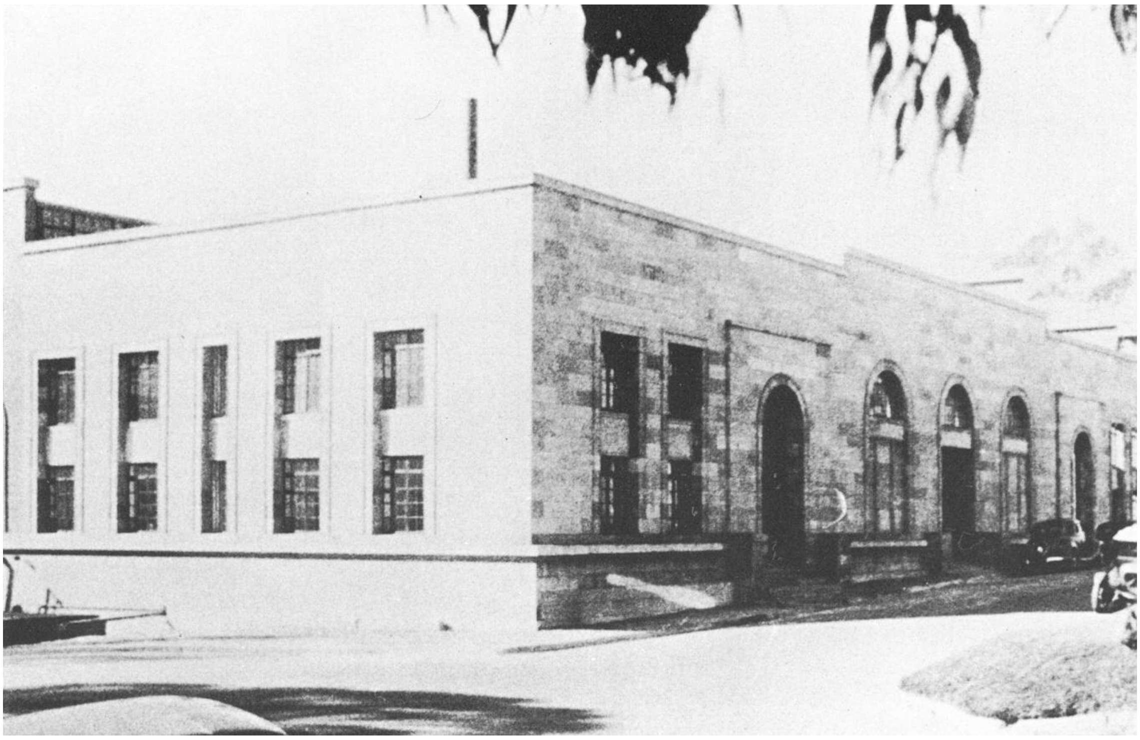

Figure 1: The Minerals Research Laboratory in the grounds of the University of the Witwatersrand (1935 – 1948)

Figure 2: The Yale Road site (~1965)

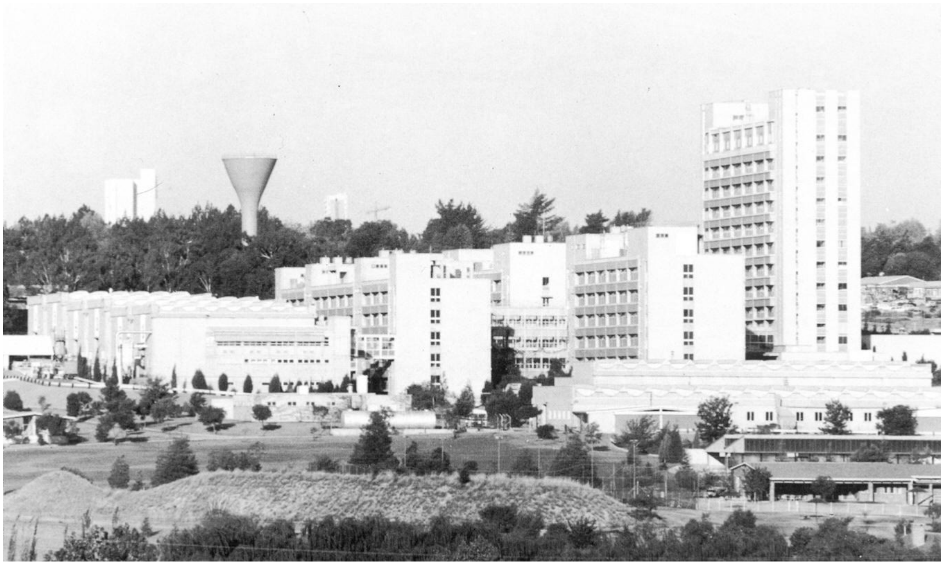

Figure 3: Mintek's Randburg site

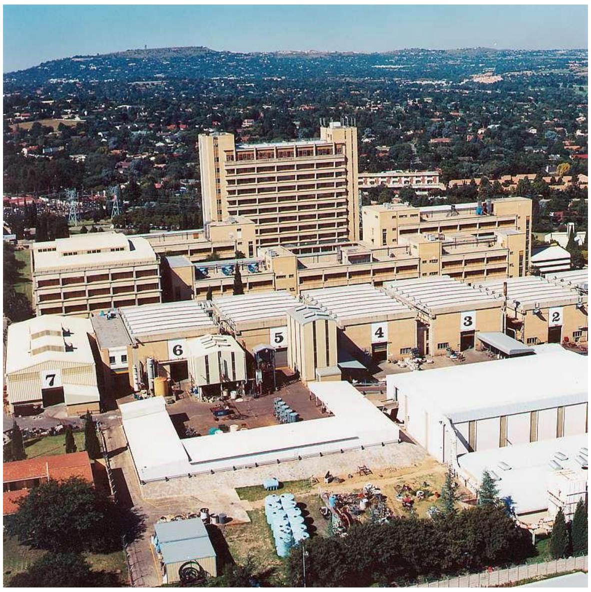

Figure 4: Mintek's Randburg site – offices, laboratories, and pilot plants

EARLY PYROMETALLURGICAL WORK

Pyrometallurgy was a prominent part of Mintek's work during the 1930s. The first published paper[2] in this field, written by R.P. Forsyth, dealt with the use of South Africa's low-grade chromite ores in the direct production of stainless steel. In those days, stainless steel manufacturers required ferrochromium with a low carbon content, which could only be produced by reduction with a non-carbonaceous agent such as ferrosilicon. (It is interesting to read that some of the problems encountered then are similar to those facing researchers in this field today: "On attempting to sample this specimen no impression could be made with a drill, and a section could not be cut with a hacksaw.") Apart from the production of small amounts of stainless steel during the years of the Second World War, this work had no immediate outcome in practice. Pyrometallurgical work was rather limited during the war years, because of the major focus on uranium production, and it was even necessary to remove the existing pyrometallurgical equipment to provide space for the uranium-refining pilot plant. However, the importance of South Africa's resources of chromium, manganese, and titaniferous iron ores was not forgotten, and the intention to undertake investigations in these fields remained. Although ferrochromium and stainless steel were first produced in South Africa in 1943, it was not until the early 1960s, with the advent of the argon-oxygen decarburisation (AOD) process, that the country's ferroalloys industry was able to expand significantly.

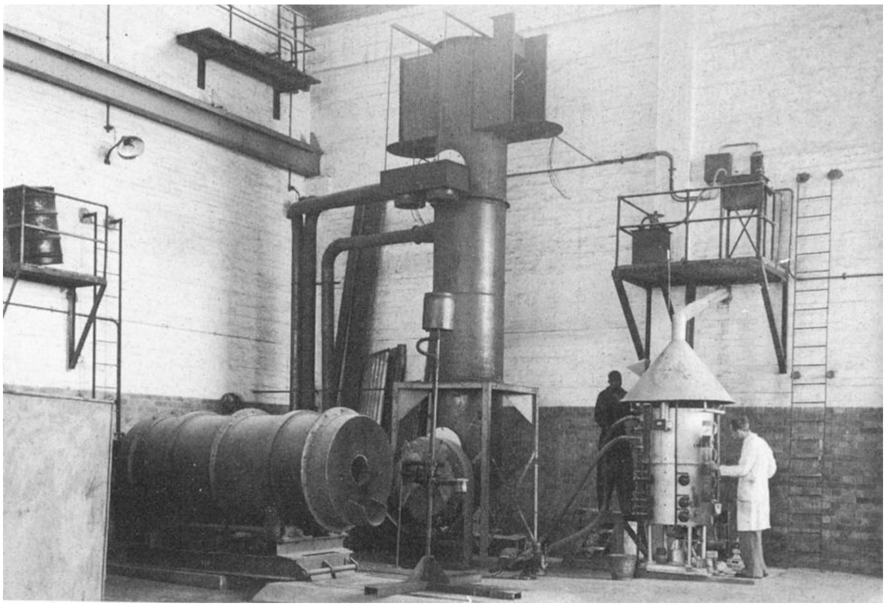

Figure 5: The Pyrometallurgical Laboratory in the Yale Road buildings (~1950)

In 1968, Mintek's Pyrometallurgy Research Group was established within the Department of Metallurgy at the University of the Witwatersrand. Professor David Howat started work on the properties of slags, as part of an investigation into the operations of the Highveld Steel and Vanadium plant. Some of the people involved there that later became an important part of Mintek included Bruce McRae, Peter Jochens, Gunter Sommer, and Nic Barcza. The work of the Pyrometallurgy Research Group led to a fundamental understanding of the reactions that take place in the production of ferrochromium. Mintek's strength in pyrometallurgy grew further with the formation of the Measurement and

Control Research Group at the University of Cape Town. This group was established to acquire expertise in the use of microprocessors and the development of special instruments for the control of plant operations. It was the combination of the knowledge derived from these two sources that put Mintek in a position to undertake its work on the automatic control of electric furnaces. The first large-scale application of Mintek's new-found knowledge was on a 48 MVA ferrochromium furnace at Witbank. This furnace was used for the development of computerised data-logging and control systems, and a microcomputer-based electrode controller based on a unique measurement technique for estimating resistance in the circuit was developed and implemented, increasing production of the furnace by more than 60 per cent – a spectacularly successful result that, in 1979, was claimed to be a world record for that size of furnace.[1] This technology was subsequently commercialised in the 'Minstral' furnace-control system, which has been implemented on more than 80 furnaces worldwide, mostly in the ferroalloy industry.

The techniques and instruments developed were applied to other furnaces, and, as a result of the close cooperation with the industrial organizations concerned, Mintek's field of interest widened to include several of the problems of furnace design and operation.

CHROMITE SMELTING

Mintek began investigating alternative smelting methods for ferroalloy production in the mid to late 1970s. The growing ferroalloy industry in South Africa faced the problem of how to deal with the significant quantity of fine material (< 6 mm) that was generated from the friable local chromite ores. In 1976, studies commenced on the possible use of plasma smelting (DC transferred-arc technology), motivated by its potential ability to utilise fine feed materials directly, without costly agglomeration. A further advantage was that the metallurgical and electrical parameters of the smelting process are independent, unlike in a conventional submerged-arc furnace. (Further details have been published previously.[3])

In 1979, Middelburg Steel & Alloys (now Samancor Chrome[4]) asked Mintek to take part in tests on plasma smelting at Tetronics in the United Kingdom. After that, Mintek committed itself to the investigation of plasma technology, and to the demonstration to industry of its benefits, particularly the ability to smelt fine materials. Equipment for this purpose was installed in the pilot bays, and was based initially on a power supply of 100 kVA (and later on one of 3.2 MVA). The first ferrochromium was produced in a bench-scale DC arc furnace in 1979. The installation of the large experimental furnaces in the pyrometallurgy pilot bay, Bay 1, demanded an extension of the original building, and in June 1982 a formal opening ceremony marked, not only the completion of the building operations, but also the inauguration of the 3.2 MVA furnace.[1] The 1 t/h DC arc furnace pilot plant was commissioned in 1984.

Figure 6: The 3.2 MVA DC arc furnace at Mintek being tapped

As a result of successful initial testwork, Mintek and Middelburg Steel & Alloys undertook a longer-term R&D programme to develop the technology commercially. A 16 MVA (14 MW) transferred-arc furnace was commissioned at Palmiet Ferrochrome in Krugersdorp at the end of 1983, and was uprated to 40 MVA (32 MW) in 1988. Based on the successful operation of the DC arc furnace for chromite smelting, Middelburg Ferrochrome started up a 62 MVA (~40 MW) DC arc furnace, the largest of its type, in 1997. The DC-arc process allows the use of unagglomerated chromite fines and cheaper, non-coking coal. This furnace technology is regarded as one of the lowest-cost options for the production of ferrochromium.

Figure 7: The 40 MVA DC arc furnace at Palmiet Ferrochrome

Mintek's work in the field of ferroalloys led, amongst other things, to the establishment of Infacon (the International Ferroalloys Congress) in 1974, as a Mintek initiative, with the support of the Ferro Alloy Producers' Association (FAPA) and the South African Institute of Mining and Metallurgy (SAIMM). Infacon is the name of a series of international ferroalloys congresses. Its significance for Mintek was the recognition by the South African industry of the practical importance of Mintek's work, and the international recognition of the growing importance of South Africa's production of ferroalloys.

ILMENITE SMELTING

Ilmenite from beach sands in South Africa is of too low a grade to be used directly for the production of pigment or synthetic rutile. Instead, it is smelted to produce a titania slag suitable for the production of TiO_2 pigments. The principal reaction involved is shown simplistically as:

$$FeO.TiO_2 + C = TiO_2 + Fe + CO \qquad [1]$$

The high electrical conductivity of titania slags and the accurate control of the slag composition effectively rule out the use of conventional submerged-arc technology for the smelting of ilmenite. Richards Bay Minerals[5] (RBM) uses process technology originally developed by Quebec Iron & Titanium (QIT Fer et Titane) of Sorel, Canada, employing rectangular six-in-line graphite-electrode furnaces in open-bath mode with AC open-arc operation.

An alternative to this process, based on single hollow-electrode DC-arc furnace technology, was developed by Mintek and Anglo American Corporation for the Namakwa Sands project.

Figure 8: Ilmenite smelting testwork at Mintek

Phase one of the testwork, in 1990, involved four 15 kg batch tests at 30 kW, and showed that the process was feasible, and that a freeze lining was required. Phase two, in 1991, involved smelting two tons of ilmenite, with continuous feeding at 50 kg/h, at a power level of 100 kW. This produced an on-specification slag, and a metal that was high in Ti. Phase three, also in 1991, saw the smelting of 35 tons of ilmenite, fed continuously at 300 kg/h, at power levels of 500 kW (to 1 MW), with on-grade slag and metal produced. Phase four, in 1995, processed 200 tons of ilmenite at 1 t/h and 1.5 MW, and primarily involved the development of the furnace start-up procedure, process control, and operator training.

The first 25 MW furnace built at Namakwa Sands,[6] began production of ilmenite slag and pig iron in 1995. A second furnace, this time 35 MW, was in place by 1999.

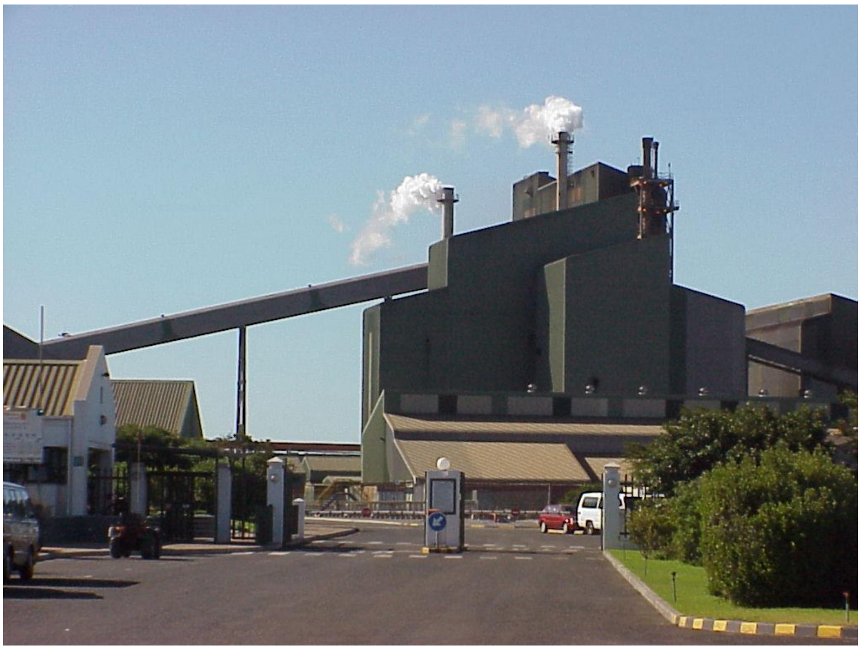

Figure 9: Namakwa Sands smelter

Smelting of ilmenite in a DC arc furnace has also been adopted by Ticor SA[7], where they have two 36 MW DC arc furnaces that were commissioned in 2003.

COBALT RECOVERY FROM SLAG

Valuable metals, such as cobalt, can be recovered from non-ferrous smelting slags by treating these waste materials with a carbonaceous reducing agent in a DC-arc furnace (a process developed at Mintek since 1988). Mintek has investigated the use of this technology for the recovery of cobalt from copper reverberatory furnace slags, as well as for the recovery of nickel, cobalt, copper, and platinum group metals from furnace and converter slags in plants treating nickel sulphide concentrates. Early pilot-plant testwork at Mintek demonstrated recoveries of 98% for nickel and over 80% for cobalt, at power levels of up to 600 kW.

The technology was further developed by Mintek and Anglovaal Mining Ltd (Avmin) for the recovery of cobalt from the 20 Mt reverberatory furnace slag dump at Nkana in Zambia. Testwork at the 150-250 kW scale was conducted at Avmin's research laboratories, and larger scale piloting was conducted at Mintek (in partnership with Avmin) in a 3 MW DC arc furnace. Approximately 840 tons of Nkana dump slag (ranging from 0.66% Co) was processed at power levels around 1-2 MW. Good overall cobalt extraction was achieved, and approximately 100 tons of cobalt-bearing alloy was produced (containing 5 to 14% Co). This testwork demonstrated that the Nkana dump slag could be processed in a DC arc furnace of suitable design, to produce a cobalt-bearing alloy suitable for further hydrometallurgical processing. A relationship was established between the amount of iron reduced and the amount of cobalt recovered to the alloy product.

A 40 MW DC arc furnace, designed by Bateman Titaco, was built at Chambishi Metals; and power to the furnace was switched on during January 2001.[8] Notable features of the furnace include an ABB power supply of unusually high voltage, a Concast conductive hearth, and copper cooling of the side-walls. The furnace cooling system was subsequently modified by Hatch. The furnace is currently operating at design capacity.

Figure 10: DC arc furnace at Chambishi Metals, Zambia

ZINC FUMING

There are numerous waste materials that are classified as hazardous waste because of their lead content, but contain sufficient zinc to be worth treating further. Mintek has undertaken considerable work on the treatment of lead-blast-furnace slags, steel-plant dusts, and leach residues. A technically viable process has been demonstrated for lead-blast-furnace slags, which involves the feeding of a molten stream of slag into a DC arc furnace where carbon is added and zinc vapour is produced. The zinc vapour is then absorbed in an ISP lead-splash condenser. Unfortunately, this process has not yet been implemented industrially, because of commercial reasons.

Figure 11: 5.6 MVA DC arc furnace pilot plant at Mintek
(2 t/h pilot plant, including a zinc condenser, was commissioned in 1994)

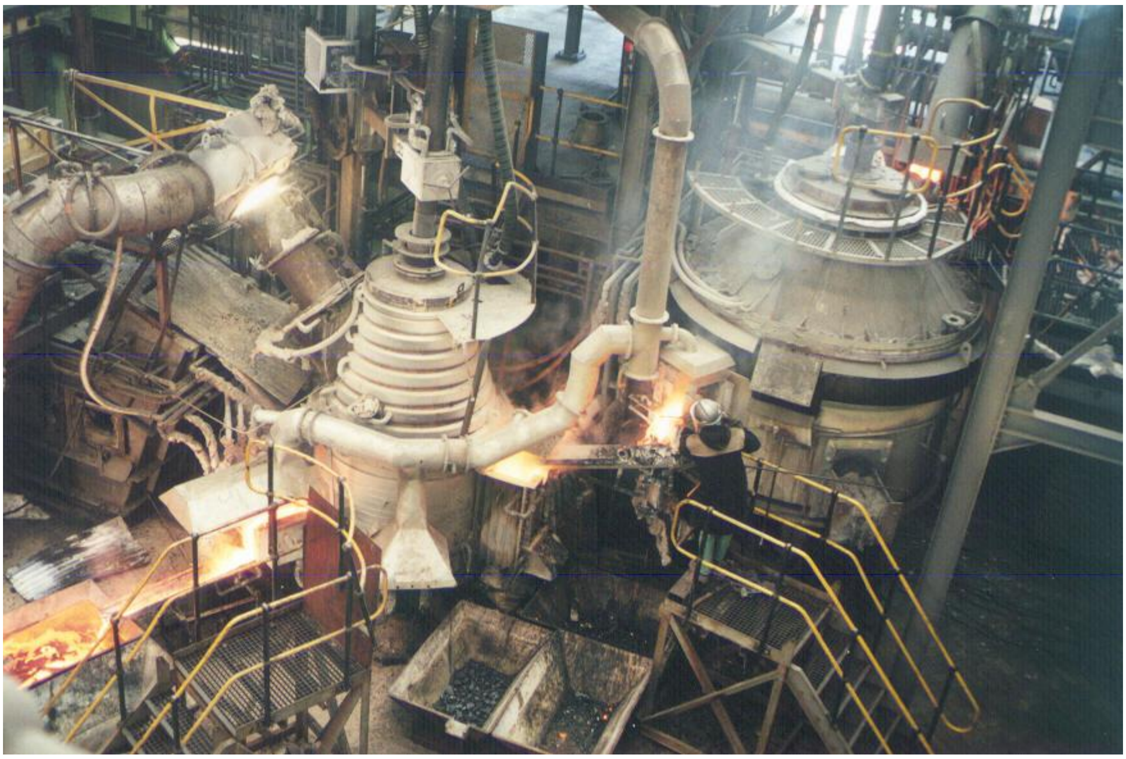

Figure 12: 5.6 MVA DC arc furnace pilot plant at Mintek
Molten slag flows from the pre-melter into the fuming furnace

STAINLESS-STEEL-PLANT DUST TREATMENT

Steel-plant dusts give rise to disposal problems because they contain hazardous heavy metals that pollute groundwater. These materials are extremely fine, and are thus difficult to treat. Mintek has developed the Enviroplas process (using DC arc furnace technology) for the treatment of solid wastes from the metallurgical industry (including both carbon- and alloy-steel dusts without requiring agglomeration). The process has the following benefits:

- Valuable metals such as zinc are concentrated in the vapour phase, and can be condensed directly from the furnace off-gases.
- The recovery of alloying elements such as chromium, nickel, and molybdenum in the hot metal exceeds 90%.
- The resulting innocuous slag can be safely disposed of, as it complies with environmental legislation.

Mintek has successfully processed about 1 700 tons of AOD/EAF dust on a toll-treatment basis, in order to recover the contained chromium and nickel. The metal produced contained 18 per cent Cr, and 6 per cent Ni. All slag samples tested conformed to US EPA regulations for disposal. The chromium and nickel recovery to metal, on a once-through basis without recycling secondary dust generated during the testwork, was 92 and 94 per cent respectively.

The process has been adapted for operation on an existing 40 MVA DC arc ferrochromium furnace at Mogale Alloys.

MAGNESIUM

Magnesium is an important component of light alloys used in the aerospace and transport industries, but continuous production of the metal requires the use of more sophisticated technology than for most other metals.

Thermal production of magnesium, at normal atmospheric pressure, was demonstrated in the late 1980s by Albert Schoukens. Initial testwork was carried out in a DC arc furnace at a scale of 50 to 100 kVA. This work eventually led to the development of the Mintek Thermal Magnesium Process (MTMP). Mintek's use of an open DC arc for the production of magnesium vapour provides the freedom to operate at 1700°C or more. The higher temperature provides a greater choice of slag composition and feed recipes. Atmospheric pressure (instead of under a vacuum as in the conventional process) can be used at this temperature, thereby avoiding batch operation and allowing scale-up beyond 10 MW units. By avoiding vacuum conditions, there is reduced leakage of air and consequent re-oxidation of magnesium.

The MTMP is based on DC open-arc smelting of calcined dolomite (dolime) at atmospheric pressure in the presence of ferrosilicon (Figure 13). As such, the process is not constrained by the electrical resistivity of the slag and allows the furnace to be operated at relatively high voltage. The volatilized magnesium is captured as liquid metal in a surface condenser, which permits periodic tapping of the crude magnesium. Doing so, in conjunction with conditions at atmospheric pressure, makes possible the operation of a large-scale facility 'continuously' (or semi-continuously). The Mintek Thermal Magnesium Process has resulted in the production of high-purity magnesium metal. This process has lower capital costs, and is economically viable on a much smaller scale than the conventional electrolytic process.

The process is a more continuous one (designed to run for more than 72 hours at industrial scale), although periodic cleaning is required to remove accretions from ducts. Longer operation means less downtime, therefore higher availability and lower production costs. There is greater ability to scale up, which also lowers production costs. Lower impurity levels result in lower refining costs.

The past couple of years have seen an increased focus on the condensing aspect of the process, and there have been some significant developments on this front. Some key results include:

- Produced Mg at atmospheric pressure
- Condensed Mg as a liquid
- Tapped crude liquid Mg on line
- Mg quality better than industry average
- Produced over a ton of Mg so far.

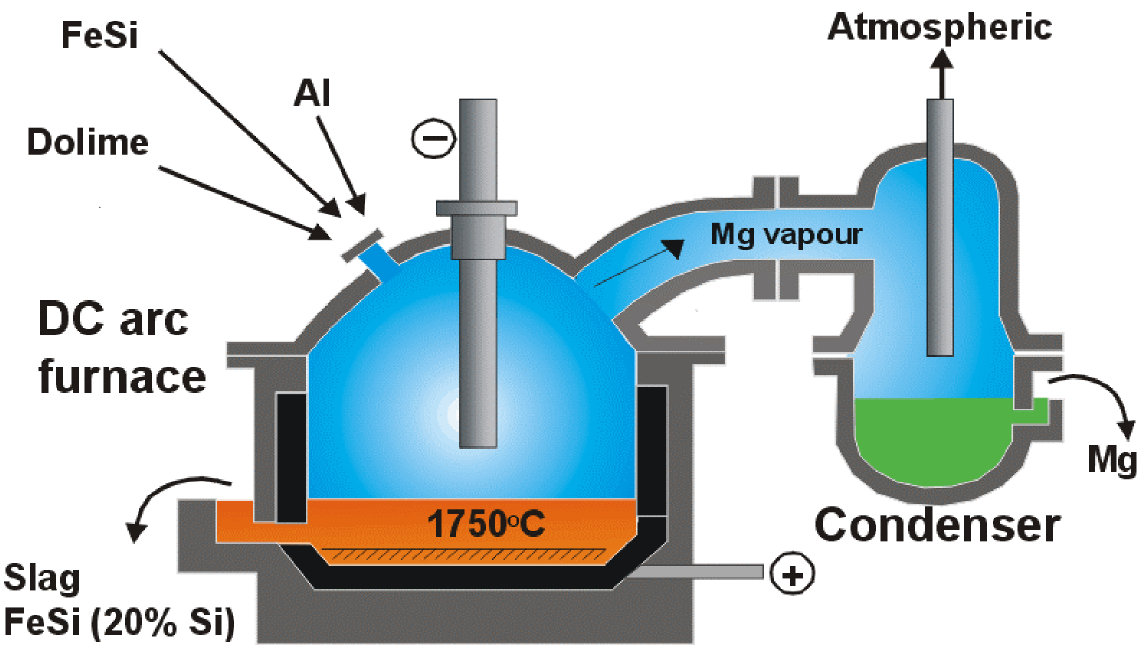

Figure 13: Mintek Thermal Magnesium Process – simplified diagram

FERRONICKEL

Laterites and other oxidized nickel ores constitute a very important part of worldwide nickel reserves. In the conventional production of ferronickel from these ores, much fine material is produced which cannot readily be accommodated directly in existing three-electrode or six-in-line AC furnaces. DC arc furnace technology allows ore particles less than 1 mm in size to be treated directly, thereby improving the overall recovery of nickel without the need for expensive agglomeration techniques. Because of the high moisture content of laterites, the ores should be dried and calcined before smelting. A further saving in energy consumption can be achieved by pre-reducing the ores.

Mintek has been working on the production of unrefined ferronickel from nickel-containing laterite in DC arc furnaces since 1993. In this process, lateritic material is fed, together with a carbonaceous reducing agent, to the central region of the molten bath of a cylindrical DC arc furnace. Nickel laterites of a wide compositional range can be smelted in a DC arc furnace, to produce ferronickel. The flexible operation of a DC arc furnace (especially its lower dependence on electrical properties of the slag, because of open-arc operation, in addition to the ability to run at an optimum slag temperature, due to the open-bath mode of operation) allowed for the successful treatment of ores with a SiO_2/MgO ratio between 1.2 and 3.0, as well as ores containing up to 30 per cent by mass of iron (which tends to cause slag foaming in a conventional immersed-electrode furnace). A frozen lining can be maintained between the molten bath and the refractory lining, in order to minimize refractory wear (especially at high SiO_2 contents).

The largest planned application of this technology is Falconbridge's Koniambo project in New Caledonia, based on milled ore, fluidized beds, and two twin-electrode 80 MW DC arc furnaces, with cyclone pre-heaters. It is envisaged that Koniambo aims to produce 60 kt/a of Ni in FeNi, and that the new smelter will employ about 800 people.

Figure 14: Nickel laterite smelting at Mintek

UG2 smelting

Concentrates from Merensky ores are amenable to traditional sulphide matte smelting.[9] However, UG2 ores, with their very high chromite content, require a different approach. From 1980 onward, Mintek undertook intensive research, in collaboration mainly with Western Platinum, leading to the development of a flotation procedure to reduce the amount of chromite in the concentrate, and a novel smelting technique, using higher current densities and temperatures than normally employed, in order to deal with the still-high chromium content. The development of these processes effectively more than doubled South Africa's PGM reserves - today, most producers exploit both the Merensky and the UG2 reefs, and an increasing number of new projects are targeting the UG2 alone.

Mintek has considerable expertise in the concentration and smelting of both conventional and high-chromite-containing PGM ores. The information that has been accumulated enables the performance of commercial plants to be optimized with a minimum of research and development, although some testwork is always necessary. Matte smelting testwork can be carried out at Mintek using a 300 kVA submerged-arc furnace, and a top-blown rotary converter (TBRC), of 15 litre liquid capacity, which has been developed for the conversion of copper-nickel mattes.

Following the success of the DC arc furnace for chromite smelting, and realising that the UG2 Reef of the Bushveld Complex is rich in both chromite and platinum group metals, it was said, as early as 1985, that "the application of the plasma-arc technique to the treatment of platiniferous concentrates appears equally possible".[1] However, this was to take a while to come to fruition.

ConRoast

The development of the ConRoast process[10] for PGMs, over the past eight years, has been focused on improving the environmental aspects (in terms of lower SO_2 emissions) of PGM smelting, as well as the ability to treat PGM-containing materials that have very high chromium contents. The ConRoast process is aimed at a very different smelter, using a DC arc furnace for alloy smelting (from oxide) instead of matte (sulphide) smelting. Sulphur is removed at the beginning of the process (as a steady SO_2 stream to an acid plant, for example), by dead-roasting the concentrate. The PGMs are collected in an iron-based alloy, which is even more efficient than matte in collecting PGMs. This flexible PGM processing route can handle a wide range of feeds, all the way to 100% UG2, as it has no need for much Ni and Cu (or S) in ore, as Fe is the collector. The reducing conditions in the furnace (and high temperatures, if required) allow much higher levels of Cr_2O_3 in feed (> 5%) without causing a problem with spinel precipitation. The iron is removed either by converting, or with a few modifications to the base metals refinery.

Roasting removes sulphur (98% elimination of S in a fluid bed has been demonstrated) and other impurities very effectively. Roasting and smelting removed most (70 – 100%) of the minor impurity elements: As, Bi, Mn, Pb, Se, Te, and V. Alloy smelting collects PGMs very well, resulting in very clean slags; consistently less than 1 g/t PGM in slag, with < 0.3 g/t PGM in slag being demonstrated. If iron removal is to be done hydrometallurgically (in a similar process to that used at Chambishi Metals), the final levels of C, Si, and Cr in the alloy can all be brought down to less than 0.05% by ladle refining. Water atomization produces very fine particles (< 100 μm) that leach rapidly. A high-grade high-recovery clean PGM concentrate (> 60%) was produced.

ConSmelt

In order to demonstrate the viability of the DC-arc-furnace smelting step in the ConRoast process, Mintek has, over the past two years, treated a significant quantity (more than 13 000 tons, so far) of low sulphur, high chromium (otherwise virtually 'untreatable') material.[11] The furnace has run, very reliably, at power levels of about 1.6 MW, and feed-rates of about 35 tons per day (1 000 tons per month). At this scale of operation, the demonstration is a very convincing one, as well as producing sufficient product to make the process economically profitable in its own right.

Figure 15: ConSmelt process – alloy being tapped

Figure 16: ConSmelt process – alloy being tapped

PILOT PLANT EQUIPMENT & PEOPLE

The Pyrometallurgy Division at Mintek employs 17 engineers (2 PhD, 6 MSc, 7 BSc, 2 Dip.) with an average of 16 years pyrometallurgical experience, as well as about 120 operating staff (of which 30 are permanent staff, and 90 employed on a short-term contract basis).

The division operates two large pilot-plant bays. Bay 1 contains a variety of research equipment, and Bay 2 is currently set up to operate a single large furnace (with a 5.6 MVA power supply) on long-term demonstration-scale projects. The pilot plants can operate at up to 2 t/h (or 4 t/h for shorter periods). There are four DC arc furnaces, from 30 kW to 3 MW, as well as a 300 kW AC furnace. Other equipment includes a top-blown rotary converter (TBRC), a circulating fluidized bed (150 mm ID, 6 m high), a zinc condenser (300 kg/h), a rotary kiln (4 t/h at 900°C), and extensive gas-cleaning equipment. The replacement cost of the equipment (excluding buildings and services) is estimated to be about R40m.

Laboratory-scale investigations are carried out in Mintek's High Temperature Technology Division. This division was originally an offshoot of the Mineralogy Division, when an expertise base grew from a small group of people with skills in applied mineralogy and experience in studying the products of pyrometallurgical systems. Small-scale work and fundamental studies carried out in the HTT division provide valuable complementary support for the pilot-scale and process modelling and development work done in the Pyrometallurgy Division.

Figure 17: 200 kW furnace – either AC or DC, with 1, 2, or 3 electrodes

Figure 18: Rotary kiln

Figure 19: 100 kVA DC arc furnace

Figure 20: Top Blown Rotary Converter (TBRC)

Figure 21: Gas cleaning equipment at Mintek

PROCESS MODELLING AND CONTROL

In the mid 1980s, Mintek developed Pyrosim computer software for calculating steady-state mass and energy balances for a variety of pyrometallurgical processes and flowsheets. This program incorporates empirical models as well as predictive ones based on free-energy minimization to predict equilibrium compositions of reacting systems from thermodynamic principles. More than 80 Pyrosim thermodynamic modelling packages have been installed in more than 20 countries around the world.

Much recent modelling work has been done on dynamic simulation of the state of a furnace. Theoretical models of energy and mass transfer processes within DC arc furnaces have been developed. Radiation in the upper freeboard area of furnaces has also been studied extensively. Currently, work is underway on the dynamic modelling of DC electrical arcs, following some successful work where steady-state arc models were correlated against a series of arc photographs. Modelling has proved to be invaluable, as the extreme conditions inside furnaces make it very difficult to measure all that one would like to.

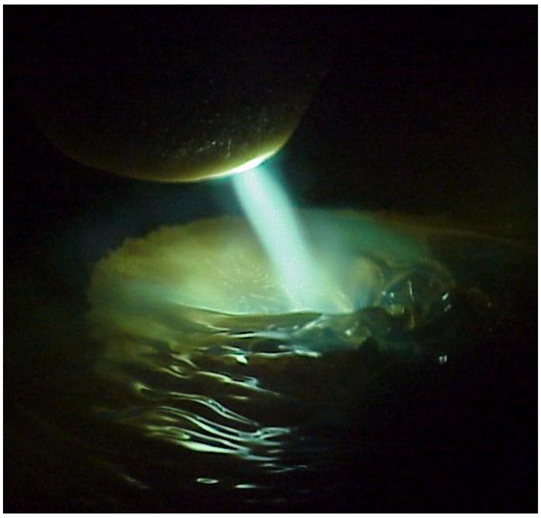

Figure 22: DC arc forms depression in slag in arc attachment zone

PUBLICATIONS

Tables I and II provide a list of the Pyrometallurgy Division's open publications, showing clearly the type of work that has been carried out over the past years. These documents are available online[12] at

http://www.mintek.co.za/Pyromet/Index.htm

Table I: Pyrometallurgy Division publications

Year	Title of paper	Authors
2006	Pyrometallurgy at Mintek	RT Jones & TR Curr
	Mintek Thermal Magnesium Process (MTMP): Theoretical and operational aspects	M Abdellatif
	Refining testwork on crude Magnesium produced in the Mintek Thermal Magnesium Process	M Abdellatif
	Metallurgy from above – a Google Earth perspective	QG Reynolds

2005	EAF Stainless Steel Dust Processing	GM Denton, NA Barcza, PD Scott, & T Fulton
	A study into the hydrodynamic behaviour of heavy minerals in a circulating fluidized bed	A Luckos & P den Hoed
	Technological breakthrough of the Mintek Thermal Magnesium Process	AFS Schoukens, MA Abdel-latif, & MJ Freeman
	An overview of Southern African PGM smelting	RT Jones
	Twin-electrode DC smelting furnaces - Theory and photographic testwork	QG Reynolds & RT Jones
	Atmospheric thermal magnesium extraction	MA Abdel-latif
2004	PGM Smelter Survey	RT Jones
	DC arc smelting of difficult PGM-containing feed materials	RT Jones & IJ Kotze
	A new process for the thermal refining of zinc	AD McKenzie
	Semi-empirical modelling of the electrical behaviour of DC-arc smelting furnaces	QG Reynolds & RT Jones
	Fluidization and flow regimes of titaniferous solids	A Luckos & P den Hoed
	Direct smelting of stainless steel plant dust	TJ Goff & GM Denton
	An improved DC-arc process for chromite smelting	GM Denton, JPW Bennie, & A de Jong
	Economic and environmentally beneficial treatment of slags in DC arc furnaces	RT Jones
2002	DC arc photography and modelling	RT Jones, QG Reynolds, & MJ Alport
	Thermal radiation modelling of DC smelting furnace freeboards	QG Reynolds
	Pilot plant production of ferronickel from nickel oxide ores and dusts in a DC arc furnace	IJ Kotze
	Fundamentals of zinc recovery from metallurgical wastes in the Enviroplas process	MA Abdel-latif
	Recovery of vanadium and nickel from petroleum flyash	MA Abdel-latif
	ConRoast: DC arc smelting of dead-roasted roasted sulphide concentrates	RT Jones
2001	ConRoast for the platinum industry	RT Jones
	Recovery of cobalt from slag in a DC arc furnace at Chambishi, Zambia	RT Jones, GM Denton, QG Reynolds, JAL Parker, & GJJ van Tonder
	The processing of jigged ferromanganese fines in a DC arc furnace	K Bisaka, GM Denton, & JAL Parker
	Preliminary Investigation into the Roasting of Ilmenite in a CFB Reactor	A Luckos
2000	Platinum smelting in South Africa	RT Jones
	An anatomy of furnace refractory erosion: Evidence from a pilot-scale facility	P den Hoed
1999	Computer modeling and analysis of processes for the production and use of DRI	AE Morris, AC Deneys, & RT Jones
1998	Using a direct-current arc furnace to recover cobalt from slags	RT Jones & AC Deneys
	Recovery of cobalt, nickel and copper from slags using DC-arc furnace technology	RT Jones
	Emerging pyrometallurgical processes for zinc and lead recovery from zinc-bearing waste materials	G Assis

1997	Production of ferronickel from nickel laterites in a DC arc furnace	H Lagendijk & RT Jones
	Influence of DC-arc furnace geometry on a 'cobalt from slag' process	RT Jones, TG la Grange, & G Assis
	Recovery of cobalt from a Viburnum trend lead blast furnace slag	AC Deneys, DGC Robertson, RT Jones, & AW Worcester
	An evaluation of some possible integrated flowsheets for the pyrometallurgical recovery of cobalt using DC-arc furnace technology	TG la Grange, RT Jones, & GM Denton
	The high current DC arc in extractive metallurgy	TR Curr
1996	Cobalt recovery from slag	RT Jones, DA Hayman, & GM Denton
	The Enviroplas process for the recovery of zinc, chromium and nickel from steel-plant dust	AFS Schoukens, MA Abdel-latif, MJ Freeman, & NA Barcza
	A review of new ferrochromium smelting technologies	TR Curr
1995	Pilot-plant production of Prime Western grade zinc from lead blast-furnace slags using the Enviroplas process	AFS Schoukens, GM Denton, & RT Jones
	Enviroplas technology for the recovery of lead and zinc from lead blast furnace slags	NA Barcza, DGC Robertson, AFS Schoukens, F Shaw, GM Denton, AW Worcester, & DJ Bailey
1994	Solubility of nitrogen in experimental low-nickel austenitic stainless steels	L Iorio, MB Cortie, & RT Jones
1993	Thermal Magnesium	AFS Schoukens
	Breakthrough for Enviroplas Process	AFS Schoukens
	The treatment of metallurgical wastes using the Enviroplas process	NA Barcza, CJ Hutton, MJ Freeman, & F Shaw
	The Enviroplas process for the treatment of steel-plant dusts	AFS Schoukens, F Shaw, & EC Chemaly
	Practical desktop supercomputing	RT Jones
	Plasma Developments in Africa	RT Jones, NA Barcza, & TR Curr
	Developments in plasma furnace technology	RT Jones, TR Curr, & NA Barcza
1992	Effect of reductant injection on chromite smelting	GJ Dreyer & RH Eric
	The solid-state reduction of chromite	RJ Dippenaar & MJ Niayesh
	Solid-state fluxed reduction of LG-6 chromite from the Bushveld Complex	RH Eric & P Weber
1991	The application of plasma-arc technology for the production of calcium carbide	LJ Erasmus
	Theoretical study of electrically based thermal processes for the treatment of steel-plant dusts	LR Nelson
	Plasma-arc treatment of steel-plant dust and zinc-containing slag - theoretical and practical considerations	AFS Schoukens, LR Nelson, & NA Barcza
1990	Metallurgy of open-bath plasma processes	NA Barcza, TR Curr, & RT Jones
	Technology for treatment of steel-plant dusts	NA Barcza & LR Nelson
	The pyrometallurgical recovery of gold from leached calcine residues	ASE Kleyenstuber & LB McRae

1989	A plasma-arc process for the production of magnesium	AFS Schoukens
	Description of non-ideal slag and metal systems by the intermediate-compound method	RT Jones & BD Botes
	Pre-reduction of fluxed chromite-ore pellets under oxidizing conditions	NA Barcza & RC Nunnington
	Kinetics and mechanism of the chlorination of ferrochromium	LR Nelson & RH Eric
	Fluidized-bed reduction of fine iron ore by the in situ combustion of coal	JC van den Berg & RJ Dippenaar
	Solid-state reduction of composite chromite pellets in an externally heated moving-bed shaft furnace	MJ Niayesh & RJ Dippenaar
	Mintek's new 1MW plasma furnace	DA Hayman
	Mintek's role in the development of plasma-arc technology based on a graphite cathode	NA Barcza, TR Curr, GM Denton, & DA Hayman
1988	Energy considerations for the melting of DRI as a function of the degree of pre-reduction	RT Jones, NA Barcza, & RJ Dippenaar
	A quantitative assessment of mixed ionic and electronic conduction in some commercially available magnesia-stabilized zirconia electrolytes	MJUT van Wijngaarden, JMA Geldenhuis, & RJ Dippenaar
	The dissolution of a Transvaal chromite in liquid silicate slags under neutral conditions between 1545 and 1660°C	TR Curr, A Wedepohl, & RH Eric
1987	The effect of feed pretreatment on the efficiency of a plasma-arc furnace	WFAT Meihack, TR Curr, NA Barcza, & RT Jones
	Computer simulation of pyrometallurgical processes	RT Jones
1986	The potential role of fluidized beds in the metallurgical industry	WFAT Meihack
	Factors affecting the reduction rate of chromite	NF Dawson & RI Edwards
	An assessment of smelting reduction processes in the production of Fe-Cr-C alloys	MJ Niayesh & GW Fletcher
	Technology for the production of new grades and types of ferro-alloys using thermal plasma	D Slatter, NA Barcza, TR Curr, KU Maske, & LB McRae
	Process routes for beneficiation of noble metals from Merensky and UG-2 ores	KS Liddell, LB McRae, & RC Dunne
	The control and operation of a pilot-plant DC plasma furnace	KC Nicol, MS Rennie, & AB Stewart
	The production of ferrotitanium in a d.c. transferred-arc plasma furnace	AD Brent, LB McRae, & H Lagendijk
1985	The application of thermal plasma technology to large-scale pyrometallurgical processes	NA Barcza, TR Curr, & KU Maske
	The attainment of high power densities in transferred-arc plasma smelting processes	TR Curr, KU Maske, & KC Nicol
	Development in refractories for plasma technology	RC Nunnington, KU Maske, AFS Schoukens, TR Curr, & NA Barcza
	The 3,2MVA plasma facility at Mintek	TR Curr, KC Nicol, JF Mooney, AB Stewart, & NA Barcza
	The production of manganese ferro-alloys in transferred-arc plasma systems	AFS Schoukens & TR Curr
	The aluminothermic reduction of the oxide of reactive metals	NA Barcza, GW Dreibrodt, & JA Theron
	Metallurgical reaction philosophies of transferred-arc plasma furnaces	KU Maske & KJ Reid
1984	The dissipation of energy in D.C. transferred-arc plasma systems and the consequences for the production of ferro-alloys	AB Stewart
	The application of transferred-arc plasma to the melting of metal fines	LB McRae, NA Barcza, & TR Curr

1983	The design and operation of transferred-arc plasma systems for pyrometallurgical applications	TR Curr, NA Barcza, KU Maske, & JF Mooney
	Recent developments in pyrometallurgical plasma technology	KU Maske & NA Barcza
	The 'dig-out' of a ferrochromium furnace	A Wedepohl & NA Barcza
1982	The growth of ferro-alloy production in South Africa	RA Featherstone & NA Barcza
	Recent developments in the ferro-alloy field in South Africa	NA Barcza, RA Featherstone, & CWP Finn
1981	Optimum slag-alloy relationships for the production of medium- to low-carbon ferromanganese	DP O'Shaughnessy & NA Barcza
	The production of ferrochromium in a transferred-arc plasma furnace	NA Barcza, TR Curr, WD Winship, & CP Heanley
1979	Slag-metal equilibrium in the production of low-carbon ferromanganese	NA Barcza
	The 'dig-out' of a 75 MVA high-carbon ferromanganese electric smelting furnace	NA Barcza, A Koursaris, JB See, & WA Gericke
1977	Plasma technology and its application to extractive metallurgy	SML Hamblyn
1975	Phase equilibria in the Cr-Fe-Si-C system in the composition range representative of high-carbon ferrochromium alloys produced in South Africa	JCM Wethmar, DD Howat, & PR Jochens
1936	A study of a Direct Method of Stainless Steel Production	RP Forsyth

Table II: Pyrometallurgy Division patents

Year	Title of patent	Inventors
2004	Method of and apparatus for refining zinc	AD McKenzie, GM Denton, H Lagendijk, MD Shapiro, & DP Mitchell
2001	Treatment of metal sulphide concentrates	RT Jones, NA Barcza, G Kaiura, G O'Connell, & T Hannaford
1998	The processing of zinc bearing materials	NA Barcza, AFS Schoukens, & GM Denton
1996	Ferrochromium production	HL Smith, GM Denton, & NA Barcza
1995	The recovery of metal values from slags	DA Hayman & GM Denton
1994	The production of ferronickel from nickel containing laterite	H Lagendijk, AFS Schoukens, P Smith, & PWE Blom
1993	The production of stainless steel	MJ Niayesh
	The recovery of titanium from titanomagnetite	MD Boyd, AFS Schoukens, & GM Denton
1992	The production of high titania slag from ilmenite	GM Denton & AFS Schoukens
1991	The recovery of platinum-group metals and gold from sources containing same	LB McRae & EB Pretorius
	The production of calcium carbide	LJ Erasmus & AFS Schoukens
1988	The production of mattes containing PGMs and gold	LB McRae & JPR de Villiers
	The thermal reduction of agglomerated metallurgical feed materials with oxide coatings	NA Barcza, RA Featherstone, & RC Nunnington
	The thermal reduction of agglomerated feed materials with metallic coatings	NA Barcza & RC Nunnington
1987	Process for the enhanced reduction of chromite ores	NF Dawson & RI Edwards

1986	The thermal production of magnesium	AFS Schoukens & NA Barcza
	Electrically heated fluidized bed reactor and processes	NA Barcza, MJ Dry, & WFAT Meihack
1984	The aluminothermic reduction of the oxide of reactive metals	NA Barcza, GW Dreibrodt, & JA Theron
	Materials feeder assembly	T Monaci
	Process for the production of silicomanganese and ferromanganese-silicon alloys	NA Barcza & AFS Schoukens
1983	The refining of silicon	LB McRae
	Electrode assemblies for thermal plasma generating devices	TR Curr & JF Mooney
	The protection of water cooled plasma generating devices	NA Barcza & JF Mooney
	The treatment of ferromanganese	TR Curr & IE Schmidt
1982	The production of mattes containing platinum group metals and gold	LB McRae, TR Curr, & JP Loo
	The production and treatment of ferrochromium	TR Curr & NA Barcza
	The refining of ferrochromium metal	TR Curr & NA Barcza
1977	The control of electrical arc furnaces	IJ Barker & AB Stewart
1976	Improvements relating to briquettes	LB McRae
1975	A process for the treatment of mixtures of platinum group metals and gold	RI Edwards, JP Loo, & DI Ossin
	Stainless steel production	DI Ossin
1972	Improvements in or relating to the production of ferrochromium alloys	PR Jochens

CONCLUSIONS

Mintek has developed a major pyrometallurgical capability over the past thirty years, specialising in DC electric furnaces. It offers fundamental understanding to assist in scale-up studies and commercial implementation. Pilot plant facilities and staff are capable of demonstrating new processes at about one tenth commercial scale, running continuously for months, treating more than 1000 tons of feed.

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3. R.T. Jones, N.A. Barcza, and T.R. Curr, Plasma Developments in Africa, *Second International Plasma Symposium: World progress in plasma applications*, organized by the CMP (Center for Materials Production) of EPRI (Electric Power Research Institute), 9-11 February 1993, Palo Alto, California. http://www.mintek.co.za/Pyromet/Plasma/Plasma.htm

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12. Index of Pyrometallurgy Division technical papers http://www.mintek.co.za/Pyromet/Index.htm