FOUR YEARS OF DC ARC SMELTING OF PGM-CONTAINING OXIDE FEED MATERIALS AT MINTEK

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ABSTRACT

Mintek has developed and demonstrated an alternative process for smelting PGM-containing oxide feed materials that contain low amounts of sulfur and, often, high amounts of chromium oxide. A DC arc furnace is used to provide the appropriate conditions to generate an iron alloy in which PGMs and base metals are collected. The process is chromium-tolerant, very efficient in the collection of PGMs, and significantly reduces sulfur emissions compared to current matte-smelting processes in use in the PGM industry. Between April 2004 and August 2008, Mintek's pilot-plant furnace processed over 37 000 tons of PGM-containing feed materials on a toll-treatment basis - demonstrating the sustainability and efficiency of the process over a period of four and a half years. Various feed materials (including low-grade concentrates, converter slag, and revert tailings) have been treated successfully at power levels of up to 1.5 MW in a 3 m DC arc furnace, thereby demonstrating the robustness and versatility of the process, and proving that it is possible to sustainably produce PGM-containing alloy and discardable slag from the DC furnace operation.

INTRODUCTION

Conventional PGM matte smelting requires the presence of a certain quantity of base metal sulfides in order to collect the platinum group metals (PGMs) in a molten sulfidic phase in the furnace. The quantity of chromium oxide in the feed materials is also strictly controlled, in order to avoid the build-up of high-melting chromite spinels. Mintek has developed and successfully demonstrated an alternative process, known as the ConRoast process, which can be used for the production of PGMs using a DC arc furnace. The complete ConRoast process flowsheet has been described in much detail previously [1] but, essentially, instead of matte smelting, the process is based on alloy smelting of dead-roasted sulfide concentrates in a DC arc furnace. The DC furnace is used to provide the appropriate conditions to generate a small amount of an iron alloy in which PGMs and base metals are collected, resulting in slag with very low levels of residual PGMs. As the process does not rely on matte collection, there are also no constraints on the minimum quantity of base metal sulfides in the feed material, as the collection of PGMs is done in an iron-rich alloy. The desired degree of recovery of valuable metals is efficiently controlled by the addition of a small amount of carbon. The ConRoast process offers advantages in terms of being able to contain SO_2 emissions (by removing essentially all of the sulfur in a continuous enclosed roaster upfront of the smelting), and being able to accommodate a wide variety of feed compositions. The drive towards more environmentally friendly processes remains a strong positive feature of the ConRoast process. DC arc furnaces are used industrially for a number of processes, including the smelting of chromite [2], which clearly demonstrates that chromite quantity in the feed is not an operational constraint, as it is in the traditional matte-smelting operations.

In order to adequately address not only the inherent risks associated with any new smelting technology, but also to win the hearts and minds of a risk-averse industry, prolonged processing of PGM-containing feedstock was initiated at Mintek. Between April 2004 and August 2008, Mintek's pilot-plant furnace processed more than 37 000 tons of PGM-containing feed materials on a toll-treatment basis – thereby demonstrating the sustainability and efficiency of the process over a period of four and a half years.

Demonstrating new technology

Alternative or new technology inevitably requires piloting and demonstration prior to implementation and this is even more true for a pyrometallurgical operation, as any smelting operation has inherent risks associated with the process and equipment. Large-scale demonstration testwork adds significant value to any project but it is, however, very expensive to demonstrate the smelting step at large scale and for an extended period. The need to address the risks versus the cost of testwork and the availability of suitable feed typically determines the scale and duration of smelting testwork.

Mintek's Pyrometallurgy Division provides pilot-plant smelting testwork services to the metallurgical industry. The duration of a typical pilot-plant smelting campaign is usually restricted by cost, and the availability of raw materials, particularly when the feed requires upgrading or pre-treatment (like roasting or calcining, for example). Generally, a once-off test is commissioned during which a significant quantity of specially prepared feedstock is processed at an appropriate scale. The operational and metallurgical data from these test campaigns are processed and evaluated to provide input into feasibility and, ultimately, design studies. Mintek has developed significant expertise in this field of pyrometallurgical research, from demonstration testwork through to providing furnace and power-supply design parameters. This model was also followed during the development of the ConRoast process and, prior to the prolonged smelting campaign, batches of up to 30 tons of roasted material were processed, demonstrating the process flowsheet, and allowing for a range of downstream evaluations to be conducted on the products.

While this initial testwork was remarkable only in its success, the ConRoast process so radically departs from the traditional PGM production flowsheet that large-scale demonstration of the process was inevitably deemed a vital component in the progression towards the ultimate commercialization of the technology. Although Mintek's smelting facilities can process large quantities of feed, currently no pilot facilities are available to produce the large quantities of dead-roasted concentrate on a continuous demonstration basis. Thus, demonstrating the full ConRoast flowsheet on an ongoing basis was not a practical or affordable option. Fortunately, alternative PGM-containing materials with a low sulfur content became available from various sources. These materials were sufficiently similar to dead-roasted concentrates to allow for long-term demonstration of the smelting step of the ConRoast flowsheet. These materials included, for example, low- to medium-grade PGM concentrates that are high in chromite and low in sulfur, tailings from a milling-flotation process for the treatment of revert materials (also low in sulfur), from an existing smelter, and other PGM-containing wastes or by-products.

It is important to note that as the scale and duration of the demonstration testwork increase, it becomes possible for the testwork to effectively pay for itself (and potentially even realise a profit for a client). Recovery of contained metals is a significant economic incentive when treating valuable waste materials from dumps. Remediation of tailings dams or other dumps removes the environmental and economic liabilities typically associated with dumps and also makes valuable land available for more productive uses, whilst processing these materials provides an opportunity to demonstrate the sustainability of DC arc furnace technology to the PGM industry via a continuous, environmentally friendly operation.

From large-scale demonstration testwork to continuous production

Mintek commenced an extensive pilot-plant smelting campaign in April 2004, initially treating a variety of PGM-containing feed materials and the results from the first 2 000 tons processed were previously described in detail [3]. In short, a number of feed materials were initially tested to establish their suitability for the process. For example, a medium-grade UG2 concentrate (high in chromium and low in base metal sulfides) was found to work very well when mixed with a small quantity of converter slag. (It is necessary to mention that the iron that is used to collect the valuable metals is typically reduced to the metallic state from the iron oxide that occurs naturally in most PGM-containing feed materials. In cases where the feed materials contain less than the necessary quantity of iron, an additional iron source may need to be added to the furnace feed. Converter slag can be very useful for this purpose, and the use of this material has the added benefit that it obviates the need for recycling to a conventional matte-smelting furnace, and does away with the requirement for a separate slag-cleaning furnace. Because the ConRoast process operates with the addition of some carbon to the furnace, the stable state of the iron oxide is FeO rather than the Fe_3O_4 that causes operational problems in matte smelting.)

The primary focus of the work described here was on the treatment of stockpiled revert tailings (the waste generated by a milling-flotation process used in the treatment of revert materials from an existing smelter). As the testwork progressed, the focus of the continuous smelting operation changed from a research or demonstration operation to a production-oriented operation. As is the nature of any production operation (and perhaps more so for a smaller unit operation), throughput, availability, efficiencies, and process optimization became increasingly important measures.

GENERAL DESCRIPTION OF THE PROCESS

As delivered to Mintek, the moisture content of the feed material ranged from about 10% during the dry winter months to about 25% during the wet summer season. After being delivered by bulk side-tipping trucks, the material was loaded by front-end loader and a hydraulically operated scoop into a feed hopper, which discharged onto a conveyor belt that fed an electrically heated rotary kiln. The kiln operation produced approximately 30 to 50 tons per day of dry, bagged product (with 2 to 3% residual moisture). The bottom-opening bulk bags of dried feed material were lifted by crane and discharged into the furnace feed hoppers (which were mounted on load cells). The feed materials were discharged onto conveyor belts that delivered the feed into the furnace via a conical funnel, and feed pipe situated in the furnace roof. The furnace consisted of a refractory-lined cylindrical steel shell, with an outside shell diameter of 3 m.

The furnace had separate tap-holes for the removal of alloy and slag. During stable operation, the furnace was fed more or less continuously, and tapped intermittently via the dedicated tap-holes, with slag being removed from the furnace approximately every three hours, and alloy tapped about once a day. The slag tap-hole had a water-cooled copper insert, which performed well and rarely required maintenance. The alloy tap-hole performance was good, but the refractory lining generally required a partial replacement every two to three months of continuous operation. Each tap-hole maintenance shutdown typically lasted between 8 and 12 hours, during which time other maintenance on the plant was generally carried out. A weekly maintenance shutdown was also put into practice, in an attempt to improve the overall availability of the furnace, with the primary focus on preventative maintenance.

A single solid graphite electrode was used as the cathode, and the anode at the bottom of the furnace was made up of a number of steel pins that protruded through the refractory hearth to come into intimate contact with the molten alloy. The gas leaving the furnace was combusted and then passed through a bag-house to remove any entrained dust (for continuous recycling to the smelter) before being treated in an SO_2 scrubber prior to discharge through the stack.

The particular furnace used in the work reported here was equipped with film water-cooling on the side-walls, which placed some upper limits on the smelting intensity of the operation. (This was done deliberately to avoid the higher-intensity copper coolers that have failed often in PGM matte smelters elsewhere.) The furnace was operated in such a way as to maintain a freeze lining, and the operational intensity was reduced if the protective layer required reformation. Crushed, high-magnesia bricks were occasionally added to the furnace as a feed material to supplement the formation of the protective solidified layer on the side-walls. The temperature distribution in the furnace was very responsive to such factors as arc length and bath condition. These aspects were usefully monitored, and adjustments were made to arc length and operating intensity to achieve a desired mode of operation depending on the condition of the freeze lining, and process objectives. In this way, the furnace operation was managed by controlling the temperature distribution, especially with regard to the maintenance of the freeze lining.

OPERATIONAL HISTORY

From 16 May 2004 to 8 August 2008, a period of about 52 months, nearly 37 000 tons of revert tailings was processed in the 3 m DC arc furnace. Table 1 provides a brief summary of the history and the duration of the various campaigns. Overall, 2 687 tons of PGM-containing iron alloy and 31 999 tons of slag was produced, with 1 224 tons of off-gas dust being internally recycled to the smelter.

Table 1 - Summary of campaign duration, start-up and end dates, and tonnage processed

	Duration			Ave Power	Feedrate	Reason for shutdown
	From	To	Days	MW	tons/day	
C-1	16-May-04	15-Aug-04	92	0.97	17	Facility required for other testwork
C-2	28-Sep-04	31-Jan-05	126	1.26	27	Facility required for other testwork
C-3	13-Apr-05	25-Sep-05	166	1.35	29	Furnace re-lined after moving
C-4	04-Nov-05	04-Apr-07	517	1.39	34	Changed to new client
C-5	29-Sep-07	08-Aug-08	315	1.20	30	Decommissioned furnace for upgrade
	Overall		1216	1.29	30	

The furnace was generally operated continuously, with two short shutdown periods during 2004 and 2005 due to previously contracted commitments for demonstration-scale testwork (about two months in total). In 2007, the testwork facilities at Mintek were upgraded to allow for both the testwork and production facilities to operate without the need to interrupt the production during other research or demonstration testwork campaigns. A third shutdown, in September 2005, was used to relocate the furnace to a more accessible and permanent position in the building and the opportunity was used to re-line the furnace, as it was envisioned that a long-term contract would be implemented to reclaim and process the bulk of the revert tailings dump. The longest shutdown period was in 2007, during which the contractual client changed, and the furnace was effectively mothballed for a period of six months. The smelting operation was re-commissioned at the end of September 2007, with a new client, followed by the decommissioning of the 3 m furnace during August 2008 (to make way for a much larger unit).

FURNACE OPERATION

Overall, the furnace was in production for more than 40 months without any major incidents. The furnace operation became increasingly efficient as the throughput, availability, and process parameters were optimized. A summary of the general process parameters, that is, tons processed, slag and alloy make, dust carry-over, gross energy requirement, and electrode consumption for each of the five campaigns, is listed in Table 2. The alloy make was directly controlled by changing the addition of carbon (in the form of anthracite) to the furnace, and the degree of reduction was controlled to achieve the desired optimized PGM recovery. The electrode consumption was good, with an overall consumption of 1.5 kg electrode per MWh.

Table 2 - Summary of some aspects of the furnace operation, for the five campaigns

No.	Tons processed	% Anthracite	% Alloy	% Slag	% Dust[#]	MWh/ton[*]	Electrode kg[$]/ton
C-1	1 577	5.0	11.3	80	1.4	1.218	1.89
C-2	3 344	3.9	9.3	83	2.5	1.007	1.34
C-3	4 878	3.8	7.9	84	5.0	0.936	1.29
C-4	17 628	2.9	5.5	86	3.0	0.871	1.30
C-5	9 525	3.2	8.9	80	3.6	0.834	1.38
Overall	36 952	3.3	7.3	84	3.3	0.897	1.35

[#] Dust collected and continuously recycled to furnace, expressed relative to mass of PGM-containing feed
* Gross energy consumption MWh/ton PGM-containing feed
[$] Electrode consumption expressed as kg graphite per ton of PGM-containing feed processed

Energy consumption (gross) decreased from an average of 1.22 MWh/t in the first campaign to 0.83 MWh/t for the fifth. The lower gross energy consumption was associated with increased throughput and higher equipment availability. The energy consumption per day of operation is graphically presented in Figure 1, illustrating the continued improvement in efficiency.

Although the operating crew maintains a mass and energy balance as part of the daily furnace control strategy, the furnace is seldom in true thermal equilibrium. Feed and product compositions change, maintenance interruptions occur, and the mode of operation is continuously adjusted to manage the mass and energy balance in order to compensate for these factors, therefore always striving towards operating at equilibrium but not ever achieving true thermal equilibrium.

The daily gross energy consumption data depicted in Figure 1, illustrates the variability in the day-to-day energy consumption due to the normal operational interruptions. Despite this inherent variability, a distinctive trend towards improved efficiency is clear - both as a function of campaign duration and throughput (tons processed and average power input). Figure 2 presents the monthly gross energy consumption data as a function of average power input and as a function of PGM-containing feed material processed per month. Both graphs show the improved efficiency trend as throughput and availability increased.

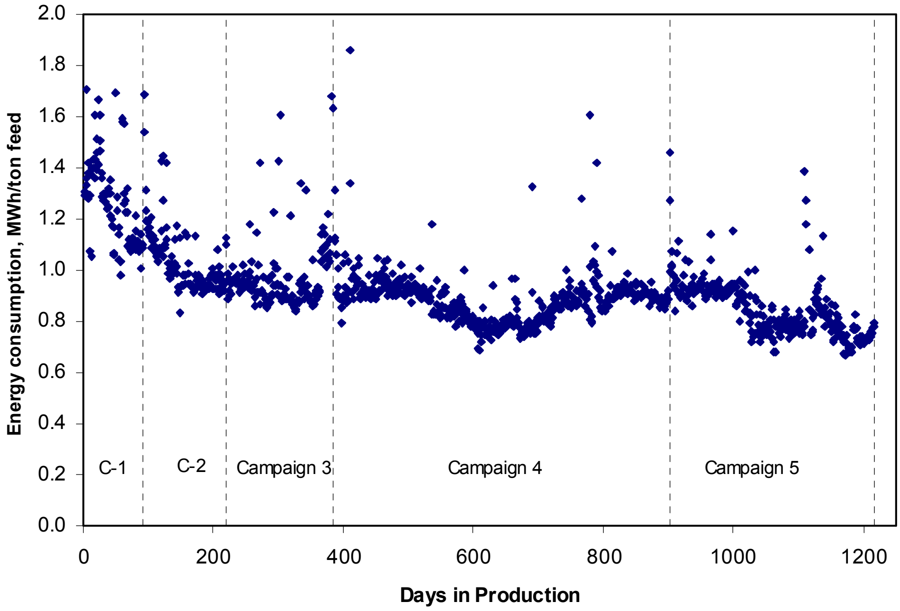

Figure 1 - Daily gross energy consumption per ton of feed, MWh/t

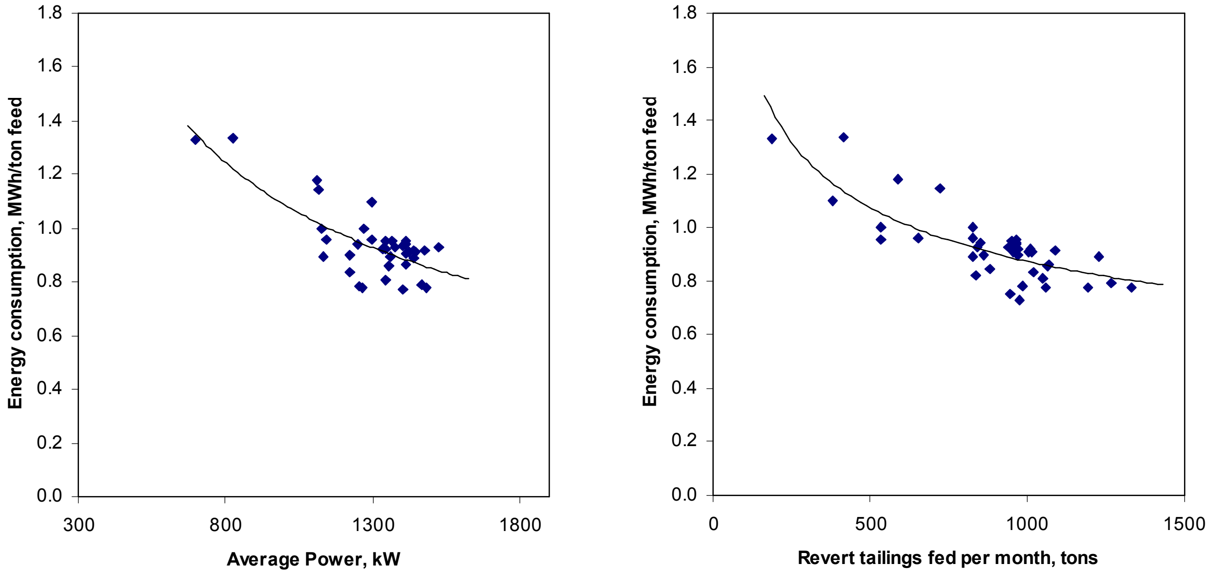

Figure 2 - Monthly gross energy consumption

The average gross energy consumption for the months with a throughput exceeding 900 tons was 0.866 MWh/t, while the average for months with less than 900 tons throughput was 1.018 MWh/t. The average throughput per month and estimated thermal efficiencies according to this criterion is summarised in Table 3. The figures quoted for 'specific energy consumption' have taken into account the energy losses from the furnace vessel, and reflect only the energy that is required for the process itself.

Table 3 - Summary of energy consumption and thermal efficiencies based on throughput

No of months	Throughput	Average monthly throughput	Average Power	Total energy consumption	Specific energy consumption	Thermal efficiency
	tons	tons	kW	MWh/ton	MWh/ton	%
17	< 900	674	1148	1.018	0.634	62
25	> 900	1037	1366	0.866	0.632	73
42	All	895	1286	0.897	0.631	70

Table 4 summarises the weighted average chemical composition of the revert tailings treated during the five campaigns. PGM content was analysed by fire assay, with the total reported here (as PGM 4e) representing the sum of the individual values for Pt + Pd + Rh + Au. In general, the chemical composition of the tailings was fairly consistent, although a marked drop in PGM content occurred during the fourth campaign. Upon investigation it was found that the revert tailings dumpsite had been disrupted and contaminated with significant amounts of lower-grade slag. The PGM grade of the feedstock varied significantly during the last two campaigns, and continuous attempts were made to salvage the highest possible grades from the dumpsite by implementing systematic reclamation or selective mining, as well as visual screening of the stocks prior to moving the materials off the dumpsite. Overall, a maximum PGM content of 130 g/t was measured, whilst the grade dropped as low as 6 g/t for a short period during the fourth campaign. The overall weighted average PGM grade for the 36 952 tons processed was 51 g/t.

Table 4 - Revert tailings composition, mass % (PGM listed in g/t)

Campaign	Al_2O_3	C	CaO	Co	Cr_2O_3	Cu	FeO	MgO	Ni	S	SiO_2	PGM 4e
1	3.65	0.22	6.04	0.17	2.56	0.29	34.7	10.14	0.99	0.84	34.2	64
2	3.76	0.20	6.69	0.18	2.67	0.31	33.2	10.55	1.08	0.86	33.4	72
3	3.51	0.24	6.62	0.17	2.53	0.30	34.0	10.39	1.04	0.76	34.6	61
4	3.79	0.30	6.52	0.13	2.37	0.26	31.5	12.49	0.74	0.72	37.1	39
5	3.74	0.28	6.09	0.14	2.30	0.38	31.8	11.91	1.00	0.78	36.5	58
Overall	3.73	0.27	6.42	0.14	2.41	0.30	32.2	11.79	0.89	0.76	36.2	51

Typically, slag with very low levels of residual PGMs was produced, and no appreciable entrainment of PGM-containing alloy prills in the slag was encountered. The weighted average overall PGM content in the slag was 1.1 g/t, with contents less than the 0.28 g/t analytical detection limit frequently reported. The degree of reduction was controlled by adjusting the carbon addition, generally controlling the reducing conditions to produce the minimum alloy fall whilst maintaining an acceptable recovery of the PGMs. (Anthracite, with about 75% fixed carbon, was utilized as the carbon source.) Although very low levels of PGMs in slag are achievable, a deliberate decision was taken to limit the degree of iron reduction (minimizing alloy fall) whilst marginally compromising on PGM recovery for the sake of minimizing the amount of alloy that would require further downstream treatment. (It is an important feature of the process that it allows this degree of control.) All alloy was re-melted and granulated off-site, and the quantity of alloy impacted directly on the treatment costs. The barren slag was initially returned to the client's own slag stockpile, but, later, the approximately 8 000 tons of slag from the final campaign was crushed and utilized as aggregate or backfill. The weighted compositions of the slag produced during the various campaigns are listed in Table 5. The PGM content of the slag was analysed by a fire assay - gravimetric procedure (fire assay fusion followed by cupellation and a gravimetric finish) and so represents the approximate total of Pt + Pd + Rh + Au (PGM 4e). The average slag tapping temperature was 1585ºC, at which temperature the physical properties of the slag were acceptable, and the alloy could be tapped at temperatures within 100ºC of the alloy liquidus.

Table 5 - Furnace slag composition, mass % (PGM listed in g/t)

Campaign	Al_2O_3	C	CaO	Co	Cr_2O_3	Cu	FeO	MgO	Ni	S	SiO_2	PGM 4e
1	4.78	0.06	7.46	0.04	3.09	0.07	28.2	12.71	0.10	0.32	43.1	1.55
2	4.75	0.06	7.86	0.05	3.28	0.08	28.8	12.75	0.08	0.32	40.1	1.29
3	4.56	0.07	7.98	0.05	3.08	0.09	31.0	12.34	0.11	0.34	40.1	1.72
4	4.46	0.06	7.33	0.05	2.76	0.10	29.2	14.12	0.12	0.34	41.5	1.00
5	4.06	0.02	6.51	0.03	2.61	0.08	26.5	15.56	0.10	0.34	41.5	0.90
Overall	4.41	0.05	7.27	0.05	2.83	0.09	28.7	14.06	0.11	0.34	41.3	1.12

Figure 3 shows the normalized slag compositions derived from the average slag compositions for the five campaigns on a ternary FeO-MgO-SiO_2 phase diagram, to illustrate the approximate regimes of operation. For plotting on a three-component basis, the amount of CaO in the slag was divided in two and the equal amounts were added to the FeO and MgO. The effect of the minor components (such as Al_2O_3, Cr_2O_3, and Mn_2O_3, totalling about 8%) is likely to reduce the liquidus isotherms slightly as opposed to the normalized points shown on the graph which made the slag and alloy very compatible with regards to liquidus temperature.

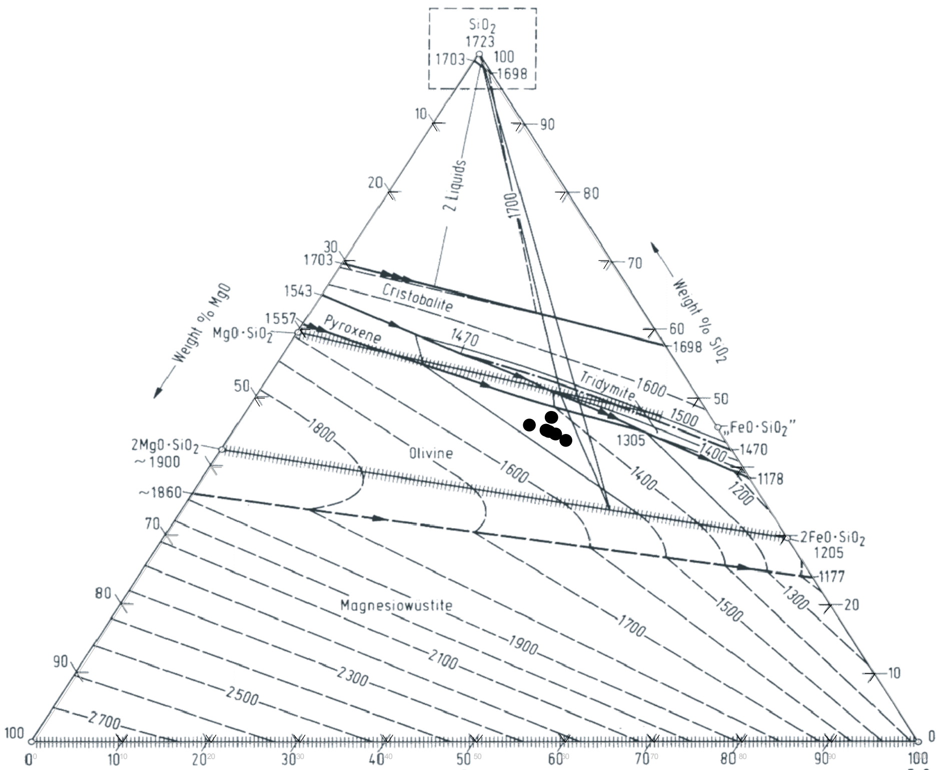

Figure 3 - Phase diagram with average slag compositions for the five campaigns presented

The mass and weighted compositions of the alloy produced are listed in Table 6.

Table 6 - Alloy composition, mass % (PGM listed in g/t)

Campaign	Tons	C	Co	Cr	Cu	Fe	Ni	S	Si	PGM 4e
1	179	0.11	1.23	0.21	2.05	83.7	8.1	3.71	0.49	462
2	313	0.08	1.43	0.18	2.69	79.2	11.0	5.94	0.27	771
3	385	0.10	1.60	0.14	3.07	75.6	12.5	5.78	0.25	880
4	964	0.06	1.48	0.16	3.17	74.8	10.8	6.57	0.24	634
5	846	0.05	1.23	0.19	3.67	77.9	10.5	6.13	0.16	597
Overall	2 687	0.07	1.40	0.17	3.18	77.0	10.8	6.05	0.24	662

When carbon is added to the molten bath in a furnace, the various metallic elements reduce to different extents, at a given level of carbon addition. This behaviour allows a reasonable degree of separation to take place during smelting. It is well known that an increase in the amount of the reductant added to the furnace results in increased quantities of the various metallic elements that report to the alloy that is produced. The intention in this process is to separate the valuable metals from the Fe and the gangue constituents that are present in the slag. The desirable area of operation is clearly somewhere in the region where the recovery of PGMs and valuable base metals is high, and the recovery of Fe to the alloy is still reasonably low. This is possible, because Co, Cu, and Ni are preferentially reduced over Fe, especially under less reducing conditions. The addition of carbon is therefore one of the primary variables utilized in order to control the selective deportment of the valuable metallic elements to the alloy phase, in order to optimize recovery of PGMs and other valuable metals, whilst minimizing the recovery of Fe to the alloy phase. This operating philosophy is depicted in Figure 4 in the context of varying feed grade (PGMs and Ni) and illustrates the adjustments made to the degree of reduction (via the Fe recovery) in order to optimize PGM recovery and minimizing the deportment of Fe to the alloy. For the two longest campaigns (4 and 5), sub-periods were evaluated based on the average grade processed, with each period representing roughly equivalent tailings throughput. The overall data for campaigns 1 to 3 is evaluated as these campaigns were significantly shorter and the feed grade did not vary significantly during these campaigns.

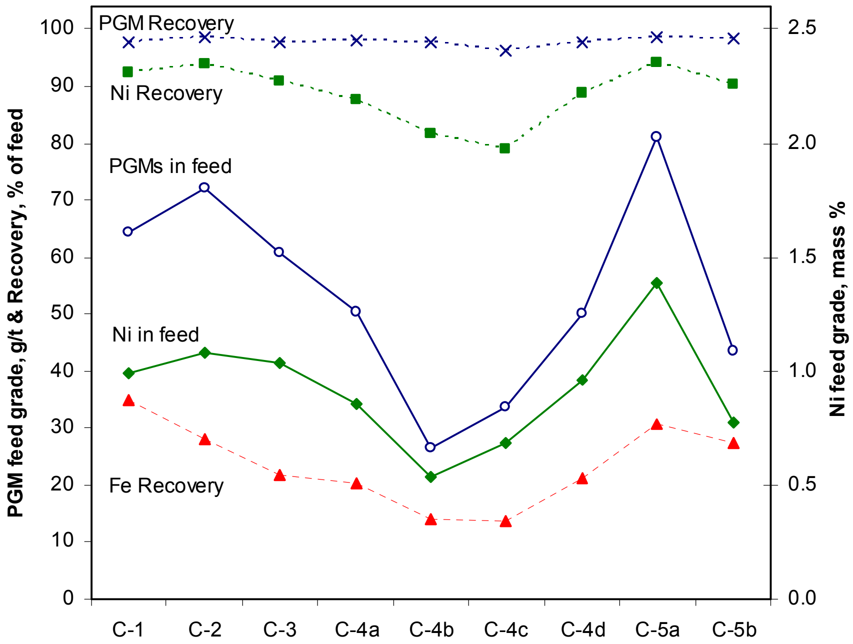

Figure 4 - PGMs and Ni feed grades and associated achieved recoveries per campaign

The degree of deportment of the various elements to the alloy phase is, of course, of principal interest in any metal recovery process. During the life of the project, a detailed daily elemental mass balance was compiled which provided the detailed deportments of various elements of interest. The recovery of a given element is here expressed as the ratio between the mass of its content in the alloy divided by the combined mass of its content in the alloy and slag. The basis of this assumption is that all dust captured in the baghouse was fully recycled to the furnace, and the overall elemental accountability was good. The recoveries of various elements of interest are listed in Table 7. Please note the earlier comment that the operation of the furnace was focused not on maximum recovery, but on balancing a good recovery with the production of a minimum amount of alloy.

Table 7 - Recovery of elements to the alloy, % of feed

Campaign	Co	Cr	Cu	Fe	Ni	PGM 4e
1	80.4	1.4	80.4	34.8	92.2	97.7
2	76.7	0.9	78.6	28.0	94.0	98.5
3	74.3	0.6	74.8	21.6	91.0	97.8
4	63.1	0.5	66.5	16.9	84.5	97.5
5	81.3	1.1	82.2	28.7	92.1	98.6

A recovery equation, described in detail elsewhere [4-6], was established for the conditions of interest. The recovery, or degree of collection, of the valuable metals is a function of the extent of reduction in the furnace, which, in turn, is indicated by the fraction of iron present in the feed materials that reports to the alloy. The recovery equation relates the recovery of various metals (such as Ni, Co, PGMs, and Cr) to the recovery of Fe. This recovery equation (for each metal) is characterised by a single parameter ($K\gamma$) that can either be empirically fitted to the data, or expressed in terms of the equilibrium constant and the ratios of the activity coefficients involved. This equation is a useful tool to model the recovery relationships during smelting.

$$R_{\mathrm{X}} = \frac{R_{Fe} K\gamma}{(1-(1-K\gamma)R_{Fe}} \quad \text{where x => Ni, Co, Cu, Cr, or PGMs} \qquad (1)$$

There is no apparent reason for why the PGMs should behave in a similar fashion to the elements participating in reduction reactions, but there are good indications from the data collected during the five campaigns that they do, and it is on this basis that PGM recovery is also usefully modelled using the $K\gamma$ recovery equation. Figure 5 shows the recovery of PGMs, Ni, Co, and Cr as a function of Fe recovery to the alloy. The best fit $K\gamma$ values for Co, Ni, Cr, and PGMs were calculated by using the Least Squares Fit method.

Although the degree of recovery is critical in the process, the grade of the alloy tapped from the furnace is a direct and practical method of assessment. Highly reducing conditions will provide high recoveries of the valuable metals, but, at the same time, Fe will dilute the grade of the product with very little benefit in metals recovery, but with significantly higher alloy production. From Figure 5, it can be seen that this is particularly true for the PGMs and Ni, as high recoveries are achieved under relatively mild reducing conditions. The best-fit $K\gamma$ values provide a valuable tool through which optimum operating conditions can be established with respect to the recoveries. The grade-recovery relationship, as a function of Fe recovery is depicted in Figure 6.

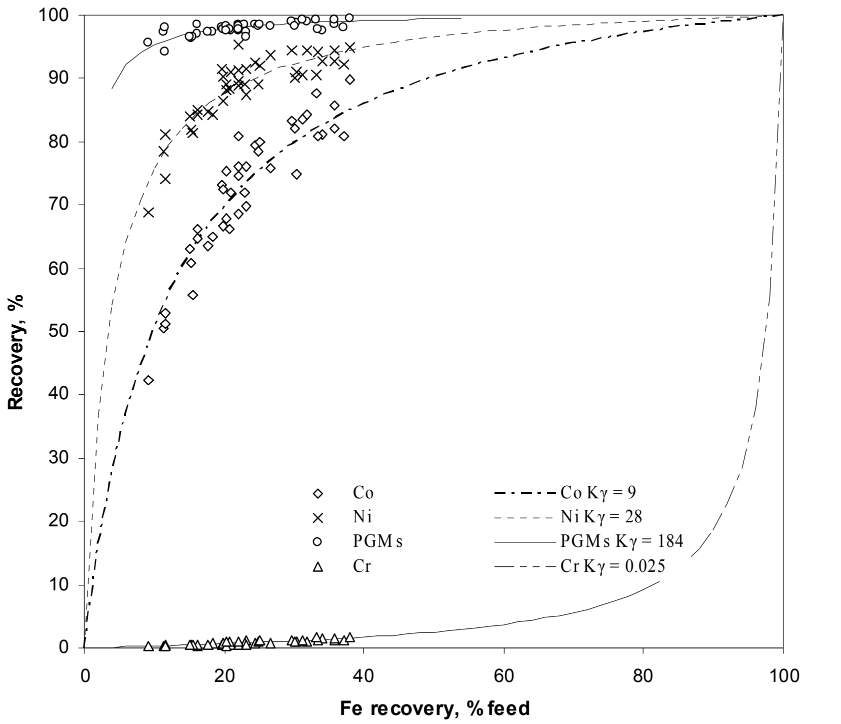

Figure 5 - PGM, Ni, Co, and Cr recovery as a function of Fe recovery (monthly)

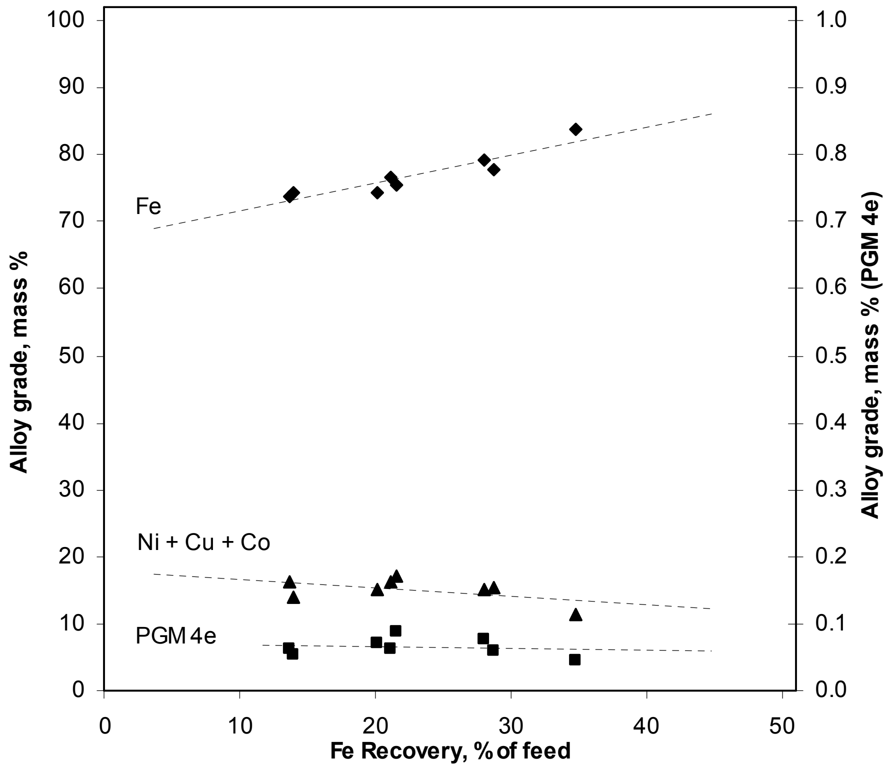

Figure 6 - Alloy grade as a function of Fe recovery (per campaign)

FUTURE DEVELOPMENTS

The ConRoast process has indeed become a hot topic in the PGM industry due to its divergence from the traditional matte-smelting process and the opportunity the technology has created for new and developing miners to utilise high-chromium ores without the penalties imposed on producers by the existing smelters. Independence Platinum Limited (IPt) was formed to undertake the commercial development and exploitation of Mintek's ConRoast technology, with the strategic objective of establishing an independent smelting and refining facility in South Africa. IPt entered into an agreement with Mintek to fund a three-year development and demonstration programme in order to set up a smelter based on Mintek's ConRoast technology, in exchange for a ten-year period of exclusive use of this technology. Independence Platinum was acquired by Braemore Resources plc in December 2006 and renamed as Braemore Platinum [7]. Braemore Platinum identified Mintek's toll-treatment facility as an excellent vehicle to demonstrate the ConRoast technology on a continuous basis and also establish the company's footprint as a new, independent platinum producer in South Africa. As part of the strategy, the 3 m furnace was upgraded to a new 4.25 m furnace with the feed and off-gas handling systems upgraded to suit, effectively doubling the throughput of the original facility. In addition to the smelting facility upgrade, a flash drier replaced the electrically heated kiln previously utilized. Commissioning of the new facility commenced in September 2008. The first slag and alloy was tapped from the furnace in October 2008, with a ramp-up to full capacity being aimed at early 2009. The objective of the upgrade was to demonstrate the smelting of PGM-containing low-sulfur and/or high-chrome materials on an even larger scale as part of Braemore's strategy to establish a commercial-scale ConRoast smelter.

CONCLUSIONS

Over a period of four and a half years, one of Mintek's pilot-plant facilities was transformed from a highly technical research facility into a full-time production plant. Although the aim and targets for the smelter obviously moved away from a pure research approach, significant and detailed metallurgical and process data was captured and compiled throughout. The production campaigns demonstrated that a DC arc furnace could be operated on a continuous basis smelting low-sulfur PGM-bearing materials, whilst producing an iron-based alloy without adverse operational problems.

The following general principles were established:

- The operation became increasingly efficient as the throughput, availability, and process parameters were optimized. Energy consumption decreased from an average 1.22 MWh/t during the first campaign to 0.83 MWh/t during the last, and a direct correlation was observed between throughput and efficiency.
- The temperature distribution in the furnace was very responsive to such factors as arc length and bath condition. Distribution of temperature was a useful tool through which the furnace operation was managed, in particular with regard to the maintenance of the freeze lining.
- The grade of the alloy is overwhelmingly dependent on the degree of Fe recovery. Under highly reducing conditions, increased reduction of iron is easily achieved without a significant benefit in terms of recovery of the base metals to the alloy phase. Selective deportment of the valuable metallic elements to the alloy phase is very effectively controlled with a view to achieve the desired recovery of the valuable constituents whilst minimizing the Fe recovery.
- Recovery of the valuable metals, including PGMs, can be reliably modelled as a function of Fe recovery, allowing for the efficient control of the Fe production by adjusting the carbon addition as required.
- Chromium deports preferentially to the slag, with limited deportment to the alloy (in this context, a deleterious contaminant in post-taphole processing).
- An overall PGM recovery of 98% was achieved under relatively mild reducing conditions.

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