

# The recovery of platinum group metals from low-grade concentrates to an iron alloy using silicon carbide as reductant

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Currently, the matted-based collection process is most widely used for platinum group metal (PGM) recovery. However, because PGM-containing concentrates are becoming more enriched with UG2 (Upper Group 2) low-grade concentrates, this is expected to be integrated or replaced with an alloy collection process.

The reduction LG (low-grade) concentrates with silicon carbide (SiC) was investigated. The purpose of the study was to ascertain the feasibility of using SiC as reductant with regard to metal fall, PGM grade in the alloy, slag composition, and overall PGM recovery, and if possible, the integration of such a process in the current matte-based collection process. Rowland and Easterns LG concentrate samples from Lonmin were analysed by X-ray diffraction (XRD), X-ray fluorescence (XRF), and inductively coupled plasma mass spectrometry (ICP-MS). It was found that SiO<sub>2</sub> and MgO are the most abundant oxides and Pd is the most abundant of the PGMs. Sulphide-bearing minerals such as chalcopyrite were detected in low concentrations (below 1%), and Cr<sub>2</sub>O<sub>3</sub> concentrations are between 2–4%. SiC reduction of Rowland and Easterns concentrate were conducted at 1600°C, with reductant to concentrate ratios ranging from 2.5 to 3.5 kg SiC per 100 kg concentrate.

The reduction experiments revealed that PGM recoveries from Rowland concentrate were poor. SEM images showed entrained metal prills in the slag phase. The slag viscosity at the end of the melt was calculated by using FactSage, and the results indicated that the viscosity was higher than 4 poise, which is above that of Easterns slag. PGM recoveries for Easterns concentrate were significantly better. More than 85% of the Ir and Pd and almost 60% of the Pt were recovered in a test with a reductant to concentrate ratio of 3.5 kg SiC per 100 kg Easterns concentrate. At this reductant to concentrate ratio, Fe recovery was also the highest, at 66%. SEM imaging of a slag sample revealed few or no metal prills entrained. The FeO content in the initial concentrate charge was then increased by adding Peirce-Smith converter slag in order to decrease the slag viscosity and further increase PGM recovery. A test was conducted with the addition of 10 kg converter slag per 100 kg Easterns concentrate. The reductant to concentrate ratio was kept at 3.5 kg SiC per 100 kg Easterns concentrate. The Ir and Pd recoveries were more than 95%, while Pt recovery was almost 70%. Fe recovery increased to 76%. On the basis of these results an optimum feed ratio between Easterns and Rowland concentrates and Peirce-Smith converter slag were calculated. FactSage predicted that the concentrate charge should consist of 70–80% Easterns concentrate with 20–30 kg converter slag per 100 kg LG concentrate. SiC reduction of this optimum LG concentrate charge is expected to recover more than 90% of all PGMs. Cr and Si concentrations in the alloy will be below 1% in total.

The effectiveness of SiC as reductant was also compared to carbon reduction. Carbon reduction of an optimum concentrate charge at the same reductant to concentrate ratio resulted in a marginally higher metal fall than SiC reduction. However, gas emissions and energy requirements are higher for carbon reduction.

The study has shown that base metals and PGMs can be recovered in an iron alloy by SiC reduction of LG concentrate with converter slag additions. Integration of such a process into the matte-based collection process could be considered as a future alternative for smelting UG2 LG concentrates.

## **Introduction**

South Africa is the world's leading supplier of platinum group metals (PGMs). Most of the PGMs are contained in the Merensky and UG2 reefs of the Bushveld Igneous Complex, and are associated with nickel and copper mineralization. In Merensky ore, the major base-metal sulphide mineral is pyrrhotite, with pentlandite, chalcopyrite, pyrite, and minor amount of other sulphides also present. In UG2 (Upper Group 2) ore, the major base-metal sulphide present is pentlandite. Pyrrhotite is found in moderate amounts, and millerite and pyrite in minor amounts. Because of the cheaper mining costs, platinum mining is becoming more UG2-based, and the resulting concentrates contain high levels of chromite unless blended with Merensky ore. It is therefore critical that new and improved extraction methods need to be developed and implemented.

The methods used in the recovery of the PGMs from these ores consist of physical concentration techniques, pyrometallurgical processing, and hydrometallurgical extraction of the base metals followed by the PGMs (Jones and Kotze, 2004; Nell, 2004). During pyrometallurgical processing, the nickel-copper concentrates from milling-flotation step are smelted to bring about physical and chemical changes that enable the recovery of base metals, PGMs, and other valuable metals in a crude form. In general, the idea is to melt the concentrate in a furnace to produce a matte that contains all the sulphides below a carefully maintained slag layer. This matte, which still contains large amounts of iron and sulphur, is oxidized in a converter (known as a Peirce-Smith converter) in order to lower the iron and sulphur contents, while at the same time increasing the PGM grade. Conventional PGM matte smelting essentially requires a certain quantity of base metal sulphides in the feed in order to collect the PGMs in a molten sulphidic phase in the smelting furnace. However, the quantity of chrome oxide in the feed materials (particularly UG2 materials) need to be strictly controlled to avoid the build-up of high melting-point chromite spinels (Jones and Kotze, 2004; Nell, 2004).

Currently, the matte-based collection process is the most widely used for PGM recovery, but because increasing amounts of UG2 concentrates are being processed, it is expected to be integrated with or replaced by an alternative processes. Mintek has developed an alternative process, known as the Conroast process, for smelting PGM-containing oxide feed materials low sulphur contents, and often with high chromium oxide contents. The process involves the smelting of dead-roasted sulphide concentrates in order to generate a small amount of an iron alloy in which PGMs and base metals are collected. A slag is also produced, which mostly contains unwanted materials and very low levels of residual PGMs. The degree of reduction is controlled by adjusting the carbon addition. However while strongly reducing conditions provide high recoveries of the valuable metals, collection in a large volume of -iron alloy dilutes the PGM grade, resulting in an unacceptable product (Jones and Kotze, 2004; Nell, 2004).

In this study, low-grade (LG) concentrates from Lonmin's Rowland and Easterns operations were smelted with SiC as reductant. The effect of process parameters such as reductant to concentrate ratio, temperature, and different reductants on metal fall, alloy composition, slag composition, and gas composition were investigated. The results from FactSage simulations were used to analyse the experimental results. The detailed chemical and mineralogical characterization of feed and alloy, slag was conducted by X-ray diffraction (XRD), X-ray fluorescence (XRF), scanning electron microscopy (SEM), and inductively coupled plasma mass spectrometry (ICP-MS).

The primary objectives of this study include understanding the reducing conditions required to produce the minimum amount of alloy while maintaining as high as possible recovery of PGMs; quantifying the deportment of the various elements to the alloy and slag phase and establishing which factors will affect the recovery of PGMs; and comparing the gas emissions from different reductants in terms of environmental impact. The benefits of the new process would include removing the constraint on the minimum quantity of base metals required in the feed material, as the PGMs are collected in an iron-based alloy; the ability to integrate the relatively large quantities of the alloy product into an existing smelter complex, possibly through a converter; the possibility of hydrometallurgical refining of the alloy; chromium tolerance and efficient collection of the PGMs; reduction in sulphur emissions compared to current matte-smelting processes; and the possibility of treating other waste materials in a similar manner.

## **Materials and methods**

A Carbolite STF 1800 tube furnace with a programmable Carbolite controller was used for the experiments. The alumina tube is heated by five surrounding lanthanum elements. A calibrated thermocouple (K-type) was inserted at the top of the furnace and readings were taken at different sections of the tube. The furnace was set at 1600°C. Once temperatures close to 1600°C were measured, a small hot zone could be marked on the furnace. A set-point of 1600°C was set on the controller and the measured temperature recorded by a thermocouple located in the furnace. The initial plan was to attach a crucible to a wire and then suspend it from the top of the furnace, at the tube outlet, and lower it down to the marked hot spot. In order to facilitate the operation, the furnace was removed from its original supporting brackets and fitted on to a fork-lift (Figure 1. After the adjustment, the furnace could easily be moved up and down in a vertical direction, the movement being carefully controlled by a hydraulic lever or foot pedal). After the furnace had reached the set temperature, the MgO crucible containing the sample mixture was placed into the tube furnace.

Roughly 10 g of concentrate could accumulate in a crucible; however, some frothing was expected to take place and no more than 8 g of concentrate was used at any one time in order to accommodate frothing. High-purity MgO crucibles were used to minimize interaction with slags produced by melted concentrates that are saturated in MgO. Before the sample was placed into the hot zone, the Al work tube was purged for 20 minutes with high-purity argon at a flow rate of 5 l/min. The sample was then raised to the hot zone. The Ar flow rate was reduced to about 600 ml/min at the start of the experiment. After a predetermined time of reduction, the furnace was raised and the sample allowed to cool rapidly under an Ar flow rate of 5 l/min for about 10 minutes.



**Figure 1.A** Carbolite STF 1800 tube furnace with controller, modified with a fork-lift. (1) Fork-lift, (2) gas outlet with extraction fan, (3) argon gas inlet, (4) temperature controller

Representative samples for analytical and experimental work were obtained by riffle and sectorial splitting. Although these sampling techniques are not ideal and could contribute to sampling error, no other techniques could be conceived that would eliminate sampling error on the LG concentrates and SiC reductant. It is therefore assumed that some small inconsistencies could appear in the results, although these should not significantly influence the base metal and PGM recovery results. If some inconsistencies are noted in PGM recoveries, the base metal recoveries should be adequate to support any significant findings from the experiments. Experiments were also limited by the availability of crucibles, analytical costs, and research time. Replicate experiments were therefore not possible in all cases.

The screen analysis showed that  $P_{80}$  values for Easterns and Rowlands LG concentrates and SiC reductant were 320  $\mu\text{m}$ , 180  $\mu\text{m}$ , and 380  $\mu\text{m}$  respectively. The chemical compositions of the LG concentrates used in the smelting tests are given in Tables I–III.

**Table I. XRF results for Rowland and Easterns LG concentrates**

Constituent	Rowland LG concentrate (wt %)	Easterns LG concentrate (wt %)
$\text{Al}_2\text{O}_3$	5.41	5.00
$\text{CaO}$	2.72	3.03
$\text{Cr}_2\text{O}_3$	2.94	4.31
$\text{Fe}_2\text{O}_3^*$	12.73	14.24
$\text{K}_2\text{O}$	0.10	0.10
$\text{MgO}$	22.79	23.05
$\text{MnO}$	0.15	0.18
$\text{Na}_2\text{O}$	0.38	0.30
$\text{P}_2\text{O}_5$	0.02	0.02
$\text{SiO}_2$	49.40	47.81
$\text{TiO}_2$	0.31	0.32
LOI *	3.08	2.32
<b>Total</b>	100.05	100.66

\* LOI includes the total volatiles content (including the water combined in the lattice of silicate minerals) and the gain on ignition related to oxidation of the sample (mostly due to Fe),  $\text{Fe}_2\text{O}_3$  converted to  $\text{FeO}$ .

**Table II. ICP-MS results for PGM values (wt %) in the LG concentrates**

Material	Au %	Ir %	Pd %	Pt %	Rh %	Ru %
Rowland LG concentrate	<0.005	0.057	0.10	0.059	<0.005	<0.005
Easterns LG concentrate	<0.005	0.064	0.11	0.083	<0.005	<0.005

**Table III. XRD results for Rowland and Easterns LG concentrate bulk samples**

Mineral	Rowland LG concentrate (wt %)	Easterns LG concentrate (wt %)
Actinolite	3.33	0.91
Augite	4.5	5.44
Biotite	6.91	5.03
Calcite	0.57	0.15
Chalcopyrite	0.33	0.16
Chlorite	4.88	5.31
Chromite	4.68	7.57
Enstatite	43.63	48.22
Kaolinite	4.84	4.26
Plagioclase	5.82	4.38
Quartz	1.11	1.07
Talc	19.42	17.5

## Results and discussion

### *FactSage simulations*

Initial FactSage simulations were conducted prior to laboratory-scale experiments in order to establish a range of optimum conditions. Minor oxides (<1%), including Na<sub>2</sub>O, TiO<sub>2</sub>, MnO, and K<sub>2</sub>O were neglected in order to reduce total number of species in the FactSage output. Cu, Ni, and other easily reduced base metals were also neglected. The major oxides include CaO, MgO, Al<sub>2</sub>O<sub>3</sub>, FeO, SiO<sub>2</sub>, and Cr<sub>2</sub>O<sub>3</sub>, and all composition percentages were normalized to yield a total weight percentage of 100%. The final settings before determination of equilibrium conditions by FactSage are summarized in Table IV.

**Table IV. Selection of databases, species, and phases in FactSage**

Databases selected	FACT 53, FToxide, FTmisc and SGTE
Species involved	CaO, MgO, SiO <sub>2</sub> , FeO, Al <sub>2</sub> O <sub>3</sub> , Cr <sub>2</sub> O <sub>3</sub> , SiC, C, and CuFeS <sub>2</sub>
Phases selected	Gas, pure solids, matte, alloy, and slag

Experimental results are compared with FactSage results and discussed. However, modelling of the physical properties of the melt with FactSage can be investigated only in a limited paradigm. These physical characteristics, which include, viscosity, interfacial tension, entrainment of alloy or matte in the slag phase, and size of matte/alloy droplets, could significantly influence phase separation. FactSage is therefore expected to over-predict metal fall and base metal recoveries compared to the experimentally determined values.

Without any reductant in the system, MgCr<sub>2</sub>O<sub>4</sub>(s) spinel accumulates, therefore a reductant mass of 3 kg SiC per 100 kg LG concentrate was chosen as a base case. During the prediction of optimum temperature range, the requirement was that Fe concentrations should be high, while Cr and Si should remain low. The liquidus temperatures of Rowland and Easterns concentrates during SiC reduction are 1420°C and 1410°C respectively. Therefore the temperatures investigated were above 1400°C. The results indicated that Fe and Cr concentrations in the alloy should not be significantly affected, while Si concentration will increase with increasing temperature from 1400°C to 1650°C. The solubility of C in the alloy decreases when the temperature is increased. The metal fall is not significantly affected, and a temperature of about 1600°C should yield a good metal fall (8-12%) and avoid formation of solid phases like MgSiO<sub>3</sub>(s) (proto-enstatite). Therefore 1600°C was selected as the temperature to investigate the SiC reduction of the LG concentrates.

The effect of reductant to concentrate ratio was investigated in the range 0.5–4 kg SiC per 100 kg LG concentrate. Tables V and VI display the results from the FactSage simulations.

**Table V. FactSage prediction on metal fall and alloy composition as a function of reductant mass (values of Cr, C, Fe, and Si expressed as wt %). Evaluation for Rowland LG concentrate**

<i>SiC</i> <i>Concentrate</i> ratio ( $\times 10^2$ )	Metal fall %	Cr %	C %	Fe %	Si %
0.5	0.89	0.47	0.09	95.31	0.01
1.0	2.87	0.62	0.12	96.71	0.03
1.5	4.82	0.89	0.16	97.03	0.06
2.0	6.73	1.45	0.26	96.64	0.17
2.5	8.46	2.84	0.49	94.72	0.68
3.0	9.76	5.41	0.83	90.32	2.30
3.5	10.78	8.28	1.10	85.03	4.55
4.0	11.65	10.77	1.29	80.02	6.94

**Table VI. FactSage prediction on metal fall and alloy composition as a function of reductant mass (values of Cr, C, Fe, and Si expressed as wt %). Evaluation for Easterns LG concentrate**

<i>SiC</i> <i>Concentrate</i> ratio ( $\times 10^2$ )	Metal fall %	Cr %	C %	Fe %	Si %
0.5	0.49	0.59	0.08	99.32	0.01
1.0	2.44	0.75	0.10	99.14	0.01
1.5	4.38	1.01	0.13	98.84	0.03
2.0	6.30	1.48	0.18	98.27	0.06
2.5	8.16	2.50	0.30	97.00	0.20
3.0	9.79	4.82	0.57	93.80	0.82
3.5	11.05	8.21	0.91	88.62	2.26
4.0	12.11	11.57	1.22	83.19	4.02

From the analysis it was found that an increase in reductant mass will cause more oxides, particularly FeO, to reduce, thereby increasing metal fall. For both concentrates a molten metal phase starts to form when only 0.5 kg of reductant is present, emphasizing the ease of reduction and sensitivity. Almost all Cr<sub>2</sub>O<sub>3</sub> is reduced to CrO, thereby increasing the solubility of Cr in the slag phase. The metal fall continues to increase and therefore recovery of PGMs becomes easier. A better metal fall for reductive smelting of Easterns LG concentrate is expected at higher reductant to concentrate ratios, since Easterns concentrate has a marginally higher FeO concentration. The molten metal phase consists primarily of Fe and other easily reduced base metals, although some Cr and Si deport to the metal phase once the SiC to concentrate ratio is increased. Si and Cr start to dissolve in the molten metal at significant concentrations when the reductant mass exceeds 3 kg SiC per 100 kg concentrate. Carbon concentrations in the alloy also become more significant at a higher ration of SiC to concentrate. Cr solubility in the slag phase is greatly affected by the atomic state of Cr (Nell, 2004; Jones, 2009). Chrome in its trivalent state (spinel) has a very low solubility in the slag phase, in contrast to divalent chrome, which is highly miscible in the slag phase (Nell, 2004). The FactSage simulation in Figure 2 shows how Cr changes from a trivalent state to divalent state as a function of SiC addition (in steps of 0.02 g) to Easterns LG concentrate charge. From the graph it can be noted that undissolved chrome in the slag is highly unlikely at a reductant to concentrate ratio of 2.5–3.5 kg SiC per 100 kg LG concentrate.

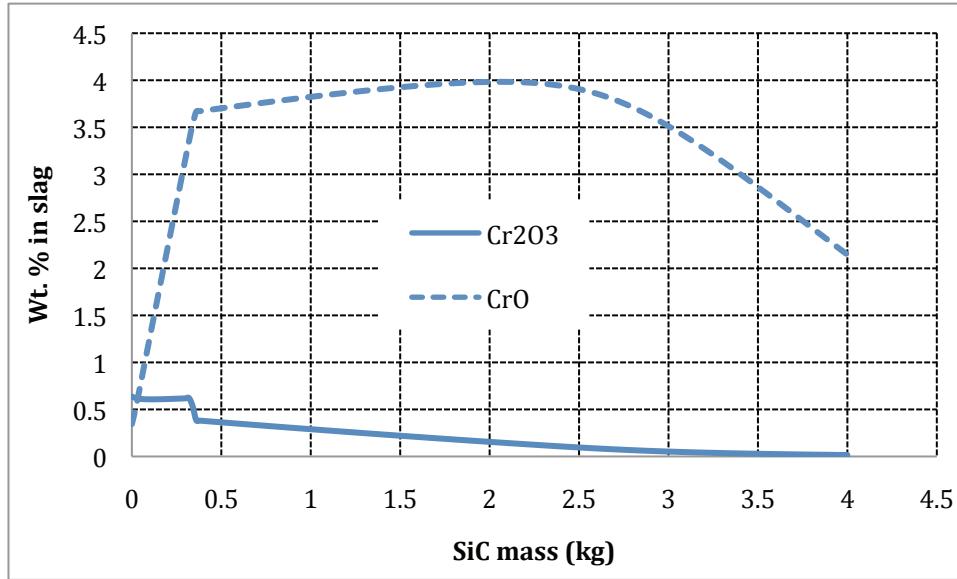


Figure 2. The distribution of chromium between the phases as a function of SiC additions to Easterns LG concentrate

### Experimental results

The alloy from each experiment was separated from the slag phase and weighed. The mass of slag could not be determined accurately due to separation difficulties. The percentage metal fall for each experiment was determined as the mass of alloy formed per unit mass of concentrate. The results revealed that an increase in the residence time from 60 minutes to 180 minutes and a greater reductant to concentrate ratio increased metal fall. Andrews (2008) also concluded that a longer residence time will improve the settling of matte droplets. Also, increasing the amount of SiC causes more FeO to be reduced to Fe, causing more metal prills to form and increasing the probability of coalescence. This again agrees well with previous work (Shahrokh and Shaw, 2000; Saffman and Turner, 1956; Ammann *et al.*, 1979).

The chemical compositions of the alloys obtained from SiC reduction of Rowland and Easterns LG concentrate are shown in Tables VII and VIII respectively.

Table VII. ICP-MS analysis of alloys from SiC reduction of Rowland LG concentrate as a function of reductant mass and reduction time (wt %)

SiC Concentrate ratio ( $\times 10^2$ )	Reduction time (min)	% metal fall	Fe %	Cr %	Si %	Cu %	Ni %	S %	Ir %	Pt %	Pd %
2.5	60	2.75	81.2	0.24	<0.01	3.67	<0.01	<0.01	0.05	0.02	0.08
3.0	30	4.13	67.6	8.81	<0.01	2.65	<0.01	0.01	0.04	0.01	0.08
3.0	45	4.30	71.7	9.36	<0.01	2.36	<0.01	<0.01	0.06	0.01	0.06
3.0	60	5.43	81.4	2.72	<0.01	2.08	<0.01	<0.01	0.05	0.01	0.04
3.0	75	5.39	76.4	5.9	<0.01	2.25	<0.01	<0.01	0.05	0.01	0.06
3.0	90	5.64	75.1	6.12	<0.01	2.67	4.42	1.11	0.04	0.07	0.04
3.0	180	5.28	74.9	6.35	<0.01	2.71	4.51	1.13	0.05	0.08	0.06
3.5	60	5.82	65.1	9.59	0.01	2.02	<0.01	0.01	0.04	<0.01	0.05

Table VIII. ICP-MS analysis of alloys from SiC reduction of Easterns LG concentrate as a function of reductant mass and reduction time (wt %)

SiC Concentrate ratio ( $\times 10^2$ )	Reduction time (min)	% metal fall	Fe %	Cr %	Si %	Cu %	Ni %	S %	Ir %	Pt %	Pd %
2.5	180	3.62	81.2	0.24	<0.01	3.67	<0.01	<0.01	0.34	0.02	0.08
3.0	180	6.80	84.5	1.47	0.05	1.47	4.49	2.04	0.8	0.52	1.24
3.5	180	7.47	88.6	1.33	0.15	1.08	2.81	1.52	0.8	0.65	1.26

Fe is the major constituent in all the alloys obtained from SiC reduction of Rowland LG concentrate. This agrees well with work done by Perry *et al.* (1988) and Qayyam *et al.* (1976), who also concluded that reduction of FeO will take place before the reduction of CrO. Cr concentrations increase sharply when the reductant to concentrate ratio is increased. At a reductant to concentrate ratio of 3.5 kg SiC per 100 kg Rowland LG concentrate, the Cr content of the alloy reaches almost 10%. Cr concentrations are more than 5% in alloys from tests with different reduction times respectively. These high concentrations of Cr could cause difficulties during downstream processing, particularly during converting, and in the base metals refinery (BMR) and precious metals refinery (PMR). Ni concentrations seem to be affected by residence time, together with S concentrations. The source of these two elements is most likely the mineral pentlandite. However, some inconsistencies are possible because of the small scale of the experiments. PGM concentrations are lower in Rowland LG concentrate, and recoveries could be marginally more inconsistent than those from Easterns LG concentrate. Both concentrates are sensitive to a small increase in reductant *i.e.* metal fall increases by 3% when the reductant to concentrate ratio is increased from 2.5 g to 3 g SiC per 100 g concentrate. This was also predicted by the FactSage simulations.

Easterns LG concentrate has a higher FeO content than Rowland LG concentrate, hence the higher Fe concentration in alloy samples produced from Easterns LG concentrate. The same observation was predicted from the FactSage modelling. The low Cr and Si concentrations in the alloy are very favourable for downstream processing because of the difficulties in removing these elements during converting, and also in the BMR and PMR. Pt and Pd are higher in alloys from Easterns LG concentrate, probably as a result of the better metal fall and Fe recovery in these alloys.

The PGM recoveries (Ir, Pd, and Pt) to the alloy phase for the two concentrates are shown in Table IX and Table X.

**Table IX. Recovery of Ir, Pd, and Pt by SiC reduction of Rowland LG concentrate**

<i>SiC Concentrate ratio (<math>\times 10^2</math>)</i>	<i>Reduction time (min)</i>	<i>Fe recovery %</i>	<i>Ir recovery %</i>	<i>Pd recovery %</i>	<i>Pt recovery %</i>
2.5	60	25.0	2.4	2.2	0.9
3.0	30	31.4	2.9	3.3	0.7
3.0	45	34.7	4.5	3	0.7
3.0	60	49.6	4.5	2.	0.9
3.0	75	46.2	4.5	3.2	0.9
3.0	90	47.6	4	2.6	6.7
3.0	180	44.4	3.8	3.5	7.5
3.5	60	46.8	4.1	2.9	1

**Table X. Recovery of Ir, Pd and Pt by SiC reduction of Easterns LG concentrate**

<i>SiC Concentrate ratio (<math>\times 10^2</math>)</i>	<i>Reduction time (min)</i>	<i>Fe recovery %</i>	<i>Ir recovery %</i>	<i>Pd recovery %</i>	<i>Pt recovery %</i>
2.5	180	24.7	19.2	2.6	0.9
3.0	180	57.7	69.7	62.9	35
3.5	180	66.4	94.5	86.6	59

From Table IX it is seen that the recovery of PGMs from Rowland concentrate is very low. The highest Pt and Pd recovery was achieved at a reductant to concentrate ratio of 3 kg SiC per/100 kg concentrate and residence time of 180 minutes. It may be possible to improve PGM recoveries at 3.5 kg SiC per 100 kg concentrate by increasing the reduction time to 180 minutes. However, Pt and Pd recoveries remain very low in all of the other tests. Fe recoveries are less than 50% throughout, which explains the poor PGM recoveries. A further factor that may contribute significantly to the low PGM recoveries is the high slag viscosity (see later).

The recoveries of Ir, Pd, and Pt by SiC reduction of Easterns LG concentrate are significantly better (Table X). Ir, Pd, and Pt recoveries increase significantly with increasing quantity of reductant. Overall, Ir has the highest recovery, followed by Pd and Pt. The very low Cr and Si concentrations in these alloys will allow for a further increase in reductant quantity and it should be possible to recover more than 90% of the PGMs by SiC reduction of Easterns LG concentrate. The better PGM recoveries may be ascribed to improved Fe recovery together with better metal fall.

The slag compositions from the SiC reduction of Rowland and Easterns LG concentrates are shown in Tables XI and XII respectively.

**Table XI. XRF analysis of slag from SiC reduction of Rowland concentrate**

<i>SiC</i> <i>Concentrate</i> <i>ratio</i> ( $\times 10^2$ )	Reduction time (min)	Al <sub>2</sub> O <sub>3</sub> %	CaO %	CrO* %	FeO* %	MgO %	SiO <sub>2</sub> %	TiO <sub>2</sub> %	Total %
2.5	60	5.41	2.78	2.34	6.11	28.72	54.29	0.34	100.00
3.0	75	5.52	2.88	2.57	3.49	30.00	55.20	0.34	100.00
3.0	90	5.56	2.87	2.49	3.27	30.01	55.44	0.35	100.00
3.0	180	5.57	2.87	2.47	3.23	29.97	55.54	0.35	100.00
3.5	60	5.46	2.81	1.68	3.11	30.07	56.51	0.35	100.00

\*Some minor constituents have been neglected, together with the conversion of Fe<sub>2</sub>O<sub>3</sub> and Cr<sub>2</sub>O<sub>3</sub> to FeO and CrO due to the gain on ignition from XRF sample preparation. Slag composition is thereafter normalized to a total of 100%.

**Table XII. XRF analysis of slag from SiC reduction of Easterns concentrate**

<i>SiC</i> <i>Concentrate</i> <i>ratio</i> ( $\times 10^2$ )	Reduction time (min)	Al <sub>2</sub> O <sub>3</sub> %	CaO %	CrO %*	FeO* %	MgO %	SiO <sub>2</sub> %	TiO <sub>2</sub> %	Total %
2.5	180	4.89	3.17	3.20	6.71	29.99	51.69	0.34	100.00
3.0	180	4.90	3.22	3.21	6.08	31.27	50.97	0.34	100.00
3.5	180	4.98	3.25	3.28	3.25	31.04	53.84	0.34	100.00

\*Some minor constituents have been neglected, together with the conversion of Fe<sub>2</sub>O<sub>3</sub> and Cr<sub>2</sub>O<sub>3</sub> to FeO and CrO due to the gain on ignition from XRF sample preparation. Slag composition is thereafter normalized to a total of 100%.

The results from Tables XI and XII show a significant decrease in FeO concentration compared with the initial concentrates. The lowest FeO content corresponded to the experiments with the highest quantity of reductant. The composition of the slag has a large effect on the viscosity, and FeO, NiO, CuO, and CrO will all contribute to lower the viscosity. Once the SiC comes into contact with these oxides, it will reduce them and settle to join the alloy phase, thereby removing them from the slag phase and increasing the viscosity. .

The viscosity module in FactSage was used to determine the viscosities at 1600°C. At 1600°C it can be safely assumed that the slag is a molten liquid and that no solids are present. The calculated viscosities of the slags from SiC reduction of Rowland and Easterns LG concentrates at the beginning of the melts are 3.74 and 3.06 poise, respectively. The significantly higher slag viscosity for Rowland material would make it more difficult for small metal prills to settle and coalesce.

Table XIII shows viscosities of the slags at the end of the melt, calculated in the FactSage viscosity module from the slag compositions in Tables XI and XII.

**Table XIII. Slag viscosities at the end of the melt**

Concentrate	<i>SiC</i> <i>Concentrate</i> <i>ratio</i> ( $\times 10^2$ )	Reduction time (min)	Viscosity (poise)
Rowland	2.5	60	3.781
Rowland	3	75	3.992
Rowland	3	90	4.070
Rowland	3	180	4.107
Rowland	3.5	60	4.435
Easterns	2.5	180	3.280
Easterns	3	180	3.165
Easterns	3.5	180	3.438

Table XIII shows that the calculated viscosities of the slags from all tests are higher than the viscosities of the initial melts. This is because the bulk of the Fe is in the alloy. Some Cr has also deported to the alloy phase. The viscosity of slags from the SiC reduction of Rowland LG concentrate is significantly higher than for slags from Easterns LG concentrate. This could explain why PGM recoveries are significantly lower from Rowland LG concentrate.

According to the literature (Eric, 2004; Eric and Hejja, 1995), PGM smelting slags have a viscosity of 1.5-4 poise, which could restrict the settling of particles of 15 µm or less in size. The FeO/SiO<sub>2</sub> content of such a slag seems to have a major influence on the viscosity. Rowland LG concentrate has a lower FeO/SiO<sub>2</sub> ratio than Easterns LG concentrate. When FeO is reduced, the slag viscosity will increase and valuable metal prills will not settle. The high initial slag viscosity will contribute to insufficient coalescence of metal prills and phase separation. The viscosities of slags from Rowland LG concentrate fall mostly above the range of 1.5–4 poise. Therefore, it seems that a high slag viscosity is the primary reason for the low PGM recovery from Rowland concentrate. The viscosities of the slags from SiC reduction of Easterns LG concentrate do, however, fall in the recommended range. The lower viscosities will aid in the coalescence of metal prills, enhance phase separation, and induce good PGM recovery. Other factors such as alloy-slag surface tension could also contribute to poor phase separation; however, this was not investigated in this study.

Figures 3 and 4 are SEM images of the slag phases from SiC reduction of Rowland and Easterns LG concentrate respectively, from experiments conducted at the same reductant to concentrate ratio and reduction time. These were replicate experiments, and the analytical results were fairly consistent with the results from Tables XI and XII.

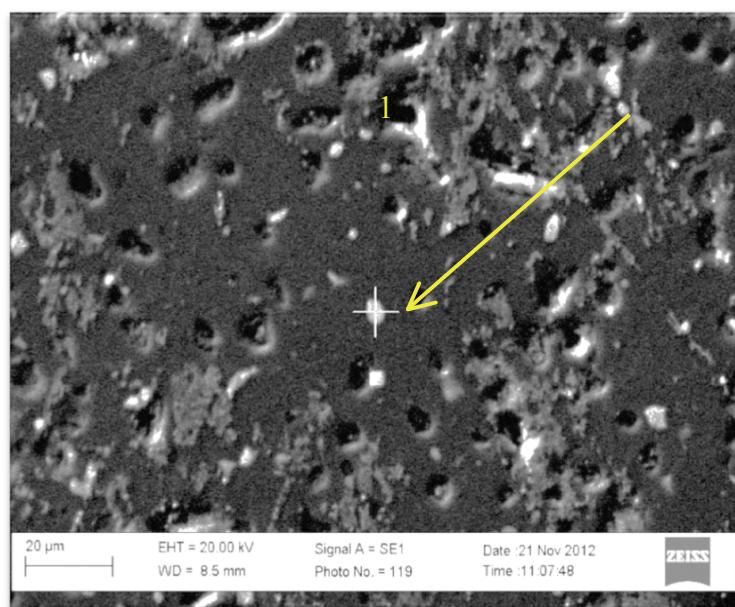
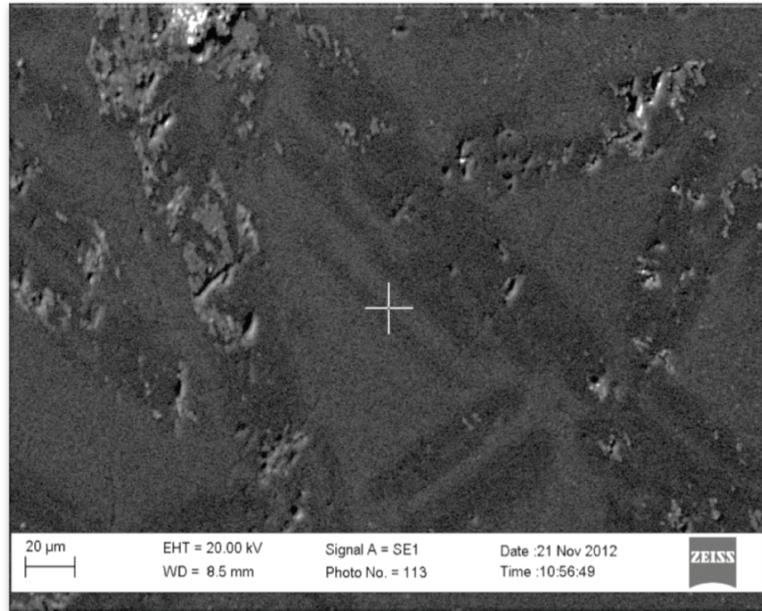


Figure 3. SEM image of slag phase (darker) containing metallic prills (bright spots) from Rowland LG concentrate. Reduction time 180 min, reductant to concentrate ratio 3 kg SiC per 100 kg concentrate

Figure 3 shows a SEM image of the slag phase from SiC reduction of Rowland LG concentrate, with metal prills entrained in the slag. These metal prills are very small and are most likely trapped in the slag phase and will never settle or coalesce with other prills of similar size. According to the literature, many small metal prills (< 2 µm) are expected never to settle under the force of gravity alone. This phenomenon agrees well with the work done by Fagurland and Jalkanen (1999) and Poggie *et al.* (1969), who also reported that very small droplets may either settle very slowly or be trapped as ‘rafts’ of droplets floating on the surface of the slag or suspended below small gas bubbles. However, the high viscosity of the slag is most likely the major restriction on the coalescence and settling of the metal prills. Ir and Pd were detected by EDX spot analysis of the metal prill indicated by the arrow.



**Figure 4.** SEM image of the slag from Eastern LG concentrate. Reduction time 180 min, reductant to concentrate ratio 3 kg SiC per 100 kg concentrate

Figure 4 shows a SEM image of the slag phase from SiC reduction of Easterns LG concentrate. This is a smoother slag phase with fewer entrained metal prills, indicating that metal prills coalesced better and settled well within the slag phase. It is thus fairly clear that the lower slag viscosity contributes significantly to the better PGM recovery from Easterns LG concentrates, which corresponds to similar findings in the literature (Shahrokhi and Shaw, 2000; Saffman and Turner, 1956; Ammann *et al.* 1979).

From the results of the experimental work, it can be concluded that Easterns LG concentrate should form the bulk of the dry LG concentrate feed to a DC arc furnace, since it has a higher FeO/SiO<sub>2</sub> ratio. This is significant in reducing slag viscosity and increasing overall PGM recovery. The slag viscosities need to be kept in the region of approximately 3.2 poise (the average viscosity determined from experiments on the SiC reduction of Easterns LG concentrate) or lower in order to recover PGMs. The two concentrate streams could be combined, with the main fraction being Easterns, and/or material could be added from another source to lower the slag viscosity. The slag from a Peirce-Smith converter has a high FeO/SiO<sub>2</sub> ratio (Table XIV) and would be suitable for this purpose.

**Table XIV.** Normalized wt % of major oxides and elements of Lonmin Peirce-Smith converter slag

CaO	MgO	Al <sub>2</sub> O <sub>3</sub>	FeO	SiO <sub>2</sub>	Cr <sub>2</sub> O <sub>3</sub>	Ni	Cu
0	0	0	64.560	29.994	2.219	2.048	1.179

FactSage was used to model such a scenario and an experimental test was also conducted to back up the modelling results. Figure 5 shows the results from FactSage modelling at 3.5 kg SiC per 100 kg Eastern LG concentrate at 1600°C with various additions of converter slag.

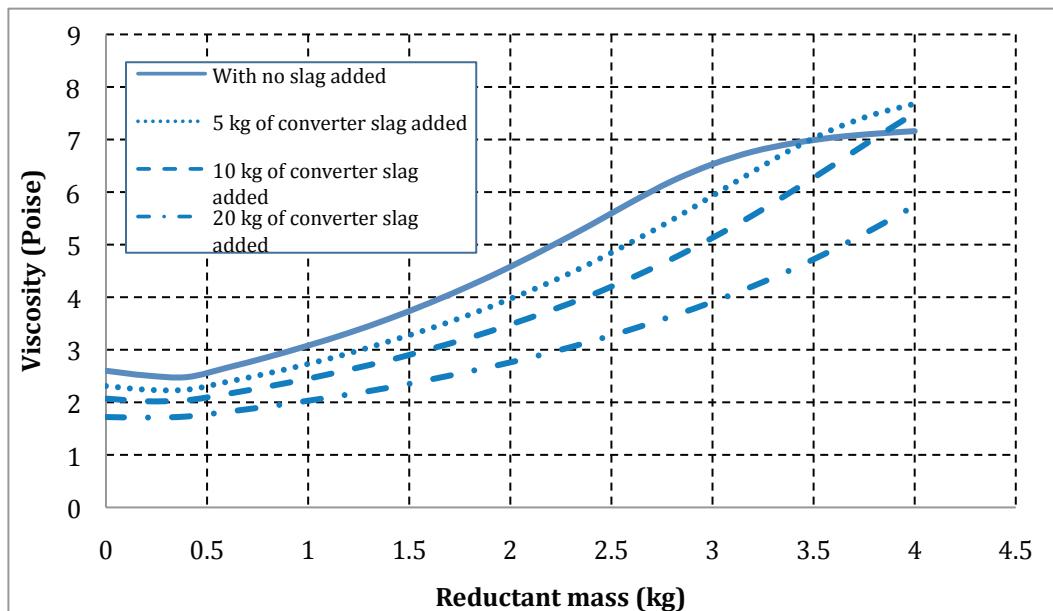


Figure 5. Viscosity of slags from SiC reduction of Easterns LG concentrate modelled as a function of reductant mass and converter slag mass added

Figure 5 shows that addition of converter slag does decrease the slag viscosity. The converter slag is rich in FeO and thus the FeO/SiO<sub>2</sub> ratio is increased, causing the slag viscosity to decrease. However, the converter slag also contains about 30 wt % SiO<sub>2</sub> which could increase the slag viscosity once again. This is evident from Figure 5, as an increase in reductant will cause more FeO to be reduced, consequently a system with 5 kg and 10 kg converter slag addition will have a higher slag viscosity than a system with no converter slag if the reductant additions are increased beyond about 3.5–4 kg. Another critical point is that the conductivity and viscosity of the slag are inversely related. A decrease in viscosity will increase the conductivity of the slag; increasing iron oxide serves to depolymerize the slag and creates sites for electronic conduction (Nell, 2004; Eric, 2004). It is clear from the findings that around 10 kg of converter slag addition to a 100 kg concentrate sample would decrease slag viscosity while not increasing the total slag quantity significantly. The alloy would also be expected to have a good PGM grade. A test was therefore conducted to compare the results from experiments and FactSage modelling for similar conditions.

From Table XV, it is apparent that FactSage predicts a slag with similar composition to the experimental slag. The marginally lower FeO/SiO<sub>2</sub> ratio in the slag from FactSage modelling will cause the viscosity to be somewhat higher than for the experimental slag. Table XV also shows an improved PGM recovery with a converter slag addition, which is likely to be a result of the decrease in slag viscosity. The Pd and Ir recoveries are nearly 100%, compared to Pd and Ir recoveries of 94.5% and 86.6% respectively obtained experimentally with no slag addition. The Pt recovery has also improved from 59.2% to almost 70%. It is expected that Pt recovery should improve if the metal fall increases, which could be achieved by increasing the reductant addition. Overall, this is a significant finding. A portion of the converter slag could be recycled together with any LG concentrate to increase metal fall and PGM recoveries.

**Table XV. Effect of converter slag addition – comparison between experimental results and FactSage modelling**

Experimental slag		FactSage modelling	
Metal fall %	8.82	Metal fall %	10.5
Alloy	wt. %	Alloy	wt. %
Fe	85.3	Fe	95.687
Cr	4.13	Cr	1.172
Si	2.73	Si	0.0565
Cu	1.10	Cu	0.982
Ni	2.59	Ni	1.95
S	1.53	S	Not included in feed
Ir	0.81	Ir	Not included in feed
Pd	1.21	Pd	Not included in feed
Pt	0.65	Pt	Not included in feed
Slag	wt. %	Slag	wt. %
Al <sub>2</sub> O <sub>3</sub>	4.4	Al <sub>2</sub> O <sub>3</sub>	5.358
CaO	2.95	CaO	3.154
CrO	3.88	CrO	3.891
FeO	7.657	FeO	6.809
MgO	28.85	MgO	23.997
SiO <sub>2</sub>	49.75	SiO <sub>2</sub>	56.588
TiO <sub>2</sub>	0.32	TiO <sub>2</sub>	Not included in feed
Alloy	Recovery %	Alloy	Recovery %
Ir	97.867	Ir	100 %
Pd	97.040	Pd	100 %
Pt	69.086	Pt	100 %
Fe from concentrate	75.5	Fe from concentrate	96.89

FactSage modelling was used to predict an optimum ratio of Rowland and Easterns LG concentrate in the feed. The reductant to concentrate ratio was fixed at 3.5 kg SiC per 100 kg LG concentrate and temperature fixed at 1600°C. FactSage predicts that adding more than 30 kg converter slag per 100 kg LG concentrate decreases the alloy to slag ratio. Therefore a for 0.7–0.8 fraction of Easterns LG concentrate in the feed, 20–30 kg converter slag per 100 kg LG concentrate should not significantly increase the quantities of furnace slag, and the FeO/SiO<sub>2</sub> ratio should be adequate to sustain a slag viscosity close to 3.5 poise (the average slag viscosity determined from FactSage by using experimental compositions from the results). At these operating conditions more than 90% of the PGMs should be recovered from a LG concentrate feed into an alloy with a high PGM grade. The Cr and Si concentrations in the alloy are less than 1% in total, and C concentrations are less than 1%.

SiC reduction was also compared to carbon reduction in order to determine the feasibility of reduction by SiC, using FactSage for predictions. The optimum feed conditions, namely 75% Easterns LG concentrate, 25% Rowland LG concentrate, and 25 kg converter slag per 100 kg LG concentrate, with 0–4 kg reductant per 100 kg LG concentrate and a temperature of 1600°C, were used in the comparison. It is assumed that slag viscosity will be low enough to ensure good phase separation and PGM recovery. The results indicated that carbon reduction of a LG concentrate charge results in a marginally higher metal fall; the alloy composition was very similar and only small differences in Fe, Cr, and Si concentrations were noted. Gas emissions and energy requirements are higher for C reduction, (Figures 6 and 7), arguably due to C reacting endothermically with FeO to produce Fe(l) and CO(g) in contrast to SiC reacting exothermically with FeO to produce Fe(l), SiO<sub>2</sub>(l), and CO(g).

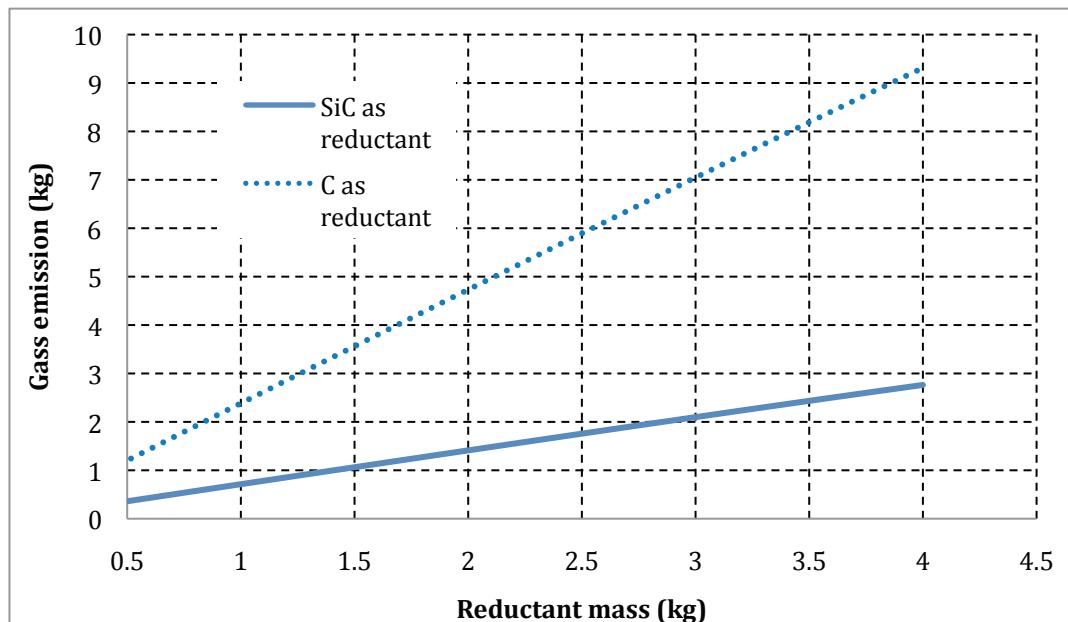


Figure 6. Gas emissions as a function of reductant mass

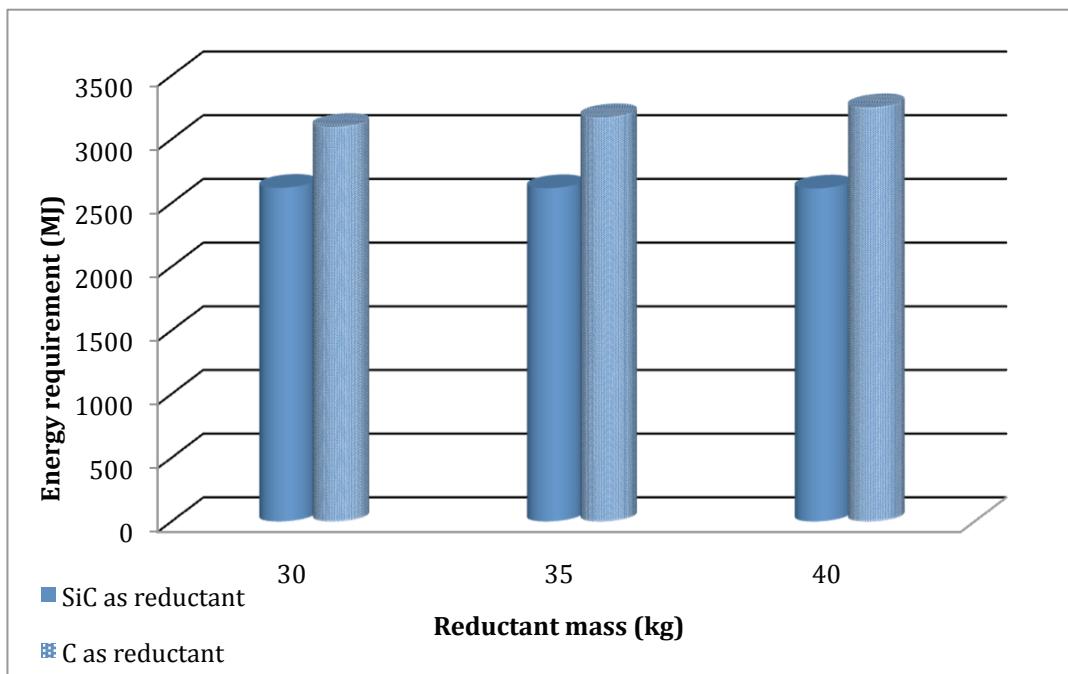


Figure 7. Energy required to smelt 1 t of LG concentrate (25% Rowland and 75% Easterns) as a function of reductant mass

## Conclusions

In this study, SiC reduction of Rowland and Easterns low-grade PGM concentrates was investigated to ascertain the feasibility of using SiC as reductant with respect to metal fall, PGM grade in the alloy, slag composition, and PGM recovery. Experimental work using MgO crucibles in a vertical tube furnace was conducted in combination with FactSage modelling.

SiC reduction of Easterns LG concentrate resulted in significantly better metal fall, Fe recovery, and PGM recoveries compared with Rowland concentrates. At a reductant to concentrate ratio of 3.5 kg SiC per 100 kg Easterns LG concentrate, recoveries were more than 85% for Ir and Pd, and more than 60% for Pt. The higher FeO/SiO<sub>2</sub> ratio, and

resulting lower slag viscosity, is most likely to have contributed to the improvement of recoveries. SEM images of a slag from SiC reduction of Easterns LG concentrate showed no entrained metal prills, indicating that most metal prills had coalesced and settled. Cr and Si concentrations were below 2% in total in all alloys. In order to further improve PGM recoveries, the FeO content of the initial charge had to be increased. For this purpose, Peirce-Smith converter slag from Lonmin was added to increase the FeO/SiO<sub>2</sub> ratio. FactSage predicted that 10 kg converter slag to 100 kg Easterns LG concentrate would be acceptable to increase FeO/SiO<sub>2</sub> and thereby decrease slag viscosity. The reductant to concentrate ratio was 3.5 kg SiC per 100 kg Easterns LG concentrate. In order to confirm these FactSage findings, an experiment was conducted with the same conditions, and Ir and Pd recoveries of more than 95%, and a Pt recovery of about 70%, were obtained. The improvement in results from the addition of converter slag was utilized in FactSage to calculate an optimum feed ratio between Rowland LG concentrate, Easterns LG concentrate, and converter slag. FactSage predicted that Easterns LG concentrate should make up 70–80% of the LG concentrate charge, and 20–30 kg of converter slag should be added per 100 kg LG concentrate to attain a low viscosity for phase separation. It is expected that this would result in more than 90% PGM recovery from the LG concentrate charge, in conjunction with a good PGM grade in the alloy.

Using this optimum LG concentrate charge, the effectiveness of SiC compared to carbon as a reductant was investigated through thermodynamic modelling in FactSage. Carbon reduction of a LG concentrate charge results in a marginally higher metal fall than SiC reduction at the same reductant to concentrate ratio. The alloy compositions were very similar and only small differences in Fe, Cr, and Si concentrations were noted. Gas emissions and energy requirements are higher for carbon reduction.

It is clear that SiC reduction seems a reasonably attractive alternative to carbon-based reductants. Finally, from the overall findings of this study, it is conclusive that base metals and PGMs can be recovered into an iron alloy by reductive smelting of LG concentrates with SiC as reductant and Peirce-Smith converter slag addition. Therefore, integrating such a process into the matte-based collection process could be considered as a future alternative for smelting low-grade PGM concentrates.

### Acknowledgements

The authors wish to thank Lonmin Plc for the financing of this work.

### References

- Ammann P.R., Kim J.J., and Loose T.A. 1979. The Kennecott Process for nickel slag cleaning. *Journal of Metals*, vol. 1, no. 2. pp. 20-25.
- Andrews, L. 2008. Base metal losses to furnace slag during processing of platinum-bearing concentrates. *Metallurgy in the Faculty of Engineering*. University of Pretoria, Pretoria.
- Eric, R.H. 2004. Slag properties and design issues pertinent to matte smelting electric furnaces. *Journal of the South African Institute of Mining and Metallurgy*, vol. 104, no. 9. pp. 499-510.
- Eric R.H. and Hejja, A.A. 1995. Dimensioning, scale up and operating considerations for six electrode elctric furnaces. Part 2: Design and scale-up considerations for furnaces treating PGM-containing copper-nickel concentrates. *Proceedings of EPD Congress, TMS Annual Meeting*, Las Vegas, Nevada. Warren, G.W. (ed.). The Minerals, Metals and Materials Society, Warrendale, PA. pp. 239-257.
- Fagurland K.O. and Jalkanen H. 1999. Some aspects on matte settling in copper smelting. *Proceedings of the Copper 99-Cobre 99 International Conference*, Phoenix, Arizona, 10–13 October 1999. The Minerals, Metals and Materials Society, Warrendale, PA. pp. 539-551.
- Jones R.T. 2009. Towards commercialisation of Mintek's Conroast process for platinum smelting. *Pyrometallurgy of Nickel and Cobalt: 48th Annual Conference of Metallurgists of CIM*, Sudbury, Ontario, 23–26 August 2009. The Metallurgical Society of CIM, Montreal. pp 159-168.
- Jones R.T. and Kotze I.J., 2004. DC arc smelting of difficult PGM-containing feed materials. *International Platinum Conference: 'Platinum Adding Value'*, Sun City, South Africa, 3-7 October 2004. *Symposium Series S38*. South African Institute of Mining and Metallurgy, Johannesburg. pp.33 - 36.

- Nell J. 2004. Melting of platinum group metal concentrates in South Africa. *Journal of The South African Institute of Mining and Metallurgy*, vol. 104, no.7. pp. 423-428.
- Perry K.P.D., Finn C.W.P., and King R.P. 1988. An ionic diffusion mechanism of chromite reduction. *Metallurgical Transactions B*, vol. 19B. pp. 677-684.
- Poggie D., Minto R., and Davenport W.G. 1969. Mechanisms of metal entrapment in slags. *Journal of Metals*, November. pp. 40-45.
- Qayyam, M.A. and Reeve, D.A. 1976. Reduction of chromites to sponge ferrochromium in methane-hydrogen mixtures. *Canadian Metallurgical Quarterly*, vol. 15, no. 3 pp. 193-200..
- Saffman P.G. and Turner J.S, 1956. On the collision of drops in turbulent clouds. *Journal of Fluid Mechanics*, vol. 1. pp. 16-30.
- Shahrokhi H. and Shaw J.M. 2000. Fine drop recovery in batch gas-agitated liquid-liquid systems. *Chemical Engineering Science*, vol. 55. pp. 4719-4735.

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