



Optimising blend ratios, grinds, and reagent schemes to recover platinum group metals from lower group reef spiral tailings

by T.L. Moodley^{1,2}, I. Govender^{1,2,3}, S. Pikinini¹, J. Sehata¹, J. Tshilongo¹, M. Raedani⁴

Affiliation:

¹Minerals Processing and Characterisation Cluster, Mintek, South Africa

²Discipline of Chemical Engineering, School of Engineering, University of KwaZulu-Natal South Africa

³Department of Chemical Engineering, Centre for Minerals Research, University of Cape Town, South Africa

⁴Dwarsrivier Chrome Mine, South Africa

Correspondence to:

T.L. Moodley

Email:

taswaldmoodley1@gmail.com

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ORCID:

T.L. Moodley

<http://orcid.org/0000-0001-9530-8718>

I. Govender

<http://orcid.org/0000-0003-3080-8505>

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Abstract

In the face of dwindling Merensky ore reserves in the early 1990s, Mintek developed the MF2 flotation circuit to economically recover platinum group metals from the shallow upper group-2 chromitite reef. By aligning the primary and secondary grind to the platinum group metal liberation kinetics, excessive fine chromite generation was avoided, and thus one could consistently produce high-grade concentrates (>200 g/t platinum group metals) with low chrome content (<3% Cr₂O₃), well within smelter tolerances. This, coupled with upper group-2's low-cost open-pit mining, made it particularly attractive to investors and mining houses alike. As a result, deeper lying reefs like middle group and lower group with lower platinum group metals grades and complex mineralogy, were primarily mined only for chromite using density-based separation processes (like spirals), of which the waste tailings are best classified as secondary platinum group metals resources.

Today, with global platinum group metal demand rising and high grade upper ground-2 reserves rapidly diminishing, the industry must revisit these middle group and lower group tailings. Mineralogical analysis reveals several challenges: Middle group tailings feature platinum group metals locked within silicate matrices, while lower group tailings contain fine chromitite fragments, and are hosted within non-floating laurite grains, each presenting liberation and gangue issues. Smelter constraints still demand concentrates below 3% Cr₂O₃, requiring solutions that consider both platinum group metals recovery and chrome entrainment.

To develop a solution, two lower group chrome spiral tailings samples were obtained from a large chrome mine: Sample A (+425 μm – 106 μm) and Sample B (–106 μm). Initial assays showed Sample B contained higher platinum group metal grades but also higher Cr₂O₃. As such, different blends of flotation feeds were evaluated using ratios of 90:10 (C1) and 80:20 (C2) of Sample A to Sample B, targeting the coarse fraction's lower chrome content while recovering valuable platinum group metals from the fines.

This work proposes a practical route for mining houses to unlock additional platinum group metal value from lower group ore spiral tailings. By optimising blending ratios and reagent suites, it is possible to meet smelter chrome and platinum group metal grade thresholds, whilst still obtaining economically viable PGM recoveries.

Keywords

PGM flotation, Fuerstenau selectivity curves, Kelsall kinetic modelling, LG (Lower Group) Chromitite

Introduction

The Bushveld Igneous Complex (BIC) is home to the world's largest vanadium, chrome, and platinum reserves. It is divided into five zones: marginal, lower, critical, main, and upper. The lower group (LG) reefs occur in the Critical Zone, which is known for its stratiform chromitite layers. These layers are laterally extensive, with the LG reefs stretching over tens of kilometres (Scoon, Teiger, 1994). LG reefs hold significant concentrations of platinum group metals (PGM) (Viljoen, 2016). Chromite serves as the primary host for PGMs, often containing microscopic inclusions of laurite [(Ru, Os, Ir)₂S₃] and Pt-Fe alloys, while base metal sulphides (BMS) such as pentlandite, pyrrhotite, and chalcopyrite act as secondary hosts for platinum group elements (PGE) (Kinloch, 1982). PGEs like Pt, Pd, and Rh are often associated with sulphide phases, while Ru, Os, and Ir are more commonly found in chromite-hosted inclusions. The LG reefs, while less PGE-rich than the Merensky and UG2 reefs, are a significant untapped resource due to their wide spatial mapping and high chromite content (Cawthorn et al., 2002). South African mining houses have historically processed LG reefs for chrome and UG-2 and the Merensky reefs for PGMs.

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Froth flotation is a critical process for the selective recovery of PGMs, relying on differences in surface chemistry to separate valuable minerals, that is, PGMs from gangue (Cr_2O_3 in this case). The process relies on the attachment of hydrophobic mineral particles to air bubbles, which rise to the froth phase for collection, while hydrophilic particles remain in the slurry. Corin et al. (2021) discussed why those PGMs respond effectively to the collector reagents used in froth flotation due to their association with sulphides, arsenides, and tellurides. Reagents play an important role in optimising flotation performance. Collectors, such as xanthates and dithiophosphates, enhance the hydrophobicity of PGM minerals, while depressants like carboxymethyl cellulose (CMC) selectively suppress gangue minerals, including naturally floatable silicates and talc (O'Connor et al., 2018). Frothers stabilise the froth phase, reducing bubble surface tension and improving froth recovery (Bradshaw et al., 2005). Kinetic models, such as the modified Kelsall model (Jovanovic, Miljanovic, 2015), are increasingly used to predict PGM recovery by accounting for fast, e.g., chalcopyrite and slow-floating, e.g., pentlandite PGM species. These models, when integrated with mineralogical data, embed mode-of-occurrence information to improve recovery and grade (Doubra et al., 2023).

There are several challenges with processing the LG reef. Their lower PGM grades require bulk mining methods, which increase operational costs. Additionally, the high chromite content complicates PGM recovery, as chromite-hosted PGMs like laurite resist flotation treatments. This differs from the Merensky and UG2 reefs, where sulphide-hosted PGMs are more amenable to conventional flotation methods (Barnes, Maier, 2002). Hence, the aim of this study is to evaluate flotation performance of LG spiral tailings and blends to balance PGM recovery with chrome rejection.

Materials and methods

Sample characterisation

The material used in this study was obtained from a large LG chrome operation. Two primary streams were sampled: a spiral tailings stream and a classification cyclone overflow stream. In this work, these are referred to as Sample A (size fraction +425–106 μm) and Sample B (size fraction –106 μm), respectively. In addition, two blended samples were prepared by mixing A and B at fixed A:B mass ratios: 90:10 (denoted Sample C1) and 80:20 (denoted Sample C2).

Because of confidentiality agreements, the feed grades cannot be disclosed directly. Instead, the results presented here are expressed relative to the undisclosed feed. To provide context, Sample A contained about one-third of the PGM content measured in Sample B, which is consistent with the tendency of PGMs to concentrate

in finer fractions. The Cr_2O_3 content showed an opposite trend: Sample A contained about two-thirds the Cr_2O_3 level found in Sample B. This is important because high chrome levels (above ~3% in concentrate) can result in downstream smelting penalties and negatively affect flotation performance.

Mineralogical analysis indicated that laurite was more abundant in Sample B than in Sample A. Laurite is commonly locked in chromite in the LG reef and is often lost to tailings during processing. This suggests that although Sample B appears to be richer in PGMs overall, its flotation response may not fully reflect this advantage.

Methodology

Flotation tests were carried out in duplicate using 2 kg batches to provide sufficient mass for assay. As such, concentrates were composited prior to assay. Recovery variability was therefore estimated by propagating the standard deviation of duplicate mass pulls, assuming constant concentrate grade. This provides a conservative estimate of repeatability. Sample A was milled in a laboratory rod mill at 50% solids by mass. Milling times were selected from the milling curve to achieve target grind sizes of 90% and 80% passing 75 μm . Sample B, which was already fine, was floated without further milling.

The milled slurry was transferred to a 5 L flotation cell mounted on a Denver D12 flotation machine, operated at an impeller speed of 1200 rpm. Concentrates were collected by scraping the froth every 15 seconds. For the cleaner flotation stages, a 1 L cell was used at an impeller speed of 1000 rpm. All products were filtered, dried, weighed, and submitted for PGM and Cr_2O_3 assay. The assay methods used in this project are detailed in Table 1.

Standard UG2-type reagents were employed. These included:

- ▶ CuSO_4 activator, to enhance pentlandite and pyrrhotite recovery, but also to be a froth modifier (Bryson, 2004).
- ▶ SIBX xanthate, to promote sulphide hydrophobicity.
- ▶ Dow 200 polyglycol frother to reduce bubble surface tension and stabilise the froth.
- ▶ KU5 CMC depressant, to selectively depress talcaceous gangue and improve concentrate grade.

The rougher flotation flowsheets used in the kinetic tests are shown in Figure 1.

Results and discussion

Recovery kinetics

The recovery kinetics of PGMs and Cr_2O_3 were determined by fitting flotation data to first-order Kelsall models. The recovery-time data are shown in Figure 2 and Figure 3.

Table 1

Analytical methods for samples

Package number and description	Analyte list	Determination limit
ICPI: Ores and slags Fusion followed by acid dissolution in aqua regia (HCl/HNO_3)	Cr_2O_3	Lower limit 0.05% Upper limit 40%
FA4S:	Pt, Pd, Rh, Au, Ru and Ir (6E)	0.02 g/t

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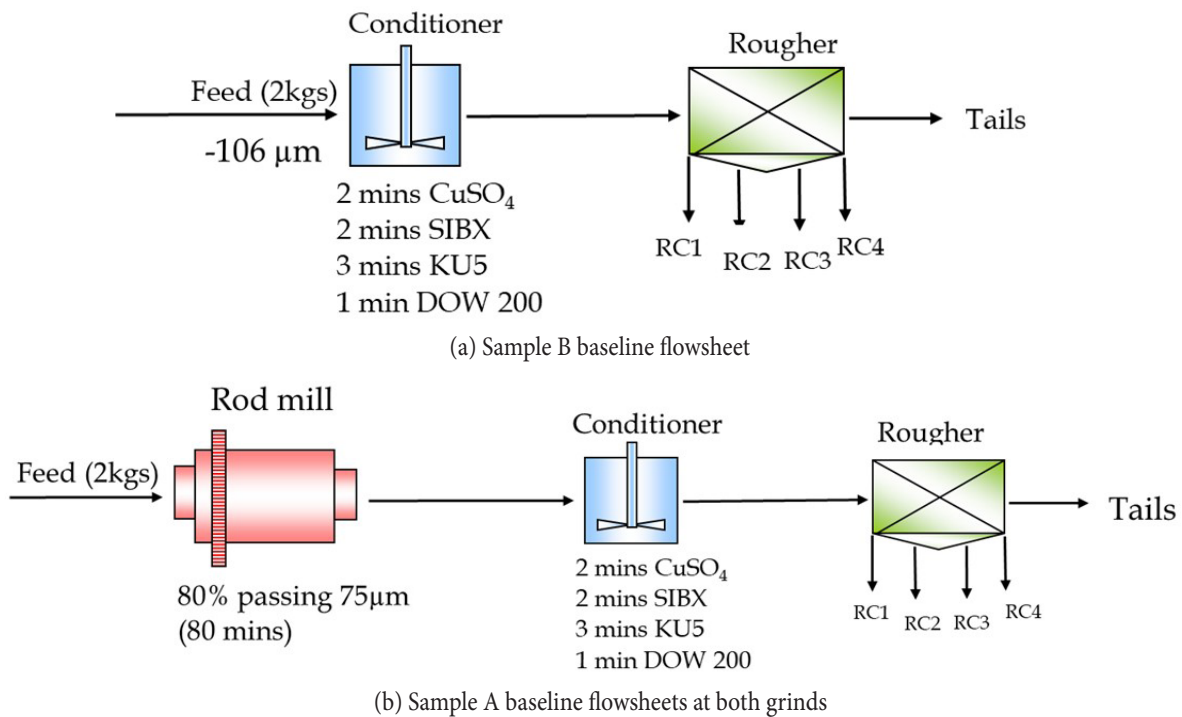


Figure 1—Rougher rate test flowsheets for each sample

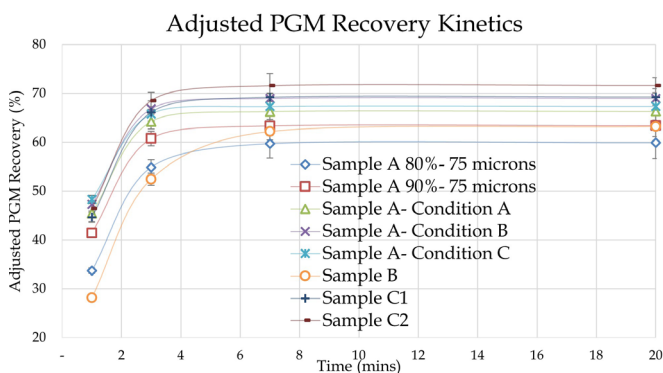


Figure 2—Adjusted PGM recovery kinetics (Kelsall model)

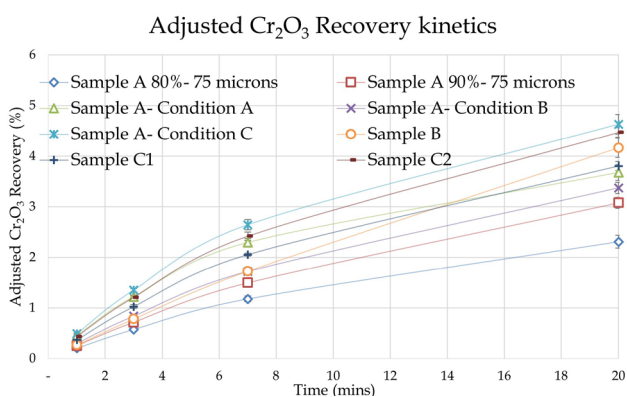


Figure 3—Cr₂O₃ recovery kinetics (Kelsall model)

Tests were performed on Sample A (two grind sizes), Sample B, and the blended composites (C1 and C2). Additional conditions were applied to Sample A, as indicated in the naming convention as per Table 2.

Baseline	Condition A	Condition B	Condition C
40 g/t CuSO ₄	60 g/t CuSO ₄	40 g/t CuSO ₄	40 g/t CuSO ₄
150 g/t SIBX	150 g/t SIBX	200 g/t SIBX	150 g/t SIBX
40 g/t KU5	40 g/t KU5	40 g/t KU5	60 g/t KU5
30 g/t Dow 200	30 g/t Dow 200	30 g/t Dow 200	30 g/t Dow 200

Data normalisation for confidentiality

Due to confidentiality agreements, the reported recoveries are normalised. To protect client data, Kelsall model parameters (R_m and k) were perturbed within $\pm 10\%$, while maintaining the physical trends in flotation kinetics. This adjustment prevents back-calculation of absolute grades or recoveries.

Kinetics interpretation

The PGM recovery curves exhibit the typical two-stage trend: a steep initial rise in the first three minutes, indicating recovery of readily floatable PGMs, followed by a plateau around 70% as slower-floating or poorly liberated particles dominate. In contrast, the Cr₂O₃ recovery curves are nearly linear with little curvature, consistent with recovery by entrainment rather than true flotation. We have attempted to quantify the PGM recovery dynamics of the recovery using the popular two-parameter Kelsall model (Kelsall, 1961), adjusted by perturbation variables to ensure the confidentiality given by Equation 1:

$$R_c = R_m(1 + R_p) \times [1 - e^{-k(1-k_p) \times t}] \quad [1]$$

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Where R_c normalised recovery of PGMs or Cr_2O_3 (%), R_m is the maximum recovery parameter (%), k is the first-order flotation rate constant (min^{-1}), and R_p and k_p are the perturbation constants introduced for confidentiality. The fitting was performed using nonlinear regression, where the parameters R_m and k are adjusted to minimise the error between experimental data and model predictions. In practice, this was achieved using a gradient-based optimisation routine, and iterative updates were performed until the change in error (between model predictions and measurements) falls below a 10^{-4} tolerance.

A summary of the fitted parameters is given in Table 3.

Discussion of fitted parameters

Model fit: For PGMs, most mean absolute percentage error (MAPE) values, representing the difference between the initial and fitted data, are below 10%, indicating that the Kelsall model sufficiently captures the kinetics. The exception is Sample B, which contains more fines, where entrainment is likely the dominant mechanism. For Cr_2O_3 , many MAPE values are at, or above 10%, again pointing to entrainment rather than true flotation as the dominant recovery mechanism.

Rate constants: PGM rate constants (k) are much larger than those of Cr_2O_3 , typically ranging from 0.6 min^{-1} to 1.3 min^{-1} compared to 0.03 min^{-1} – 0.13 min^{-1} . This confirms that PGMs are preferentially fast floating, while Cr_2O_3 reports slowly to concentrate. This behaviour is desirable and results in high PGM recovery with minimal chromite entrainment.

Maximum recovery: PGM R_m values are higher in blended samples (C1, C2), while Cr_2O_3 recoveries remain relatively low, indicating that blending may provide a practical means of enhancing PGM recovery without detriment to concentrate quality.

Fuerstenau selectivity curve

Selectivity between valuable PGMs and unwanted Cr_2O_3 can be quantified using the Fuerstenau curve proposed by Drzymala (2003). Rearrangement of Equation 1 for PGMs and Cr_2O_3 eliminates time as a variable, yielding Equation 2:

$$R_{PGM} = R_{m,PGM} \times \left[1 - \frac{R_C}{R_{m,C}} \right]^{k_{PGM}/k_C} \quad [2]$$

Where R_{PGM} is the predicted PGM recovery, $R_{m,PGM}$ and $R_{m,C}$ are the maximum recoveries of PGMs, and Cr_2O_3 and k_{PGM} and k_C are

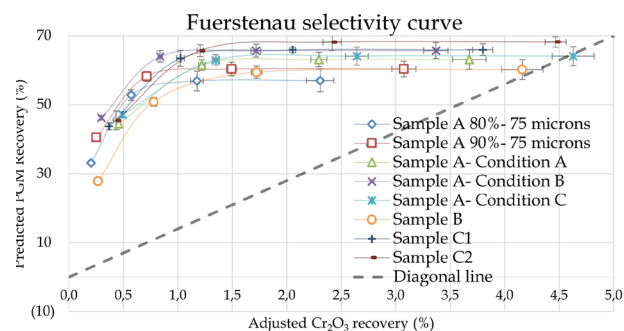


Figure 4—Fuerstenau selectivity curves for all test conditions

the flotation rate constants for PGMs and Cr_2O_3 . The ratio k_{PGM}/k_C is the selectivity index: values close to 1 indicate poor selectivity, while values much greater than 1 indicate preferential PGM recovery (Drzymala, Ahmed, 2005). Using Equation 2, one can plot the expected PGM recovery against the actual Cr_2O_3 recovery to determine the selectivity of the process, as shown in Figure 4.

Interpretation of selectivity

Figure 4 compares the selectivity curves to the diagonal line representing no preferential selectivity. Curves lying above this line indicate preferential PGM flotation. The most selective conditions were: (i) Sample A – Condition B, (ii) Sample C1, and (iii) Sample C2. In contrast, Sample B exhibited the poorest selectivity, consistent with its fine particle size distribution and higher entrainment. These results suggest that blended feeds (C1, C2) and condition B merit further investigation in cleaning stages, where selectivity is key to producing concentrates that comply with smelter Cr_2O_3 limits (typically <3%).

Preliminary conclusions

- PGM recoveries follow first-order kinetics well, while Cr_2O_3 recovery is dominated by entrainment.
- Nonlinear regression of the Kelsall model, solved using gradient-based optimisation, provides a basis for quantifying flotation recovery kinetics.
- The Fuerstenau curve provides a clear metric for selectivity: higher k_{PGM}/k_C ratios imply better separation.
- Sample B showed poor selectivity compared to other tests.
- Sample A under Condition B (with increased SIBX xanthate) also exhibited improved selectivity.

Table 3

Summary of Kelsall fitted parameters characterising PGM and Cr_2O_3

Test	PGM			Cr_2O_3		
	R_m (%)	k (min^{-1})	MAPE (%)	R_m (%)	k (min^{-1})	MAPE (%)
Sample A 80%-75 μm	57,03	0,87	7,27	2,95	0,07	2,76
Sample A 90%-75 μm	60,38	1,11	6,89	4,27	0,06	16,36
Sample A- Condition A	63,14	1,22	5,94	3,85	0,13	13,15
Sample A- Condition B	65,69	1,22	5,47	4,31	0,07	11,56
Sample A- Condition C	64,10	1,33	4,70	5,19	0,10	0,77
Sample C1	65,94	1,09	5,47	4,50	0,09	6,29
Sample C2	68,20	1,10	5,49	5,29	0,09	5,45
Sample B	60,21	0,62	11,32	9,38	0,03	9,98

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- Blends (C1, C2) and Condition B offer the best balance between PGM recovery and gangue selectivity. Further work will investigate their behaviour.
- PGM R_m values are higher in blended samples (C1, C2), while Cr_2O_3 recoveries remain relatively low, indicating that blending may provide a practical means of enhancing PGM recovery without detriment to concentrate quality.
- These findings suggest that further investigation into the optimisation of both blend ratios and reagent conditions could be valuable for maximising PGM recovery while controlling Cr_2O_3 entrainment.

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