

## **PROCESS DEVELOPMENT OF THE NKOMATI PCMZ BASE METALS SULPHIDE ORE**

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### **ABSTRACT**

In light of soaring commodity prices, Nkomati has investigated the potential of processing additional low grade nickel ores to add to their reserves. The Chromititic Peridotite Mineralised Zone (PCMZ) was identified as one ore type with the potential of producing a high grade nickel concentrate. In addition to the nickel, copper, cobalt and PGM's, the ore also contains a significant amount of chromite which adds substantial value to the project. Pyrrhotite, pentlandite, chalcopyrite and chromite are the dominant minerals within the ore, which on average grades around 0.23% Ni and 12% Cr<sub>2</sub>O<sub>3</sub>. The PCMZ ore contains excessive amounts of fibrous silicates which makes it a challenging float, with gangue control as the key element to success.

Extensive laboratory testwork, which eventually led to a pilot plant campaign, was undertaken with the aim of developing a process route for treating the PCMZ ore. Several flotation circuit configurations were tested and results from the optimal circuit indicated that a nickel concentrate grading at 8.5% is achievable at a recovery of 78%, with substantial recoveries for the copper, cobalt and PGM co-products. The chromite concentrate, grading at 45%, was extracted from the flotation rougher tailings via a spiral plant. These promising results were incorporated into the plant design and are currently being evaluated in a bankable feasibility study, which will see the current 100ktpm MMZ concentrator being upgraded to a 250ktpm PCMZ concentrator as part of Nkomati's Phase II expansion.

### **1. INTRODUCTION**

Nkomati Joint Venture, a joint venture between African Rainbow Minerals Limited and Lionore South Africa (Proprietary) Limited, produces mainly nickel and copper and is situated between the towns of Machadodorp, Waterval Boven and Badplaas in Mpumalanga. Nkomati's mineral rights stretch over the farms Slaaihoek and Uitkomst.

As part of Nkomati's Phase II expansion project, Nkomati evaluated the potential of adding the Chromititic Peridotite Mineralised Zone (PCMZ) to their reserves. This low grade nickel ore was identified to have the capability of producing a high grade nickel concentrate. In addition to the nickel, copper, cobalt and PGM products, this ore also contains a significant amount of chromite which adds substantial value to the project. Pyrrhotite, pentlandite, chalcopyrite and chromite are the dominant minerals within the ore, which on average grades around 0.23% Ni and 12% Cr<sub>2</sub>O<sub>3</sub>.

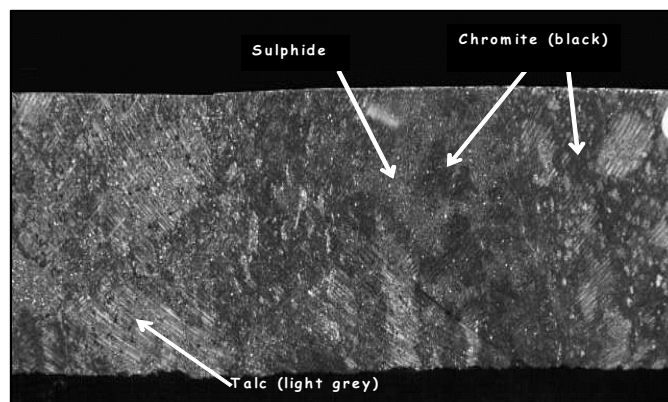
## 2. GEOLOGY

The Chromititic Peridotite Mineralised Zone (PCMZ) collectively refers to the sulphide mineralisation within the Chromititic Peridotite Unit (PCR) irrespective of grade. The lower contact of the PCR with the underlying Lower Pyroxenite Unit is gradational and is often recognisable only by the first appearance of thin chromitite bands or lenses. The PCR is largely confined to the trough of the Uitkomst Complex, but there are areas where the unit is developed on the flanks.

Chromitite layers, pods, lenses and wisps or schlieren characterise the PCR, which is a highly altered unit (Figure 1 & Figure 2). Little evidence of its primary igneous precursor is preserved. Chlorite, talc and amphibole are the main silicate minerals. Serpentine, plagioclase, biotite, phlogopite, quartz, calcite and dolomite are less abundant. The PCR is extensively altered to talc-rich assemblages and is often sheared into talc schist bands. These shear zones often obscure the contacts with the overlying Massive Chromitite Unit and underlying Peridotite Unit. Semi-massive chromitite within the PCR is formed by fine (100µm) euhedral to rounded chromite grains.



**Figure 1: Chromititic Peridotite - the black material is fine-grained chromite and the light grey is altered talcose peridotite**



**Figure 2: Split core of PCMZ**

Mining in the open pit will bench through the PCR, which will be classified as ore or waste depending on its grade. Sulphide mineralisation tends to be concentrated in the silicate rich areas.

### **3.        MINERALOGY**

Pyrrhotite, pentlandite and chalcopyrite are the dominant sulphide minerals within the PCR. Pyrite represents minor amounts, 5% or less, of the total sulphide content of this zone. In general sulphide minerals are more abundant in relatively chromite poor, or silicate-rich, parts of the Chromititic Peridotite Unit (PCR).

In some instances pyrite-millerite-chalcopyrite assemblages were observed, but it is expected that this assemblage will be rare in the PCMZ and more common within the chromititic ores of the PCR, as well as within the overlying Massive Chromititic Unit. Small inclusions of cobaltite, gersdorffite, ullmanite, tucckite ( $\text{Ni}_9\text{Sb}_2\text{S}_8$ ), galena, stibiopalladinite and gold were observed within the other sulphides, where there are indications of alteration of the primary minerals.

All the primary magmatic silicate gangue minerals of the PCR have largely been replaced by talc, chlorite and amphibole. It is to be expected that the sulphide mineral recoveries will be affected by the greater abundance of these fibrous silicates in the PCR than in the other mineralised zones. Investigated composite samples contain between 15 and 26% talc.

Preliminary test work has indicated that cobaltite, which is present, as small inclusions mainly within pyrrhotite, may be lost during flotation. The sulphide minerals form disseminated, anhedral intergrowths, interstitial to the silicate minerals. The average grain size of the chromite within the PCR is 102 $\mu\text{m}$ .

### **4.        PROCESS DEVELOPMENT**

During 2005, an extensive laboratory program was initiated with Mintek to develop a process route for treating the PCMZ ore. Mintek performed the following metallurgical testwork to develop and optimise a process strategy that can be integrated into the future expansion phase:

- Laboratory Flotation
  - Rougher Circuit Evaluation
  - Cleaner Circuit Evaluation
  - Re-cleaner Circuit Evaluation
  - Rougher Concentrate Re grind Evaluation
  - Locked cycle testwork
- Chromite concentration testwork
- Heavy liquid separation

Three PCMZ composite core samples were delivered to Mintek. The first sample, PCMZ 1, was a fresh underground sample. The other two samples were fresh open pit composites. The PCMZ 2 sample was drilled from Pit 3 covering a 30m section, while PCMZ 3 was drilled 300m away from PCMZ 2 also covering a 30m intersection. The majority of the testwork was completed on the on PCMZ 1 whilst the PCMZ 2 & 3 samples were used as confirmatory tests. The HLS and gravity concentration tests were completed on both the PCMZ 1 & 2 material.

#### **4.1    Laboratory Testwork**

##### *4.1.1    Flotation*

Nkomati's standard flotation procedure was used for the tests and results indicated the following findings:

- Satisfactory base metal grade concentrates were obtainable from the PCMZ ore if suitable talc depressant reagents were used.
- Lower Cobalt and PGM recoveries are expected from the PCMZ ores. This phenomenon confirms previous testwork which revealed cobaltite intergrowths in the silicate minerals lost during flotation.
- Base metal and PGM product recovery was unaffected by variations in the head grade, whilst the product grade increases with increasing head grades.
- The open pit PCMZ comprised of more floatable gangue (especially talc) as compared to the underground PCMZ sample. However, once the sample went through the second stage of cleaning even higher grades and recoveries were achieved.
- A rougher concentrate regrind circuit did not produce better metallurgical efficiencies than the conventional rougher, cleaner, re-cleaner circuit.
- The PCMZ is a highly altered ore body containing zones of extremely high levels of talcacious gangue. The most effective way to beneficiate this ore will be to mine and process this unit in bulk, in order to dilute the high talc zones.
- Effective talc control in the flotation process will be critical to unlock the PCMZ potential.

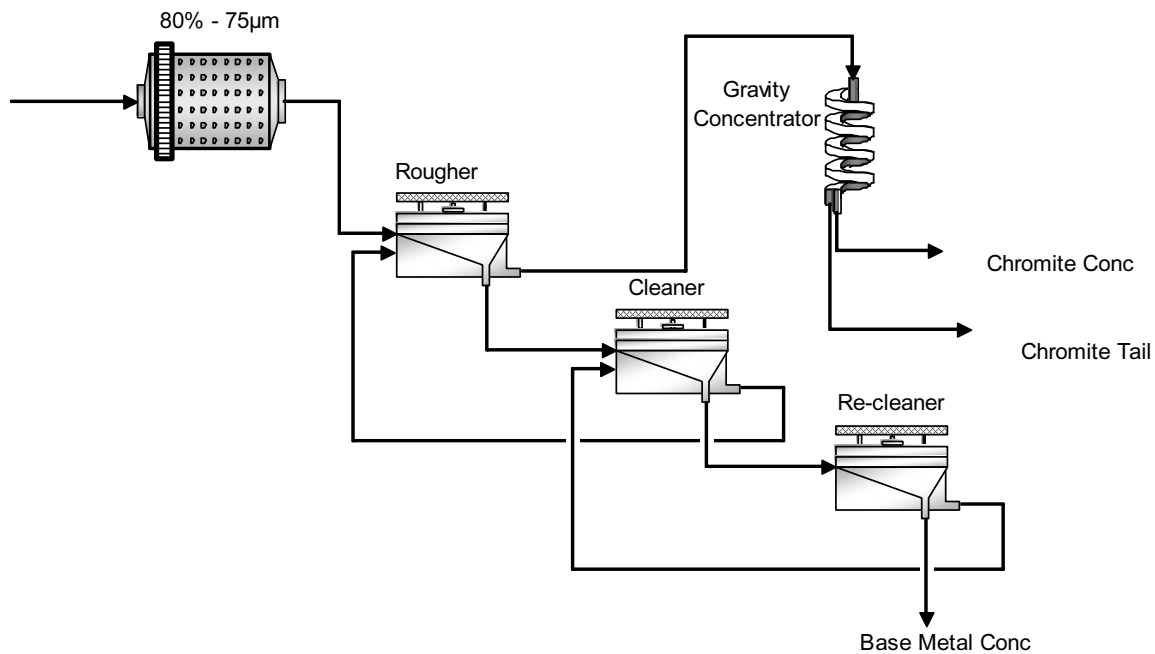
##### *4.1.2    HLS*

Heavy liquid separation was conducted to investigate the potential of increasing the PCMZ head grade by rejecting waste material. The results showed that the HLS proved to be ineffective due to the Ni losses almost equal to the mass rejection.

##### *4.1.3    Gravity Separation*

The objective of the testwork was to determine the Cr<sub>2</sub>O<sub>3</sub> upgrade potential of the PCMZ rougher flotation tailings. Results indicated that saleable chromite concentrates (+40% Cr<sub>2</sub>O<sub>3</sub>) can be produced at high (+70%) recoveries, which will add further value to the project.

The proposed pilot plant circuit configuration was a conventional rougher, cleaner, re-cleaner circuit followed by a gravity separation circuit as shown in Figure 3 below.



**Figure 3: Proposed PCMZ flowsheet from laboratory tests**

The independent metallurgical testwork provided adequate motivation to seriously consider a separate flotation stream for the PCMZ material. In order to evaluate the continuous operation and metallurgical efficiencies from the PCMZ ore, it was imperative to run a pilot campaign, integrating the base metal and chromite recovery process routes.

#### **4.2 Pilot Plant Campaign**

Based on the positive results from the laboratory scale testwork on the PCMZ ore, Nkomati moved forward with a pilot plant campaign during June 2006 for both base metal and chromite recovery. Mintek was commissioned to achieve the following key objectives:

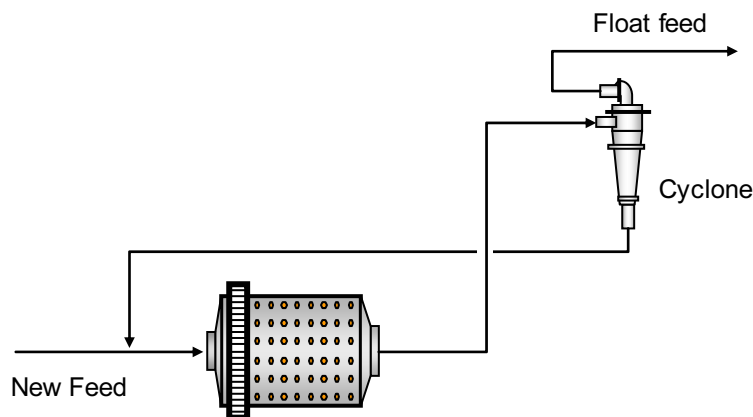
- To test the PCMZ milling and flotation flowsheet developed at laboratory scale at a continuous, pilot plant scale.
- To identify and rectify any operational /metallurgical issues encountered at pilot scale.
- To develop a grade-recovery profile for the PCMZ ore using the recommended flowsheet.
- To determine if the flotation plant tails could be adequately treated by a spiral plant to produce a saleable grade  $\text{Cr}_2\text{O}_3$  product at a suitable recovery.
- To test any alternate flowsheet based on the results obtained during the continuous run.

A fresh PCMZ bulk sample was extracted from underground, covering a 30m cross section, for the testwork. Approximately 110 tons were delivered to Mintek where the sample was

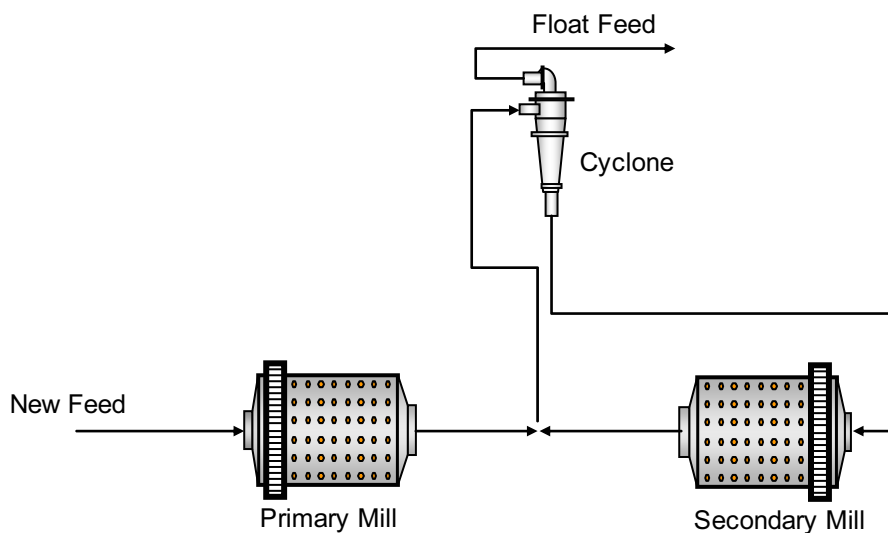
crushed in preparation for the pilot plant campaigns. Sub-samples were taken for head analysis which indicated that the nickel head grade for the campaign was ~0.25%.

#### 4.2.1 Milling circuit

To aid in the initial design of the pilot plant, laboratory grindmill tests were conducted. The objective of this testwork was to use the breakage and selection parameters generated by the tests to estimate ball charges, mill power draws and circulating loads for two distinct milling circuits. The two circuits are shown below.



**Figure 4: Single Stage Milling Circuit**



**Figure 5: Two-stage milling circuit**

Results indicated that both circuit options were viable in producing the required mill product of 80% passing 75 $\mu$ m. However, the single stage milling option had the drawback of running at a considerably higher power draw (20.8kW vs 2 x 8kW) and circulating load

(250% vs 108%) than the two-stage milling circuit. The two stage milling circuit was selected because of its superior power efficiency.

Two Sala rubber roller-mounted (0.86m Ø × 1.5m, 15kW) were used during the pilot plant campaign. The primary mill had a grate discharge arrangement and operated in closed circuit with a 600µm screen. The secondary mill was run with an overflow arrangement and operated in closed circuit with a 100mm cyclone with an 18mm spigot. Both mills were operated with a seasoned charge of 35% of the mill volume and a mill speed of 75% of critical.

The pilot plant mills were achieved the milling target of 80% passing 75µm. The gross power draw for the primary and secondary mill was 10kW and 11kW respectively.

#### 4.2.2 Flotation Circuit

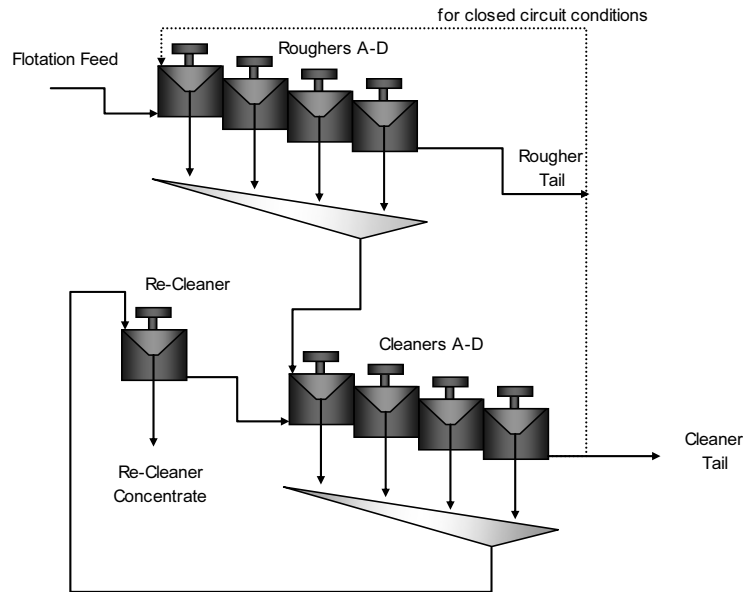
Several flotation circuits were tested during the pilot plant commissioning. Samples were taken of each circuit to assess the circuit performance. Table 1 shows the list of all equipment used during the campaign. All flotation banks were Sala forced air float cells connected to the level control system, Floatstar®.

**Table 1: Flotation Equipment List**

Float Banks	Volume L	# of motors	Installed Power kW	Motor speed rpm
Rougher A	4 x 80	2	3.00	1420
		2	3.50	1720
Rougher B	6 x 80	3	3.00	1420
		3	3.45	1720
Rougher C	6 x 80	6	1.50	1410
Rougher D	4 x 80	4	1.50	1410
Cleaner A	4 x 30	2	3.00	1420
		2	3.45	1720
Cleaner B	4 x 30	2	3.00	1420
		2	3.45	1720
Cleaner C	4 x 30	2	3.00	1420
		2	3.45	1720
Cleaner D	4 x 30	2	3.00	1420
		2	3.45	1720
Cleaner E	4 x 80	2	3.00	1420
		2	3.50	1720
Cleaner F	4 x 80	2	3.00	1420
		2	3.50	1720
Re-Cleaner A	6 x 15	6	0.75	1420
Re-Cleaner B	4 x 15	4	0.75	1410

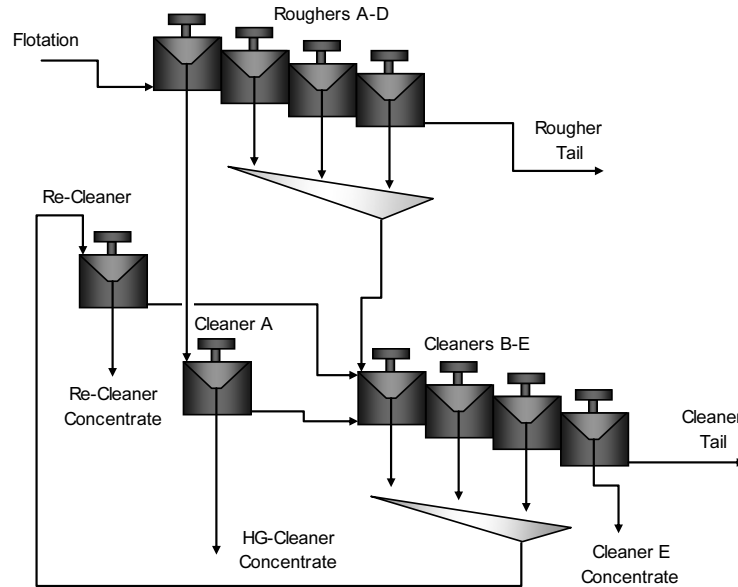
The first flowsheet was obtained from the circuit developed at laboratory scale, shown in Figure 6. The circuit was operated in both open circuit and closed circuit mode. The results indicated that both the re-cleaner grades and recoveries were low. The general consensus after the run was that it was unsuccessful, due to a number of reasons:

- Ineffective Froth drainage; solid density to cleaners and re-cleaners too high.
- Too much mass reporting to the re-cleaner.
- Poor operability of re-cleaner.



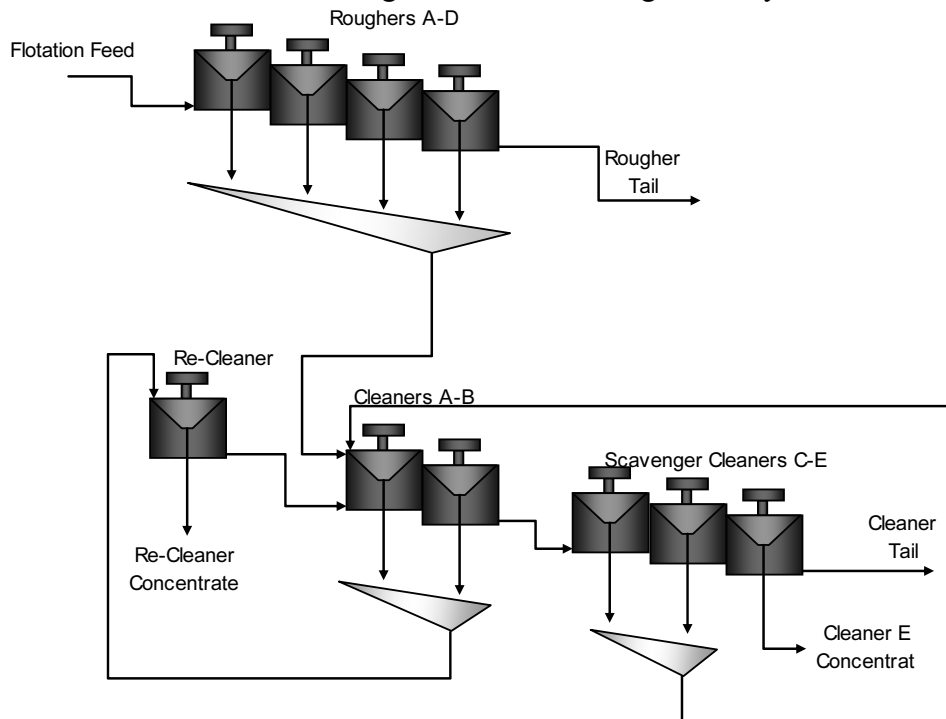
**Figure 6: PCMZ flowsheet 1 (developed at laboratory scale) at pilot scale**

The second flowsheet, Figure 7, attempted to remove a high-grade, fast floating concentrate from a HG-cleaner bank (Cleaner A). The logic behind this was to unload the re-cleaner as well as to secure a high-grade concentrate at a high recovery relatively quickly with the balance of the recovery produced by the re-cleaner. An additional cleaner bank was also incorporated to recover slow floating minerals in the cleaner tail. Strict density control was implemented around the cleaner and re-cleaner banks where solid densities were controlled at 15% solids. Results indicated that the additional cleaner bank reduced the cleaner tails grade, but the HG-cleaner was unable to produce a high grade concentrate in excess of 8% Ni. Low re-cleaner grades were also observed in the re-cleaner concentrate. It was decided to abandon this flowsheet and attempt another.



**Figure 7: PCMZ flowsheet 2 with fast floating concentrate**

The third flowsheet, Figure 8, incorporated cleaner scavengers to reduce the load to the re-cleaner while allowing a circulating load to build up to assist in increasing the final concentrate grade. The additional cleaner (Cleaner E) was kept online to reduce the tailings grade, but the concentrate was collected separately. Results indicated it was possible to achieve a high Ni recovery at an acceptable grade using this flowsheet. The low cleaner tail grade achieved by adding another scavenger cleaner indicated that there was no need to re-circulate the cleaner tails back to the roughers since it was significantly lower than the feed grade.



**Figure 8: PCMZ flowsheet 3 with scavenger cleaners**

It was decided to further investigate this circuit by making minor adjustments and run it over a prolonged period to optimise the reagent suite. This design run circuit incorporated all the comments from the previous flowsheets and is given in Figure 9. During the design run the following three scenarios were evaluated by varying reagent conditions and mass pulls:

- Intermediate Grade/Recovery
- Low Grade/High Recovery
- High Grade/Low Recovery

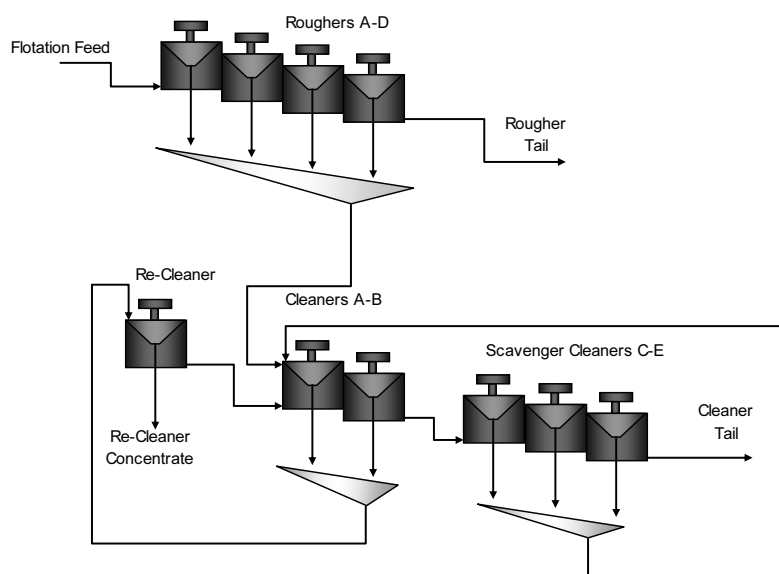


Figure 9: PCMZ flowsheet 4 for design run #1

The results for the three scenarios are shown in Table 2 below.

Table 2: Grade/Recovery/Mass pull relationship for the three scenarios

		Combined recleaner concentrate					
		Masspull (%)		Ni recovery (%)		Ni grade (% Ni)	
		Measured	Smoothed	Measured	Smoothed	Measured	Smoothed
External 1	Intermediate grade/recovery	2.0	2.4	82.5	79.9	7.70	8.01
External 2		2.2	2.4	82.9	80.6	7.76	8.74
External 3	Low grade/high recovery	2.4	2.3	65.7	73.7	7.49	6.94
External 4		2.8	2.9	75.4	78.2	6.75	6.23
External 5	High grade/low recovery	1.9	2.1	80.9	77.8	8.00	8.70
External 6		1.9	2.1	73.1	76.3	8.18	8.67
Average of 1 and 2		2.1	2.4	82.7	80.3	7.73	8.38
Average of 3 and 4		2.6	2.6	70.6	76.0	7.12	6.59
Average of 5 and 6		1.9	2.1	77.0	77.1	8.09	8.69

Interestingly, the results indicated that the three operating conditions did not behave significantly different from each other and seemed to gravitate towards a common recovery

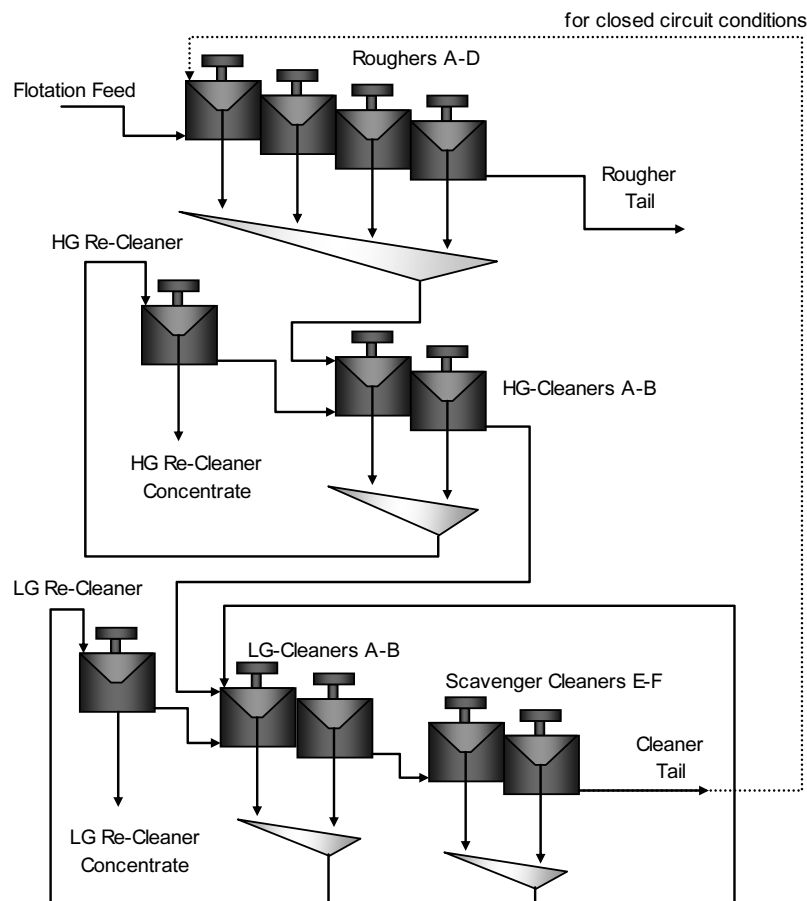
point on the grade-recovery relationship. The average grades and recoveries for Ni and the major co-products are indicated in Table 3.

**Table 3: Average grades and recoveries of Ni and co-products**

	Grade		Recovery (%)
Ni	%	8.5	78
Cu	%	2.3	82
Co	ppm	2800	40
Pt	ppm	3	30
Pd	ppm	8	50
Au	ppm	0.5	50
S	%	35	55
Cr2O3	%	1.5	0.5

For the second design run the circuit was modified in an attempt to obtain another point on the grade recovery curve by increasing recovery whilst sacrificing grades. This was accomplished by decoupling the fast and slow floating material and producing two products. The flowsheet is given below in

Figure 10. The circuit was operated in both open and closed circuit mode.



**Figure 10: PCMZ flowsheet 5 for design run #2**

The results indicated that it was possible to produce a high grade concentrate (>10% Ni) via re-cleaner 'A' during the open circuit testwork, but the overall nickel recovery was lower than the PCMZ Design run #1 results. The combined average concentrate was at an acceptable grade.

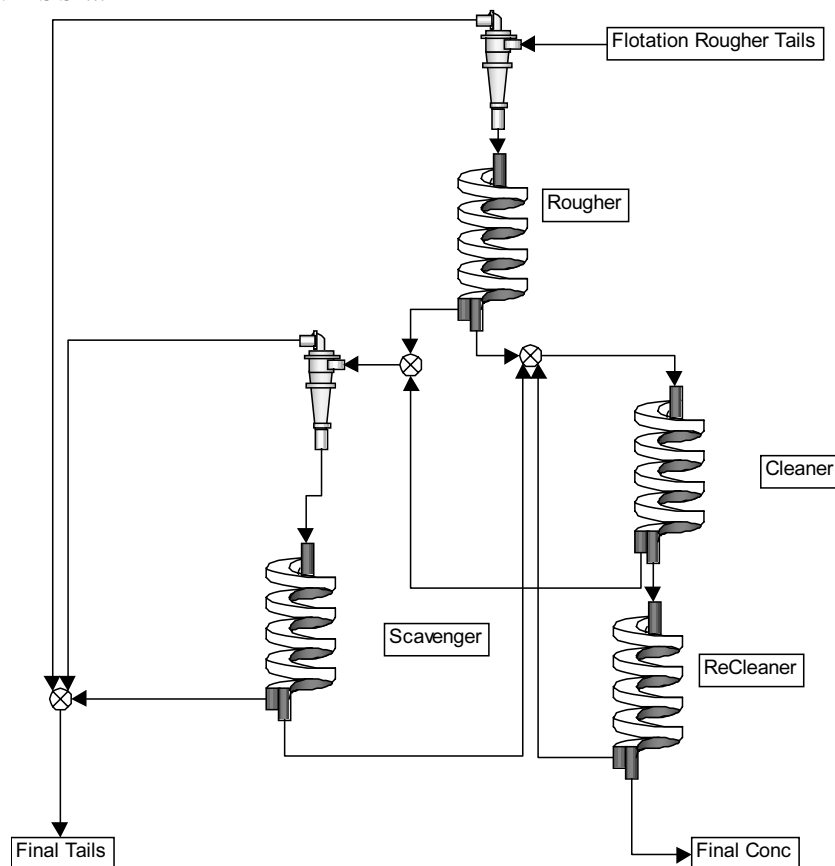
When the closed circuit condition was tested, the combined re-cleaner recovery increased slightly, but the high grade concentrate grade (re-cleaner 'A' concentrate) was severely compromised as it dropped significantly. While the data suggests that the flowsheet tested during the PCR Design run #1 was better, it may be possible that, due to time constraints, the open/closed circuits tested for the PCR Design run #2, had not completely stabilised.

#### *4.2.3 Spiral Circuit*

Mintek investigated the Cr<sub>2</sub>O<sub>3</sub> upgrade potential of the flotation rougher tailings on laboratory samples and concluded that the PCMZ material is amenable to gravity concentration. To validate the laboratory results Mintek performed testwork on a pilot spiral plant. Bulk samples of the flotation tailings were collected during the PCMZ flotation pilot plant campaign and used as feed for the chromite recovery circuit. The testwork consisted of rougher, cleaner, re-cleaner and scavenger runs. A Multotec SC18 spiral with 7 turns and a 0.75m diameter was used for the testwork.

It was found that the significant presence of the -38µm fraction of material had an adverse effect on the spiral results due to the known inefficiencies of spirals to treat material below 53µm. Therefore the flotation rougher tailings had to be de-slimes prior to spiral treatment.

The proposed flowsheet for the recovery of chromite from the PCMZ flotation tailings is shown below in Figure 11.



**Figure 11: Proposed Spiral Circuit**

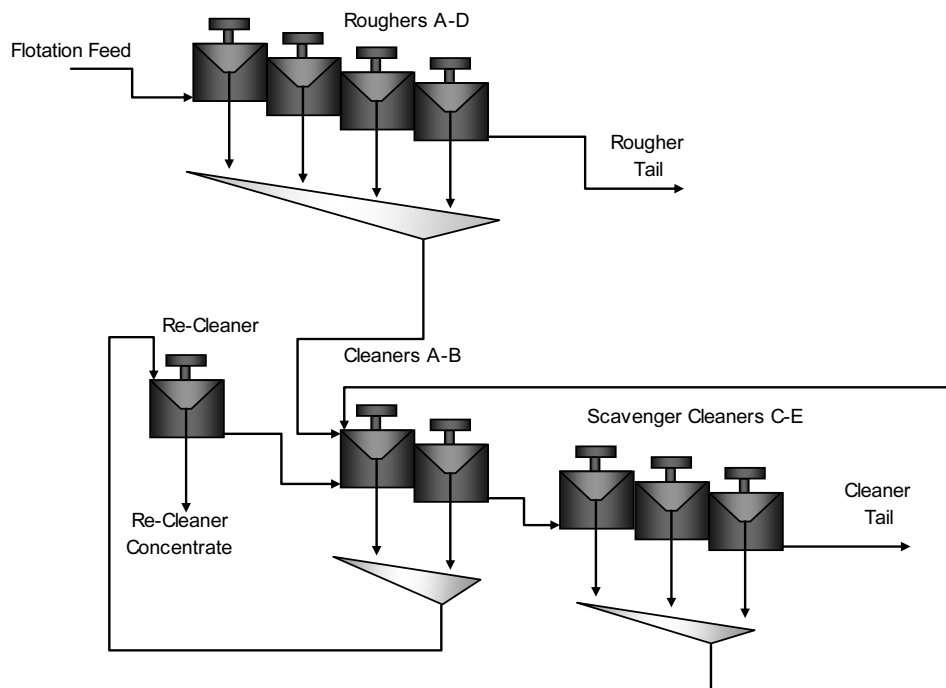
A closed circuit simulation of the proposed circuit was completed by taking into account the effect of recycle streams that alter the spiral head grade and consequently its performance characteristics. The constraint for the process was a final product grade of at least 45%  $\text{Cr}_2\text{O}_3$  and less than 3.5%  $\text{SiO}_2$ . The simulation results achieved a  $\text{Cr}_2\text{O}_3$  recovery of 35%, based on the flotation rougher tail, at a  $\text{Cr}_2\text{O}_3$  grade of 45.0% and  $\text{SiO}_2$  grade of 3.5%. The chrome to iron ratio was 1.53.

Additional testwork was motivated to recover the chromite through flotation as an alternative process route. The results from this testwork were promising, producing a concentrate  $\text{Cr}_2\text{O}_3$  grade of 46.3% at a 49.6% recovery. This recovery was ~11% higher than the spiral plant results using a similar de-slimes rougher tail. When the flotation rougher tail was de-slimes at  $10\mu\text{m}$ , the recovery increased to 75% but graded lower at 41.6%. Despite the higher  $\text{Cr}_2\text{O}_3$  recoveries, the spiral plant was considered to be the best option due to the following reasons:

- The high reagent consumption and acidic operating environment would certainly increase the operating costs significantly.
- The extreme difference in pH range and reagent properties will need separate tailings disposal and water management systems which will complicate the overall design and could expose potential risks for the nickel flotation circuit.

#### 4.2.4 Design Circuit Recommendations

After reviewing the flowsheets, results and the quality of the data, the flowsheet and operating conditions deemed to be the most robust and suitable to processing the PCMZ ore were selected. Below is a summary of the flowsheet and its key parameters.



**Figure 12: Proposed design flowsheet**

**Table 4: Final pilot plant design operating conditions**

Parameter	Unit	Target
Cyclone Overflow/Float feed grind	% passing 75µm	80
Float feed density	% solids	30
	Relative density	1.26
Rougher concentrate mass pull	%	20
Rougher concentrate density	% solids	15
	Relative density	1.12
Cleaner concentrate mass pull	%	25
Cleaner concentrate density	% solids	15
	Relative density	1.12
Re-cleaner concentrate mass pull	%	2
Re-cleaner concentrate Ni recovery	%	78
Re-cleaner concentrate Ni grade	%	8.5

**Table 5: Final design reagent conditions**

Reagent and type	Dosage	Addition Point
	g/t	
Senkol (Collector)	5	Primary Mill
SIBX (Collector)	150	Conditioner
Deptan100 (Depressant)	400	Conditioner
XP 200 (Frother)	40	Rougher A
Deptan100 (Depressant)	100	Rougher B tails
SIBX (Collector)	20	Cleaner A
Deptan100 (Depressant)	80	Cleaner A
Deptan100 (Depressant)	90	Cleaner C
SIBX (Collector)	20	Re-cleaner A
Deptan100 (Depressant)	60	Re-cleaner A
<b>Total</b>		
Senkol (Collector)	5	
SIBX (Collector)	190	
Deptan100 (Depressant)	730	
XP 200 (Frother)	40	

Based on the results, Mintek recommended that the roughers be designed for a residence of 55 minutes. While the results showed that a total cleaning circuit residence time of 30 minutes (with the first 6 minutes thereof accommodating the high grade cleaners) would be sufficient, Mintek recommended that the “rule-of-thumb” calculation of cleaner residence time being, at least, equal to the rougher residence time be adopted.

**Table 6: Final design residence times**

Unit	Recommended Residence Time
	min
Roughers	55
Cleaners	13*
Cleaner Scavengers	42*

\* scaled up using "rule of thumb" recommendation

The table below gives envisaged grades and recoveries for Ni and the main co-products. Total S and Cr<sub>2</sub>O<sub>3</sub> are also given.

**Table 7: Anticipated flotation grades and recoveries for products**

	Grade		Recovery (%)
Ni	%	8.5	78
Cu	%	2.3	82
Co	ppm	2800	40
Pt	ppm	3	30
Pd	ppm	8	50
Au	ppm	0.5	50
S	%	35	55
Cr <sub>2</sub> O <sub>3</sub>	%	1.5	0.5

The testwork showed that the majority of the Ni losses were in the slimes fraction (-38 $\mu$ m fraction) and the recovery of these could represent significant upside potential.

The new spiral plant facility will be based on the Mintek design (Figure 11) consisting of de-sliming cyclones, rougher, scavenger, cleaner and re-cleaner spirals, and a dewatering cyclone. The spiral testwork was able to produce a Cr<sub>2</sub>O<sub>3</sub> product grade of 45.6% at a recovery of ~39% and a Cr:Fe ratio of 1.53.

The key factors to the success of the pilot plant were:

- Effective talc/gangue control
- Density control
- Circuit Configuration

High depressant dosages were required for effective talc/gangue control. A total of 730g/t depressant was required with the majority (500g/t) distributed in the rougher circuit. This ensured that a significant quantity of gangue material reported to final tails and assisted with the good upgrade ratios observed in the cleaner circuits. Density control was essential to ensure good solids loading in the cleaner circuit.

The circuit configuration ensured that a sufficient circulating load was created to upgrade to the required concentrate grade. Low cleaner tail grades indicated that it is not necessary to operate the plant in a closed circuit configuration. Long residence times were required in the rougher and scavenger circuits to ensure that the maximum nickel recovery could be achieved, whilst shorter residence times in the cleaner and re-cleaner circuits ensured that high grade concentrate was collected.

## **5 CONCLUSIONS**

These favourable results provided adequate motivation to have a separate flotation stream for the PCMZ ore. The project was included in the Nkomati Phase II expansion project as Phase II B, with Phase II A being a 375ktpm MMZ concentrator. Phase II B will be a brown fields project with the objective of upgrading the existing 100ktpm MMZ to a 250ktpm PCMZ plant. The option to further upgrade the concentrator to a 300ktpm plant also exists with modifications to the crushing circuit.

DRA - MP were awarded a contract to undertake a feasibility study for the expansion of the new and existing plant facilities located at Nkomati. The study deliverables for both Phases II A and II B were:

- $\pm$  15% CBE (not bankable)
- Process Design Criteria
- Mass Balance
- PFD's and PCD's
- Equipment Lists
- Site Plan and Plant Layouts

- Implementation Schedule
- Design Procedures
- EPCM Proposal

Upon completion of the study the Nkomati Phase II project will be presented to the board members of the joint venture partners, African Rainbow Minerals Limited and Lionore South Africa (Proprietary) Limited. The document is currently under review. Project release is anticipated in August 2007.

## **6        REFERENCES**

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