Flotation cell technology and circuit design—an Anglo Platinum perspective

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Synopsis

Froth flotation is the primary mineral processing separation step employed in the beneficiation of PGM ore bodies. Anglo Platinum operates a significant portion of the total installed flotation capacity in the PGM industry, which is installed at 20 operating plants across the Bushveld.

PGM flotation has undergone a considerable evolution in both the capacity of flotation cells employed as well as in the circuit design configuration over the past 30 years. Certain of Anglo Platinum's flotation circuits have been in operation for a relatively long time (in some operations installed equipment dates from the 1960s), and this allows comparative operating performance between various equipment types and circuits to be evaluated. This paper summarizes some aspects of this experience.

Research trends in flotation are continuously monitored so that appropriate findings can be incorporate into existing and future circuit designs. Continuous evaluation and monitoring of flotation performance is undertaken to identify opportunities for increasing flotation efficiencies. Mineralogical and fractional analyses of plant composites and survey samples are analysed to interrogate speciation and association data. This analysis has enabled a better understanding of priorities and opportunities for improved metallurgical performance.

These opportunities are divided into three improvement areas: stability, liberation, and fines flotation. The paper discusses these, as well as the circuit design improvements required to take full advantage of the opportunities identified

Introduction

Most companies that extract PGMs from base metal sulphide deposits currently use flotation as a primary extraction process. For the foreseeable future, comminution followed by froth flotation will continue to be the major focus areas in the PGM mineral beneficiation process. Continuous effort is being made to improve the technical and operational efficiency of flotation.

Anglo Platinum has 20 operating concentrators sited around the Eastern, Northern and Western limbs of the Bushveld complex, as illustrated in Figure 1.

The concentrators treat mainly Merensky and UG-2 ores, with Potgietersrust (PPL, Sandsloot) and PPRust North being the only two plants designed to treat the Platreef ore. Since the early 1990s, an increasing proportion of UG2 ore has been processed. This has increased dramatically in recent years, reaching a level of 54% of all ore treated in FY 2006 (excluding WLTR, the Rustenburg tailings retreatment operation).

The capacities of individual concentrators range from small plants handling 50 thousand tons per month (ktpm) plants to large operations treating in excess of 600ktpm. A rationalization of concentrator operations where much of the old equipment and plants are being replaced and modernized is currently in progress. This has resulted in a reduction in the number and an increase in the unit size of installed flotation cells. Anglo Platinum-managed operations currently treat over 4 million tons of ore per month through hundreds of flotation cells of varying capacities, and produce about 90 thousand tons of flotation concentrate. Examples of the wide variety of installed capacity of flotation units in Anglo platinum are given in Table I.

The figures illustrate the transition to fewer, larger cells, which are shown in red, as compared with the older generation plants Frank and Klipfontein, built in the 1960s. The best example is shown in the Rustenburg operations figures—the new Waterval complex, UG2 and Retrofit, commissioned in 2002 and 2007.

Recent history, evolution and current situation

The evolution of Froth Flotation in Anglo Platinum can be simplistically summarized into three different 'concentrator eras' as follows:

* *Concentrators, Anglo Platinum.*

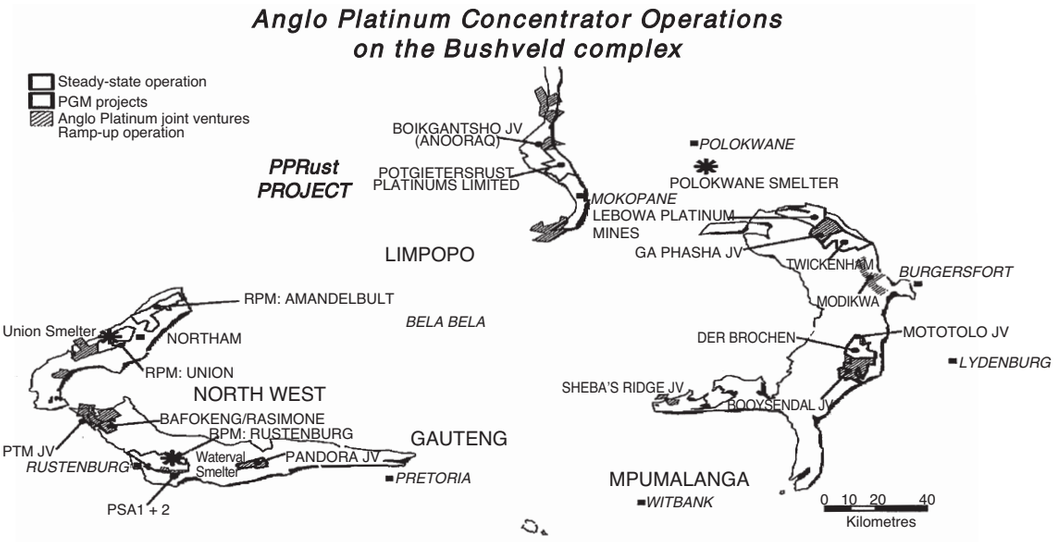

Figure 1—Anglo Platinum concentrator operations

Table I

Summary of installed flotation equipment in Anglo Platinum (as at end 2007)

Operation	Ore type processed	Plants	Capacity ktpm	No. of cells		m³ installed	
	Roughers	Cleaners	Roughers	Cleaners			
BRPM	Merensky	1	240	18	24	900	380
Waterval concentrators	Merensky/UG2	2	1.120	72	38	4.656	1.325
Klipfontein/Frank	Merensky/UG2	2	220	224	68	596	418
WLTR	Tailings	1	525	15	12	1.290	240
Union Mortimer	UG2	3	425	92	93	715	208
Union Ivan	UG2/tailings	1	110	10	20	500	118
Amandebult Merensky	Merensky	1	320	50	94	1.068	359
Amandebult UG2	UG2	2	300	78	70	1.864	724
PPL	Platreef	1	385	63	84	747	342
PPRust	Platreef	1	600	30	32	3.480	1.280
Lebowa	Merensky/UG2	2	140	50	26	474	196
Modikwa	UG2	1	240	21	39	1.080	455
Mototolo	UG2	1	200	13	21	910	459
Waterval slag	Converter and furnace slag	1	50	10	7	109	8

- *Pre 1980s*—Mineral extraction circuits were characterized by multiple small flotation machines (typically 1m3) with short residence times, employing a single mill-float configuration. Typically a three-stage crushing, closed circuit ball mill comminution circuit was used to prepare feed for flotation. These circuits treated Merensky ore only.
- *1980s–1990s*—Individual flotation machine capacities increased to up to 30m3. 'MF2' circuits, which had evolved from rougher tailings regrind work done in mid 1980s, were employed. Typically 60 minutes mainstream residence time was installed. Induced air rougher cells and forced air cleaning cells were the norm. The '3kW/m³' mantra evolved, originally driven by grind-psd suspension requirements, principally for primary FAG operation and UG2 ores.
- *2000s*—Larger tank cells, with capacities up to 130 m³, were installed. Longer residence times were utilized, especially in concentrate cleaning. The '3kW/m³' doctrine was discarded, particularly on the larger cells. R&D and operational improvements efforts focused on minimizing flotation losses, advanced process control and circuit stability. Circuits treating UG2 became more predominant.

Flotation improvement priority areas

In pursuing opportunities for optimization, Anglo Platinum constantly evaluates flotation operations within the group. Technological advances in mineralogical analysis have allowed accurate measurement and quantification of the loss profiles across all reef types and operating plants within the Anglo Platinum group. A typical PGM distribution profile for selected streams in a UG2 operation is shown in Figure 2.

Approximately 80% of the PGM minerals in the feed are either individually liberated, or are attached to or associated with base metal sulphides (BMS). The remainder are locked or middlings particles. The concentrate consists of liberated and BMS associated/enclosed particles, with a much smaller proportion of locks and middlings.

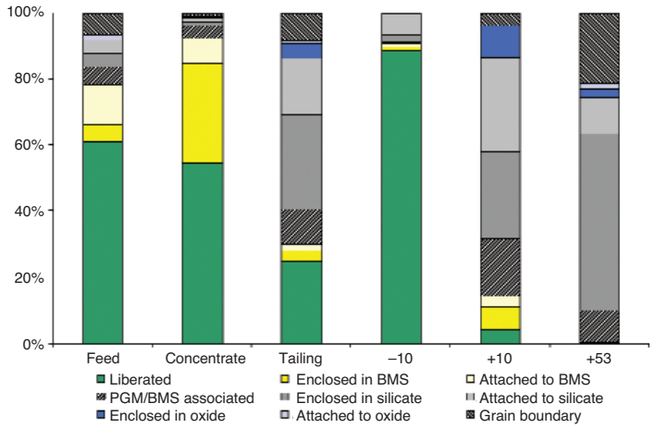

Figure 2—Typical UG2 PGM association profile—monthly composite

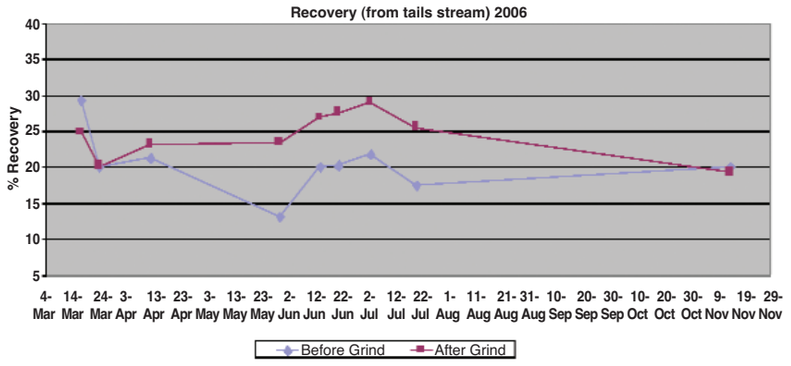

Figure 3—Additional 'hot float' and 'regrind hot float' flotation potential for an operating UG-2 plant

The tailings display appreciable proportions of liberated. BMS associated and locked/middlings particles, but it is imperative to note the distribution of these losses between the various size classes. In this particular case the total tailings amounted to ~ 0.5 g/t 4E, (Pt, Pd, Rh & Au). Of this, 0.35 g/t occurs as locked PGM particles and 0.15 g/t as liberated/BMS associated PGMs. The deportment in size classes shows the majority of 'fines losses' occur in the -10 micron fraction.

For simplicity, the causes of these losses are loosely grouped into three categories:

- *Inefficient flotation*—predominantly fine liberated PGM (and BMS) losses
- *Incomplete or non-liberated values*—composites with gangue
- *Plant instability*—sub-optimal process control and plant stops/start-ups; poor operation.

The second and third categories of loss have almost obvious solutions—improved grinding (resulting in increased liberation) and improved plant operation and especially stability. Three priority areas have been identified for optimization: stability, liberation, and fine particle flotation. These three factors are interrelated, but will be discussed separately in this paper.

Stability

For the purposes of this discussion, all process inefficiencies are collected under the definition of plant instability. This would include the non-recovery of adequately liberated (but not 'fine' which can be arbitrarily defined as <10 μm) flotable value minerals. Selectivity issues, gangue competition, surface coating covered by, and inhibited flotation are all included in this definition, which includes all the particles that should have been recovered in the float, but were not.

Operational instability includes, among others, sub-optimal process control, plant stops and starts, and sub-optimal circuit configuration (such as insufficient residence time and inappropriate reagent regimes). The extent of extra flotation potential in this category of losses can be gauged by performing tailings re-floats, or the so-called 'hot floats' that are routinely performed on the various operations. These re-floats generally produce roughly 10% recovery (of the tails stream) for more stable operations, but up to 25% recovery (of the tails stream) for less stable plants. These 'hot floats' are done on 'as is' material and after additional regrinding. A typical example of 'hot float' results for a UG-2 operation is shown in Figure 3.

The biggest opportunity for recovery improvement is clearly linked to improved liberation. The mineralogical analyses and assay work on sized composite samples from the plants indicate that the majority of PGM losses in plant final tails are due to either un-liberated or partially liberated minerals—composites or locked particles. The proportion varies between plants and between ore types.

Once plant stability has been consistently achieved, the largest opportunities that remain for flotation improvement are finer grinding of flotation feed, and improvement in the flotation of the fines thus generated.

The need to grind more finely

The economics of acquiring additional capital equipment and the associated operating costs in pursuit of optimum liberation and hence recovery of metals needs to be justified by an actual business application. Grinding more finely has limitations with respect to flotation performance, and also in areas such as filtration of concentrates and the thickening and deposition of tailings. All of these must be considered in the overall proposal.

However, numerical evaluation of the data certainly shows the potential of finer grinding—assuming that flotation can recover fine PGMs.

In summary the data show:

- *Feeds*—clearly this is a 'relatively' good UG2 ore. The majority of PGMs are either liberated or associated with sulphides, say 83% in these classes
- *Concentrates*—clearly demonstrates that recovery of PGMs is predominantly of liberated or sulphide associated PGMs, say 97% in these classes
- *Tailings*—as mentioned earlier, the losses are split between liberated and partially liberated particles, fines losses in the -10 micron fraction predominantly and partially or not liberated losses in the coarser fractions.

The following tailings MLA-sourced photomicrographs indicate the difficulty of PGM liberation—a case of 'needles in haystacks'.

In summary, Table II and Figure 4 illustrate the following:

- The PGMs in the coarser fraction (+53 micron) of the tails are not sufficiently liberated

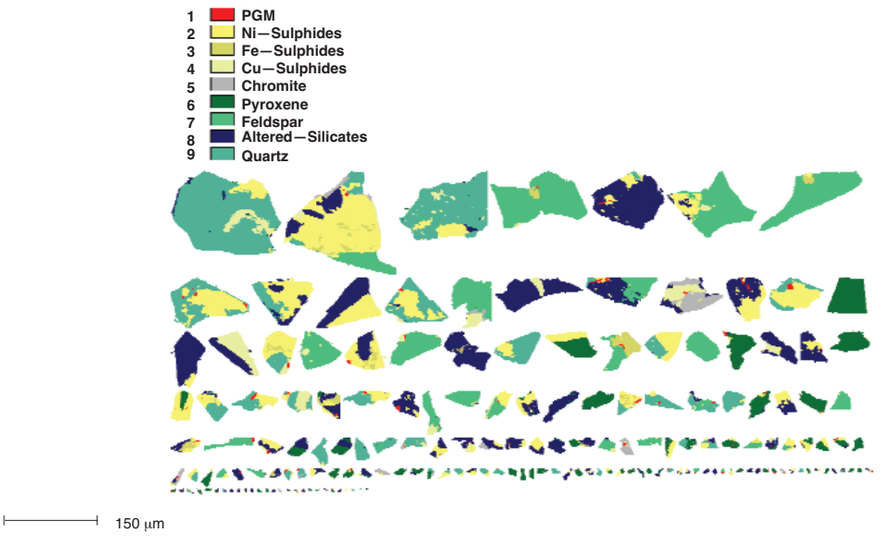

Figure 4—MLA output for PGM losses in the flotation tails—typical sample

Table II

UG2 Plant—Typical PGM association table for feeds, concentrates and tailings

	Feed	Concentrate	Tailings	Tailings-10	Tailings+10	Tailings+53
Liberated	61.0	54.8	25.1	89.0	4.2	0.0
Enclosed in BMS	5.2	30.3	3.2	0.8	7.0	0.2
Attached to BMS	12.2	7.4	1.7	1.2	3.3	0.1
PGM/BMS associated	5.4	4.0	10.5	0.4	17.5	9.7
Enclosed in silicate	3.9	1.1	28.6	2.0	26.4	53.3
Attached to silicate	4.3	1.3	17.2	6.4	28.5	11.3
Enclosed in oxide	0.1	0.1	4.8	0.0	9.6	2.4
Attached to oxide	1.4	0.1	0.7	0.2	0.0	1.9
Grain boundary	6.5	0.9	8.2	0.0	3.5	21.1
Total	100.0	100.0	100.0	100.0	100.0	100.0
No. of particles	132	958	255	100	80	75

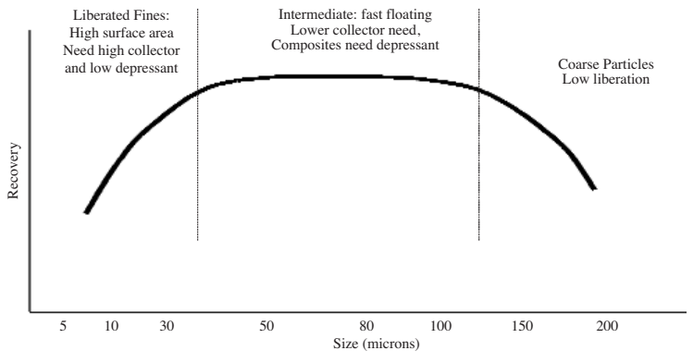

Figure 5—Typical flotation size/recovery curve

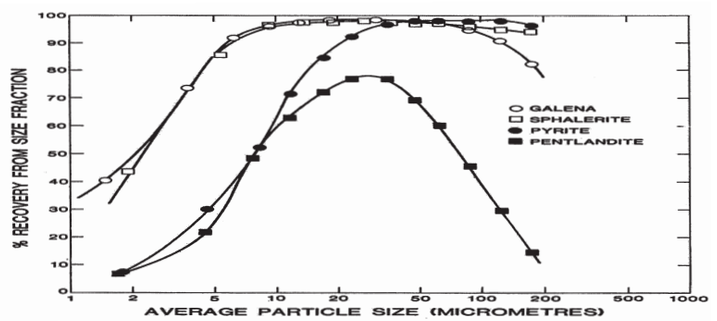

Figure 6—Flotation recovery versus size for different minerals

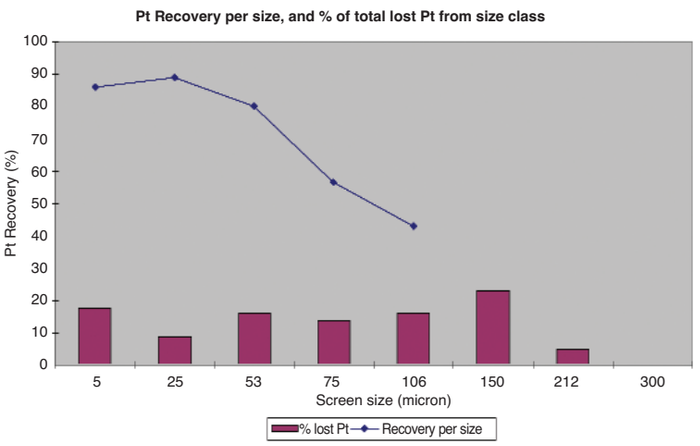

Figure 7—Particle size versus flotation recovery; and % of lost PGM from different particle size classes in an Anglo Platinum UG2 plant[2]

- The PGMs contained in the ultra-fines fraction (-10 micron) of the tails are well liberated.

This is not surprising information—given that in typical UG2 ore, PGMs are typically less than 10 microns in size. In fact, it can be said that the typical industry-wide definition of 'poor' or 'good' metallurgically characterized ore types are simply shows relativity with respect to the degree of sulphide mineral association with total PGMs: 'poor' ore has higher PGM particle association with silicates.

Having ground more finely, can we float 'fines'?

Classically, flotation recovery per size classes is known to have a flattened 'n' shape as indicated in Figure 5, which also provides some explanations for the drop-off in ultra-fines and very coarse particles.

Even though the general shape remains for most minerals, the absolute numbers of the threshold (for drop-offs etc) vary for different minerals and flotation systems, as indicated in Figure 6, an excerpt from a paper by Professor Jameson that illustrates typical relationships.

For typical UG2 ores, for example, the finer natural PGM grain size in the in situ ore and the relative performance of PGM flotation plants indicate that the 'watershed' size where flotation drops off significantly must be relatively fine. This is indicated in Figure 7, where data collected from a UG2

concentrator illustrate the relative recovery by size fraction in the mainstream roughers and scavengers. The surprising feature is the very good fines flotation and steep drop-off in coarse fraction PGM recovery.

This shows that finer particles have a better chance of recovery than coarser (> 53 micron) particles. More evidence for the ability to float fines is given for Zn-Cu systems (Mt. Isa) as well as PGMs (Anglo Platinum) in the sections that follow.

Lessons from Pb/Zn, McArthur River and Mt Isa mines

The ore mineralogy required that ultra-fine flotation was needed in the operating regime to produce a saleable concentrate product. The only option was therefore to develop an ultra-fine grinding technology, and design the appropriate circuit to float the fines generated. McArthur River and George Fisher, Mt Isa plants therefore implemented a flotation circuit performance and optimization through ultra-fine grinding (UFG), as illustrated in Figure 8.

IsaMill technology was developed by scaling up from existing grinding technology specifically to enable these particle size distributions to be achieved. The technology is recognized as the reason that both plants are in operation today. The enhanced fines flotation from the Mt. Isa Mine, George Fisher plant, can be seen in Figure 9, which shows recovery per size class results. The successful use of IsaMilling for production of fine particle size distributions presents useful lessons applicable to in the PGM industry.

Fines flotation at Anglo Platinum

Typical size-by-size analysis of flotation feed products and tails across a full scale flotation plant produces the curves shown in Figure 10.

The data in Figure 10 show that fines have a much better chance of flotation. This trend is in agreement with the analysis of UG2 monthly composites of feed tails and concentrates (an example of which is shown in Figure 7). Even with the present flotation equipment, sub 10 micron particles are floating reasonably well. Work is currently ongoing to identify better ways of improving ultra-fine (less than 5 micron) flotation. It is the authors' opinion that a different flotation technology will solve this problem eventually. It is unlikely to be achieved by the introduction of more and more power into conventionally available mechanical cells. In this increasingly energy-aware world, the use of energy forinefficient flotation systems in inherently wrong!

Circuit considerations

A typical Anglo Platinum UG-2 circuit is as shown in Figure 11.

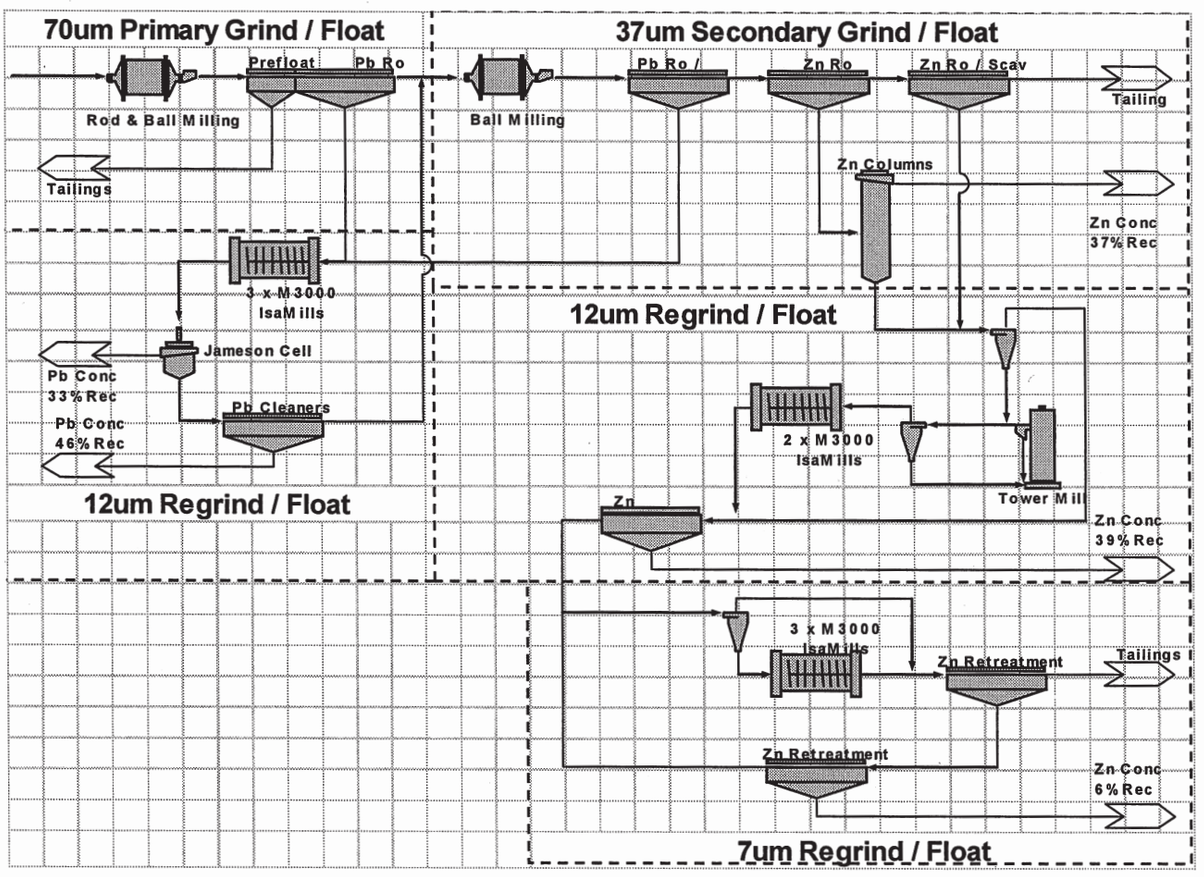

Figure 8—Mount Isa lead zinc concentrator flow sheet

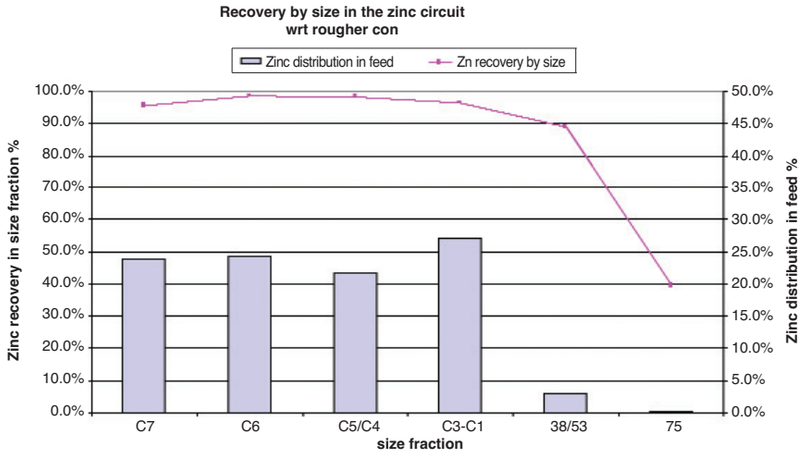

Figure 9—Recovery by size class in the zinc circuit

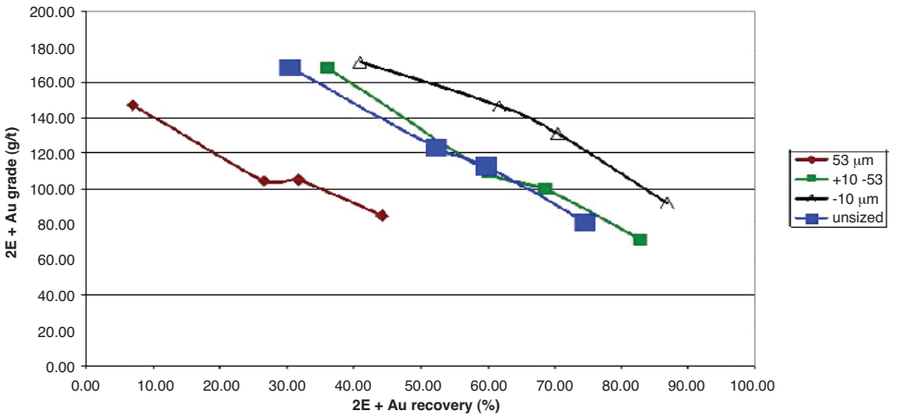

Figure 10—PGM grade-recovery profile down a rougher bank for different particle size fractions[2]

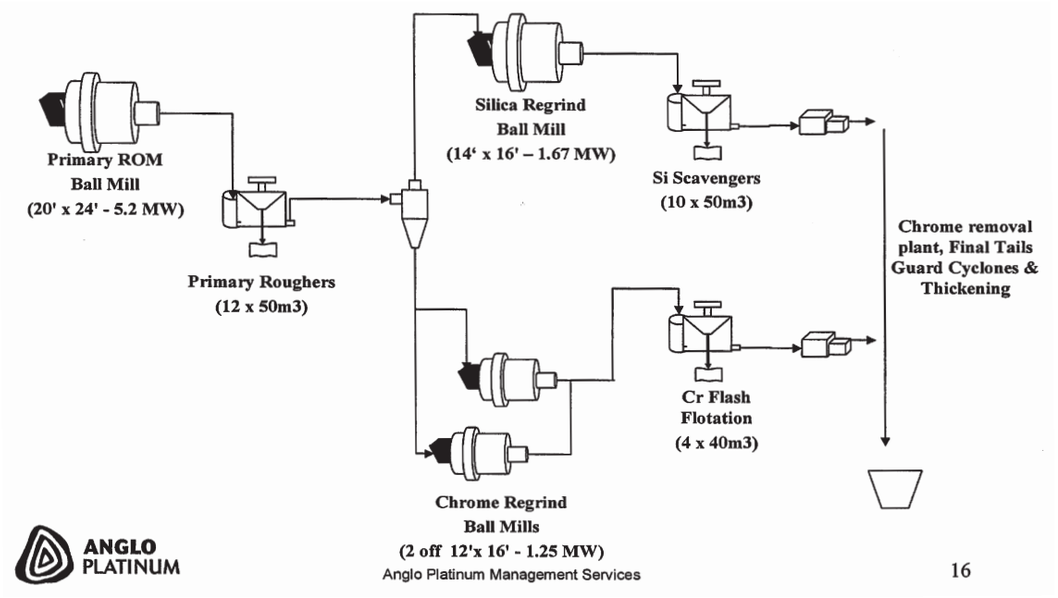

Figure 11—Flowsheet overview of a UG-2 operation at Anglo Platinum

Research into important factors considered for flotation circuit design are monitored and incorporated into Anglo Platinum's designs where appropriate. Much of this work is done with external initiatives and partners, e.g. AMIRA.

Factors include parameters such as:

- Mineralogical analysis
- Residence time and circuit configuration—size, number and arrangement of cells
- Fundamental flotation cell design
- 'Flotability' matching or kinetic matching philosophy
- Machine type, cell size, launder and froth transport, and grade control.

The need for ultra-fine flotation (especially for UG2 ores and altered ores generally) presents challenges that must be met in current and future flotation circuit designs. In order to achieve metals recoveries in excess of 90% for all UG2 ores, for example, these problems and issues must be successfully addressed. Issues that are current areas of focus include the following:

- There is a physical constraint on fines flotation due to the energy requirement for a very small particle to attach to a bubble. How is this to be overcome? Recovery decreases because viscous and electrostatic forces have a strong influence on ultra-fine particle attachment. With ultra-fines, increased surface area flux is required to carry a given mass of solids. Will a new flotation cell technology in a design different from the currently available cells evolve for widespread commercial use?
- Scaling up flotation performance designs from the laboratory to the pilot stage and then full commercial application raises questions about, Is putting more and more power into conventional cell designs a solution? Does the increased turbulence resulting have a negative impact? Drive designs and associated cost for large capacity cells are a real constraint on cost effectiveness. Is this an energy-efficient route?

Future circuit considerations and conclusions

Certain factors will have to be considered in the flotation circuits of the future, in order to take advantage of research findings for enhanced PGM flotation. These include, but are not limited to:

- The marriage of available and new technology flotation machines in 'hybrid circuits' for optimal flotation circuit design could easily involve conventional cells, 'contact' cells and column cells, arranged optimally in one flotation circuit
- The use of mechanical cells of sizes to match required residence time and configuration, with high power cells restricted to portions of the mainstream is likely. Classic cell configurations could be developed with respect to by passing driving installed cells per bank; other factors that influence overall residence time and cell sizes are froth launder lip length to cell volume ratio and duty
- A combination of mechanical and column cells should be used for UG2—overall grade-Cr_2O_3 optimization drivers also taking into account, flexibility from 'flotability' matching, cell size, lip length ratios and open circuit arrangementsd
- Froth recovery and launder lip length are important issues for optimizing mainstream recovery. In particular the recovery of 'difficult' and 'slow' floating species can be affected by reagents and more significantly by intermediate concentrate regrinding
- Process control and circuit assessment will drive open circuit operation in conjunction with UFG (ultra-fine grinding) of intermediate concentrate streams. Open circuit operation has numerous advantages, not the least of which is being of which is able to monitor performance in real time
- New flotation technology will be required to improve ultra-fine flotation i.e. sub 5 micron particles. This may well be an external bubble generator, possibly in hybrid design Flotation in size classes is desirable
- The flotation circuit of the future could be a multi-stream plant targeting specific size fractions with specific equipment employed to maximize the recovery characteristics of the particular stream

Acknowledgments

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Excerpts from various papers and private communications from Xstrata Technology, published information related to the development of the IsaMill technology and the impact on the McArthur River and Mt Isa-George Fisher Concentrators.

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Analyses of numerous studies at plant, pilot and bench scale conducted over the years within Anglo Platinum. ◆