FULLY AUTOGENOUS GRINDING AT UNKI MINE CONCENTRATOR – A CASE OF SUCCESSFUL VALUE ENGINEERING

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Abstract

The Unki Platinum Mines concentrator, employing an MF2 circuit configuration which includes fully-autogenous primary milling of run-of-mine (ROM) ore, was commissioned in November 2010. The project was Anglo American Platinum's first PGM concentrator in Zimbabwe and would form a significant contribution to the group's platinum production. The project financials demonstrated that the project was operating-cost sensitive.

After reviewing the metallurgical testwork, mineralogical examinations, and the history of similar operations, it became apparent that the Unki ore characteristics rendered it amenable to autogenous milling. The primary ball mill, structurally designed for 30 per cent steel load, could be operated at the required initial phase throughput with fully-autogenous primary milling, realizing savings in both power requirements and grinding media consumption. The original mill sizing had been done with fully-autogenous milling in mind, but allowing for flexibility and mitigation in case of varied mining fragmentation.

Since attaining steady state, target grinds have been achieved. This paper looks at the Unki ore characterization programme, design considerations, and the operational and control philosophy for a successful comminution circuit, and discusses the design to produce a flexible, low opex, mitigated comminution and overall MF2 flowsheet that is easily expanded in line with the potential for optimum exploitation of the orebody.

Introduction

The Unki Mines platinum project is the first Anglo American Platinum operation in Zimbabwe to exploit the rich platinum resources of the Great Dyke. Due to the size of the ore resource, future expansion of the scale of the Unki operation is an important consideration. The circuit design considered this aspect carefully. The exploitation strategy adopted for the Unki ore resource was to start the operation at 120 kt/month and ramp up to 240 kt/month after five years.

It was imperative for the design to produce a flexible, low operating cost, but fully risk-mitigated comminution and overall MF2 flowsheet that is easily expanded in line with the potential for optimum exploitation of the orebody. Figure 1 is the locality map for the Unki Mine.

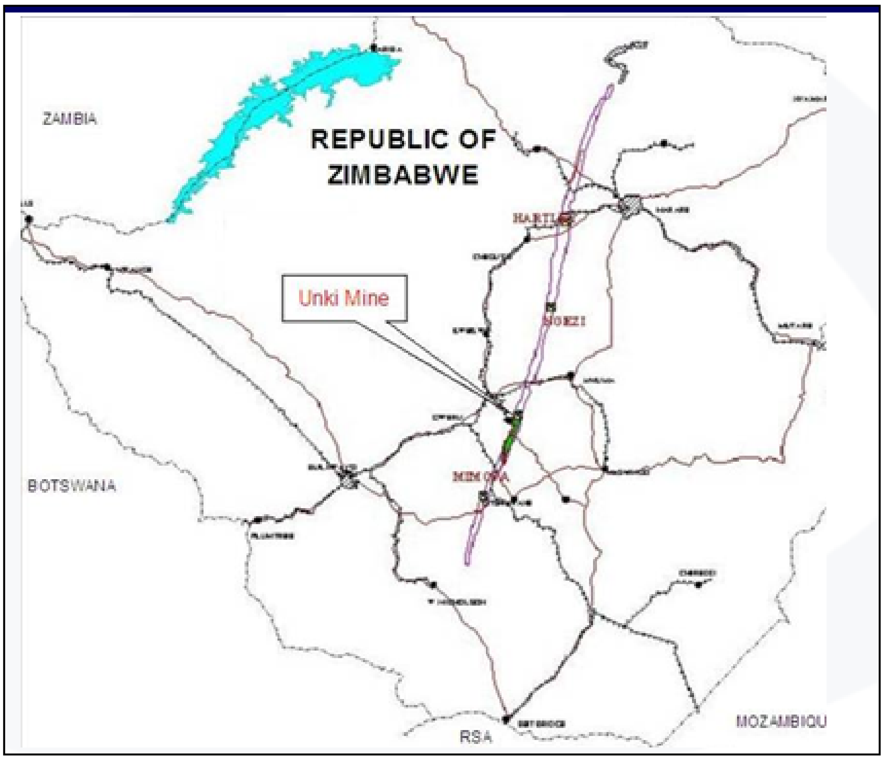

Figure 1- Map of Zimbabwe showing the location of Unki on the Great Dyke

A MF2 circuit configuration employing run–of-mine (ROM) primary ball milling, followed by secondary ball mill regrinds, was initially proposed after a full risk evaluation, based on the comprehensive testwork programme conducted on borehole cores and bulk samples from the property. Target grind for primary milling was 35 to 40 per cent passing 75 µm (corresponding to a P_{80} of 212 µm), with a final grind of a minimum 80 per cent passing 75 µm. The target platinum recovery for this circuit was 82 per cent. The financial evaluation of the project demonstrated that the project was primarily operating-cost sensitive.

The ore characteristics from drop weight tests conducted on geological and metallurgical samples and the estimated ’as is’ ROM ore size distribution presented an opportunity for changing the primary milling circuit from ROM primary ball milling to fully autogenous (FAG) primary milling. An important interpretation for FAG milling utilization is the expected fragmentation from blasted ore mined by mechanized bord and pillar’ mining. This would result in a saving in grinding media and power in the primary milling stage.

By suitably sizing the mills, future circuit flexibility could be incorporated in the design for minimal initial cost.

There was concern regarding this approach, as testwork had previously indicated that the Unki ore exhibited some degree of bimodality from a perspective of broken ore particle size, and this could result in critical size build-up in the mill, and as such represented a risk to the success of autogeneous milling.

The Unki concentrator has achieved the design target of throughput and grind with the projected savings in grinding media and primary mill power by employing a FAG primary milling circuit.

The paper discusses the testwork programme, design, and evaluation of the plant performance.

Test work

Extensive metallurgical test work over a prolonged period was conducted to characterize the orebody and to formulate the plant flow sheet. Laboratory and pilot-plant testwork were conducted at Geomet (Harare), AARL (Crown Mines), ARC (Anglo Research Centre, Germiston), Mintek (Randburg), and DML (Anglo American Platinum's Divisional Metallurgical Laboratory, Rustenburg). Eurus Mineral Consultants (EMC) validated the laboratory and pilot-plant scale testwork results using their 'Kincalc' and 'Supasim' simulation software. Significant evaluation of the Unki ore resource commenced in 1992 with testwork conducted on 22 drill cores over the mining area and six bulk ore samples from a trial mining shaft. Further test work was continued from the early 2000s up to the time of project execution. The test work from 2002 to 2008 was on more drill cores and two bulk ore samples (2005 and 2008).

Mineralogy

The mineralogical work indicated that the ore was typical of the Great Dyke ores.

Methods of investigation used involved:

- X-ray diffraction (XRD) for comparative semi-quantitative gangue mineral investigation
- Scanning electron microscopy (SEM) and optical microscopy to determine the mass distribution of sulphides
- Mineral Liberation Analyser (MLA) and QEMSEM for analyses of mineral associations
- X-ray fluorescence (XRF) scans to identify other valuable constituents of the ore samples
- ICP scans to check for variations in composition between the drill core and bulk samples.

The ore has high talc (8 to 12 per cent) and pyroxene (approximately 70 per cent) contents. The predominant platinum group minerals (PGMs) are sperrylite and Pd-Bi Tellurides. The bulk of the platinum group elements PGEs occur as free PGMs. The platinum-bearing PGMs are mainly associated with pyrrhottite (approximately 66 per cent) and lesser amounts (approximately25 per cent) with pentlandite, while the palladium-rich minerals are associated with gangue (approximately 79 per cent). The gold particles are mostly associated with chalcopyrite[1, 2]

The base metals sulphides are predominantly pyrrhotite, pentlandite, chalcopyrite, and pyrite. The average size of the PGMs varies from 5 to 30 μm with a maximum of 90 μm. The base metal sulphides vary from 5 to 20 μm. The detailed head analysis for the ore at a mining cut of 1.8 m is as follows:

Pt 1.83 g/t, Pd 1.56 g/t, Rh 0.16 g/t, Au 0.30 g/t, Ni 0.21%, and Cu 0.15%.

The mineralogical data formed the basis for optimizing key design parameters and also for benchmarking against the other Great Dyke operations.

Comminution

AARL, ARC, Mintek, and later DML conducted a series of drop weight test (DWT) and Bond Work Index (BWI) test work on core and bulk samples of the Unki ore. JKMRC analysed the Mintek work. Comparison between Unki and other Great Dyke ores was also done. The Unki ore characteristics are typical of the Great Dyke ore. The ore displays moderately hard range of resistance to impact breakage and medium abrasion range. Test methods used included:

- Calibrated AARL Rod Mill by AARL
- JKRMC standard procedure for the DWT and the Warren Spring Laboratory standard procedure for BWI by ARC.
- Mintek used their batch mill (which conforms to the standard Bond batch ball) to determine the Bond ball mill Work Index
- The DML's Magotteaux pilot mill demonstrated that the Unki ore was amenable to autogenous primary milling and there was no critical size build-up. A target grind of 35 to 40 per cent -75 µm was achieved at a coarse to fine ore ratio of 25:75

The results for the ARC test work are summarized in Table I:

Table I- Unki BWI test work results benchmarked against Great Dyke ore

		Limiting size (µm)		
Sample		300	150	106
Unki ore	BWI (kWh/t)	11.6	17.7	17.6
Other G Dyke tests:	BWI (kWh/t)	15.1	*16.5**	18.1
* calculated				

Mintek results are shown in Table II:

Table II-Mintek BWI test work results for Unki Ore

Sample	Limiting screen (µm)	F_{80} (µm)	P_{80} (µm)	Work Index KWh/t
Unki ore	75	1906.18	57.56	18.2
	150	1906.18	114.02	15.0

The above confirms that the design BWI for the primary ball mill is between 15 kWh/t and 18.2 kWh/t. As will be shown later, for sizing the primary mill motor the Bond method is used. The design Bond Work Indices for the primary and secondary ball mills are 16.5 kWh/t and 20.5 kWh/t respectively. Inefficiency factors to mimic industrial applications were considered.

Flotation

AARL, ARC, and Mintek conducted laboratory flotation test work on core and bulk samples to determine the metallurgical response of the Unki ore and develop a flow sheet. The test work also compared the performances of MF1 and MF2 circuit configurations. The challenge the Unki ore posed was the presence of a footwall shear containing high levels of altered silicates, raised levels of talc, and swelling clays. The impact of treating ore that included the footwall material was also investigated and quantified in the DML pilot plant. The recoveries obtained for the MF1 and MF2 circuits from different test work campaigns are shown in Table 3.

Table III- MF1 and MF2 recovery

Test work	4E Recovery (%)	
	MF1	**MF2**
Mintek pilot	84.6	87.0
DML pilot	77.9	80.4
EMC (simulation)	78.3	84.0

DML's pilot trials indicated that the 4E PGM recovery dropped by as much as 7.7 per cent and 3.7 per cent due to the higher hydrophobic, talcose component of the shear zone foot wall material. This and the above results favour an MF2 circuit configuration.

Design

The Unki concentrator MF2 flow sheet is shown in Figure 2. The flow sheet included an in-circuit crushing (ICC) or pebble-milling circuit to mitigate potential comminution problems. The ICC circuit was planned to consist of pebble transfer system to a cone crusher or HPGR. A pebble stockpile and reload facility would be allowed to provide optimum mill load control.

However, this circuit was deferred during the project risk review; but importantly a relatively easy future retrofit was enabled in the built circuit.
A strategic decision was made to standardize the sizes of the Unki mills with mills that had been recently installed within the group; these conservatively sized units could thus permit first-phase FAG operation if ore characteristics permitted, and hence fitted well with Unki's long-term expansion plans. Bond and SMC/JK models were used to estimate final installed motor power requirements. Estimated gross power requirements were 2.7 MW and 3.7 MW for the primary and secondary mills respectively. However, 5.2 MW motors were selected for both mills to cater for future expansion potential and the future potential usage of steel grinding media.

The comminution circuit design was reviewed by the Centre for Minerals Research at the University of Cape Town, confirming the efficacy of the design. After a review of the liner design by JKMRC, 14 mm slot width grates and an open area of 7.5 per cent (equivalent to 2.05 m^2) were specified for the discharge grates.

It should also be noted that Great Dyke ores generally form slurries with low viscosities and good discharge characteristics, even with the raised hydrophobic gangue content.

The overall flow sheet offered flexibility for future expansion (see the aerial photo of the plant in Figure 4). Expansion footprint allowances were made. The future ICC is shown in Figure 3.

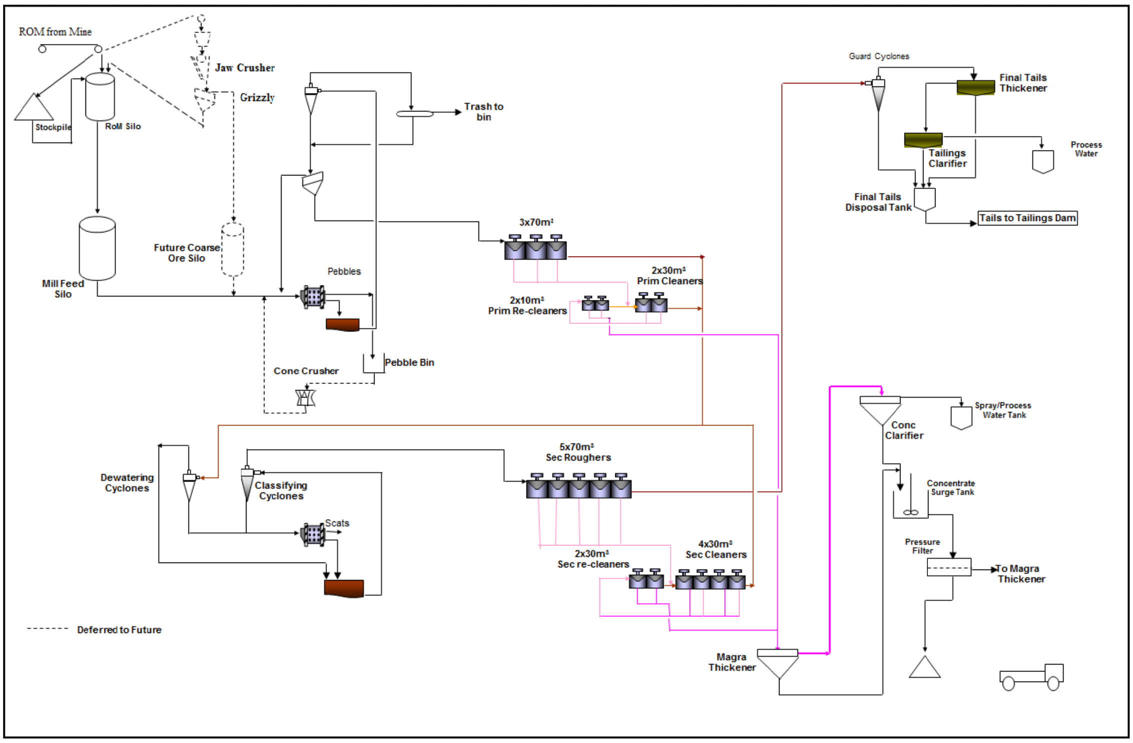

Figure 2- Design flow sheet for Unki [(3)]

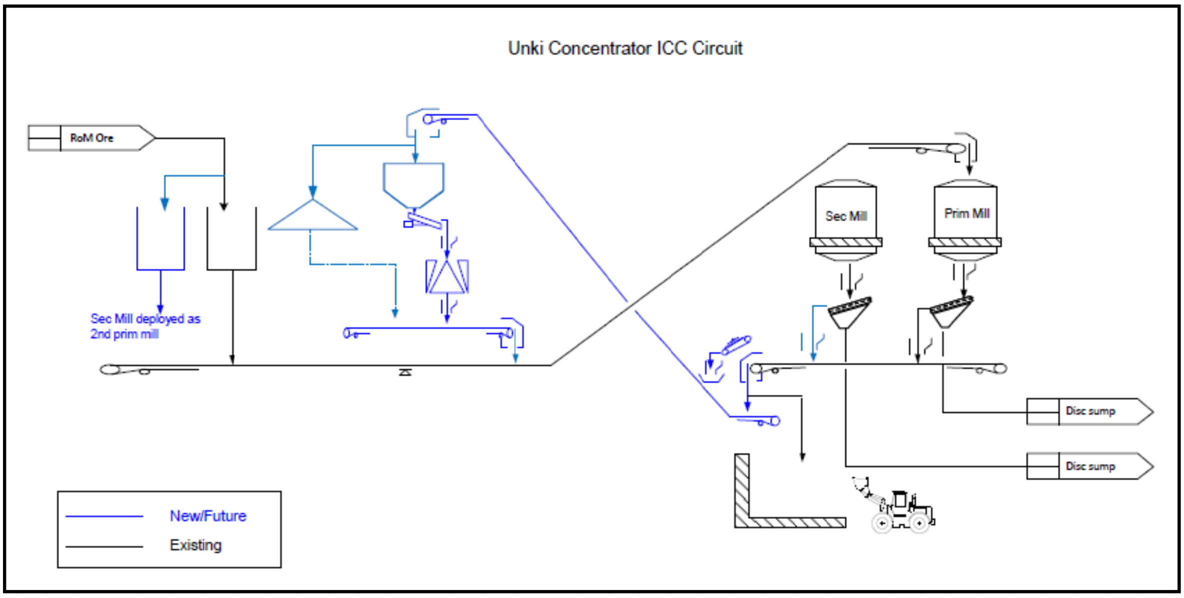

Figure 3-Flexible design for the Unki ICC circuit

Figure 4-Unki concentrator aerial view (March 2011)

Process description

The Unki concentrator design is for a nominal capacity of 120 kt/month using a 20 foot diameter by 28 foot length primary mill with 5.2 MW installed mill motor power as a ROM AG mill in closed circuit with a classification screen (with 0.63 mm to 0.8 mm aperture opening) and a 20 foot diameter by 28 foot length secondary mill with 5.2 MW installed mill motor power as a ball mill in closed circuit with a classification cyclone cluster for secondary regrind. Mills were sized to enable a future twin-module primary milling configuration – future alternative milling equipment could then be fully evaluated.

The flotation circuit consists of a short residence-time, primary roughing stage comprising 3x70m^3 flotation cells and primary cleaning and re-cleaning stages. Primary rougher tails report to the secondary mill ahead of scavenger flotation, and cleaning and re-cleaning. Two concentrates are produced, a high-grade concentrate from the primary re-cleaner flotation circuit and a medium-grade concentrate from the secondary re-cleaner circuit. These combine to form the final concentrate. Open- or closed-circuit cleaning in the scavenger circuit is an option

Concentrate handling consists of a Magra thickener and a conventional clarifier, and Larox high-pressure filtration of the thickened concentrate. Tailings thickening circuitry includes guard cyclones, a high-rate thickener, and clarifier. Final tails are pumped to a tailings storage facility about 5 km away from the plant.

The original design concept offers great flexibility and expansion potential for Unki. The layout provided for a future ICC to allow a sequential expansion of a single module, from 120 to 140 kt/month using suitably oversized 20 foot diameter mills and then by utilizing ICC technology to potentially achieve a throughput of as much as 180 kt/month, once FAG operation had been proven. This is achieved through an $F80$ of 300 mm and $P80$ of 250 µm in the primary AG mill, with a circuit grind of 36 per cent and 80 per cent -75 µm in the primary and secondary mill respectively. It is worth noting that mitigation in this design is by:

1. Oversized 20 foot diameter mills
2. Mill and mill drive designed for 30 per cent steel loading, allowing for a SAG and high-steel ROM ball milling option. The mill was designed for 75 per cent critical speed and 10 per cent circulating load
3. ICC circuit addition in the event of critical size build-up and retention of FAG. The circuit will be designed for 20 to 30 per cent pebble generation. The primary mill grate discharge grate will be modified to include ±65 mm pebble ports (design to be confirmed from operational data)
4. Possibility of converting the mill drive to VSD as mitigation for throughput and FAG constraints due to unsuitable ore fragmentation.

Ore characterization

Competent ore and a sufficient coarse fraction component are prerequisites for successful autogenous milling. An extensive review of literature of all previous and current test work and operations treating similar ore from mechanized and non-mechanized mined operations was conducted. Ore hardness and grindability tests demonstrated that the ore could be classified as hard. The results are shown in Table IV. These results were also used to estimate power requirements for comminution circuit design.

Table IV- Summary of comparative ore hardness test and operational results

SAMPLE	DWT				BWI (kWh/t)	
	A	b	A*b	T_a	106 µm	75 µm
2004 Test work	67.6	0.62	41.9	0.38	19.2	20.5
May 2011	78.5	0.67	52.6	0.37	19.7	21.1

Analysis of *t*10 (size passing 10 per cent of the original particle size) and unit specific energy (Ecs) established that the Unki ore displays the normal trend of decreasing slope with decreasing energy (Ecs values). A study of the distribution of the relative density of particles showed no evidence of bimodality (that is, no evidence of dense particles that could build up in the mill and cause mill load problems).

Two measures were put in place to cater for possible risk of failing to achieve the target primary grind. An in-circuit crusher circuit was provided for in the layout, but its installation was deferred. The primary mill liners were designed for both FAG and SAG operation; the first set was designed conservatively, as is normal practice.

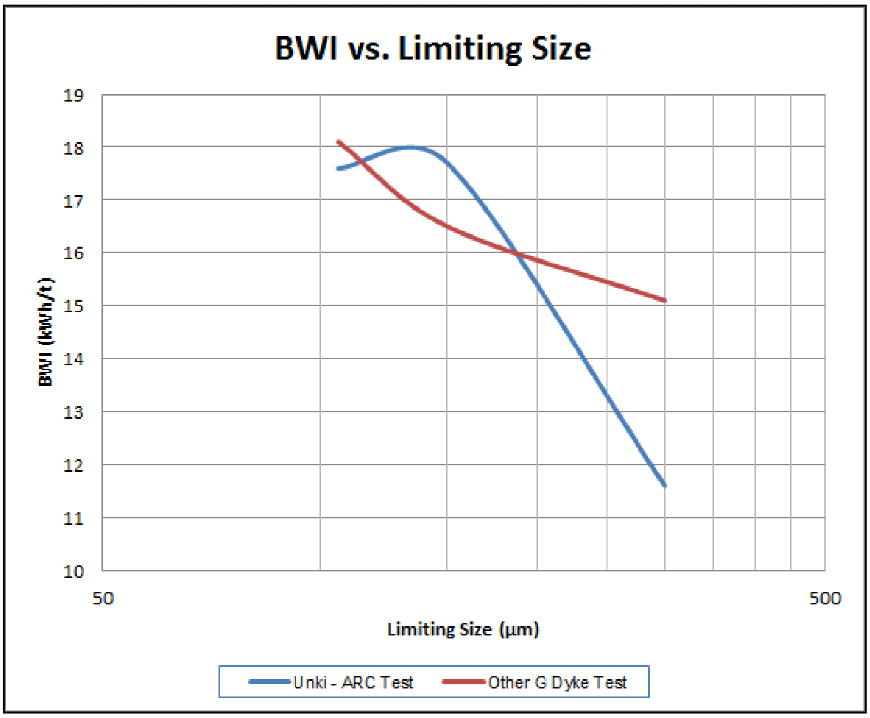

Figure 5- BWI vs. limiting size test work results

Pilot plant test work conducted at Anglo American Platinum's DML facility in Rustenburg on a bulk ore sample confirmed that the Unki ore was amenable to autogeneous milling, and that there was no evidence of critical size build-up in the mill.

Feed ore size

About 65 per cent of the RoM ore sample was in the coarse fraction (>106 mm). The literature[4,5] indicated that the maximum coarse fraction should be ±15-25 per cent. The representavity of the bulk ore sample represented a major potential risk. The experience of the Anglo American Platinum Process Group on a recently commissioned FAG primary mill with similar dimensions had demonstrated that FAG primary milling could be successful for higher contents of coarser fractions (this particular mill had been designed for a ROM ore of 20-30% >190mm). The Unki ROM ore size distribution curve indicated 30 per cent >200 mm (Figure 4). It is important though to minimize the amount of very fine material (say <1 mm) in the feed as it tends to build up and load the mill.

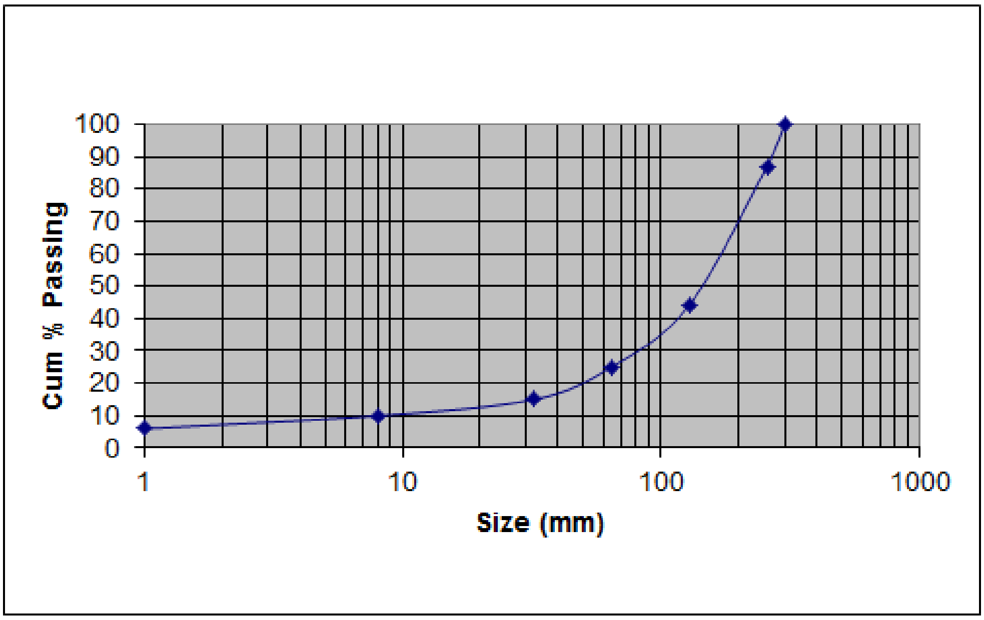

Figure 6-Unki trial mining ROM size distribution

Mill liners

A cautious approach was adopted to mitigate potential flaws. Liners were designed for FAG operation but able to operate in SAG mode. Working with the mill vendor and liner supplier, a mill liner design was proposed. This design was reviewed by JKMRC[6]. The trajectories of the outmost particles were analysed using MillTraj software (Figure 7). A third-paryt liner vendor also analysed the trajectories of the outmost particles. In both cases the findings confirmed that the liner design was suitable for AG/SAG operation. The optimum liner design (with a face angle of 70^{o} measured from the base, and 85^{o} for the trailing angle) was recommended and implemented.

Key aspects of the liner design were the face and trailing angles and the liner spacing to height ratio (S/H). As the mill was unidirectional the trailing angle was made steeper, resulting in a wider liner top, which adds to liner life. Due consideration was also given to the design of the discharge grate for optimum mill performance (open area). Typically for mills in this operation, a grate discharge opening of between 12 and 16 mm is recommended. As there had been indications that the Unki ore could possibly generate a critical size (estimated at approximately 13 mm), a discharge grate opening of 14 mm was specified.

To cater for the possibility of SAG operation the design team shied away from a harder material and opted for Moly-Chrome (approximately 2 per cent chromium). The liner material has since been changed to a harder material.

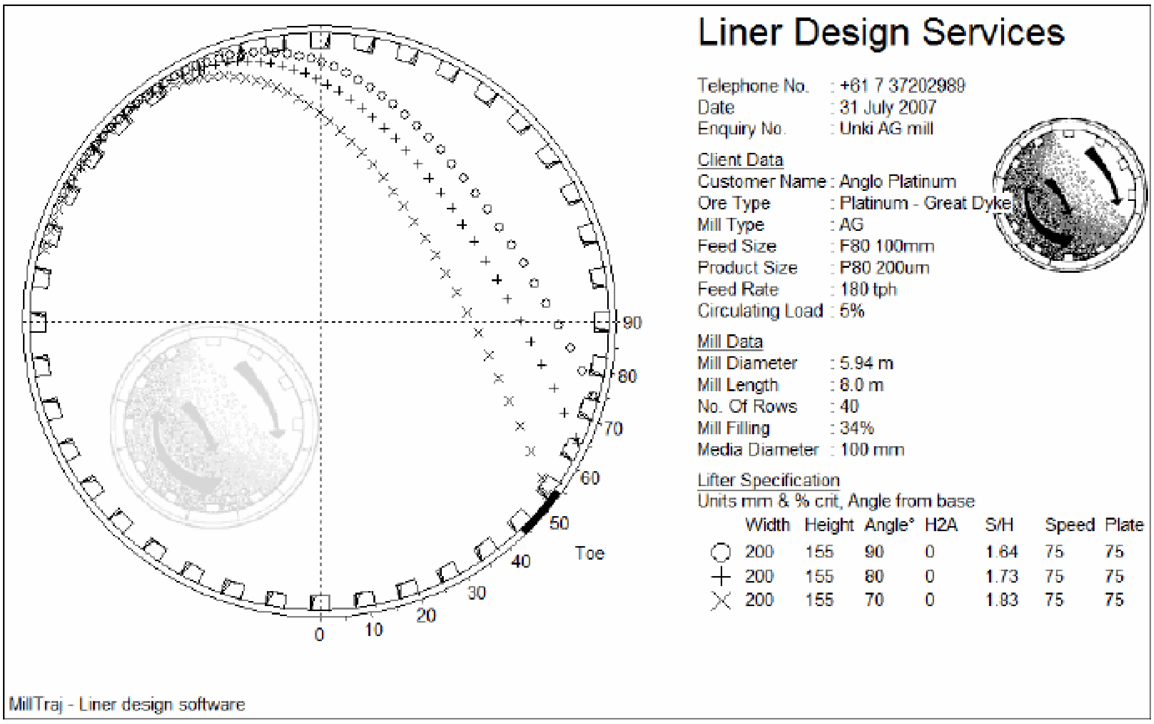

Figure 7- Example of projected trajectories for the Unki primary mill

Operation and post-commissioning

Mill control

The application of Anglo American Platinum's APC (Advanced Process Control System) guaranteed the performance of the mill. The installation of a mill feed silo with enough buffer capacity (>20 hours) ahead of the mill also enhanced the control solution.

Plant performance

The Unki concentrator has been able to operate at above design throughput (approximately 130 kt/month *versus* design of 120 kt/month) with a primary grind meeting design specification (approximately 42 per cent -75 µm *versus* design of 35 to 40 per cent -75 µm) and final grind of approximately 80 per cent -75 µm. The oversize (>19 mm) material generated from the primary mill is much less than predicted. Figure 8 is a typical size distribution curve for the Unki concentrator comminution circuit.

The predictions made on power requirements during design were very close to what is prevailing on the plant (power draw of approximately 2870 kW for the operational plant *versus* approximately2974 kW for design, equivalent to specific energy of 16.2 kWh/t and 16.5 kWh/t respectively). This is significant as it gives the confidence to estimate power savings between FAG milling and ROM milling using standard packages (e.g. Austin and Bond correlations).

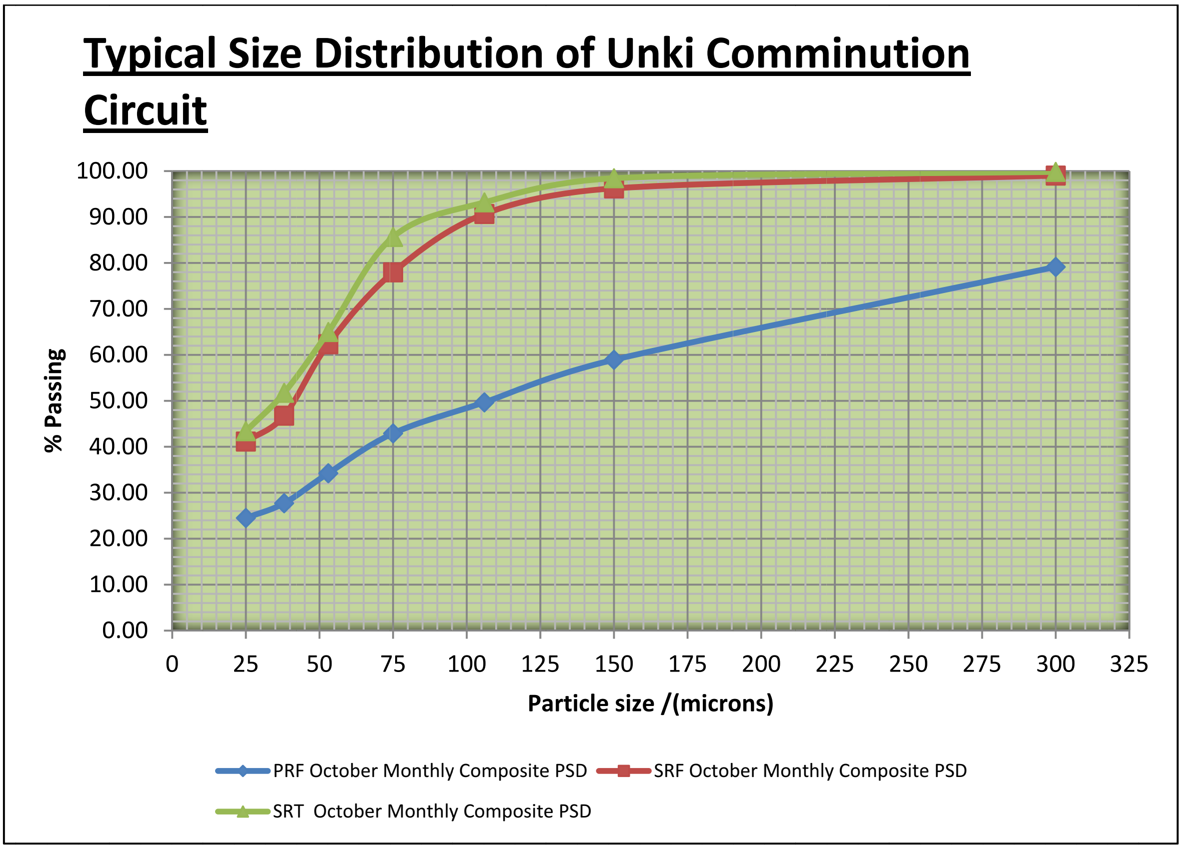

Figure 8- Example of Unki comminution circuit PSD curve. PRF: primary rougher feed (primary grind); SRF: secondary rougher feed (secondary grind); SRT: secondary r tails

Operating experience

Mill and feed control

It was evident during commissioning and operation that by maintaining a consistent feed size distribution the mill would reach an equilibrium position and operated very stably. Figure 9 is a typical mill power draw plot over a three-day period of plant operation. The vertical axis represents measured power draw (kW) for both the primary and secondary mills. The horizontal axis is time period. The fact that power draw fluctuates within an acceptable range demonstrates stability of the comminution circuit.

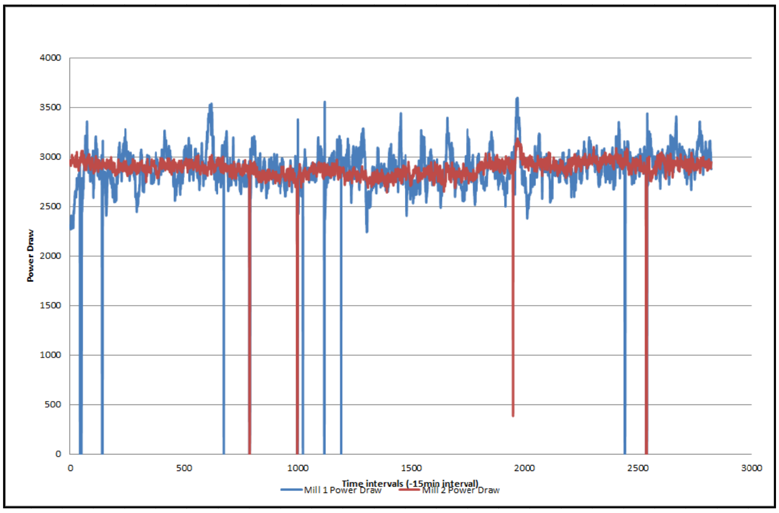

Figure 9- Power draw plot for the mills

However, the introduction of insufficient coarse fraction creates disturbances, which the operator manages. As can be imagined, by its very nature the ROM ore is prone to segregation, which worsens when the mill feed silos are running low. The strategy is therefore to maintain high silo levels. The mill feed silo has two discharge chutes and the ore would segregate at low silo levels, differentially between the chutes. When such situations occur (theseoccur only occasionally) the operator draws from the chutes proportionately. A coarse/fine ore split was considered during design, but as the brief was for a plant fit for purpose this cost was considered excessive. Figure 10 shows examples of the feed ore on the feed conveyor.

Figure 10-Ore on mill feed conveyor (helmet as scale)

Primary mill liner wear

The first set of liners were of an abrasion-resistant, air-hardened pearlitic chrome-molybdenum alloy steel approximately 2% Cr). These liners were deliberately selected for possibility of adding steel (SAG operation) due to 'critical size potential' and were expected to last between 9 and 12 months. The liners were replaced after nine months. After demonstrating that FAG primary milling is feasible, the liner material has been changed to a martensic abrasion-resistant high-chrome iron (16.5-24.5% Cr). This material is not tolerant to steel media. The high-chrome iron liners are approximately 32 per cent more expensive than the Moly-Cr liners, but last approximately twice as long. This has been confirmed to date by monitoring of liner wear. Table V demonstrates the benefit of using a more durable and expensive liner for the primary mill operated in FAG mode. The throughput for the new liners is a projected from wear rates over a six month period.

Table V-New and old mill liner comparison

Liner type	**Throughput to replacement (t)**	**Liner cost (R)**	**Liner cost (R/t)**	**Liner life (months)**
Old (Moly-Cr : Low Cr)	725 012	6 392 585	8.82	9
New (High Cr)*	2 625 000	10 010 291	3.81	21
Estimated from liner wear monitoring on plant				

Platinum recovery

The current ROM material contains significant footwall shear zone material, which is depressing recovery due to raised hydrophobic gangue levels and hence greater competition with slower-floating value minerals. Target recoveries are for mechanized mining cut excluding the FWSZ. Figure 11 represents a cross-section through the typical Unki mineral width (mining cut of 2.2 m), with platinum grades peaking at the Main Sulphide Zone (MSZ) and decreasing into the hangingwall and footwall. The zone in the footwall is characterized by presence of hydrophobic altered silicate talcose material that impacts negatively on plant PGM and BMS recoveries.

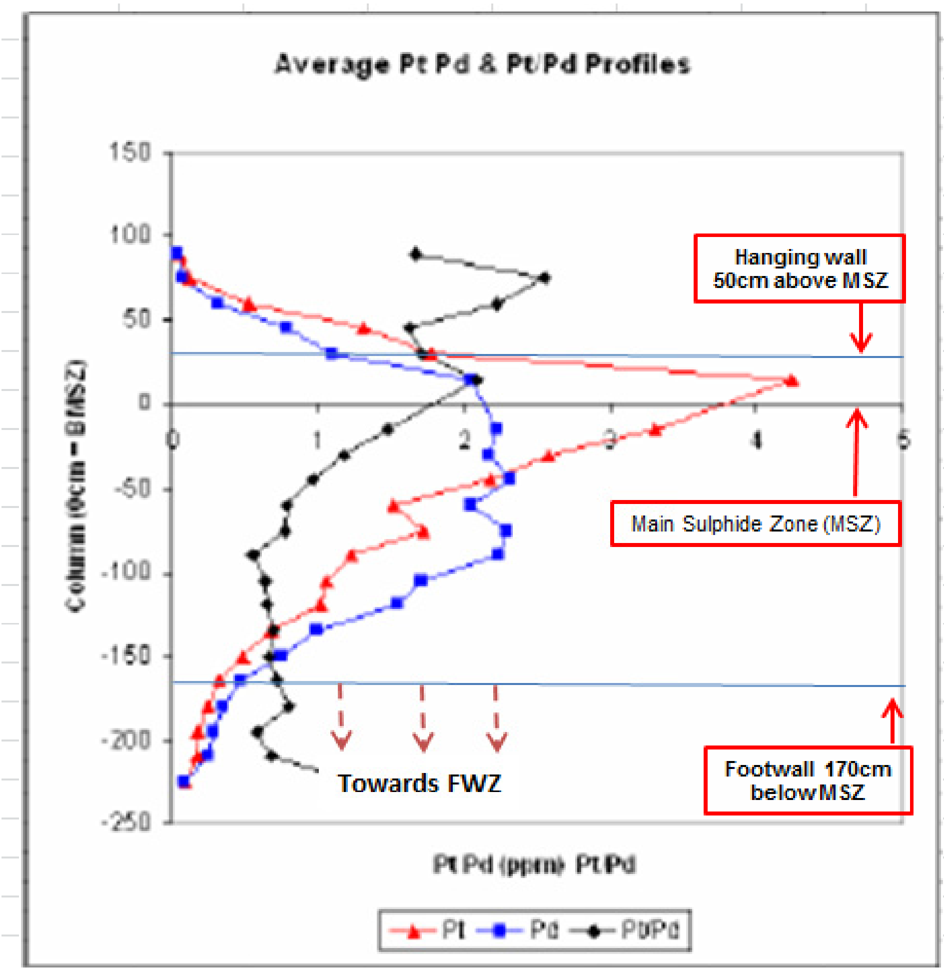

Figure 11-Cross-section through Unki mining width

The successful operation of the FAG mill in the Unki communition circuit can also be seen in the platinum recovery. By continuously attaining the target grind, the platinum recovery has been showing a positive trend since commissioning. Figure 12 shows the Unki recovery from January 2011 to March 2012.The average target platinum recovery over the project life for this circuit is 82 per cent, and within 7 months of operation (June 2011) the platinum recovery had reached 80 per cent. In the August 2011, the spike of up to 86 per cent was due to metal accounting factors caused by reduced tonnage, mill relining and a high head grade. From September 2011 to March 2012, the platinum recovery has been consistent, averaging around 78 per cent with evidence of a steady upward trend towards the targeted 82 per cent, despite the impact of the FWSZ.

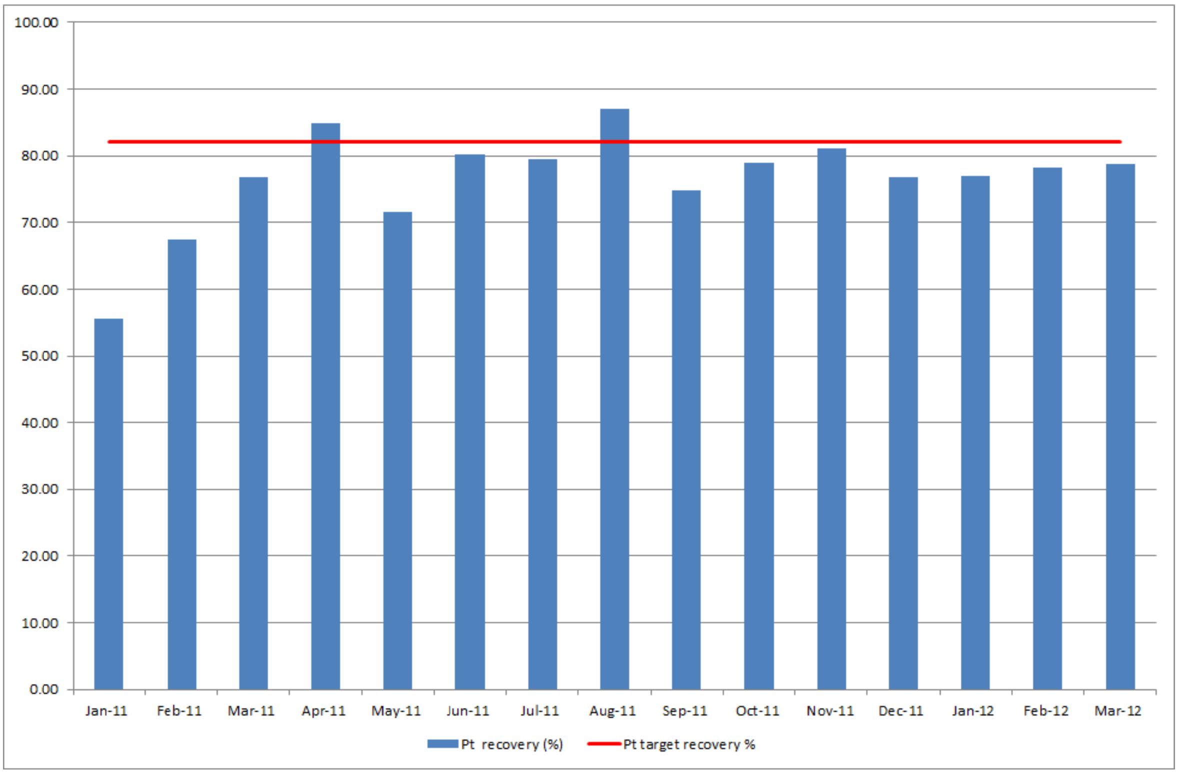

Figure 12-Unki platinum recovery

Production ramp-up

Figure 13 shows the Unki concentrator production ramp-up from start of production. Within 10 months of commissioning the plant was able of exceeding design nameplate capacity, and has been able to maintain the high throughputs consistently.

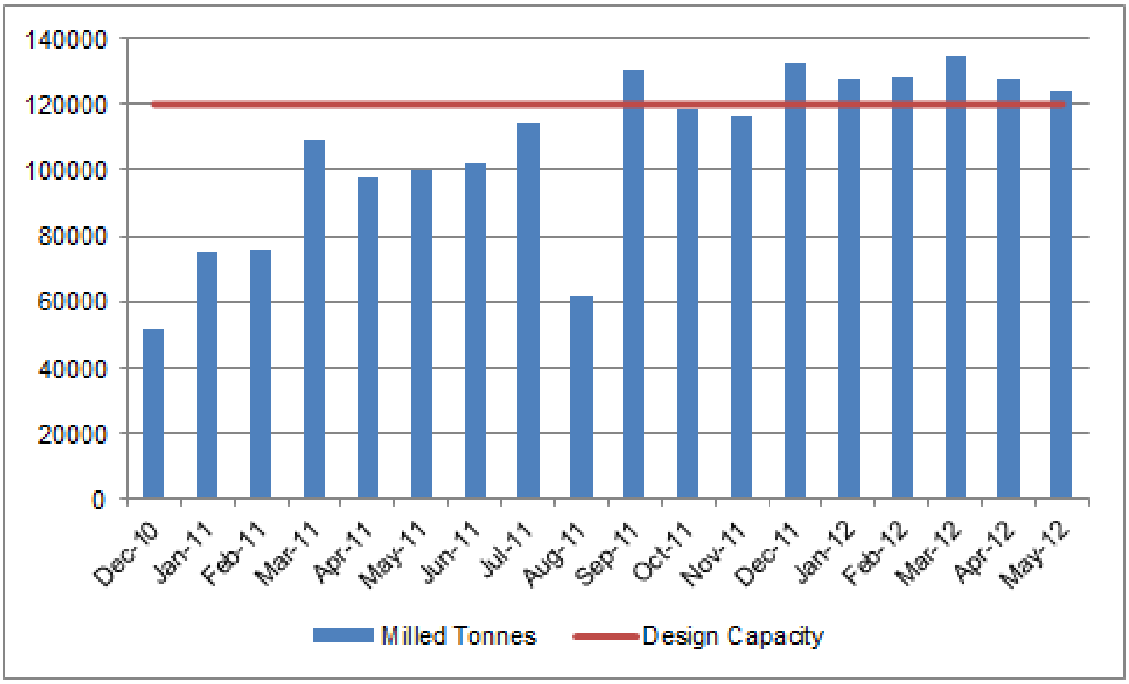

Figure 13-Unki production (kt/month) from commissioning

Comminution circuit performance: grind data

Figure 14 shows the grind achieved from commissioning. The data shows slight decreases in grind as production increased above nameplate capacity, but still close to the target grind ranges.

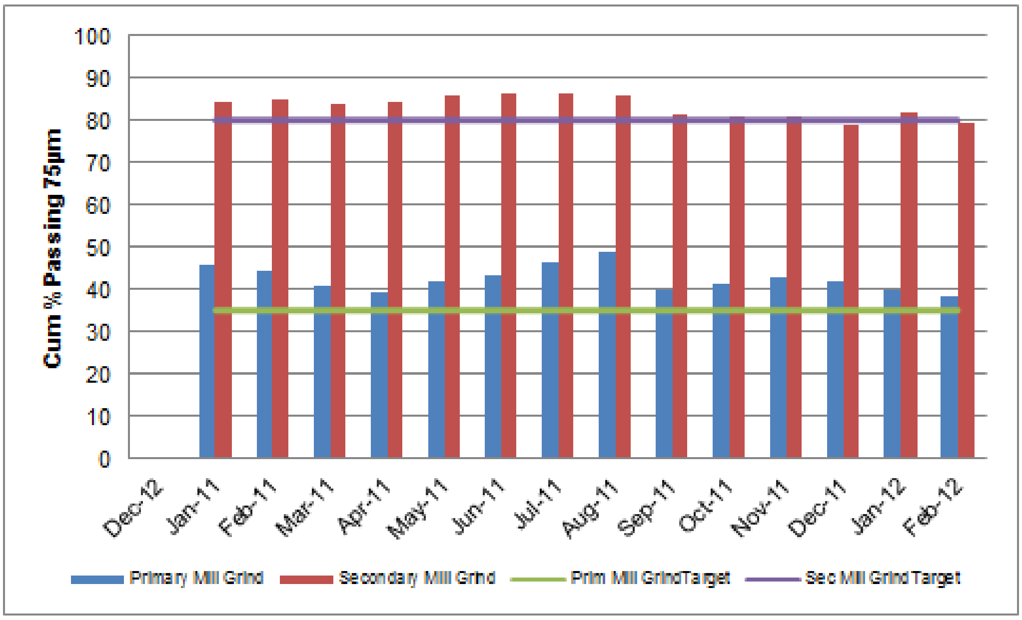

Figure 14-Unki grind data

Conclusion

Fully autogenous primary milling was successfully implemented at Anglo American Platinum's Unki Mines Concentrator. It has not been necessary to implement the comminution mitigating measures provided for in the design. The benefits are significant as reflected in the reduction in operating costs, amounting to approximately R14 perton milled and made up as follows:

- R3.81 – reduced primary mill liner costs, excluding savings in reduced relining requirements
- R4.80 – saved grinding media from estimated steel consumption for mill operating as ROM primary ball mill
- R5.80 – saved mill power. Comparing actual power consumption on the primary mill and estimated power requirements for the primary mill operated as a ROM primary ball mill.

No assessment has been made of the reduction in capital as a result of not including crushing ahead of the primary mill. Ongoing optimization initiatives on site include optimization of ore fragmentation in conjunction with the mining team.

A lesson learnt from the Unki experience is that designers of processing plants can add significantly to shareholder value by fully evaluating the potential design envelope. However, this approach must be supported by a thorough understanding of the orebody and sensible interrogation of technical data available.

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Tony also spent more than fifteen years working for multinational companies in thecChemicals and household and personal hygiene goods industries in engineering and operation roles in Zimbabwe and Tanzania.