# Merits of Optimised Milling Configuration on Process Performance: Case Study of Mixed Ore Circuit at Kansanshi

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The original configuration of the Kansanshi transitional ore grinding circuit consisted of a primary semi-autogenous (SAG) mill with a trommel screen, a pebble crusher and a dedicated cyclone cluster. Crushed pebbles and primary cyclone underflow streams provided feed to a secondary grate discharge ball milling stage that was closed by a separate nest of cyclones. The mechanical and process design of the circuit included identical dimensions of both the SAG and ball mills, which are both low aspect, with added flexibility of feeding both mills simultaneously with fresh feed or feeding the ball mill exclusively, depending on the quality of the fresh ore or downtime on the SAG mill. The secondary ball mill discharge was screened to remove pebbles that were combined with pebbles from the SAG mill to feed the common pebble crusher before recycling to the ball mill. Test work was performed on the circuit and the data obtained were used to develop models in *JKSimMet*. The simulator was used to test various scenarios to assess which of the plausible alternatives would lead to optimal performance with respect to throughput and grind. The options simulated included making changes to both the circuit configuration and operating variables. From the simulated results, circuit configuration and operating set points were proposed and implemented. A series of surveys were subsequently conducted to assess the change in performance of the circuit following the recommended changes. This paper compares the performance of the transitional ore circuit before and after the changes.

## INTRODUCTION

Kansanshi mine, the largest copper mine in Africa by production (2017), is owned and operated by Kansanshi Mining PLC, which is 80% owned by a First Quantum Minerals subsidiary. The remaining 20% is owned by a subsidiary of the parastatal, Zambia Consolidated Copper Mines – Investments Holding (ZCCM-IH). The mine is located approximately 10 km north of the town of Solwezi and 180 km to the northwest of the Zambian Copperbelt town of Chingola.

The Kansanshi Mine process plant consist of three concentrators, each equipped with a dedicated comminution circuit with a total installed power of 36 MW, processing primary and secondary sulphide ores, transitional mixed ores and highly weathered oxide ores, depending on the mining plan. The three comminution circuits are referred to as the S0 comminution circuit (currently treating oxide ore and feeding the oxide concentrator, Figure 1), S1 circuit (currently treating mixed ore and feeding the mixed concentrator, Figure 2) and the S2 circuit (currently feeding the sulphide concentrator, Figure 3). In 2017, close to 28 million tonnes of ore was treated through the plant.

To optimally operate the three independent comminution plants, different operating philosophies are followed for each. This is due to differences in the mill geometry, feed ore characteristics and operating constraints for the different circuits, as shown in Table I. Of note are the different mill diameters, aspect ratios and operating speeds. In addition, the two semi-autogenous (SAG) mills on the S0 and S2 circuits have variable speed drives installed. The SAG mills used in all cases are operated with very high ball loads compared with standard mills and the operating speeds of each are fairly different.

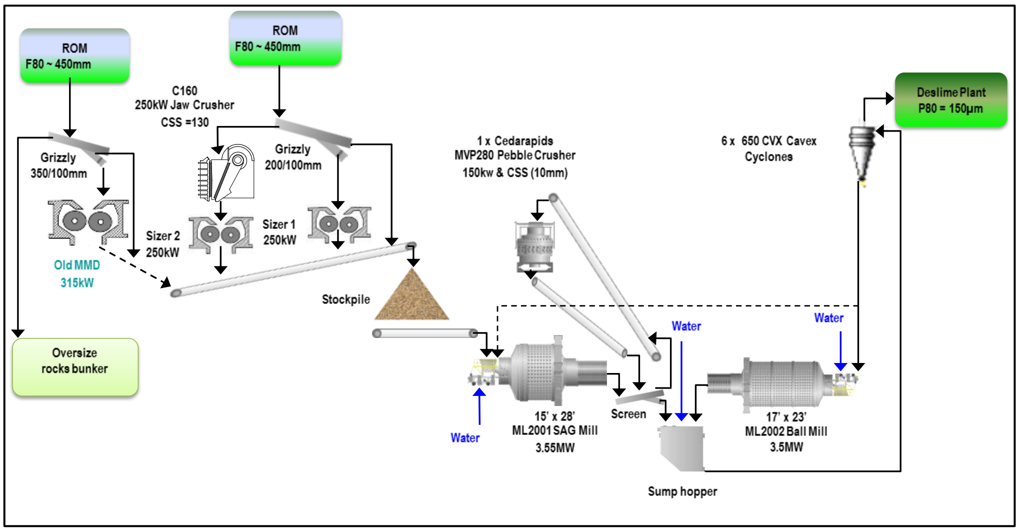



*Figure 1: S0 circuit (current oxide circuit) configuration.*

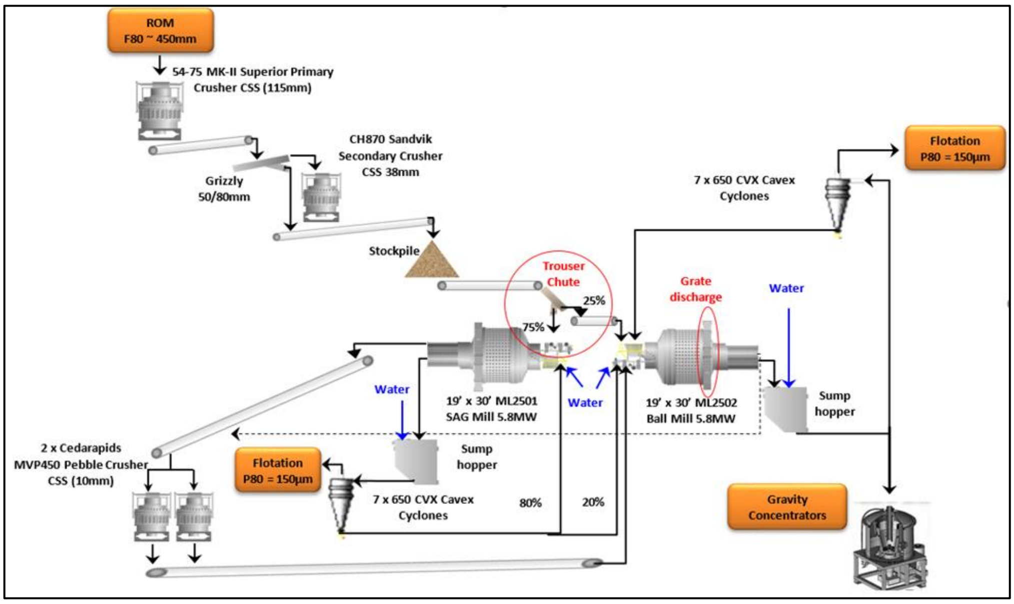



*Figure 2: S1 circuit flowsheet (current mixed ore circuit).*

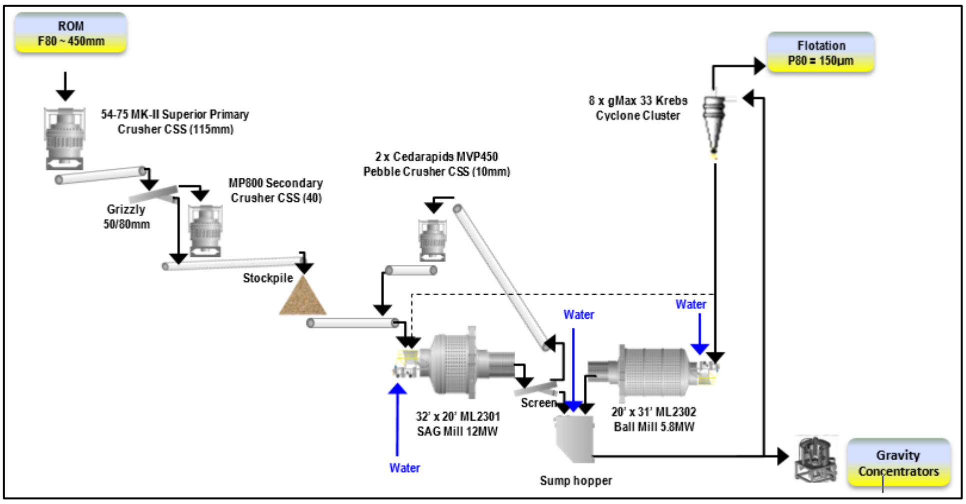



*Figure 3: Sulphide circuit flowsheet (S2 circuit).*

*Table I: Main design and operational consideration for Kansanshi milling circuit.*

| | Sulphide (S2) | Mixed (S1) | Oxide (S0) |
|---|---|---|---|
| **SAG mills** | | | |
| Internal diameter (m) | 9.75 | 5.80 | 4.60 |
| Internal belly length (m) | 6.10 | 9.18 | 8.68 |
| Centre line length (m) | 8.9 | 10.3 | 8.68 |
| Feed trunnion diameter (m) | 2.1 | 1.6 | 1.68 |
| Feed end cone angle (°) | 20 | 15 | 0 |
| Discharge end cone angle (°) | 20 | 15 | 0 |
| % of critical speed (rpm/%) | 75 | 75 | 88 |
| Load fraction (%) | 15 | 15 | 15 |
| Ball top size (mm) | 100 | 125 | 100 |
| **Secondary milling** | | | |
| Internal diameter (m) | 6.10 | 5.80 | 5.08 |
| Internal belly length (m) | 9.30 | 9.10 | 7.10 |
| Centre line length (m) | 10.5 | 10.2 | 7.101 |
| Feed trunnion diameter (m) | 1.6 | 1.6 | 1.43 |
| Feed end cone angle (°) | 15.0 | 15.0 | 0.0 |
| Discharge end cone angle (°) | 15.0 | 15.0 | 0.0 |
| % of critical speed (rpm/%) | 75 | 75 | 75 |
| Load fraction (%) | 25 | 26 | 26 |
| Ball top size (mm) | 50 | 100 | 68 |

Following a period of plant expansions and commissioning additional equipment that included the transitional ore circuit (S1), it become apparent that the Kansanshi comminution circuit needed to be optimized to get the full throughput potential from the various additional installations. The original definitive feasibility study ore characterization and subsequently the ore processing capability also needed to be substantiated. In 2012, Kansanshi took the step of requesting the University of Cape Town (UCT) Centre for Mineral Research (CMR) to assist to benchmark the entire comminution circuit. The objectives of the benchmarking study were as follows:

1. calibrate the circuit performance of the three comminution circuits at Kansanshi;
2. perform tests to develop grind curves for different volumetric fillings, which would provide information on the optimal operating strategy where high throughputs can be obtained at reasonable product size;
3. develop models for use in simulation studies aimed at evaluating various optimization routes to achieve maximum throughputs.

Two full surveys were conducted per circuit at conditions as close to steady state as possible. All key streams were sampled and corresponding operational information, such as feed rate, mill load, mill power, cyclone pressure and flow rates of water and slurry were recorded in accordance with survey methodology guidelines suggested in Napier-Munn *et al*. (1996). Models of the major equipment were then constructed in *JKSimMet* software using dimensions and process data (stream solids flow rates, percent solids and size distributions) collected from trends and samples taken during the surveys. Mass flow rate and particle size analysis data were first reconciled using the mass balance simulator in *JKSimMet* prior to model fitting. The equipment models fitted include the SAG mill and ball mill models and vibratory screen, recycle crusher and cyclone models in *JKSimMet*.

The test work was designed to explore the throughput capabilities of the then circuit configuration (Bepswa et al., 2015). In closed SAG/ball mill circuits, conditions in the SAG mill mainly determine circuit throughput, while ball mill and cyclone operations largely control product grind (Putland, 2005). The throughput performance evaluations in this study were therefore centred primarily on assessing the SAG mill response to maximum throughput conditions. The SAG model in *JKSimMet* provided a useful investigative tool for analyzing breakage rates in the SAG mill in order to understand the throughput capabilities of the three circuits.

The SAG model in *JKSimMet* is based on a plot of breakage rates fitted at five knots located at different particle sizes. This relationship is expressed as a continuous function on logarithmic coordinates using a cubic spline function at the knots positioned at the particle size values of 0.25, 4.0, 16.0, 44.8 and 128 mm. Hence, the model parameters are the loge (breakage rate) values at these five knots. The appearance function is determined for each size fraction, based on the impact breakage and abrasion parameters ($A$, $b$ and $t_a$). These parameters are obtained from drop weight test results or SMC Test® results. A simple classification function is used to model discharge from the mill.

## OUTCOME OF THE SURVEY

From a site perspective, the two most important outcomes from this survey were the ore characterization work (Table II) and operating philosophy proposed for each mill to take into consideration the differences in mill and ore characteristics (Table III).

*Table II: Impact and abrasion resistance parameter values of Kansanshi ores.*

| Ore | Impact ($A$×$b$) | | Abrasion ($t_a$) | |
|---|---|---|---|---|
| | Value | Category | Value | Category |
| Sulphide | 51.0 | medium | 0.36 | hard |
| Mixed | 47.9 | medium | 0.54 | moderately soft |
| Oxide | 64.2 | soft | 0.76 | soft |

*Table III: Performance recommendations and expected results for the Sulphide, Mixed and Oxide circuits.*

| Variable | Sulphide | Mixed | Oxide |
|---|---|---|---|
| Impact resistance ($A$×$b$) | medium hard | medium hard | soft |
| Abrasion resistance ($t_a$) | hard | soft | soft |
| Recommended SAG setting | low filling | high filling | low speed |
| Throughput response | increased | increased | unchanged |
| SAG specific energy | reduced | reduced | reduced |
| SAG product fineness | decreased | increased | increased |
| Circuit product fineness | decreased | decreased | increased |

The four-year period after the survey saw an overall throughput performance improvement of 12.5% (Figure 4). This is divided into an overall operational runtime improvement of the mills of 6% from 88.4% in 2012 to 95.5% in 2016, accounting for 7% of the increase in throughput. A significant proportion of this improvement emanated from the oxide circuit where a reduction of speed resulted in increase of liner life from 5 to 6 relines per year down to 3 relines by 2016. The other important mechanical downtime improvement resulted from lower recirculating loads resulting in lower tip speeds and longer cyclone feed pump life.

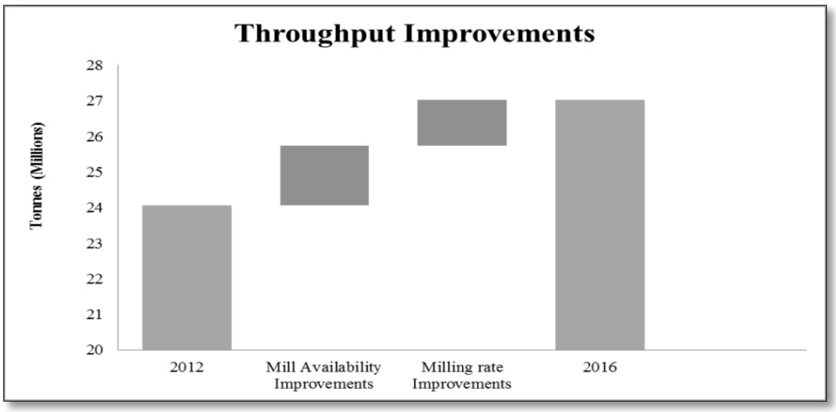



*Figure 4: Throughput performance improvement breakdown.*

Later work by the site around the ore characterization, hardness and power utilization of the milling circuit determined a huge gap between the available installed power and the actual milling rates. Despite the good achievements in throughput and availability increase in the prior years, mill power utilization, especially for the S0 and S1 circuits, remained low (Figure 5).

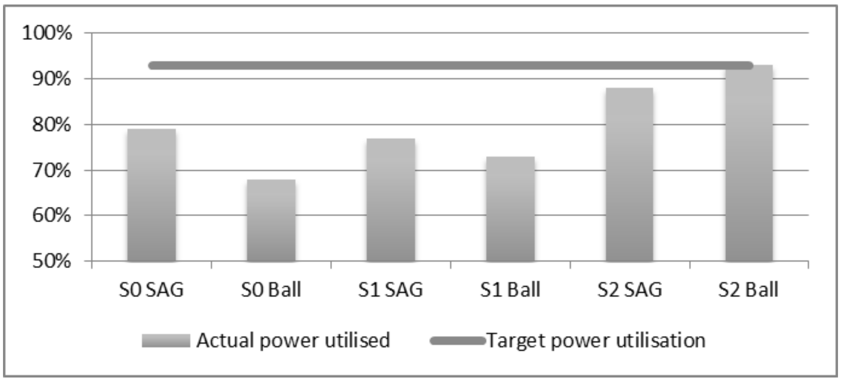



*Figure 5: Kansanshi milling circuit installed power utilisation vs. installed mill motor power 2015.*

## MILL CONFIGURATION CHANGES

Following from this poor power utilization scenario, a plan was formulated to increase available power utilization. It was expected that increased power utilization would either result in higher throughput or finer grind. A throughput improvement plan, targeting increased throughput by increasing power utilization was developed for each of the circuits. This study focuses on the work done around the Kansanshi (S1) mixed ore circuit.

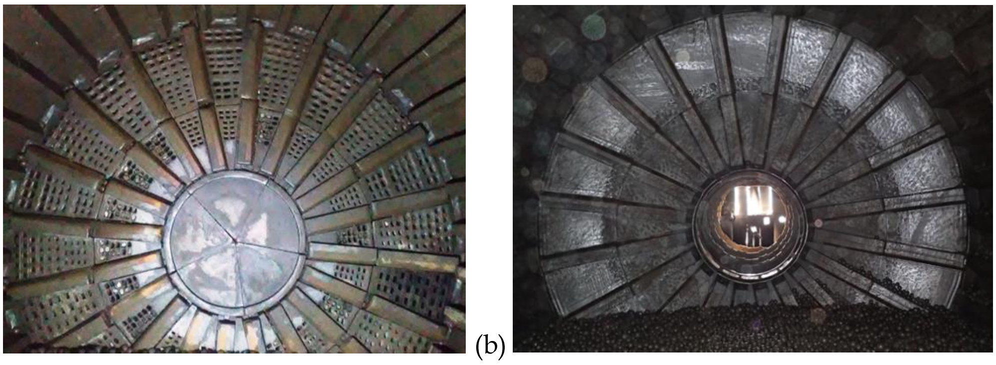
The original configuration of the S1 grinding circuit at Kansanshi, currently treating transitional ore, consisted of a SAG mill with a trommel screen, a duty and standard-by pebble crusher and a dedicated cyclone cluster. Crushed pebbles, primary cyclone underflow streams and a minority portion (~ 25%) of fresh feed provided feed to a grate discharge ball mill that was closed by a separate nest of cyclones. The mechanical and process design of the circuit included identical dimensions of both the SAG and ball mills, which are both low aspect, with added flexibility of feeding both mills simultaneously with fresh feed or feeding the ball mill exclusively depending on the quality of the fresh ore or downtime on the SAG mill. The secondary ball mill discharge was screened to remove pebbles that were combined with pebbles from the SAG mill to feed the common pebble crusher before recycling to the ball mill. Despite the benefit of high plant availability realized from this configuration, the overall circuit performance was not optimal.

In the original configuration, the majority (70%) of under flow from the primary cyclone nest was recycled back to the SAG mill; however, with the SAG discharge head being a radial design, running only pebble ports (60 mm × 100 mm), and a total open area of 8.7%, the mill was usually running in a slurry pool condition. The mill was operated at total filling of 28 to 32% and ball filling between 15 to 18%, depending on the trajectory within the shell liner life cycle.

Both the SAG and ball mills run on fixed speed drives with mill speed at 75% of critical. Low power utilization on the SAG mill identified (i) limited speed due to the fixed drive; (ii) recirculation of excessive under flow stream from the SAG mill cyclone cluster back to the SAG mill due to power constraints on the ball mill. Any extra throughput achieved on this circuit would have to be ground using the available power of the SAG mill as the ball mill is completely power constrained. The ball mill on the other hand was limited by (i) the grate discharge design that limited the ball charge to 21%; (ii) high circulating loads due to low ball charge. The low ball charge, coupled with the use of large make-up ball size of 100 mm, led to poor grind performance on the ball mill. The use of the 100 mm ball size was dictated by the design need to feed run-of-mine (ROM) material straight into this mill and the limitation of the grate discharge aperture size.

The planned circuit changes included:

- Replace the ball mill grate discharge end with its associated pulp lifters with an overflow discharge system. Figure 6 shows the conversion of the ML2502 discharge head from a grate system to an overflow set-up.
- Without the constraints posed by the grate discharge, increase the ball charge to over 25% and reduce the top size of the balls from 100 mm to 60 mm.
- Switching from use of 125 mm steel balls to 100 mm steel balls on the SAG mill and introduction of a 35 mm aperture grate
- Reduction of trommel screen panel aperture size from 22 mm to 15 mm on the SAG mill and 12 mm on the ball mill to improve cyclone performance by reducing feed top size to the cyclones.
- When operational, it was planned that the recirculating underflow from the SAG cyclone cluster would be reduced and eventually cut off completely.



(a) (b)

*Figure 6: S1 secondary mill discharge head system before and after ball mill conversion: (a) grate discharge and (b) overflow discharge head.*

## RESULTS OF THE CONVERSION

### Effect of Circuit Changes on Mill Power Utilization

The primary aim of the conversion was to utilize more of the installed mill motor power by raising the ball charge to the level at which a typical ball mill is expected to run. Before the conversion, both the SAG and ball mills could only draw about 4.4 MW on average, against an installed power of 5.8 MW. After the ball mill discharge conversion, the ball charge was progressively increased while the recirculating load back to the SAG mill was correspondingly reduced. The results were a 2.5% increase in power utilization on the SAG and more importantly, 17.8% increase power draw on the ball mill (Figure 7).

Overall, 1.14 kWh/t was observed after ball mill conversion. The increase in specific power (Figure 8) was attributed to ore competence for the period when tarnished sulphide ore was being treated, during which the milling rate also dropped.

### Effect of Ball Mill Conversion on Throughput

After the conversion of the ball mill to an overflow discharge, the mill volume increased by 3.3% while the ball charge was raised from 21% to 26%. The result of this was increased power draw on both the SAG and ball mills, with the result that more fresh feed could be introduced to the SAG mill. Immediately after the conversion, a 4.87% increase in milling rate was realized (Figure 9). However, six weeks into the conversion, the run of mine (ROM) ore changed from mixed ore to tarnished sulphide, a more competent ore, which led to a drop in milling rate by 8.49%. After two months and three weeks of treating tarnished sulphide ore, the ROM was changed back to mixed ore but with an occasional blend of tarnished sulphide ore. In a typical case, treating tarnished sulphide or sulphide through the S1 circuit results in a 13.6% drop in throughput. This still implied that there was about a 4% improvement in circuit performance while treating the more competent ore.

The reduction of the trommel screen aperture sizes on both SAG and ball mills, coupled with the fact that the ball mill power draw had increased by 17.8% (about 1 MW more), resulted in one important operational change: the SAG mill cyclone underflow did not need to be recycled back to the SAG mill with the result that fresh feed could be introduced into the SAG instead.

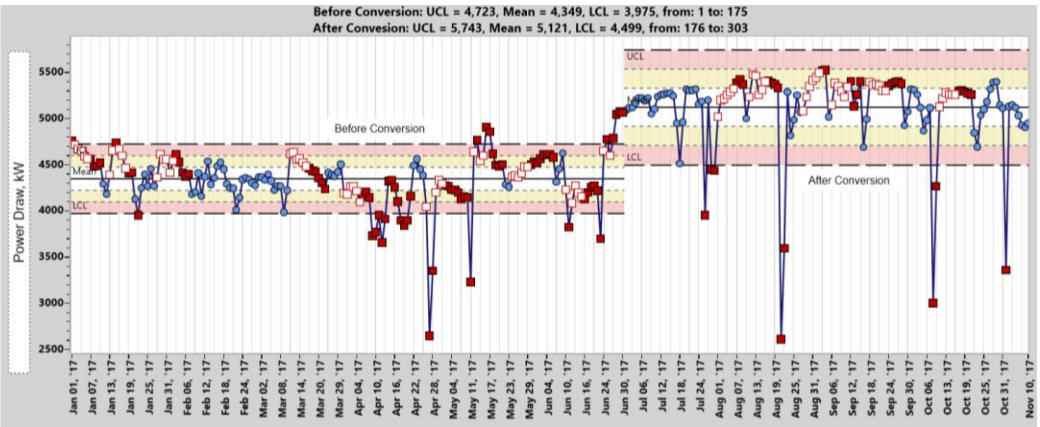



*Figure 7: Illustration of ball mill power draw before and after ball mill conversion.*

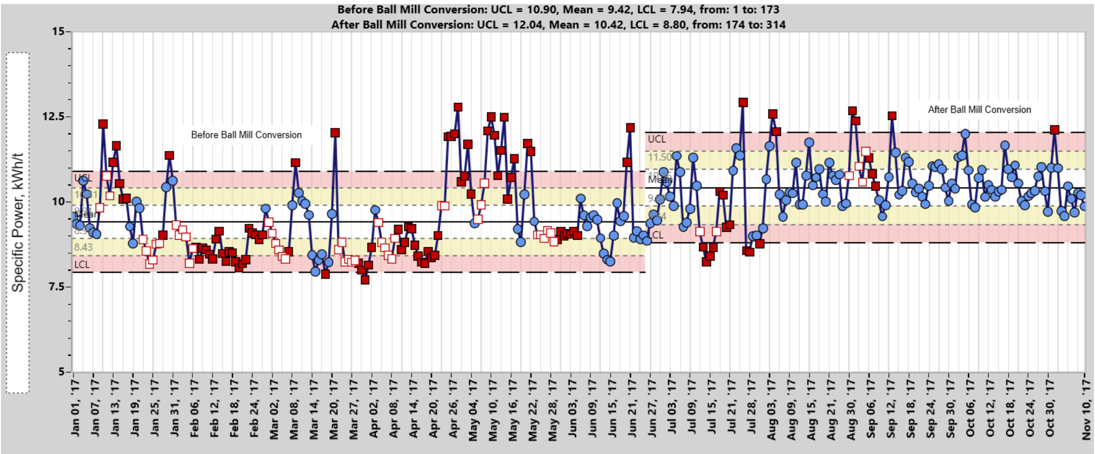



*Figure 8: Illustration of circuit specific power before and after conversion.*

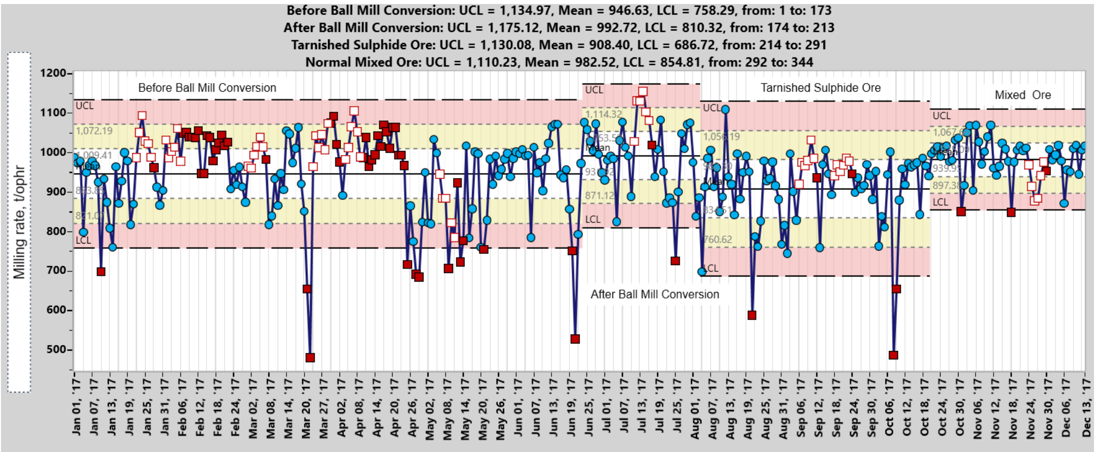



*Figure 9: Effect of ball mill discharge conversion from grate to overflow on milling rate.*

**Effect of Circuit Changes on Grind**

It was expected that an increase in power draw on the ball mill would result in either a higher throughput or finer grinding. An assessment of the grind after the conversion confirmed that both were the case. The effect of higher ball charge and fine grind media size after the conversion manifested in an increase of ball mill grind quality (measured by 80% passing 150 µm or $P_{80}$) and higher power draw. This $P_{80}$ improved from 71 to 82% after the conversion. On the SAG mill, the effect was a subsequent reduction in $P_{80}$ of 86.6% to 85.3%. Figures 10 and 11 illustrate the particle size distribution (PSD) change on grind streams before and after conversion.

Overall, although the $P_{80}$ only reduced from 86.6% to 85.3% on the SAG mill cyclone cluster product, the most significant change occurred in the sub −38 µm, where a 7.3% reduction of slimes generation was observed on the primary cluster final product after the conversion. On the ball mill cluster, the overall % passing 150 µm increased by 11%, but a reduction in the −38 µm fraction was also observed, attributed to improved grind with higher ball charge and the use of smaller steel balls, coupled with the reduction in circulating load.

With the improved grind on the ball mill, fewer cyclones were operated after the conversion. Only three cyclones were required, compared with five cyclones operated before conversion, leading to a higher cyclone feed pressure with an increase of about 5 kPa. On the SAG mill cluster, the number of cyclones operated remained same (three) but the cyclone feed flow reduced after conversion with the resultant drop in operating pressure.

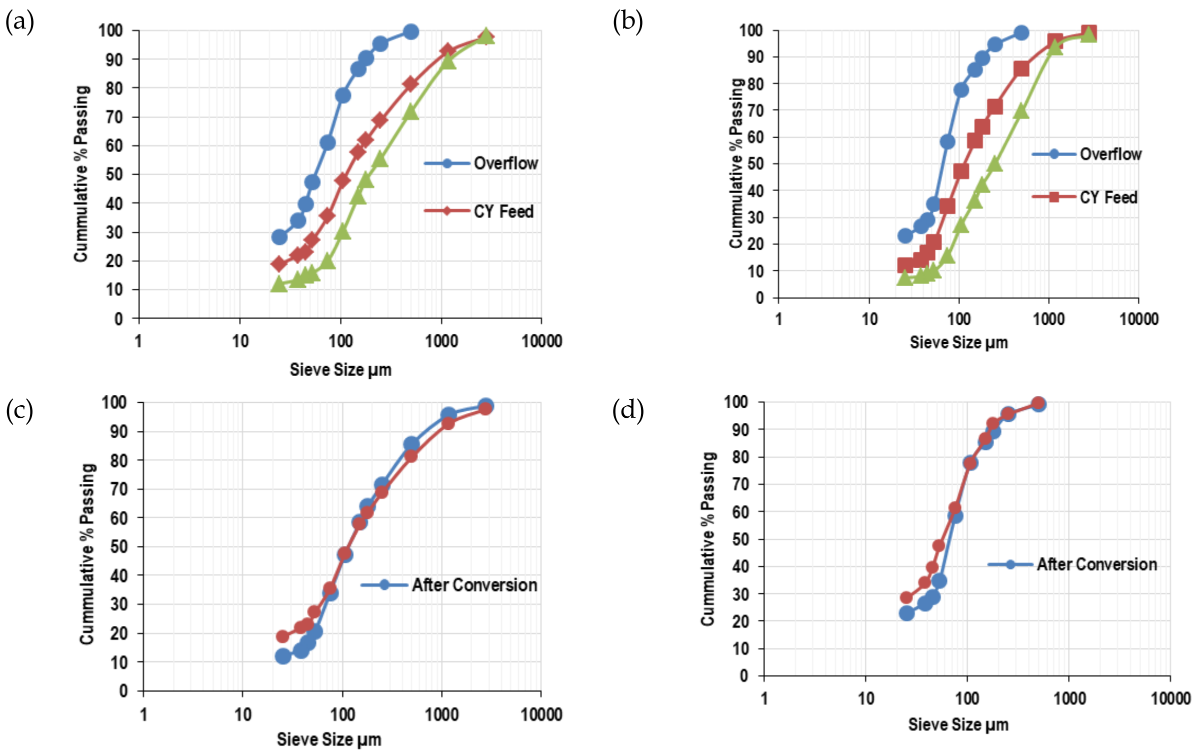



*Figure 10: Particle size distribution for S1 circuit SAG mill. Primary cyclones PSD (a) before and (b) after ball conversion. Comparison of cyclone PSD of (c) cyclone feed and (d) cyclone overflow streams.*

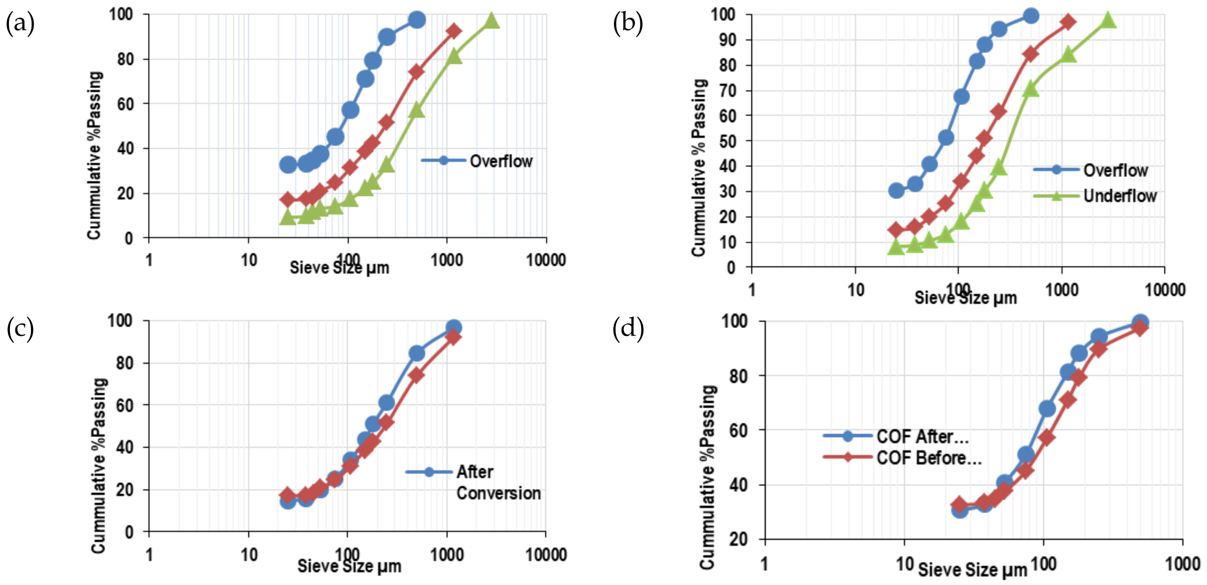



*Figure 11: Particle size distribution for S1 circuit ball mill. Ball mill cyclone PSD (a) before and (b) after ball conversion. Comparison of PSD of cyclone (c) cyclone feed and (d) cyclone overflow streams.*

**Effect of Ball Mill Conversion on Downstream Processes**

After the conversion, an increase in flotation recoveries of about 6% (from 68% to 74%) for typical mixed ore and 5% with inclusion of the tarnished sulphide period was observed after the conversion (Figures 12 and 13**).** Other factors may have contributed to the recovery after the conversion but the main driver of this improvement could be attributed to better grind quality, with more material reporting to the floatable fraction than before the conversion. The particle size distribution (PSD) results (Figure 14) on float feed, final concentrate and final tails from onsite mineralogy program showed a decrease in –38 µm and +150 µm size fractions and an increase in the 38–150 µm size fraction (the optimal floatable range), explaining the increase in float recovery. The mineralogy analysis was done over the six weeks before and after the conversion. Using site mineralogy, it has been proved that the main source of losses of copper from the mixed circuit was attributable to recovery losses in the −38 µm (slimes) and +150 µm size fraction (due to slimes flotation difficulties and mineral liberation issues respectively).

It was also observed that, before the ball mill conversion, the average actual float recovery was 1.6% below predicted (modeled recovery based on at least four years of actual plant data correlated with the acid soluble/acid insoluble ratio in feed). After the conversion, the average actual recovery was above the expected predicted grade by an average of 4.6%.

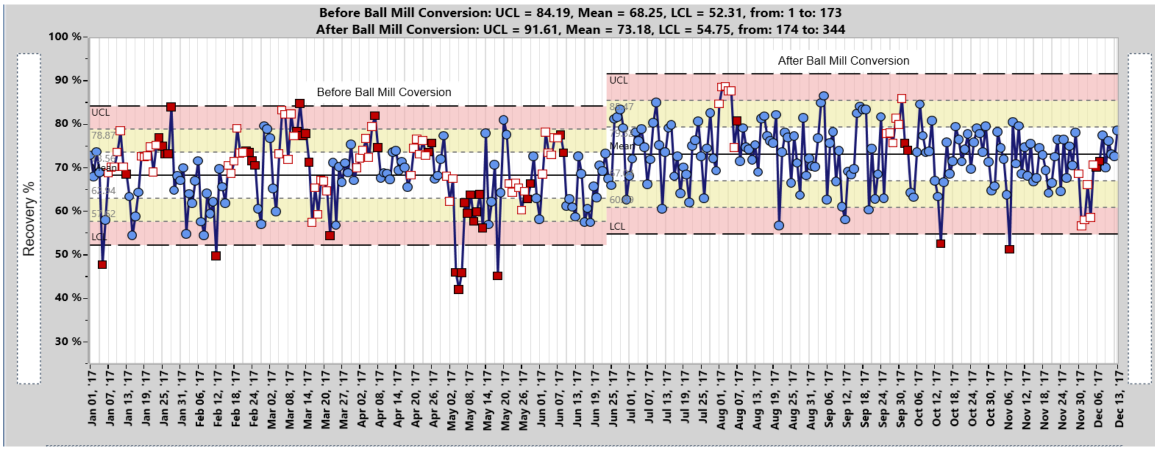



*Figure 12: Effect of grind change with ball mill conversion on float recovery.*

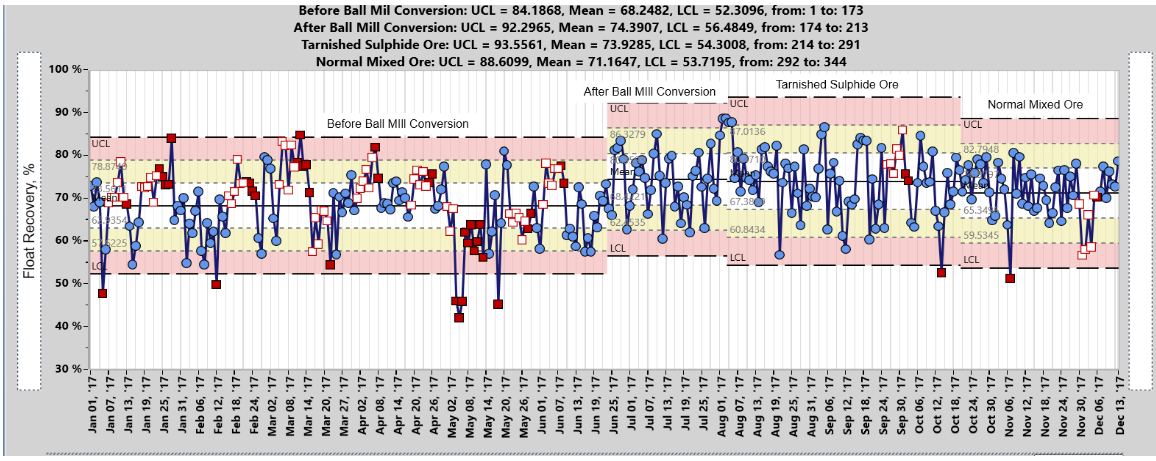



*Figure 13: Effect of grind change with ball mill conversion on float recovery with tarnished sulphide ore isolated.*

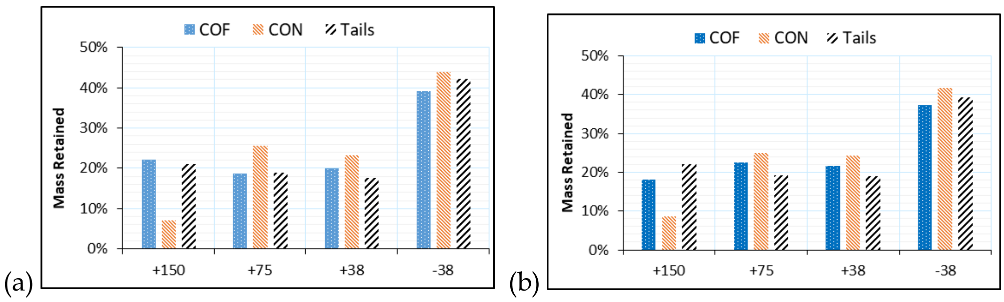



*Figure 14: PSD of S1 overall cyclone overflow, concentrate and final tails (a) before and (b) after conversion.*

**Effect of Circuit Change on Maintenance**

A 4.1% reduction in cyclone feed flow was observed on the SAG mill from 1840 to 1764 $m^3/h$. A 16.8% reduction was observed on the ball mill down from 2439 to 2030 $m^3/h$. The reduction in top-size particles and flow of cyclone feed streams on both SAG and ball mills resulted in reduced wear on cyclone feed pumps, extending their life and availability (Figure 15).

A13.3% increase in cyclone feed pump running hours between change-outs was observed on the SAG mill, from 1500 to 1700 h. On the ball mill cyclone feed pump, a significant 85.7% increase in cyclone feed pump life was observed, with running hours increasing from 1400 to 2600 h. The higher life extension on the secondary cyclone feed pump is attributed to the finer material and smaller top-size particles on the 12 mm ball mill compared with 15 mm on the SAG mill. The extended life on the pumps translates into fewer change-outs, moving from six change-outs per year on both SAG and ball mill to five and four change-outs on SAG and ball mill, respectively. The potential annual saving for pump life increases corresponds to $218,049 (Table IV).

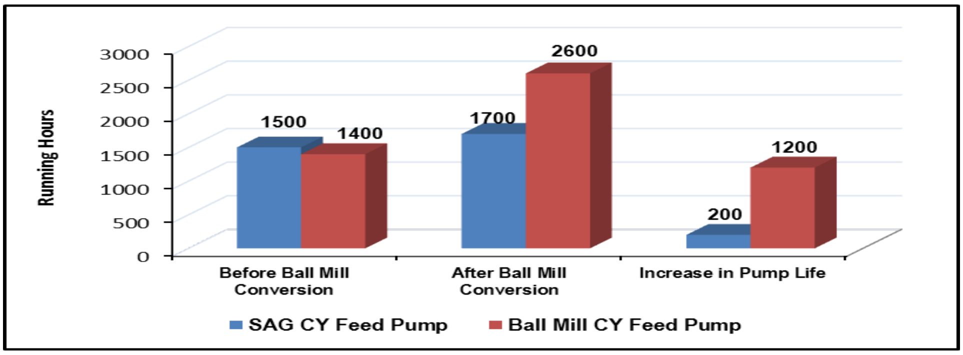



*Figure 15: Illustration of cyclone feed pump life before and after ball conversion.*

*Table IV: Summary of cyclone feed pumps before and after ball mill conversion.*

| Period | Before conversion | | After conversion | |
|---|---|---|---|---|
| | SAG | Ball | SAG | Ball |
| Pump running hours. | 1500 | 1400 | 1700 | 2600 |
| Plant availability (h/year) | 8497 | 8497 | 8497 | 8497 |
| Annual change-outs | 6 | 6 | 5 | 4 |
| Pump change-out cost (USD/unit) | 66,934 | 75,558 | 66,934 | 75,558 |
| Cost (USD/year) | 401,605 | 453,345 | 334,671 | 302,230 |
| Potential annual cost saving ( USD) | – | – | 66,934 | 151,115 |

**CONCLUSION**

The value of systematic research, use of modelling tools and practical surveys to substantiate and calibrate plant practice is shown. The successful conversion of S1 circuit ball mill discharge head from a grate to an overflow discharge is the end product of practical systematic research resulting in 2.5 and 17% increases in power utilization realized on SAG and ball mill, respectively. This has translated into finer grinding and reduced recirculation load, and consequently increased capacity of the SAG mill, resulting in a 4.8% increase in milling throughput realized on typical mixed ore.

Actual recovery was up 6.6%, taking into consideration changes in feed quality but using the predicted modelled recovery as reference. Six months prior to the conversion, actual float recovery averaged 1.6% below predicted; after conversion, the actual recovery was 4% above predicted. Other factors may have also contributed to the recovery after the conversion but the main driver of this improvement is the grind quality improvement from the conversion (i.e., less slimes generation due to reduced circulating load and less coarse particles due to use of smaller balls and higher ball charge (11% improvement in grind quality ($P_{80}$) was realized).

The grind quality improvement and reduced circulating load have increased the life of cyclone feed pumps on both SAG and ball mills – a benefit to the maintenance team, with about 13.3 and 85.7% increases in pump life realized on the SAG and ball mill, respectively.

Further throughput increase opportunities on this circuit will be realized by converting the SAG drive from fixed to variable speed drive and converting the discharge head from radial design to a vortex design for higher discharge efficiency of both slurry and pebbles.


## ACKNOWLEDGEMENTS

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