CONTINUOUS IMPROVEMENT AT SENTINEL (WITH REMOTE GRINDING SUPPORT)

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Abstract

Continuous improvement is a major key performance indicator (KPI) for many metallurgical operations. Improvement never happens by itself and is rarely attributed to a single party or person, but is rather the culmination of different factors, ideas, and efforts towards the overall improvement of a system, which is ultimately driven by culture. Nameplate capacity of 55 million tonnes per annum (Mt/a) has been achieved at the Sentinel Copper Project (First Quantum Minerals Limited) through the continual efforts of the team, steadily improving throughput and tightened operational control of the process. This paper provides some background on the project, challenges faced, and explores the observations, recommendations, and changes made at Sentinel involving site personnel, vendors, and external experts. Specific focus is given to the continuous comminution circuit operating data analysis, evaluation, and feedback reporting processes utilized and the positive improvements resulting from the ongoing relationship.

Keywords

Grinding Support, RGS, Sentinel, Optimization, Continual Improvement

Introduction

The Sentinel Copper Project (Sentinel) operation is 100% owned by Kalumbila Minerals Limited (KML), a First Quantum Minerals Ltd. (FQML) subsidiary. Sentinel is located approximately 150 kilometres (km) west of the town of Solwezi in North Western Province of Zambia. In January 2010, FQML acquired the Kalumbila project copper deposit, which included the Sentinel Copper Project. In May 2012, the Company's Board approved construction of Sentinel with development and construction commencing in the second half of 2012. Fluor Australia designed the crushing circuit, concentrate thickening, filtration, and tailings pumping; Lycopodium Minerals designed the grinding and flotation sections. KML and FQML self-performed the construction. Staged commissioning started in October 2014 and Sentinel was declared in commercial production on November 1, 2016. The yearly production target was set at a 55 million tonnes per annum (Mt/a) to produce approximately 230,000 tonnes per annum (t/a) of copper.

Orway Mineral Consultants (OMC) provided remote grinding support (RGS) for Sentinel from May 2017 with weekly evaluations to assist site with feedback on the comminution performance, circuit stability, bottlenecks, and potential circuit improvement strategies. Once initial improvements were made, the evaluations changed to a monthly format with focus on optimizing controllable variables to balance the milling circuit power split thus maximizing throughput at the target grind size. The RGS analysis included comparison to theoretical models to provide feedback on the comminution mass balance, ball charge, mill superficial velocities, cyclone operation, etc.

By improving the circuit stability, the circuit is primed to react to implemented changes, which can be correlated to actual performance increases. From a statistical perspective, having more data is useful in improving the long-term analysis and corroborating correlations.

The advantage of continuous involvement and expansive data collection is discussed in this overview. This paper covers the evaluation of the implemented circuit changes and the effect they had on the overall circuit performance.

Circuit Design

The comminution circuit at Sentinel consists of a partial secondary crushing circuit feeding two semi-autogenous ball mill crushing (SABC) grinding trains (T1 and T2) as shown in Figure 1. The secondary crushers are operated in open circuit without any pre-screening. The primary crushed and secondary crushed ore is stacked onto a common stockpile.

Each grinding train consists of a semi-autogenous grinding (SAG) mill and ball mill with associated cyclones, pumps, and flash flotation cells. New feed from the reclaim system is conveyed to the SAG mill feed chute. The SAG mill discharges via a trommel and vibrating discharge screen into a dedicated SAG discharge hopper. The SAG mill operates in partial closed circuit with classifying cyclones. The SAG mill cyclone cluster underflow (U/F) feeds the ball mill directly with provision to return part or all the underflow to the SAG mill feed box. SAG cyclone overflow (O/F) reports to the flotation surge tank.

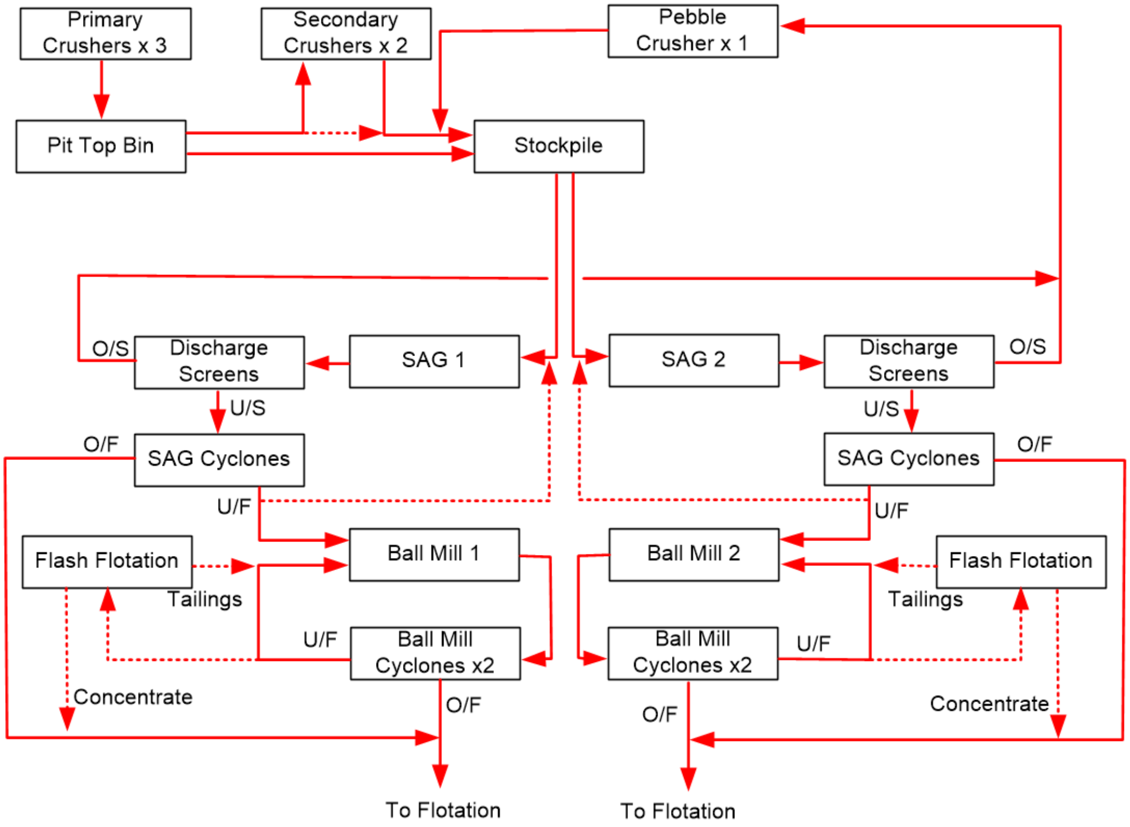

Figure 1 – Comminution Circuit Block Flowsheet

Figure 2 – The Mills at Sentinel

Pebbles from the SAG mills are crushed and returned to the crushed ore stockpile. The ball mills operate in closed circuit with two clusters of classifying cyclones each. Two ball mill discharge pumps each feed a dedicated cyclone cluster. The cyclone underflow returns to the ball mill feed box while overflow gravitates to the flotation surge tank. A portion of each ball mill cyclone cluster underflow is fed to a flash flotation cell with flash flotation concentrate reporting to the cyclone O/F (and therefore the rougher feed) and tailings returning to the ball mill feed box.

The basic design parameters and major equipment sizes are summarized in Table 1 to Table 3.

Table 1 – Design Criteria

Parameter	**Unit**	**Design**
Plant throughput	Mt/a	55.0
Head grade	% Cu	0.5
Recovery	%	90
Crushing		
Operating time	%	57
Throughput	t/h	12,000
Secondary crushing	% of new feed	50
Milling		
Operating time	%	91.3
Throughput	t/h	6,876 (3,438 / train)
Grind size P_{80}	µm	212
Ore Characteristics		
UCS	MPa	18 - 160
Abrasion index	g	0.06 – 0.165
Bond rod work index	kWh/t	6.2 – 20.6
Bond ball work index	kWh/t	9.9 – 19.3
JK Drop Weight Parameters (Axb)		34 (20.0 – 118)

Table 2 – Major Comminution Equipment – Crushing

Parameter	Unit	Value
Primary Crusher		
Make		ThyssenKrupp
Model		KB 63 – 89
Number installed		Three
Installed power	kW	1,000 (each)
Secondary Crusher		
Make		Metso
Model		MP2500
Number installed		Two
Installed power	kW	2,200 (each)
Pebble Crusher		
Make		Metso
Model		MP1250
Number installed		One
Installed power	kW	935

Table 3 – Major Comminution Equipment – Milling

Parameter	Unit	Value
SAG Mill x 2		
Make		FLS Minerals
Inside shell diameter	m	12.19
Effective grinding length	m	7.151
Imperial measurements	ft x ft	40 x 23.5
Installed power	MW	28
Ball Mill x 2		
Make		FLS Minerals
Inside shell diameter	m	8.53
Effective grinding length	m	13.36
Imperial measurements	ft x ft	28 x 43.8
Installed power	MW	22

There were a number of differences between the SAG mills that are worth noting, namely shell liner design (higher lifters in T2, in Hi-Lo configuration compared to lower lifter height in T1 in Hi-Hi configuration), and discharge grate design (T1 had radial pulp lifters while T2 had Vortex head pulp lifters). As a footnote, unfortunately, with the available data, no conclusive decision can be made as to which discharge configuration is best despite having a high level of instrumentation, process automation, and data logging.

Operational Data

Operational data preceding any evaluation or circuit change is extremely important, as external factors may already have introduced circuit changes outside of the controlled variables. From this perspective, it is important to include feedback from operating personnel, who will have a firsthand account of controlled and uncontrolled variables influencing the recorded circuit throughput.

This evaluation focuses on data collected from January 2017 up to March 2019. During this period, as seen in the operating work index, there has been significant ore hardness variability and an overall steady increase in ore competency as the mine has increased in depth.

OPERATING WORK INDEX

To assist in standardising the evaluation basis, the operating work index (W_{io}) was calculated as shown by Equation 1 [Eq. 1]. The feed size (F_{80}) is based on the most recent measured mill feed particle size distribution (PSD) and the product size (P_{80}) based on the daily average generated from hourly operator measurements. Similarly, the drive train efficiency ($Eff_{DriveTrain}$) is assumed constant over the evaluation period and relates to the electrical losses for transmission method.

Figure 3 depicts the normalized (calculated) operating work index over time along with the percentage of the ore that was subjected to secondary crushing, and also the mill power utilization (as a percentage of installed power). It is evident that a fair amount of ore variability and possibly inefficiency occurred, with a distinct increase in ore hardness since mid-2018. Note the periods of the RGS reports shown for reference.

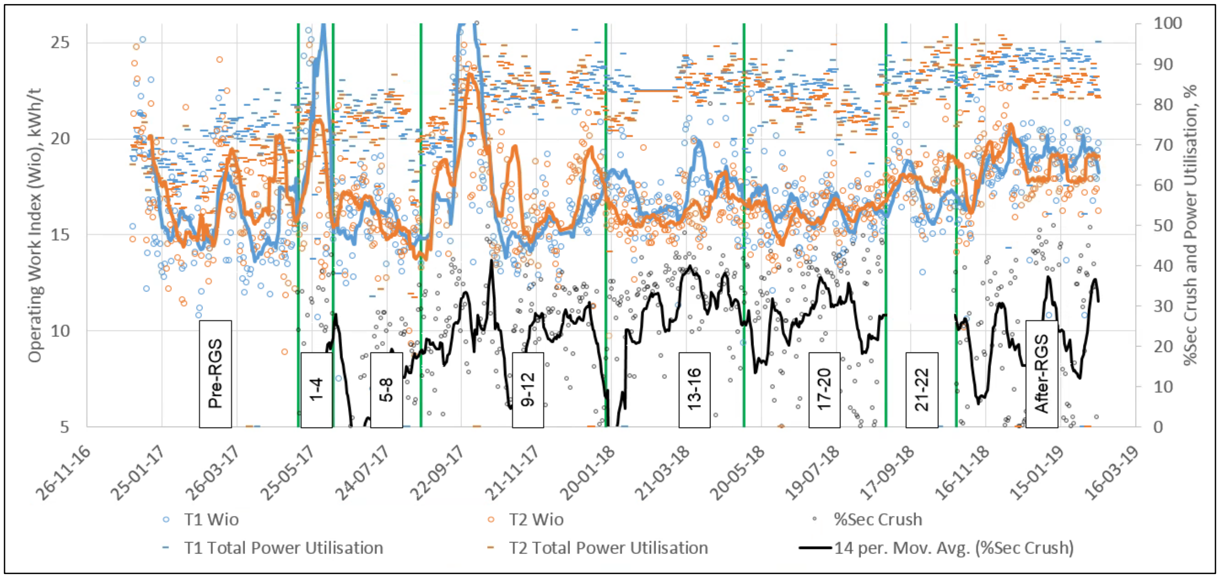

Figure 3 – W_{io} vs. Time Relationship

Operating Work Index, kWh/t:

$$W_{io} = \frac{Specific\ Energy}{10\left(\frac{1}{\sqrt{P_{80}}}-\frac{1}{\sqrt{F_{80}}}\right)} \qquad \text{(Eq. 1)}$$

Where, Specific Energy, kWh/t:

$$SE = \frac{(SAG\ Power + BM\ Power) * Eff_{DriveTrain}}{Throughput} \qquad \text{(Eq. 2)}$$

Figure 4 and Figure 5 show the daily average SAG and ball mill specific grinding energy (SGE) for Train 1 and Train 2, respectively. It is interesting to note that the SGE in the SAG mill is reasonably stable even though the ore hardness increased somewhat over time. Varying the portion of secondary crushing along with fine blasting, assists greatly with keeping the SAG mill stable.

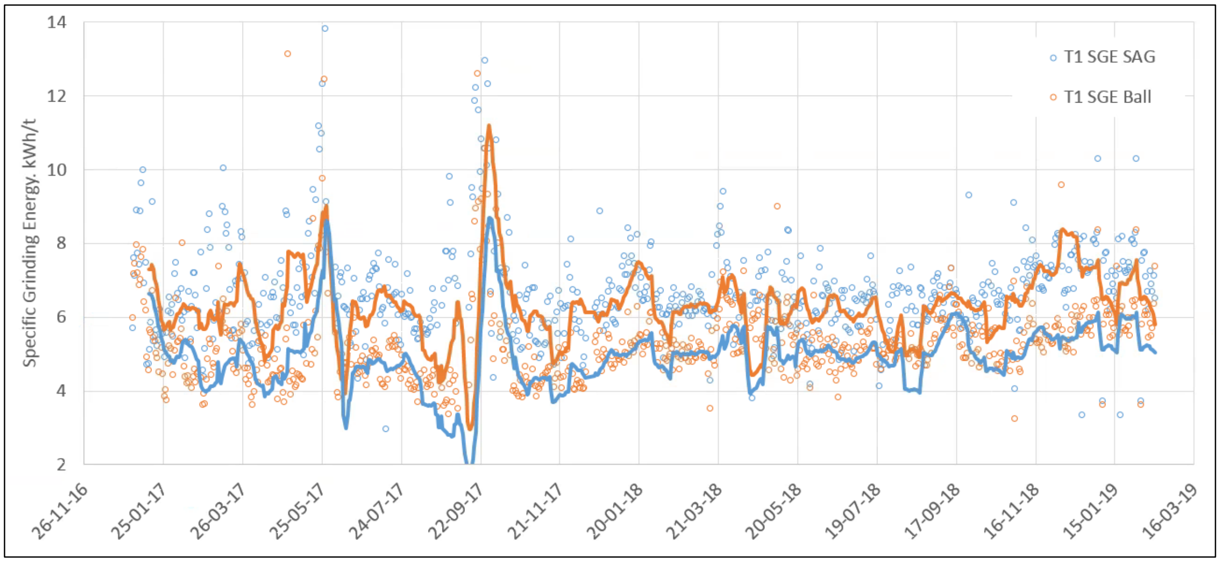

Figure 4 – Train 1 SAG and Ball Mill Specific Energy

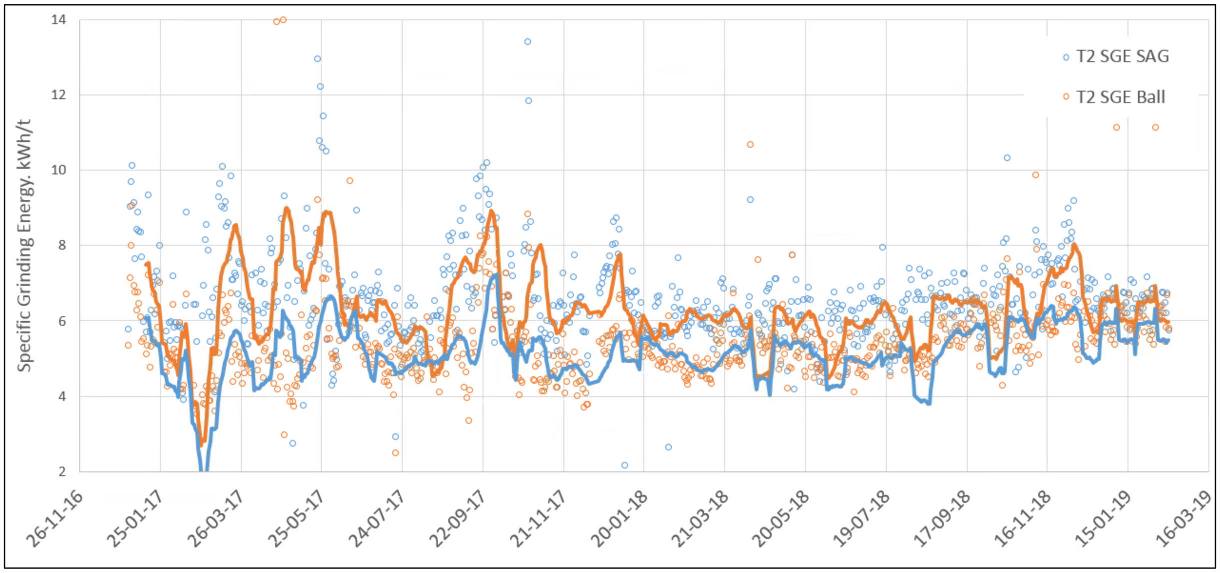

Figure 5 – Train 2 SAG and Ball Mill Specific Energy

OMC assesses the relationship between throughput and W_{io} to compare the grinding trains as shown in Figure 6 and Figure 7. It is interesting to note that there was a distinct difference in the average performance between the two grinding trains (amount of scatter in the data) prior to the optimization, but that the two circuits are more in line on average afterwards.

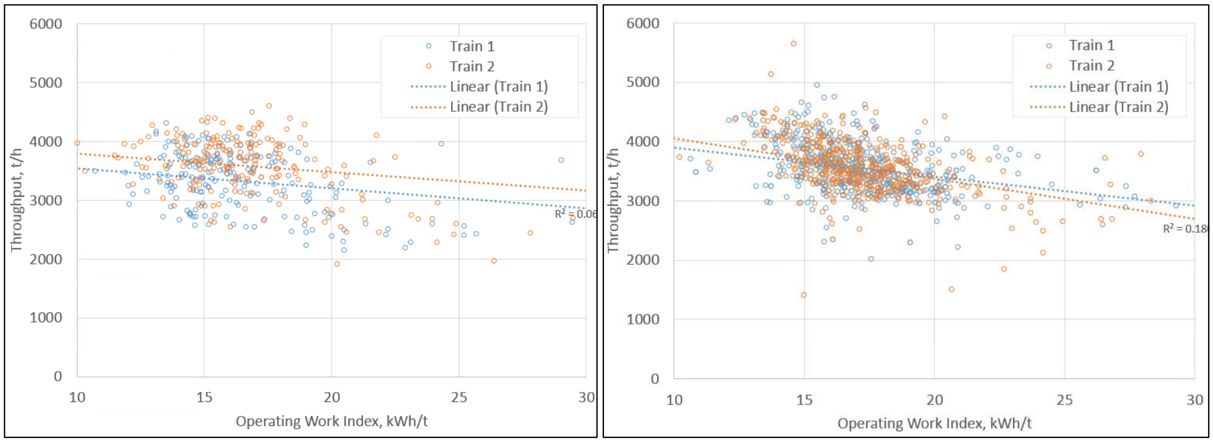

Figure 6 – Wio vs. Throughput (Pre-RGS)

Figure 7 – Wio vs. Throughput (RGS)

By normalizing for utilization of power (i.e., dividing the throughput by the ratio of utilized to installed power), a very tight correlation is evident (Figure 8). This tight correlation shows that the circuit is limited by the grind size selected and is not SAG mill limited when aided by secondary crushing. The available power is well utilised and balanced with the amount being secondary crushed. If the circuit was SAG mill limited, less power would have been required in the ball mill (i.e., the power utilisation ratio would be smaller), or the grind would be finer (i.e., the Wio would be lower). This would introduce more scatter in the data.

The scatter data points reflect grind excursions.

Figure 8 – W_{io} vs. Throughput / % Utilized Power

Despite inherent circuit differences such as potential feed segregation, different liner profiles, different pulp lifter designs and equipment wear, a fair correlation is shown between both milling circuits in terms of operating work indices.

The correlations indicate that changes in the ore characteristics have a noticeable effect on both milling trains (as expected) and further gives confidence in the ability to discern the effect that circuit changes would have on throughput and grind.

CIRCUIT CHANGES AND TRIALS

Table 4 references the notable circuit changes implemented and trialled during the RGS evaluations.

Table 4 – Major Circuit Changes

Mill Train	Trial Description	Start Date	End Date
Train 1 and 2	Cyclone pressure control	May-17	Current
Train 1	T1 SAG(radial) grate slots change from 60 mm to combination of 50 mm and 60 mm	Jun-17	N/A
Train 2	BM retaining ring installed	Jun-17	Current
Train 1	Limit SAG CUF bleed back	Jul-17	Current
Train 1 and 2	Increased BM ball charge	Jul-17	Current
Train 1 and 2	Improved gyratory crusher CSS management	Oct-17	Current
Train 1 and 2	High intensity blasting and blasting pattern	Nov-17	Current
Train 1 and 2	Optimized mill and cyclone inspection schedule	Dec-17	Current
Train 2	Limit SAG CUF bleed back	Feb-18	Current
Train 2	140 mm SAG mill balls	Apr-18	Aug-18
Train 2	SAG Reline and Vortex grates	Apr-18	N/A
Train 1 and 2	Cyclone 350 mm Vortex finder	Apr-18	Current
Train 1 and 2	Improved secondary crushing utilization	Jun-18	Current
Train 1	140 mm SAG mill balls	Jul-18	Current
Train 2	T2 SAG grate (Vortex) slots change from 60 mm to combination of 50/55 mm and 60 mm	Jun-17	N/A
Train 2	125 mm SAG mill balls	Aug-18	Sep-18

Figure 9 and Figure 10 depict how the Sentinel circuit throughput and cyclone overflow grind have changed (over time as manually measured by operators and checked against online PSD instrumentation) for Train 1 and Train 2. The throughput stabilized towards the end of the analysis period, but was slightly below design. The grind has stabilized significantly after the control philosophy (discussed later in the paper) was changed, but is still slightly finer than the target. Throughput vs. grind evaluations did not find suitable recovery benefits at finer grinds to offset the financial benefit of increased throughputs at the coarser grind target.

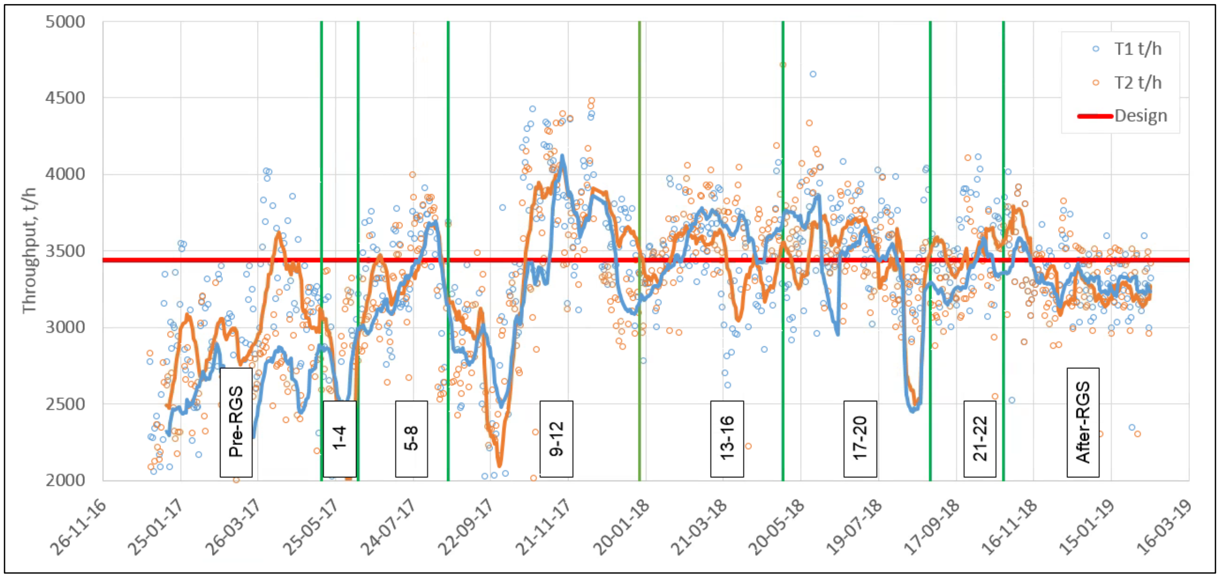

Figure 9 – Mill Throughput

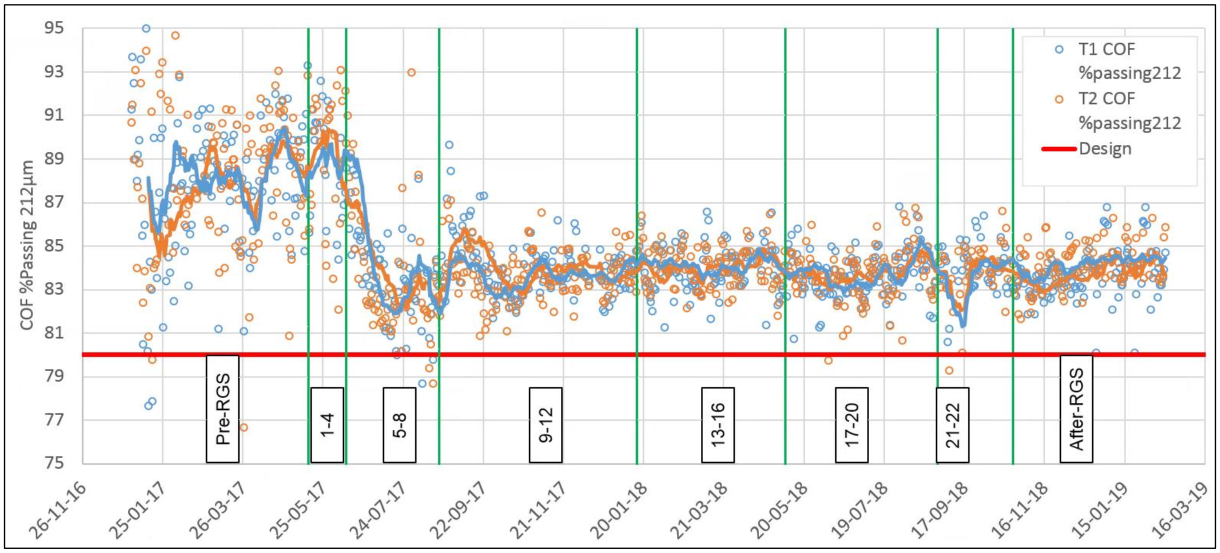

Figure 10 – Grinding Circuit Product Size (% passing 212 µm)

The grind is finer than design, which presents the opportunity to increase throughput. The power utilization of the milling circuit has increased from 60% to 70% of installed power to around 83% to 84% for T1 and T2, respectively over the period analyzed. The SAG mills are now operating with ball charges around 17% to 20% by volume and an average speed of 65% to 70% of critical speed. The ball mills are operating with ball charges around 28% to 31% by volume and an average speed of 77% to 79% of critical speed.

It was identified during design that the mills will not be able to fully utilize the installed power consistently, i.e., the SAG mill can only draw 26 MW of the available 28 MW consistently due to volumetric constraints. That means 7% of the SAG mill power cannot be drawn. That said, investigations to increase power draw should continue since the throughput is restricted by total circuit power draw at the current grind size.

Table 5 gives a statistical extract of the feed rate, cyclone overflow percent passing 212 µm and power utilization (as a percent of installed power) data over the periods of analysis.

Table 5 – Statistical Extract of Cyclone Overflow and Mill Feed Rate Data

Parameter Date	**Pre RGS**	**RGS 1-8**	**RGS 9-16**	**RGS 17-20**	**RGS 21-22**	**Post RGS**
From	**01/01/17**	**14/05/17**	**21/08/17**	**07/05/18**	**27/08/18**	**22/10/18**
To	**13/05/17**	**20/08/17**	**06/05/18**	**26/08/18**	**21/10/18**	**14/02/19**
T1 Feed Rate, t/h						
Average	2,992	3,144	3,429	3,412	3,484	3,315
Std. Dev.	469	561	522	729	395	414
Std. Dev. (%)	15.7	17.8	15.2	21.4	11.3	12.5
T2 Feed Rate, t/h						
Average	2,582	3,121	3,403	3,368	3,316	3,323
Std. Dev.	379	469	481	790	268	261
Std. Dev. (%)	14.7	15.0	14.1	23.5	8.1	7.9
T1 COF % passing 212 µm						
Average	87.9	84.9	84.0	83.7	83.7	83.7
Std. Dev.	3.2	3.2	1.2	1.1	1.9	1.1
Std. Dev. (%)	3.9	3.7	1.4	1.3	2.2	1.3
T2 COF % pass						
Average	88.2	85.1	83.9	83.7	83.6	84.1
Std. Dev.	3.3	3.7	1.1	1.2	2.0	0.9
Std. Dev. (%)	3.9	4.4	1.3	1.4	2.4	1.1
T1 Power Utilization (% of Installed Power)						
Average	0.70	0.72	0.80	0.82	0.82	0.84
Std. Dev.	0.11	0.14	0.14	0.06	0.18	0.18
Std. Dev. (%)	15.65	20.06	17.82	6.98	22.34	21.37
T2 Power Utilization (% of Installed Power)						
Average	0.63	0.73	0.80	0.79	0.82	0.83
Std. Dev.	0.11	0.10	0.13	0.12	0.17	0.21
Std. Dev. (%)	17.96	14.30	16.43	15.57	20.76	25.11

An extensive evaluation of operating data (and associated variables), shows that “change takes time.” This relates to time to implement, time to troubleshoot, and time to optimize. Similarly, maintaining the benefits realized from the change takes an equal amount of effort.

The difficulty in quantifying these changes is to account for uncontrolled circuit changes, such as mine blast fragmentation, changes in feed blend and ore characteristics, all the way to engineering related stoppages. With enough data, the prediction models can be further refined and thereby increase the prediction confidence.

CYCLONE CONTROL PHILOSOPHY CHANGES

Overall, changing the cyclone control philosophy to constant pressure resulted in the most notable improvement to circuit stability and inherent efficiency, as shown in Figure 10. There are two primary control schemes for operating closed grinding circuits based around the characteristics of hydrocyclones. The cut-point of a cyclone is influenced by both, the flow (pressure-effect) and the slurry density (hindered settling-effect). This gives rise to operation using one of the two philosophies, constant flow and variable feed density, or constant feed density and variable flow. In each case, the aim is to stabilize both variables, one with water, the other circuit control (capacity, feed rate, etc.). The reaction of the circuit to change in each of the two systems is very different.

By adopting a pressure-controlled cyclone operating philosophy, a drastic improvement in the consistency of the grinding circuit performance was achieved. This is significant to the overall operation of the comminution circuit, as the cyclone operation is only responsible in achieving an efficient cut of the grind that the comminution circuit produces. This in turn allows for maximum utilization of the available circuit power, by linking the throughput to the circuit grind automatically.

It is important to note that this evaluation does not take into account intangible benefits associated with improved circuit stability, such as reduced equipment downtime due to blockages or improved metallurgical performance due to stable operating conditions (particularly important for flotation operations).

RECIRCULATING LOAD

As a by-product of achieving stable control of the cyclone cluster, the recirculating load of the circuit was brought back in line with target design figures. A common practice in daily operation was to vary the amount of cyclones online to address short-term operating instability, particularly relating to the cyclone feed density or pressure. This artificially increases the recirculating load due to reduced separation efficiency, which in turn results in near grind size material returning to the mill and being ultimately, over-ground.

By operating the cyclone cluster efficiently, the recirculating load may be maintained by matching the circuit feed rate to the target number of online cyclones. A reduced recirculating load has other benefits less often focused on, such as reduced discharge pump power draw, reduced wear on the pumps, pipeline, and cyclone wear components, as well as reduced superficial velocity through the ball mill. High superficial velocities caused by high circulating loads impact on power draw and ball retention in the mill and, therefore, grinding efficiency and throughput.

Recirculating loads have decreased from around 380% and 550%, respectively for the Train 1 and Train 2 ball mills (Pre-RGS) to an average recirculating load of 202% to 243% (RGS 22). This effectively decreased the average superficial velocity in the ball mills from ≈0.4 m/s to ≈0.2 m/s (ideally less than 0.24 m/s) (Morrell, SAG 2001), which greatly improved the overall circuit performance as it allowed higher power draw on the ball mill.

Figure 11 illustrates how the recirculating load variability changed over time, as the recirculating load was progressively shed, and how the number of online cyclones were systematically reduced (Figure 12) to adapt the throughput set point.

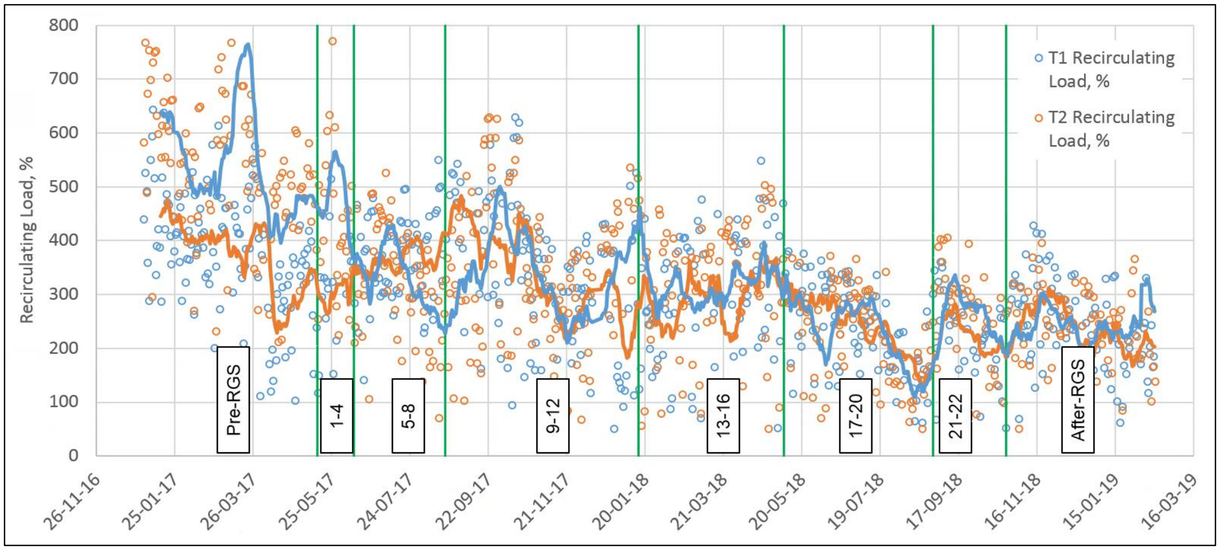

Figure 11 – Train 1 and 2 Ball Mill Recirculating Load Changes

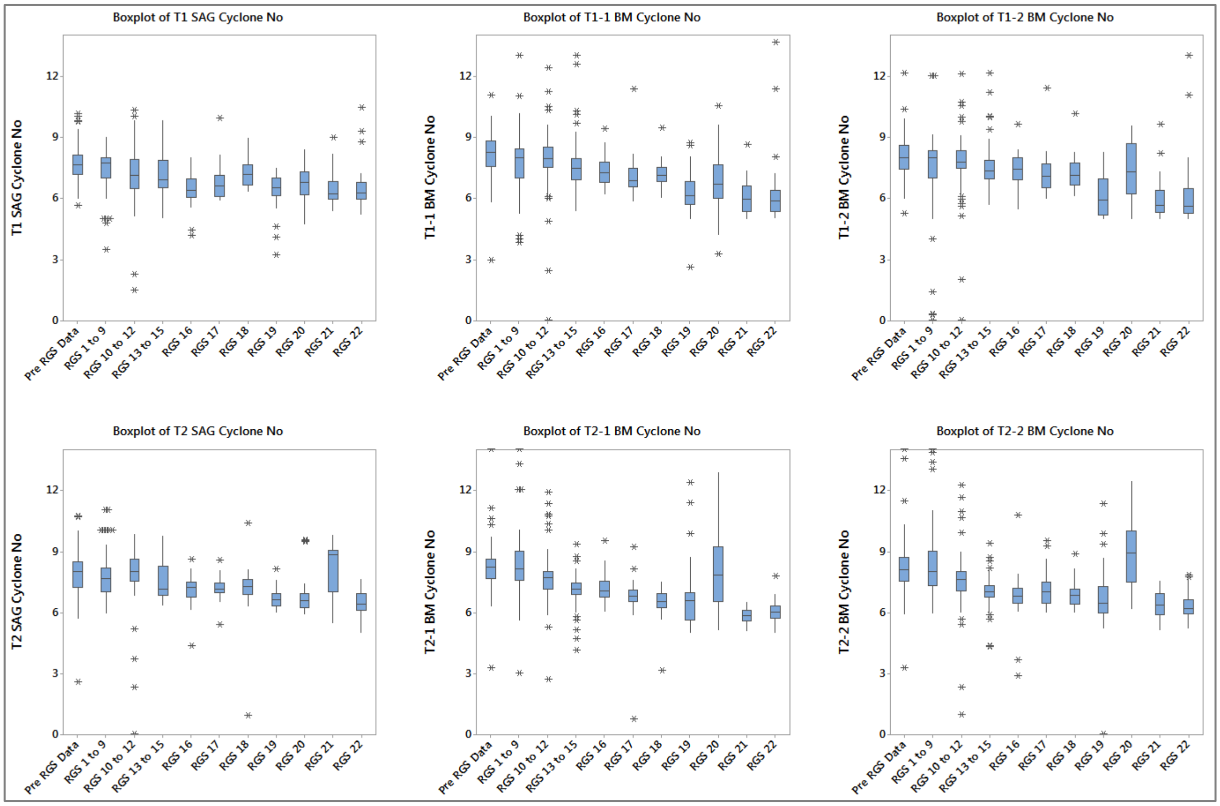

Figure 12 – Box Plot of Online Cyclones

MILL GRINDING MEDIA CHANGES

An increase in grinding media size was also implemented with minimal improvement observed through the analysis of the data. It is, however, difficult to quantify the effect of the media size change due to the improved circuit throughput observed for the period preceding the increased ball size addition. Furthermore, as shown in Figure 8, the circuit is not SAG mill limited with the inclusion of secondary crushing and is in fact limited by the utilized power. However, the use of the larger ball size did not have a negative impact and could be beneficial if the circuit becomes SAG mill limited.

Figure 13 depicts the effective change in throughput and pebble generation brought about by a change in media top size. The figures on the left summarize performance data for the period of 3 June 2018 to 30 June 2018, during which period Train 1 was charged daily with 125 mm top size ball and Train 2 was charged daily with 140 mm top size balls. The figures on the right summarize performance data for the period of 1 July 2018 to 19 August 2018 (directly following the previous period) with both Train 1 and Train 2 being charged daily with 140 mm balls.

As shown by the operating work index benchmark, the input variables did not stay consistent during the evaluation period, although both Train 1 and Train 2 responded in a similar manner. From a relative perspective, it appears that increasing to the 140 mm ball for the Train 1 SAG mill translated into a slight throughput benefit (+1.7%).

Similarly, although the Train 2 pebble generation decreased (no change in ball size during the analysis period for this mill), the Train 1 pebble generation remained fairly constant, which indicates that on a relative basis, the increased ball diameters did translate into a very small change in pebble generation rate and limited change in throughput.

From a theoretical perspective, an increased ball top size could potentially assist in increasing the breakage component within the SAG mill by increasing the ball mass and thereby increasing the potential kinetic energy imparted on rock. However, the trade-off is an increased risk to liner damage when proper mill (rock) load management is not achievable with the control system. This risk coincides with optimized operating conditions, which typically corresponds to a high SAG mill operating speed, which could result in the rock-ball impact zone rapidly transitioning into a ball-liner impact zone, which will impart higher energy thanks to the increased ball mass. In cases such as this, it is advisable to either have a responsive control system or operate at slightly reduced operating speeds to allow for operational leeway.

The need for larger balls does not appear to be warranted when up to 50% of the feed can be secondary crushed. If the ore competency increases, the larger balls could show a more significant benefit and may warrant the repeat of the trial.

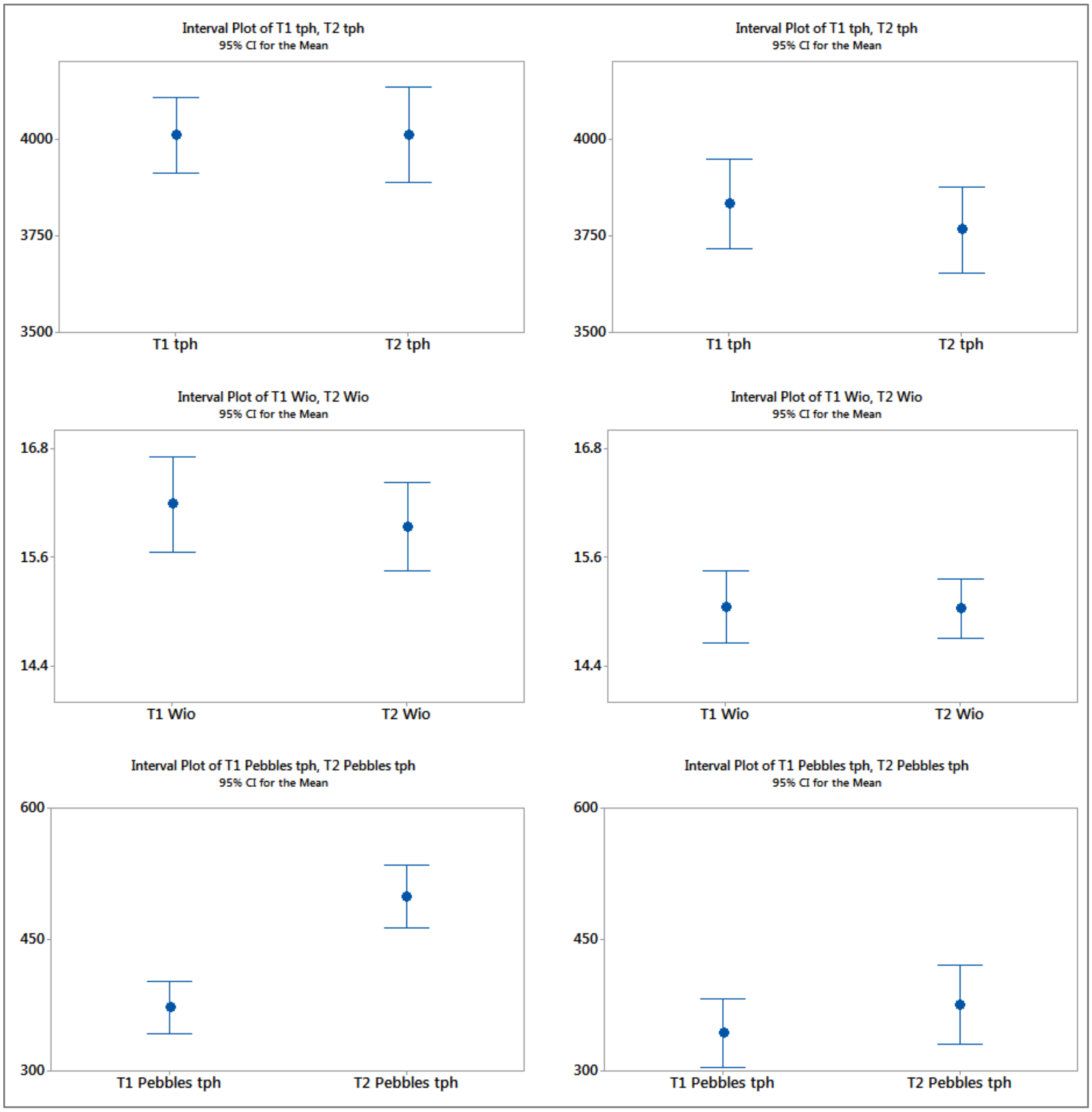

Figure 13 – Effect of Media Top Size Change
[Left T1=125 mm T2=140 mm] [Right T1=140 mm T2=140 mm]

The grinding media consumption was also considered for the period June to October 2018, as shown in Figure 14. No conclusion could be drawn whether there is a consumption benefit by using the larger balls.

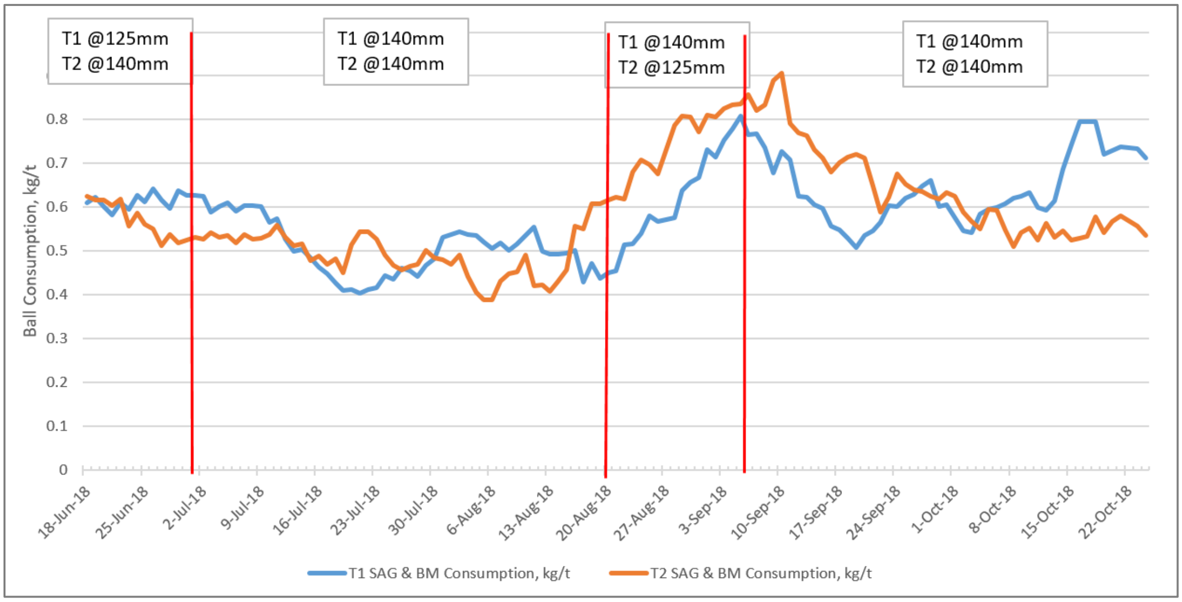

Figure 14 – Total Grinding Media Consumption (SAG + Ball Mill)

MILL WEIGHT SET POINTS

When operating large SAG mills, the aim is to control the mill at an optimal load volume in relation to the liner design and mill speed. The Sentinel SAG mills originally did not have any volume indication installed, and therefore mill weight indication was historically used to infer this.

Unfortunately, other factors like charge density (due to variable steel ball addition) and liner wear affect the volume even if the weight is kept constant. Regular manual measurement of the load and adjustment of the mill weight set point were implemented. This was of particular importance following relining due to the inherent change in mill mass (and resulting change to mill volume). Additional instrumentation in the form of a MillSlicer (shell mounted vibration monitor that infers impact intensity and charge volume) has subsequently been installed to manage the volume in real time. Detailed analysis of the effect of this measurement was not available at the time of writing this paper.

Feedback on the back-calculated ball charge was provided to the client regularly as part of the RGS to assist with keeping this parameter as constant as possible.

CYCLONE MODELLING

Operating cyclone data was used in the models run by OMC as part of the RGS to confirm the expected optimal operating conditions. Notable differences were initially shown between the expected outputs and achieved performance.

Investigation found that due to the size and layout of the cyclone cluster and the position of the pressure transducer on top of the distributor relative to the cyclone inlet, a significant difference exists between the measured pressure and the actual cyclone pressure. Pressure adjustment of up to 40 kPa was required to account for the physical difference between the pressure transducer location and the actual cyclone inlet.

This highlights the importance of comparing the actual values to a theoretical model to flag areas where discrepancies exist and focus the troubleshooting and optimization effort.

BALL RETAINER (BALL MILLS)

Installation of a ball-retaining ring for both, Train 1 and Train 2 ball mills resulted in an improvement to the achievable circuit power draw. The operational data recorded for the Pre-RGS period indicated that both, Train 1 and Train 2 ball mills were achieving an average power draw of 16.0 MW at the motor. Since the installation of the ball retainer (and optimization of the ball charge and circulating load), both ball mills were able to consistently draw upwards of 18.7 MW of power.

Although difficult to see when evaluating the throughput values because of the increased ore hardness represented by the increased operating work index, it is clear that if this improvement in power draw was not realized, a noticeable drop in throughput would have resulted.

POWER BALANCE

One of the major challenges with any SABC circuit is to balance the power split between the available SAG and ball mill power. The Sentinel comminution circuit has been designed with the ability to control the percentage of the feed that can be sent to the secondary crushers, the percentage of scats that get pebble crushed, and the ability to bleed back cyclone underflow to the SAG mill.

These control mechanisms are utilized to try to control the transfer size between the SAG and ball mill. For example, increasing the amount of secondary crushing of the feed to the SAG mill effectively coarsens the feed size to the ball mill and increases throughput when SAG mill constrained.

The circuit design also incorporates the ability to bleed cyclone underflow back to the SAG mill. This is an effective way to utilize the total installed power when the circuit is ball mill limited, but could constrain the circuit when it becomes SAG mill limited. Frequent monitoring of the power utilization split and adjustment of this bleed stream is therefore required to fully maximize mill power utilization at all times.

Understanding the ore characteristics with specific reference to the breakage (Axb) parameters and the Bond Ball Mill Work index (BBWi) guides optimization of the selected operating parameters. It is therefore imperative that the plant metallurgist understands what is being fed to the circuit, and how to select the optimal operating condition.

Maximum throughput is therefore achieved when optimally utilizing the available circuit power, and is dictated by the target grind and ore characteristics.

The Sentinel circuit evaluation in May 2017 indicated that approximately 14% of the new feed was secondary crushed. Although this was acceptable at the time due to the softer ore, the current secondary crushing requirement has increased to 45% to maintain throughput levels at the time of RGS 22.

The key learning point for this is that optimal operating conditions in the past may not be optimal in the future, particularly when changes to the ore characteristics are expected. All stakeholders should plan for future changes well ahead of time to ensure sufficient preparation is made to adequately address processing challenges.

Conclusions

Analyzing 24 months worth of operating data in a holistic manner, covering a multitude of differing feed and operating conditions, allowed for a focused approach to continuous improvement. This can be seen clearly in the evolution of the plant operation from primary crushed feed and closed circuit SAG milling, to 45% secondary crushing and open circuit SAG milling. The throughput has dropped slightly below design in the last of the data analyzed, and the optimization effort will now move to further opportunities for increased power utilization and the impact of coarsening the grind.

As with most things in life, time and effort are required to achieve results. Improvement is seldom attributed to one single factor (or person), but rather the culmination of numerous incremental changes, which progressively pushes the previous benchmarked target higher. These changes included an increase in power utilization, in both the mills, changes in control strategy, changes in equipment specification and liner configuration, etc., all adding to the continuous improvement of circuit operation.

Focus on getting the fundamental approach correct, and thereby generating a suitable baseline from which other circuit improvements can be measured is crucial. Circuit stability generally translates into other intangible benefits, such as steady load control, improved circuit efficiency, and reduced recirculating loads.

Similarly, by having a stable evaluation platform the circuit may respond as intended to circuit upsets and allow a modicum of comparability when trialling circuit changes. Moreover, if nothing is risked then nothing more can be gained; operators must be continually challenged in their approach to operation.

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