BATU HIJAU MILL THROUGHPUT OPTIMIZATION: MILLING CIRCUIT CONFIGURATION STRATEGY BASED ON ORE CHARACTERIZATION

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ABSTRACT

PT Newmont Nusa Tenggara – Batu Hijau site mine to mill program has been systematically improved and resulting in Geo-Metallurgical detailed ore characteristics is successfully being used for short and long term business planning and mill throughput predictions. Actual plant operating and ore characterization data is continuously correlated, and is subsequently used to identify milling circuit constraints. This further enables a robust milling circuit configuration strategy to be implemented based on forecasted ore blends from the mine.

This paper discusses the development of the Batu Hijau Milling Circuit Configuration Strategy, which incorporates mine ore scheduling, mill shutdown planning, SAG Mill discharge grate, trommel and pebble screen panel aperture selection. The overall objective is to control the transfer size within the milling circuit, optimize power used for breakage in all installed comminution equipment and maximize throughput rates for all ores of varying grade and hardness characteristics.

KEYWORDS

Mine to Mill, Geo-metallurgy, Ore Characterization, Mill Throughput Improvement, Milling Circuit Configuration.

INTRODUCTION

The Batu Hijau copper-gold porphyry deposit is located in South Western Sumbawa and was discovered in 1990 by Newmont Mining Corporation. Project construction commenced in 1996 and the plant was commissioned in 1999 (McLaren et all, 2001).

Throughput of the Batu Hijau grinding circuit is highly variable, ranging from 3,500 tph to 7,500 tph driven by ore hardness characteristics mining sequence and blast fragmentation. The copper grade varies from 0.25%Cu – 0.9%Cu and averages 0.5%Cu. SAG feed 80% passing (F80) size is a product of blasting and primary crushing and varies from F80 of 40mm to 90 mm. The two parallel SABC grinding circuits are followed by a typical bulk sulphide flotation flow sheet to produce a copper-gold-silver concentrate for sale.

A Mine to Mill program commenced at the Batu Hijau site in 2001. The objectives of the mine to mill program were to (1) increase mill throughput by improving blast fragmentation and (2) improve production forecasting based on an improved understanding of the Geo-metallurgical characteristics of the ore-body. Strategy at Batu Hijau has been to continually improve ore body geo-metallurgical characterization and, via practical use of this data, to improve the ability to accurately forecast mill throughput and other production performance parameters despite the widely varying ore characteristics. The ore body is well characterised through continuously refining the geological block model via in-fill drilling and testing. The focus has not only been on improving geo-statistical data density and quality of the geological and geotechnical data bases, it has also been extended to throughput forecasting, designing the milling circuit configuration setup (based on forecasted ore characteristics) and blending requirements in order to maximize metal recoveries.

The major ore characterization parameters applied at Batu Hijau which correlate closely with throughput for the given plant flow sheet are;

- Copper Head Grade
- Rock Quality Designation (RQD),
- Point Load Index (PLi)
- Bond Ball Mill Work Index (BWi)
- JK Drop Weight (modified and full test) parameters

The overall objective of implementing a structured ‘milling circuit configuration strategy based on ore characterization’ is to optimize power utilization for breakage in all installed comminution equipment and consistently maximize throughput rates for all ores of varying grade and hardness characteristics.

This paper focuses on how the geo-metallurgy ore characterization (predominately ore hardness) information based on short and medium term (11 to 22 weeks) mine plan scheduling is use to forecast the mill configuration setup in order to maximize the milling rate. The mill circuit configuration in this case only includes SAG Mill Discharge Grates, SAG Trommel Screen and Pebble Screen aperture sizes. It also discusses the strategy used to mitigate throughput reductions post mill relines.

The key to the successful and sustainable implementation of this overall program involves several cross functional groups working closely with one common objective of maximizing throughput and overall production to achieve or exceed business plans. The functional groups are; mine engineering, drill and blast, geology and mine operations from the mine department and process metallurgy, operations and maintenance from the process department. Important elements which complement the team work are; sharing knowledge on the business challenges based on the mine plan sequencing and changes and ensuring the relevant personnel have the knowledge to correlate the ore variability against the plant performance and resulting milling circuit limitations.

PROCESS FLOWSHEET

Batu Hijau general Crushing and Milling process facility is presented in Figure 1. Further information on Batu Hijau process plant original flow sheet and performance post plan commissioning was described by McLaren et all, 2001 and further circuit modifications made to maximize the milling circuit performance to current levels was discussed by Burger, B et all 2006. The current key features after 15 years operation include:

- 2 x 60”x89” Svedala 750 kW Primary Gyratory Crushers
- A 6.1 km Overland Conveyor discharging ore to a 360,000 tonnes Mill Coarse Ore Stockpile
- 2 x 36’ x 19’ ABB Svedala Gearless Motor Drive 13.4MW SAG Mills
- 4 x 20’ x 33.5’ Svedala 7,400 kW Ball Mills
- 4 x MP1000 750 kW Pebble Crushers
- 4 x clusters of 26” WEIR Cavex Cyclones

The circuit was designed for a milling rate of 120,000 tonnes per day based on an assumption of 92% mill availability. This was based on the given ore characterization parameters of 0.18-0.33 Abrasion Index, 7 kWh/t -10.6 kWh/t Crushing Index and 8.5 kWh/t -10.85 kWh/t Ball Mill Work Index with a resultant optimum grind size of 80% passing 212 microns. The flotation circuit was expected to achieve a copper recovery between 78% and 94% for given feed grades of between 0.25%Cu to 0.8%Cu (Fluor Daniel, Process Design Criteria, 1996).

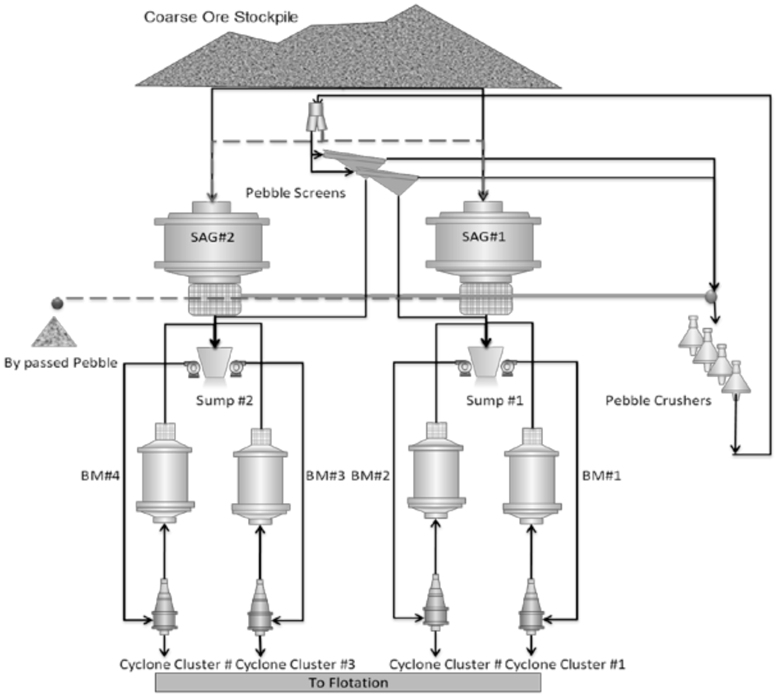

Figure 1 – PT Newmont Nusa Tenggara Batu Hijau Project Comminution Circuit

The SAG Mill was designed with 13.4 MW of installed power for a size reduction from 175mm feed size down to 2 mm -10 mm of product size with a given maximum ball charge of 13% by volume (using 127 mm diameter grinding media). The aperture of the SAG Trommel Screen was 10 mm x 25 mm providing a 25% pebble circulating load. The current SAG Mill operation is still rated at 13.4 MW power draw however has been operated at higher ball charges up to 18% and with 133 mm diameter grinding media.

The Ball Mill was originally designed for a 7,000 kW power draw, with a maximum ball charge of 31% (65mm diameter ball size) to perform size reduction from a 2 mm -10 mm feed size range to a 180 microns - 250 microns product size range. The mills are equipped with trommel screens having an aperture of 12.7 mm x 31.8 mm. The ball mill classification circulating load design basis was 230%. The ball mill clutch and motor power were up graded to 7,400 kW to accommodate a maximum 40% ball charge level and currently is operated with 100% of 80mm grinding diameter media size with a final product target size of 80% passing 230 microns.

ORE HARDNESS VARIABILITY

The geo-metallurgical ore characterization within Batu Hijau deposit is well understood and modelled to provide information required for business planning/forecasting and also to identify the milling circuit bottlenecks both for daily operations and future improvements. This is a key factor of the current mill operations strategy, to ensure that the circuit is appropriately configured to anticipate milling circuit limitations driven by ore characterization variability. More detailed information on Batu Hijau systematically improving the geo-metallurgy model and correlation of ore characteristics to deliver throughput prediction was discussed by Wirfiyata, F. et all 2011.

There are three major ore hardness characteristics which influence the milling performance. These have been identified through a comprehensive study conducted via the Batu Hijau Mine to Mill program and supported by the expertise of external expert modelling consultants such as Metso Process Technology

& Innovation (Metso PTI) and SMCC Pty Ltd (SMCC). The following major hardness characteristics are used to correlate the comminution characteristic for blast design, throughput modelling and identify the milling circuit bottlenecks.

- Point Load Index (PLi) - At Batu Hijau, the PLi measurement provides a reasonable indication of ore hardness from a SAG mill throughput perspective when the feed grade of ore is more than 0.6% copper. Where the grade is lower than this, PLi does not correlate well with plant throughput performance.
- Rock Quality Designation (RQD) - An inverse relationship between RQD and mill throughput applies at Batu Hijau, however the throughput varies more widely than can be wholly explained by a variation in the RQD.
- Bond Ball Mill Work Index (BWi) - There is a strong inverse relationship between BWi and mill throughput. This is stronger than the RQD and throughput inverse relationship. BWi is strongly inversely related to copper head grade also. As the copper head grade decreases below 0.5% copper, grinding specific energy (SAG mills and ball mills kWh/t) appears more strongly influenced by BWi and suggests grinding will tend to be more ball mill circuit limited at lower head grades. The limiting changeover point coincides with a Ball Mill Work Index of about 12 kWh/t to 13 kWh/t.

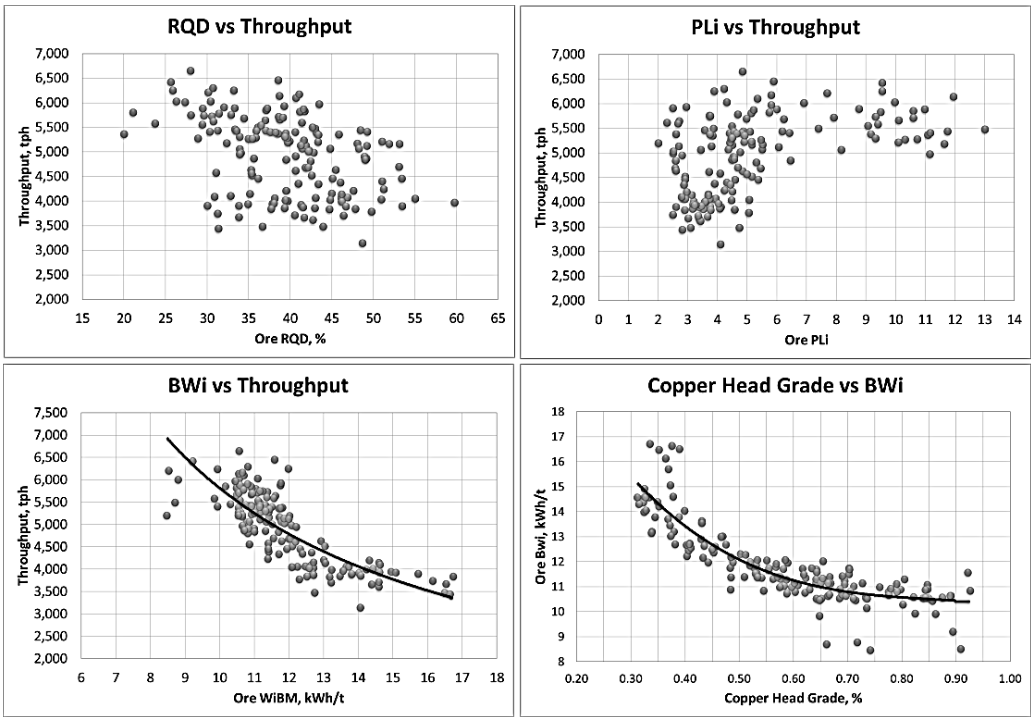

Figure 2 – Batu Hijau Ore Hardness, Copper Grade and Throughput Correlation from 2002 to 2015

CURRENT MILLING CIRCUIT PERFORMANCE AND LIMITATION

Depending on the ore characterization results, the Batu Hijau milling circuit limitation is categorized into three major areas; SAG Mill Limited, Ball Mill Limited and Pebble Circuit Limited.

- *SAG Mill Limited:* the overall grinding circuit is constrained by the SAG mill and the Ball Mill and Pebble Crusher circuits have spare capacity. During these periods the throughput can be as high as 6,000 tph to 7,500 tph for both grinding lines.
- *Ball Mill Limited:* the overall grinding circuit is constrained by the Ball Mill capacity and the SAG mill and Pebble Crusher circuits have spare capacity. This limitation is commonly experienced during the processing of the low grade ores (less than 0.4%Cu). This also confirms the BWi ore hardness – grade correlation. The typical plant throughput rates are in the range of 3,000 tph to 4,500 tph for both grinding lines.
- *Pebble Crusher Limited:* The overall grinding is circuit constrained by the pebble crushers and the SAG mill and ball mill circuits have spare capacity. During these periods the throughput can vary from 3,100 tph to 7,200 tph depending on the ore copper head grade.

Table 1 – Summary of Plant Limitation and Ore Characteristic

Plant Limitation	Ore Hardness Characteristics		
	PLi (MPa)	RQD (%)	BWi (kWh/t)
SAG Mill Limited (SML)	>5	40-60	<12.5
Ball Mill Limited (BML)		30-60	12.5 – 15, >15 (extreme BML)
Pebble Crusher Limited (PCL)		<30	

Due to the cyclical nature (phase by phase) of the mining sequence, variation of ore hardness presented to the mills results in the circuit limitations moving between the SAG Mills, Ball Mills and Pebble Crushers as illustrated in the historical graph presented in Figure 3 (Figure 3 presents only the three major milling circuit limitations for the purposes of this paper, in reality the issue is slightly more complex than summarized here). The higher ore BWi, the more frequent the milling circuit is Ball Mill limited (the year of 2013 was an extreme one). The lower ore BWi, the milling circuit is more SAG Mill limited. According to the long term mine plan schedule, the frequency and durations of treating higher BWi ores will increase and therefore result in more periods where the ball mills will be the constraint. There will still be periods of SAG Mill and Pebble Crusher limitations depending on the mine sequence and available blend. It has therefore been critical to have a sound strategy in place to ensure the best utilization of total installed comminution power regardless of the ore types presented to the Batu Hijau mills.

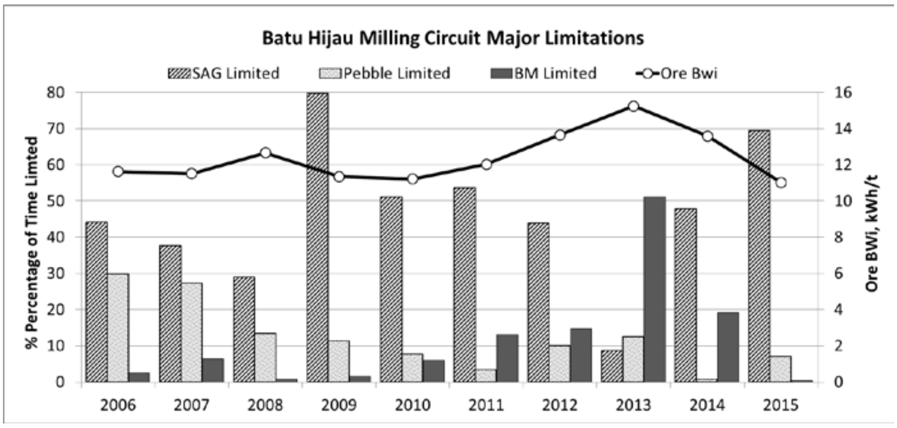

Figure 3 – Batu Hijau Historical Milling Circuit Limitation

The key objectives of the strategy employed at Batu Hijau to manage the three distinct milling constraints (given the known variability in ore hardness), and thereby select and implement an appropriate mill circuit configuration are:

- Balancing the load between the SAG mills, ball mills and pebble crushers so that no specific unit becomes excessively constrained, leaving the other units with excessive spare capacity (Figure 4).
- The ball mills should be running on the limit (and cyclones producing the targeted grind size), however not so excessive that SAG power is sacrificed through slowdowns.
- Pebble crushers are targeted to operate at ~75% utilization (3 of the 4 crushers operating full time), to provide;
  - A pebble production rate surge capacity without causing SAG mill slowdowns and power reductions.
  - In addition to provide some maintenance spare capacity; on average, one crusher is scheduled down each week to change wear liners, as well as provide some capacity for unscheduled downtime of the pebble crushers.

A typical Batu Hijau power utilization range is illustrated in Figure 4. Note that prior to March 2015, Batu Hijau experienced issues with SAG Mill Torque settings which limited the ability to maximise the ball charge and power in the mill. This issue has since been rectified.

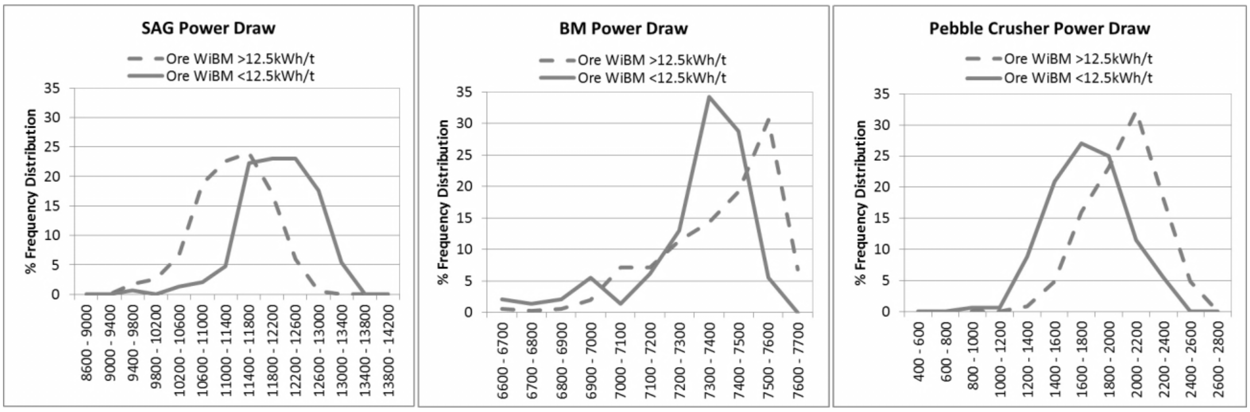

Figure 4 – Batu Hijau Power Draw in Milling Circuit (Jan 2012 to May 2015)

The enabler to achieve this purpose is to plan and execute a specific mill circuit configuration for each of the milling circuit limitations based on forecasted ore blends. These milling circuit configuration changes are carried out in alignment with the maintenance shutdown schedule in order to minimize downtime whenever grate changes are required. The mill circuit configuration includes: SAG Mill Discharge Grates, SAG Mill Trommel Screens, Crushed Pebble Screens and Ball Mill Trommel Screens.

MILL CONFIGURATION STRATEGY

Upstream Enablers

Implementation of the milling circuit configuration strategy alone does not guarantee that the operation will achieve its objectives. Overall success of the strategy is also highly dependent on the other non-ore hardness (process variability) related contributors of variability introduced up stream of the Milling Circuit. These additional sources contribute to variability in ore size distribution and delivery rates that also need to be minimized prior to introduction of ore into the SAG Mills.

At Batu Hijau, the main factors influencing the SAG feed upstream process variability are;

- Blast fragmentation optimization to cater for both coarse and fine mine product size variability
- Mine to mill blending management. This is includes mine equipment availability to provide the planned blends and at a delivery rate consistently matching or exceeding mill throughput rates.
- Primary crusher gap control – operating at target
- Primary crusher/ ore transport equipment availability
- Mill Coarse Ore Stockpile management. Aimed at minimizing the impact of size segregation resulting from the mill stockpile level draw down and the method of dozers operating on the pile.
- SAG feeder operation (process control configuration for ratio controlling the three feeders to stabilize feed size distribution)

Strategic Fit with Plant Maintenance Schedule

The maintenance shutdown schedule at Batu Hijau is based on an 11 and 22 weeks cycle. Relevant to the components included in the milling circuit configuration strategy, the following applies:

- At 22 weeks, a major plant shutdown occurs where full and/or partial mill relines are conducted, including a change-out of 100% of the SAG Mill discharge grates and also the trommel screen panels for SAG and Ball Mill.
- At 11 weeks, a minor shutdown occurs where a partial change out of SAG Mill discharge grates and trommel screen panels for both SAG and Ball Mill is conducted.
- Depending on the top size of the grate aperture in use, an extra short shutdown is planned at 5 to 6 weeks after the major shutdown only to conduct a partial change of SAG Mill discharge grates.

Challenges and Opportunities

<u>SAG Mill Discharge Grates</u>

SAG mill discharge grate configuration selection relates to the aperture sizes, open area and number of each to be installed. In most cases this is challenging due to:

- The grate configuration and aperture selections are based on the mine planned ore blend hardness characteristics and expected average size distributions relevant to those characteristics. The Batu Hijau short term planning provides information in average weekly resolution for the first 11 weeks of a cycle, whilst the information for the second 11 weeks is provided to an average monthly resolution.
- In the short term reality, the actual ore delivery on an hour by hour and day by day basis can vary widely from these plans in both hardness and size which directly impacts milling circuit capacity and limitations on a daily and shift by shift basis.

These short term variations are managed through a Mine to Mill blending protocol as the initial control to bring ore hardness and size variations back into an acceptable range to suit the installed SAG mill grate configuration. Online process control is then used as real time control for the milling circuit.

In an extreme event where the planned blend changed totally (e.g. a failure in the pit and a forced return to stockpiled ore processing for an extended period), this may require an unscheduled mill shutdown to change the grate and panel configuration.

<u>Screen Panels</u>

Unlike SAG grates where feed size and hardness drives the selected grate configuration, the SAG Mill and Ball Mill Trommel Screens configuration is simpler as is based on a longer term averaged BWi.

Crushed pebble vibrating screen panels can also be changed with a short shutdown of the screens alone and therefore has very little impact on overall mill production rates.

BATU HIJAU MILL CONFIGURATION SCENARIOS

Discharge Grates and Screen Configuration Selection and Management

To manage each of the distinct mill circuit limitation categories, there are three standard SAG Mill discharge grate configurations and three standard configurations for the SAG Mill trommels, Ball Mill Trommels and crushed pebble vibrating screens used.

From all ore hardness characteristics, the BWi is the major factor considered when deciding to step from one category to the next, while the RQD and PLi are also taken into account when conducting the grate configuration planning. Mill setup configuration planning is based on the 11 and 22 weeks ahead mine planned ore blend hardness characteristics.

Standard SAG Mill Discharge Grate Configurations

There are three standard configuration categories of SAG mill discharge grate aperture sizes and the number of each installed for three distinct categories of ore hardness ranges. When transitional ore types are identified in the mine plan scheduling, modifications to these variation are possible.

Table 2 – SAG Mill Discharge Grate Configuration

Grates Apertures	**Ore BWI Categories**		
	<12.5 kWh/t	**12.5 – 15 kWh/t**	**>15 kWh/t**
Target Open Area (total m^2)	8.54	8.14	7.51
50 mm			18
60 mm		18	12
70 mm	12	12	
80 mm	18	6	6
90 mm	6		

Standard Screen Configurations

The following table presents three standard screen aperture size and configuration categories. Similar to the SAG mill discharge grate variation, when transitional ore types are identified in the mine scheduling, modifications to these options are possible.

Table 3 – Screen Aperture Size Configuration

Screen Apertures Width (mm) x Length (mm)	**Ore BWi Categories**		
	<12.5 kWh/t	**12.5 – 15 kWh/t**	**>15 kWh/t**
SAG Trommel Screen	16 x 36	Row 1-5: 15 x 35 Row 6-16: 14 x 40	Row 1-5: 15 x 35 Row 6-16: 14 x 40
Ball Mill Trommel Screen	23 x 70	23 x 70	23 x 70
Pebble Vibrating Screen	12 x 38 Several rows of 14 x 38	12 x 38 10 x 38 7 x 38	10 x 38 7 x 38

Progressive Grate Change-Out Strategy

A progressive grate change-out approach is taken to avoid;

- Excessive SAG Mill limit and large reductions in throughput rates immediately following mill relines/grate changes caused by an excessive reduction in grate open area.
- Excessive pebble circuit limitations caused by high pebble production at the end of the life of the worn grates.
- Excessive grinding ball consumption caused by large grate apertures at the end of the life of the worn grates (of particular concern when using 90mm grates).
- SAG Discharge Grate aperture size and configuration is based on;
- Initially setting up the grates at the desired open area and with enough large aperture grates to act as pebble ports (especially relevant for ores of high RQD and PLi) and to target pebble crusher installed power utilization of 75%.
- A smaller portion of the grates are replaced at each of the scheduled shutdowns targeted at maintaining the open area over the longer term.

Table 4 summarizes the SAG Mill Discharge Grate progressive change-out strategy for the three categories of ore hardness. Variations to these standards may be implemented, depending on operation and ore blends at the time.

Table 4 – Progressive SAG Mill Discharge Grate Change-Out Strategy

Ore BWi <12.5 kWh/t		**Schedule Shutdown**		
Grate Apertures (mm)	New Installation	5-6 Weeks	11 Weeks	22 Weeks
70	12		6 new installed	All new installed
80	18		6 worn removed 6 new installed	All new installed
90	6	6 worn removed 6 new installed	6 worn removed No new installed	All new installed
Ore BWi 12.5-15 kWh/t		**Schedule Shutdown**		
Grate Apertures (mm)	New Installation	5-6 Weeks	11 Weeks	22 Weeks
60	18			All new installed
70	2		6 worn removed 6 new installed	All new installed
80	6		6 worn removed 6 new installed	All new installed
Ore BWi >15 kWh/t		**Schedule Shutdown**		
Grate Aperture s(mm)	New Installation	5-6 Weeks	11 Weeks	22 Weeks
50	18			All new installed
60	12		6 worn removed 6 new installed	All new installed
80	6		6 worn removed 6 new installed	All new installed

DESIGNING THE MILL CONFIGURATION PROCEDURE

As a result of learning from past experience followed by continuous improvement, a robust procedure has been implemented to guide the metallurgists and operations personnel to design the most appropriate mill circuit configuration. The information in the procedure applies for all various combinations of hardness indices.

The procedure also provides guidance to ensure that the required stock levels of grates and screens are maintained in on-site inventory. In addition, the mill setup planning incorporates ore characterization and planned blending information from the short term mine plan for the next 11 and 22 weeks ahead. The 11 and 22 weeks' time frame is critical as this aligns with the process maintenance shutdown schedule.

There are five steps taken to complete the designing mill configuration as summarized in the following Figure 5:

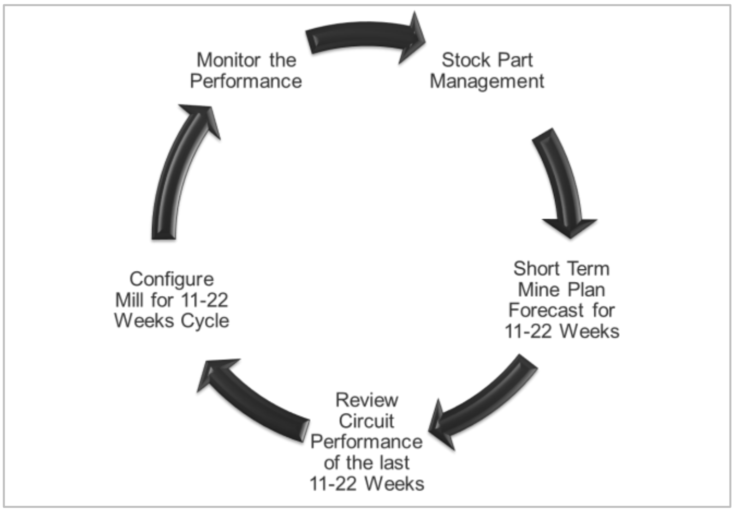

Figure 5 – Mill Configuration Change Management Flowchart

Stock Parts Management

Activities included in the first step involve multi-departmental coordination for a historical data usage review and also conducting future forecasts in alignment with supply chain management protocols. These key activities include; coordination with maintenance, Supply Chain Management (SCM) & suppliers; management of high inventory cost parts, long supplier lead time, delivery and dynamic usage of the parts; carrying a wide range of grate aperture sizes on site at all times, and parts design review to achieve life time and production performance.

Short Term Mine Plan Forecast

Mine Engineering releases the mine plan for the first 11 weeks on a weekly resolution and the second 11 weeks on a monthly resolution. The information contained in the mine plan includes information on ore grades, hardness indices (RQD, PLi and BWi) and also mill throughput estimates based on the Batu Hijau SMCC BWi Corrected Throughput Model. The Table 5 below illustrates the information required for mill set up configuration planning.

Table 5 – Batu Hijau Ore Characteristic 3 Months Rolling Plan

			Rolling Plan				
Weekly	From	To	%Cu	%RQD	Mpa PLI	kWh/t BWi	tph Tput
wk1	6-May	12-May	0.589	61.27	9.19	12.12	4,736
wk2	13-May	19-May	0.554	41.37	5.59	10.19	5,134
wk3	20-May	26-May	0.666	43.67	5.57	10.79	5,395
wk4	27-May	2-Jun	0.653	49.95	5.45	10.78	5,195
wk5	3-Jun	9-Jun	0.703	49.10	5.99	10.41	5,364
wk6	10-Jun	16-Jun	0.684	46.31	5.67	11.85	5,305
wk7	17-Jun	23-Jun	0.583	46.64	7.93	11.28	5,025
wk8	24-Jun	30-Jun	0.540	47.26	6.34	10.36	4,905
wk9	1-Jul	7-Jul	0.706	46.65	5.31	10.59	5,465
wk10	8-Jul	14-Jul	0.626	38.95	5.80	11.33	5,368
wk11	15-Jul	21-Jul	0.583	50.57	6.36	11.20	4,947
wk12	22-Jul	28-Jul	0.767	60.32	7.82	12.55	5,174
wk13	29-Jul	4-Aug	0.647	38.64	6.16	10.83	5,496
wk14	5-Aug	11-Aug	0.663	29.56	5.75	10.86	5,741
wk15	12-Aug	18-Aug	0.581	50.66	7.05	12.58	4,790

Based on this information, the metallurgist will design several mill circuit configuration options and review the inventory stock levels for availability.

At least 2 weeks prior to a shutdown, the options will be reviewed by the metallurgy and operations key personnel and a decision made on the most appropriate option based on the most recent mine plan forecast.

Reviewing Circuit Performance

The process of selecting an option for the mill circuit configuration is initiated by reviewing the most recent historical plant performance for the last 11 and 22 weeks against the characteristics of the ore that was actually milled. During this review, the key elements assessed carefully are production achievements, circuit limitations and other key circuit parameters. Figure 6 shows the typical information used during the review:

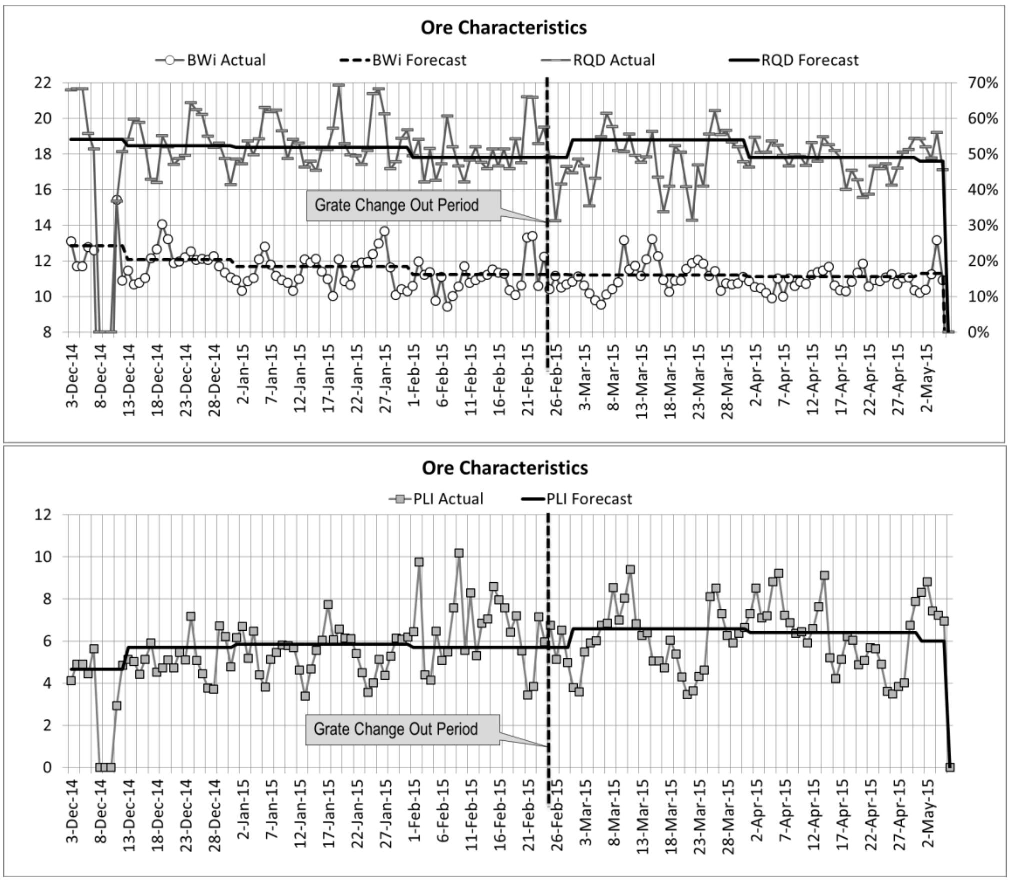

Figure 6 – Batu Hijau Ore Hardness Characteristic – Mine Plan vs Actual

The information in Figure 6 outlines the actual ore characterization against the previous forecast, this information allows an evaluation of the previously installed mill circuit configuration, which was configured based on the mine plan forecast information provided at that time. If the actual ore characteristic was found to be close to forecast then the milling performance is used as a reference for the next mill circuit configuration, or alternatively, to be used to identify improvements; for example, to be more aggressive or conservative in grate configuration in order to achieve the objectives.

Case Study

In mid-February 2015, a minor plant shutdown was carried out and a partial grate change was conducted in each SAG mill. Learning from the previous and foreseeing forecasted ore characteristics (Figure 6) also reviewed the milling circuit performance and limitations prior to the grates being changed (Figure 7), the site metallurgists and operations decided to install a more aggressive grate configuration based on the previous 11 weeks milling period. The actual ore characteristic prior change out was in average of 51% RQD, 11.8 kWh/t BWi and 6 MPa PLi vs the forecast after change out was in average 51% RQD, 11 kWh/t BWi and 6 MPa PLi, which were basically similar ore hardness characteristic. A review of this information assisted in identifying the next appropriate mill circuit configuration.

Figure 7 illustrates that for the previous 11 weeks (early December through mid-February 2015) the plant limitation for the given ore blend characterisation was bearing pressure or SAG milling limited for 70% of time while both the ball mills and pebble circuits had spare capacity being rarely limited. For the forecasted ore blends, the site team established that the ore characteristics would be similar to that prior to the February shutdown and this provided an opportunity to be more aggressive in opening the SAG mill grate apertures aimed at allowing higher pebble production rates to increase both mill throughput and pebble crusher utilization.

After the more aggressive grate configuration was installed, the milling rate improved (a month ave. ~5,000 tph before and ~5,125 tph after grate change out or 2.5% improved throughput) along with an increase in pebble circuit utilization (a month ave. ~72% before and ~76% after grate change out). Moreover, for the given ore hardness characteristics post grate change out period, the actual milling rate was higher than the modelled throughput.

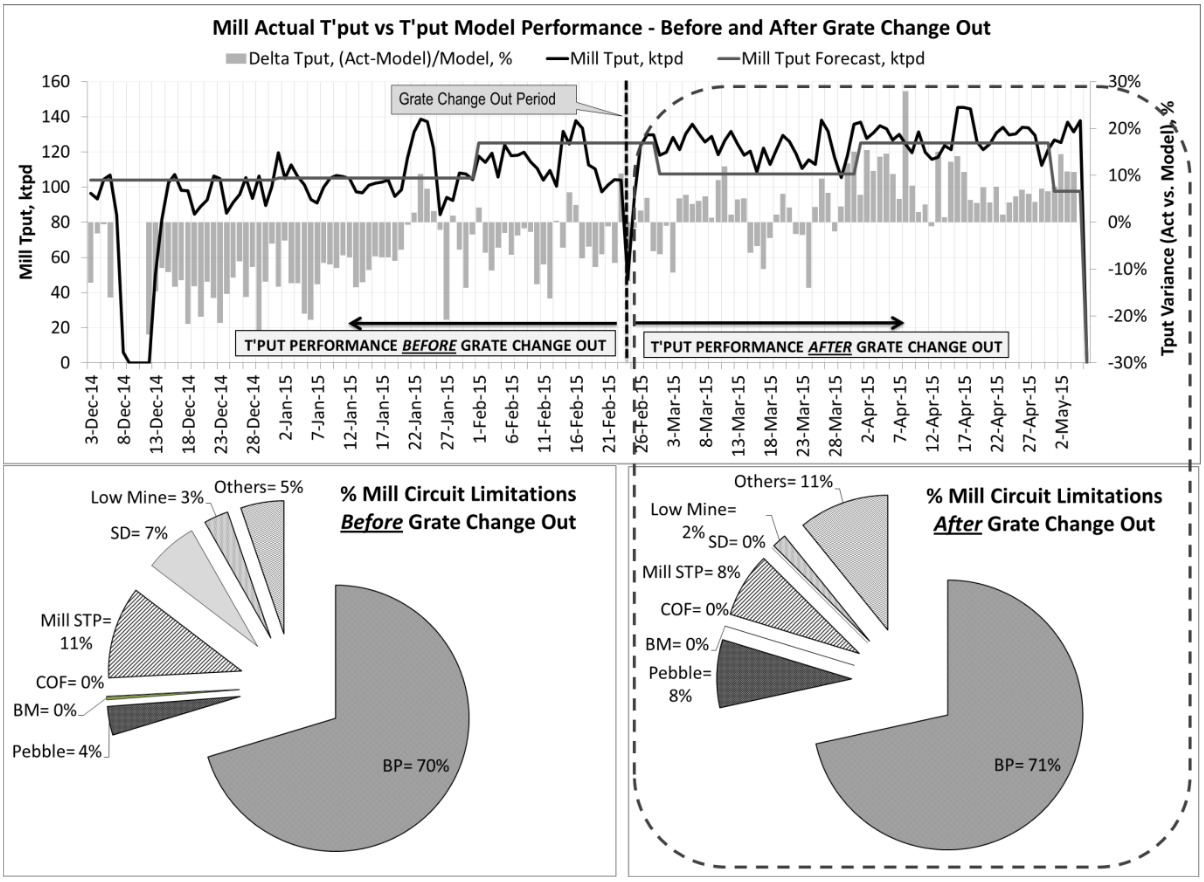

Figure 7 – Plant Throughput Model vs Actual and Plant Limitation Before and After Grate Change Out

Designing Mill Circuit Configuration

Following a review of the past 22 weeks, the mill circuit configuration is designed by the metallurgist, after which a proposal is made, discussed with and agreed between the Metallurgy and Operations teams. A breakdown of these steps is as follows:

- Metallurgy and Operations review, discuss and agree on the history and proposed options of new mill set up configuration including;
    - SAG discharge grates
    - SAG mill trommel screen panels
    - Pebble screen panels
    - Ball mill trommel screen panels
        - Review with and obtain final approval by the process manager through the change management process.
        - The agreed configuration is sent to the maintenance planning team who prepare for the shutdown.
        - Metallurgy and Operations are responsible for the quality control of the mill set up configuration installation during the shutdown.
        - As the progressive grate out strategy is used, it is also critical in this design stage to ensure the grates to be changed during the upcoming minor shutdowns are also planned in advance. In doing so, the grate configuration is designed strategically to minimize the number of times the mill must be inched during the future grate change-out process so mill downtime is minimized.
        - Figure 8 is an example of how the different grate apertures are laid out inside the SAG mill in a proposed drawing format for installation. Every row of liners is permanently marked on the outside of the mill shell. When the mill is inched and set in position there are13 rows of grates under the floor level in between those accessible for changing. The inching sequence information illustrates the specific installation location of the different aperture sized grates in relation to the positioning of the mill. This method allows a minimum inching frequency.

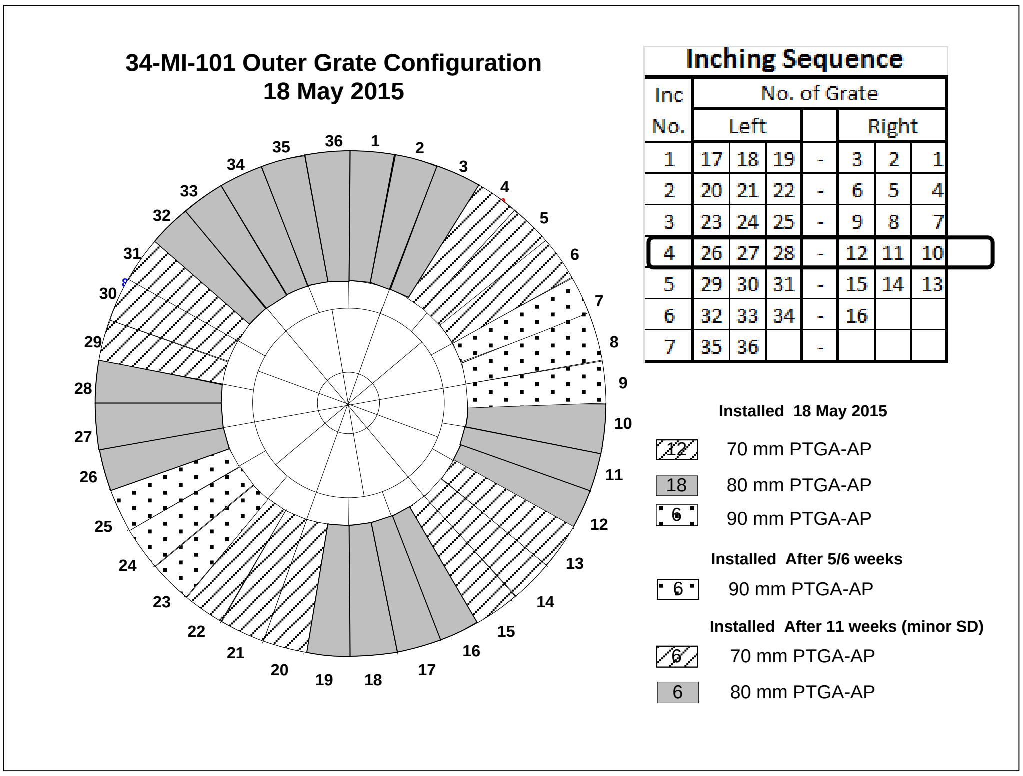

Figure 8 – Batu Hijau SAG Discharge Grates Configuration Design

Monitoring Mill Configuration Performance

The ideal mill configuration set up should ensure no significant throughput rate reductions post new liner and grate installation and no significant reduction in corresponding pebble production rates.

MEASURING THE SUCCESS

Measuring the success is always challenging in many operations mainly if it involves a small incremental improvement or measurement based on estimated expected figures. Batu Hijau has the benefit of having a robust throughput model which has been built based on ore characterization, and through refinement over time performs close to the actual plant performance.

Other success metrics used in Batu Hijau to evaluate that the mill configuration design is suitable for a given ore hardness are:

- Consistent throughput before and after the Major Shutdown (where all grates are changed), and after minor shutdowns (where a partial grate change outs are conducted); and
- Pebble Crusher Utilization to be close to the target of 75%.

Figure 9 demonstrates the benefit of consistent throughput with the base throughput rate before a full set of grates were installed in one SAG mill during December 2014. Prior to the total plant shutdown the SAG mill throughput was 1,800 tph (with the worn grate condition). After the full sets of grates were installed, the throughput rate increased to 2,000 tph. During the minor shutdown in January 2015, the six largest grates were replaced and the throughput rate was well maintained. The decision on the numbers of grates to be changed out and also which grates to change considers the performance of the actual throughput rate against the throughput model. In May 2015, a full set of worn grates were due for replacement after 22 weeks in operation. The averages SAG mill throughput rate leading up to the shutdown was 2,600 tph. After the new full set of grates was installed the throughput rate remained 2,700 tph. This indicates that the new grate configuration performed as expected and no throughput loss following the grate change out occurred.

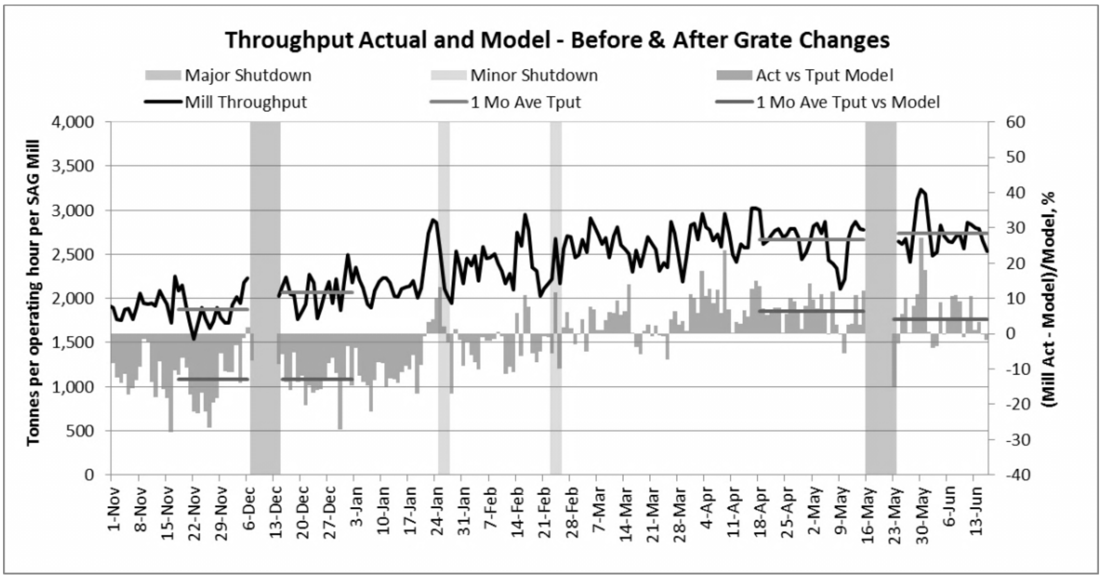

Figure 9 – Throughput Actual vs Model Before and After Grate Change-Out

Figure 10 demonstrates that the pebble rates prior to the December 2014 grate installation was consistently underperforming the site target. After the new grates were installed and further optimized through gradual changes in aperture at 6 and 11 weeks, the overall pebble production rate during the 22 weeks period increased to the target level. However there is clearly a wide range of pebble rates during the period (with power utilization ranging from 40 to over 95%), and ability to manage these surges with limited stockpiling and reclaim capacity presents the next operational challenge to overcome.

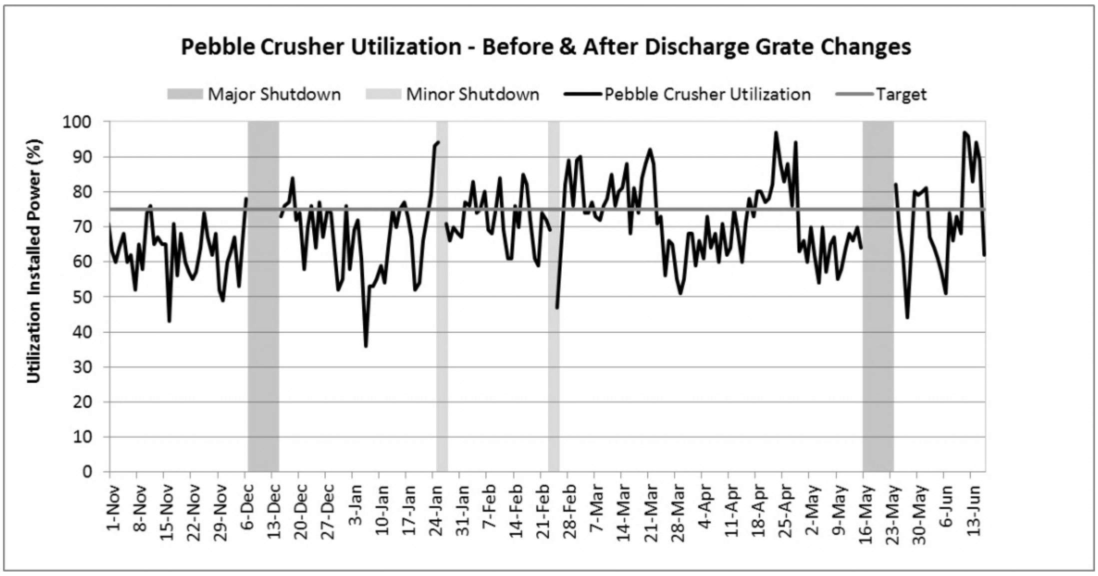

Figure 10 – Pebble Crusher Utilization, Before and After Grate Change-Out

Batu Hijau also engaged expertise from Metso PTI in late May 2015 to review the mine to mill and milling circuit optimization programs. Analysis of the correlations between throughput and ore hardness over time has shown that Batu Hijau has increased throughput consistently over the last three years, compared to the predicted performance, often in spite of harder ore and coarser feed, thus indicating good operating practices from the continuous improvement programs. Metso PTI advised that based on their database of copper/gold operations around the world for SAG Mills of 36' diameter and above, the Batu Hijau SAG Mills are operating at a specific energy consumption close to or even lower than the industrial practice for the given ore hardness. This suggests that very good operating practices are in place at Batu Hijau; both mills are operating close to their capacity under the current operating conditions.

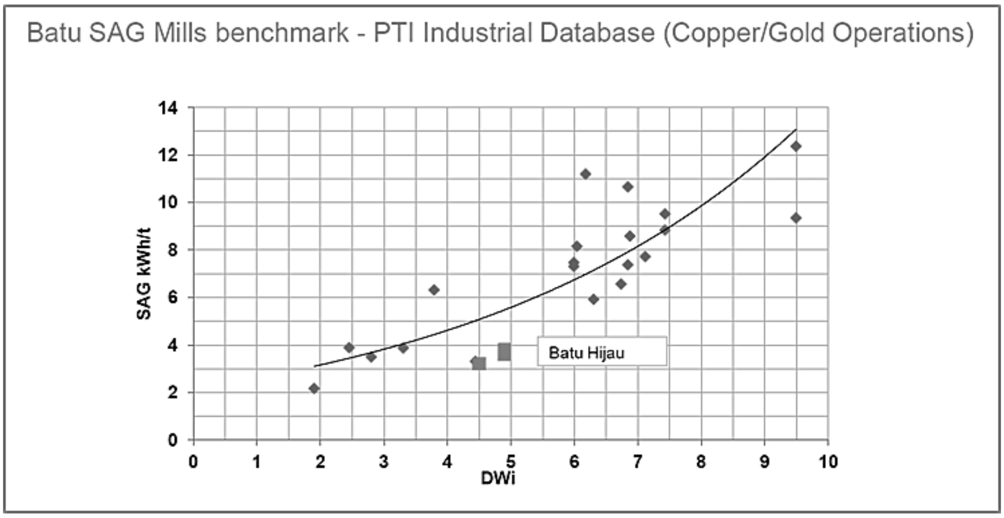

Figure 11 – Batu Hijau SAG Mills Benchmark vs Other Copper/Gold Operations

CONCLUSIONS

- Batu Hijau has successfully applied the mine to mill tools not only for Mine Plan forecasting and budgeting but also using the geo-metallurgy information in a practical application to guide metallurgists and operations personnel in designing appropriate mill circuit configurations.
- The mill circuit configuration is designed based on the forecasted ore blend hardness characteristics to proactively manage the predicted Plant Limitations. This allows Batu Hijau operation to maximise the utilization of installed power for comminution and also balance the milling circuit to maximise throughput.
- The progressive grate change-out approach ensures throughput reductions are mitigated post relines and lends to better utilization of all comminution units in the grinding circuit between shutdowns.
- Batu Hijau has realized the opportunity of consistently maximizing throughput rates for all ores of varying hardness through implementation of the mill circuit configuration strategy.
- A reliable plant limitation tracker and up to date mine to mill geo-metallurgy information database is required to ensure the sustainable success of the mill circuit configuration strategy.

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