Integrated Mine-To-Mill Optimization of the Toromocho Operation at Minera Chinalco, Perú

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Abstract

Minera Chinalco (Chinalco), owner of the Toromocho copper mining complex in Perú, has conducted an integrated mine-to-mill optimization project with the aim to maximize the throughput of the Phase 1 semi-autogenous grinding mill, ball mill, and crusher (SABC) grinding circuit, using the existing assets while maintaining the product size specifications. Following a typical mine-to-mill approach, improvement in the drill and blast operation resulted in significantly finer run-of-mine (ROM) fragmentation and finer SAG feed size. In 2020, Hatch Consulting & Technology was engaged to identify and quantify comminution circuit optimization opportunities for Phase 1, leveraging the full benefits of the fine SAG feed, and developing a throughput forecast model for the medium and long term.

The project identified various opportunities in Phase 1 to increase throughput by up to 14%, with 10% of the increase attributed to the SAG mill discharge system, despite the very-fine SAG feed size. Chinalco is currently implementing the recommendations to capitalize on all benefits and extending the study for the Phase 2 SABC grinding circuit, which has a different installed capacity. This will ensure that the mine-to-mill approach is applied to the complete comminution circuit.

Keywords

Mine-to-mill optimization, comminution efficiency, SAG milling, SABC grinding circuit, specific energy

Introduction

In 2007, the Aluminium Corporation of China established Minera Chinalco Peru S.A. (Chinalco) to build, develop and operate the Toromocho copper mega-project. The Toromocho mine, in the Junín Region of central Perú, is one of the largest copper reserves in Peru and the world, with estimated reserves of 1.52 billion tonnes of ore grading about 0.48% copper. The process plant is at approximately 4,500 metres above sea level.

The Toromocho comminution circuit (Figure 1), comprises a 60 x 113-inch (745 kilowatt [kW]) gyratory crusher that feeds a coarse-ore stockpile. The material from the stockpile is fed towards two semi-autogenous grinding mill, ball mill, and crusher (SABC) grinding circuits, namely Phase 1 and Phase 2. Phase 1, the first circuit commissioned , comprises one 40-foot diameter x 26-foot long semi-autogenous grinding (SAG) mill (28 megawatt [MW] gearless motor), two Raptor XL 1100 pebble crushers (750 kW each), and two parallel 28-foot diameter x 44-foot long ball mills (22 MW gearless motor) that operate in closed circuit with four clusters of 650 millimetre (mm) hydrocyclones (16 cyclone units per cluster). The Phase 2 grinding circuit, commissioned in early 2021, includes one 36 x 17-foot SAG mill (13.5 MW gearless motor), one MP1000 pebble crusher (750 kW), and one 28 x 44-foot ball mill (22 MW gearless motor) in closed circuit with two clusters of 650 mm hydrocyclones (16 cyclone units per cluster).

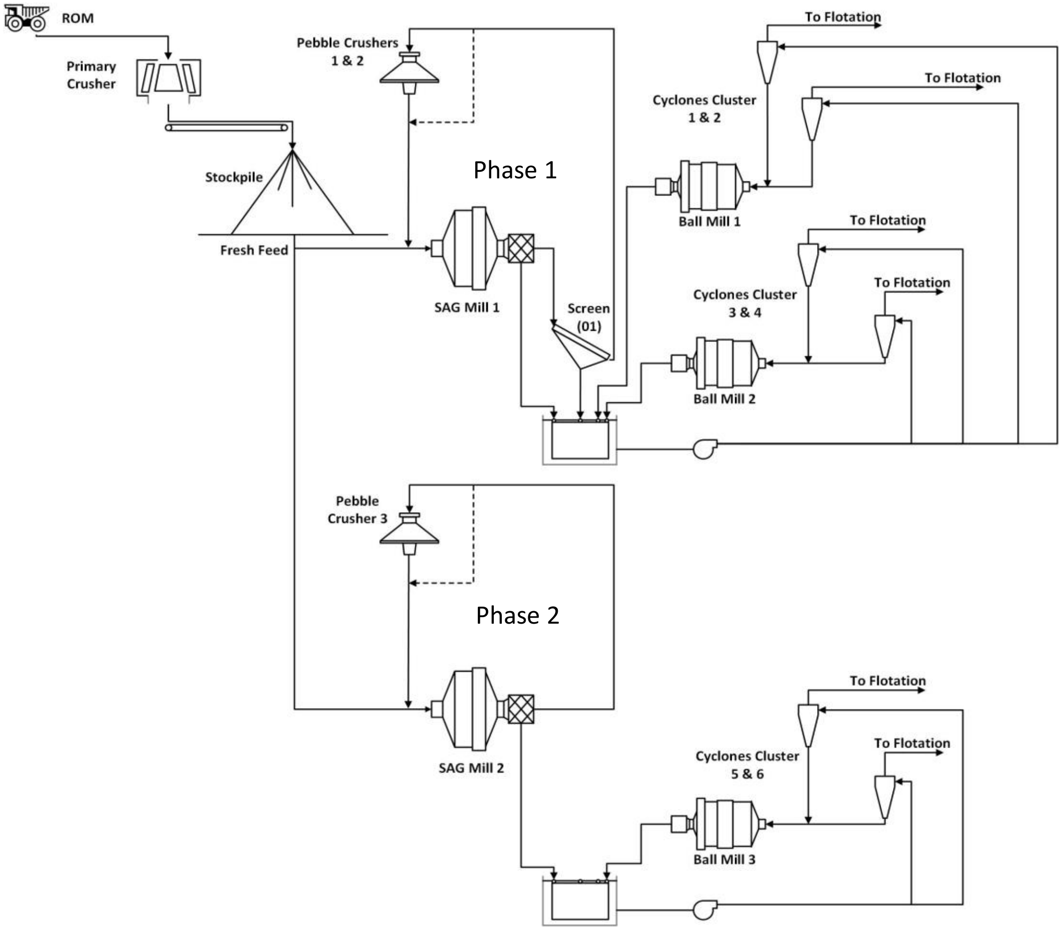


Figure 1—Toromocho Comminution Circuit Flowsheet with Phase 1 and Phase 2 Grinding Lines

Since the early stage of its operation, Chinalco encountered challenges in achieving the design throughput of 5,250 tonnes per hour (t/h). One of the most significant challenges was that the ore was harder than expected, as discussed below. In response to this challenge, Chinalco implemented a series of initiatives in the drill and blast operations to provide a finer run-of-mine (ROM) to the comminution circuit, and thereby increase throughput.

Following the initial improvements in ROM fragmentation, Chinalco initiated an integrated mine-to-mill optimization project aiming to maximize production in the Phase 1 grinding circuit while maintaining the final product size of cyclone overflow 80% passing (P_{80}) using the existing assets, and minimize additional capital expenditure. This approach involves proper planning; an accurate ore characterization program; equipment and operational knowledge; audits; sampling; detailed analysis of process variables; mathematical modelling; and simulations under various scenarios to identify the necessary modifications to maximize throughput.

During the mine-to-mill optimization project, Hatch was engaged to identify and quantify comminution circuit optimization opportunities for Phase 1 and develop a throughput forecast model for the medium and long term. The Hatch team identified a potential production increase in the Phase 1 circuit throughput of up to 14%, without compromising the final target product size of P_{80} 195 µm (Valery at al., 2020). The recommended changes in the grinding circuit considered leveraging the benefits of the fine feed from the ROM. The SAG mill feed F_{80} for Phase 1 ranges from 1.6 inches to 4 inches (40 to 100 mm),with a significant proportion of fines (% passing 1 inch) of 30–50%, to which the SAG milling is particularly sensitive. Evaluating the circuit configuration and installed capacity considered primary crushing, SAG mill (with modification to internal components such as grates, pulp lifters, shell liners, and ball charge), trommel and discharge screen, pebble crushers, ball mills, and cyclones.

The study results highlighted the criticality and significance of conducting integrated optimization. Despite having a very fine SAG mill feed particle-size distribution, the primary bottleneck identified in the Phase 1 grinding circuit was the SAG mill discharge system. Chinalco has already implemented some of the short-term recommendations in the Phase 1 grinding circuit, and the long-term recommendations are under evaluation for future implementation. These changes, when combined, will enable the anticipated throughput to be achieved.

The installation and commissioning of the Phase 2 grinding circuit has resulted in a substantial increase in the overall production of the Toromocho mine. At present, efforts are underway to optimize the Phase 2 circuit, which receives a coarser SAG mill feed than the Phase 1 circuit, as a result of segregation generated in the coarse-ore stockpile.

Methodology

EFFECT OF SAG FEED SIZE

Optimizing the drill and blast operation and improving the ROM fragmentation are critical steps in optimizing SAG mill feed size for maximizing plant throughput. Most of the fines in the SAG mill feed are generated in the crushing zone – area around the blasthole where rock is pulverized under compressive-shear stress mechanism, from high pressure and temperature exerted to the blasthole wall . The amount of fines is influenced by the intensity of blasting and ore hardness. Meanwhile, the top-size of the mill feed is influenced by the rock structure and the primary-crusher setting. By optimizing both the blast intensity and the crusher gap, a finer SAG mill feed can be achieved, allowing for the grinding circuit throughput to be optimized. This methodology is the typical optimization approach that has been successfully applied in many operations through mine-to-mill projects (Valery et al., 2019). Chinalco has already made significant improvements in the drill and blast operations, resulting in an improvement of the ROM fragmentation, as demonstrated in Figure 2.

Figure 2 shows the evolution over time of three main ROM fragmentation parameters defined by Chinalco in terms of P_{80} and content of fines (% passing 1 inch and % passing ½ inch). Since 2017, the ROM P_{80} was successfully reduced from an average of 5.5 to 2.5 inches. Conversely, the amount of fines (% passing 1 inch), increased significantly from 29% to 49% for the period 2018–2019, reaching up to 51% in 2020.

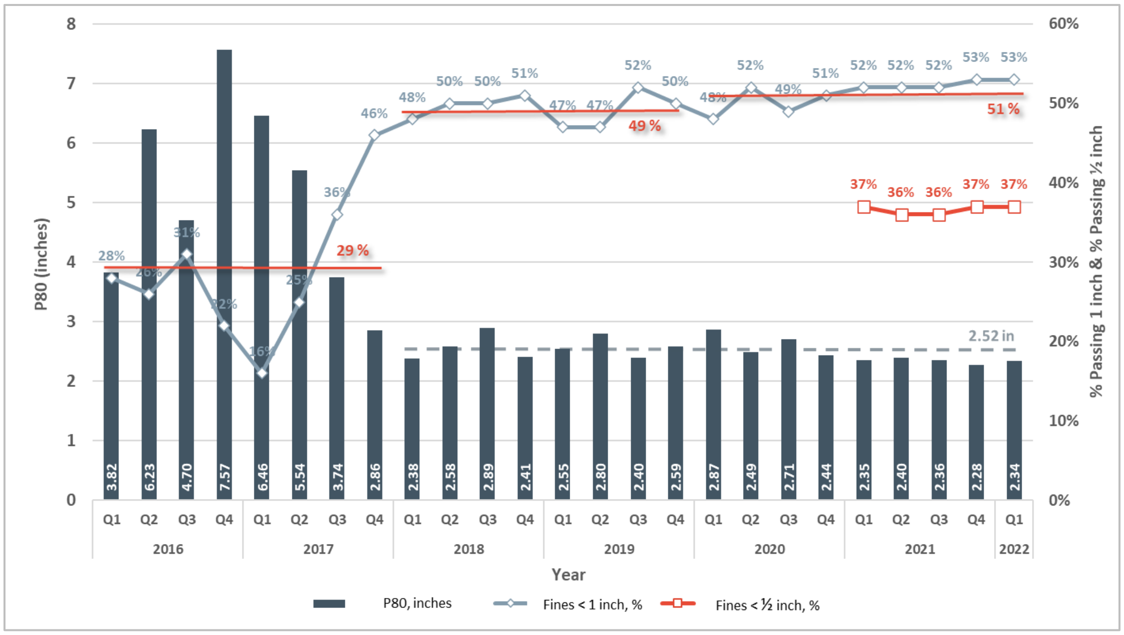


Figure 2—Historical ROM Fragmentation Measurement from Image Analysis

The improvement in ROM fragmentation since 2017 demonstrates the successful implementation of the drill and blast optimization approach. However, this strategy was primarily motivated by the need to mitigate the impact of unexpectedly harder ore properties. Table 1 illustrates that there is a significant and consistent difference between the ore hardness parameters of samples collected during past surveys and from more recent testing programs, compared to the hardness parameters considered during the design phase. The harder ore properties resulted in higher comminution specific energy than originally estimated, thereby negatively impacting plant throughput. To alleviate these comminution circuit constraints, the production of finer ROM fragmentation, and consequently finer SAG feed size, was necessary.

Table 1—Ore Hardness Parameters Used for Design Compared to Survey Samples and Geometallurgical Testwork

	Unit	**Design**	**2014 Samples**			**2019 Survey**	**2022 Geomet Testwork**
BWi	kWh/t	12.9	13.3	14.3	13.2	14.2	14.2
SAG Power Index	minutes	75	129	120	99	-	-
DWi	kWh/m^3	6.2[1]	8.9[1]	8.5[1]	7.5[1]	7.3[1]	7.0

Note: [1] Estimated from Hatch in-house relationships.

The finer SAG feed resulted in a reduction of the SAG mill specific energy; however, this should be followed by optimizing downstream operations to ensure the ball mill circuit can deal with the additional load and the grinding circuit leverages the full benefits from the fine ROM, and fine SAG feed.

The SAG feed size distributions from belt cut samples and online conveyor-belt image analysis (Split-Online) are shown in Figure 3. These were benchmarked against the feed size from other operations with similar ore properties using the Hatch Pty Ltd database. The grey envelope shows the range of SAG feed size distributions obtained at other operations after implementing recommended drill and blast optimization guidelines. The solid and dotted blue lines represent particle-size distributions from belt cuts collected during 2019 surveys at Chinalco, and are in the middle of this envelope. This indicates that the ROM, and thus SAG feed size distribution, was within the expected range after implementing the drill and blast optimization approach.

While sizing and sieving belt cut survey samples provides a snapshot of the process at a point in time, the data from Split-Online provide an indication of the variability of the SAG feed size over time. The orange and grey bars in Figure 3 indicate the range of SAG feed F_{80} and % passing 1 inch, respectively, from Split-Online. The SAG mill-feed size distributions of September 2019 surveys were at the finest end of the range measured by Split-Online. This indicated the SAG mill occasionally received coarser particle sizes, but the SAG mill feed size was predominantly fine.

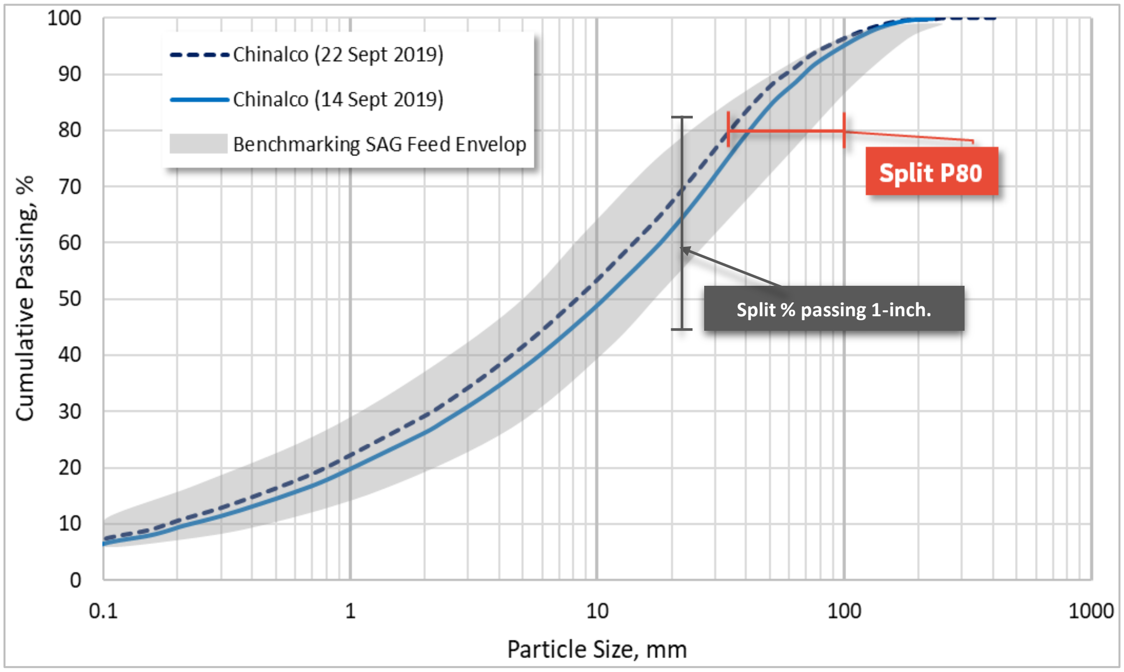


Figure 3—Phase 1 SAG Feed Size Distributions, 2019 Surveys and Split-Online Data

ORE CHARACTERIZATION AND TYPICAL BLENDING

As mentioned above, ore hardness and feed size have a significant impact on the throughput and energy consumption of the Phase 1 comminution circuit. There are five main alteration types used to characterize ore domain and hardness classifications in the Toromocho deposit: Intrusive Potassic, Intrusive Phyllic, Serpentine Magnetite, Hornfels, and Tremolite–Actinolite.

During the initial optimization study of the Phase 1 grinding circuit, the ore characterization data were limited, with ore hardness measures being limited to Bond work index (BWi), Macon crushability index, and SAG Power Index (SPI). Hatch used in-house breakage/comminution relationships to convert the available hardness parameters into hardness parameters typically used for SAG mill modelling, namely, the Drop Weight Index (DWi) and JK breakage index (Axb), as explained below.

Subsequently, a more extensive Geometallurgical testwork program was conducted consisting of 189 SMC tests®, directly providing the hardness parameters used in SAG mill modelling, and Bond Work Index tests, across the different alterations within the ore deposit. The results of the ore breakage testwork are summarized in Table 2, and were in line with the hardness parameters previously estimated from Hatch relationships.

Table 2—Summary of the 2022 Geometallurgical Testwork Results

Alteration	**Unit**	**Tremolite–Actinolite**	**Phyllic**	**Hornfels**	**Magnetite Massive**	**Potassic**	**Serpentine**
No. of Samples		43	27	45	28	103	43
BWi	kWh/t	13.5	13.7	15.3	13.6	14.0	15.0
DWi	kWh/m^3	5.8	6.9	7.9	5.9	7.3	6.7
Mia	kWh/t	16.5	20.4	21.2	13.7	21.6	17.9
SG	t/m^3	2.79	2.61	2.81	3.45	2.59	2.89
Axb		48.5	38.0	35.4	58.5	35.7	43.5

Note: DWi = Drop Weight Index; Mia = coarse ore work index from SMC Test; SG = specific gravity.

The Phase 1 comminution model was developed and calibrated based on data from a plant survey Toromocho conducted in September 2019. However, the hardness parameters required to develop a site-specific comminution model were not available at the time, as the ore from the survey was not independently tested. To overcome this, the proportion of alteration domains fed to the plant during the survey were used to back-calculate the ore hardness during the survey using the historical hardness parameters of each alteration domain.

Two surveys were conducted on September 14 and 22, 2019. The feed blend composition during the surveys was compared to the monthly averages for 2019 (Figure 4). A higher proportion of hornfels, the hardest alteration, was fed during the September 22 survey, accounting for 26% of the feed. During the September 14 survey, the proportion of hornfels was lower than 10%, but the proportion of potassic alteration was significantly higher. Consequently, the overall blend for both surveys would have been harder than the typical feed. The weighted average DWi of the blend fed to the plant during the two surveys was estimated at 7.3 and 7.1 kWh/m^3, respectively, and was then converted to Axb using the average ore specific gravity (SG) for development of the site-specific process (JKSimMet) models.

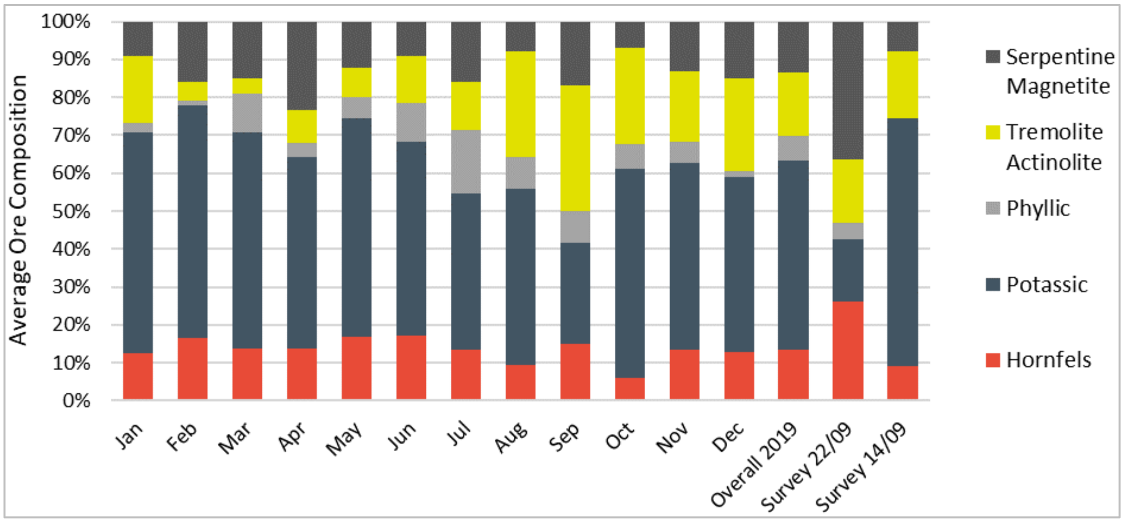


Figure 4—2019 Toromocho Feed Blend Composition by Alteration

COMMINUTION CIRCUIT ASSESMENT

Historical operating data from 2019 and 2020 were used along with the 2019 grinding surveys to assess the performance of the Chinalco comminution circuit, identify opportunities to increase throughput, and calibrate process models. The main findings of the process data analysis are summarized below.

Primary Crushing

The primary gyratory crusher at Chinalco typically processed around 7,000 t/h of ROM ore, with peak throughputs exceeding 8,200 t/h, meeting the designed crusher capacity. However, the crusher power draw was consistently low, ranging from 150 to 300 kW for 75% of the time, indicating potential for increased power utilization by reducing the crusher gap. The crusher open side setting (OSS) was generally set to 7½ inches, resulting in a closed side setting (CSS) of about 5¼ inches. Therefore, the impact of a smaller crusher gap on the primary crusher volumetric capacity and crusher product size was investigated with simulations, as discussed in Results.

SAG Milling

Two sets of process data were analyzed, covering March to September 2019 and January to June 2020. The results indicated that the SAG mill was generally operated at a rate of approximately 4,700 dry tonnes per hour (dt/h). The power utilization was typically in the range of 75%–80% of the installed power, corresponding to 21 to 22 MW (Figure 5). The low SAG mill power utilization was the result of low rock charge in the mill, which was caused by the fine SAG feed, as explained in further detail below.

The SAG mill was operated at a relatively consistent speed (Figure 6). The mill was initially operated at 9.0 revolutions per minute (RPM) when the liners were new, corresponding to approximately 73% of critical speed (CS). As the liners wore out, the speed was increased to 9.4 RPM (76% of CS). Additionally, the SAG mill was operated in both directions due to the bi-directional shell-lifter design and radial pulp-lifter design. To enhance operational efficiency, also investigated were: taking advantage of the fine SAG feed size, improving shell liner design, and installing curved pulp-lifters for uni-directional operation.

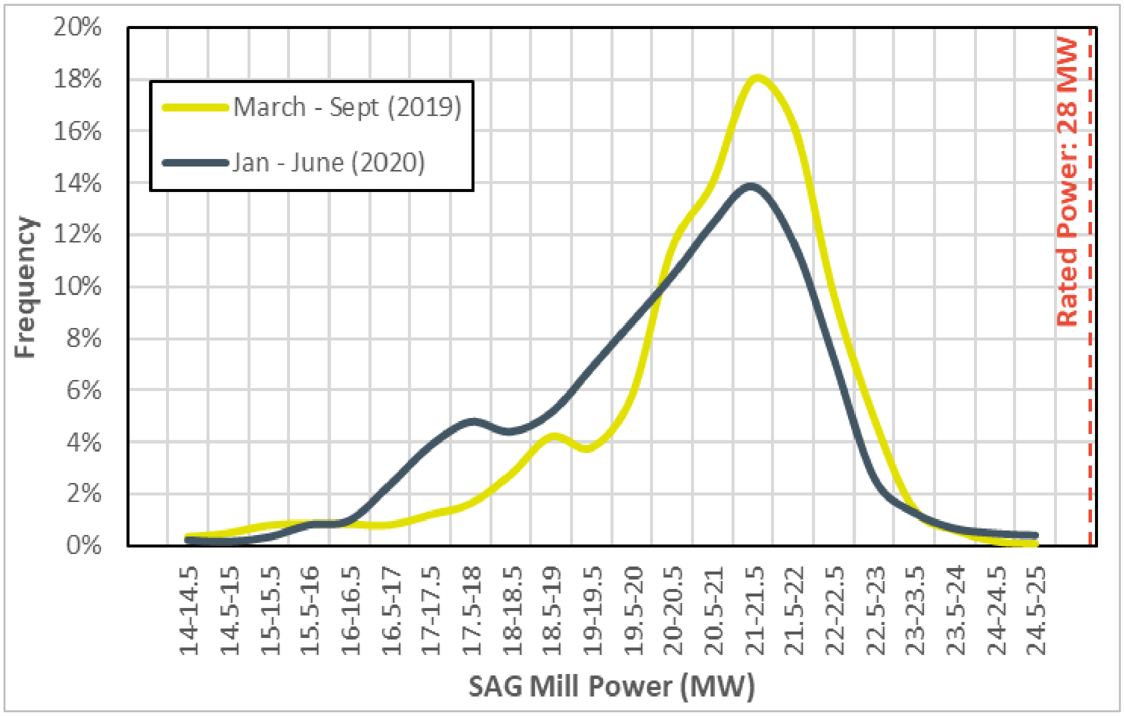


Figure 5—Distribution of SAG Mill Power Draw (2019 and 2020)

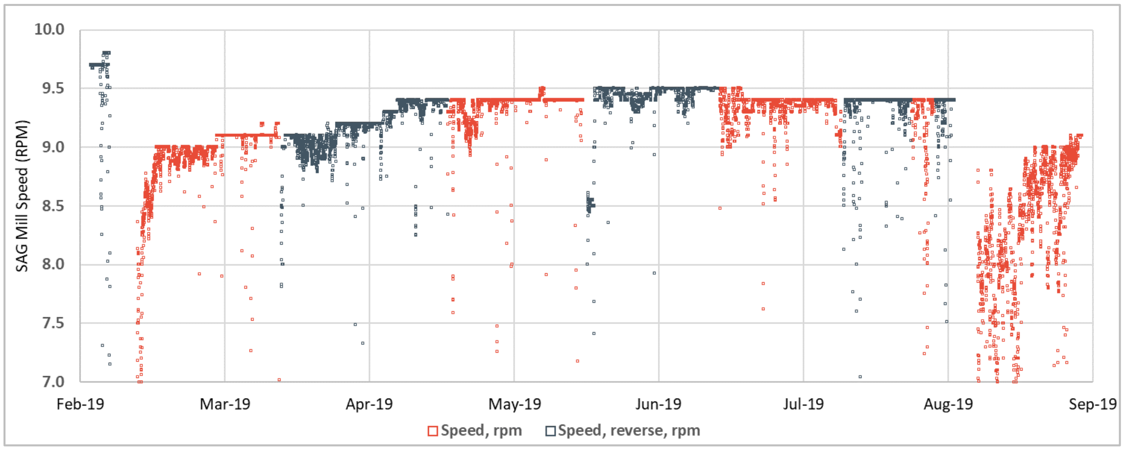


Figure 6—SAG Mill Speed Change Over the Liner's Lifetime

The Morrell tumbling mill power draw model (Morrell, 1996) was used to back-calculate the SAG mill total filling, which ranged from 22% to 28 % by volume, using a ball charge between 16% and 19% by volume, as measured during grind-outs. The low to medium volumetric filling of the mill is consistent with the fine feed fed to the

Phase 1 grinding circuit. With the fine feed, the SAG mill does not maintain a large rock load and operates more like a large ball mill, where most of the rock particles are much smaller than the steel balls. Sufficient surface area of steel grinding media is necessary for the ore particles to be broken. Therefore, the SAG mill should be operated more like a large ball mill with a high ball charge to increase grinding efficiency and throughput. In light of these conditions, lifter and liner design, mill speed, and discharge grate and discharge pulp-lifter arrangements were optimized, as detailed in Results.

Pebble Crushing

Analysis of historical and survey data indicates that the production of pebbles with respect to fresh feed was approximately 18%(Figure 7). During the period analyzed, the pebble crushers were found to operate with different liner designs, resulting in a power draw range of 450 to 650 kW (Figure 8). This range was below the installed power of 750 kW (1,000 horsepower), equivalent to 60%–78% of rated power. To optimize throughput, it was recommended to operate at power draws between 80% and 100% of rated power (600 to 750 kW), which can be achieved by modifying the liner profile to operate with a CSS of 11 mm, as highlighted in Figure 8 by the red arrow representing changes for Pebble Crusher 1. Furthermore, simulations were conducted to evaluate the potential benefits of operating both crushers with smaller CSS, and minimizing the operational mode of bypassing the crushers (from historical data this occurs for around 10%–15% of the operating time).

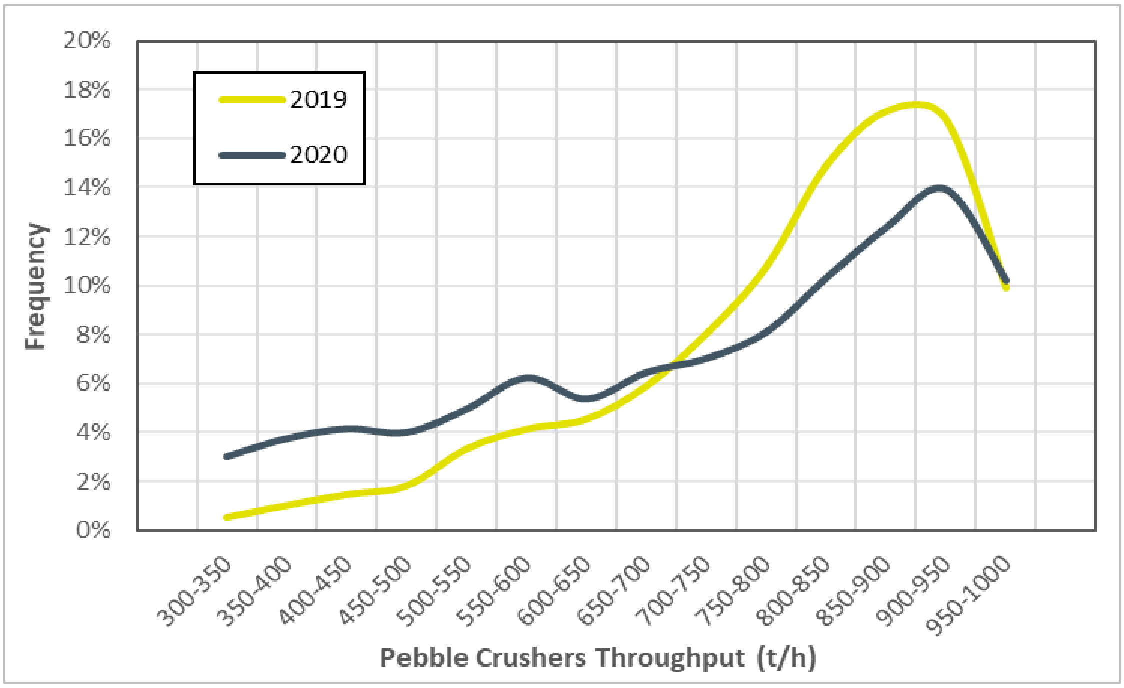


Figure 7—Frequency Distribution of Pebble Throughput

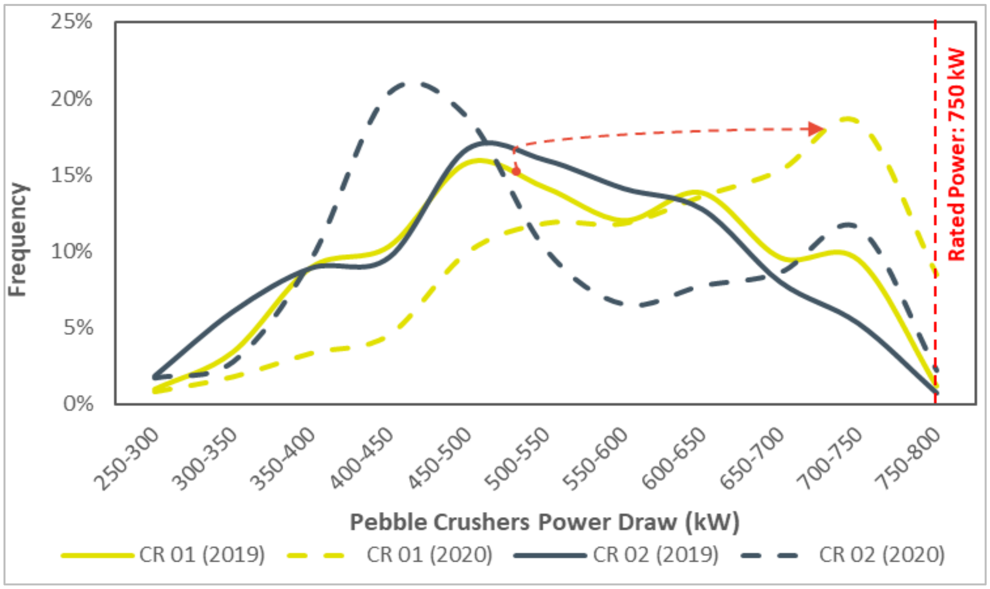


Figure 8—Frequency Distribution of Pebble Crushers Power Draw

Ball Milling

The two ball mills (BM 1 and BM 2) were operated over a relatively wide range of power draws, from 18.0 to 20.5 MW, equivalent to 80% to 93% of the installed power of 22 MW (Figure 9). The wide range of power draws was the result of variations in ball charge levels in the mills.

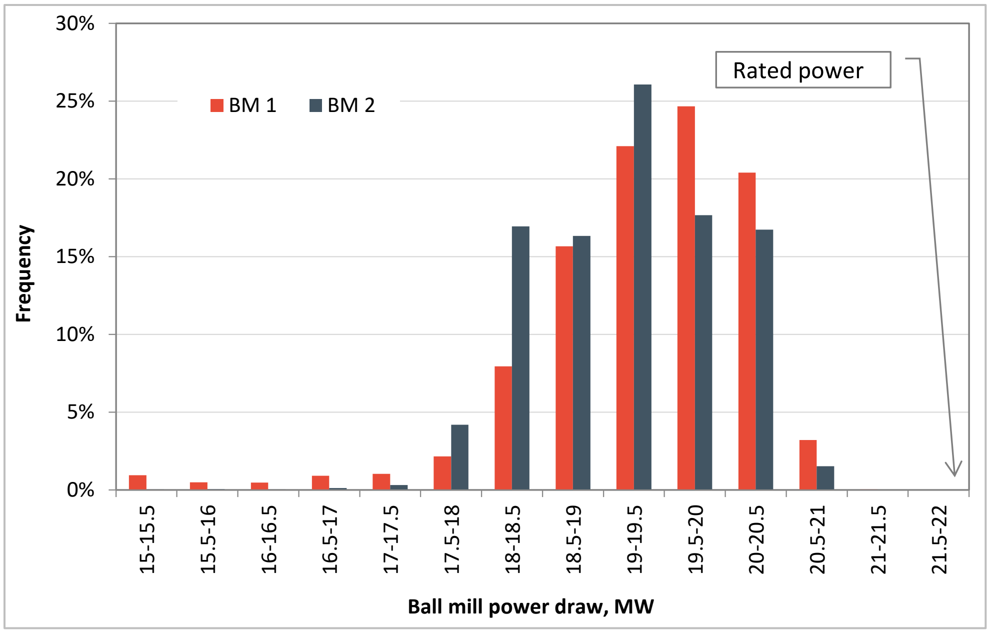


Figure 9—Frequency Distribution of Ball Mill Power

To maximize ball mill power at Chinalco, the ball mill speed was previously around 80% of CS, which is considered higher than typical for ball mill operation. As ball mills have gotten larger in the mining industry, gearless drives are required, such as the ones installed at Chinalco. These have variable speed for maintenance activities and to release compacted loads after prolonged stoppages (inching and creeping modes).

However, from a process optimization perspective, it is preferable that ball mills are operated within a narrow range of speeds. Changing the ball mill speed frequently affects the balls trajectory, diverging from the optimum, and also increasing the risk of liner and grinding-media damage. These issues can also adversely impact the recirculating load, final product size, and cyclone efficiency and stability, which can make the circuit more challenging to control. For maximum performance, ball mills are generally operated at around 75% of CS. This promotes more contacts between the grinding media and ore by the cascading motion of the balls, instead of the cataracting motion (higher speed) which is advantageous for impact breakage in SAG milling. While higher speed allowed for higher power draw at Chinalco, Hatch recommended reducing the speed and increasing ball charge to maximize ball mill power draw. This would provide more grinding media and ball surface area to generate more grinding action. The Morrell tumbling mill power draw model was used to estimate the incremental power draw resulting from higher ball charges. To allow for an additional 1% in ball charge, the speed could be reduced slightly from 80% CS to 78% CS, and it was determined that a ball retaining-ring would be required to facilitate a higher ball charge. Detailed simulations, reported in Results, were conducted with the objective of using the additional ball mill power (obtained from higher ball charge) to maintain the product grind size while increasing SAG mill throughput.

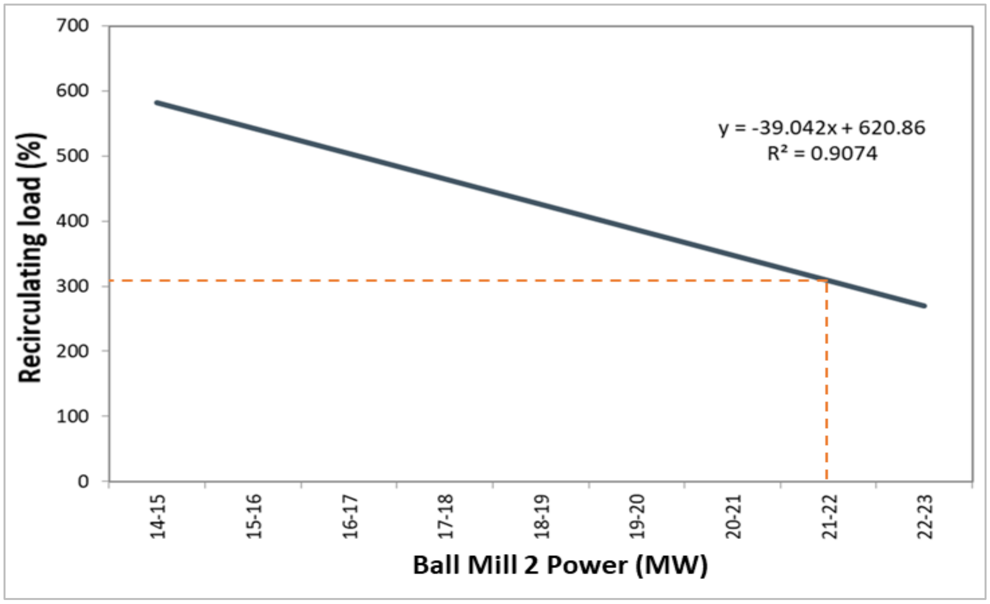


Figure 10—Influence of Ball Mill Power Draw on the Recirculating Load

Maintaining a constant ball charge and ball mill power draw is critical for controlling both the recirculating load and product grind size in the ball mill circuit. In fact, the recirculating load for both ball mills showed a wide variation, ranging from 300% to 500%. However, between March and September 2019, a significant reduction in the recirculating load was observed. This reduction in recirculating load was linked to the reduction of variation in ball mill speed and increase of power draw through higher ball charge over the period (Figure 10). This was also confirmed after BM 2 power was successfully increased to 21–22 MW, which resulted in a recirculating load of around 300%, as expected from the linear relationship between recirculating load and power derived from the operating data (Figure 10). Since August 2020, this ball mill is operated at around 77%–78% CS at maximum ball charge, which reduced the recirculating load, and with decreasing cyclone feed density resulted in more efficient classification in the cyclones.

Results

GRINDING CIRCUIT SIMULATIONS

Hatch analyzed the data Toromocho collected during the Phase 1 grinding circuit surveys on September 14 and 22, 2019, to develop a detailed site-specific (calibrated) mathematical process model. Laboratory sizing data from both surveys were mass balanced. The survey data from September 14 achieved a good mass balance and were considered suitable for model development. A model was developed, then calibrated for the Toromocho Phase 1 grinding circuit using model fitting, based on the ore characterization data (hardness) and survey results. The resulting JKSimMet model flowsheet (Figure 11) was used for simulations of the identified optimization strategies discussed below.

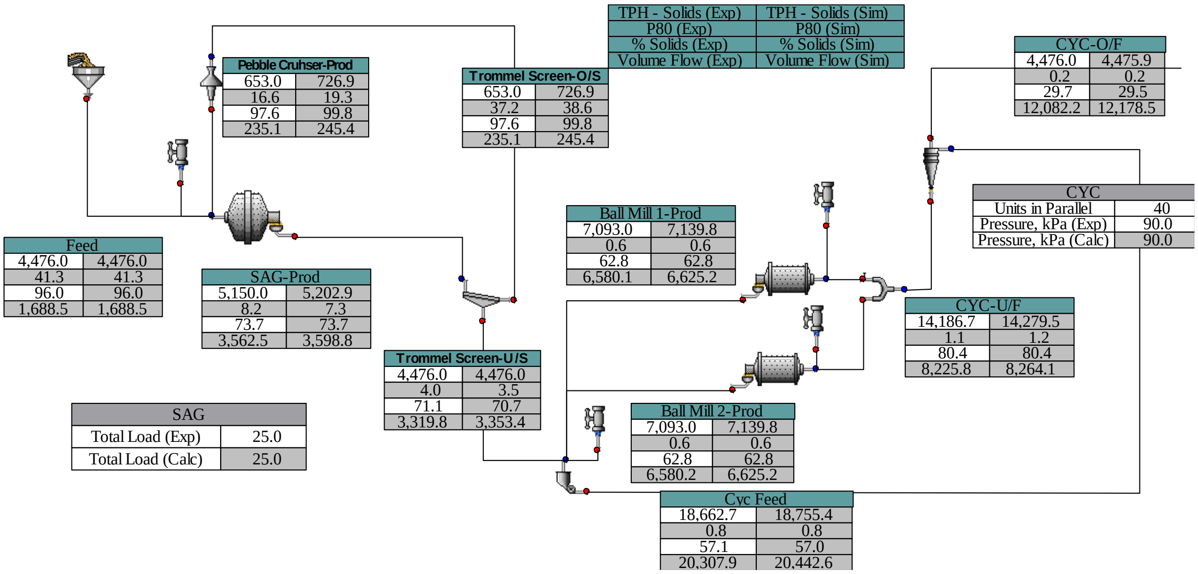


Figure 11—JKSimMet Model Flowsheet, Phase 1, Calibrated to September 14, 2022, Survey Data

Simulations were conducted to evaluate the improvement opportunities identified in the analysis section, above, and to quantify their benefits. These opportunities included:

- Simulation 1: Increase SAG mill pebble ports size and pulp lifter discharge capacity
- Simulation 2: Simulation 1 plus optimized SAG mill ball charge
- Simulation 3: Simulation 2 plus reduced both pebble crushers CSS to 11 mm
- Simulation 4: Simulation 3 plus increased ball mill power to maintain current P_{80} product grind size
- Simulation 5: Simulation 4 plus wider primary crusher OSS.

The results of the simulations are summarized in Figure 12 and discussed further in the subsequent sections. In Figure 12, survey conditions and results are included for reference, and simulations are compared to the base-case simulation, which represents the average operating conditions for 2019. Figure 12 also includes the detrimental impacts of SAG mill discharge grate-pegging and bypassing of the pebble crushers.

The simulations indicated the throughput can be increased up to 14% while maintaining the current P_{80} product grind size. Further details and recommendations to achieve this are discussed below. The fifth simulation was conducted to demonstrate the impact of operating with a wider primary crusher gap, required to meet the crusher throughput and volumetric capacity requirements following the installation of the additional Phase 2 grinding circuit.

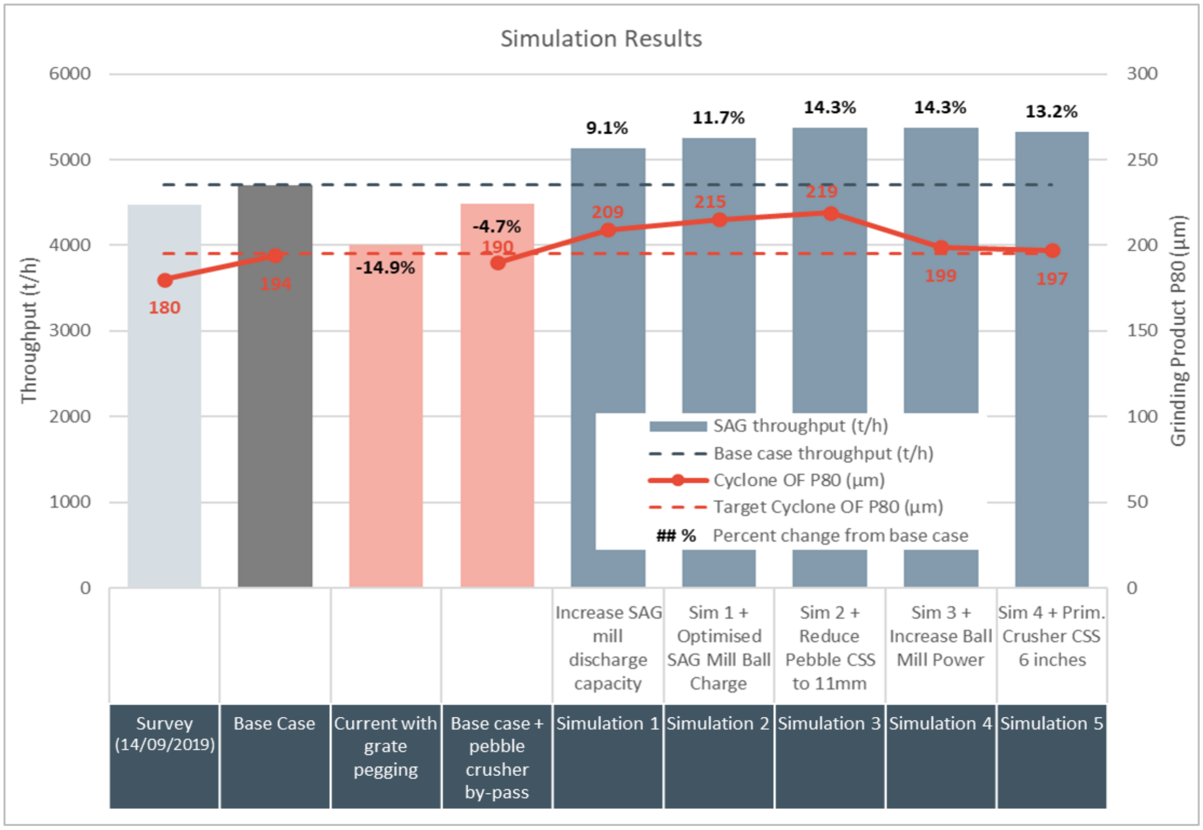


Figure 12—Summary of the Main Process Simulations and Recommendations for Increasing Throughput of the Phase 1 Grinding Circuit

Recommendation 1: Optimize the SAG mill discharge grate, discharge cone, and pulp-lifter designs

The greatest opportunity to increase throughput at Toromocho was to improve the discharge capacity of the SAG mill. At the time of the study, mill throughput had been significantly reduced due to severe grate-pegging, and the pulp lifters were volumetrically constrained.

Larger pebble ports were recommended to mitigate the issue of grate pegging and increase the volumetric flow rate of both pebbles and slurry. According to simulations, increasing pebble ports aperture from 65 to 80 mm would significantly increase the pebble discharge rate. This change would allow the worn balls to be ejected from the mill before reaching a critical size and deformed shape that are more prone to pegging. Similar improvements in pebble discharge rate have been reported by Hart et al. (2001) and Rybinski et al. (2011) when increasing pebble port size. In addition, pulp-lifter capacity must also be sufficient to accommodate for the increase of flow rate due to larger pebble port apertures. As a result, design changes to pulp lifters were also proposed. Simulations revealed that just by increasing pebble port apertures to 80 mm and improving discharge capacity (with the proposed modifications to the pulp-lifter design discussed below) the throughput should increase by almost 10%.

The benchmarking of Toromocho's SAG mill against Hatch's database indicated that the Phase 1 SAG mill is currently on the cusp of being discharge limited, and likely to be slurry pooling intermittently. Any effort to increase throughput rates with higher power draws and circuit optimization will be limited by the discharge capacity of the mill (maximum of 3600 m^3/h at 25% total filling with existing radial pulp lifters), leading to slurry pooling that reduces mill power draw and milling efficiency.

Hatch developed optimized radial and curved pulp-lifter designs (Figure 13) for the Phase 1 SAG mill to improve the discharge capacity. Both designs incorporated removing the single-piece discharge cone. A single-piece discharge cone often results in a higher curvature of the discharger—that is, a tight bend. This integrated cone design limits the volume of the pulp discharger. Having sufficient capacity in the pulp discharger is particularly important as this region of the pulp lifter will naturally act as a choke point as the slurry and ore are taken from the periphery of the mill and funnelled to the discharge trunnion.

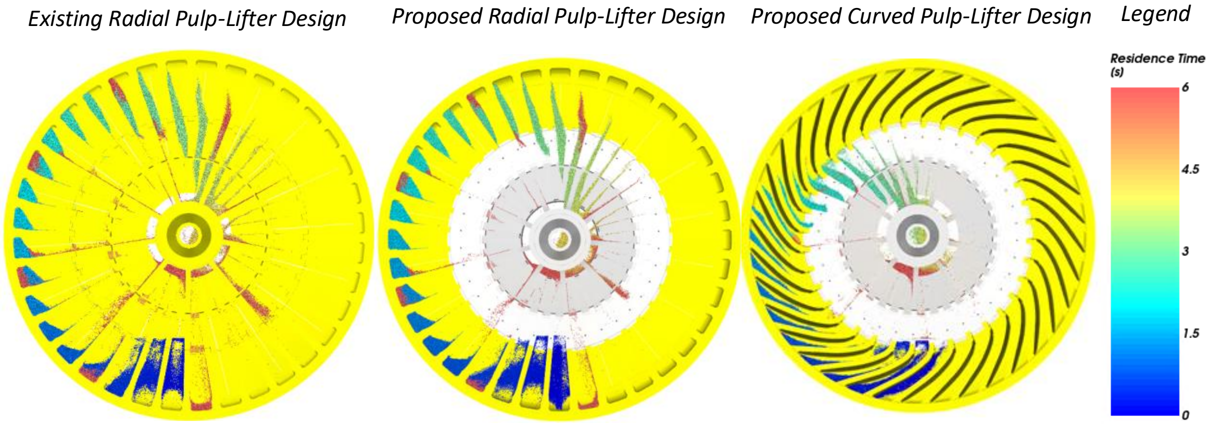


Figure 13—Residence Time Profiles for Proposed Pulp-Lifter Designs Simulated by Discrete Element Modelling for Phase 1 SAG Mill

Both proposed designs feature separate discharger pieces on each pulp-lifter vane, allowing for a smaller curvature of the discharge cone and a 10% increase in volume. To investigate the benefits of replacing the existing radial pulp-lifter system with the proposed curved design, discrete element modelling (DEM) simulations were completed in Rocky DEM software. Key inputs to the DEM model were the existing and proposed lifter geometries and the mill discharge particle-size distribution. The mill discharge particle-size distribution used was determined from the mathematical SAG mill model developed from survey data (Figure 11) and was truncated at the fine end to achieve practical computation times.

The pulp-lifter DEM simulation outputs confirmed that carry-over is virtually eliminated with a curved design compared to the existing and optimized radial design. This is visibly evident in the residence time profiles in

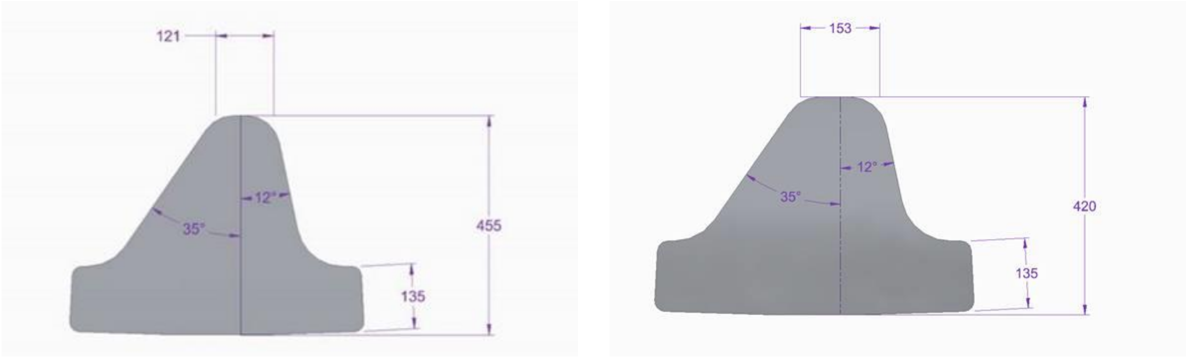
Figure 13. Large pockets of returning particles (red) can be seen taking up space in the lifter cavities of the existing and proposed radial designs, while the proposed curved design exhibits a significantly reduced carry-over of particles. The curved pulp-lifters also display an earlier discharge of particles from the lifter cavity than the radial equivalent. Where the curved pulp-lifter design discharges at around the 11 o'clock position, the radial pulp-lifter designs discharge closer to the 1 o'clock position allowing for the large amount of carry-over.

The DEM modelling indicated an 8% increase in discharge capacity with the proposed radial pulp-lifters because of the increase in chamber volume. The curved pulp-lifter design has a larger discharge volume in addition to curved vanes and provided an increase of 23% capacity for the pulp lifters. The larger capacity increase for the curved pulp-lifter is due to the material being discharged earlier in the mill rotation compared to the radial pulp-lifters. Murariu (2019) reported up to 40% increase in simulated discharge capacity of the solids between radial to curved pulp lifters designs using DEM-SPH modelling, and similar effect of reduced carry over and hold up in the pulp lifter chamber were observed with curved pulp lifters. The optimized radial pulp-lifter design discharge-capacity has improved over the existing design, but there is still a risk of the SAG mill becoming discharge-limited before the 14% throughput increase (simulated for implementation of all recommendations) can be realized. Therefore, the curved pulp-lifter design was recommended.

The SAG mill grates arrangement was later modified by replacing 15 of the 18 grate panels with panels featuring 65 mm and 75 mm pebble ports. The issues caused by pegged previously observed were resolved. While the pulp-lifter configuration is currently still the same radial design, the detailed design and supply of the curved pulp-lifters is currently being discussed with vendors for implementation.

Hatch also evaluated opportunities to improve the design of the SAG mill shell lifters considering single-direction rotation, which is required for the curved pulp-lifters, and to exploit, as much as possible, the fine SAG feed size. Analysis of the liner wear from historical mill internal scans indicated that the dual-rotation shell lifters were generally worn beyond their stated reline limit, which can increase the risk of liner failure. The severe wear on the shell lifters and liners was attributed in large part to the limited top span of the high lifter. On the existing dual-rotation liners, the top span of the high lifter was 40 mm on the feed end and 104 mm on the discharge end, which is significantly narrower than the typical top span of single-direction lifters for SAG mills of this size. Limiting the top span reduces the wear life of the high lifter and limits the extent of the "shadowing" effect, by which the high lifters protect the plate liners.

Hatch proposed a single-directional liner design with a 35° face angle, featuring a 121 mm and 153 mm top span on the high lifters at the feed and discharge ends. The increased top span should help to address the high wear on both components while providing an optimized media trajectory for the recommended mode of operation, as discussed below. The proposed design is shown in Figure 14. While no increase in the service life of the shell lifters was expected, the proposed design should provide a higher safety margin and plate thickness at the time of relining due to the increase in top span, as well as improved grinding-media trajectory.


35° Face Angle, Single Direction, Feed End

35° Face Angle, Single Direction, Discharge End

Figure 14—Proposed Single Rotation Design, Single Direction 35° (Left)

Simulations using MillTraj software (V2.3.78) compared the media trajectories of the existing and proposed lifter designs; results are shown in Figure 15. The simulation results indicate that with the existing dual-rotation lifter design and 30° face angle, the media would strike the charge at the midpoint of the expected position of the charge's toe, assuming a total filling of 26%. Conversely, the simulations with the proposed single direction lifter, which had 35° face angle, indicated that the media would strike beneath the toe position of the charge, as expected. This lower trajectory is expected to promote more attrition and abrasion breakage, which is consistent with the recommended mode of operation for the SAG mill (like a large ball mill), based on a high ball charge-level and receiving fine feed.

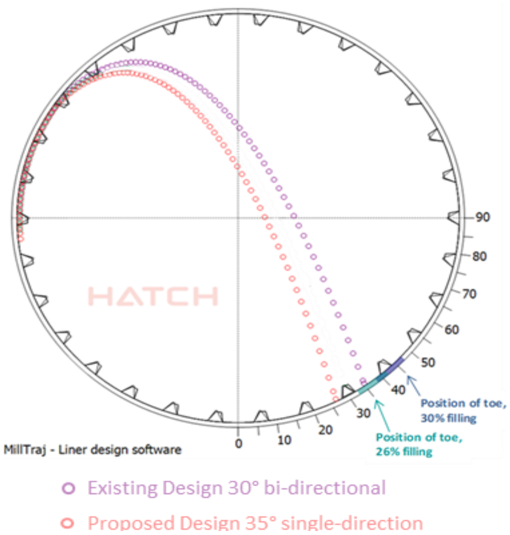


Figure 15—MillTraj Simulation of Outermost Charge Trajectories

Recommendation 2: Increase SAG mill power by increasing ball charge in the SAG mill

The Toromocho Phase 1 SAG mill is fed with relatively fine material, meaning that most of the rock particles are much smaller than the steel balls in the SAG mill. As a result, it is recommended to operate the SAG mill more like a large ball mill, with a high ball-charge to increase grinding efficiency of finer breakage. Mill performance will be optimized when there is more attrition and abrasion (for finer breakage) rather than impact breakage (which is required to break coarse material, which is not present in the Toromocho Phase 1 SAG mill feed). To achieve this, it is suggested to use a higher ball-charge and optimize the lifter and liner design as discussed previously.

Simulations indicated that even a small increase in SAG mill ball charge, from 19% to 20%, would give an additional 2% to 3% increase in throughput, thus giving a total throughput increase of almost 12% when combined with a larger pebble-port and improved discharge capacity (Recommendation 1). As identified earlier, the SAG mill has sufficient installed power for the increased ball charge.

Recommendation 3: Pebble crushing circuit optimization with smaller CSS while minimizing bypass

In 2019, chamber design changes were implemented on one of the two pebble crushers, allowing operation at a reduced CSS of 11 mm. Simulations confirmed that operating both pebble crushers consistently with a tighter CSS of 11 mm would provide an additional 2% increase in throughput.

However, further analysis of the existing pebble crushing circuit revealed that with higher throughputs due to the improved SAG discharge system, pebble production will increase significantly, becoming the new bottleneck. Therefore, extra crushing capacity would be required to maintain the tighter CSS of 11 mm in both crushers. Consequently, the following additional scenarios were also simulated:

- Comparing a) the effect of bypassing a portion of the pebbles and sending them back uncrushed to the SAG mill, against b) no bypass, but operating crushers at wider CSS
- Upgrading the pebble crushers with additional power or replacing them with a larger model.

It is generally preferred to minimize the bypass of pebble crushing by maximizing the availability and utilization of both pebble crushers. Simulations confirm that the throughput of the SAG mill would gradually decrease as the amount of bypass increases, and bypassing 100% of the pebbles reduces the SAG fresh feed by around 5%. Additional simulation indicated the reduction in throughput may be larger than 10% for harder ores. As indicated earlier, operating both crushers at a smaller CSS of 11 mm would help to increase SAG mill throughput by 2%. However, when the SAG mill discharge system is improved, and pebble tonnage is increased, a wider CSS would be required to avoid any pebble crusher bypass. Additional simulations indicated it would be more beneficial to operate with a wider CSS and no bypass, rather than a smaller CSS of 11 mm and bypassing a portion of the pebbles.

Two potential upgrade paths for the pebble crushers were identified. The XL1100 crushers could be fitted with a larger 820 kW motor, which would provide an increase in available power of 9%; however, this would not increase the volumetric capacity of the crushers. The XL1100 crushers could also be replaced with XL1300 crushers. This would increase crushing capacity, but this larger model would not allow operating with a CSS of 11 mm as is the case with the XL1100.

Recommendation 4: Install retaining ring and increase ball charge in the ball mills

Implementing all previous recommendations is expected to increase throughput by up to 14%. However, the simulations also showed that the grinding product would coarsen slightly to about P_{80} 220 µm.

Increasing the ball mill power draw would reduce the grinding product size, which is back in line with the target (simulations estimated P_{80} 195 µm) at the higher SAG throughput rate. As discussed earlier, the power draw model demonstrated that it is possible to increase the ball mill power draw by increasing the ball charge with the installation of an inner retaining ring. Simulations also indicated that the water addition to the cyclone underflow launders (required at the time due to volumetric limitations) should be reduced to provide an increased ball mill feed density of around 76% solids by weight. Evaluation of the slurry superficial velocity and of slurry retention time in the ball mill after installation of a ball retaining ring and higher ball mill slurry density of 76% indicated that the slurry flow would not exceed recommended limits (Morrell, 2001; Shi, 2016).

Recommendation 5: Optimizing primary crusher gap

As the primary crusher throughput for a given CSS is largely controlled by the largest rocks in the ROM, optimization of the drill and blast operations, and finer ROM fragmentation generally results in the opportunity to reduce primary crusher CSS and further reduce SAG mill feed size. At the time of the study, the primary crusher power draw was also low, presenting an opportunity to operate with a tighter CSS. Primary crusher simulations indicated that the primary crusher operating OSS of 7.5 inches could be reduced to 6.8 inches while maintaining sufficient crushing capacity. Simulations indicated that this decrease in the primary crusher gap should increase SAG mill throughput by about 1%.

However, the installation of the additional grinding circuit (Phase 2) in parallel with the existing grinding line required an increase in the primary crushing throughput. The volumetric capacity of the primary crusher would not be sufficient to provide feed to both grinding circuits if the gap was reduced. It was identified that the gap would need to be increased to provide sufficient capacity, which would, in turn, increase SAG feed size. Simulations indicated coarser SAG mill feed would result in a reduction in SAG throughput of about 1%. Instead of increasing the gap, the primary crusher was upgraded, and the primary crusher speed was increased. This resulted in an increase in the primary crusher volumetric capacity while maintaining the OSS at 7.5 inches.

Additional recommendations and simulations for short-term circuit optimization

While the detailed design and supply of the optimized SAG mill pulp-lifters were in progress, additional simulations were conducted to explore opportunities to optimize the Phase 1 grinding circuit in the short term (quick-win opportunities), while the existing radial pulp-lifters remained in the SAG mill. Some recommendations had already been implemented, such as increasing ball charge and power draw at lower speed. Additional assessments and simulations from Hatch provided alternatives to maximize throughput while reducing size of the grinding circuit, leveraging from the improvements already made. Some of the opportunities identified were around SAG mill discharge-screen aperture, ball mill feed density, ball charge and ball size, as discussed below.

It was recommended to increasing the SAG mill discharge screen apertures from 10 mm to 15 mm. The SAG mill trommel is equipped with 13–15 mm apertures, and the trommel oversize material is discharged onto a double-deck vibrating screen with 10 mm bottom-deck apertures, unnecessarily recirculating material finer than the CSS of the pebble crushers. Using similar aperture size on the screen as the trommel would help reduce the recycle to the pebble crushers, while transferring grinding load to the ball mills. Simulations indicated this change resulted in a 2% increase in circuit throughput.

Increasing ball charge in the ball mill was progressively implemented in BM 2, currently drawing about 21–22 MW, which allowed reducing the recirculating load to 300%–320%, as expected from the data presented in Figure 10. Similar results are expected for BM 1 once the ball charge is also progressively increased.

Slurry density in the ball mills was ranging between 70% and 72% solids due to significant water addition required in the cyclone underflow launders. Simulations revealed that a reduction in P_{80} can be achieved by increasing the ball mill feed slurry-density up to about 76% solids.

Grinding efficiency could also be improved by adding smaller balls than the current ball make-up size of 3 inches (76 mm). Hatch conducted a ball size compliance analysis using both the Azzaroni (1980) methodology and

Molycop's methodology based on the theory of linear ball wear and continuous addition of one size of balls (Sepulveda, 2004). The ball size compliance method is used to evaluate the optimal ball size required to grind each size fraction of the ball mill feed size distribution (red bars in Figure 16) against the actual size distribution of the grinding media (grey and dark blue bars in Figure 16). The results indicated that smaller balls of 2½ inches (64 mm) will promote more effective grinding (overall compliance resulted 24.5% for 2½ inches versus 16.2% for 3 inches). These results were then validated using the ball mill mathematical models in JKSimMet to scale the breakage rates as a function of ball size. The models confirmed that further reduction in grinding product P_{80} size was achievable. However, it was also recommended to maintain a proportion of 25% of 3 inches balls in the make-up ball mix, to ensure breakage of coarse particles fed to the ball mills.

Overall, these short-term changes are expected to result in a 2% increase in throughput combined with a reduction of recirculating load, and final grind reduction of about P_{80} 20 µm. Implementation is in progress.

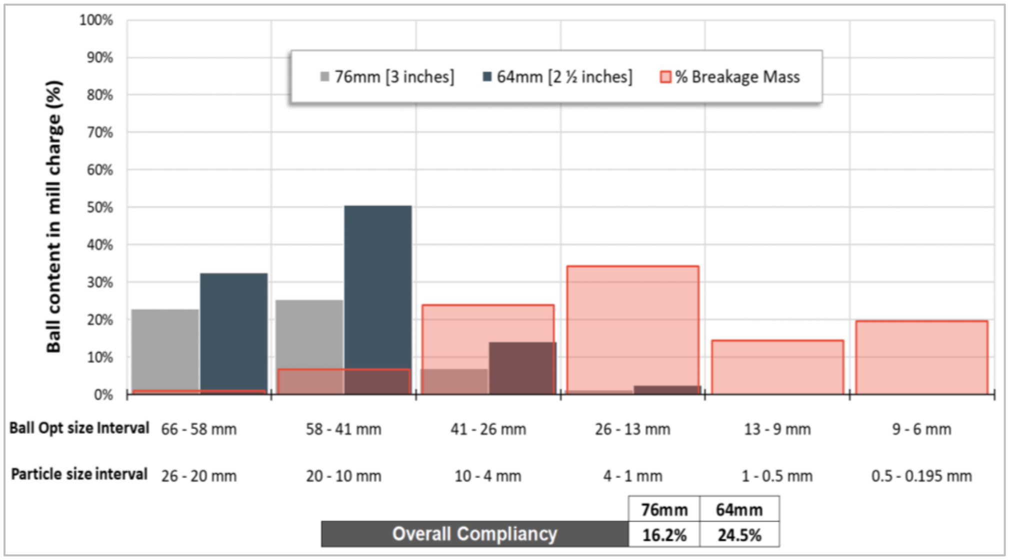


Figure 16—Comparison of Ball Size Distribution Compliance for Ball Mills

THROUGHPUT FORECAST MODELLING

During the optimization project, Hatch gathered all the information required to develop a throughput forecast model. Accurate throughput forecast models are useful production tools that can assist in improving production reliability, strategic planning, and which can maximize profit over the life-of-mine (LOM). Power-based modelling is widely adopted for comminution circuit design and can also be used for throughput forecasting when the future ore properties are known. Hatch developed a power-based throughput forecast model for the Toromocho comminution circuit, and has successfully developed and implemented similar throughput forecasting tools (Brennan et al., 2022; Farmer et al., 2021).

Feed size has a strong influence on throughput, and is thus an important imput for throughput forecasting, but it is influenced by ore characteristics and blasting practices. Therefore, it is necessary to establish a reliable model of feed size to provide an accurate throughput forecast. Specifically, the throughput forecast model developed for Toromocho calculates SAG feed F_{80} based on a regression model between the proportion of each alteration domain in the blend and the SAG mill F_{80} measured by Split-Online. The model then calculates the total circuit specific-energy, as well as SAG mill specific-energy, based on ore hardness properties and the calculated SAG mill feed F_{80}, using equations derived from Morrell (2009). The specific energy is then used for a given SAG milling and ball milling power to determine plant throughput.

The throughput forecast model was calibrated and then validated using historical production data (March 2019–February 2020) and was supported by mathematical process models developed during the optimization project. A comparison of the model estimated-throughput (grey dashed line) and actual plant throughput (red dots) is shown in Figure 17. In this figure, the red line represents the separation between the data used for model calibration and the data used for model validation. On the left side of the line, the data were used to calibrate the specific-energy calculation (the site-specific SAG kWh/t and total kWh/t equations), on the right side of the line, the predicted data were compared with the actual data without further modification of the model parameters.

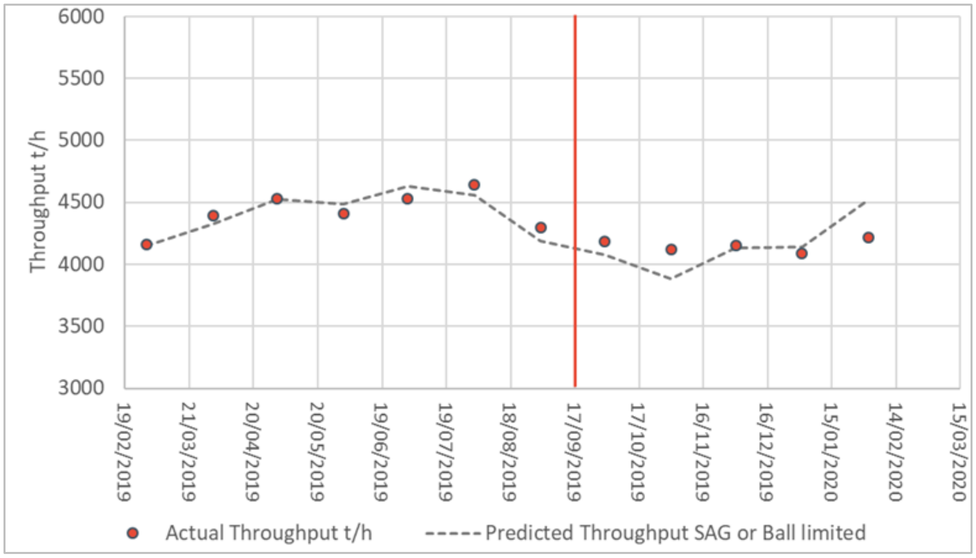


Figure 17—Actual Monthly Average Plant Throughput Compared with Predicted Throughput

Despite limitations in terms of ore characterization available at the time when the model was developed, the model predicts throughput quite well on a weekly and monthly basis, with errors of 11% and 3.5%, respectively, at the 95% confidence level. Improvements in model accuracy are expected when the additional ore hardness testwork and variability testing are incorporated into the block model and are used to improve the estimation of the present and future hardness values of the different alterations.

The model was then used to forecast the specific energy, throughput of the circuit based on the annual ore composition from LOM planning, and the future ore characteristics of the different alterations in the feed blend. The outputs of the LOM throughput model are expressed as annual throughput, using a typical plant availability, and indicate if the circuit is limited by the SAG or ball mills.

Conclusions

Chinalco has already improved the drill and blast operation, resulting in significantly finer ROM fragmentation. This fine fragmentation has led to a fine SAG mill feed, and the main objective of the study presented here was to optimize the Phase 1 grinding circuit operating conditions, leveraging the already fine SAG mill feed. Review of historical grinding circuit operating data, plant observation, benchmarking, power calculations, and mine-to-mill optimization experience from the Hatch team were used to identify opportunities to increase throughput for the Toromocho Phase 1 comminution circuit. Site-specific modelling and simulations have confirmed that throughput may be increased by about 14% while maintaining grinding product size.

The greatest opportunity to increase throughput of the Toromocho Phase 1 circuit is to improve the discharge capacity of the SAG mill. Larger pebble ports and improved pulp-lifter design have been proposed. Process simulations indicated that increasing pebble port aperture and improving discharge capacity would increase SAG throughput by 10%. The SAG mill, which receives a fine feed, should also be operated more like a large ball mill (high ball charge and modified trajectory through speed and lifter design) to increase grinding efficiency and throughput for fine feed. Proposed lifter designs will not only promote attrition and abrasion breakage for more-efficient fine grinding, but also reduce the risk of liner failure. Increasing SAG mill power utilization can be achieved by increasing SAG mill ball charge to 20%. Simulations indicated an additional 2%–3% increase in SAG mill throughput with a higher ball charge, totalling a 12% increase in SAG mill throughput with the improved discharge system. DEM simulations of the existing radial pulp-lifters and proposed curved pulp-lifters indicated the increase of the discharge capacity of the proposed design should safely accommodate the expected increase in SAG mill throughput. The detailed design of the pulp lifters is currently being discussed with vendors for implementation.

Simulations initially indicated operating both pebble crushers with a smaller CSS of 11 mm would provide an additional 2% increase in throughput. However, the pebble crushing volumetric capacity limitations would mean that a portion of the pebbles would need to bypass the crushers. Avenues for increasing pebble crushing capacity are still being investigated, to ensure the pebble crushing circuit can handle the additional pebble rate when the SAG mill discharge system is debottlenecked, while still allowing operation at the recommended CSS.

Implementing all the above recommendations is expected to increase throughput by up to 14%. However, the grinding product would coarsen slightly to about P_{80} 220 µm. Increasing the ball mill power by increasing ball charge would reduce the grinding product size back in line with the target (simulations estimate P_{80} 195 µm) at the higher SAG throughput rate.

Opportunities to reduce the primary crusher gap to further decrease SAG mill feed size were evaluated and simulated (1% throughput increase with OSS reduction from 7.5 to 6.8 inches). However, due to the installation of the Phase 2 grinding circuit, increased primary crushing capacity would be required, and the gap reduction was not feasible. Instead, primary crusher upgrades were successfully implemented to maintain current primary crusher gap settings.

Additional quick-win opportunities were identified in the Phase 1 grinding circuit related to SAG mill discharge screen aperture, ball mill feed density, ball charge, and ball size. These recommendations, when combined, would allow a 2% in throughput increase, with reduction of recirculating load and a decrease of final grind to P_{80} 20 µm. Implementation is in progress.

The information and mathematical models generated in this optimization project were also used as a basis to develop a throughput forecast model to facilitate long-term strategic planning. Despite limitations in terms of ore characterization data available at the time of the model development, the model predicts throughput quite well on a weekly and monthly basis, with errors of 11% and 3.5 % respectively, at the 95% confidence level.

Further improvement in model accuracy is expected with new data, and the results of recent geometallurgical testing programs.

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