

Evaluating the Operating Performance of 40-Foot SAG Mill Circuit Designs

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Abstract

There are 23 operating 40-foot SAG mills in 2023, with another nine under construction or fabrication. Among these massive mills are significant variations in the design of the grinding circuit, with the main variables being pebble management and the ball milling circuit. This paper discusses and evaluates the various circuit designs, accounts for mill feed characteristics, and attempts to provide a high-level guide to future circuit designs. Specifically, operational performance in terms of the throughput rate and specific energy consumption are the main variables for consideration along with ore characteristics, operability, and maintainability.

Keywords

SAG, ball mill, pebbles, design, optimisation



Introduction

There are 23 operating 40-foot (ft) SAG mills in 2023 at 18 mine sites, with another nine mills under construction or fabrication. It is no surprise that most of these operations are in South or Central America, even though the first 40-ft SAG mill was commissioned in Australia in 1998 at the Newcrest Cadia Valley Operations (CVO) near Orange, NSW. This paper discusses and evaluates selected circuit designs and attempts to provide a high-level guide to future circuit designs based on operational performance and other observations.

The authors consider this paper to be a first attempt at a high-level evaluation of the biggest SAG mills globally. It is also recognised that comparing the operational performance of any SAG mill to another is challenging. The reader is cautioned that the intention of this paper is to increase general knowledge of 40-ft SAG milling circuits with some specific examples, while providing some general comparisons using the most basic and familiar mineral processing data. In this paper, all mill measurements are 'diameter inside shell (in feet)' x 'flange-to-flange length (in feet)'.

Overview of 40-Foot SAG and Ball Mill Circuits

As expected in the mineral processing industry, there are variations in the fresh feed characteristics of each 40-ft SAG mill, including the feed size distribution and mineral hardness. There are also significant differences in circuit configuration, ball milling capacity, and pebble management.

HISTORY

CVO is owned and operated by Newcrest Mining Limited and became the first operation to feature a 40-ft SAG mill. The grinding circuit consisted of a 40 x 22 SAG mill (20 megawatt [MW]), with two 22 x 36 (9.8 MW) ball mills and pebble crushing. A review of related technical papers in the late 1990s reveals that the mineral processing industry was anticipating many more 40-ft SAG mills to follow over the next two decades, and these predictions became a reality (some papers even suggested 44-ft SAG mills were possible).

The Collahuasi operation in northern Chile (then owned by Falconbridge Mining) commissioned the second 40-ft SAG mill in 2002. This expansion to the existing plant consisted of a 40 x 24 SAG mill (21 MW) with two 26 x 38 (15.5 MW) ball mills and pebble crushing.

The global market copper price was just over US\$1 (per pound) in 2003 and increased over the next four years to >US\$3.5 in 2007. This was the main driver for some major mining companies to proceed with plans for more massive operations, which would include the proven application of a 40-ft SAG mill. The Centinela operation was next in 2008 and was the first to feature a secondary and tertiary crushing circuit combining with a complex pebble circuit intended to bypass the SAG mill directly to the ball milling circuit.

During 2011–2016, 12 more 40-ft SAG mill operations commenced, but at this time the copper price steadily decreased to US\$2.5 which placed several projects on hold. Copper remained at <US\$3 until 2020, but this consistency, combined with confidence that the price would continue upwards, prompted further commitments. As such during 2019–2022, another nine 40-ft SAG mill operations commenced; the copper price also made another step upwards, as per the general market expectations, to the current value of about US\$4.

Figure 1 shows the chronology of the 23 operating 40-ft SAG mills over the past 25 years, and Figure 2 shows the current ownership of the manufacturers.

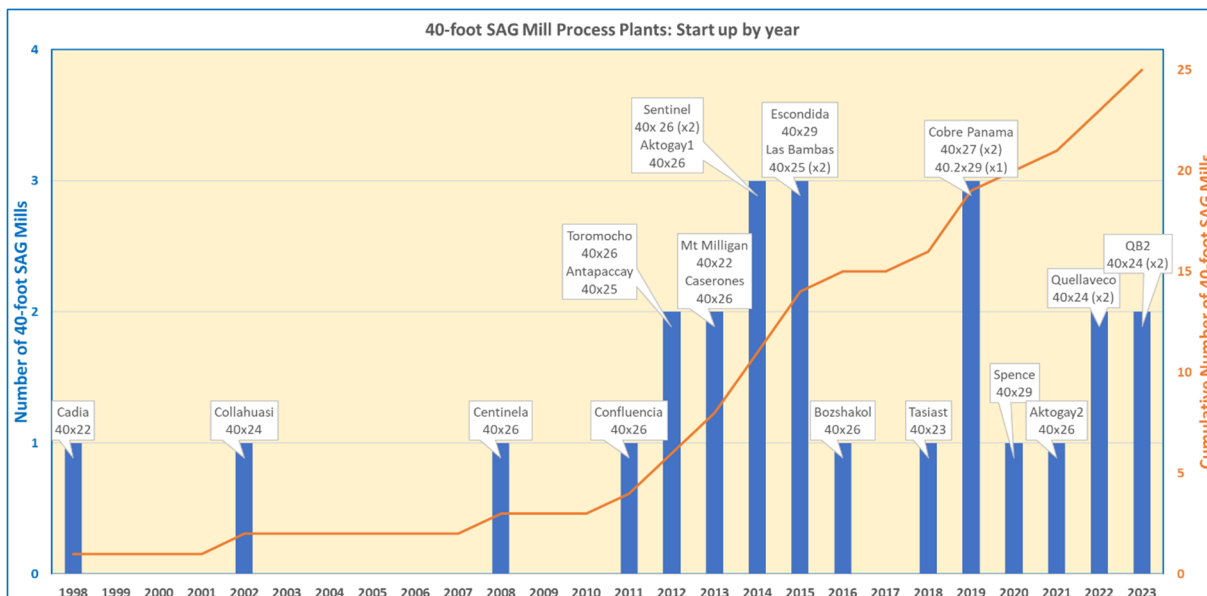


Figure 1—40-ft SAG Mill Process Plant Commissioning Year

❖ 16 Mills:		❖ 9 Mills:	
SAG 5 OGP1 - MEL	Ø40' x 29'	SAG 3 - Cobre Panamá	Ø40.2' x 29'
SAG - Spence	Ø40' x 29'	SAG 1/2 - Cobre Panamá	Ø40' x 26.7'
SAG1 - Toromocho	Ø40' x 26'	SAG CF - Los Bronces	Ø40' x 25.5'
SAG - Centinela	Ø40' x 26'	SAG 1/2 - Quellaveco	Ø40' x 24'
SAG - Caserones	Ø40' x 26'	SAG 1011 - Collahuasi	Ø40' x 24'
SAG 1/2 KAZ - Aktogay	Ø40' x 26'	SAG - Mount Milligan	Ø40' x 22'
SAG KAZ - Bozshakol	Ø40' x 26'	SAG C1 - Cadia	Ø40' x 22'
SAG 1/2 - FQM Sentinel	Ø40' x 26'		
SAG 1/2 - QB2 Project	Ø40' x 25'		
SAG 1/2 - Las Bambas	Ø40' x 25'		
SAG - Antapaccay	Ø40' x 25'		
SAG - Kinross Tasiast	Ø40' x 23'		

Figure 2—Manufacturers, Locations, and Lengths of 40-ft SAG Mills

The CVO mill was manufactured by Svedala which eventually became part of Metso in 2001; after 23 years of operation, the original 20 MW motor was replaced with a new 21.8 MW drive in 2021.

SAG AND BALL MILL CIRCUIT DESIGN

There is no standard design for SAG mill circuits, and design criteria usually involve the ore reserves, mining capacity (driving the desired plant feed rate), ore characteristics, feed size distribution, geographical considerations, and budget. In addition, the plant design will be based on experience (good and bad) of the operator or the selected engineering, procurement, and construction management (EPCM) company.

SAG mill design variations include, but are certainly not limited to the following:

- SAG mill feed stockpile will have primary crushing, possibly including secondary and tertiary stages.
- SAG mill discharge to vibrating screen deck, trommel screen, or both.
- Pebbles returned via water jet, recycled (crushed or uncrushed) to the SAG feed conveyor or to the SAG feed stockpile, directed to a separate stockpile, crushed and bypassed to the ball mill circuit.
- Configuration in open circuit, with discharge transferred to a secondary grinding circuit consisting of one or several ball mills, or in closed circuit with classifier coarse fraction as a circulating load, and fines to a secondary circuit.

SAG circuit design at the most basic level is a distribution of the total grinding work required between the SAG and ball milling circuits. Extensive testwork is conducted on a wide variety of ore samples to establish the mineral characteristics as well as the variability associated with each test. In addition, there will always be benchmarking against comparable operating circuits, steady-state tests, simulation, and experience.

Despite the extensive testwork and simulations, given the enormous capital cost of any large-scale mining operation and process plant, the main grinding equipment is generally upsized by 15% to ensure the target feed rate can be achieved and will provide a product at the size of interest, even at the extreme ends of the ore's expected resistance to breakage or when other operating conditions change. In addition, flexibility is built into the circuit to shift the grinding work from the SAG mill to the ball mill, and vice versa if required, due to inevitable changes in ore characteristics and other operational disturbances.

In summary, the designed SAG mill size and operating conditions typically dictate the plant throughput, while the ball mill circuit equipment (particularly the total installed power capacity) dictates the final product grind size.

EXISTING 40-FOOT SAG AND BALL MILL CIRCUIT DESIGNS

The most common configuration for 40-ft semi-autogenous grinding mill, ball mill, and crusher (SABC) circuits—SABC1—has the SAG mill discharge slurry transferred to a ball mill circuit feed sump, while pebbles are directed to a crushing circuit, and are then returned to the SAG mill feed conveyor or returned to the SAG mill feed stockpile. The ball milling circuit consists of two to four ball mills in closed circuit with cyclone classification, with the product fines delivered to the downstream processes.

One variation of interest in SABC1 circuits is the FQML Sentinel plant, where the SAG mill discharge slurry is pumped to a classification stage, with fines bypassed directly to the flotation stage and the coarse fraction transferred to feed the ball mill, while pebbles are directed to a crusher and returned to the SAG mill feed stockpile. The ball milling circuit consists of a single ball mill in closed circuit with cyclone classification, with the product fines delivered to the flotation stage.

A second variation of interest in SABC1 circuits is the Antapaccay plant, where pebbles are directed to a separate stockpile; from here the pebbles are reclaimed, crushed, and directed to the SAG mill feed conveyor according to the fines content in the fresh feed. The flexibility of operating one or two crushers provides a very wide operating range for the SAG mill, and as such any variability in the fresh feed mineral characteristics can be managed to consistently achieve the target throughput rate.

SABC2 circuits have the SAG mill discharge slurry transferred to a ball mill circuit feed sump, while pebbles are directed to a crushing circuit, which is delivered directly to the ball mill feed. The ball mills are in closed circuit with cyclone classification, with the product fines delivered to the flotation stage.

There is also the flexible SABC1-2 circuit, where the SAG mill discharge slurry is transferred to a ball mill circuit feed sump, while pebbles are directed to a crushing circuit including a secondary crushing stage and are generally transferred to the ball mill feed with an option to return to the SAG mill feed conveyor. The ball mills are in closed circuit with cyclone classification, with the product fines delivered to the flotation stage.

Finally, a SAG mill and crusher (SAC) circuit has the mill discharge slurry pumped to a classification stage, with the coarse fraction recycled directly to mill feed, while the fines become feed for a small secondary grinding circuit in which pebbles are directed to a crushing circuit and are then returned to the mill feed conveyor. The ball mills are in closed circuit with cyclone classification, with the product fines delivered to the pre-leach thickener. Tasiast (in Mauritania) is the only such 40-ft SAG mill operation with this closed-circuit configuration.

Design Variables Versus Operating Optimisation

It is important for any metallurgist to appreciate the difference between design and optimisation variables (Table 1). The EPCM will include as much flexibility as possible, for example pebbles being directed to the SAG mill feed conveyor or the SAG feed stockpile, but this is generally a function of available capital.

Table 1—Design and Optimisation Variables

Design Variables	Operating Optimisation
Ore Characteristics (Axb, BWi, etc.)	Mill Speed
SAG Mill Feed Size (F_{80}) and Distribution	Mill Density
SAG Mill Feed Rate (t/h)	Liner Design (slot, %open area, bucket vol, lift angle, slurry discharge system, etc.)
Grinding Circuit Product Size (P_{80})	Ball Size(s)
Circuit Configuration (including pebble management)	Ball Load (Jb%) and Total Load (Jc%)
	Classification Circuit (CLR, density, etc.)
	SAG Mill Feed Size (F_{80}) and Distribution (Antapaccay only)

The most significant differences between the various 40-ft SAG mill circuits are the feed characteristics (as measured by the drop weight test [Axb], Bond work index [BWi], and particle size distribution [PSD]), the pebble management system (to SAG mill feed conveyor, to SAG mill feed stockpile, to ball mill circuit feed), and the ball mill capacity (usually as dictated by the P_{80} ‘size of interest’).

By design, plant throughput rate is constrained by the most expensive equipment: the grinding circuit. Ideally, the constraint shifts between the SAG mill and the ball milling circuits, either naturally through variations in ore characteristics, or purposely through any, or all, of the operating optimisation variables listed in Table 1.

It is also important for metallurgists and operators to understand and appreciate that the total rock breakage work (in other words, the journey from the F_{80} to the P_{80}) must be balanced between the SAG mill and the ball mill circuits; there is no point in simply transferring grinding work to exceed the capacity of one or the other.

If the plant throughput rate is constrained by the SAG mill, operators will generally increase the SAG mill power draw (by increasing ball filling level [Jb], total load filling level [Jc], lift, ball size, speed); install discharge grates with larger slots; trial various discharge designs (radial, vortex, curved, etc); and increase pebble crushing work (or bypass crushed pebbles to the ball mill circuit if possible). Generally, the target power draw of SAG mills will be 88% of the installed motor capacity (Sherman, 2021).

SAG Mills

The general purpose of the SAG mill is to break ore to a size suitable for secondary grinding. Several hundred papers have been written about SAG mills over the past five decades. SAG mills remain the least energy-efficient component of a grinding circuit, where most of the energy is dissipated as heat in the tumbling mill load. This is understandable given the severe variations in operating conditions and ore characteristics that are common and expected in large-scale mineral processing operations.

A SAG mill will always be expected to accomplish three tasks (Sherman, 2019):

- **Grind** the ore through the known rock-breakage mechanisms.
- **Classify** the mill rock charge into two components: excessively coarse material that is retained within the mill, and the finished product that flows out of the mill.
- **Pump** the finished product out of the mill.

Over the last few decades, the cost of power has increased, resulting in the mineral processing industry working towards improving the efficiency of SAG mills by, for example, introducing pebble crushing; improving control systems; presenting a finer mill-feed size distribution (generated via more intense blasting and crushing, i.e., mine-to-mill programs, or secondary or tertiary crushing of the SAG mill feed); or improving lifter design. These initiatives have contributed to an improvement in the performance of SAG mills to varying degrees.

SAG Mill Feed

The effects of ore hardness and the feed PSD are the most significant drivers of SAG performance and will always influence variations in circuit throughput. With SAG mills, the consensus is typically that for coarser ores throughput declines, and vice versa. Compounding the challenge of feed size is that, for most ores, the overall coarseness of the primary crusher product is correlated to feed hardness. Coarser and more competent material consumes mill volume and limits throughput.

Many operations have implemented a secondary crushing circuit prior to the SAG circuit for further comminution of primary crusher product. Such a circuit can counteract the effects of harder and coarser ore, but notably, compared to softer ore, harder ore often presents itself to the SAG circuit as coarser—less comminution occurs in blasting and primary crushing, and therefore the impact on SAG throughput is compounded.

Pebble Crushing

The general purpose of the pebble crushing circuit is to manage and control the critical size fraction of the SAG mill discharge (usually 25–75 mm particles). It is well documented that accumulating critical-size material is detrimental to SAG mill performance. Pebbles are generally cone crushed to a size that ensures most of the particles will experience further breakage within the SAG mill and will pass through the discharge screen for delivery to the ball mill circuit. The most common circuit design is for crushed pebbles to be directed either to the SAG mill feed stockpile or to the SAG mill feed conveyor.

A typical rock-breakage curve is shown in Figure 3, and demonstrates the cause of this phenomenon.

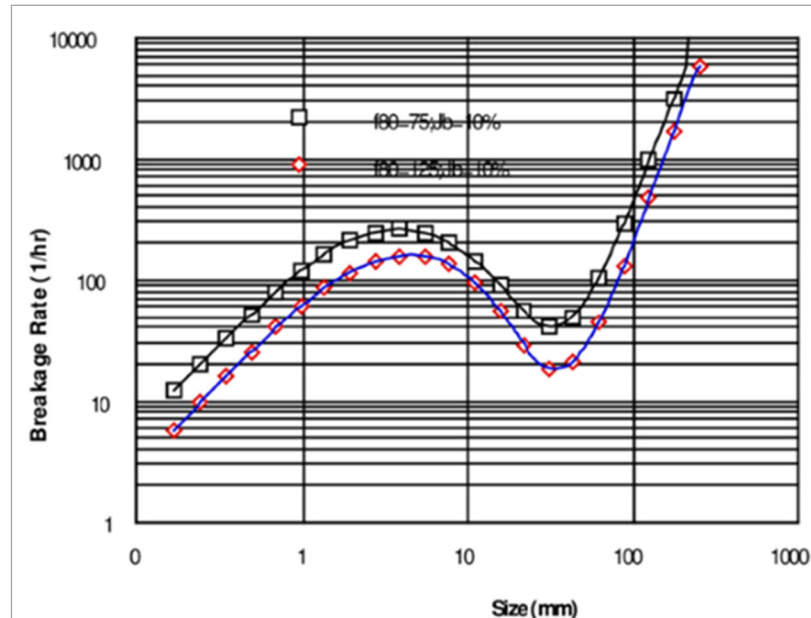


Figure 3—Typical Rock-Breakage Curve

Generally, the rock-breakage rates by attrition and abrasion are high for the particle size range of 1–25 mm, and rock-breakage rates by impactation are very high for the particle sizes >75 mm. The particle size range of 25–75 mm is the critical size tending to escape impactation in the outer layers of the charge, while also avoiding attrition buried in the charge kidney and eventually exiting the mill. Such particles depend on a low-probability impactation breakage event near the feed end of the mill, because soon after they will become engulfed in slurry and tend to be absorbed into the charge kidney where breakage by impactation is highly unlikely, and where there is generally only attrition and abrasion breakage. These particles cannot be allowed to accumulate, and thus need to exit the mill into the pebble circuit. Further, there is no guarantee that crushed or uncrushed pebbles will not be recycled again to the SAG mill feed.

To create capacity for an increase in SAG mill fresh feed, pebbles can be crushed once or twice, and bypassed directly to secondary grinding feed (SABC2); this circuit option is used in some 40-ft SAG mill plants, most notably the KAZ Minerals operations in Kazakhstan and Caserones in Chile.

Transfer Size

One of the SAG mill discharge (screen undersize) variables is the transfer size (T_{80}). Given the enormous volume of this flow and the segregation of various particle sizes, it is extremely challenging to sample manually, and there are few effective automatic systems. The T_{80} is a function of ore characteristics, discharge grate slot size, ball size, and the operational performance of the mill; as such it is generally misunderstood and difficult to control in practice. This stream becomes the ball mill circuit feed, which is usually pumped into cyclone classifiers. Fine particles at or below the P_{80} continue to the downstream processes while the coarse fraction becomes ball mill feed and circulating load. The T_{80} and P_{80} drive the ball size used in the ball mill(s), with the intention of providing a balance between managing variations in the coarse fraction and maximising the production of particles at the P_{80} .

When designing circuits, it is important to consider that the SAG mill will always provide some particles that are at (or below) the size of interest. Whilst the standard for circuit design is to simply transfer the entire SAG mill discharge screen undersize stream to the ball milling circuit, it may be favourable to include a SAG circuit cyclone

stage to enable bypass of SAG product already at the P_{80} . The design compromise in this case is to downsize the ball mill circuit, and this is indeed the design of the Sentinel grinding circuits in Zambia.

Ball Mills

The general purpose of the ball mill circuit is to grind the SAG mill discharge from the T_{80} to the P_{80} for optimum metal recovery in the downstream processes. The T_{80} is usually <4 mm with the P_{80} in the 100-to-300-micron (μm) range for most if not all 40-ft SAG mill operations. For optimisation purposes, the metallurgist must consider the entire ball mill circuit (including the classification system) rather than just the mill. There is arguably more opportunity for optimisation in a ball mill circuit rather than the SAG mill circuit.

Like the SAG mill, it is undesirable to allow coarse particles to accumulate in the ball mill circuit. Precise control of the cyclone classifiers and the circulating load is essential, especially if the downstream processes are sensitive to fluctuations in product size-distribution. Ball size also plays a significant role, as larger balls are the primary control of coarse particles; however, this comes at the expense of grinding efficiency, and a balance of variables is required.

If the plant throughput rate is constrained by the ball mill circuit, operators will generally maintain the maximum ball mill motor power draw (by maximising J_b , speed). The complexities of ball milling circuits are well known with continuous interaction between the mill and the classification stage, but nevertheless can be optimised through a *functional performance* evaluation (Bartholomew et al, 2019) that targets maximising all the following variables:

- Mill power draw
- Classification system efficiency
- Mill grinding efficiency
- Ore grindability.

Grinding mill operating performance is optimised with achieving the highest P_{80} production rate, and this will occur when all of these variables are maximised.

Generally, the target power draw of ball mills will be about 95% of the installed motor capacity (Sherman, 2019). Classification efficiency can be manipulated through water addition, cyclone feed pressure, and cyclone configuration (whilst also understanding the downstream process constraints). Ball mill grinding efficiency is manipulated mainly through ball size selection and control of the circulating load, but also by liner design and mill speed. Finally, ore grindability is generally all about the mineral characteristics, but can be controlled to some extent by efforts to drive a smaller T_{80} (SAG mill doing more work), which may include directing crushed pebbles to the SAG mill if the option exists.

Evaluating and Describing Operating 40-Foot SAG Mill Circuits

OPERATING PERFORMANCE

SAG mill operating performance is dependent on many factors, but at the highest level can be characterised by the throughput rate—tonnes per hour (t/h)—and the specific energy consumption (SEC)—kilowatt hours/tonne (kWh/t). The product of these two figures is the actual power draw (kW), which can be fairly compared to the installed power capacity. The main reason for applying this operational performance chart is that it captures the most basic and critical data for any grinding circuit:

- Operating time (hours)
- Throughput (tonnes)
- Energy consumption (kWh).

Figure 4 is an operational performance chart capturing a wide variety of monthly data points from 21 of the 23 operating 40-ft SAG mills. Each mill generally has a definable operating range with some sites clearly demonstrating a journey of continuous improvement. This chart is ideal for demonstrating differences between sites, and improvements or declines in operational performance at any given site.

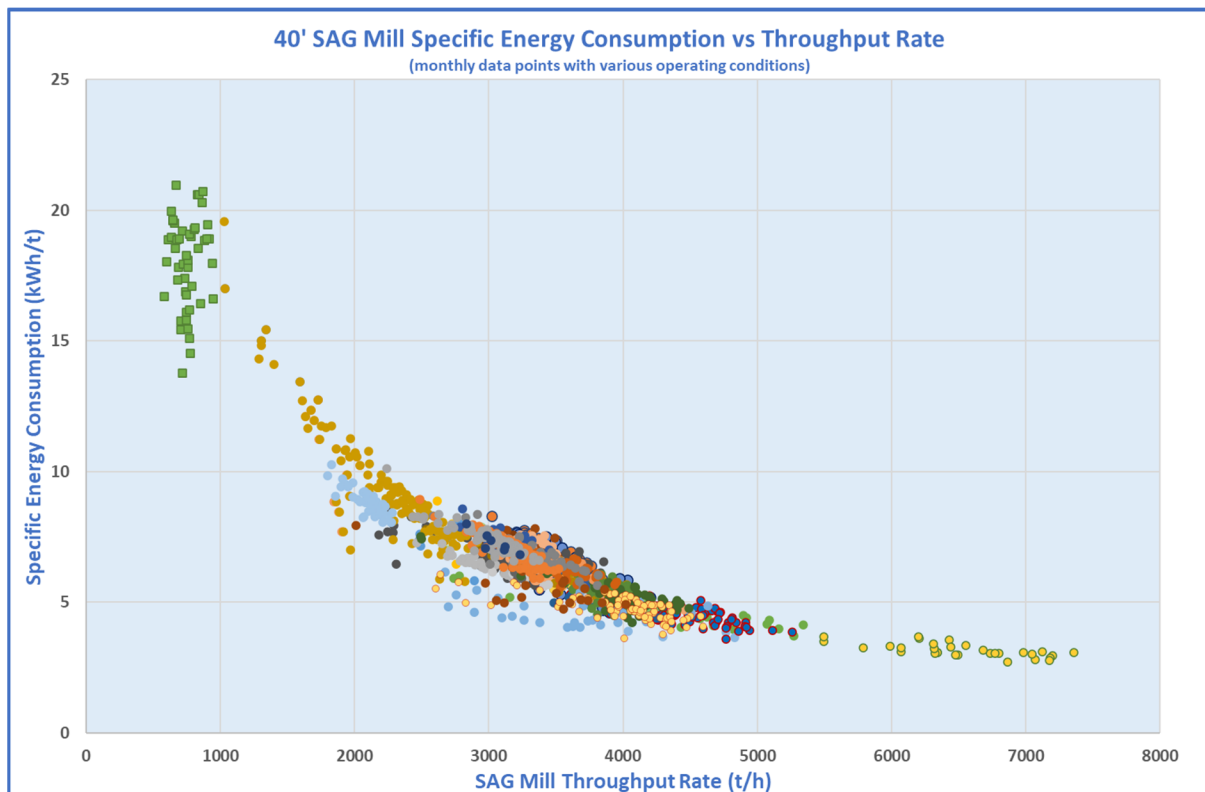


Figure 4—40-ft SAG Mill Operational Performance

The extreme diversity of SAG mill applications is clear, especially when one considers the outliers of Tasiast (750 t/h at 19 kWh/t) and Escondida SAG5 (6,800 t/h at 2.4 kWh/t). The factors setting each of these operations apart include, but are not limited to, the following:

- Grinding circuit configuration including pebble and ball milling circuits
- SAG mill feed size and mineral characteristics
- Crushing circuit configuration (ultimately driving SAG mill feed size)
- Operating variables (liner design, ball size, mill speed and density, etc.)
- Grinding circuit size of interest (T_{80} and P_{80}) for downstream processes.

OVERVIEW OF SELECTED 40-FOOT SAG MILL CIRCUITS

Ten of the 23 operating 40-ft SAG mill operations were selected to best demonstrate the extreme diversity of applications, as well as representing the current circuit designs and variations. The plant throughput rate and total energy consumption are the main evaluation variables, along with the SAG and ball mill dimensions, feed characteristics, and target product size.

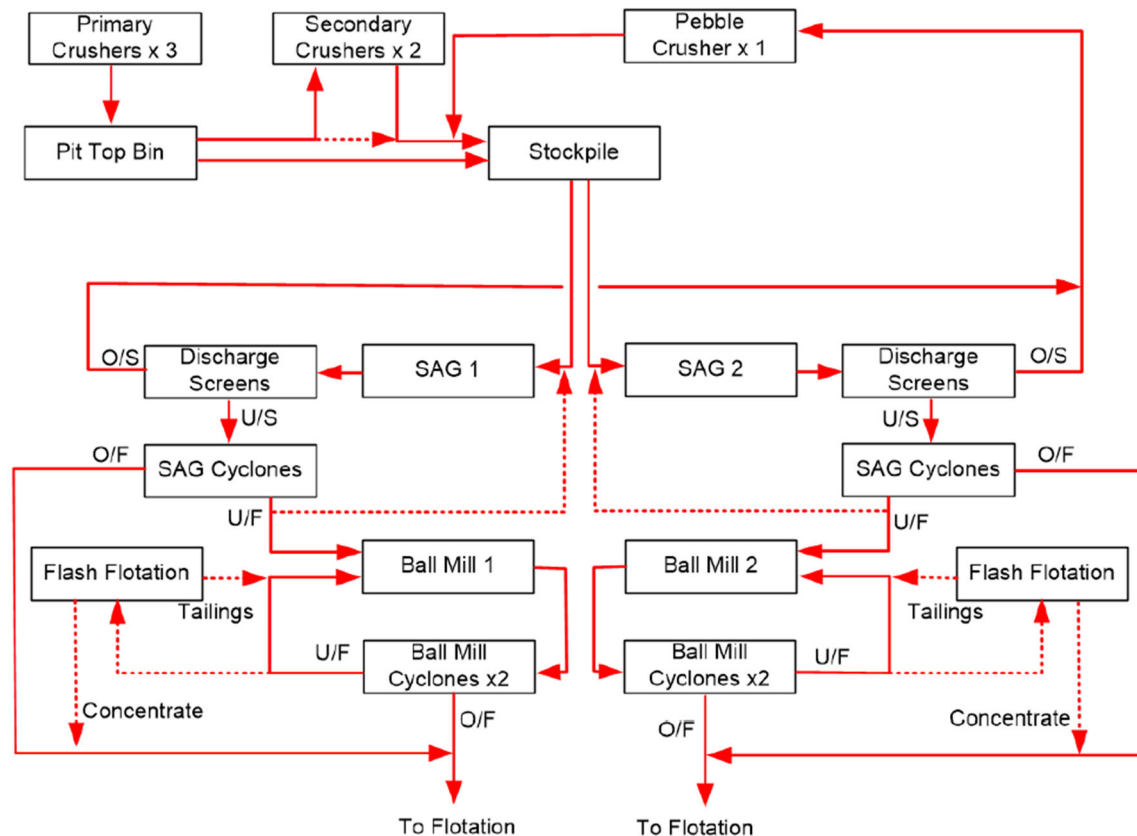
The sites featured in this evaluation are:

- Sentinel T1 and T2—First Quantum (Zambia)
- Aktogay1 and Bozshakol—KAZ Minerals (Kazakhstan)
- Tasiast—Kinross (Mauritania)
- Antapaccay—Glencore (Peru)
- Mount Milligan—Centerra Gold (Canada)
- Escondida SAG5—BHP (Chile)
- Caserones—Lumina (Chile)
- Collahuasi SAG1011—Glencore/AngloAmerican (Chile).

There are significant differences in the fresh feed characteristics (F_{80} and mineral hardness) to each of these 40-ft SAG mills. There are also variations in circuit configuration, ball milling capacity, and pebble management. The operational performance of each is evaluated in this paper with the intent of balancing capital cost, operational complexity, and maintenance costs.

A table of the physical features and other variables for each of the selected circuits is in Appendix 1.

This circuit involves primary gyratory crushing to partial (open circuit) secondary crushing providing $F_{80} < 100$ mm to stockpile feeding two parallel trains consisting of a 40 x 26 (28 MW) SAG mill with one 28 x 44 (22 MW) ball mill; pebbles are crushed and returned to the SAG feed stockpile. New feed from the stockpile 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. Figure 5 shows the grinding circuit flowsheet.



These circuits feature a SAG circuit and twin ball mill classification stages; the SAG mill Cyclopak is a rare feature that enables particles already at the P_{80} to be fast-tracked directly to the flotation surge tank. The SAG mill cyclone cluster underflow feeds the ball mill directly, with provision to return part or all the underflow to the SAG mill feed box.

Sentinel ore is structurally modified, sediment hosted copper deposit with an Axb of 45 and BWi of 18 kWh/t; the SAG mill F₈₀ is 100 mm (with partial secondary crushing) and the overall grinding circuit P₈₀ is 250 µm.

The grinding circuit configuration of one SAG mill, one ball mill, with crushed pebbles returned to the SAG feed stockpile features lower capital cost, operational simplicity, and lower maintenance costs.

Tasiast

The Tasiast circuit involves a primary gyratory crusher to stockpile feeding a 40 x 23 (26 MW) SAG mill in closed circuit with cyclone classifiers. The pebbles are crushed and returned to the SAG mill feed conveyor. The SAG circuit cyclone underflow is returned to the SAG mill feed while the overflow becomes the secondary grinding circuit feed, consisting of two 14 x 28 (2.2 MW) ball mills. Figure 7 shows the grinding circuit flowsheet.

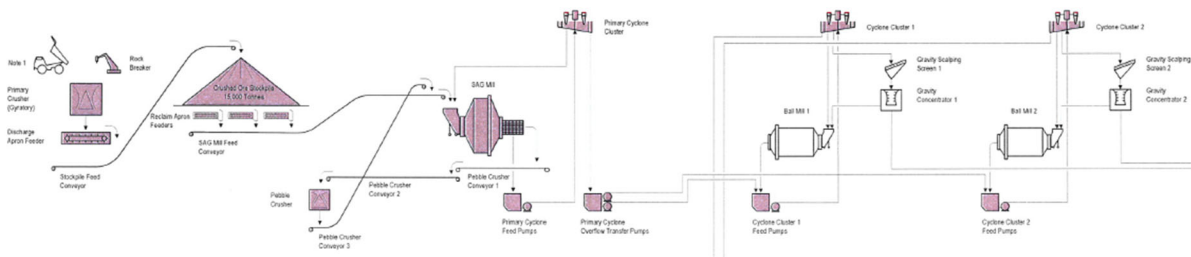


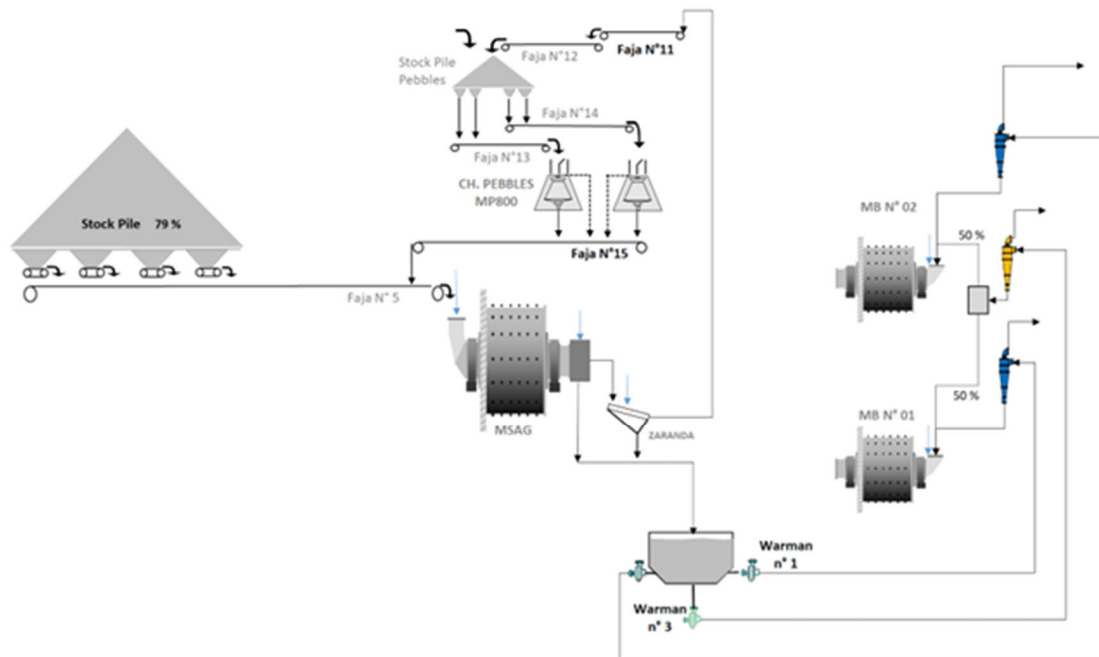
Figure 7—Tasiast Grinding Circuit Flowsheet

It is important to note that the Tasiast plant originally operated as a three-stage crushing circuit feeding the two ball mills in parallel, delivering a P_{80} of 90 μm to the pre-leach thickener. The 40-ft SAG mill was purchased and installed by the current owner as stage one of a two-stage plant expansion.

There are two gold mineralisation deposits at Tasiast: one hosted in meta-sedimentary rock and the other hosted in quartz-carbonate veins within sheared and hydrothermally altered meta-diorites. The ore has an Axb of 30 and BWi of 14.5 kWh/t; the primary crushed SAG mill F_{80} is 100 mm with a SAG and ball mill circuit P_{80} of 90 μm .

The grinding circuit configuration of one SAG mill operating in closed circuit, with crushed pebbles returned to the SAG mill feed conveyor, and with two relatively small ball mills, is a unique 40-ft SAG mill circuit, and rare for a SAG mill of any size. As such, the only value of benchmarking Tasiast against other 40-ft SAG mills is that it provides the extreme outlying case of a low fresh-feed rate and high SEC.

At Antapaccay the circuit involves a primary gyratory crusher to stockpile feeding a 40 x 25 (24 MW) SAG mill with two 26 x 40.5 (16.4 MW) ball mills. The grinding circuit features a pebble stockpile feeding pebble crushers at a steady rate, which in turn feed the SAG mill; pebble reclaim and operation of the circuit is adjusted according to the fines content of the fresh feed and the SAG mill rock load. Figure 8 shows the grinding circuit flowsheet.



Antapaccay ore is copper skarn-porphyry with an Axb of 40 (28-50) and BWi of 18 kWh/t (16-20 kWh/t); the primary crushed SAG mill F_{80} is 75 mm with an overall grinding circuit P_{80} of 240 μ m. There is no secondary crushing stage at Antapaccay due to the unusually low crushing work index (CWi) of 6 kWh/t.

The grinding circuit configuration of one SAG mill and two ball mills with a semi-detached pebble crushing circuit is worthy of evaluation. Intuitively there should be operational performance and control benefits in having an independent pebble circuit that can be placed on and off as conditions allow.

Mount Milligan

This circuit involves a primary gyratory crusher discharging to stockpile with a variable diversion (gate range 0%–100%) to a vibrating screen; the oversize is directed to secondary crushing with the product to stockpile. The stockpile reclaim system provides a F_{80} of 50 mm to a 40 x 22 (23.5 MW) SAG mill with two 24 x 41 (13 MW) ball mills. Pebbles are crushed and returned directly to the SAG mill feed conveyor. Figure 9 shows the grinding circuit flowsheet.

The operation commenced in 2012 with only a primary crusher and operated with $F_{80} > 100$ mm at a SAG mill feed rate of 2,100 t/h for several years before the secondary crushing circuit was commissioned in 2017. It has been well-documented that the original design was based on average ore hardness data leading to the SAG mill operational performance routinely at $>88\%$ of the installed power capacity (Sherman, 2023 and Staples et al, 2015). Eventually, a SAG mill feed rate of $>2,500$ t/h was achieved routinely.

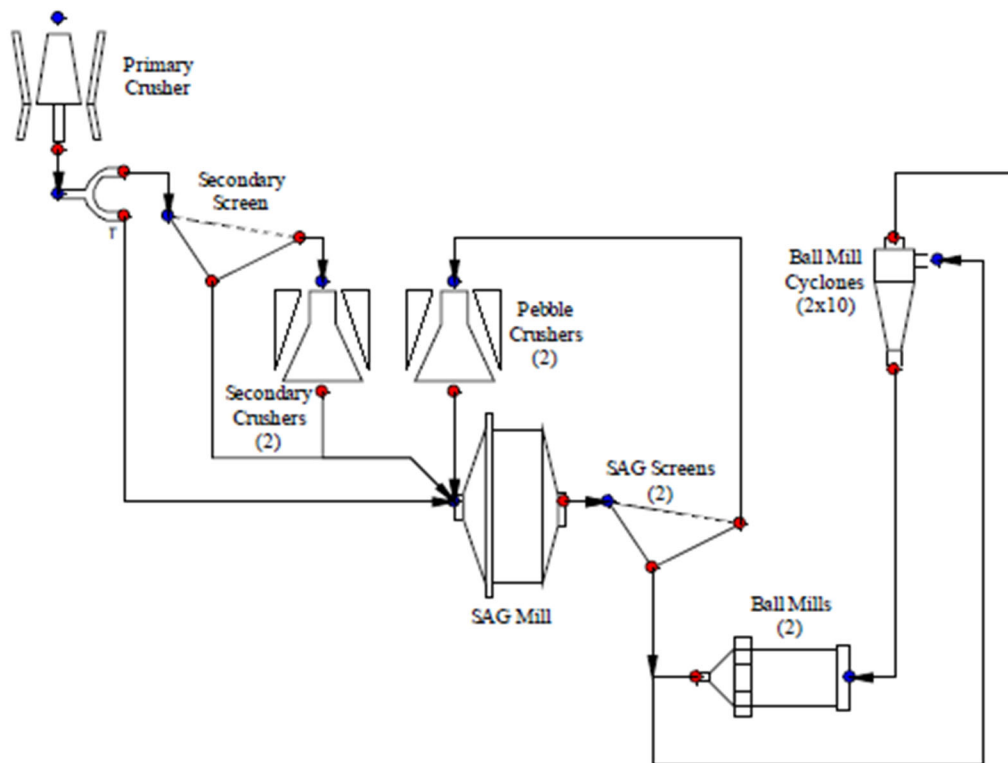


Figure 9—Mount Milligan Grinding Circuit Flowsheet

Mount Milligan ore is copper porphyry with an A_{xb} of 32 and BW_i of 20 kWh/t; the secondary crushed SAG mill F_{80} is 50 mm with an overall grinding circuit P_{80} of 200 μ m. The low A_{xb} provides a flag for further detailed analysis of the ore properties and for applying additional grinding capacity if ore hardness is routinely above average. The high crushing work index of 20 kWh/t also points towards the need for the secondary crushing stage.

The grinding circuit configuration of one SAG mill and two ball mills with crushed pebbles returned to the SAG feed conveyor is comparable to similar operations and provides an opportunity to benchmark the operating performance of harder ores with and without secondary crushing. Indeed, Mount Milligan can also be compared to itself, before and after installation, and successful operation of the secondary crushing circuit.

Escondida Laguna Seca SAG5

The SAG5 plant involves a primary gyratory crusher to stockpile feeding a 40 x 29 (24 MW) SAG mill with four parallel 26 x 42 (15.7 MW) ball mills. This circuit features the longest SAG mill effective grinding chamber length, very soft ore, and massive secondary grinding capacity. Figure 10 shows the grinding circuit flowsheet.

Laguna Seca ore is copper porphyry with an Axb of >75 and BWi of <13 kWh/t; the ore crushes easily due to the high Axb providing a SAG mill F_{80} of <50 mm, and an overall grinding circuit P_{80} of 165 μm .

The ore has very low resistance to breakage and as such the SAG mill operates more as a massive pump with some classification and rock grinding required. There is enormous secondary grinding capacity in the ball milling circuit, and this is due to the equally massive slurry flow through the plant.

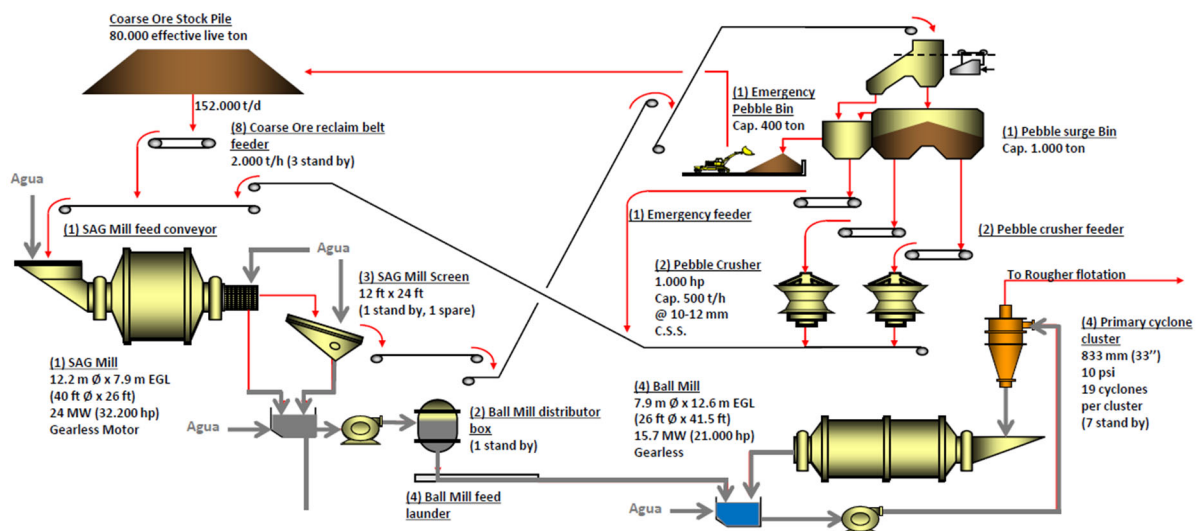


Figure 10—Escondida Laguna Seca SAG5 Grinding Circuit Flowsheet

The SAG5 grinding circuit configuration of one SAG mill with crushed pebbles returned to the SAG mill feed conveyor, and four large ball mills is the largest total mill volume by far. However, there is value in benchmarking against other 40-ft SAG mill operations, but with caution. In terms of the basic operational performance chart, SAG5 with the highest feed rate and lowest SEC provides the opposite extreme outlying case to Tasiast.

BHP Escondida is the largest copper operation globally, by a large margin, and the SAG5 Organic Growth Project has been the third major expansion of the operation.

Caserones

This circuit involves a primary gyratory crusher to stockpile feeding a 40 x 26 (28 MW) SAG mill with two 28 x 44 (22 MW) ball mills. The pebble crushing circuit is designed to provide three options for crushed pebbles: (1) directed to the ball mill circuit (SABC-B 'open'); (2) returned to the SAG mill feed conveyor (SABC-A 'close'); (3) returned to SAG mill feed. Figure 11 shows the grinding circuit flowsheet albeit a simplified version without the options.

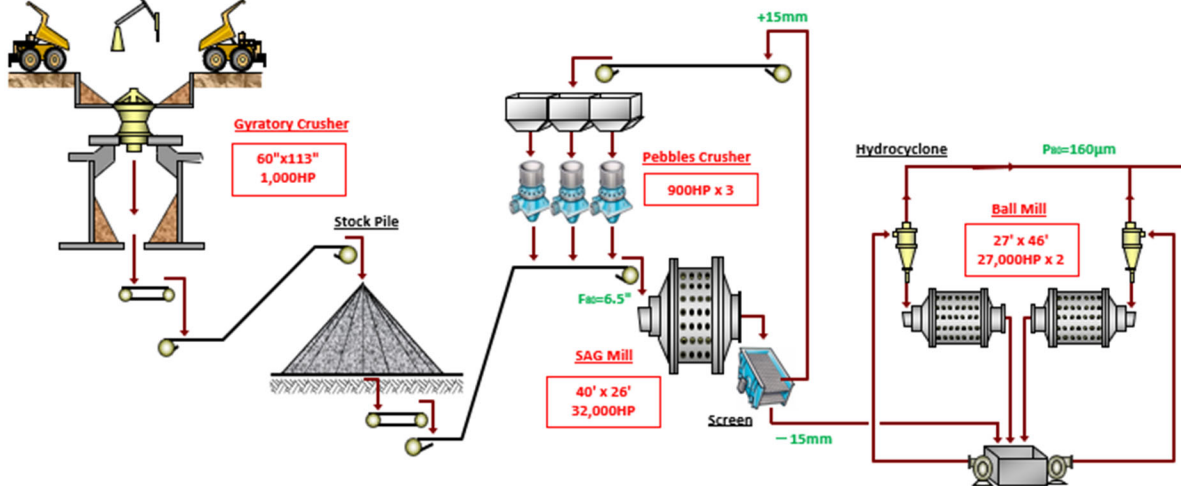


Figure 11—Caserones Grinding Circuit Flowsheet

The ore is copper porphyry with an Axb of 50 and BWi of 12.3 kWh/t; the primary crushed SAG mill F_{80} is 100 mm with an overall grinding circuit P_{80} of 175 μ m.

The grinding circuit configuration of one SAG mill and two ball mills with a flexible crushed and uncrushed pebble management system provides an opportunity to benchmark Caserones against other similar circuits with medium hardness ores.

Collahuasi SAG1011

The SAG1011 circuit involves a primary gyratory crusher to stockpile feeding a 40 x 24 (24 MW) SAG mill with two 26 x 38 (16.4 MW) ball mills. This circuit features a dual pebble screening stage with undersize returning to the SAG feed conveyor, while the oversize is crushed and returned to the SAG feed stockpile. The SAG1011 circuit is an expansion of the original two 32 x 14 SAG mills each with one ball mill. Figure 12 shows the grinding circuit flowsheet.

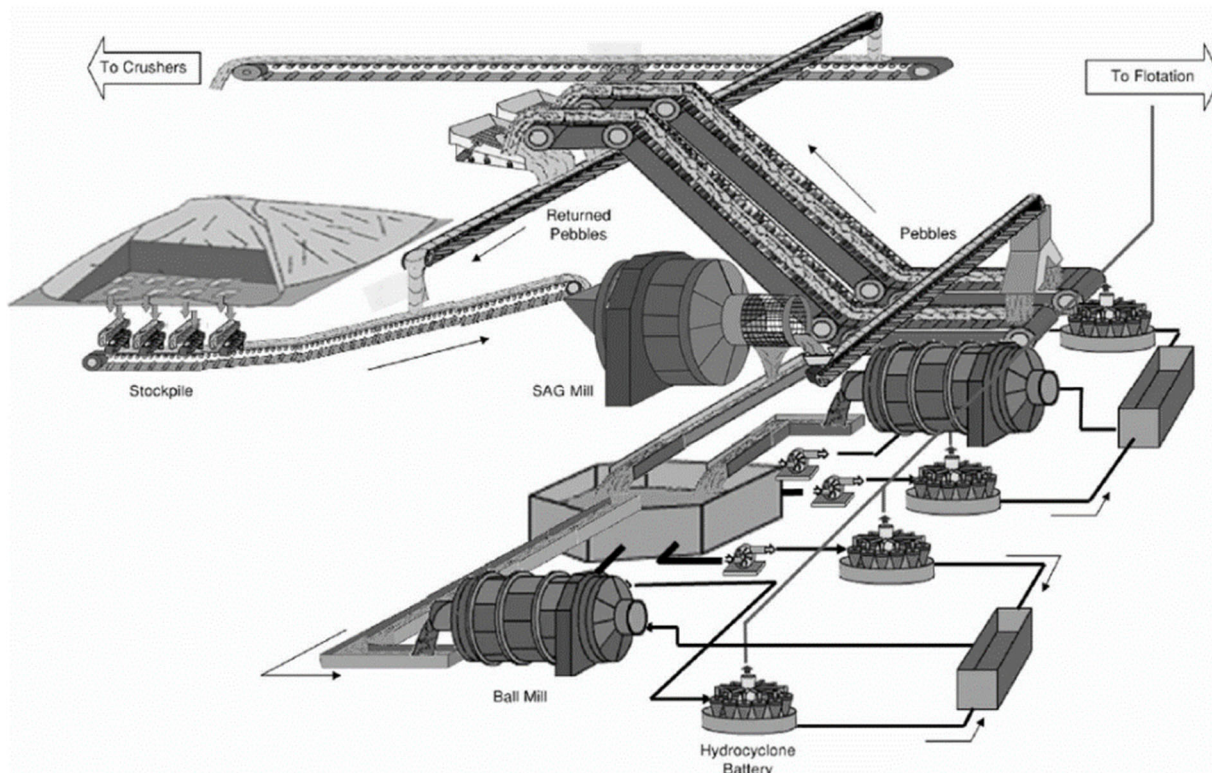


Figure 12—Collahuasi SAG1011 Grinding Circuit Flowsheet

Collahuasi ore is copper porphyry with an Axb of 48 and BWi of 12 kWh/t; the primary crushed SAG mill F_{80} is 55 mm with an overall grinding circuit P_{80} of 200 μm .

The grinding circuit configuration of one SAG mill and two ball mills with crushed pebbles returned to the SAG feed stockpile provides an opportunity to benchmark Collahuasi against other similar circuits with medium hardness ores.

EVALUATION, BENCHMARKING, AND OBSERVATIONS

SAG Mills

SAG mill operating performance can be characterised by the throughput rate (t/h) and the SEC (kWh/t), as stated earlier, and the product of these two figures is the actual power draw (kW) which can fairly be compared to the installed power capacity. Monthly data points over the past five years for each of the selected 40-ft SAG mills, described above, are shown in Figure 13.

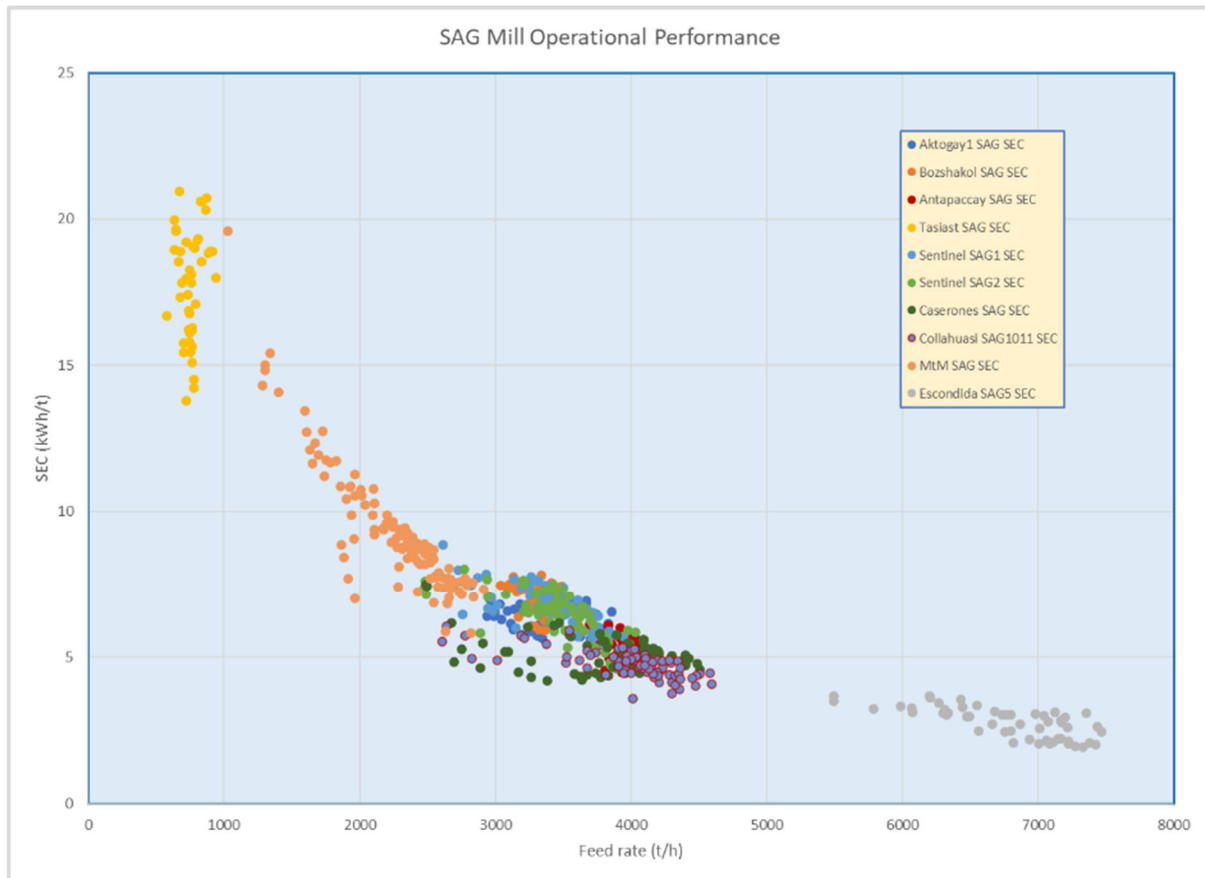


Figure 13—Selected 40-ft SAG Mill Operational Performance

Tasiast, at the far left, and Escondida SAG5, at the far right, are clear outliers. However, the mills represented by the data in the middle of the chart (processing medium to hard ores) can be investigated and compared in more detail. This chart also clearly shows that these SAG mills have similar installed power capacity, although the utilisation varies somewhat, as shown in Figure 14.

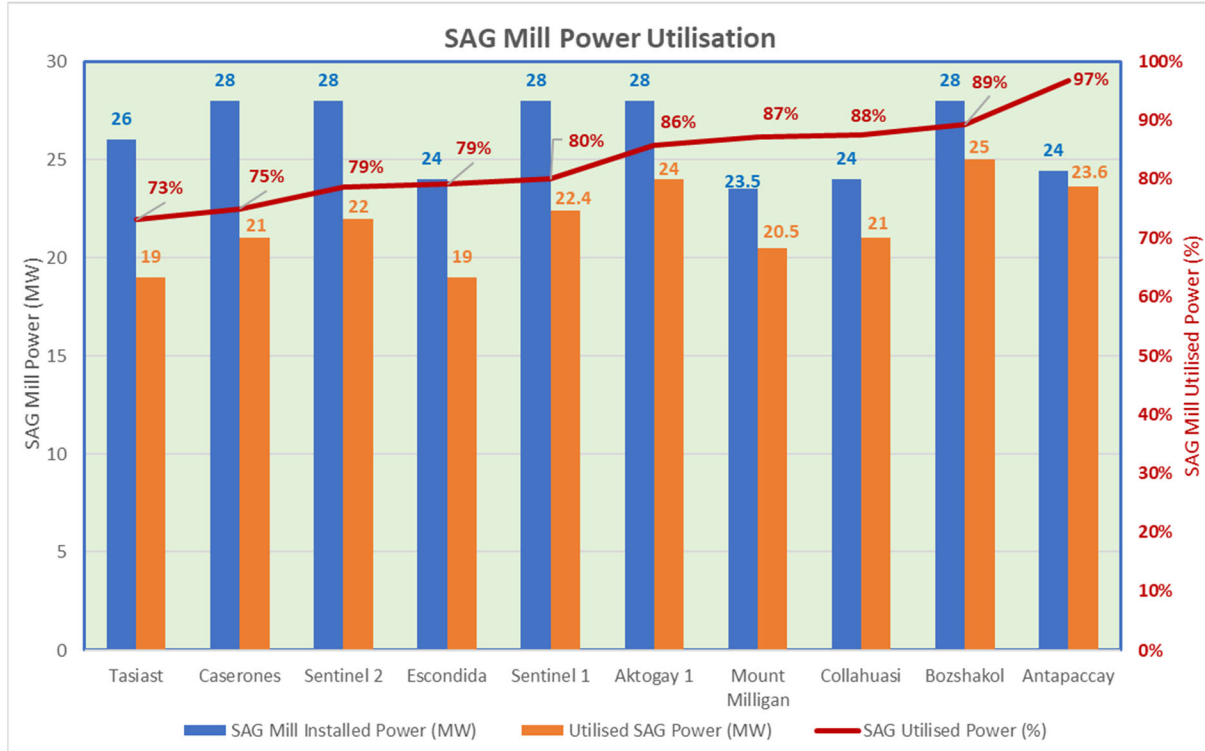


Figure 14—SAG Mill Motor Installed Capacity, Nominal Power Draw, and Utilisation

Aktogay1, Mount Milligan, Collahuasi, Bozshakol, and Antapaccay are all >85% utilisation and generally align with the standard SAG mill design criterion of 88% utilisation. The independent pebble crushing circuit and control system at Antapaccay enables a very high SAG mill power utilisation of ~97%.

Ball Mills

Evaluating ball mill operating performance using the same method is challenging, and not practical due to the wide range of installed mill sizes and motor capacity, circuit configurations, P_{80} targets, and the complex interactions with the cyclone classification stage. These variations are shown in Figure 15.

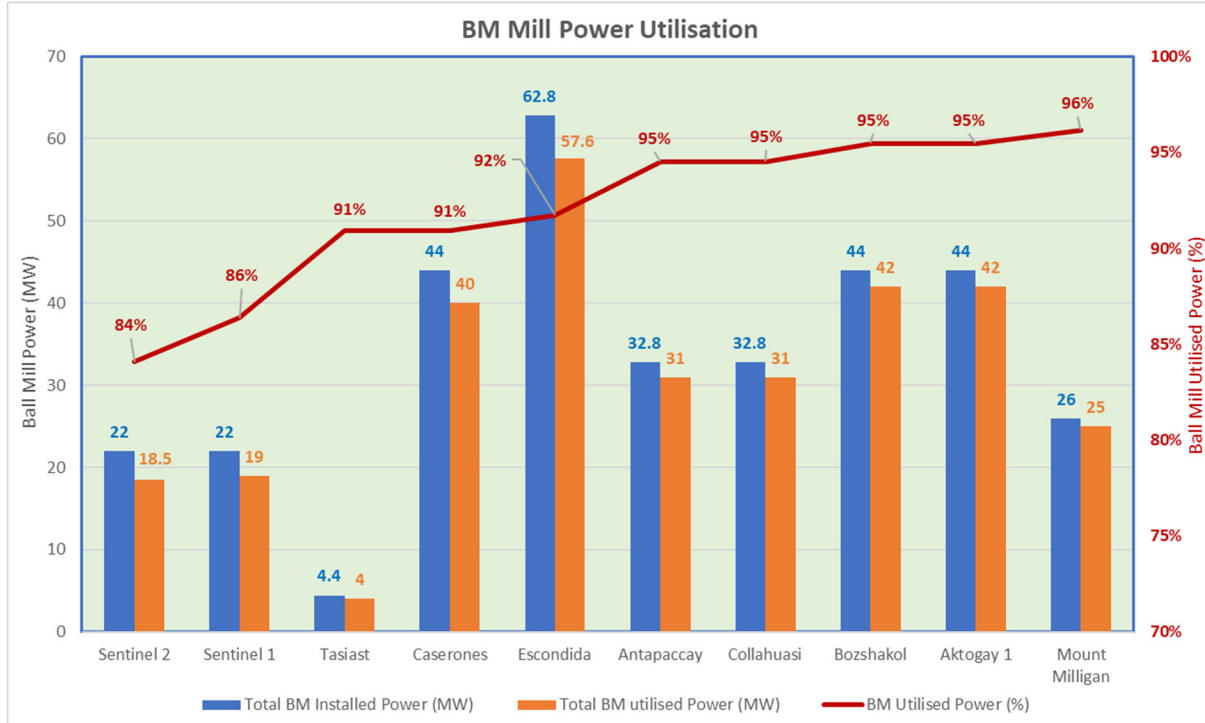


Figure 15—Ball Mill Motor Installed Capacity, Nominal Power Draw, and Utilisation

Of interest, the same five sites—Collahuasi, Antapaccay, Aktogay1, Bozshakol, and Mount Milligan—also have the highest ball mill power utilisation (all >95%) aligning with the standard ball mill design criterion of 95% utilisation. All ball mills are >91% utilisation, except the two Sentinel ball mills, at about 85%.

Secondary Crushing of SAG Mill Feed

In general, secondary crushing is unnecessary given ores with a high Axb and a low CWi as coarse particles will break easily upon entering the SAG mill. In such cases (such as Escondida) the F_{80} is almost irrelevant. However, there is a direct relationship between F_{80} and SAG SEC, and in the case of Mount Milligan, the operating performance chart in Figure 16 proves there has been a clear benefit moving the F_{80} from 100 to 50 mm.

Given the low Axb of 32 at Mount Milligan, the ore has a very high resistance to breakage, and decreasing the SAG mill F_{80} has driven a measurable improvement in operational performance, in this case by about 25%.

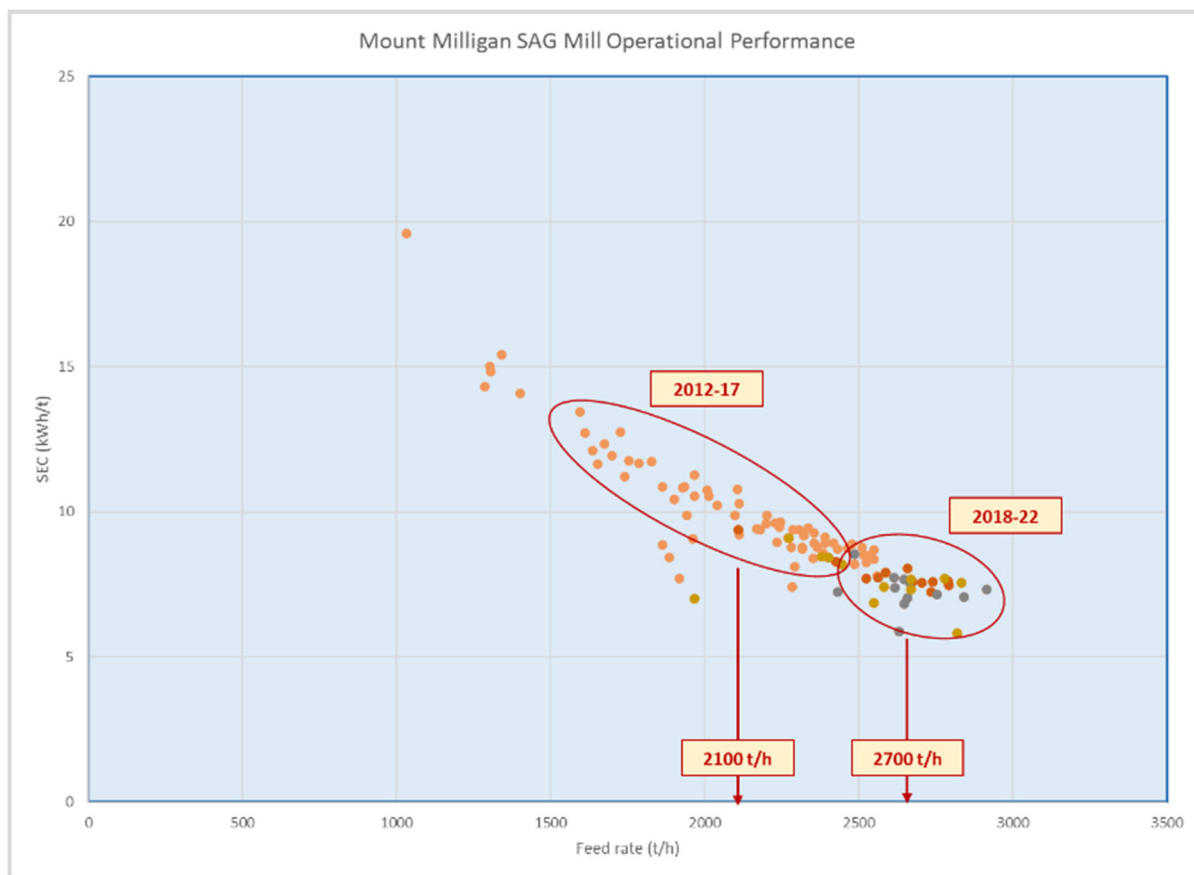


Figure 16—The 2012–2022 Mount Milligan SAG mill Operating Performance

Pebble Circuit Options

It is well known that SAG milling will always generate some portion of critical size particles that have a lower probability of impaction or abrasion breakage; these particles need to be managed and cannot be allowed to accumulate. Critical-size particles depend on a low-probability impaction event near the feed end of the mill before entering the charge kidney along with the slurry. If the SAG mill is not the plant constraint, the critical-sized particles can be maintained in the mill by using a smaller grate slot size and by increasing the mill density. Given that it is desirable to maximise the feed rate to 40-ft SAG mills, the grate slot size is generally >65 mm to allow pebbles to easily be released to the pebble circuit.

There are no standard pebble circuit configurations, and there are several options:

- Crushed or uncrushed pebbles return directly to the SAG mill feed conveyor
- Crushed or uncrushed pebbles return to the SAG mill feed stockpile
- Crushed pebbles are bypassed directly to the ball mill circuit feed.

Ideally a pebble circuit will be designed to accommodate operational disturbances and mechanical failures, and as such, there will be bypass options in one or more circuit locations.

Of particular interest is the Antapaccay pebble circuit, where pebbles are directed to a separate stockpile, after which they are reclaimed, crushed, and delivered to the SAG mill feed. This stockpile enables the inevitable disturbances in SAG mill load caused by variations in mineral hardness to be controlled and absorbed in the stockpile. If this is successful, the SAG mill operational performance should provide some indication of improvement.

The Antapaccay, Caserones, and Collahuasi SAG mills all have roughly the same operating conditions, with a feed rate of about 4,000 t/h. The most significant difference is the pebble stockpile at Antapaccay, recalling that the Collahuasi screened and crushed pebbles are returned to the SAG feed stockpile, and the Caserones crushed pebbles are directed to the SAG feed conveyor or bypassed to the ball mill circuit. The operational performance chart in Figure 17 contains roughly the same number of data points for each of the three SAG mills.

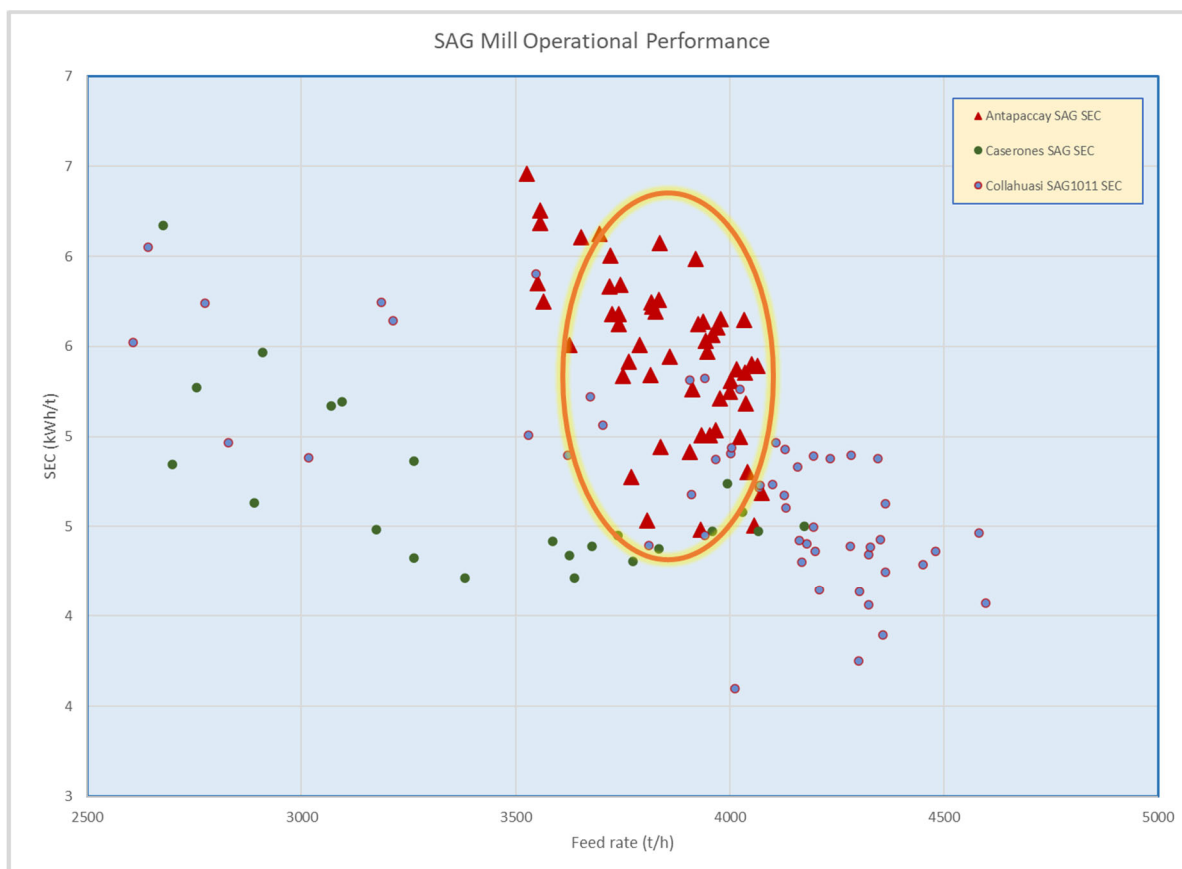


Figure 17—The Antapaccay, Caserones, and Collahuasi SAG Mill Operational Performance

The Antapaccay SAG mill feed rate shows significantly less variability than Caserones and Collahuasi, with all data points roughly in the 3,600–4,100 t/h range. This is arguably indirect evidence that the pebble stockpile with controlled reclaim and addition of crushed pebbles enables a very high (97%) SAG mill power utilisation which in turn contributes to optimal operation due to improved control of the rock load. Such a system minimises opportunities for pebbles to accumulate and accommodates variations in pebble mineral characteristics. Further, it is fair to state that the Antapaccay SAG mill has less feed rate variability than all the other 40-ft SAG mills (except for the outlier Tasiast).

Also of interest are the Aktogay and Bozshakol circuits, where crushed pebbles routinely bypass the SAG mill to feed the ball mill circuit (SABC2). With the absence of pebbles in the SAG mill, there should clearly be more capacity for fresh feed, and it is known at both KAZ Minerals operations that the bypass enables an 27% increase in the mill throughput rate. Further, it is reasonable to consider the capital cost of the SABC2 down-sized pebble circuit compared to SABC1; intense comminution, especially with HPGR, results in micro-fracturing of the coarsest particles which could lead to improved ball mill grinding efficiency.

The Mount Milligan and KAZ Minerals grinding circuits have roughly the same feed conditions, with an Axb in the 32–42 range and F_{80} of 50–90 mm. The most significant difference is that the crushed pebbles at Mount Milligan are recycled to the SAG mill feed conveyor (SABC1); recall that the KAZ Minerals pebble circuits have a cone crush stage as well as a closed HPGR stage to ensure <3 mm particles feed the ball milling circuits (SABC2). Figure 18 contains roughly the same number of data points for each SAG mill:

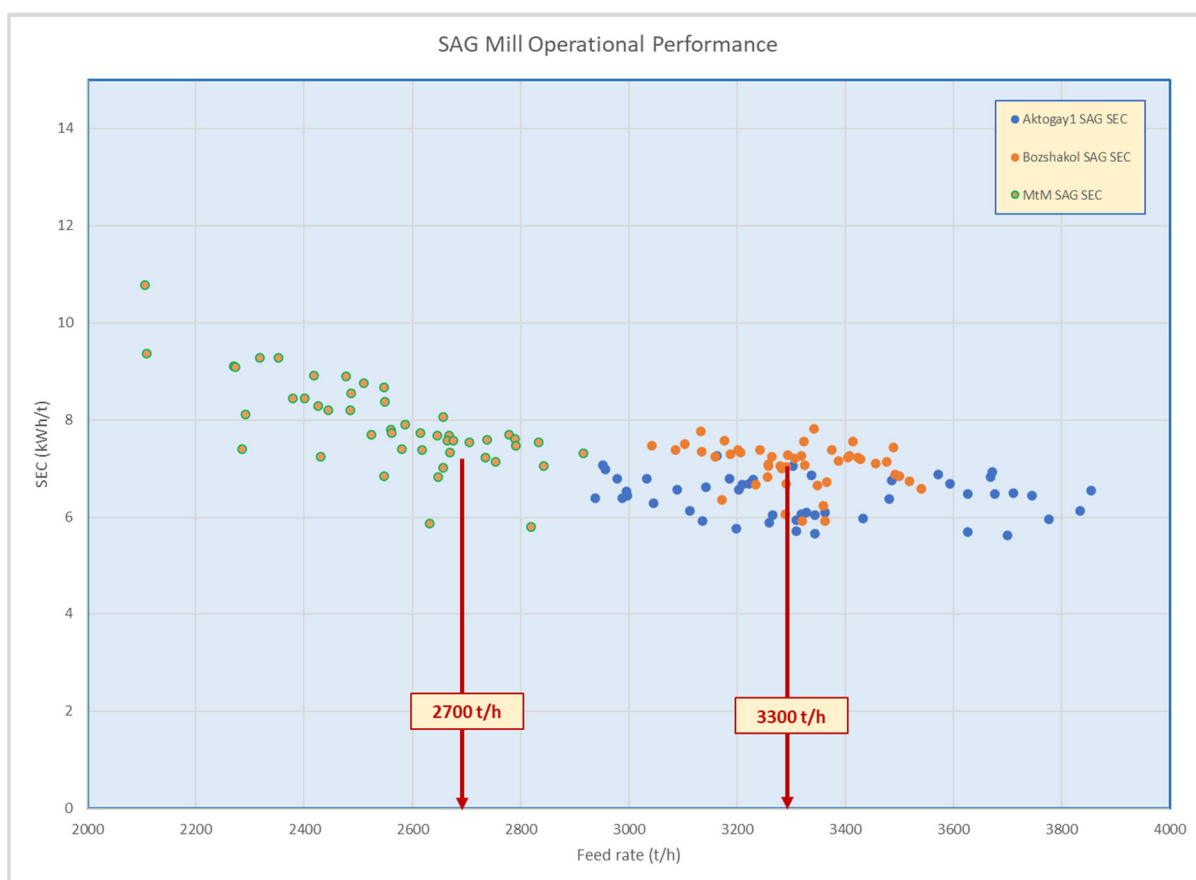


Figure 18—Mount Milligan, Aktogay, and Bozshakol Operational Performance

The KAZ Minerals SAG mill feed rates indicate they are >20% than Mount Milligan, which aligns with the plant trials at Bozshakol. Significantly offsetting the increase in feed rate with a pebble bypass configuration are the capital cost, operational complexity, and maintenance costs. It is also important to note that directing crushed pebbles to a ball mill feed sump will only exacerbate the usual particle-size bias, with individual cyclone feed pumps to each ball mill; this is a challenging design issue for any grinding circuit. However, a SAG mill free of crushed and recycled pebbles has one less complexity to manage, and operational stability is arguably easier to

achieve and maintain. The potential for improved ball mill grinding efficiency due to HPGR micro-fracturing of the coarsest particles is worthy of further analysis and plant trials.

Secondary Milling Capacity

As stated earlier, there are significant differences in the secondary grinding circuits for the 40-ft SAG mill plants, making it very challenging to perform any specific benchmarking evaluation. However, at a high level, we have the Sentinel SABC1 circuits with one SAG and one ball mill in each train. While Sentinel has the highest P_{80} , at 250 μm , we could consider comparison with other operations with medium hardness ores and $P_{80} > 200 \mu\text{m}$.

As leveraged previously, the Antapaccay, Caserones, and Collahuasi SAG mills all have roughly the same operating conditions, with a feed rate of about 4,000 t/h; the Sentinel circuits also fit into this regime, with the significant difference of having only one ball mill. Figure 19 demonstrates the operational performance of each total grinding circuit.

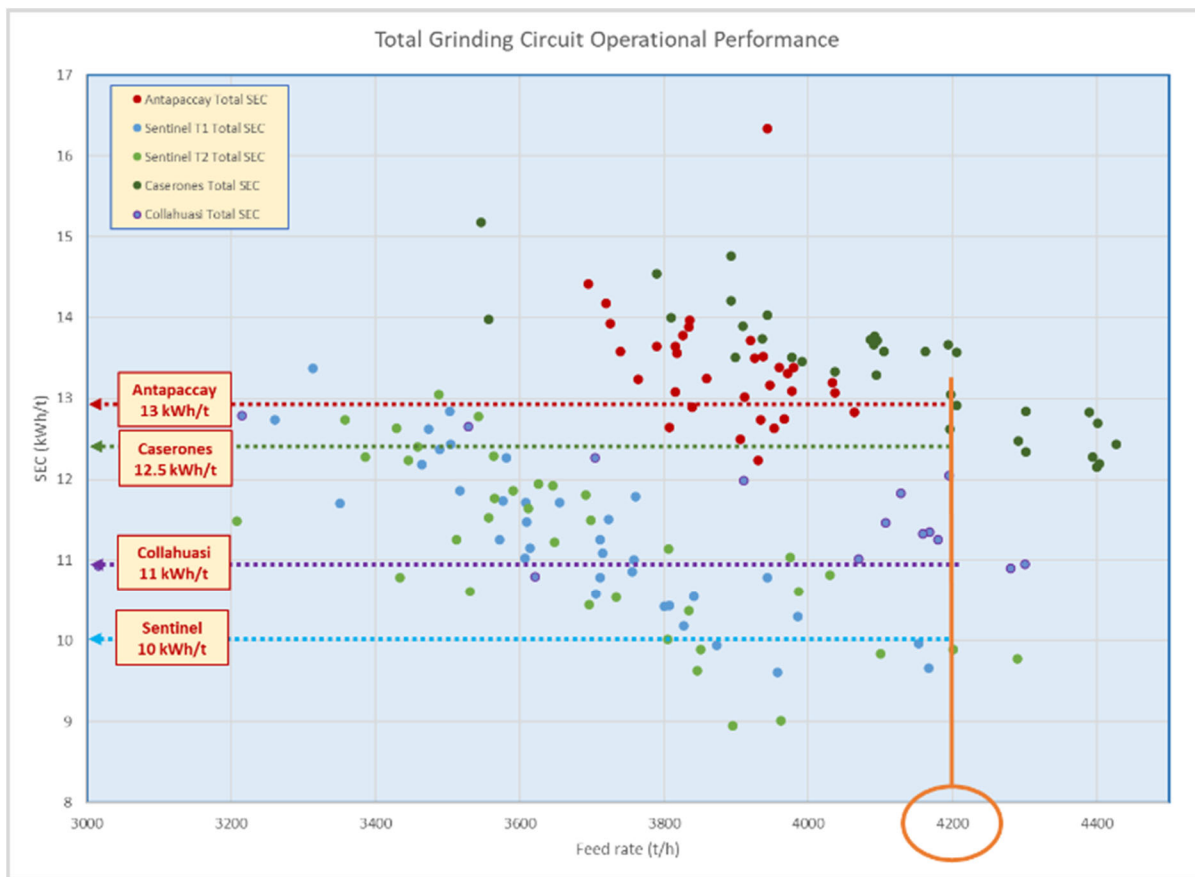


Figure 19—Sentinel, Antapaccay, Caserones, and Collahuasi SAG Mill Operational Performance

Whilst there are numerous data points, it is fair to consider the total grinding circuit SEC while operating at 4,200 t/h (at or near the top of the range). It is noteworthy that Antapaccay and Sentinel ores have a similar BWI in the range of 17-18 kWh/t while Caserones and Collahuasi are at 12 kWh/t. This high level comparison demonstrates the superior energy efficiency of the Sentinel SAG and ball mill circuits despite generally processing harder ore.

Another method of benchmarking these circuits is to evaluate the production rate as a function of installed grinding mill volume. This novel measure is the circuit fresh feed rate per unit grinding mill volume, or t/h/m^3 . Figure 20 shows the calculated measures for each of the four operations.

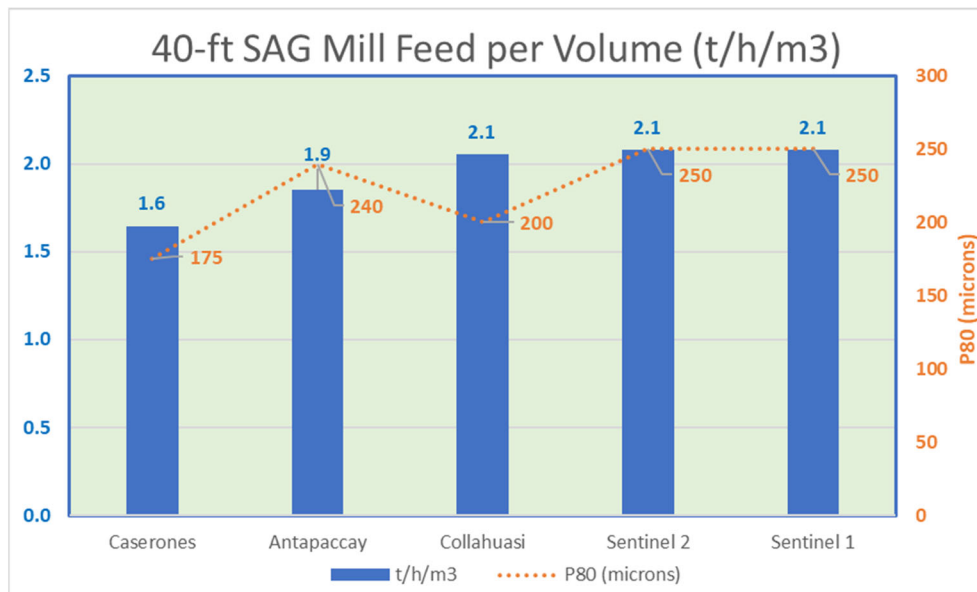


Figure 20—The Sentinel, Antapaccay, Caserones, and Collahuasi SAG Mill Production Rate as a Function of Mill Volume

The Sentinel and Collahuasi circuits appear to be providing the highest production rate of 2.1 t/h/m^3 . The basic fact that the Sentinel circuits can process about 4,200 t/h with one ball mill rather than two, at a reasonably similar P_{80} , is worthy of consideration in future 40-ft SAG mill circuit designs (Sentinel also has a larger F_{80} and higher BWi than Collahuasi). The additional pumping and classification equipment as a replacement for the absent second ball mill is a worthy trade-off, specifically regarding generally predictable and lower operating and asset maintenance costs of pumps and cyclones as compared to a ball milling circuit. A noteworthy bonus (given the capability of operating the SAG mill as a single-stage circuit), is that a catastrophic failure of the ball mill can be accommodated whilst continuing production at a reduced rate. It may also be possible to strategically utilise a partial-closed circuit operation when required, such as the first few weeks with new SAG mill liners. The SmartNoise system recently installed on the Sentinel SAG2 mill will provide the precise acoustic measurements necessary to control and evaluate this strategy.

Summary

The first 40-ft SAG mill was commissioned in 1998 and has become the standard SAG mill size for many massive mining operations. There are now 23 operating 40-ft SAG mills globally, with nine more planned to be commissioned over the next few years.

There are several variations in the grinding circuit design which include:

- Secondary milling equipment and configuration

- Secondary crushing of SAG mill feed
- Pebble management options
- Secondary milling capacity.

A detailed circuit description and evaluation of ten of the 23 operating 40-ft SAG mills offers some high-level guidance for the design of future plants. Each of the case studies in this paper provide support for the following general comments that are already known by most metallurgists and EPCM personnel.

Given very soft ores, the SAG mill is primarily a pump, and as such the priorities are efficient slurry transport and managing the rock load as best as possible at the highest throughput rate. In these cases, pebble management is not critical, and pebbles can be directed to the most convenient location, either the SAG mill feed stockpile or feed conveyor. The F_{80} is also not particularly critical, and secondary crushing will not be required. However, control of the J_c is critical; an increase in mill speed or decrease in mill density will result in more pumping action and potentially a rapid decrease in the J_c , generating undesirable ball-on-liner impacts that could damage the liners, cause ball breakage, and peg the grate slots. The ball mill circuit will need to have the capacity to accommodate the enormous volume of slurry and to achieve the target P_{80} for the downstream processes.

For medium to hard ores, in addition to the pumping capacity, the SAG mill functions of grinding (rock breakage) and classifying (discharge grates) are much more critical. The harder the ore (low A_{xb}) the more likely there is to be benefit in secondary (or even tertiary) crushing of the SAG mill feed. Pebble management is important, and a robust and flexible crushing circuit can accommodate expected (or unexpected) variations in mineral characteristics. A pebble stockpile can be designed to absorb operational variations and contribute to operational stability of the SAG mill, which will indirectly improve stability of the downstream processes – all of which comes with a higher capital cost. Bypassing crushed pebbles directly to the ball milling circuit (SABC2) enables significantly more capacity for fresh feed in the SAG mill, but the crushed pebble size must be tightly controlled, and may require more than one crushing stage. Further, design of the ball milling circuit feed sump is made even more challenging with accommodating the crushed pebbles along with the main slurry volume of the SAG mill discharge screen undersize material.

Lastly, for medium and hard ores, given that the SAG mill produces a significant portion of particles at the P_{80} , it may be beneficial to include a SAG circuit classification stage to bypass such particles directly to the downstream processes, with the coarse fraction becoming the secondary mill feed. The SAG cyclone stage significantly reduces the required milling and pumping capacity of the secondary circuits, and thus enables reductions in operating and maintenance costs. The SAG cyclone stage also enables additional circuit flexibility, and plant optimisation testwork can be conducted to improve operational performance during the first phase of a SAG mill liner life cycle.

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Appendix

Region	Country	Operation	Year	Ore type	SAG Mill EGL (ft)	SAG Mill Installed Power (MW)	Utilised SAG Power (MW)	SAG Utilised Power (%)	SAG mill volume (m3)	SAG Ball size (mm)	SAG SEC (kWh/t)	Secondary crushing	Pebble Crushing circuit overview
South America	Chile	Collahuasi	2002	Cu	24	24	21	88%	854	150	4.7	No	yes, screen with coarse to crush and SAG feed stockpile, fines to SAG feed conveyor
South America	Peru	Antapaccay	2012	Cu	25	24	23.6	97%	890	140	5.5	No	yes, to separate stockpile then crushed and added to SAG feed conveyor when load allows
South America	Chile	Caserones	2013	Cu	26	28	21	75%	926	140	5.4	No	yes, pebbles to crush and then to SAG feed conveyor
North America	Canada	Mount Milligan	2013	Au	22	23.5	20.5	87%	783	125	7.5	Yes 100%	yes, pebbles to crush and then to SAG feed conveyor
Africa	Zambia	Sentinel 2	2014	Cu	26	28	22	79%	926	140	6	Yes partial	yes, pebbles to crush and then to SAG feed stockpile
Africa	Zambia	Sentinel 1	2014	Cu	26	28	22.4	80%	926	140	6	Yes partial	yes, pebbles to crush and then to SAG feed stockpile
South America	Chile	Escondida	2015	Cu	29	24	19	79%	1032	140	2.4	No	yes, pebbles to crush and then to SAG feed conveyor
Asia	Kazakhstan	Bozshakol	2016	Cu	23	28	25	89%	819	140	7.2	No	yes, pebbles to crush and then to HPGR, screen, then to BM feed sump
Asia	Kazakhstan	Aktogay 1	2017	Cu	23	28	24	86%	819	125	6.6	No	yes, pebbles to crush and then to HPGR, screen, then to BM feed sump
Africa	Mauritania	Tasiast	2018	Au	23	26	19	73%	819	150	19	No	yes, pebbles to crush and then to SAG feed conveyor

Region	Country	Operation	BM diameter	BMEGL	BM Installed Power (MW)	BM Utilised Power (MW)	BM Utilised Power (%)	Number of BMs	Total BM Installed Power (MW)	Total BM utilised Power (MW)	BM Utilised Power (%)	BM total power (MW)	BM circuit SEC (kWh/t)	F80 (mm)	A*b	Bond Wi (kWh/t)	P ₈₀ (microns)
South America	Chile	Collahuasi	26	38	16.4	15.5	95%	2	32.8	31	95%	32.8	6.8	55	48	12	200
South America	Peru	Antapaccay	26	40.5	16.4	15.5	95%	2	32.8	31	95%	32.8	8	75	40	18	240
South America	Chile	Caserones	28	44	22	20	91%	2	44	40	91%	44	8.4	100	50	12.3	175
North America	Canada	Mount Milligan	24	41	13	12.5	96%	2	26	25	96%	26	9	50	32	20	200
Africa	Zambia	Sentinel 2	28	44	22	18.5	84%	1	22	18.5	84%	22	5.2	100	45	18	250
Africa	Zambia	Sentinel 1	28	44	22	19	86%	1	22	19	86%	22	5.2	100	45	18	250
South America	Chile	Escondida	26	42	15.7	14.4	92%	4	62.8	57.6	92%	62.8	7.8	50	75	13	165
Asia	Kazakhstan	Bozshakol	28	43.5	22	21	95%	2	44	42	95%	44	11.5	90	37.5	19.4	140
Asia	Kazakhstan	Aktogay 1	28	43.5	22	21	95%	2	44	42	95%	44	10.5	90	42	16	160
Africa	Mauritania	Tasiast	14	28	2.2	2	91%	2	4.4	4	91%	4.4	5	100	30	14.5	90