HARD ROCK – CRUSH IT OR LET IT BREAK ITSELF?

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Abstract

Many ore bodies are getting harder, more abrasive, and lower in grade. One of the issues designers face is minimizing capital and operating costs when treating such ores. Designers often look to secondary or tertiary crushing followed by grinding in a semi-autogenous grinding mill with recycle crusher followed by a ball mill (SABC) or ball mill only circuit when treating extreme ores (Axb<30, BWi >18 and Ai>0.5). This approach is capital intensive and for abrasive ores often results in a circuit with high maintenance and operating costs.

This paper looks at how these extreme ores can also be treated successfully using primary crushing and single stage semi-autogenous or autogenous grinding (S/AG) milling. Benchmarking of this style of circuit is provided with detailed case studies of the design and operation of single stage SAG milling circuit with recycle crushing (SAC) at the Mt. Carlton Au/Cu/Ag and Mako Au projects. Discussed are why these circuits were successful and the challenges encountered.

Lastly, the learnings from these circuits are used to explore the part that autogenous grinding circuits may play in future comminution circuits.

Keywords

SAG, ramp up, design, commissioning, comminution circuit selection, competent ore, single stage.

Introduction

As ore bodies get increasingly harder, more abrasive, and lower in grade, one of the biggest challenges designers face is minimizing capital and operating costs when treating such ores. Designers often look to secondary or tertiary crushing followed by grinding in a semi-autogenous grinding mill with recycle crusher followed by a ball mill (SABC) or ball mill only circuit when treating extreme ores (Axb<30, BWi >18 and Ai>0.5). This approach is capital intensive and for abrasive ores often results in a circuit with high maintenance and operating costs.

For these "extreme ore" projects and particularly for ores that have a high Bond ball work index (BWi) and a relatively fine target grind, a viable option is to use single stage autogenous grinding (AG) or SAG milling circuits. When using a single stage SAG mill, the specific energy is high because all the grinding is undertaken in a single stage. In these cases, the SAG mill is often twice the size of that used in a SABC circuit. As a result, there is twice the rock volume and rock residence time in the SAG mill to break and abrade away the rock load. This large residence time means the mill set-up does not need to be as aggressive as in the SAG mill of an SABC circuit where the mill operates on a knife-edge; the rock can slowly abrade away. The result is a more stable circuit with lower variations in throughput associated with changes in feed distribution. Furthermore, not requiring secondary or tertiary crushing significantly reduces capital and operating costs compared to the single stage options if the ore is abrasive.

Circuit Selection

Circuit selection for extremely hard and abrasive ores is difficult because all options have associated shortcomings. In primary crush, SABC configurations, it may be difficult to get sufficient breakage in the open circuit SAG mill. Ore variability can impact the power split, and this can result in large swings in throughput.

Some form of pre-crushing of the feed is typically recommended to combat these issues; however, modelling and benchmarking of projects that have changed to secondary crushing shows these options do not yield a significant reduction in the total energy requirement. This is because extreme ores display both high resistance to impact breakage and abrasion grinding, meaning that a significant proportion of the total energy is still required for fine grinding. As a result, only a small reduction in total circuit specific energy is observed for the reduction in feed size.

Having the ability to crush some or all of the feed does provide an advantage from a risk perspective when compared with primary crushing, because it gives better certainty of throughput and increased circuit stability rather than an energy saving. However, this option becomes a higher capital option because there is an increase in the required unit processes to achieve design with only a moderate reduction in the energy requirement. This option also comes with the disadvantage of high media consumption and wear rates of the crusher liners and chutes.

Tertiary crush-ball milling circuits typically provide a more energy efficient option and the lowest installed power requirement for extreme ore types compared to a SAG option. However, as with secondary crushing industry experience has shown the overall capital cost will be significantly greater than the primary crushing options, particularly for lower throughput projects. The high consumables cost for a conventional tertiary crushing circuit will often offset any operating cost savings from the increased energy efficiency. The highly abrasive nature of extreme ores also means that the maintenance requirements on the crushing circuit will be extreme. Weekly crusher liner change outs will likely be required at all stages of crushing. This may make this option untenable from an operating or maintenance perspective unless duty standby crushers are installed further increasing the capital cost. The availability of the circuit will be very low and there will be the need for a large maintenance team. Ball consumption with a tertiary crushing ball mill circuit also remains very high.

For large capacity processing plants, the opinion of the author is that the use of high-pressure grinding rolls (HPGRs) for tertiary crushing is the preferred option because of the reduced maintenance requirements and the reduced circuit complexity in terms of number of tertiary crushers. HPGR roll change outs, for very abrasive ores, are expected to be in the range of 8,000 h once optimized compared to only hundreds of hours for cone crushers. The energy efficiency is also further improved.

The observation of the author from decades of comminution circuit design is the selection of secondary crushed SABC circuits and HPGR ball mill circuits by engineers as the preferred flowsheets for treating extreme ores. Secondary crushed SABC circuits are typically selected at lower capacities and HPGR ball circuits at higher capacities. One option that is often overlooked as a viable alternative to these circuits, particularly at lower throughputs, is single stage AG or SAG milling with or without pebble crushing.

As long as careful consideration is given to the ore characteristics and target grind size in the design phase, single stage circuits can offer reduced operational complexity, a smaller footprint, lower capital costs, and reduced ongoing wear-related operating costs. Based on this type of assessment the primary crush single stage SAG option was selected as the lowest risk and capital cost comminution circuit option for both case studies provided in the paper—the Mt. Carlton project in Australia and Mako project in Senegal.

CIRCUIT SELECTION COMPARISON

This section provides a comparison of three comminution circuit options suitable for processing an extreme ore type. To assist in the circuit selection a high-level capital and operating cost comparison is recommended to differentiate between the circuits. To demonstrate this, a comparative operating and capital cost is presented comparing tertiary crush ball milling, secondary crush SABC and primary crush single stage SAG milling. Table 1 presents the design criteria used in the assessment.

Table 1 – Design Criteria

Parameter	Unit	Value
Annual Plant Throughput	Mt/a	2.0
Primary Crushing		
Availability / Annual Operating Time	%/h	80/7,000
Throughput	t/h	285
Secondary/Tertiary Crushing		
Availability / Annual Operating Time	%/h	65/5,694
Throughput	t/h	351
Milling		
Availability / Annual Operating Time	%/h	91.3/8,000
Throughput	t/h	250
P_{80}	µm	106
Testwork for Design		
BWi	kWh/t	18.0
Ai	g	0.5
Axb		26.3
SG		2.91

Based on the design criteria the selected equipment is presented in Table 2 and modelled power utilization in Table 3.

Table 2 – Equipment Summary

Parameter	**Unit**	**3 Stage Crushing Ball Mill**	**2 Stage Crushing SABC**	**Primary Crushing SAC**
Primary Crusher		Metso	Metso	Metso
Model		C130	C130	C130
Installed Power	kW	160	160	160
Secondary Crusher		Metso	Metso	
Model		HP400	HP4	
Installed power	kW	315	315	
Tertiary Crusher		Metso		
Model		HP800		
Installed power	kW	600		
Product screen	m x m	3.0 x 8.5	2.4 x 7.3	
		Multi-slope	Incline	
SAG Mill				
Mill diameter (inside shell)	m		6.10	8.50
Effective grinding length (EGL)	m		4.40	6.10
Mill speed	%Nc		75 (VSD)	75 (VSD)
Selected motor size	kW		3,000	8,000
Pebble Crusher			Metso	Metso
			HP100	HP200
	kW		90	132
Ball Mill				
Mill diameter (inside shell)	m	5.80	5.49	
EGL	m	9.35	8.25	
Mill speed	%Nc	75	75	
Selected motor size	kW	5,750	4,100	
Cyclones		Weir	Weir	Weir
Model		400 CVX10-111	400 CVX10-111	400 CVX10-111
No installed		12	12	12
Total Installed Power	**kW**	**6,825**	**7,665**	**8,292**

Table 3 – Power Utilization

Parameter	**Unit**	**3 Stage Crushing Ball Mill**	**2 Stage Crushing SABC**	**Primary Crushing SAC**
BWi	kWh/t		18.0	
Axb	kWh/t		26.3	
Process Parameters				
Feed rate	t/h	250	250	250
Mill feed size, F_{80}	mm	10	35	125
Product size, P_{80}	µm	106	106	106
Pebble crushing	% feed	-	10.4	23.1
	t/h	-	36	58
Power Utilization				
Crushing specific energy	kWh/t	1.87	0.78	0.20
SAG mill specific energy	kWh/t		9.8	26.0
Ball mill specific energy	kWh/t	20.9	14.8	
Pebble crusher specific energy	kWh/t		0.10	0.23
Auxiliary specific energy	kWh/t	2.50	2.00	1.50
Total Specific Energy	**kWh/t**	**25.3**	**27.5**	**28.0**

The operating cost is based on consumables and the general maintenance cost factored from the predicted capital and does not include labour. The capital cost estimate is a factored estimated based on major equipment costs and is a direct capital cost only. The unit costs used in the operating expenditure (OPEX) estimate are presented in Table 4 and the consumables estimates in Table 5.

Table 4 – Unit Costs

Consumable	**Unit**	**Unit Cost**
Power	US$/kWh	0.15
Primary liners	US$/set	23,694.00
Secondary liners	US$/set	11,126.00
Tertiary liners	US$/set	28,733.00
Pebble crusher liners consumption	US$/set	7,500.00
Steel balls	US$/t	1,000.00
SAG mill liners	US$/t	2,900.00
Ball mill liners	US$/t	2,600.00

Table 5 – Consumables Estimate

Parameter	Unit	3 Stage Crushing Ball Mill	2 Stage Crushing SABC	Primary Crushing SAC
Crusher Liners				
Primary	Liner sets/a	9.1	7.5	12.4
Secondary	Liner sets/a	9.1	12.4	
Tertiary	Liner sets/a	8.5		
Crushing specific energy	kWh/t	1.87	0.78	0.20
SAG Mill				
Ball consumption	kg/t milled		0.54	0.96
Steel liner consumption	kg/t milled		0.09	0.23
Gross specific energy	kWh/t		9.8	26.0
Ball Mill				
Ball consumption	kg/t milled	1.44	1.02	
Steel liner consumption	kg/t milled	0.18	0.13	
Gross specific energy	kWh/t	20.9	14.8	
Recycle Crusher				
Liner consumption	Liner sets/a		10.8	10.7
Gross crusher specific energy	kWh/t milled		0.10	0.23
Auxiliary Power				
Gross specific energy	kWh/t milled	3.00	2.50	1.50

Based on the inputs the comparative capital and operating costs are presented in Table 6.

Table 6 – Comparative Capital and Operating Cost

Parameter	Unit	3 Stage Crushing Ball Mill	2 Stage Crushing SABC	Primary Crushing SAC
Comparative Direct Capital Cost	**US$ M**	**43.10**	**40.20**	**34.10**
Comparative Operating Cost				
Power	US$/t	3.79	4.12	4.19
Crusher liners	US$/t	0.28	0.19	0.19
Steel balls	US$/t	1.44	1.56	0.96
Mill liners	US$/t	0.51	0.36	1.02
Maintenance	US$/t	1.08	0.80	0.51
Operating Cost	**US$/t**	**7.11**	**7.04**	**6.87**

The assessment indicates that the primary crushing SAC option has the lowest capital and operating cost. Using the model produced to Look at sensitivity, the single stage SAG mill option is preferred economically, even if the power cost doubled or the media cost was 50% higher, or the Ai dropped to 0.3.

Design Considerations

Single stage SAG milling has historically been more difficult when the ore has competency (Axb) and abrasion grinding requirements (BWi) that are significantly different in terms of hardness combined with a grind size that is not compatible to the SAG milling conditions selected. An example of this is when the ore has a high Axb combined with a high BWi and a relatively fine grind. In this case, the ore will have a high specific energy requirement, but because of the low competency, there will not be enough media to undertake the grinding. This becomes an issue if there is insufficient ball charge to provide additional media.

At the other end of the spectrum, if the ore has a low Axb, moderate BWi, and a grind size that is relatively coarse (i.e., high competency combined with a moderate specific energy requirement). The risk in this case is that too much rock media will be present in the mill with low breakage and high abrasion conditions causing over-grinding and reduced throughput. This scenario would require a pebble crusher and may still encounter difficulties.

For extreme ores, the Axb is extremely low and the BWi is very high. This means that the ore is high competency and there is also a high specific energy requirement to achieve the grind size. The rock will require significant energy input or residence time in the mill to wear down, but this is provided because of the high specific energy requirement (and thus the large mill size) to achieve the grind size. Significant energy input and residence time is available for rock destruction in this case.

As indicated in the above examples, designing a single stage SAG mill requires careful consideration when selecting a configuration that suits the ore characteristics and grind size. In a paper on single stage S/AG mill design, Orway Mineral Consultants WA Pty. Ltd. (OMC) defined seven major configurations all suited to different criteria. The key is providing a circuit that balances coarse rock destruction with abrasion requirement to meet product specification. If the coarse rock breaks down too quickly, there will be no grinding media left to achieve the grind and a coarse product will result. If the rock media is not destroyed quickly enough, over grinding will occur and will probably result in a loss of throughput.

A single stage S/AG mill circuit selection diagram is presented in Figure 1, and a table defining these options with example projects is included in Table 7. The selection criteria used in the diagram is the Axb and the required specific energy.

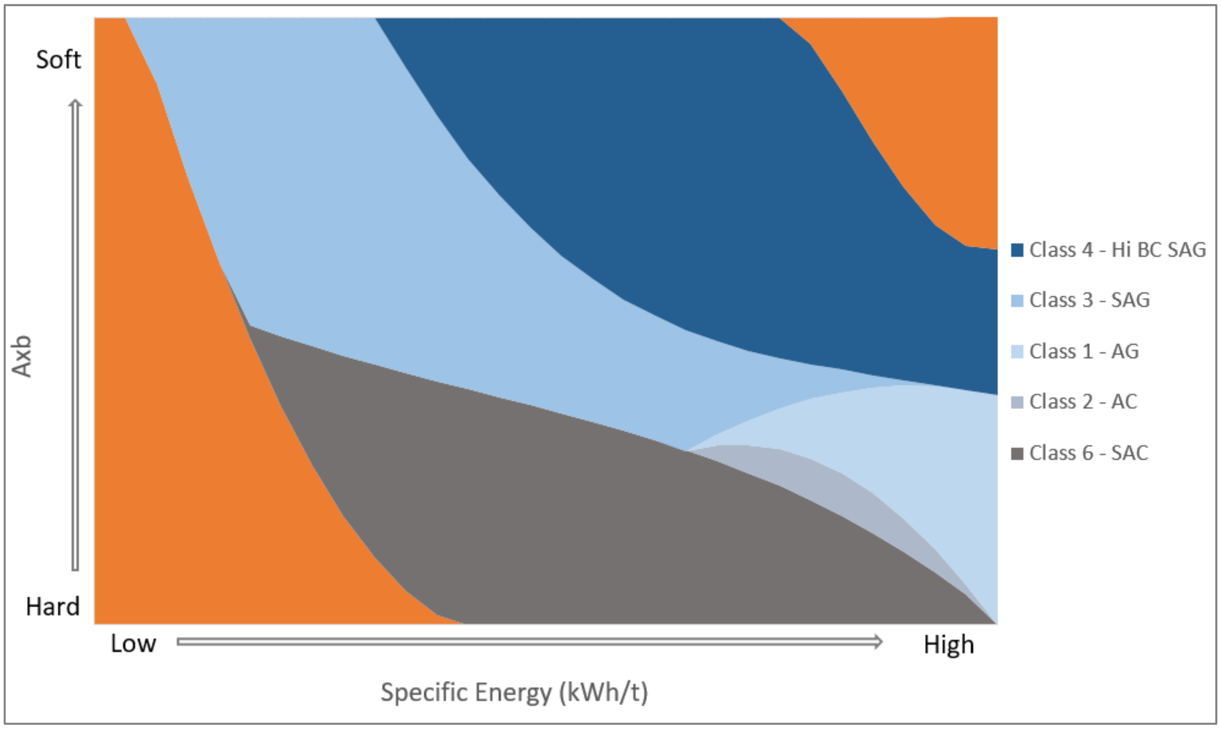

Figure 1 – Single Stage S/AG Mill Selection Diagram

Table 7 – Single Stage Circuit Configurations

Class	Single Stage Configurations	Examples
1	AG mill	Leinster, Olympic Dam, Tara
2	AG mill + a recycle crusher	Kambalda, Olympic Dam, Sino Iron, Cannington
3	SAG mill (8% to 15% ball charge)	Tarkwa, Leinster, Golden Pride, Obotan, Henty, Fosterville, Yanacocha, Kittila, Cosmos, Cosmic Boy, Jundee, Tanjianshan
4	High ball charge SAG mill or run-of-mine (ROM) Ball mill (15% to 25% ball charge)	Hidden Valley, Nzema, Sepon, Sissingue, UG2 ores (South Africa)
5	Low ball charge, high speed SAG mill (4% ball charge, 90% critical speed (Nc))	Driefontein (Underground), Kloof, Jacobina
6	SAG mill with recycle crusher (6% to 15% ball charge)	St Ives, Granny Smith, Mako, Mt Carlton, Edikan, Jundee
7	SAG mills treating partially secondary crushed feed	Darlot, Jacobina, Driefontein (Surface)

Table 8 benchmarks five circuits that have treated extremely hard ores using single stage SAG mills—Mako, St. Ives, Mt. Carlton, Jundee, and Granny Smith. All of these are treating hard felsic material (rhyodacite or granodiorite) or basalt.

Table 8 – Benchmarks

Parameter	**Mako**	**St. Ives**	**Mt. Carlton**	**Jundee**	**Granny Smith**
Rock type	Felsic/Basalt	Basalt	Felsic	Basalt	Felsic
Axb	22–30	22–40	23–41	18–30	30–40
BWi (kWh/t)	18–23	15–18	15–22	17–24	18–19
Ai	0.6–1.0	0.3–0.7	0.5–0.8	0.3–0.4	0.3–0.4
Capacity (Mt/a)	1.8	4.5	0.8	0.8	1.2
SAG mill (D m x EGL m)	8.50 x 6.10	10.72 x 5.48	7.32 x 3.80	5.50 x 8.68	8.53 x 3.66
Ball charge	8–12	12	12	17	7
Installed power (MW)	8.0	13.0	3.6	3.8	4.0
Pebble crusher (installed / used)	Y / Y	Y / Y	Y / N	Y / Y	Y / Y
Pebble crushing (% new feed)	25-50	17-25	0	5-10	25–40
F_{80} (mm)	140	100	100	110	105–120
P_{80} (µm)	115	100–125	85–120	70–114	120–155
Specific energy (kWh/t)	28	14–17	24–26	26–30	20–22

NOTE: Jundee is restricted by the mill diameter being a low aspect; it requires a high ball charge to draw sufficient power and had no pebble crusher when commissioned as it was designed to treat an oxide blend.

As discussed, it is essential to understand the rock and pebble and rock consumption rate and to align this with the energy requirement to achieve the target grind size when selecting a single stage grinding circuit. This presents a big challenge for designer. However, there is a lot of scope to optimize this relationship in operation by adjustment of the utilization of the recycle crusher, the mill speed, load level, milling density, circulating load, ball diameter, and grate aperture.

If the grind is fine and the perceived risk is that not enough media will be present in the mill charge due to low ore competency, then the mill would be designed without pebble crushing and at a low SAG mill speed. In extreme cases, high steel media levels are required for design. The design would also employ use of small diameter balls and smaller grate apertures. If excess media (from high competency ore) and over grinding were the likely risk, then pebble crushing would be included in the design in combination with a lower design ball charge level. The design would also use pebble ports and large diameter balls. Many of the optimization strategies discussed above were implemented successfully at Mt. Carlton and are further discussed in the Case Study.

Good control of the feed size to the SAG mill is also vital for the success of single stage grinding circuits. Feed top size is controlled by the primary crusher and the design is based on producing an F_{80} close to 100 mm. The second factor is the volume of fines in the feed. The design should be based around 25% to 30% passing 10 mm in the primary crusher product at an F_{80} of 100 mm. If contract mining is used this should be a specification for the product in any contract negotiations. Poor blasting practices resulting in low fines content will impact performance.

In the case of the single stage SAG mill with a recycle crusher, the major issue is coarse rock build up in the mill. This circuit will be sensitive to stockpile segregation. If a build-up of coarse rock occurs, the throughput will be reduced and over grinding of the ore may occur. As such, the use of this circuit is feasible if over grinding can be tolerated with sufficient power contingency in the design. The negatives of the additional power and ball consumption in this instance will be somewhat offset by the removal of all maintenance costs associated with secondary and tertiary crushing circuits and hopefully improved recovery associated with increased liberation when over grinding of the ore occurs.

Partial secondary crushing can be used to manipulate the feed to the single stage SAG mill circuit, but without a recycle (pebble) crusher, finer critical size can build up in the mill. The partial secondary crushing circuit will still produce material in the 50 mm to 20 mm range, which will not break easily in the mill given the ore characteristics. The use of both secondary and recycle crushing results in a high capital cost option. If large SAG mill grates are used to increase the average ball diameter within the mill to assist breakage, recycle conveyors will still be required which will add capital. For these reasons, secondary crushing into a single stage SAG mill is not a preferred route unless the secondary crushing can achieve a fine product, essentially a coarse ball mill feed.

Mako Case Study

The Mako Gold Project, 100% owned by Toro Gold, is located in southeastern Senegal in the Kedougou region, close to the Gambia River and Township of Mako. The process plant is designed to treat 1.8 Mt/a of ore and produce 128 koz to 143 koz of gold per annum.

This case study discusses the engineering design considerations that were made with respect to the ore interpretation, grinding circuit selection and design, and comminution modelling, as well as an overview of the commissioning and ramp-up of the mill.

ORE CHARACTERISTICS

The Mako ores have consistent comminution characteristics and can be classified into three groups: felsic, basalt, and weathered ore. A total of 17 samples were submitted to comminution testing. The 85th percentile of the comminution testwork parameters are presented in Table 9. Felsic and basalt ores have very high competency with very high grinding energy requirements and are extremely abrasive. Weathered felsic ores have moderate to high competency with above average grinding energy requirements and are moderate to highly abrasive. A review of the testwork indicated the Axb parameter in the top 1% of the OMC database.

Table 9 – Ore Comminution 85th Percentile Testwork Parameters

Parameter	Unit	Basalt	Felsic	Weathered	Design
Crushing work index	kWh/t	22.0	16.5	10.5	18.3
Bond rod work index	kWh/t	20.0	17.0	18.4	-
Bond ball work index	kWh/t	21.5	22.0	15.3	21.8
Abrasion index	g	1.04	1.05	0.61	1.05
Axb	-	21.8	27.5	39.5	25.6
Relative density	-	2.84	2.75	2.53	2.78

FLOWSHEET SELECTION

Through a number of studies and design reviews, the following findings were noted:

- Key design considerations were to minimize up front capital costs and de-risk the final design as far as achievable.
- A tertiary crush ball milling option provided the most energy efficient option and the lowest installed power requirement; however, the overall capital cost was predicted to be higher than the primary crushing options and consumable costs were predicted to offset any operating cost savings from the increased energy efficiency. The high abrasion index also indicated that the maintenance requirements on the crushing circuit would be very high, making this option untenable from an operating or maintenance perspective.
- The high ore competency (low Axb) indicated that SAG milling alone of felsic and basalt ores may be difficult and was associated with the risk of not getting sufficient breakage in an open circuit SAG mill to achieve the design throughput.
- Secondary crush options were considered but did not yield a significant reduction in the energy requirement because the ore is highly resistant to both impact breakage and finer abrasion grinding (grindability). Additionally, high wear rates of crusher liners would contribute to reduced crushing circuit availability and a need for larger equipment sizes to achieve throughput requirements. If partial secondary crushing were to be considered, it would be for risk mitigation only (ensuring mill throughput and grind size) and not to decrease installed power, up-front capital, or operating costs.
- A primary crush single stage SAG mill with recycle crusher option was then considered, with the major concern being the potential coarse rock build up in the mill. This could result in limited throughput and over grinding of the ore. Assessments indicated that contingency in the form of installed milling power would be cost effective to mitigate risk if this became a problem. The negatives of the additional power and ball consumption with over grinding, if it occurred, would be somewhat offset by the removal of all maintenance costs and availability reductions associated with either secondary/tertiary crushing and ball milling as well as improved gold recovery from a finer/ over grind. Tight specifications for the feed to the primary crusher where also issued to the contract miners at the tendering stage to mitigate the risk associated with treating poorly blasted feed (low in fines content), F_{100} and % Passing 25 mm.

Based on these assessments, primary crushing single stage SAG milling with recycle crusher (1oCR SS-SAC) was selected for the Mako project. This circuit design reduced operational complexity, capital costs, ongoing wear-related operating costs, and overall risk of not achieving design.

CIRCUIT DESIGN CRITERIA

The Mako comminution circuit design was based on treating 1.8 Mt/a of the life-of-mine blend of 73% felsic ore and 27% basalt ore. The circuit was designed to crush ROM ore from F_{80} 800 mm to D_{80} 100 mm and to subsequently grind the ore to a product size P_{80} of 125 µm. Comminution circuit process design criteria are presented in Table 10.

Table 10 – Comminution Circuit Design Criteria

Specifications	Unit	Value
Annual throughput	t	1,800,000
Crushing Circuit		
Availability / Annual Operating Time	% / h	85 / 7,438
Design crushing hourly rate	t/h	242
Feed F_{100}	mm	800
Feed F_{80}	mm	330
Product P_{80}	mm	100
Grinding Circuit		
Availability / Annual Operating Time	% / h	91.3 / 8,000
Design grinding hourly rate	t/h	225
Feed F_{80}	mm	100
Product P_{80}	µm	125
SAG mill specific energy	kWh/t	26.1
Pebble recycle rate	% Feed	25–50
Recirculating load	% Feed	400

FLOWSHEET DESCRIPTION AND MAJOR EQUIPMENT

This section provides the flowsheet description and major equipment for the Mako comminution circuit. The flowsheet is presented in Figure 2.

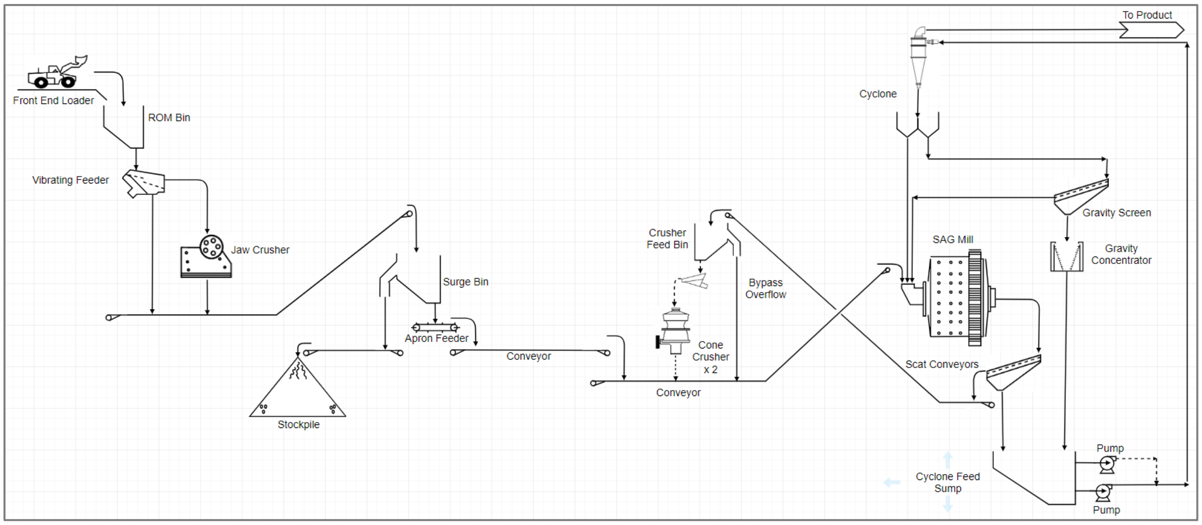

Figure 2 – Mako Comminution Circuit Flowsheet

ROM from open pit mining is fed by front-end loader (FEL) into the ROM bin. The ROM bin has a static grizzly to protect the jaw crusher from oversize lumps. Ore is withdrawn from the ROM bin by a Metso VF561 vibrating grizzly feeder. The grizzly oversize cascades into the primary jaw crusher. The jaw crusher is a Metso C130 (1,300 x 1,000 mm opening) single toggle design with a 160-kW motor, and it operates at a closed side setting (CSS) of 100 mm. Grizzly undersize and jaw crusher discharge are recombined and conveyed to the coarse ore (dead) stockpile (6,750 tonnes or 30 h capacity) via an overflow/reclaim bin (100 tonnes or 27 minutes).

Primary crushed ore can be fed directly from the reclaim bin by apron feeder to the SAG mill feed conveyor and into the SAG mill, or reclaimed by FEL from the dead stockpile and fed via the same bin. SAG mill feed is combined with recycle crusher product, cyclone underflow, and inlet dilution water to achieve the correct milling density.

Grinding is accomplished in an 8.50 m inside shell diameter x 6.10 m EGL Outotec grate discharge single stage SAG mill, complete with an 8000-kW variable speed drive (VSD). Having variable voltage variable frequency (VVVF) drive for VSD control allows the mill to be run up to 78% of critical, giving flexibility during the commissioning and ramp-up phases, and to adjust performance for changes in future ore hardness and liner wear.

The SAG mill discharges over a 3.0 m x 6.1 m Vibramech pebble dewatering vibrating screen with 15 mm x 50 mm apertures. The screen undersize material reports to the cyclone feed hopper. The pebble screen oversize passes under a cross belt magnet to remove tramp metal while being conveyed to a pebble crusher feed bin. Pebbles are withdrawn by one of two feeders into one of two pebble crushers (duty/standby), or overflow the bin and bypass the crushers. The pebble crushers are Metso HP200 cone crushers with 150 kW motors and designed to operate at CSS of 10 mm. The crushed and uncrushed pebbles report back onto the SAG mill feed conveyor.

The requirement for a pebble crusher was borderline and was included in the design to reduce risk. Consideration of up to 50% pebble extraction was noted for design if the circuit was ever to be expanded to two stage. The 112 t/h crushing rate is higher than is required for single stage utilization. The installation of one crusher for half the capacity was used as the basis of design of the single stage circuit with the second crusher as standby or for expansion if required.

The pebble screen undersize is diluted with water to achieve a density range prior to pumping to the cyclones. The cyclones are a cluster of ten Weir Cavex 400CVX10-111 with 150 vortex finders and 100 mm spigots. The cyclones classify the ground slurry with the cyclone overflow at the target grind size of P_{80} 125 µm reporting as product to the trash screen. The coarse underflow gravitates back to the SAG mill for further size reduction. A percentage of the coarse cyclone underflow is bled off to be fed to a Knelson gravity concentrator, the tailings of which then report to the mill discharge hopper. Figure 3 shows the grinding circuit.

The grinding circuit is followed by a pre-leach thickener, carbon in leach circuit (CIL), Zadra elution electrowinning, and cyanide detoxification circuit.

Figure 3– Mako Comminution Circuit

COMMISSIONING AND RAMP-UP

The Mako commissioning was undertaken on Felsic ore, close to design hardness, specifically reserved by the Toro mining department in the lead up to commissioning. This allowed ramp up and performance testing under design ore conditions. First ore was crushed to the stockpile on November 18, 2017 following successful dry plant commissioning. First ore was treated through the grinding circuit on December 26, 2017 and continuous operations achieved on January 3, 2018.

Following these milestones, the team focused on understanding, controlling, and ramping up the grinding circuit in order to achieve design throughput and product grind size. Being a single stage design (closed with hydrocyclones), the Mako mill performs the combined duties of a traditional SAG and ball mill in one mill. As a result, one of the biggest challenges was associated with waiting for the initial ball charge (100 mm and 125 mm balls first fill) to season, which is required to achieve efficient grinding at both coarse and fine rock sizes. Pegging of the grates with steel balls occurred during the commissioning period. This is not uncommon for single stage SAG mills with populations of grate aperture size balls reaching the grate in waves until the ball distribution reached equilibrium. In the first six weeks of operation, the average steel ball consumption was 1.41 kg/t.

A decision was made not to crush the pebbles during the initial period of operation providing more autogenous grinding media at smaller size fractions in the absence of smaller balls. The mill power/load response initially proved to be very sensitive to feed water addition and cyclone underflow flow rates returning to the mill. This sensitivity was reduced, and control improved after changing to a smaller spigot size, 90 mm from 100 mm. Even so, finding the correct mill load, speed, and ball charge to avoid sanding and restricting total throughput was a fine balancing act. Control stabilization was initially difficult, necessitating a robust overall control philosophy including:

- Feed water control in a ratio to new feed, adjustable based on the current mill power/load relationship.
- Cyclone control at a constant pressure set point with make-up water addition tied loosely to discharge hopper level. This allowed a stable circulating load and self-regulation of the circuit product size. This control method has the additional benefit of being able to use cyclone feed density as a direct indicator of cyclone overflow product grind size (P_{80}).
- Mill load control in cascade to new feed rate, which required a lot of work to tune.

- Mill speed was not implemented as a primary form of control; however, maximizing power using speed for a given ore type was left as an operator-controlled parameter. Speed was also used to allow protection of the SAG liners during periods of lost feed and to allow initial build-up of an operating charge following shutdowns or grind out events. Having a VSD also allowed inching of the mill (breaking of locked charge) to be automated and carried out without conventional swapping to a dedicated inching drive.

Grinding efficiency was initially poor; however, the calculated daily operating indices steadily improved with time achieving design conditions in mid-February, indicating that the ball charge was seasoned. The rubber spigots wore out rapidly with the abrasive ore and the mill became noticeably less stable. This changed following replacement of the spigots with a size smaller than originally installed, with throughput and grind size achieving design on February 14, seven weeks after first ore (six weeks after first continuous operation). Figure 4 shows the grinding throughput and product grind size achieved across the ramp-up period. Figure 5 shows the gradual increase in mill power and decrease in operating work index achieved across the ramp-up period.

A slight decrease in throughput occurred at the end of the recorded ramp up period. This was the consequence of inaccurate laboratory sizing results, which indicated that the product had coarsened significantly. This was not detected in the hourly wet grind determinations or by an increase in the cyclone feed density and was questioned; however, the throughput was reduced to bring the product into specification while investigations continued as this occurred during a performance trial. A repeat screening of the samples found that the products were within specification and the coarse results were due to a laboratory error. The result was a finer than target grind and slightly below design throughput during that period.

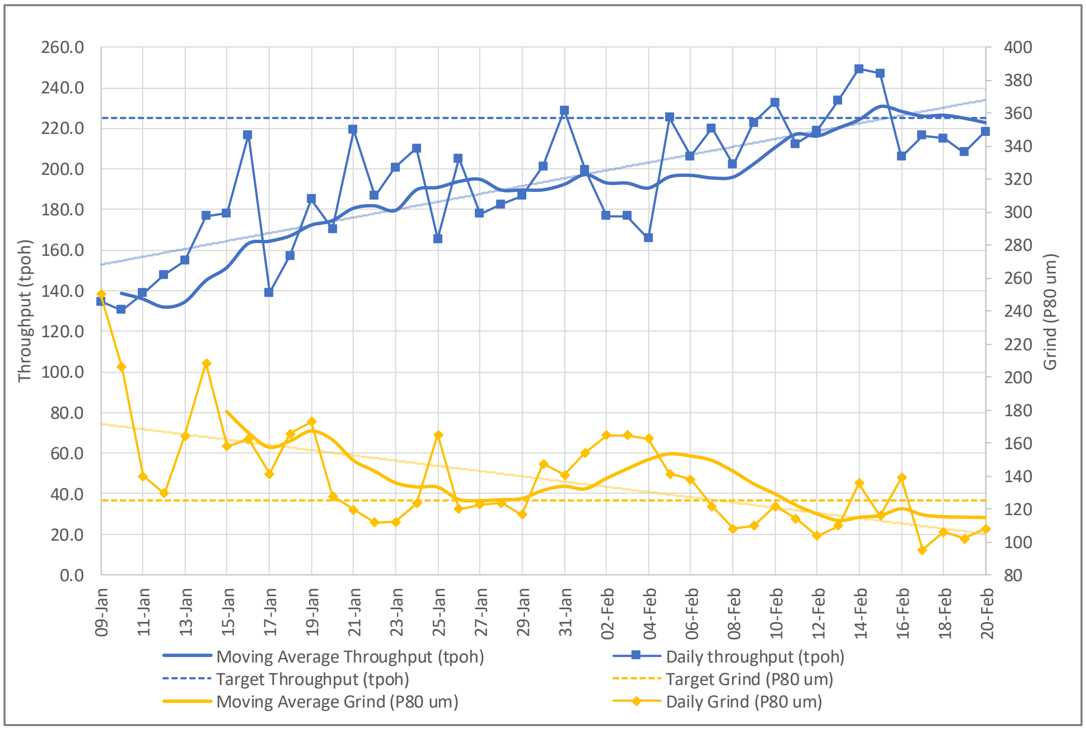

Figure 4 – Mako SS-SAG Ramp-Up Throughput and Grind

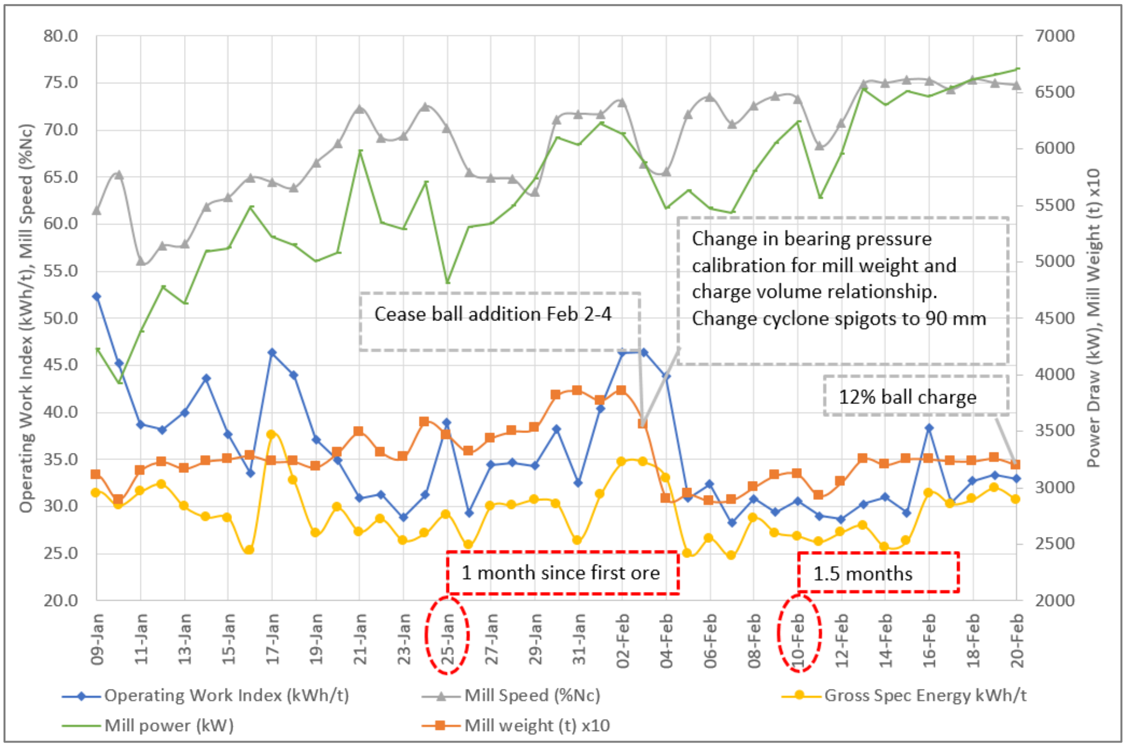

Figure 5 – Mako SS-SAG Ramp-Up Power and Operating Work Index Summary

- A number of option studies and design reviews identified a single stage SAG circuit with recycle crusher as the most suitable option for Mako to suit ore characteristics and project budget constraints. It was the simplest flowsheet with the lowest capital expenditure (CAPEX) and OPEX.
- A Ø 8.50 m x 6.10 m EGL, 8.0 MW SAG mill was selected for the SS-SAG duty. A Metso C130 was selected for the primary crusher duty and Metso HP200 units were selected as recycle crushers.
- The plant was commissioned between October 2017 and February 2018, with first gold poured on January 26, 2018. Design throughput and grind size was achieved seven weeks after first ore (six weeks after first continuous operation) without the use of the recycle crushers.
- A number of issues were dealt with during commissioning including operation as the charge seasoned, pegging of the grates, and implementation and optimization of the control philosophy. Once implemented and bedded in, the circuit was very stable. The recycle crushers are now utilized to increase throughput and coarsen the grind.
- Since the performance trial, the circuit has exceeded the design in terms of throughput and recovery with an oxide component included in the blend. Treatment of predominantly fresh ore is scheduled for 2019.
- Mako is a good example of how very competent and abrasive ore types can be treated without the need for multistage crushing and the associated high capital, maintenance, and operating costs.

Mt. Carlton Case Study

The Mt. Carlton project, 100% owned by Evolution Mining (Evolution), in Queensland's North East sits on a high-sulphidation epithermal style deposit rich in gold, copper, and silver. The project comprises gold, silver, and copper primarily as copper arsenic sulphides (enargite) and silver arsenic sulphides (tetrahedrite/polybasite) and some native gold (within pyrite).

The Mt. Carlton deposit has two discrete zones: the large gold dominant V2 deposit, and the smaller, silver-rich A39 deposit. Both deposits were to be mined and processed in three monthly campaigns. Mining and processing of the A39 deposit has since been completed in August 2014 with production now coming solely from the V2 deposit. The main rock types are from an intrusive and extrusive felsic volcanic metamorphic ore complex. The ore lithology is predominately rhyodacite with varying degrees of brecciation and silicification.

Mt. Carlton is an open pit mining operation with ore processed using a primary crusher, single stage SAG mill, and flotation to produce a concentrate for sale. OMC was involved in the original design of the comminution circuit and the project was commissioned in late 2012, with first concentrate shipped in March 2013.

In 2015, Evolution sought to optimize the project and OMC was invited to assist by undertaking a circuit review to identify opportunities for the optimization. During 2016, the Mt Carlton site team implemented the optimization strategies developed in conjunction with OMC.

This case study discusses the grinding circuit selection with respect to the ore interpretation, as well as an overview of the strategies employed to optimize circuit performance.

ORE CHARACTERISTICS

Twenty samples with geographical details were subjected to comminution variability testing during the study phases of the project. The testwork undertaken included bond ball and rod mill work indices, abrasion indices, and SAG mill comminution (SMC) testing. The 15th or 85th percentile rankings of the ore properties were used for design of the comminution circuit in the absence of a detailed lithology based mining schedule (Axb 24.9, BWi 20.7 kWh/t).

The BWi variability was high with a coefficient of variation of 26.6%. This variability made the design of a suitable circuit more complex particularly as the ore competency (Axb) variability did not correlate with the variability in BWi.

The tested samples were also observed to be highly abrasive with the average Ai for the dataset at 0.5 and the 85th percentile being 0.64. These values sat in the 84th and 94th percentile of the OMC testwork database (+8,500 samples) respectively.

FLOWSHEET SELECTION

Through a number of design reviews, the following findings were noted:

- OMC did not recommend the two-stage grinding, such as SAB or SABC, because of the very high variation in power requirement in both SAG and ball mills due to the high variability of the samples tested.
- Given the importance of a constant feed and product size for their downstream flotation performance, a detailed economic comparison of a single stage SAG mill with recycle crusher and tertiary crusher-ball milling option was carried out. The conclusion to this study was the selection of the single stage SAG mill with recycle crusher circuit configuration.

- The tertiary crushing and ball milling circuit was considered because it offered increased processing stability. However, due to the high abrasiveness of the material, extreme wear rates on the secondary and tertiary crusher liners were predicted. The stability achieved would therefore come at a high maintenance and capital cost (low availability or a requirement for standby units). For these reasons, the tertiary crushing circuit configuration was not selected.
- The single stage SAG milling option was well suited to the high variability in ore characteristics. It also provided the simplest flowsheet with the smallest footprint and minimized material handling. This combined with the expectation that this circuit offered the lowest operating costs led to the recommendation of a single stage SAG mill circuit with recycle crusher.

The target throughput for this project in the final study was set at 800,000 t/a (or 100 t/h) and a product P_{80} of 106 µm was nominated for the grinding circuit.

FLOWSHEET DESCRIPTION AND MAJOR EQUIPMENT

This section provides the flowsheet description and major equipment for the Mt. Carlton comminution circuit. The flowsheet is presented in Figure 6.

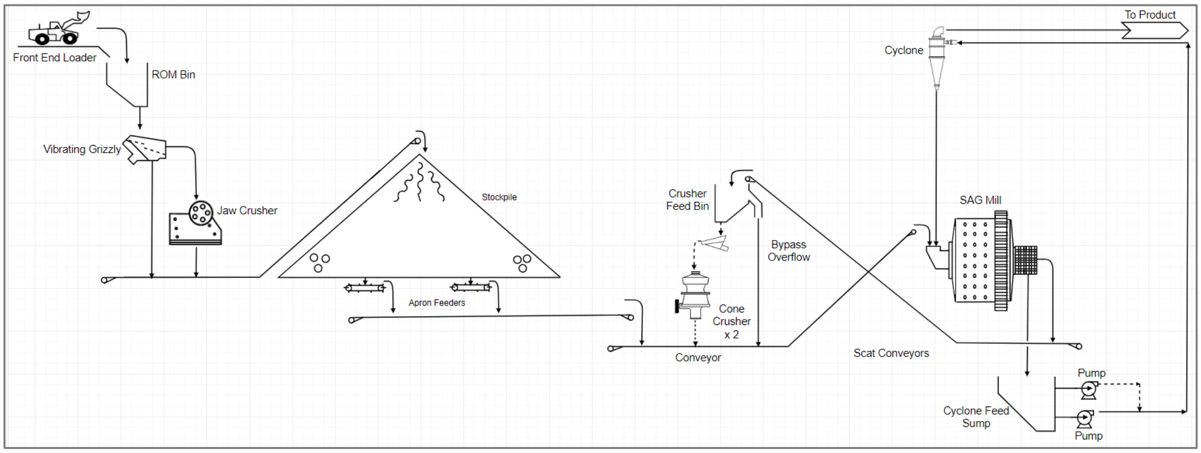

Figure 6 – Mt. Carlton Comminution Circuit Flowsheet

Ore at Mt Carlton from open pit mining is truck dumped or fed by FEL into the ROM bin. The ROM bin has a static grizzly to protect the jaw crusher from oversize lumps. Ore is withdrawn from the ROM bin by a vibrating grizzly feeder. The grizzly oversize cascades into the jaw crusher (Terex JW430, 1,070 x 760 mm, 110 kW) before being discharged and conveyed to the coarse ore stockpile. The grizzly undersize discharges onto the same conveyor as the jaw discharge for transport to the stockpile.

Primary crushed ore is reclaimed from the stockpile by two apron feeders onto the SAG mill feed belt to feed the SAG mill (Outotec Ø 7.32 m x 3.80 m EGL, 3.60 MW). SAG mill feed is combined with recycle crusher product, cyclone underflow, and inlet dilution water to achieve the correct milling density. The SAG mill discharges over a trommel with the undersize material reporting to the cyclone feed hopper. The trommel oversize passes through magnets to remove tramp metal while being conveyed to a pebble crusher feed bin. Pebbles are withdrawn by one of two feeders into one of the two pebble crushers (Sandvik CH420, 90 kW), or overflow the bin and bypass the crushers. The crushed and uncrushed pebbles are conveyed back onto the mill feed conveyor.

The mill trommel undersize is diluted with water to achieve the correct density prior to pumping to the cyclones (8 off Weir CVX400). The cyclones classify the ground slurry with the cyclone overflow at the target grind size reporting as product to the trash screen. The coarse underflow gravitates back to the SAG mill for further size reduction. Figure 7 shows the primary crusher, stockpile, pebble crushers, and SAG mill.

Figure 7 – Primary Crusher, Stockpile, Pebble Crushers, and SAG Mill

CIRCUIT OPTIMIZATION

OMC undertook a site visit and circuit performance review in November 2015. This involved a review of production data and operating philosophy, and a grinding circuit survey conducted on November 21, 2015.

The production data presented in Table 11 suggested that the design throughput (100 t/h) was being achieved at an average COF P_{80} of approximately 120 µm. The ore treated during the survey was found to be softer than the design, although within the historical testwork range for the fresh ore.

Table 11 – Data Review Summary

Parameters	Unit	Design	Model Prediction Survey Ore	Actual Survey	Production Data
Ball mill work index	kWh/t	21.0	17.6	17.6	17.6*
Axb	kWh/t	24.9	37.0	37.0	37.0*
Net SAG milling rate	t/h	100	108	108	97.6
SAG mill pinion power	kW	2,491	2,041	2,493	2,347
SAG F_{80}	µm	125,000	100,000	100,000	100,000
SAG mill P_{80}	µm	106	148	148	118
Power Utilization					
SAG milling specific energy	kWh/t	24.9	18.9	23.1	24.1
Specific recycle crushing energy	kWh/t	0.55	0.00	0.00	0.00
Total Circuit Specific Energy	**kWh/t**	**25.5**	**19.0**	**23.2**	**24.1**
f_{SAG}		1.21	1.25	1.46	1.42

NOTE: *Production ore characteristics assumed to be the same as the survey

OMC uses an 'f_{SAG}' efficiency factor (Scinto, P., Festa A., & Putland, B., 2015) for determining total grinding circuit specific energy. The power required for the grinding circuit standardized to an F_{80} of 150 mm and P_{80} of 75 µm is compared to the Bond BWi based power that is theoretically needed to effect comminution from the same size range. The ratio of the two values is referred to as the 'f_{SAG}' efficiency or design factor. The historic importance of using a standard product size in the OMC methodology has often been overlooked by others but this standardisation is key to delineate the role of high impact comminution (t10) and abrasion grinding (BWi) in the calculation of total specific energy. To determine the efficiency of an operating grinding circuit, OMC compares the actual f_{SAG} of the plant to the theoretical value calculated using testwork results. The major inputs from laboratory ore characterisation testwork needed to define the f_{SAG} are the Bond BWi (low energy breakage) and the t10 parameter from a high energy breakage test.

The following points summarize the key findings and recommendations of the optimization study:

- The power consumption of the SAG mill compared to the theoretical power consumption based on the testwork showed that the circuit was operating inefficiently. Actual f_{SAG} values over 1.4, compared to the predicted f_{SAG} of 1.25 for the surveyed ore, indicated that the circuit was using approximately 22% more energy than it should for the duty, or the sampled ore characteristics were not representative. A high fines content was observed in the cyclone overflow, indicating that sliming could also be contributing to the observed inefficiency.
- SAG mill speed was not used as much as it should be due to the operating conditions in the SAG mill. A suggested grind and load based control philosophy was provided by OMC for use in conjunction with set point changes.
- The SAG mill was operating at a low speed of 67% Nc, coupled with a relatively high ball charge of 12.5% and low total load of 18% to 25%. This resulted in operation at close to the maximum rotor current (maximum power draw for the operating speed). The power draw at 2.6 MW was just enough to achieve the target throughput and grind; however, it limited the operating range for the mill and contributed to much higher than design media consumption rates (3 kg/t). Following the assessment of the survey data, it was also suspected that operating at such a low speed was contributing to the observed energy inefficiency. It was recommended to move away from this mode of operation by reducing the ball charge and increasing the mill speed. This required a reduction in the current kinetics of coarse rock breakage in the SAG mill to ensure that a sufficient rock load could be maintained in the mill at the higher speed.
- To reduce the coarse rock breakage kinetics, OMC recommended that the two pebble port sections be removed to limit the amount of fine media being removed. This would allow the average diameter of the balls in the mill to decrease. If this was not sufficient, the amount of 105 mm diameter media was to be increased as a portion of the 125 mm / 105 mm ball size blend.
- Simulations indicated that under the above conditions, the ball charge could be reduced to 9% and the speed increased to 75%, while maintaining an adequate load level in the mill at the design throughput and grind. This was a significant reconfiguration of the circuit and required a gradual transition with the mill speed increased only as the charge facilitated to prevent destruction of the load and liner damage.
- It was recommended that the recycle crusher be bypassed, as the throughput was higher than design, but the grind was coarser. With very competent ores, rock is more likely to hold up in the mill and overgrind and, as such, recycle crushing is typically only used in SS SAG circuits to assist in coarsening the grind where coarser grinds are targeted. Recycle crushing could be required in the future when harder ore closer to the design range is treated; however, it was not required for the surveyed ore type.
- Reducing the ball charge to 9% and removing the ported sections of the mill was predicted to reduce the media consumption rate by 36%, a significant operating cost saving. While it was also envisaged that energy efficiency would improve, it was not possible to estimate this effect with the survey model. It was

recommended that a second survey be conducted following the implementation of the circuit changes to provide a new benchmark for further optimization.

- Although the grind was found to be coarser than design, the shape of the overflow PSD was somewhat unconventional and indicated excessive fines generation in the circuit. The cyclones were also operating with very low circulating load and displayed poor water split to the overflow. OMC recommended reducing the vortex finder size and increasing the number of cyclones operating to increase the circulating load and assist in reducing the sliming that was observed in the circuit, improving the milling efficiency.
- A constant feed flow (constant pressure) control philosophy was recommend for implementation to improve circuit stability.

During 2016, site personnel did excellent work implementing most of the optimization strategies developed with OMC, which had a significant impact on plant performance.

Pebble ports were removed, allowing the average ball size and ball consumption in the mill to decrease. The smaller ball diameter reduced impact breakage, allowing the mill to operate at higher speed and under more autogenous conditions. This increased efficiency and utilized more installed SAG mill power. The cyclone operation was changed to constant pressure and the vortex finder size was decreased improving cyclone performance.

The removal of the pebble ports facilitated a change in the mill operating speed to hyper-synchronous from sub-synchronous prior to the change. This allowed higher SAG mill power utilization. Before the change, the SAG mill power utilization was about 65.1%. This increased to 72.4% post the grate change, further increasing to 80% SAG mill power utilization later in 2016.

Comparing the pre and post pebble port removal production datasets, the impact of the changes becomes apparent.

Table 12 – Key Performance Indicators Pre- and Post-Removal of Pebble Ports

Parameter	Unit	Pre	Post	Change	% Change
Mill feed rate	t/h	94.5	98.3	3.8	4.0
SAG mill speed (% Nc)	%Nc	62.5	70.4	7.9	12.6
SAG mill power	kW	2345	2607	262	11.2
Daily grind size (P_{80})	µm	114	88	-25	-22.4
SAG mill specific energy	kWh/t	23.1	24.7	1.6	6.8
Operating work index – Wio	kWh/t	25.4	23.7	-1.7	-6.5
f_{SAG}		1.35	1.32	-0.03	-2.5

Removing the pebble ports reduced the average ball size in the mill, preserving rock media, which has allowed the mill to run 12.7% faster with an 11.3% increase in power draw when combined with a slight reduction in ball charge. This additional power has been used to grind 4% more throughput while achieving a 25 µm reduction in product size. This reduction in grind size has been achieved with only a 6.8% increase in specific energy consumption because of the 6.5% average increase in grinding efficiency (as expressed by the operating work index). The energy efficiency is now only slightly higher than would be expected based on last plant survey ore characteristics and further improvements to the cyclone performance are expected to reduce fines generation further, bringing the grinding efficiency in line with theoretical.

Before the pebble port change, the grinding media consumption was 3.02 kg/t, over twice that of the design. After the change, the ball consumption has been 2.16 kg/t. This would represent savings close to a million dollars per annum. In the later months of 2016, the ball consumption seems to have levelled out at around 2.4 to 2.5 kg/t. This higher value is a result of the higher average power draw being sustained (2607 kW compared to 2345 kW) and subsequently the finer grind size. The blend of 50% 125 mm and 50% 105 mm steel balls currently being used appears adequate for the current duty. If a higher throughput and a coarser grind were to be targeted, a higher portion of 125 mm balls could be used as the SAG mill is now close to being lump rock limited.

The SAG mill is currently not the circuit bottleneck, achieving the design capacity at a finer than design grind size. Under the current conditions, ball consumption and energy efficiency has been optimized at the target plant capacity.

Further optimization is still ongoing with several new initiatives identified in the review following the original optimization study.

SUMMARY

- The Mt. Carlton deposit comprises two discrete zones: the large gold dominant V2 deposit and the smaller, silver-rich A39 deposit. The comminution testwork indicated that the ore is competent and variable. This variability made the design of a suitable circuit more complex, particularly as the ore competency (Axb) variability did not correlate with the variability in BWi (Axb 24.9, BWi 20.7 kWh/t).
- A number of option studies and design reviews identified a single stage SAG circuit with recycle crusher as the most suitable option for Mt. Carlton to suit the variable ore characteristics. It was also the simplest flowsheet examined and was predicted to have the lowest operating cost. Detailed modelling showed that the requirement of a pebble crusher was marginal; however, this was included to reduce design risk by giving more control over the grind.
- A grinding circuit review conducted by OMC in November 2015 found that the circuit was operating inefficiently, with f_{SAG} values over 1.4, compared to the predicted f_{SAG} of 1.25 for the ore surveyed. The SAG mill speed was not being used to its full ability, and operating with a high ball charge with low total load meant the mill was operated at close to the maximum rotor current. Grinding media consumption rates were also excessive with the high operating ball charge, at 3 kg/t.
- A series of simulations were conducted which lead to recommendations that were implemented by the Mt. Carlton operations team. Three key modifications were made, as follows:
    1. Pebble ported segments were removed from the SAG mill discharge and replaced with fine grates allowing both the average ball size diameter and media consumption rate to decrease. This increased efficiency and allowed for utilization of more of the installed power.
    2. The cyclone control philosophy was changed to constant pressure (flow). The vortex finer size was decreased to increase the recirculating load. This improved circuit stability, which was subject to surging prior to the changes and sanding in the cyclone feed sump.
    3. Removal of the pebble ports allowed for the SAG mill load to be increased to a point where the mill speed could be increased. This in turn led to the overall SAG mill power utilization increasing from 65.1% to 80%.
- The combined strategies improved energy efficiency and allowed higher SAG mill power utilization. The additional power has been used to increase throughput by 4% while achieving a 25 µm reduction in product size (P_{80}) to gain downstream recovery improvements of approximately 2%. The reduction in grind size has been achieved with only 6.8% increase in specific energy consumption because of a 6.5% increase in grinding efficiency. The circuit product size is also notably more consistent due to the improvements made to the

cyclones, providing benefit to the downstream flotation circuit. A significant decrease in ball consumption was also gained (down by 20%), saving hundreds of thousands of dollars a year in operating costs.

- Following the optimization in 2015, the milling circuit is no longer the plant bottleneck, achieving design throughput at finer than design grind size and improved flotation recovery.
- Mt. Carlton is a good example of how very hard ore can be treated without the need for multistage crushing and the associated high capital, maintenance and operating costs, by using the high specific energy demand to consume the coarse rock as autogenous media. It highlights the importance of understanding the relationship between rock and pebble consumption rate and aligning this with the energy requirement to achieve the target grind size. Once identified and understood, this relationship can be used to guide optimization strategies to achieve the required circuit performance.

Conclusions

The Mt. Carlton and Mako projects defy the current industry stereotype that the best way to treat hard abrasive ore is to crush the feed fine.

The use of the rock to reduce media costs, removing the need to crush it, has significant economic benefits. The use of autogenous circuits was historically more common and needs more serious consideration in modern designs when treating abrasive ores.

The use of closed-circuit AG or SAG mills requires a greater portion of the grinding to be undertaken using autogenous media compared to open circuit mills followed by ball mills. This increased use of the autogenous media allows the single stage mills to adequately destroy coarse rock that would be costly to crush. The additional energy cost associated with grinding primary crushed feed to product in a single stage is not significant compared to options with finer crushed feed if the ball work indices of the ore are high. In these cases, the majority of the energy is used to grind the ore fine in comparison to that required for coarse rock breakage. This minimal change in total energy, in percentage terms, resulting from a change in feed size is also a reason why these circuits are relatively stable compared to open circuit AG/SAG mills when the setup is optimized.

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