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SHEDDING LIGHT ON SECONDARY CRUSHING

A. Festa, Orway Mineral Consultants Canada Ltd., Mississauga, ON, Canada
B. Putland, Orway Mineral Consultants Canada Ltd., Mississauga, ON, Canada
P. Scinto, Orway Mineral Consultants Canada Ltd., Mississauga, ON, Canada

ABSTRACT

Secondary crushing often gets good press for its increases in energy efficiency and SAG milling rates but for a project considering this option the proposed benefits soon get overshadowed by implementation concerns. Reverse engineering from the published case studies is risky unless the reader understands the drivers impacting stability and operability of the circuit.

This paper discusses the features of secondary crushing for Greenfield and Brownfield SAG mill grinding circuits. It is the author's view that secondary crushing rarely adds value to a Greenfield project and restricts future expansion. Its application is best retro fitted to Brownfield operations where the benefit gained for capital expended is excellent. Two case studies are presented to reaffirm these statements. The first case study shows that the implementation of partial and total secondary crushing increases SAG mill power efficiency and it offers substantial incremental increases in milling throughput with staged capital investments for the crushing and grinding circuits respectively. The paper provides a critical analysis of process conditions for secondary-crushed grinding circuits, with particular emphasis on Brownfield circuit retrofits. Furthermore, the second case study quantifies the economic impact of secondary crushing on circuit design for plant start up and it illustrates the limit imposed on plant expansion.

INTRODUCTION

Secondary crushing often gets good press for its increases in energy efficiency and SAG milling rates but for a project considering this option the proposed benefits soon get overshadowed by implementation concerns. Reverse engineering from the published case studies is risky unless the reader understands the drivers impacting stability and operability of the circuit.

OMC has specialised in the areas of Crushing and Grinding since 1983 and uses a multitude of in-house and commercially available computer software for circuit design and optimisation. A large database and considerable experience in modelling, design and implementation of secondary crushing circuits have been acquired over the intervening years. Relevant experience with secondary crushed feed SAG mill circuits includes: Abosso, Fimiston, Geita, Granny Smith, Iduapriem, Kidston, Mt Keith, Mt Rawdon, North Mara, Ridgeway, St Ives, Tarmoola, Tarkwa, Sabodala and Meadowbank, all two stage grinding circuits and Bonikro, Darlot, Carosue Dam and Kirkalocka, which are single stage SAG mill circuits. The combination of experience with modelling and simulation packages in conjunction with extensive experience in comminution circuit design, commissioning and optimisation, places OMC in a strategic position to accurately comment and offer insight to secondary crushing circuit designs.

This paper discusses the features of secondary crushing for Greenfield and Brownfield SAG mill grinding circuits. It is the author's view that secondary crushing rarely adds value to a Greenfield project and restricts future expansion. Its application is best retro fitted to Brownfield operations where the benefit gained for capital expended is excellent. Two case studies are presented to reaffirm these statements. The first case study shows that the implementation of partial and total secondary crushing increases SAG mill power efficiency and it offers substantial incremental increases in milling throughput with staged capital investments for the crushing and grinding circuits respectively. The paper provides a critical analysis of process conditions for secondary-crushed grinding circuits, with particular emphasis on Brownfield circuit retrofits. Furthermore, the second case study quantifies the economic impact of secondary crushing on circuit design for plant start up and it illustrates the limit imposed on plant expansion.

SECONDARY CRUSHING OVERVIEW

Secondary crushing of the SAG mill feed, when implemented correctly, has been shown to significantly reduce SAG mill and total circuit specific energy. Very fine feed, good process control and or the presence of some coarse rock in the feed (partial secondary crushing) has been required to make a successful project.

The reason secondary crushing works is relatively simple. The frequency of impact events greater than 100 Joules impacts, even in a large SAG mill, is very low, less than 1 per second (Morrison & Cleary, 04). Rocks requiring more than 100 Joules of energy to first fracture severely limit the throughput rate of a mill. Such rocks grind slowly by abrasion and chipping. Typically they are coarser than either the grate or pebble port opening and as such the recycle crusher is not effective. To increase throughput, the number of these rocks in the feed must be minimized. Analysis of different ore types, looking at the energy to first fracture and rock size (Figure 1) shows that, regardless of how hard the rock is, the energy required is typically less than 100 joules if the rock size is less than 50 mm. Stability and throughput of the circuit increase further once the maximum energy requirement is reduced to less than 50 joules.

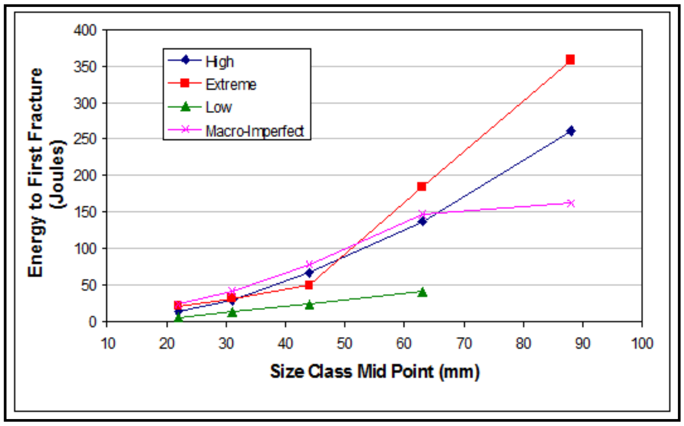

Figure 1. Typical Impact Profiles – OMC Database.

Rocks in the 50 mm to 80 mm range do not provide useful autogenous media for impact breakage and can only be reduced in size by abrasion. This size of material (often referred to as critical size) is therefore detrimental to high throughput and stability in an open circuit SAG mill. The ideal feed is made up of +100 and -60 mm material.

Types of Secondary Crushing Circuits

A number of screening and feed splitting options are available to achieve a secondary crush feed. These include:

- Open circuit, no screening – 100% of feed direct to secondary crushing.
- Open circuit, with scalping screen – Scalping of feed ahead of the secondary crusher to remove fines.
- Open circuit, with intermediate crushing – Primary crushed feed is sized on a double deck screen with the top deck oversize and the bottom deck undersize bypassing the crusher and the bottom deck oversize feeding the crusher.
- Closed circuit with product screen – Secondary crusher in closed circuit with a product screen.
- Two stages of secondary crushing (i.e. tertiary crushing) – Required to produce a -50 mm product.

All these configurations may be operated as partial secondary crushing circuits with the feed split ahead of secondary crushing. Table 1 defines selection criteria for partial secondary crushing circuit configurations based on ore competency, secondary crusher reduction ratios and downstream processing.

Table 1. Configuration Selection Criteria.

Configuration	Pros	Cons	Comment
Open Circuit, No Screening	Low capital.	Requires a fine CSS on the primary crusher and operates at a coarse CSS on the secondary crusher which results in more intermediate critical size material. High crusher wear as fines are not removed.	Suitable for primary mills with recycle crushers, for a moderate throughput increase. Good for non abrasive ore with low fines content and low moisture content.
Open Circuit, With Scalping Screen	Medium capital.	Secondary crusher CSS may be restricted by the primary crusher product size	Suitable for primary mills with recycle crushers. Good for abrasive ores, to increase life of crusher liners.
Open Circuit, With Intermediate Crushing	Medium capital. Allows operation of finer secondary crusher CSS.	Not suitable for extremely top end competent ores. The amount of secondary crushed material is influenced by the primary crusher product size distribution.	An alternative to the installation of a recycle crusher or partial secondary crushing using pre splitting of the ore.
Closed Circuit With Product Screen	No intermediate critical size generation.	High capital.	Suited to primary mills without pebble crushers or single stage mills. Provides high degree of control on top size for extremely high competency ores.
Two Stage Closed Circuit Secondary Crush	Full process control flexibility.	Highest capital.	Normally only considered for extremely hard ores where size reduction in a single step will affect crusher performance and increase maintenance.

A partial secondary crushing circuit is selected if the SAG mill cannot operate at high ball charge levels or when only a moderate increase in capacity is required.

CASE STUDY I – IMPLEMENTATION OF SECONDARY CRUSHING IN A BROWNFIELD SABC CIRCUIT

Secondary crushing of the SAG mill feed is undertaken to increase SAG mill power efficiency, thus allowing higher throughput in existing circuits. Its application is best retro fitted to Brownfield operations where the benefit gained for capital expended is excellent. The implementation of partial and total secondary crushing increases SAG mill power efficiency and it offers substantial incremental increases in milling throughput with staged capital investments for the crushing and grinding circuits respectively.

Initial Circuit Design

Run of mine (ROM) ore is fed by front end loader onto a static grizzly (deck aperture of 800 mm) above the ROM bin, which feeds the primary crushing circuit. Material from the ROM bin is withdrawn by apron feeders onto a grizzly scalper screen. The 1.8 m x 3.9 m scalper screen (deck aperture of 150 mm) classifies the material with the oversize (+150 mm) advancing to the primary jaw crusher, which operates in open circuit. The jaw crusher feed opening is 1500 mm x 1070 mm and the installed power is 200 kW, operating at a closed side setting of 135 mm. The jaw crusher discharge product and the scalping screen undersize produce a mill feed that is 80% passing 135 mm, which is conveyed to the stockpile that provides surge between the crushing and milling circuits.

The grinding circuit consists of an SABC circuit, with a SAG mill followed by a ball mill and a pebble crusher to crush the SAG mill trommel oversize material. Primary crushed ore is reclaimed from the stockpile via two apron feeders which can operate individually or in parallel to provide the 385 t/h. The mill feed is conveyed to the primary grinding mill feed chute, where it is mixed with water to achieve a milling density 70% solids. The primary mill is a Ø 8.50 m inside shell diameter x 3.68 m EGL (27.9 ft x 12.2 ft) SAG mill equipped with a 4,900 kW variable speed drive. The SAG mill discharge passes over a trommel. The trommel oversize material is discharged onto a conveyor and the pebbles are crushed in a 315 kW pebble crusher prior to return to the SAG mill feed. The trommel undersize is discharged into the common cyclone feed hopper with the ball mill discharge. The ball mill is a Ø 6.10 m inside shell diameter x 8.53 m EGL (20.1 ft x 28 ft) ball mill equipped with a 5,700 kW motor. The ball mill operates in overflow configuration, discharging slurry over a trommel screen protecting the pumps from steel media. Trommel undersize discharges into the common cyclone feed hopper. Grinding balls are charged to the ball mill to maintain power draw. Slurry exiting both the SAG mill and ball mill is combined and diluted to 75% solids prior to pumping. The cyclones classify the ground slurry with the cyclone overflow reporting to a trash screen ahead of the downstream circuit. The cyclone underflow gravitates to the ball mill for further size reduction.

During the first half of the life of mine (LOM), the grinding circuit became SAG mill limited by the competency of the mill feed. Ore characterisation tests were undertaken and the SMC test work revealed that the Axb parameter was 32.0 compared to 44.9 for the initial circuit design. The Bond Crusher Work Index (CWI) and the Bond Ball Mill Work Index (BWI) were determined to be 19.5 kWh/t and 16.8 kWh/t respectively. The objective of the study was to increase grinding circuit tonnage and maintain the final product target at 80% passing 106 µm.

Circuit Modelling

Three cases have been modelled for the purpose of this study:

1. Base Case: Primary Crush, SABC Circuit
2. Option A: Partial Secondary Crush, SABC Circuit
3. Option B: Total Secondary Crush, SABC Circuit

The Base Case considers the primary crush SABC circuit, wherein the grinding circuit throughput is SAG mill limited with spare power in the ball mill. Grinding throughput can be increased by the implementation of either: open circuit partial secondary crushing (Option A), or closed circuit total secondary crushing (Option B). Table 2 summarizes the grinding circuit modelling and Table 3 summarizes the grinding mill specifications.

For the Base Case, the SAG mill capacity is limited to 385 t/h, operating with a 12% ball charge (maximum), 26% total load and drawing 4,224 kW at the pinion. The SAG mill produces a transfer size of 80% passing 1,037 µm to the ball mill, which operates with a low ball charge of 25% and it draws 4,274 kW at the pinion. The specific energies for the SAG mill and ball mill are 11.0 kWh/t and 11.1 kWh/t respectively. The grinding circuit efficiency f(SAG) factor is 1.36.

Option A considers the installation of supplementary crushing equipment to provide a partial secondary crushed feed to the SABC circuit in order to increase SAG mill throughput and fully use the installed power on both mills. The secondary crushing arrangement is operated in open circuit. It comprises a surge bin, a 3.0 m x 6.0 m double deck screen (deck apertures of 100 mm and 38 mm) and a 315 kW cone crusher. A vibrating feeder transfers ore from the surge bin to the screen with screen oversize feeding the crusher. The feed rate to the screen is controlled such that a set portion of primary crushed material overflows the surge bin, which then combines with the crushed material to achieve a partially secondary-crushed blend. Varying the rate of discharge from the bin modifies the amount of primary crushed material overflowing to the grinding circuit. The circuit is configured for a partially secondary-crushed blend of 55% primary, 45% secondary crushed material,

Table 2. Grinding Circuit Modelling Summary.

Parameters	Units	Base Case Primary Crush SAG-Limited	Option A Partial Crush Crush	Option B Total Crush	Option B Total Crush Fully Utilized
Ore Parameters					
Ball Mill Work Index	kWh/t	16.8	16.8	16.8	16.8
Crushing Work Index	kWh/t	19.5	19.5	19.5	19.5
Axb	-	32.0	32.0	32.0	32.0
Process Parameters					
Net SAG Milling Rate	t/h	385	460	637	637
Net SAG Milling Rate	Mt/a	3.10	3.71	5.14	5.14
Percentage of Base Case Tonnage	%	100	119	166	166
% Recycle	%	32	26	19	19
SAG Mill F_{80}	mm	135	92*	39	39
SAG Mill T_{80}	µm	1,037	1,358	2,009	1,277
Ball Mill P_{80}	µm	106	106	106	75
Pebble Crusher F_{80}	mm	42.8	42.8	42.8	42.8
Pebble Crusher P_{80}	mm	15.0	15.0	15.0	15.0
Specific Energy					
SAG Mill	kWh/t	11.0	9.2	7.0	7.0
Ball Mill	kWh/t	11.1	11.8	12.6	15.3
Pebble Crusher	kWh/t	0.6	0.5	0.4	0.4
Total Specific Energy	**kWh/t**	**22.7**	**21.5**	**20.0**	**22.7**
f(SAG)	-	1.36	1.30	1.24	1.19
Required Pinion Power					
SAG Mill	kW	4,244	4,244	4,461	4,461
Ball Mill	kW	4,274	5,408	8,010	10,056
Pebble Crusher	kW	103	83	62	62
Total Required Power	**kW**	**8,620**	**9,735**	**12,533**	**14,579**

*Note: Partial-crushed SAG mill feed contains bimodal distribution.

Table 3. Grinding Mill Specifications.

Parameter	Units	Base Case Primary Crush	Option A Partial Crush	Option B Total Crush
Mill Type		SAG Mill	SAG Mill	SAG Mill
Number of Mills	-	1	1	1
Inside Shell Diameter x EGL	m	8.50 x 3.68	8.50 x 3.68	8.50 x 3.68
Mill Speed Range	-	68-75	68-75	68-75
Mill Speed – Duty	%Nc	75	75	75
Grinding Media Top size	mm	127	127	101.6
Ball Charge – Maximum	%	12	12	16
Total Load – Duty	%	26	26	20
Total Load – Maximum	%	35	35	24
Throughput – Duty	t/h	385	477	637
Pinion Power – Duty	kW	4,244	4,244	4,461
Pinion Power – Maximum	kW	4,530	4,530	4,653
Installed Power	kW	4,900	4,900	4,900
Mill Type		Ball Mill	Ball Mill	Ball Mill
Number of Mills	-	1	1	2
Inside Shell Diameter	m	6.10 x 8.53	6.10 x 8.53	6.10 x 8.53
Mill Speed – Duty (Fixed)	%Nc	75	75	75
Grinding Media Top size	mm	50	50	65
Ball Charge – Duty	%	25	36	23
Ball Charge – Maximum	%	36	36	34
Throughput – Duty	t/h	385	477	637
Pinion Power – Duty Per Mill	kW	4,274	5,408	4,005
Pinion Power – Maximum Per Mill	kW	5,408	5,408	5,367
Installed Power - Per Mill	kW	5,700	5,700	5,700
Total Installed Mill Power	**kW**	**10,600**	**10,600**	**16,300**

By implementing partial secondary crushing, the SAG mill specific energy is decreased by 16% to 9.2 kWh/t and the throughput is increased to 460 t/h. The SAG mill operates with the same loading conditions as the Base Case (12% ball charge and 26% total load) and it draws 4,224 kW at the pinion. With partial secondary crushing, the SAG mill transfer size increases to 80% passing 1,358 µm. This in turn increases the ball mill specific energy to 11.8 kWh/t when grinding to 80% passing 106 µm. The ball mill operates with a maximum ball charge of 36% and it draws 5,408 kW at the pinion. It is important to note that sometimes it is not possible to increase the ball charge depending structural limitations of the ball mill, and the SAG power is then not fully utilized. In this case study, partial crushing reduced the milling total specific energy by 5%. The grinding circuit efficiency f(SAG) factor decreases to 1.30, indicating more efficient energy use.

Option B considers a total secondary-crushed feed to the SABC circuit. The secondary crushing in this option comprises a larger 520 kW cone crusher operating in closed circuit with a screen. The entire primary crusher product is screened such that material not passing through the screen decks is fed to the secondary crusher before being recombined with the screen undersize. The secondary crushing circuit provides a SAG mill feed that is 80% passing 39 mm. With the reduced SAG mill feed size, the SAG mill throughput is maximised. The SAG mill product is coarsened and therefore a second ball mill of equal size and power is installed to maintain product size.

By implementing total secondary crushing, the SAG mill specific energy is decreased by 36% to 7.0 kWh/t and the throughput is increased to 637 t/h. With the fine feed, the SAG mill ball loading conditions for stable operation were changed to 15% ball charge and 22% total load and the mill draws 4,461 kW at the pinion. With total secondary crushing, the SAG mill transfer size increases to 80% passing 2,009 µm. This in turn increases the ball mill specific energy to 12.6 kWh/t when grinding to 80% passing 106 µm. The two ball mills operate with a low ball charge of 23% and they each draw 4,005 kW at the pinion. Total secondary crushing reduced the milling total specific energy by 12% and the grinding circuit efficiency f(SAG) factor decreases to 1.24.

The low operating load in the SAG mill with the fine feed requires redesign of the lifters and precise process control. Such mills are at high risk of liner and mill damage if not operated correctly.

Total secondary crushing and the installation of a second ball mill often leads to spare power in the ball mill. This provides additional ball mill operating flexibility when processing to the design product size. Alternatively, the spare power in the ball mill can be used to grind the ore finer, approximately 80% passing 75 µm in this case.

CRITICAL ANALYSIS OF PROCESS CONSIDERATIONS FOR SECONDARY CRUSHING

Many Brownfield plants experience lengthy production ramp-up periods following the installation and implementation of secondary crushing. It is the author's view that this phenomenon can be attributed to the limited experience of the engineer in charge of the circuit design and generally low awareness of the operational issues associated with secondary crushing. These circuits are often also marginal designs implemented on a very small budget. The use of secondary crushing to generate finer mill feed can have numerous direct and indirect consequences on the downstream grinding circuits. The effects on the grinding circuit can be positive or negative and the length of their occurrence will depend on the level of care and diligence taken during the design, commissioning and plant optimisation stages.

Power Consumption and Circuit Throughput

Secondary crushing of the SAG mill feed is undertaken to decrease the SAG mill specific energy requirement, thus allowing higher throughput. A number of recent projects that have implemented secondary crushing circuits are specified in **Recent Secondary Crushing Circuits** later in this paper. A reduction in SAG mill feed size can reduce the SAG mill specific energy requirement by 1% to 50%. This is influenced by the hardness of the ore and how fine the feed is crushed. Furthermore, reducing the SAG mill feed size can reduce the total circuit specific energy requirement by 10% to 20%. Often higher reductions are achieved by coarsening the grind from historic levels which becomes possible once a circuit is no longer SAG mill limited.

Total or Partial Secondary Crushing

The extent of the grinding throughput and/or energy efficiency gains are largely governed by the ore characteristics as well as the selection and proper implementation of either partial or total crushing.

Feeding 100% secondary crushed ore to a SAG mill requires the mill to essentially be a grate discharge ball mill. Efficient operation without a recycle crusher can only occur if the feed is very fine, less than 20 mm. For large throughput applications when the secondary crusher throughput is volumetrically constrained, 20 mm feed is best achieved by using a tertiary crusher. Treating total secondary (and tertiary) crushed feed is difficult in anything other than a purpose built and controlled circuit as the SAG mill is not designed to operate at an adequate steel ball load.

Secondary crushing only a portion of the mill feed has been undertaken on a number of projects. Partial secondary crushing has a number of benefits, these include:

- Control of the energy demand in the SAG mill, which impacts transfer size and therefore ball mill specific energy demand and throughput, providing optimal power utilisation when properly deployed.
- Provides coarse rock for media in the SAG mill. This allows larger rock loads to be operated in the SAG mill, optimising power and increasing circuit stability. The higher load level protects mill liners, reducing maintenance and ball consumption. This is important for SAG mills designed with a maximum ball charge of less than 15%.
- Allows the generation of a bi-modal feed, coarse rock and fine secondary crushed material. This increases stability of the circuit by minimising critical sized rock in the feed.
- Hence the amount of crushed ore in the blend should be tailored to match the required efficiency and power split (new circuit) or the mill power installed (retrofit).

Circuit Stability and SAG Mill Load

Grinding circuits fed with total crushed fine feed are very sensitive to feed size, particularly with harder ore. Load stability at high rock levels is difficult to obtain with a high ball charge. If the mill feed is crushed fine then a SAG mill can typically only be operated in a stable manner if the rock load is restricted to 4% to 7% above the ball charge, as experienced at St Ives, Granny Smith, Kidston, Fimiston and a number of other sites. If the load is pushed higher, minimal additional power is drawn from the mill. The increase in weight is minimal but the centre of gravity will have moved more into the centre of the mill. As little additional power is drawn to grind the additional load the mass can quickly increase, overloading the mill and eventually requiring the mill to be ground out.

Increasing the SAG ball charge does not lead to an increase in throughput, despite the increase in power as the mill acts more like a ball mill. If the maximum ball charge of the SAG mill is less than 15% the load stability limitation mentioned above results in very low load levels in the SAG mill exposing the liners to ball liner impact. In this case speed control of the SAG mill is important. If speed control is not available the application is riskier and redesign of lifters becomes imperative. The use of partial secondary crushing is typically implemented in this case as it provides coarse rock for added stability. Partial crushing allows for a significant rock load (12% to 15%) in line with primary crushed feed operation, thus protecting the liners from damage.

Lifter bolt breakage can be an indirect consequence of circuit instability and can cause significant plant downtime. Lifter bolt breakages were suffered at Porgera due to coarse and variable feed size changes, this resulted in the SAG mill overloading (low sound) and underloading (high sound) (Putland and Siddall, 2007). In retrospective, this appeared to be related to load control in the SAG mill. Corresponding liner cracks were found in the feed end-shell filler liners, shell plates and lifters.

Ball Size

Given the hardness of the ores treated, the top ball size used in the SAG mill typically does not reduce below 5 inch for partial crush applications with a recycle crusher. That being said, the use of 5.5 inch balls is not recommended. The damage that can be caused to mill liners by a 5 inch ball is significant while the effect of 5.5 inch balls is extreme.

In total secondary crushing applications, the crushed rock in the mill feed is unsuitable as grinding media. Grinding takes place using steel balls as media instead of rocks. This will result in higher overall ball consumption and possible liner damage if not effectively managed. The ball size should be modified in accordance with the feed size, taking into account the interstices between grinding media.

The effect of ball size was evident during Meadowbank's transition to secondary crushed feed for the SAB circuit. The SAG mill met the throughput target on 1.5 inch secondary crushed feed by operating the SAG mill with a 22.6% load and 13.5% ball charge, which consisted of a 50:50 mix of 5 inch and 4 inch balls respectively. Simulation work suggested that increased throughput could be obtained with 4 inch and 3 inch balls, although plant trials have not been yet been performed (Allaire and Muteb, 2012).

Grate Aperture

Over time grate apertures are typically reduced to about the 100% passing size of the feed for an SABC circuit. This is however dependent on the required throughput and power utilisation between SAG and ball mill. If more grinding is required in the SAG mill then smaller grate apertures are used to decrease the minimum ball diameter retained in the mill. If higher throughput is required the reverse is undertaken.

The implication of grate aperture was found at Ray mine, such that with the reduced size of SAG mill feed less pebble port area was required to maintain a given SAG mill load (Putland and Siddall, 2007). Decreasing grate open area allowed operation at a higher mill load, resulting in increased fine grinding, and also reduced the load on the pebble crusher. This strategy appears to be in response to reported difficulties with splitting the feed between primary and secondary crushing. Another strategy to increase mill load can be to decrease the number of pebble ports, as was the case at the Phoenix Mine (Bissue, Castillo, Lee and Thies, 2013).

Lifters

The SAG mill lifter design is another parameter to consider. The extent of changes to the lifter design depends on the intended load level determined to be operable given the feed characteristics, the maximum ball charge and availability of speed control. Modelling of ball trajectories is required to determine the optimal lifter angle and pattern. The type of material used in fabrication of lifters may also be reevaluated due to the anticipated changes in wear rates. Subsequent evaluation of the mill's reline intervals can be addressed after commissioning.

Recycle Crusher Operation

Grinding circuits without a recycle crusher have often been found to be unstable and difficult to operate unless the feed is crushed very fine. In the event of feed below 50 mm to an SABC circuit, tightening of the recycle crusher closed side setting can be performed because the reduction ratio is reduced. This improves the crushing of the pebbles and further reduces the impact of critical size build up within the circuit.

Changes to the Ball Mill Circuit

A SAG mill with fine feed produces a coarse transfer size to the ball mill. Brownfield operations require modifications to the ball mill circuit in order to deal with the new constraints of increased transfer size, specific energy demand and throughput.

In the event of coarser feed and increased throughput in the ball mill, cyclone overflow will coarsen unless additional power is provided in the ball mill circuit. To maintain product size at increased tonnage additional milling power is often required. For scenarios with marginal increases in specific energy and throughput, low capital cost measures to maintain grind include increasing the ball charge, or installing a grate to enable higher power draw if motor power is available otherwise coarsening of the grind is the only option. For situations with significant increase in the specific energy requirement and throughput then new mills are added to the circuit in parallel or in series.

With respect to the grinding media, ball size should be modified in accordance with both the feed and product size requirements.

In addition, the ball mill classification system must be audited and may need to be upgraded to account for the increase in tonnage. This includes a review of the number cyclones required to meet design tonnage and cut size, along with the cyclone operating variables.

Process Control and Optimisation Strategies

In order to successfully operate a grinding circuit preceded by secondary crushing, significantly more input is required from the experienced designers and operators. With proper commissioning to address the above-stated process conditions and variables, a revision of the regulatory controllers and expert control tuning needs to be undertaken as a next step. Expert control systems can play an important role to modify both control logic and set points of circuit variables. Typical follow up - to address changes in mill speed, water addition and fresh feed rate to alter the mill's power draw, internal charge load and circulating load are required with the ultimate goal to maintain optimal performance. Process control plays a significant role in balancing the power utilization between the two stages of grinding which is important and it is a significant benefit of installing a partial secondary crushing circuit.

Maintenance

The addition of supplementary crushing power to increase capacity brings attendant difficulties including increased maintenance, availability issues and the operation of belts and screens in the crushing plant. Cold climates and arctic weather pose increased challenges for maintenance related works on the crushers (bowl and mantle replacement) as well as the dust extraction from the crusher buildings.

General Comments

Understanding of the associated consequences to the downstream grinding circuit is required prior to the implementation of secondary crushing. The transition to secondary crushed feed for a Brownfield SAB or SABC requires numerous process changes as noted. A successful program incorporates a systematic approach to troubleshoot the circuit during commissioning and later optimise the circuit.

Recent Secondary Crushing Circuits (Table 4)

Table 4. Recent Secondary Crushing Circuits.

Project	**Porgera**	**Geita**	**Ray**	**Mt Rawdon**	**Demang**
Location	PNG	Tanzania	USA	Qld. Aust.	Ghana
Grinding Circuit	SABC	SAB	SABC	SABC	SABC
Size (Mtpa)	5.5	+6	4.0	3.2	4.8
Partial/Total	Partial	Partial	Partial	Partial	Partial
Open/Closed	Open	Closed	Open	Open	Closed
Feed splitting	Screen at 25 mm	Scalped at +120 -30 mm	Scalp 120 x 30 mm	Screen at 30 mm	Scalped +120 – 40 mm
F80 (mm)	90 – 110	150	37	~50	120
% Increase	0 – 16	20	49	54	75
Project	**Meadowbank**	**Kidston**	**Wallaby**	**Phoenix**	**St Ives**
Location	Canada	Qld. Aust	WA, Aust.	USA	WA, Aust
Grinding Circuit	SAB	SABC	SABC	SABC	SABC
Size (Mtpa)	3.1	7.0	3.0	10.9	3.2
Partial/Total	Total	Total	Total	Total	Either
Open/Closed	Open	Open	Closed	Closed	Closed
Feed splitting	Screen at 100 mm and 32 mm	No	Screen at 30 mm	Screen at 76 mm and 38 mm	Screen at 35 mm
F80 (mm)	25 - 32	24	25 - 30	35 - 51	25 - 30
% Increase	16	51	37	45	60

CASE STUDY II - IMPACT OF SECONDARY CRUSHING ON GREENFIELD SABC CIRCUIT DESIGN

Secondary crush SABC circuits are often considered for Greenfield designs for one of three reasons:

1. Circuit designs that require very high throughput on extremely competent (Axb below 25) and very abrasive (Bond Abrasion Index above 1.0) in the first three years of operation can benefit from secondary crushing implemented on plant start-up.
2. The primary crush SAG milling option requires a gearless drive for the SAG mill and the application of secondary crushing reduces the SAG mill power requirement within the limits of geared drive technology.
3. The project requires capacities 10% to 25% above the capability of the world's largest Ø 12.8 m diameter (42 ft) 28 MW SAG mill.

It is the authors' view that secondary crushing rarely adds value to a Greenfield project and restricts future expansion. Outside of these circumstances secondary crushing in a new plant design should not be considered at all. There are typically better options for a Greenfield design which provide more flexibility in the future should the ore change or the circuit need to be expanded. Secondary crushing is essentially a hybrid option and does not provide the full capital benefit of a primary crush SABC circuit or the energy efficiency and stability of a tertiary crush (via cone or HPGR) followed by a ball mill circuit. Putting a secondary crushing circuit up front restricts options for the future. The objective of the following case study is to quantify, at a scoping study level, the economic impact of selecting a secondary crush SABC circuit for a Greenfield design.

Circuit Modelling

Two cases were modelled for the purpose of this study:

1. Option 1: Primary Crush, SABC Circuit
2. Option 2: Total Secondary Crush, SABC Circuit

For Option 1, the primary crushing circuit comprises a 42 x 65 inch gyratory crusher with a 375 kW motor. The crusher operates at an open side setting (OSS) of 150 mm. The gyratory crusher produces a mill feed that is 80% passing 135 mm, which is reclaimed from the crusher vault via an apron feeder and conveyed to the stockpile to provide surge between the crushing and milling circuits. Option 2 uses the same gyratory crusher as Option 1 but a secondary crushing circuit is installed between the primary crusher and the stockpile. The Option 2 secondary crusher operates in closed circuit with a product screen. In both options, the SABC circuit consists of one SAG mill, with a recycle crusher in closed circuit, followed by a ball mill.

The design criteria for the conceptual comminution circuits was developed for a 5.14 Mt/a concentrator. The design throughput for the crushing plant is 782 t/h at 75% availability. The design throughput for the grinding circuit is 637 t/h at 92% availability. The grinding circuit final product size is 80% passing 106 µm.

For Option 1, the SAG mill and ball mill specific energies were determined to be 11.1 kWh/t and 11.1 kWh/t respectively. Option 2 has SAG mill and ball mill specific energies of 7.0 kWh/t and 12.6 kWh/t respectively. These are the same grinding mill specific energies as used in the expansion case study but in this scenario the capacity is the same for Greenfield comparison. Table 5 summarizes the Greenfield SABC circuit modelling results.

The total installed power for the crushing and grinding major pieces of equipment for Option 1 and Option 2 are 18,130 kW and 15,284 kW respectively. Table 6 summarizes the major equipment selected for each option.

Capital Estimates

Capital cost estimates were developed based on the major equipment selected for the two grinding circuit options. The estimates were built up using costs associated with similar sized processing plants with a combination of quantitative and percentage based estimating methods. The estimate accuracy is set at -10% to +30%.

Table 5. Greenfield Modelling Summary.

Parameters	Units	Option 1 Primary Crush SABC	Option 2 Secondary Crush SABC
Ore Parameters			
Ball Mill Work Index	kWh/t	16.8	16.8
Crushing Work Index	kWh/t	19.5	19.5
Axb	-	32.0	32.0
Process Parameters			
ROM Feed F100	mm	750	750
ROM Feed F80	mm	431	431
Primary Crusher Feed Rate	t/h	782	782
Net SAG Milling Rate	t/h	637	637
% Recycle	%	31	19
SAG Mill F80	mm	135.0	38.9
SAG Mill T80	µm	1,021	1,896
Ball Mill P80	µm	106	106
Pebble Crusher F80	mm	43.0	29.8
Pebble Crusher P80	mm	15.0	12.0
Specific Energy			
Primary Crusher	kWh/t	0.2	0.2
Secondary Crusher	kWh/t	-	0.5
SAG Mill	kWh/t	11.1	7.0
Ball Mill	kWh/t	11.1	12.6
Pebble Crusher	kWh/t	0.6	0.4
Auxiliary Equipment	kWh/t	2.6	2.9
Total Specific Energy	kWh/t	25.5	23.6
f(SAG)	-	1.36	1.23
Required Pinion Power			
Primary Crusher	kW	183	183
Secondary Crusher	kW	-	225
SAG Mill	kW	7,050	4,461
Ball Mill	kW	7,045	8,011
Pebble Crusher	kW	322	241
Auxiliary Equipment	kW	1,628	1,867
Total Circuit Required Power	kW	16,228	14,988

Table 6. Summary of Greenfield Major Equipment Specifications.

Parameter	**Units**	**Option 1 Primary Crush SABC**	**Option 2 Secondary Crush SABC**
Primary Crusher	-	**Gyratory**	**Gyratory**
Size	inch	42 x 65	42 x 65
Open Side Setting	mm	150	150
Installed Power Per Unit	kW	375	375
Number of Units	Qty	1	1
Crusher Screen	-	**-**	**Inclined**
Model Size (W x L)	m x m	-	3.0 x 6.0
Apertures	mm		100 / 50
Installed Power Per Unit	kW	-	74
Number of Units	Qty	-	1
Secondary Crusher	-	**-**	**Cone**
Diameter	m	-	2.5
Closed Side Setting	mm	-	38
Installed Power Per Unit	kW	-	520
Number of Units	Qty	-	1
Primary Grinding Mill	-	**SAG Mill**	**SAG Mill**
Size (Diameter x EGL)	m	10.35 x 4.10	8.50 x 3.70
Installed Power Per Unit	kW	9,100	4,700
Number of Units	Qty	1	1
Pebble Crusher	-	**Cone**	**Cone**
Diameter	m	-	2.1
Closed Side Setting	mm	16	16
Installed Power Per Unit	kW	355	315
Number of Units	Qty	1	1
Secondary Grinding Mill	-	**Ball Mill**	**Ball Mill**
Size (Diameter x EGL)	m	6.40 x 11.29	6.70 x 11.35
Installed Power Per Unit	kW	8,300	9,300
Number of Units	Qty	1	1
Total Installed Power	**kW**	**18,130**	**15,284**

The cost estimates were developed primarily for comparative purposes and as such the relativity between the two estimates is more important than the absolute cost. Costs were derived from projects of similar configuration and scale for use as the basis of the capital cost estimates taking into account the equipment sizing and selection and sourcing budget level (+/-30%) pricing ex vendors for major items. All rates or percentage based estimating factors used are consistent for each of the two estimates and are based on historical data from other projects.

The battery limits of the study are the ROM bin in the primary crushing circuit through to the overflow discharge from the cyclones in the grinding circuits. No costs have been included to cover auxiliary services, power, water etc. or the downstream unit operations.

Table 7 summarises the capital cost estimates in US dollars (USD). The capital costs for the primary and secondary crush SABC circuits are $64.2 million USD and $71.9 million USD respectively. The primary crush SABC circuit (Option 1) was determined to be $7.6 million USD less expensive that the secondary crush SABC circuit (Option 2). The primary crush SABC circuit exhibits the same plant expansion potential as outlined in the first case study whereas the secondary crush SABC circuit throughput is already maximized.

Table 7. Summary of Capital Cost Estimates.

Plant Area	**Capital Cost Estimates USD, -10%+30%**		
	Option 1 Primary Crush SABC	**Option 2 Secondary Crush SABC**	**Difference**
Feed Preparation Area	9,501,407	21,404,738	11,903,331
Grinding Area	44,130,787	38,508,537	-5,622,250
EPCM Office	10,626,439	11,982,655	1,356,216
Total	**64,258,632**	**71,895,930**	**7,637,298**

CONCLUSIONS

The implementation of partial or total secondary crushing decreases the SAG mill specific energy requirement and it offers substantial incremental increases in milling throughput with staged capital investments for the crushing and grinding circuits respectively. Secondary crushing is an effective way to improve comminution circuit efficiency for high competency ores and reduces capacity variability. The expansion is capital efficient but is a difficult circuit to operate and maintain.

Understanding of the associated consequences to the downstream grinding circuit is required prior to the implementation of secondary crushing. The transition to secondary crushed feed for a Brownfield SAB or SABC requires numerous process changes and a systematic approach to troubleshoot the circuit during commissioning and later optimise the circuit.

There is a strong case for retaining some coarse material in the grinding circuit feed to provide media and minimise liner damage. Partial secondary crushing circuit arrangements should be selected if an existing SAG mill cannot operate at high ball charge levels or when only a moderate increase in capacity is required. Partial secondary crushing significantly improves operation flexibility allowing optimisation of the circuit.

Secondary crush SABC circuits are often assessed for Greenfield designs for a number of reasons discussed in the paper. The study shows that a primary crush SABC circuit design requires less capital investment compared to a Greenfield secondary crush SABC circuit design. If certainty of design is required the additional capital would be best spent of larger mills for SABC case or a change in the design to a three stage crushing ball mill circuit. Greenfield secondary crush SABC circuits are restricted on future plant expansion whereas Greenfield primary SABC circuits are not.

There must be a very compelling reason to implement a secondary crushing circuit feeding a SAG mill for a Greenfield design as in the majority of cases low capital or more efficient and stable circuits can be installed.

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