



**AN OVERVIEW OF SINGLE STAGE  
AUTOGENOUS AND SEMIAUTOGENOUS GRINDING MILLS**

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**ABSTRACT**

This paper discusses the challenges associated with the process design of single stage mills, the design flexibility required to ensure a robust circuit and the operating techniques adopted at successful installations. The discussion culminates with selection criteria and generic operating philosophy for single stage autogenous and semi autogenous grinding mills

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## INTRODUCTION

Over the years the design and operation of single stage autogenous and semi autogenous grinding mills has been a rather hit and miss affair, with some great successes and some dismal failures, with the majority of installation somewhere between. Yet the simplicity, low capital and seemingly simple operation make this a circuit of choice for many.

This paper discusses aspects of process selection of single stage mills, the design flexibility required to install a robust circuit and the operating techniques adopted by successful operations.

The major issue with selecting a single stage circuit has been the risk associated with the process design. This has been notoriously difficult for a number of reasons, most of which are associated with determination of the inter-relationship between abrasion and impact breakage.

Most test methods predict either the ability of the rock to be broken by impacting events or the rate of degradation by abrasion. The combination of these breakage mechanisms into a single breakage function is difficult in SAG and AG mills and is a source of possible error.

In regard to the selection of single stage SAG mills, Macintosh (2001) comments:

*Single stage mills appear to be reasonably power efficient at coarse grinds, but become very inefficient at grinds less than 75  $\mu\text{m}$ .*

*The grind size is more difficult to control in a single stage SAG circuit at fine target grind sizes, when compared to an SAB or SABC circuit.*

Based on an understanding of the effect of grind size on a single stage operation, this paper discusses why this has been the case, and will attempt to define general rules regarding the selection of a single stage SAG mill. (SSS)



## SINGLE STAGE SELECTION CRITERIA

The decision to go single stage or two stage grinding is generally dictated by the product required. A guide based on grind size follows:

1. **Coarse Grind – Coarser than 80% passing 106  $\mu\text{m}$ .** If determined to be reasonably power-efficient, single stage SAG milling is likely to be the most profitable grinding circuit design.
2. **Medium Grind – 80% passing size between 106 and 75  $\mu\text{m}$ .** To mill in single stage SAG configuration, the feed must be consistent, not too coarse or too fine. The downstream process must be able to handle fluctuations in the grind size. If these two factors cannot be satisfied the choice of an SAB or SABC circuit is favoured.
3. **Fine Grind – Less than 80% passing 75  $\mu\text{m}$ .** Seeking a fine product size suggests that the downstream process is sensitive to grind, otherwise the costs associated with achieving the product size would outweigh the downstream benefits. Therefore an SAB or SABC circuit is preferred because of the more stable product generated in this type of circuit. Furthermore, large circulating loads are often encountered if trying to produce a grind size less than 75  $\mu\text{m}$ . This can result in slurry pool formation due to grate and pulp lifter restrictions on the ensuing high flow, which has an adverse effect on power efficiency.

Consideration of the scale and likely power demand also has a major impact on circuit choice:

4. **Power demand less than 7 MW.** This puts the application in the realm of a single mill, single pinion operation.
5. **Power demand up to 14 MW.** This puts the application in the realm of a single motor, twin pinion or dual motor and pinion installation.
6. **Power demand exceeds 14 MW.** This puts the application in the realm of a single mill with gearless drive or, possibly, twin motors each with a twin pinion. See later discussion on aspect ratio. If the aspect ratio is low, then the limit of mill size is encountered, leading to a dual grinding line operation – which may be less attractive than a single line SAB or SABC operation.

Therefore if the ore *is not overly grind sensitive*, and the application is suited to a single mill scenario, SSS appears appropriate. If grind sensitivity is an issue or the capacity is too high for a single SAG mill, a two stage grinding circuit is recommended.



## **SELECTION OF AN APPROPRIATE SINGLE STAGE CONFIGURATION**

The first step in designing a single stage circuit is the selection of the optimum circuit configuration. Single Stage AG and SAG circuits can be sub-divided into a number of configurations, each suited to ores with certain characteristics. Therefore, accurate ore type characterisation is critical to success.

### **Ore Characterisation**

As a result of the inherent inaccuracy in the methods for predicting single stage performance, a number of tests are undertaken and compared. Even then, substantial contingency is often assigned in final design for equipment selection.

Bench scale testwork followed by a targeted piloting campaign is recommended, with the following steps :

- 1) Characterisation of the ore using bench tests (OMC's Advanced Media Competency Testing (AMCT), JK dropweight)
- 2) Determination if the use of a single stage circuit is appropriate, using defined selection criteria
- 3) Selection of the correct style single stage configuration (see Table 1). (If physical or imposed equipment constraints prevent the use of appropriate equipment, reassess if single stage operation is appropriate.)
- 4) Model the circuit to define parameters of operation and equipment selection for economic evaluation.

Undertake a small pilot campaign focused on the selected circuit to confirm design parameters if possible. The focus of the campaign is to achieve constant results for use in design, not a range of results for selection of the configuration.



**Table 1**  
**CIRCUIT CONFIGURATIONS**

	Single Stage Configurations	Application
1	AG mill	<i>Competent ore - homogenous</i> . The grind size is often dictated by the relationship between abrasion and impact breakage, especially in fixed speed mills. Often selected when low steel contamination is required.
2	AG mill + a recycle crusher	<i>Competent ore - relatively homogenous</i> (the recycle crusher is used to balance the rate of impact breakage within the circuit)
3	SAG mill (8 – 15% ball charge)	<i>Variable competency ore</i>
4	High ball charge SAG mill (15 to 25% ball charge)	<i>Incompetent ore</i>
5	Low ball charge SAG mill, high mill speed. (4% ball charge, 90% Nc)	A cross between AG and SAG for <i>competent, abrasive ores</i> . As typically operated in RSA.
6	SAG mill (configurations 3, and 5 ) with recycle crusher	Competent ores, better suited to coarse grind sizes as circulating loads can be high
7	SAG mills treating partially or fully secondary crushed feed	<i>“Top-end competent” ores</i> . Typically to achieve moderate to coarse grind sizes with 8-15% ball charge for partially secondary crushed feed, and 15- 25% ball charge for fully secondary crushed material

### **Modelling**

For a new design, the approach taken by this consultancy is to seek closure between two modelling methods: viz, power modelling and JKSimmet modelling. The former uses the results of the AMCT to determine baseline circuit efficiency whilst JKSimmet modelling (using zero constants) assesses load levels and flow issues.

### **Piloting**

Piloting should be undertaken to confirm the circuit design derived from modelling if feasible. This is particularly so for large projects where the factoring of a larger contingency can result in excessive capital expenditure. Piloting is expensive and should not be used to generate one-off results for a multitude of configurations.



The accuracy of many pilot plant tests also come into question because of a number of factors including:

- Representivity of the feed distribution used on test;
- Classification efficiency when achieving fine product sizes using cyclones at low flow rates;
- Load stability with large rock size and a small mill volume;
- Maximum available impact energy within a pilot scale mill;
- Pebble extraction rates and discharge designs in the pilot mills.

When combined, these factors often result in difficulties in stabilising the pilot circuit to obtain good data. Steps should be taken to control the variables, and multiple runs of a test should be undertaken so that consistent results can be identified.

One factor that requires exploration in the piloting phase may be mill speed. If high circulating loads are still encountered following experimentation with the mill density, the effect of reducing mill speed should be assessed. The rate of abrasion grinding may be slower than the rate of impact breakage and the two can be brought into equilibrium by decreasing the impact force available through lowering the mill speed.

Likewise, if the circulating load is low and the product too fine, even with a high ball charge, the circuit selection may be incorrect. If a recycle crusher was not included it should be trialled. If included, the use of a single stage mill is likely to be inappropriate.

### **Use of Recycle Crusher**

It is generally found that a recycle crusher is detrimental to single stage milling. This is because it removes the mid-size media in the charge, rendering it ineffective in producing finished material.

Recycle crushing is usually only effective for the treatment of very competent ores where the aim is to produce a coarse product size. In this application the crusher is used for load control, where the crusher is brought into circuit if the mill load is building up and taken out of circuit when the load drops to a pre-determined level.

### **Classification circuit**

The choice of classification method used is size dependent and moderated by the mill capacity. There are numerous examples in the bauxite industry of closure with sieve bends at product sizes around 0.7 mm. At intermediate sizes, around 0.2 mm, horizontal cyclones are used. (eg. Cobar Mines, Waihi, Mt Keith). Single stage milling circuits having product sizes of <0.15 mm tend to operate in closed circuit with cyclones.



## OPERATION OF A SINGLE STAGE MILL

### Control Philosophy

In a single stage SAG mill, there are two regimes of breakage that must be controlled in order to maximise power efficiency and hence capacity. These are the impact regime at coarse size and the abrasion regime at finer sizes.

*Impact breakage* or the lack of it is a function of rock strength and feed size. Putland and Siddall (2004) showed the spread of impact energies derived from laboratory testing, and related these to the breakage energies present in a mill. Increasing the mill speed leads to an increase in breakage energy. If this is insufficient, then limitation of the feed size by additional crushing is recommended.

*Abrasion breakage* takes place at finer sizes. A lack of abrasion grinding will generally lead to a high circulating load of slurry and is symptomatic of a lack of sufficient charge density to effect grinding. In turn, this can be due to excessive lift in the charge – liner and speed issues - or a dry charge caused by excessive slurry dilution and drainage through the grates.

Table 2 contains operating scenarios and appropriate actions that should be taken by the operators or control systems to control a single stage AG or SAG mill. The guide should form the basis of any control philosophy.

**Table 2  
GENERIC OPERATING GUIDE**

SCENARIO				ACTION
	Mill Load	Power Draw	Circulating Load	
1	↓	↓	↑	Increase the mill load by decreasing the mill speed, by coarsening the feed PSD (feeder selection) or by decreasing the recycle crushing rate.
2	↓	↓	↓	Increase the feed tonnes. If the SAG load does not recover but the circulating load increases dramatically, you are in scenario (1), decrease the mill speed etc.
3	↑	↑	↑	Decrease the feed tonnes.
4	↑	↑	↓	Increase the mill speed or decrease feed PSD or increase the recycle crushing rate.
5	↑	↓	↓	Increase the water addition ratio on the SAG mill feed. The mill is overloading, retaining fines. (or the grates are pegged)
6	↓	↑	↑	Decrease the water addition ratio on the SAG mill feed. The fines are being flushed from the mill

One or two of the master mill trend pages should be monitored at all times when operating a single stage mill treating ore of variable competency. Under such conditions, observing the



rate of change, as opposed to set points, controls the mill best. Variables to be present on the trend pages are listed in Table 3, with observation of the *Primary Trend* being the key to the operation of the mill.

**Table 3**  
**TREND PAGES**

Primary Trend Page	Secondary Trend Page
Mill Feed Rate	D/C Hopper Level
Mill Power Draw	Cyclone Feed Flow Rate
Mill Load Weight	Mill Speed
Cyclone Feed Density	D/C Water Addition
Cyclone Pressure	Feed Water Addition
Total Water Addition	Pebble Recycle Rate

### **Cyclone Operation**

The cut-point of a cyclone is influenced by both the flow (pressure-effect) and slurry density (hindered settling-effect). This gives rise to operation using one of two philosophies. These are *either* constant flow and variable feed density *or* constant feed density and variable flow.

In constant flow and variable feed density configuration the pump speed is set to maintain a set cyclone pressure. Water addition to the hopper is varied to maintain the hopper level set point. As the circulating load changes, the feed density is altered, changing the cut point of the cyclone. Under such an operating system the product size can vary markedly, however the power is always fully utilised. As the circulating load increases, the cyclone feed density increases and thus the product size increases. If the circulating load decreases, the cyclone feed density decreases thus lowering the product size. In this way the product varies but is self-compensating and so prevents rapid changes in circulating load. In essence the circuit will reach an equilibrium product for a given feed and feed rate.

This configuration is best implemented when treating ores with moderate or low process sensitive to grind size. With the cyclones operated in this way the circuit can be operated in one of three ways.

- 1) *Fixed throughput with variable product size.* In this configuration the feed rate is set based on a target of the average weight within the mill. Cyclone feed density is allowed to vary, thus varying the product size. This scenario is applicable where the down stream process is sensitive to fluctuations in throughput.
- 2) *Optimised throughput consistent with acceptable product size range.* In essence the cyclone feed density represents the circulating load and the throughput is controlled using the philosophy shown in Table 2. The cyclone feed density is thereby held within a defined range, which corresponds with an acceptable range of product size and cyclone underflow density.





- 3) *Maximised throughput with variable product size.* In this configuration the feed rate is maximised based on stabilisation of the mill weight within the mill at an optimum level. The cyclone feed density is allowed to vary, thus varying the product size.

The second control philosophy for operating the cyclones is *constant feed density and variable flowrate*. In this configuration the water addition to the discharge hopper is varied to maintain a constant feed density to the cyclones. The pump speed is varied to maintain a limited range of levels in the discharge hopper. The mill is controlled to maintain a constant mill weight and circulating load (see control philosophy above). This configuration maintains the most constant product as an increase in the circulating load increases the flow to the cyclones and thus the cyclone pressure increases. This decreases the cut point of the cyclone which causes the circulating load to increase even more. As such the operator or control system must keep the operation of the mill within a tight range otherwise a total loss of control occurs. Bringing cyclones into and out of circuit helps in this regard.

To summarise, the *constant flow with variable feed density* mode is best used for maximising throughput of ore types of moderate grind sensitivity. It is also suited to operation of an unstable circuit (Variable feed composition in terms of feed distribution, abrasion and impact requirements). The *constant feed density and variable flowrate* mode is best used for a tight control of the product for a grind sensitive ore. Operation of this configuration may be difficult for a highly variable ore.



## SINGLE STAGE MILLING IN AUSTRALIA

In the past single stage SAG milling operations in Australia fell into a two distinct categories.

### **Low Tonnage, Low Capital Treatment of Gold Ores, (short design period).**

These projects typically processed primary crushed ore in high ball-charge low aspect SAG mills, often treating oxide ore in the early years of operation. These circuits were relatively easy to design with power-based methods from traditional comminution testwork. Some circuit were initially designed for more abrasive primary ores and required SAG mill comminution testwork. Typically, larger than normal contingencies were applied to the designs, given the accuracy of the methods in use. Upgrades were often undertaken as the operation matured and the ratio of primary ore increased in the feed. This typically involved secondary or tertiary crushing of the feed or the addition of a second mill so that the circuit became two-stage (SAB or SABC).

Many of these projects were built in the 80's and early 90's with low aspect SAG mills of diameters less than 5.5 m and motors less than 4 MW. Examples of just a few of these projects include –Darlot, Peak Gold, Kundana, Marymia, Nimary, Jundee, Bronzewing and Henty.

**Large Base Metal Deposits, (lengthy design periods)** – Typically, these operations looked to operate close to autogenous with the aim of reduce operating costs and improving metallurgical performance (minimal steel consumption, improved flotation characteristics) To reduce slimes generation almost all the circuit are high aspect mills. The development of the grinding circuits for these projects was mainly undertaken using a pilot plant.

In Australia, the largest mills are at Olympic Dam treating a Haematitic/Granitic Copper/Gold/Uranium Ore. Two single stage AG mills are installed processing primary crushed feed. The larger is 11.43 m dia by 7.62 m EGL, 18 MW ring motor, V-S drive, the other is 10.36 m dia by 5.75 m EGL, twin 5 MW motors, no VS drive.

Other sites include Leinster Nickel Operations initially with an AG mill, then SAG, 9.6 m dia x 5.64 m EGL, 8 MW. The Cannington lead-zinc mine SS SAG, 8.5 m dia by 4.5 m EGL, 5.8 MW. The Kambalda Nickel Concentrator, 7.93 m dia x 4.93 m EGL AG Mill, 3.5 MW with recycle crusher.

With the economy of scale and growing confidence in the use of large SAG mills, application to the processing of large tonnage moderate to low-grade deposits appears cost effective and should be the future for single stage milling. Examples of this style of gold project are the Tarkwa Gold Project in Ghana and the St Ives Gold Project in Western Australia.



## CONCLUSIONS

The following steps are recommended for the evaluation and design of a single stage grinding circuit:

- (1) Characterisation of the ore using bench tests (AMCT, JK drop weight, etc.)
- (2) Determination if the use of a single stage circuit is appropriate, using the defined selection criteria.
- (3) Selection of the correct style single stage configuration (see Table 1).
- (4) Model the circuit to define parameters of operation and equipment sizes for economic evaluation.
- (5) If feasible a small pilot campaign focused on the selected circuit should be undertaken to confirm the design parameters for larger projects.

If piloting is not undertaken substantial contingency in the form of flexibility should be factored into the design. This would include the installation of a variable speed drive, contingency in the mill shell and motor size as well as pumping capacities through the grates, pulp lifters and discharge pumps.

To effectively operate a single stage SAG mill, an understanding of the milling philosophy is needed. Is the mill's primary aim to produce a fixed product, a fixed throughput or maximum throughput for an acceptable product range? Once this is defined an appropriate operating strategy can be applied to the mill and cyclones.

The basis of any control philosophy in a single stage mill should be the manipulation of variables to balance the intensity of the impact and abrasion comminution regimes.

The single stage AG/SAG circuit, although simple in appearance, is complex to design and control!



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