

SINGLE STAGE SAG/AG MILLING DESIGN

Brian Putland¹, Fred Kock¹ & Leigh Siddall¹

*Orway Mineral Consultants WA Pty Ltd (OMC)
Level 4, 1 Adelaide Terrace
East Perth, Western Australia 6004*

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ABSTRACT

Single stage semi-autogenous / autogenous (S/AG) milling has become a common design for a variety of ore types with the advantages of being comparatively low capital cost and flexible for future expansion. The single stage SAG/AG milling option is ideal for starter projects with significant exploration and expansion potential. Currently a number of the largest SAG mills designed are installed in single stage configuration. This paper discusses the challenges associated with the process design of single stage SAG/AG milling circuits, the design flexibility required to ensure a robust circuit and the operating techniques adopted at successful installations.

KEYWORDS

single stage, semi autogenous, autogenous, milling, design

INTRODUCTION

Over the years the design and operation of single stage semi-autogenous / autogenous (S/AG) mills has been the circuit of choice for many projects, particularly smaller projects with significant potential for growth of the existing resource. The circuits tend to have a low capital cost and can easily be designed for future expansion. Historically the performance of single stage S/AG mills has been a rather hit and miss affair with some successes and other disappointing results. However with the maturity of SAG milling as a technology, the success rate has improved significantly. These days some of the largest S/AG mills installed are in single stage configuration with the largest now installed with a 28 MW drive.

Never the less a lack of understanding and / or negative experiences make the selection of this circuit a risk in the view of many practitioners. This paper discusses the process selection of single stage mills, the design flexibility required to install a robust circuit and the operating techniques adopted by successful operations. The aim of which is to clearly define the risk associated with the circuit selection.

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 understanding the inter-relationship between abrasion and impact breakage. A major discussion point will be the robustness required in the design to counter this uncertainty and to minimise design risk.

When undertaking a comminution circuit design, the following steps should be taken to assess the selection of a single stage S/AG mill circuit.

- 1) Characterisation of the ore using bench tests.
- 2) Determining if the use of a single stage circuit is appropriate, using defined selection criteria.
- 3) Selection of the correct single stage configuration style (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.

Ore Characterisation Testwork

Characterisation of the ore using bench tests should be undertaken. Particular focus should be placed on tests that define the high energy breakage characteristics, for example: Autogenous Media Competency, JK Drop Weight, SPI or SAGDesign tests. Regardless of the test used each sample should be twinned with a Bond Ball Work Index or equivalent test to also define the low energy breakage characteristics.

Piloting can be undertaken to confirm the circuit design derived from the initial design process. This tends to be the case for large projects where the reduction in the design contingency can result in significant capital savings justifying the additional expenditure. However, piloting is expensive and should not be used to generate one-off results for a multitude of configurations, but rather repeatable performance of the well defined circuit configuration. Care must be taken in the design of the pilot circuit. Areas requiring particular attention are the preparation of the feed and the design of the classification circuit. The feed size must be realistic as an inappropriate particle size distribution (PSD) can significantly bias the result. Classification efficiency can also affect the result. Achieving a coarse grind from a

small pilot cyclone can be difficult or impossible and the use of screw classification may have a different efficiency than a cyclone, thus affecting the circulating load.

Common issues associated with pilot test include:

- Use of a representative feed distribution and ore sample in the tests.
- Classification efficiency when achieving fine product sizes using cyclones at low flow rates.
- Load stability with large rock size and a small mill volume.
- Pebble extraction rates and discharge designs in the pilot mills.

When combined, these factors often result in a situation where stabilisation of the pilot circuit to obtain good data is difficult. Steps should be taken to control the variables, and multiple runs of a test should be undertaken to identify consistent operation.

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 or mill speed, 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.

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:

- **Coarse Grind – coarser than 80% passing 106 μm .** If determined to be reasonably power-efficient, single stage SAG milling is likely to be a comparatively profitable grinding circuit design.
- **Medium Grind – 80% passing size between 106 and 75 μm .** To mill in single stage SAG configuration, the feed must be consistent and the downstream process reasonably capable of handling some fluctuations in the grind size.
- **Fine Grind – less than 80% passing 75 μm .** Requiring a fine product size suggests that the downstream process is sensitive to grind and therefore an SAB or SABC circuit may be preferred because of the increased stability associated with the constant power draw and fine media in the ball mill. Lack of grinding media in the S/AG mill will result in high circulating loads which can result in slurry pool formation due to grate and pulp lifter restrictions, further adversely affecting circuit performance. Achieving fine grind sizes in single stage mills has typically required operation of an AG mill to provide adequate grinding media surface area and a consistent and competent feed.

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

- **Power demand of less than 8 MW.** This puts the application in the realm of a single mill, single pinion operation.
- **Power demand up to 16 MW.** This puts the application in the realm of dual motor, dual pinion installations.
- **Power demand of 16 – 28 MW.** This puts the application in the realm of a single mill with gearless drive.
- **Power demand of more than 28 MW.** This will require more than one single stage mill based on current designs and as such a two stage grinding circuit is likely to have a lower capital cost.

Historically starting a single large motor that is a significant portion of the entire plant load was viewed as an issue for self generated power. However, with modern soft starting technology associated with the variable speed drive capabilities the starting inrush currents can be managed.

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

Single Stage Configuration Selection

The third 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 and project requirements. Therefore, accurate ore type characterisation and well defined design criteria are critical to the success. This is a crucial step in the design with inappropriate circuit selection the reason behind most underperforming single stage circuits (see Table 1).

Table 1 - Circuit Configurations

	Single Stage Configurations	Application	Examples
1	AG mill	Competent ore - homogenous. 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 beneficial in addition to economic benefits of not requiring steel media.	Leinster, Olympic Dam, Tara, Aitik
2	AG mill + a recycle crusher	Competent ore - relatively homogenous. The recycle crusher is used to balance the rate of media breakage within the mill	Kambalda, Olympic Dam, Sino Iron
3	SAG mill (8 – 15% ball charge)	Variable or moderate competency ore with the competency suiting the selected grind size	Tarkwa, Leinster, Golden Pride, Obatan, Henty, Fosterville, Kittila, Cosmos, Cosmic Boy, Jundee, Tanjianshan
4	High ball charge SAG mill or ROM Ball mill (15 to 25% ball charge)	Low competency ore	Hidden Valley, Nzema, Sepon, UG2 ores (South Africa), Yanacochoa
5	Low ball charge, high speed SAG mill (4% ball charge, 90% Nc)	A cross between AG and SAG for average competency, abrasive ores. Typically operated in RSA on Witwatersrand Gold Ore	Driefontein (Underground), Kloof, Jacobina
6	SAG mill with recycle crusher (8 – 15% ball charge)	Competent ores, better suited to coarse grind sizes. High aspect mills are recommended to provide adequate potential for pebble extraction.	St Ives
7	SAG mills treating partially secondary crushed feed	Suited to magnetic ores where recycle crushing is not appropriate, retro fits to circuit with insufficient room for pebble crushing or low aspect SAG mill circuit where pebble extraction rates are insufficient.	Darlot, Jacobina, Driefontein (Surface)

Modelling

For a new design, the approach taken by OMC is to seek closure between two modelling methods. Typically power base modelling is utilised. OMC generally use power based methods using either the results of an Autogenous media competency test or JK Drop Weight test in combination with a Bond Ball Work Index result. SPI or SAGDesign testwork results can also be used.

The SAG mill model in the JKSimMet software has not been shown to accurately reproduce the performance of a single stage mill for greenfield design. A review of most modern power models shows that the prediction of specific energy is influenced by the high energy breakage characteristics of the ore (DW_i, t₁₀, SPI etc.) and the low energy (BW_i). The JKSimMet SAG mill model does not include an input for BW_i and only has the t_a value for abrasion which relates to the abrasive nature of pebbles and does not correlate with BW_i. This can lead to inaccurate prediction of specific energy. The breakage rates with zero constants used also tends to result in lower circulating loads than would be expected. For these reasons the simulation of a single stage SAG mill for greenfield design using JKSimMet is not recommended as it can lead to erroneous results and conclusions. It is hoped that this is being addressed in planned future upgrades of the model.

In addition to the estimation of specific energy, modelling of grate and pulp lifter slurry flow capacity should be taken into account when selecting the aspect ratio of the mill. In essence, the diameter of the mill should be selected first based on the required slurry flow with typical grate and pulp lifter performance and the Effective Grinding Length (EGL) selected to achieve the required power draw.

The use of too small a mill diameter will result in slurry pooling which will negatively impact on power draw. This may not be a significant problem if taken into account in the initial selection and design of the mill but can be an issue if the mill is unable to generate design power draw, resulting in reduced capacity.

The presence of a slurry pool does not necessarily affect grinding efficiency as most of the required energy input is low in intensity. However, inefficiencies and over grinding can occur when attempting to achieve a coarse grind from a competent ore and the slurry pool is providing a cushion, reducing the effectiveness of coarse ore breakage.

The issue with assessment of slurry flow is determining an appropriate circulating load when not determined by a population model or piloting. In general very high circulating loads or a coarse grind are generated by a lack of media and very low circulating loads and over grinding result from excess coarse rock. These two conditions should only occur if the incorrect single stage SAG mill configuration has been selected. In the absence of extreme conditions, circulating load is driven by the cyclone configuration. The size of cyclone, pressure and conditions (spigot and vortex selection) that need to be operated to achieve the product size within the target cyclone overflow range, determines the circulating load range. Standard vendor type cyclone models can be used to evaluate this relationship and predict the likely circulating load range.

PRACTICAL DESIGN

Stockpiles

Consistency of feed distribution is important for optimal performance of a single stage S/AG mill. Changes in the feed distribution associated with stockpile segregation result in circuit instability and sub optimal performance. Given this fact, attention to the stockpile design is essential or alternatively a small intermediate feed / surge bin should be used rather than a stockpile. Design for 12 hour crushing in 24 hours is not suited to single stage operation as continual maintenance of stockpile cone is required to minimise segregation. If 12 hour crushing is imposed on the grinding circuit design, the use of a single stage circuit treating primary crushed ore should be reconsidered.

Instrumentation

Given that all the grinding is undertaken in a single mill, understanding the dynamic operation of the mill is essential. Good instrumentation to capture the performance of interrelated variables and a control system that assesses the system as a whole provides this understanding.

The relationship between power draw and grinding is well known and requires little explanation. Consequently, like with all grinding mills, measurement and recording of the mill power draw is necessary. Understanding where the power is being measured is also important with the use of variable speed drives so that the actual power being applied to the grinding chamber is recorded or calculated.

The ability to maintain a constant total load volume in the mill at the required feed rate is an essential control requirement. For this reason loads cells and or acoustic sensors are commonly used to provide an indication of changes in load level in the mill. S/AG mills are difficult to operate on power alone as the power to mill load relationship is not consistent. The power draw to mill load relationship is affected by changes in the milling density as a result of changes in viscosity and charge fluidity. Furthermore, slurry transfer through and out of the mill affects the size of the slurry

pool within the mill and the size of the slurry pool affects power draw. Therefore, changes in circulating load on a single stage mill may affect the size of the slurry pool and consequently the power draw.

Load indication is also very important for high ball charge SAG mills or Run of Mine (ROM) ball mills as changes in power draw resulting from changes in load may be insignificant. The power draw response may be relatively flat within the range of operation and may decrease if the mill is overloaded. As such, accurate measurement of changes in mill load weight is important.

The use of acoustic sensors to predict load levels in a mill is also a useful tool. However these devices may be more difficult to calibrate on a single stage mill than open circuit mills with low slurry flow. The presence of a significant slurry pool will to a degree mask the location of the charge toe and therefore changes in the load level compared to the slurry level. These conditions may make interpretation of the results more difficult.

Standard instrumentation around the classification circuit is important to achieve stable control with a density meter on the cyclone feed line, pressure transducer on the distributor for the cyclone cluster, hopper level measurement and at least measurement of total water addition to the grinding circuit. Measurement of the cyclone feed flow rate and distributed water addition points is useful for optimisation but is not essential for process control.

Variable Speed Mill Capability

Single stage mills can be run without a variable speed drive however optimal performance is rarely achieved. If the mill is not installed with a variable speed drive or a pebble crushing circuit, options for controlling the mill are limited. The parameters remaining to control the mill are feed manipulation (changing the feed rate or altering feeder ratios to adjust the ratio of rock to fines), milling density and the target mill load level. These variables are often not enough to optimise mill performance. A variable speed drive allows the mill speed to be increased, increasing coarse rock breakage if the mill is load restricted and over grinding. Slowing the mill down decreases coarse rock breakage and stabilises the load and grind if the circulating load is high and the load decreasing.

The only time justification of a variable speed drive on a single stage mill should be questioned is when the ore is consistent, competent and the coarse rock breakage rate is modulated by a pebble crusher.

Pebble Crushing

It is generally found that the inclusion of a recycle crusher in the circuit is detrimental to single stage milling. This is because it removes the mid-size media in the charge required to produce a finished product. Recycle crushing is usually only effective for the treatment of very competent ores where the aim is to produce a coarse product size.

The application of the pebble crusher is often for load control. The crusher is brought online if the mill load is building up and taken out of circuit when the load drops to below a pre-determined level.

Alternatively the amount of pebble crushing can be proportionally adjusted with a percentage of the pebbles bypassing the crusher varied by the control system. This configuration is best operated with optimisation of the pebble crusher closed side set to maximise power draw. This duty is therefore well suited to a hydroset style cone crusher which allows online automated adjustment.

In a single stage mill with pebble crushing, smaller grate apertures are typically installed when compared to a SAG mill in SABC configuration. Typically less than 50 mm apertures are used. This preserves a reasonable portion of coarse rock for use as media. Given the finer grate apertures, finer closed side sets on pebble crushers and finer trommel or discharge screen apertures are typically used.

Classification

The choice of classification method used is size dependent and moderated by the mill capacity. There are numerous examples in the bauxite industry of mills closed with sieve bends at product 100% passing (P_{100}) sizes of 1200 to 700 μm . At intermediate sizes, around 80% passing (P_{80}) sizes of 400 to 200 μm , horizontal or flat bottom cyclones are used. At P_{80} values less than 200 μm , cyclones in standard vertical installation configuration are used.

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 high energy coarse rock breakage, load control and low energy breakage to control circulating load and to meet the target product size.

The requirement for *high energy breakage* (or the lack of it) is a function of rock strength and feed size. Increasing the mill speed leads to an increase in impact breakage. If this is insufficient, then limitation of the feed size by feeder control, pebble crushing or a reduced feed rate is required.

Low energy breakage is important in grinding the finer rock sizes. For efficient grinding, sufficient media must be maintained to provide sufficient surface area for the fine grinding to occur. A lack of low energy autogenous grinding media will generally lead to a high circulating load of slurry and ultimately an increase in the grind size. This can be due to excessive lift in the charge (caused by liner and speed issues), a dry charge (caused by excessive slurry drainage through the grates), or a lack of rock in feed or excessive pebble crushing.

Understanding the breakage zone (load level) in the mill at different mill speeds and the effect of setting the load level at the breakage zone to promote high energy breakage or above to reduce breakage is important.

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), provides the best understanding of the interrelationship between variables and control of the mill. 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	Discharge Hopper Level
Mill Power Draw	Cyclone Feed Flow Rate
Mill Load Weight	Mill Speed
Cyclone Feed Density	Discharge 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, *either* constant flow and variable feed density *or* constant feed density and variable flow. In both cases the aim is to stabilise both variables, however the reaction of the circuit to change in each case is different.

In *constant flow and variable feed density* configuration the pump speed or cyclone feed hopper water addition is set to maintain a set cyclone pressure. Water addition to the hopper or pump speed 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. The cyclone cut point matches the grinding capability of the mill. As the circulating load increases, the cyclone feed density increases and thus the product size. 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.

In this scenario the circuit is controlled to a target S/AG mill load weight and a target cyclone feed density. Control variables are adjusted to maintain these set points, not water addition to the discharge hopper.

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. 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 to prevent a total loss of control. Switching cyclones into and out of circuit provides short term relief of the symptom of circulating load but does not address the issue which is that the cut point of the cyclone is not in equilibrium with the grind size achievable by the mill.

To summarise, the *constant flow with variable feed density* mode is recommended for control, particularly for a single stage mill, because of circuit stability brought about by the self compensating cyclone cut point. Constant density is still targeted but circuit variables are adjusted to maintain the slurry density rather than discharge hopper water addition. The three major benefits of this mode of operation include:

- 1) Self regulating equilibrium conditions are achieved between the mill and classification circuit.
- 2) More stable circuit conditions when compared to constant density because of equilibrium operation.
- 3) Better optimisation of the cyclone underflow density is possible through operator selection of cyclone pressure.

Cyclone switching or the number of cyclones operated should be adjusted to maintain the cyclone overflow within a target density range. Cyclones should not be taken in and out of circuit based on changes in circulating load. Cyclones should be taken in and out of circuit based on the calculated cyclone overflow density with a low set point triggering a cyclone to be closed and at high density the opening of a cyclone.

Why Circuits Haven't Performed? (Those who shall not be named.)

The reason some single stage circuits haven't worked successfully in the past is a miss match of the selected configuration and design to the ore characteristics and grind. This has resulted in three common Types of failure:

- 1) Insufficient media and difficulty achieving the grind.
- 2) Competent rock and excess media resulting in over grinding and reduced capacity.
- 3) Extremely variable ore and insufficient process control options.

Example 1

An example of a typically poor performing Type 1 circuit could be the treatment of an epithermal gold ore, incompetent but work indices average in mid teens due to the quartz content. The SAG mill was installed with a low ball charge, no variable speed and a fine grind was targeted (P_{80} 106 μm). High circulating loads and difficulty achieving the target grind size were experienced.

This type of ore should have been treated in a high ball charge SAG mill with variable speed capability.

Example 2

An extremely competent granodiorite ore (low Axb and High BWi) was treated through a low aspect single stage SAG mill targeting a coarse grind (P_{80} 150 μm). Lower than target throughput and over grinding resulted.

This ore should have been treated in a high aspect SAG mill with recycle crushing.

Example 3

Extremely variable competency ore with a relatively consistent BWi was treated through a single stage SAG mill without a variable speed drive and constant cyclone density control was operated. The circulating load was unstable if constant mill weight operation was attempted.

With this ore, the mill should have been installed with a variable speed drive and the cyclones run at constant pressure. Some variability in product from the circuit was always going to occur and selection of a single stage SAG milling circuit was inappropriate if a variable product size was extremely detrimental to downstream processing.

Successful Circuits

The Goldfields Tarkwa and St Ives gold projects presented at the SAG Conference in 2006 were two good examples of successful single stage SAG mill installations.

Tarkwa Gold Mine

The Tarkwa ore is a quartzitic conglomerate with variable competency and Ball Work Index. A fine grind at 80% passing 75 μm was selected based on kinetics and required residence time rather than ultimate recovery. Coarser grind size, up to 125 μm could be accepted with upgrades to the CIL circuit.

Based on the company's experience with low aspect mills grinding to 75 μm on the similar Witwatersrand ores in South Africa, a low aspect single stage SAG mill was selected. Significant testing was undertaken to allow characterisation of the ore variability and to allow power modelling for design.

The operations in South Africa were not without problems, with variable ore characteristics and feed distribution from the underground mines making circuit stability difficult at times. These mills were often high fixed speed, low ball charge, SAG mills.

To compensate for the identified potential problems, a number of design changes were made compared to those typically employed in South Africa.

The selected mill had a variable speed drive to cater for changes in feed competency and rock content. The SAG mill was also designed with a high maximum ball charge (18%) so that sufficient media was provided when

treating incompetent ore. At the proposed ball charge levels, the use of extremely high mill speeds would not have been possible without damage to the mill lining. As such, the maximum mill speed was reduced to 76% of critical speed.

Issues with potential slurry pooling were identified during design reviews as a result of the low aspect ratio of the mill and potential for high circulating loads associated with the sandy nature of the ore. To ensure that this would not be an issue in obtaining design power draw, a larger mill than indicated by the power modelling was selected. Power modelling indicated that a 12 MW mill would be adequate for the duty and a 14 MW mill was selected (27ft Ø x 42 ft EGL). The 14 MW mill was selected as it was anticipated that this mill would be capable of drawing 12 MW under extreme slurry pooling conditions. To further reduce potential issues related to flow through the mill, large curved pulp lifters were installed.

In the end, slurry pooling did reduce the power draw but the mill shell was sufficiently sized for the duty. The variable speed was required particularly in the early years of operation on softer ore when the mill was operated at slow speeds with a high ball charge. During the early stages of operation, circuit stability was good with constant flow to the cyclones. This was replicated with later control circuit upgrades which minimised flow variations to the cyclones.

With care to design detail and risk mitigation, the circuit exceeded design throughput within a very short period. The initial target grind, though achieved, was not maintained in the longer term largely due to a sacrifice to throughput as the impact of grind size on gold recovery was minimal.

In following the design principals discussed in this paper, the only change that may have been made to increase performance was to install a square aspect 12 MW mill achieving the same outcome with the operation of a smaller slurry pool.

St Ives Gold Mine

Similar to Tarkwa, the St Ives project had extremely variable ore, however in this case, the ore was extremely hard ($A_{xb} = 25$). The target grind size for the project was $P_{80} 125 \mu\text{m}$. A high aspect 36ft Ø x 18ft EGL, 13 MW SAG mill with recycle crusher was selected for the single stage SAG mill configuration. This design is in line with the selection dictated in Table 2.

The owner understood the circuit selection had some technical risk associated and set about mitigating these points during design and project readiness. The identified risks included:

- 1) slurry pooling
- 2) operational expertise
- 3) process instability
- 4) no leach feed thickener requiring a consistent cyclone overflow from the circuit.

Investigations showed that slurry pooling would not be an issue with adequate pulp lifts, as the mill was of sufficient diameter for the expected flow. Operational expertise was addressed with training of the operators and involvement in the development of the process control system. Process instability and cyclone overflow density control was mitigated through the substantial effort of the operations team and their appointed contractors in developing a high quality control system. This was made possible by the selection of an appropriate configuration and the installation of adequate operating variables for control.

Once again this project was highly successful in reaching design targets in a very short period of time.

CONCLUSIONS

Based on the author's experience it is recommended that the following steps are undertaken to evaluate and design of the use of a single stage grinding circuit:

- 1) Characterisation of the ore using bench tests (AMCT, JK Drop Weight, etc.).
- 2) Determine 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.

To effectively operate a single stage SAG mill, an understanding of the milling philosophy is needed. The implementation of process control that provides stable flows around the mill is extremely important. Through stable operation, the aims of the any control philosophy can be achieved (constant grind, maximum throughput etc.).

If the discussed processes are followed and the correct configuration selected the project will be successful. This said, care must be taken that adequate decisions are made during detailed design that the operational requirements of the process design are strictly met. This is demonstrated by the risk identification and mitigation plans put in place by successful projects.

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