

SAG MILLING IN AUSTRALIA – FOCUS ON THE FUTURE

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Abstract –

The paper examines the current state of equipment and circuit design, with reference to Australian practice.

Following a review of the changes in milling applications over the last fifteen years, developments in mill design are examined. Current issues include trunnion versus shell support; drive type and economic analysis for comparison of the various systems; the efficiency of the mill discharge system for slurry and pebble removal, and lining configuration. Peripheral problem areas such as pebble crushing and classification are briefly examined.

Circuit design issues are reviewed. The decision to modify the traditional primary crushed feed is examined with reference to recent and proposed installations. A retrospective look at fully autogenous installations and their successes is presented, and current views on increasing throughput are assessed.

Finally, future developments are anticipated in mill design and control, and competing processes are identified.

INTRODUCTION

This is the third review of SAG milling practice in Australia, previous surveys were presented in 1991 (Siddall and White) and in 1997 (Siddall).

The 1991 review described the early adoption of SAG milling, principally by a resurgent gold mining industry, which was mainly treating soft oxidised ores of low competence. By 1997, the applications were shifting to those capable of processing harder, more competent materials and the scale of operation was also increasing. Table 1 presents the top five mills installed, by power rating, for each of three snapshots taken five years apart over the last ten years. (See Glossary of Terms for explanations of abbreviations used).

**Table 1
Top Five Mills by Rated Power**

Company	Project	Circuit Type	Mill Size (m)	Power (MW)
2001			Dia. x EGL	
Newcrest	Cadia	SABC	12.2*6.10	20
WMC	Olympic Dam	S/S AG	11.43*7.62	18
Pasminco	Century	SAG-Ball	10.97*5.41	12
KCGM	Fimiston	SABC	10.97*4.27	12
MIM/Investco Ltd.	Ernest Henry	SAG-Ball	10.4*5.10	11
			Total MW	73
1996				
KCGM	Fimiston	SABC	10.97*4.27	12.0
WMC	Olympic Dam	S/S AG	10.36*5.75	10.1
WMC	Mt Keith	SAG-Ball	9.6*5.64	8.6
WMC	Leinster	S/S AG	9.6*5.64	7.0
MIM	Mt Isa	SAG-Ball	9.75*4.88	6.4
			Total MW	44.1
1991				
Pickands	Savage River	AG/Ball	9.6*3.65	4.5
Placer	Kidston	SABC	8.53*3.65	4.0
BGM	Boddington	S/S SAG	5.2*6.70	3.5
Dominion	Cosmo Howley	SABC	6.10*6.10	3.5
Placer	Granny Smith	SAG-Ball	7.92*2.60	2.9
			Total MW	18.4

It can be seen that the last five years has continued the trend to larger mills, and that different circuit configurations are still being installed. So what are the developments that have driven this rapid growth?

Developments in SAG Mill Design and Operation

Over the last few years, SAG mill manufacturing technology has advanced rapidly. The bounds of mill size have been pushed from two directions. Firstly, the advent of ring motors has removed the constraint applied by the power that a single pinion gear was able to transmit. Secondly, the development of dual pinions in close proximity, driven from a single motor, has doubled the power that can be applied to a geared drive from twin motors. Single pinion drives, each of 10 000 HP (7 500 kW) located on opposite sides of the ring gear, limited mill size for many years to 36-ft diameter. Today, 20 MW mills are in operation and designs exist for 24 MW units. Savings flowing from a single line operation at high tonnage – 1500 to 2000 tph, have driven down the cost of production. Recently, the rotor drive has been introduced with a consequent simplification in the drive systems. The merits of the alternative systems are reviewed here.

The next constraint was the difficulty of casting a mill head at 40-ft (12.2 m). Although it could and has been done, the number of facilities capable of achieving such castings is limited. In response, manufacturers have advanced the design of shell-supported mills that do not rely on accurate head castings. The bearings are located under the shell and mated to a riding ring. This technology has assisted in freeing up the length/diameter ratio constraints normally associated with high aspect mills.

In parallel with increases in mill size has been the development of larger pumps and higher-efficiency cyclones. Ball mill suppliers have adopted the same technologies to move beyond the traditional limit of 7500 kW.

Increasingly, liner systems have become the critical components in the mill. Developments reviewed here include

- Use of DEM and CFD for optimising the design of mill liners, grates and pulp lifters
- Innovative pulp lifter systems
- Shell supported mill discharge systems
- Larger liner handlers to handle heavier liner sections
- Improved materials

Operating techniques, too, have improved markedly. Advances have been made in understanding the effect of feed size on mill capacity, with secondary crushing now commonly adopted for very competent ores. The “Mine-to-Mill” concept has been enthusiastically incorporated, since its introduction in 1998.

Retro-fits have been favoured as operators moved to more competent ores, with open circuiting of the SAG mill and ball mill additions topping the list.

The drive for low operating cost has seen the retention of fully autogenous circuits in some large installations, notably Olympic Dam.

ISSUES IN MILL AND CIRCUIT DESIGN

Shell Support versus Trunnions

In place of trunnion bearings, mills can be supported on multi-pad hybrid type bearings mated to journals machined on the ends of the shell of the mill. This design gets away from the problem of casting large diameter heads. The first large mill installed in Australia that uses this system is at Ernest Henry, where a 10.4 m dia x 5.10 m EGL unit is operating.

On a shell-supported mill, the feed and discharge openings can be as large in diameter as may be required to suit the metallurgical process. This may facilitate reduced pulp lifter wear, and can have an open end if desired, as at Murrin Murrin allowing efficient pebble and slurry discharge.

Shell-supported mills are installed on simple foundations that are only just high enough to allow clearance for the gear guard and to allow mill discharge to flow into the sump. Erection itself is simple and a shell-supported mill does not require to be lifted for maintenance.

With such a support structure, it is no longer necessary to increase diameter to obtain a larger mill, and there is nothing to prevent a 1:1 aspect ratio mill of, say 10 m dia. x 10 m EGL equipped with a 20 MW motor from being fabricated. Such a mill would have a less arduous environment than, say, a 13.4 m (44-ft) diameter mill. Slurry transport issues then dominate the mill selection, rather than mechanical/structural constraints.

Mill Drive Developments

The economic evaluation of large multi-pinion and ring motor drive systems has led to a number of conflicting outcomes, typically hinging on the differential in mill availability based on the down-time associated with mill gear alignment and maintenance for multi-pinion systems. The assessment of mill availability is, in turn, dependent on the validity of individual project data.

Three gear driven systems are available:

- Load Commutator Inverter(LCI) – twin pinion
- Wound rotor/gearbox/twin pinion
- Rotor drive (hypersynchronous) – multiple pinion.

The LCI – twin pinion system has found acceptance overseas but has not been installed to date in Australia. The Fimiston 10.97 m (36 ft) SAG mill uses twin wound rotor/gearbox/pinion drives with variable speed achieved through CCV systems.

The CCV – ring motor (gearless) drive is used at Cadia (20 MW) and Olympic Dam (18 MW). It has been the industry standard for SAG mills above 13 MW capacity. However, pinion systems to 8 MW per pinion and dual motor systems with quadruple pinions extend the range of gear driven mills to a theoretical limit of 32 MW. The Ernest Henry SAG mill (11 MW) is currently the largest twin pinion single drive mill installed in Australia.

Problems have been experienced with the twin pinion drive at Fimiston and with the ring motor at Cadia.

At Cadia, excessive vibration and deflections in the drive stator were encountered during commissioning of the mill and later during operation (Meimaris, Lei and Cox, 2001). Vibration measurements indicated that the amplitude of the motion was approximately 7 mm (> 300 mm/s) at the top of the stator. The stator also exhibited excessive “static” or mean deflections that reduced as a function of speed from a maximum of 7 mm during inching to 3 mm at near full speed. These problems effectively reduced the drive air-gap to less than half the nominal value. The drive would often trip during inching and thus hamper mill relining. The vibration meant that the mill could not be run above about 9.0 rpm without reliance on temporary chocks installed between the stator and the foundation. A “light weight” strongback was designed that could be fitted to the stator with minimal shutdown time. The stator now behaves correctly and the motor has excellent availability. There are few inching and no vibration problems, as the strongback has provided the additional stiffness required.

The ring motor problems at Cadia were “developmental” and did not re-occur at Olympic Dam. The electromechanical problems (mainly related to torque equalisation issues) with the Fimiston mill are arguably inherent in a CCV/gear drive system with a “weak” power supply.

Rotor drives are relatively novel, but are likely to become more common in new installations due to their inherent simplicity and economic advantages. They comprise a variable speed drive, which utilises a Wound Rotor Slip Ring Motor and a regenerative PWM Transistor Inverter for narrow speed range applications.

A comparison of the rotor drive with gearless and CCV twin pinion system, on a cost and timing basis, was recently provided by Morgan (2001) – Table 2.

Table 2
Comparative Drive Systems for 13 MW SAG Mill (Morgan, 2001)

	Dual Rotor Drive	Gearless	Dual CCV Low Speed Synch
Overall System Efficiency (%)	93.1	92.7	92.7
Overall Installed Cost (US\$)	1.9m*	4.18m	3.42m
Harmonic Filtering Required	No	Yes	Yes
Typical Delivery (weeks)	26	60	52
Instal. & Comm. Time (weeks)	2	12	6
Mill Gear Lubrication	Yes	No	Yes
Clutches or Shearpins Essential	No	No	Yes
Water Cooled Semi-Conductors	No	Yes	Yes
In-built Inching Capability	Yes	Yes	Yes
No of Critical Auxiliary motors	0	18	4
V-S Back-Up System	Yes	No	No
Fixed Speed Back-Up System	Yes	No	No
Heavy Lift Craneage (+50t)	No	Yes	Yes
No of Critical Semi-Conductors	12	72	72
Plant Water Required	No	Yes	Yes

* Includes Gear Reducer.

The Rotor Drive offers a simple system that is robust to power dips and has reduced load on start-up. Unlike the CCV system, it has a unity power factor and constant torque characteristics over total speed range. No LRS is required with the SER system. A single pinion Rotor Drive is being installed at Ridgeway.

Evans (2001) presents comparative data on geared and gearless systems, indicating that a Single Motor Twin Pinion (SMTP) system reduces costs and footprint when compared to Gearless and Twin Drive systems. An SMTP system is currently proposed for a 4500kW drive retrofit in Western Australia.

Lifter/Liner Configurations

The advent of computer simulation techniques has enabled the effect of changes in liner geometry on ball trajectory to be simulated. Various sets of computer code have been used for this, ranging from two dimensional single particle flight path simulations (Powell, 1991) to full three dimensional multiple particle analyses (See, for instance, Cleary 2001). The friction coefficient used in the sliding/rolling calculations for angled lifter bars has a marked effect on the result of the simulation, and more work is required on this. The effect of non-spherical particles has also been examined using discrete element methods (DEM). However, the computational demands and lack of sound experimental verification has limited the value of the technique. (Govender, et al, 2001)

In addition, the so-called A:B ratio of optimum lifter height to lifter spacing, first proposed by Art MacPhearson, has been validated at around 4 to 4.5:1. (Bigg and Raabe, 1996)

The result has been a departure from the traditional method of installing twice the diameter (in feet) less two rows of lifters, with lifter bar heights now exceeding 250 mm in some cases. Fewer, higher bars in larger mills leads to an increase in the weight of each piece, and this has driven the development of heavy-duty liner handling machines.

Lifter Face Angle

The current trend in lifter system design for large mills was initiated at Northparkes and has greatly decreased liner damage, increased mill efficiency and reduced ball damage. Two key aspects of mill design have been improved, lifter face angle and the number of lifters.

The lifter face angle on the original Cadia mill lifters was 12 degrees and led to high ball/shell impacts and contributed to ball breakage. Increasing the face angle to 25 degrees reduced the ball trajectory, decreasing ball breakage and shell damage (Clements, 2000). The adverse theoretical consequence of this is a drop in the mill power developed.

Cadia was commissioned with 78 rows of lifters but has now been reduced to 52 rows. Decreased packing between the lifters resulted, increasing the power drawn by the mill. (Ratray, 2000)

Higher face angles have led to the adoption of “Top-hat” type lifter bars in place of “Rail” or “L-shaped” bars. (Top hats were adopted at Cadia prior to high face angles due to higher strength).

Larger Liner Pieces

The attraction of a reduced number of larger pieces is a shorter re-line time. Liner handlers capable of lifting up to 3500 kg pieces and lengths exceeding 2 m are now available, and systems have been developed for rapid removal of worn liners.

Fastening Systems

Rubber spacing pieces are routinely inserted between rows, avoiding packing by worn balls and facilitating rapid removal. As ball sizes used in SAG mills increase to 140 to 150 mm diameter, the traditional liner bolt-hole, which was a weak spot subject to high stresses, has been modified or replaced entirely. Studded lifters, in which the hole is replaced by an underside cavity for a double-threaded stud to be inserted, or bolt-holes designed for spherical-headed bolts and capped with an insert, are now common (Ratray, 2000).

Mill Discharge Systems and Pebble Discharge Issues

The efficiency of the mill grate and slurry discharge system decreases with increasing mill diameter and mill length. The efficiency of the mill discharge system for slurry and pebble discharge is compromised by the current standard pulp lifter and trunnion pulp discharge design. The need to pump the grate undersize out of the mill and the resultant run-back of slurry and pebbles causes both inefficient discharge from the mill and increased mill maintenance. The shell mounted bearing/fabricated mill end design can allow the mill to operate without pulp lifters and directly discharge pulp at the periphery of the mill as per the Dorbyl mills described by Mokken in South Africa (Mokken, 1975).

Improvements in grate design to increase flow through the grate and decrease flow back as the mill rotates have led to the development of the Twin Chamber Pulp Lifter system (Nicoli, 2001) at Alcoa’s Pinjara plant. There is perceived to be limited application of this system in high wear environments. Royston and co-workers have examined the issues involved when pebbles are to be discharged with the pulp (Royston, 2000; Denlay, Woods and Royston, 1997). They indicate that, with straight radial pulp lifters, pebble discharge is commonly

incomplete and back-flow of coarse solids down the pulp lifter is a major source of wear in the base and head-side corners of the discharge system. Use of curved pulp lifters is advocated to ensure effective discharge of solids and minimise wear.

Trials of such systems are under way at several plants.

Composite Materials

There are many benefits claimed for the use of rubber lining systems. However, the harsh environment of a large SAG mill has dictated against their use. The advent of composite liners, with steel-capped lifter bars mated to rubber shell plates has done much to counter the problems experienced. Trials are under way in several large mills, and there is a high acceptance of them in smaller mills. Recent advances in understanding the effect of face angle on performance should see this trend continue. There has been acceptance of rubber grate sections in vertical configuration for many years in all but the largest mills.

Pebble Crushing and Classification

The key criteria for installation of a pebble crusher for a large plant are:

- the direction of feed to a pebble crusher surge bin should be parallel to the pebble crusher feeder to avoid segregation in the bin;
- water removal from the pebble stream prior to the surge bin should be allowed for and the bin design should also make provision for water removal;
- belt feeders are preferred from the surge bin to the pebble crusher due to superior steady state control, and
- pebble crusher to be suited to duty, with proven tramp relief features.

Typically, the maximum pebble crusher feed rate for an SABC circuit is 35% of new SAG mill feed rate but may be higher (45%) for an autogenous (ABC) milling circuit.

Circuit Options

A number of circuit alternatives are available, with respect to:

- Number of Crushers
- Surge Capacity

The relative costs of these options, together with their relative advantages and disadvantages are listed in the Appendix.

A major concern in the selection of the recycle crushing circuit is the variability in recycle rate. This is a problem with most SAG mill circuits (Cadia's rate varies from 300 t/h – 1000 t/h (15% - 50%). If the crushers are run in a batch mode or with excessive gap openings, then the impact on SAG mill operation can be quite severe. In effect, it becomes “the tail wagging the dog”, with requirements to optimise crusher performance adversely impacting on mill performance.

An option that has been implemented is the use of a pebble stockpile. This may operate on the following basis:

- A single crusher handling the base recycle load.
- Excess pebbles report to a stockpile.

- Batch treatment over ~20 h of the excess pebbles through a “standby” crusher.
- Maintenance of the “duty” crusher during the time the pebble stockpile is being fed.

The advantages of this system include the following:

- Optimal conditions for crusher operation.
- Steady state conditions for SAG/AG mill operation.
- Significant “standby” capacity for maintenance, and maximum availability.

These advantages come with a significant capital cost penalty, but only require a relatively small increase in either overall availability or plant throughput to be justified.

Alternatively, the pebble crusher must be capable of operating at low load, a facility not available with some large crushers.

MODIFYING THE MILL FEED SIZE DISTRIBUTION

The SAG milling of ores with high levels of competency leads to high SAG mill specific power consumption and a high proportion of very fine SAG mill product. In these ores, the principal source of fines generation is abrasion of the competent charge in the mill, rather than coarser breakage. Generally, the power efficiency of an SAB or SABC circuit decreases with increasing ore competency due in the main to the high energy required to produce fines.

Siddall, Henderson and Putland (1996) reported a classification as “high competency” for rocks that exhibit relatively uniform toughness with increasing pebble size. These rocks typically show axial cleavage compressive breakage behaviour and UCS values in the range 120 - 170 MPa. They possess few imperfections and characteristically display a linear relationship between size and impact strength. The majority of fresh volcanics tested by them fitted into this category.

The lack of coarse breakage in high competency ores is in part due to the nature of the rock and also due to the inability of the ball charge to cause the rock to fracture. To counter this effect, the ball to rock ratio can be increased and/or the ball size increased. However, at best, an inefficient SAG milling operation is obtained with a power demand typically 30% more than theoretical Bond power for the same size reduction.

Over recent years, circuits have evolved in which the rock size distribution is decreased by finer crushing prior to milling. The technique was pioneered and developed at Kidston Gold Mine, with remarkable results (MacNevin, 1997)

Just prior to shut-down in 2001, the Kidston circuit was surveyed in both primary crushed and secondary-crushed mode, with the mill power and throughput shown in Table 3. It can be seen that, when secondary crushed material is introduced into the SAG mill, the specific power required decreases by 40%, allowing a very significant increase in capacity. To cope with this, additional ball milling capacity must be introduced into the circuit.

Table 3 - Effect of Feed Size on Primary Mill Capacity

SAG Mill		Secondary Crush	Primary Crush
Net Milling Rate	tph	860	570
SAG Mill Pinion Power	kW	3793	4255
F80	mm	23.6	90.6
SAG Mill T80	um	2880	1650
SAG Power from F80 to T80	kWh/t	4.41	7.46
Operating Work Index	kWh/t	36.4	35.0

Source Data: Placer Dome Asia Pacific

Kidston has found that accurate load control is essential, with acoustic methods preferred. The recycle crusher is also used with effect to counter coarse ore emanating from the open circuit secondary crusher.

The St Ives concentrator is a further example where plant throughput has been increased by secondary crushing prior to SAG milling for ores ranging from moderate to high competency.

Nelson et al (1996) have reviewed the operational difficulties posed by treating secondary crushed material in a large SAG mill. Nevertheless, judging from recent reports, the technique is set to become more accepted as a means of increasing plant capacity cheaply and simply.

Secondary crushing of SAG mill feed has also been used by plant designers to minimise the capital cost of gold projects by allowing single stage milling where the ore varies from initial oxide to competent rock over the mine life. The secondary crushing of the competent primary ore allows the same mill to be used, as the ore competency increases (within limits). For these projects the broadness of the product size distribution is not critical in downstream leaching. Examples are Jundee and Bronzewing (Lane and Lunt, 1997).

Impact of Crushed Ore Size Distribution

A number of pilot plant SABC trials have been conducted for a potential gold project in Western Australia that exhibits very high levels of rock competency. Typically, the Bond ball mill work index for the diorite ore is moderate at 15 kWh/t, but the Bond rod mill work index is high at 23 kWh/t. The high differential between the rod and ball mill work indices is an indication of high competency.

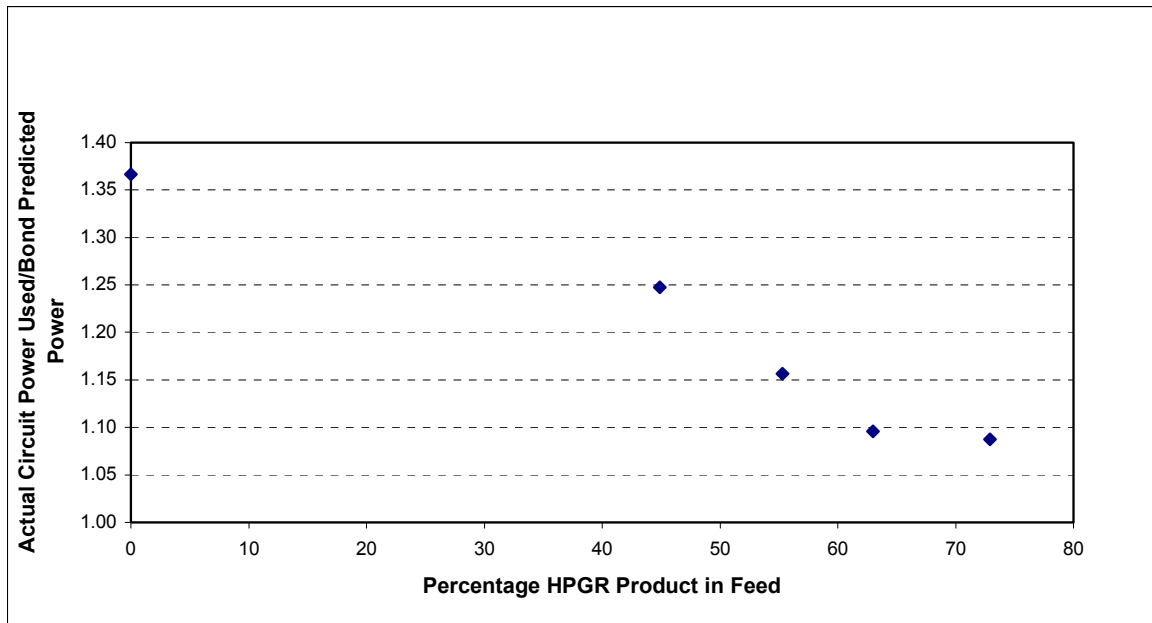
Extrapolating results from the pilot plant, Table 4 illustrates the impact of reducing the feed F80 by increasing the proportion of secondary crushed feed to the SAG mill.

Table 4
Impact of Feed Size Reduction for a Diorite Ore

F80 (mm)	% of SAG Feed Secondary Crushed	Throughput (t/h)	SAG Mill Specific Power (kWh/t)
150	0	755	11.7
103	52.5	1108	8.4
72	65	1133	8.2

Parallel pilot plant trials also considered the impact of further crushing the ore using High Pressure Grinding Rolls (HPGR) and feeding a blend of primary crushed and HPGR product to the SAG mill. The SABC power efficiency was significantly improved, as illustrated in **Error! Reference source not found.**(Rowe, 2001).

Figure 1
Relationship Between %HPGR in Feed and SABC Grinding Circuit Efficiency



Mine to Mill Concepts

An extension of the same concept has been pioneered by JKMRC in their Mine to Mill initiative. Here the manipulation of blast fragmentation to increase the proportion of fine material in the SAG mill feed has been exploited. Using blast modelling techniques and image analysis from trial blasts, the effects of altering mining variables such as powder factors and blast hole spacing have been simulated. The modified SAG feed distributions are then modelled through the SAG mill to assess the impact on plant capacity.

This methodology has, for instance, been described at the Ernest Henry Mine, (Strohmayr & Valery, 2001) For a given throughput, minimum SAG power draw and load volume is achieved with a relatively high F80. However, it is usually found that further increasing the F80 decreases the maximum throughput. This trend is emphasized with SAG mills running with a relatively high ball charge as is the case at Ernest Henry. It is believed that this is due to the fact that the large ball charge provides the bulk of the grinding media rather than the rock charge. A coarser feed size, therefore, has minimal impact on the grinding media but does provide a more difficult feed to grind. The “desired” feed size at Ernest Henry with primary ore seems to be an F80 of approximately 100-110 mm with maximum possible amount of fines (% passing 10 mm) and minimum of intermediate size fraction. By closing the primary crusher gap to 115 mm this target F80 was achieved, but the rest of the distribution was strongly influenced by the blast design.

FULLY AUTOGENOUS MILLS

The attraction of fully autogenous milling (AG mill with/without a pebble mill) is the reduction in operating cost derived by elimination of steel media. Typically, a SAG mill based circuit (P80 of 106 to 150 μm) has media costs of around A\$1/t. Providing the ore is amenable, the use of primary autogenous milling can reduce this cost by 30 to 40%. Autogenous milling is typically practiced in association with pebble crushing to improve circuit power efficiency. The pebble flow provides an ideal source of media for secondary milling and a number of circuits have been developed such as those formerly operated by Outokumpu at Forrestania (Koivistoinen and Virtinan, 1996) and WMC at Kambalda Nickel Operations.

The principal disadvantages of fully autogenous circuits are the requirements to

- undertake pilot plant testwork;
- expend additional capital for large mill shells and pebble handling systems;
- - understand the breakage characteristics of the orebody, particularly with regard to variability, and
- - are highly dependant on the feed size emanating from the stockpile/reclaim system.

To offset the risk of ore variability, developers tend to provide contingency by designing the mills to take high steel media loads, and providing very high quality stockpiling and retrieval arrangements. This adds to the already higher capital cost.

The power efficiency of a fully autogenous milling circuit is better than that of a steel media system provided that ore competency is not excessive, the primary mill screen-cut is relatively fine (2 mm) and the secondary mill media is selected appropriately (10 to 70 mm for a 2 mm aperture SAG mill screen). Some circuits have operated with relatively coarse transfer sizes to the secondary mill, requiring secondary media as coarse as 120 mm and resulting in reduced milling efficiency.

A number of fully autogenous circuits have been converted to steel media circuits due to poor control, poor power efficiency or requirements to increase throughput. Typical of these is Tarmoola. (Kar, 1999)

Single stage autogenous milling has proven effective for a number of ore types. The success of this approach is reliant on maintaining an effective rock media charge. Thus, the ore has to be sufficiently competent to establish a charge and not so competent or lacking in lumps that the media charge becomes critical, with the result that the mill product size becomes too fine, grossly decreasing circuit efficiency.

Work conducted at pilot scale for the Kambalda installation (Esveldt, 1997) indicated a strong relationship between circuit efficiency and rock charge size distribution. Over crushing of the pebble stream led to extreme circulating loads about the cyclone (>2000% at pilot scale) due to the lack of suitable media in the grinding charge.

Regulated pebble crushing can be used to control the rock charge build-up, as at Savage River (ABC circuit), where the pebble crusher is brought in circuit as the mill load builds up, and taken off-line as the load decreases.

An interesting comparison of the effect of pebble crushing in single stage AG milling has been observed at Olympic Dam. Equipment in use comprises a 10.36 m (34-ft) diameter AG mill, which operates in closed circuit with a recycle crusher and cyclones, and an 11.6 m (38-ft) diameter mill, which operated in circuit with cyclones but no recycle crusher. Typically, the 34-ft mill is using 1 to 2 kWh/t less than the 38-ft mill on similar feeds, and this difference is attributed to charge size control flowing from the recycle crusher. If the feed size distribution is not optimum (too much mid size), pebble crushing allows limited ability to improve performance.

It cannot be emphasised too strongly that the key to successful autogenous milling is correct feed preparation. Nothing is more important than preserving a consistent blend containing adequate lump media. Without this, steady operation becomes difficult to achieve.

FUTURE DEVELOPMENTS

Future developments in autogenous and semi-autogenous milling in Australia may be divided into two categories:

- ***improvements in plant operation*** to improve milling efficiency, decrease costs, or increase throughput, and
- ***implementation of emerging or new technology*** for greenfields projects or major plant expansions.

Improvements in Plant Operation

Optimising plant operation is focussed on pushing existing equipment to the limit, striving to maximise tonnage, and improving wearing life and plant availability.

Maximising Plant Throughput

The majority of operations aim to maximise plant throughput to match the maximum cost effective mining rate. The SAG mill is usually the rate limiting process stage in plant upgrades. Plants based on single stream primary mills rely on one of the following strategies to significantly increase mill throughput:

- increased ball load;
- implementation of pebble crushing;
- optimisation of blasting practice in the mine and finer primary crushing, or
- implementation of secondary crushing.

SAG mills operating at over 15% ball load in SAB circuits are increasingly common (e.g. Macraes Gold Mine) and retrofits of new or improved pebble crushing circuits are occurring where high ball loads are already in use. Limited improvement in circuit power efficiency is observed when ball load is increased unless the ore is particularly competent.

The “Mine to Mill” approach of optimising mine/plant cost through improved blasting practice and ore crushing is being adopted at the majority of medium and large scale projects. Improvements in grinding circuit power efficiency are typically related to the higher content of fines in the SAG mill feed.

The acceptance of crushing technology has, in general, been limited by historical factors of high wear, resultant maintenance costs and dust issues. However, secondary and even tertiary crushing prior to SAG milling offers opportunity to significantly increase (double or even triple) primary milling capacity.

The trend to increasing unit capacity and lower overall unit cost has resulted in a reduction in power efficiency for some of the larger capacity plants. . This is tolerated due to the economies of scale but presents opportunities for reducing power consumption in the future.

Improving Wear Life and Plant Availability

There is significant scope for increasing capacity by decreasing downtime. Improving the life of the mill internals and minimising downtime for relining gives higher availability. The use of wear resistant rubber/steel composites, larger and fewer liner pieces, and a reduction in the number of, or even elimination of, fixings presents opportunities for improved productivity.

Recent availability of DEM and CFD modelling has assisted in the acceptance of modified liner and lifter designs, and this trend will continue with ever increasing computational capacity.

Process Optimisation

The increasing sophistication of modelling and simulation as an aid to optimisation should not go unrecognised. Techniques such as power analysis for SAG and ball mills, (Siddall, 2000) JK SimMet and cyclone/screen efficiency evaluations allow the circuit to be tuned to current conditions. Similar approaches to the modelling of all unit operations in the plant will lead to improved designs and plant performance.

Once the circuit is optimised, the control strategy becomes vital in maximising its potential.

Process Control and Expert Systems

Expert systems will play a vital role in maximising grinding circuit operation. A recent paper (Broussaud, 2001) outlined the requirements for SAG mill control. Instrumentation and systems that are expected to become standard in the future include:

- Visual feed size analysis systems such as Split® and Wipfrag®
These measure size distributions on the feed belt via a camera connected to a computer. Advanced dedicated image analysis systems generate 3D distributions.
- Continuous Charge Monitoring sensors
Measuring mill load directly in rubber lined mills is now possible. Charge monitoring provides information which is complementary to bearing pressure or load cells since it may discriminate between liquid and solids, or rocks and fine ore and contains information about charge location and in some cases conditions of lifters.
- Sound sensors:
The nature and location of the sound generated by impacts within the mill contains information about what is happening inside the mill. The analysis of

frequency and amplitude data using sound sensors is a promising area of development.

- On-line estimators
Ball charge and mill load predictions are generated using algorithms derived from historical databases and models of SAG mill operation

- Optimising control systems.
When soft sensor and predictor optimisers are in operation, real time information on feed size and mill load comparisons (estimated vs observed) improve the accuracy of ore hardness and grindability inferences, and make it possible to better anticipate overload trends or opportunities for increasing feedrate.

Implementation of Emerging or New Technology

SAG Mill Circuit Design

Australia has been at the forefront of the implementation of large diameter and high powered SAG mills with the only mills greater than 36 ft diameter installed at Olympic Dam and Cadia. At this time, there are no projects in Australia considering mills of greater than 40 ft diameter. Vendors are offering SAG mills to 24 MW and ball mills to 14 MW, with single line processing at rates of up to 3000 tph contemplated. Fluid transport and residence time considerations now start to limit capacity, particularly in ball mills with their attendant circulating loads.

The remarkable success of process design from drill-core samples, pioneered in Australia, allows SAG milling to be considered for projects with no ore exposures for pilot plant testwork. The use of power, breakage rate, 2D and 3D discrete element modelling and computational fluid dynamics methods is now common practice in large mill design.

The optimum mill closure size is rarely established in plant design testwork in Australia. For large mill circuits, establishing the optimum SAG mill screen size can reduce circuit power requirements by substantial amounts. The breakage rate of +5 mm material in a large ball mill can be relatively low and these particles may be more effectively ground in the SAG mill.

Similarly, the presentation of typical primary crushed ore to the SAG mill may not provide the most cost effective outcome. Additional expenditure in primary crushing or even open (or closed circuit) secondary crushing may provide a more cost effective outcome and negate the need for pebble crushing and its associated issues in operation.

SABC Process Design

Improvements in pebble management and metal control for >50 000 tpd circuits are required to maximise the availability of large recycle crushers and optimise capital expenditure. Fail-safe designs are capital intensive and simple recycle designs are limited by the lack of operating flexibility together with maintenance issues associated with the large pebble crushers (Hart, 2001, Dunne 2001).

Screening of recycle crusher feed can be undertaken using a trommel or a vibrating screen. Using a vibrating screen is usually a higher capital cost option due to the need to further elevate the mill. However, large mills require very large (possibly >100 m²) trommel screens and screening efficiency is typically lower resulting in reduced pebble crushing efficiency. Combination trommel/screen designs with a small trommel followed by a dewatering screen prior to pebble crushing have been used at Fimiston (retrofit) and Ridgeway (plant design). Further work is required to optimise these arrangements.

The successful application of trunnion and trommel magnets will improve steel recovery from pebble crusher feed streams and the availability of cyclone feed pumps. Most new plant designs include this style of magnet and the use of ball mill trommels to protect the cyclone feed pump is diminishing with the acceptance of trommel magnets.

Shell Supported Mills

The process and plant layout advantages of shell-supported mills have been mentioned above to include improved efficiency in mill discharge due to increased discharge aperture diameter and the potential to opt for “square aspect” large capacity mills. The process advantage of eliminating pulp lifters has been reinforced by observations at many operations, including Cadia.

The use of CFD to examine the impact of “square aspect” rather than the traditional “pancake” mills will provide insight into whether this presents an opportunity for a new approach to SAG milling.

Drive Trains

There is much discussion over the interpretation of drive efficiency and mill availability issues associated with the selection of large multi-pinion geared drives and ring motor drive systems.

The improvements in drive trains in recent years have been outlined. Developments in gearless drives, improved variable speed geared systems and combination pinion systems will continue to evolve and provide opportunities for larger mills.

HPGR and SAG Milling

The use of HPGRs in association with SAG milling has been evaluated at pilot scale and presents some advantages. The current high capital cost of HPGRs at low throughput (for example < 200 t/h) will make the development of this approach on low capacity plants unappealing. The further use of HPGRs in gold and base metals mineral processing is perceived to hinge on the successful implementation of this technology for the proposed Boddington Expansion Project, described by Parker et al (2001).

Fully Autogenous Milling

Fully autogenous milling is neither emerging nor new and has been implemented for a number of projects due to the low operating costs. The acceptance of AG milling is a function of the project developers’ acceptance of the need to obtain appropriate samples and conduct pilot trials to assess ore variability. Assessment at bench scale is possible, but carries

additional risk. Nonetheless, improving control of feed size and mill load suggests that a revisit to this “smart” technology could be rewarding with the right ore.

Less accepted is the use of pebble milling to replace ball milling, with some notable exceptions. Although an “old concept”, pebble milling presents a substantial opportunity to reduce operating costs in well conceived and designed plants. Only time will tell!

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GLOSSARY OF ABBREVIATIONS

AG – Autogenous Grinding
SAG – Semi-Autogenous Grinding
HP – Horse-Power
kW - Kilowatt
MW -Megawatt
DEM – Discrete Element Method or Modelling
CFD – Computational Fluid Dynamics
EGL – Effective Grinding Length
LCI – Load Commutator Invertor
CCV – Cyclo-convertor
PWM – Pulse Width Modulated
LRS – Liquid Resistance Starter
SER – Slip Energy Recovery
SMTP – Single Motor Twin Pinion
SABC – SAG Mill/Ball Mill/Crusher
ABC – AG Mill/Ball Mill/Crusher
UCS – Unconfined Compressive Strength
HPGR – High Pressure Grinding Rolls
JKMRC – Julius Kruttschnitt Mineral Research Centre

APPENDIX

Factors in Choice of Recycle Crushing Plant for Large Plant

Crusher	Bin	Advantages	Disadvantages	Cost
1 Large	No	Eliminates cycling effect on SAG mill operation. Lowest capital cost.	Maintenance access to crusher. Loss of 100% of recycle crushing capacity during maintenance. Less than perfect feed presentation to crusher. Maximum feed rate likely to exceed capacity	Low
1 Large	Yes	Low to medium cost. Improved maintenance access to crusher. Improved feed presentation to crusher.	Maximum feed rate likely to exceed capacity. Loss of 100% of recycle crushing capacity during maintenance. Introduces cycling effect on SAG mill operation.	Low to medium
2 Smaller -Fixed set	No	Medium cost. Some duty and standby capacity.	Maintenance access to crusher. Less than perfect feed presentation to crusher. Difficult to operate unless choke fed.	Medium to high
2 Smaller	Yes	Duty and standby capacity. Maintenance access. Feed presentation.	Cycling effect on AG mill operation.	High
2 Smaller With on-line set variation	No	Flexible capacity for variable feedrate. Less impact on overall capacity during maintenance. Reduced cycling effect on SAG mill operation.	Feed distribution across multiple crushers. Maintenance access. Feed presentation. Reduced duty/standby provision.	Low to medium
2 Smaller With Hydroset	Yes	Flexible capacity for variable feedrate. Less impact on overall capacity during maintenance Maintenance access. Feed presentation.	Cycling effect on AG mill operation. Feed distribution across multiple crushers. No duty standby provision. High cost.	Medium

Crusher	Bin	Advantages	Disadvantages	Cost
3 Smaller	No	Highest flexibility in handling feed variability. Least impact on overall capacity during maintenance (except for duty/standby cases). No cycling effect on AG mill performance.	Feed distribution across multiple crushers. No duty standby provision. High cost. Maintenance access. Feed presentation.	Medium
3 Smaller	Yes	Highest flexibility in handling feed variability. Least impact on overall capacity during maintenance (except for duty/standby cases). Maintenance access. Feed presentation.	Feed distribution across multiple crushers. No duty standby provision. High cost. Cycling effect on AG mill operation.	Medium to high