

Design SAG mill production when you need it most: In day 1 and year 1

The norm for new SAG milling plant start-ups has, until now been accepted by industry as taking from 6 to 12 months to achieve full production. By accepting this as normal, large projects suffer massive revenue shortfalls, in the order of $\frac{1}{4}$ to $\frac{1}{2}$ a billion dollars during the first year because of inability to process design tonnage from day 1. In some cases, the first year is also plagued by modifications and equipment additions to rectify the production shortfalls, resulting in low net cash flow generation.

The value of investing in the proper SAG mill for start-up and the decision to make this investment, need to include an incremental analysis of the extra capital required to achieve design production at start-up versus the pay back that the expenditure creates by eliminating the ramp up period losses. This approach will shorten the project payback period and increase the confidence of the financial stakeholders in the project.

The goal of this paper is to highlight that often these production shortfalls result from financial misunderstanding, where reducing the capital cost of the grinding equipment is done without regard for production capability and risk assessment. If proper grinding equipment is selected, the production target can always be achieved without shortfalls. Clients need to participate and take responsibility for sizing the grinding mills, using their own or independent consultants and preferably, open power based technology, prior to requesting quotes for grinding equipment or verification by a third party. Geo-metallurgical studies and data, while helpful to refine day to day throughput predictions, are not required for the accurate design of new mills.

Since it is now possible to achieve design tonnage at start-up, it is recommended to use a 'mill design by ore hardness measurement and calculation' method, similar to Bond methodology, except including a SAG test. Good samples, test accuracy and understanding the basic principles of SAG mill design and operation, are the keys to make this possible.

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INTRODUCTION

The purpose of this paper is to highlight and encourage the use of a recently developed and recommended approach to designing SAG mill grinding circuits that have the capability to perform at design expectations from start-up and onward. This information is presented based on actual "how to do it" in-house experience from recent and long term trends. So far, it is not a priority for the mining industry to take advantage of available power based SAG mill design methods to eliminate long ramp-up periods when new plants start processing new and/or historic massive low grade ore reserves.

This paper is specifically addressed to senior engineering managers, mining executives and practising mineral processing engineers, who have accepted as 'normal', practices which may not be acceptable to any investment managers or owners. Indeed, if a non-technical investor realized that typically, one quarter of a billion dollars of revenue or more could be gained during the first year of operation by designing the SAG grinding circuit with proper due diligence regarding mill size and cost, using well established power based design methods, he or they, would probably insist that a more suitable design technique be used and take a different strategy or decision, prior to investing in the project.

For large tonnage projects costing in the billions to build, it is a fact that the quest for a low capital cost grinding circuit, has prevented many owners from operating highly profitable projects from day 1 because the designers failed to present options that, in retrospect, would have paid off the extra capital involved in only a few weeks or months. The reason for this is that the grinding equipment package for a new plant is the single most expensive equipment order in the plant which is an easy target for accountants to focus on. To summarize, capital cost reduction and pressure on mill sizing has resulted in non-flexibility in new SAG mill circuit designs.

In order to defend the mill size selected, the owner's engineers need to be able to quantify the loss in productivity that will occur if the SAG mill is downsized. Power based methods allow this calculation to be executed rapidly with good accuracy. Comparative or simulation based methods do not.

When cash flow analyses are done during the Feasibility Study process, ramp up losses are usually allowed for but often are not represented correctly. However, what is missed is the extra capital and delay time required to retrofit either pre-crushing of mill feed, or pebble crushing, or both, into the SAG grinding circuit to make it perform to budget tonnage specifications if the downsizing was too severe. This cash flow shortfall can also include unforeseen costly downtime due to tying into an existing facility if the details are not properly worked out in advance.

Also missing from most Feasibility Studies involving flotation and some studies involving leaching, is the proper allowance for reduced recovery that is caused by fluctuating tonnage when the SAG mill feed tonnage (and grind) is forced to fluctuate because of varying ore hardness and lack of capacity and flexibility to do otherwise.

Since the introduction of SAG milling in the 1950's, the methods used to design SAG mills have changed, moving from one proprietary method to another, often using non-engineering measurements and comparative methods to size the grinding mills. With the advent of open power based technology, first published in 2006, this situation has changed. Fundamental ore hardness measurements and engineering calculations have replaced simulation and comparative methods as

the tools of choice for those who wish to start-up their plants at design tonnage and enjoy the intended revenue stream that results from this approach.

In order to capture the full benefit of using SAG grinding technology, the SAG and ball mills need to be selected to allow the plant to run at steady design tonnage from the first day. We will now examine what needs to be done to make this happen.

Terms used in Sag Mill design and operation

To begin, it is necessary to understand the terms used when discussing SAG mill testing, design and operation. Terms frequently used are explained as follows:

Geometallurgy: It is required for predicting throughput in an existing mill. It is more expensive than design testing because many more samples are required. It should be used judiciously. Geometallurgy is not required for design but can be useful in the design context if the data is already available. It provides information on rock classification and mineralogy which enhances the knowledge of the mine and answers questions on how to control mill throughput using good mine planning, based on real data.

Feed Size, F80: Primary crushed ore is mandatory to feed any SAG mill. Typical feed size range is 80% passing 130 to 160 mm. Softer ores will be a little finer but the finer size is not sustainable when the ore becomes hard. Pre-crushing to finer sizes enhances throughput as does crushing of pebbles from the SAG mill (usually minus 60 mm). New mill design should always be done at 150 or 152 mm F80 because it is easier to build and operate this way, without pre-crushing.

Transfer Size, T80: Is the 80% passing size of ore as it passes from the SAG mill to the ball mill. It is typically about 1/3 the size of the screen opening but can be coarser than 1/3, especially when a pebble crusher is used. Screening at 5 mm ensures that the T80 will be about 10 mesh (1.7 mm) ensuring that the ball mill will work efficiently. Coarser screens than 10 mm will cause serious losses in ball mill efficiency. Ball mill feed must never exceed 80% passing 3 mm if reasonable ball mill efficiency is expected. The practice of using 1/2 inch screens (trommels) is an encroachment on this limit and is perhaps the most contentious point in setting up a smooth start-up because when hard ores are treated, the 3/8 inch scats are a problem that can only be dealt with by oversizing the ball mills where low efficiency is allowed for.

Product Size, P80: This is the size required to liberate the minerals being recovered. Final product from grinding is nearly always produced from cyclones, even when grinding is done in a single stage SAG mill. Cyclones work best when the cyclone feed size is limited to 5 mm top size, as noted above when referring to screen selection. The product size is also a function of liberation and downstream requirements.

SAG Mill ore hardness kWh/t: Energy required to grind an ore from F80 of 152 mm to T80 of 1.7 mm. It is a resulting value from the SAGDesign test. No other test accurately reports SAG hardness in kWh/t. The required SAG energy is calculated using the Bond W_i to adjust the test T80 SAG energy to the design T80 energy.

Ball Mill ore hardness, Bond Ball Mill Work Index of SAG ground ore, kWh/t: Crushed Bond BW_i testing gives a slightly different result. The SAGDesign test is the only test which measures

BWi on SAG ground ore. This BWi is used to adjust the SAG energy to the design T80 as noted above, and to calculate the ball mill size required.

SAG hardness variability diagram: This is used to select the 80th percentile of ore hardness variability or some other design point, based on what is achievable to feed the SAG mill considering the mining method. Mine design is an important part of SAG mill design.

80th Percentile Design: Recommended design point for most new plants. Typically the SAG mill will be 10 to 15% larger (more power) than an average ore design. Other design points recently used are: hardest ore (100th percentile), 75th percentile, 65th percentile, and 50th percentile which could be harder or softer than average ore, based on the variability diagram.

Pebble crusher: A pebble crusher is required to process (crush) hard pebbles at lower cost than a SAG mill can accomplish. Whenever possible, a good design strategy is to design for no pebble crusher and leave the pebble crusher addition as a way to increase design throughput. The pebble crusher should never be considered as a contingency to achieve design throughput. This mistake can cost millions in lost revenue during the first production year and is usually associated with inadequate hardness variability information at the design stage.

Representative sample: The only ore blend a SAG mill will never see.

Critical size: Ore component that is harder than the mill has power to grind at the specified rate. When a SAG mill is too small, pebble crushing allows the critical size to be eliminated and throughput is increased. Conversely, critical size pebbles occur when hard ore throughput exceeds design power required. When the tonnage is reduced, critical size problems disappear.

Maximum power gives maximum throughput: Not so – depending on the liners. Throughput peaks at 26% load while power peaks at about 35% load. When overloaded, a SAG mill loses coarse ore breakage and feed tonnage must be reduced to grind out the mill and resume production at a reduced rate. When operating flat out (not recommended), because ores are variable in hardness, maximum throughput varies. This may work in a leach plant if product size is not adversely affected, but is not recommended for a flotation plant. Steady production is better.

Liner design: With the trend of larger diameter mills, correct liner design is important. The number of lifters, spacing and face angle all play a role. However, getting quantum leaps in power draw (and throughput) with liner redesign is not realistic. SAG mill liners should be designed to draw full power at 26% volume charge loading.

METHODOLOGY

The Methodology used to evaluate this topic consists of selecting a plant that was deliberately designed for the hardest ore in the deposit, analysing the production achieved over the full life of the mine, in this case just over eight years, and comparing that production with what would have been achieved with a smaller mill designed to run on average hardness ore for the life of the open pit. The purpose here is to evaluate what additional benefit would accrue if production losses in

the first year were to be avoided and calculate the value of the additional recovery as a means to pay back the extra capital required to purchase the larger SAG mill.

In this case because the project is complete and mining is finished, a reverse engineering exercise has been done to calculate the SAG mill that would have been required to meet average design production over the life of the mine. The benefits shown herein will be actually greater because instead of a 10 year mine life, the project was completed in just over 8 years and extra production expenses, particularly for labour, would be an additional economic benefit.

ANALYSIS AND DISCUSSION OF RESULTS

The Kubaka gold plant in the Russian Far East was the first mill to be designed using the SAG Power Index power based technology. This case study was first published in the Proceedings of the CMP Conference in Ottawa, January 2001 († Starkey, Holmes, 2001). The principle of design tonnage on day 1 is explained below as we look at these results.

The following tables describe the Kubaka design and process performance information. To make this relevant, the original design data for mill power has been updated to correspond with current data, based on the test results, expressed in minutes. As published previously, the design was to be based on hardest ore and this analysis shows that that objective was achieved.

Table 1 presents the original data from the referenced paper, but also includes an update of the data to a standard that reflects the known accuracy of the work described.

Table 1 Measured Ore Hardness

Samples Tested	SPI Minutes	Gross Energy - kWh/t *		Pinion kWh/t	Pinion kWh/t	Remarks
		Original @1200 um	Correct @1200 um	Correct @1200 um	Model Input @1700 um	
Open Pit 1	58	7.5	8.41	7.22	6.95	
Open Pit 2	92	10.7	10.84	9.30	8.96	
Open Pit 3	115	12.9	12.26	10.51	10.13	
Open Pit 4	120	13.4	12.55	10.76	10.37	
Open Pit 5	120	13.4	12.55	10.76	10.37	
Underground Hardest	152	16.4	14.29	12.26	11.81	For design
Average of 5 pit samples	101	11.6	11.32	9.71	9.43	Smaller mill
Design 80th used, original		13.8	3.6% less than hardest @ 14.29 kWh/t gross.			

* Includes motor loss of 6% and operating factor of 10%

Table 1 shows the basic design data from the 6 samples tested and the correlation between the original information and the updated version when corrected calibration equations are used on the historical data. The hardest sample was used for design and the actual mill performance, seen in Table 2 below as average t/h, closely corresponds to the average of the five open pit samples tested, as seen in Table 3.

Table 2 Plant Performance

Year	Head g/t Au	Tonnes Milled	Plant Avail. %	Plant Throughput			Design t/h % Diff.	Au % Recovery
				t/h	t/d	Avg t/d		
1998	24.55	646,508	92.6	80	1,913	1,771	-0.6	98.2
1999	18.74	797,700	92.9	98	2,353	2,185	21	98.1
2000	16.28	856,780	92.9	105	2,527	2,341	30	97.9
2001	15.28	889,264	91	112	2,677	2,436	39.9	97.7
2002	14.93	850,000	91	112	2,677	2,436	39.9	97.5
2003	6.42	883,000	91	112	2,677	2,436	39.9	97.1
2004	5.07	778,000	84.7	105	2,518	212	31.6	97.2
2005	5.42	827,169	N/A	112	2,677	2,490	39.9	97.1
Overall	13.04	6,528,421		104	2,502	2,278	28.4	97.6

Table 2 also shows that because the design was based on hardest ore, it was possible to maintain scheduled production within 1% for the first year. After that, as noted above, it is seen that the average throughput appeared to be very closely correlated to the average hardness of the five open pit samples tested. As shown in Table 3 below.

Table 3 Design Performance Compared to Actual

Design Scenario	Feed Rate t/h	Model Input kWh/t @ 1700 um	Transfer Size um	SAG Mill		Unit Energy kWh/t	Remarks
				Size Dia x EGL ft	Motor kW		
Base Design	81	11.81	1200	20 x 7.5	1119	13.8	Installed
Year 1 operating results	80		1200			14.0	Actual
Avg t/h from pit samples	103.4	9.43 *	1200	20 x 7.5	1119	10.7	Calculated
LOM average results	104		1200			10.7	Actual
Smaller SAG mill	81	9.43	1200	18 x 7.7	870	10.7	Mill required

* Average hardness of the open pit samples tested.

Based on the performance of the Kubaka SAG mill, the actual performance exceeded design tonnage (t/h) over the life of the mine, by 23 t/h or 28%. Actual average tonnage was 104 t/h whereas design was 81 t/h. To provide the design throughput on average, an 18 ft diam x 7.7 EGL SAG mill with 870 kW installed, would have produced the design tonnage. This calculation was done for this analysis, but the magnitude of the variance and the need to pick the larger SAG mill, were known when the SAG mill was designed and purchased. It is worth noting that many SAG plants do just meet the design criteria and so do not have the opportunity to produce extra tonnes if this is desired by management. It is also clear that design tonnage was achieved in the first year of operation and this should be the goal of every new plant design.

The result was that the tonnage produced was 28% higher than design. The samples tested were clearly harder than average and this led to additional milling capacity. The selection of an adequately sized SAG mill resulted in big dividends for the owner, Kinross Gold.

The back calculation of the SAG mill to produce design tonnage based on actual results, is a reverse engineering exercise. In 2013 dollars, the 18 ft diameter SAG mill shown above would cost about \$4.1 million and the 20 ft diameter SAG mill actually purchased would have cost about \$5.2 million in today's dollars, an increase of \$1.100,000.

The extra capital to purchase this larger (20 ft dia) SAG mill needs to be multiplied by 2.2 to reflect the actual installed cost for the larger equipment. It is therefore estimated that the larger SAG mill when installed, would cost \$2.42 million more than the smaller 18 ft diameter SAG mill.

This SAG mill design choice virtually eliminated lost scheduled production during start up. For this analysis it is reasonable to estimate that about 22% of design production would have been lost had the smaller mill been chosen. This would have reduced tonnes produced during the first year by 141,400 tonnes grading 24.5 g/t Au, as shown in Table 2. This equates to 387 t/d and 9320 g of recovered gold per day at 98.2% recovery. At \$1,300 per troy ounce, the value of this lost production would be \$389,600 per day or \$142 million during the first year.

Total production costs varied from \$25 to \$77 per tonne over the life of the mine. If we use the highest value, the production cost for the extra tonnage processed during the first year is assessed as \$29,800 per day. Deducting this cost from the extra revenue of \$389,600 per day gives a net revenue increase of \$359,800 per day and the payback period for the extra SAG mill capacity would be less than 7 days, based on today's prices.

Note also that the lost production, after deducting operating costs, during the first year, would have been approximately equivalent to a loss of \$131 million in revenue, expressed in 2013 dollars.

The calculated money that could have been saved by purchasing a smaller SAG mill is a very small number compared to the benefit that occurred because the mill was robustly sized. It was the intention right from the start, that the mill would be robustly sized and the discussions during design focussed on the plant being able to achieve design production at all times, even when the hardest ore was being processed. This was achieved successfully, both in practice and on paper from a theoretical point of view.

The financial performance of the plant certainly justified this approach. Of course, the option to run design tonnage at lower steel load, and lower steel consumption was always an option, but management elected to run the mill at maximum throughput as a preferred option. The increase in revenue was more important than decreasing costs as much as possible. The key to a good design is to provide an option available to the client, to reduce steel consumption and control throughput at design levels by using an adequately sized mill.

SUMMARY

An investor has the right to know and expect that design tonnage will be possible at all times, unless otherwise stated in the feasibility study, that design downstream recoveries will be attained because adequate liberation is achieved, and that power usage will be within levels predicted and not impact negatively on operating costs which will be as predicted without additional capital investment.

It is unreasonable to suggest that a new plant is so tightly designed that doing production 'catch up' will not be possible when the plant is operating and the mine, for example was unable to deliver ore on schedule due to an unforeseen flood or landslide in the pit. If one plant took 12 months to achieve design production because the SAG mill was too tightly sized, is it legitimate to use that plant as a comparison point for designing a new plant? This basically is what happens when simulation/comparative techniques are used to choose the SAG mill for a new plant.

The other part of this design equation is that new SAG mill grinding circuits must be designed for the property concerned. Only measurements of ore hardness on that property are relevant to the selection of the required SAG mill. When this is done, and adequate test work is performed to understand the hardness variability function for the ore body in question, it becomes an engineering exercise to calculate how many tonnes can be processed through alternatively sized SAG mills. The value of adding extra diameter to the SAG mill can then be easily calculated.

The design objective is to prevent tonnage shortfalls when a new plant starts up. This is the revenue that is considered to be recoverable by preventing losses. After looking at the Kubaka situation, the money spent on grinding equipment was well spent. Actual required grinding power measurements on professionally selected samples are needed to perform meaningful calculations. To date we have not seen this done by simulation methods.

Not all tonnage shortfalls are due to the inability of the mill to process design tonnage. For some start-ups the mine development is allowed to lag and in other cases the ancillary facilities are not ready. Obviously, this paper does not consider these situations. It is suggested however that the urgency of having everything ready to run on day one takes on a whole different perspective if the construction on-site personnel know that the mill will not be the hold up. In this environment everything including the mine, the shops and the tailings area will be ready at the same time.

A bit of history is recalled to add perspective to how design methods have changed and not kept up to those 'good practice' methods used by our predecessors. In the period 1960 to 1985, the majority of new plants (with the exception of iron ore autogenous mills) were small and used three stages of crushing, rod mills and ball mills. By comparison today, new plants typically use primary crushing, SAG milling and ball milling if the grind required and size of the SAG mill requires a ball mill. Those older plants, because there were 5 stages of size reduction involved, had built-in flexibility because of the many stages. If a plant could not process at least 10% more than design tonnage after start-up, the design was judged to be inadequate and the designer may no longer enjoy the support of his managers (i.e. be fired).

But the methods used to design the old plants were tried and true. Every client had engineers on staff who would check the design and support its adequacy. Today, several private methods and technologies have taken this responsibility from the clients and the accountability for design has in fact been compromised unless power based open technology is used.

To implement the theme of this paper, a paradigm shift may be required. Clients will need to be involved in their mill designs and, after doing the required testing and calculations, request that the mill vendor provide the required mills with regard to size and power and not let the EPCM services provider work in isolation. To complete this change, owners should take the lead of a collaborative effort involving the owner, EPCM contractor, and the mill vendor. The final design recommendation should always be crosschecked with industry benchmarking.

Other specifics are important at the onset of the project. This includes defining circuit objectives, overall design objectives, and clearly gathering a full understanding of the ore, mine plan, and exploitation method that will be used.

Companies can take on this responsibility by hiring in-house staff or by contracting out to obtain the required expertise. This is suggested so that clients can address their need to stop unplanned revenue shortfalls at start-up.

Another problem that has happened frequently is that the new plant really cannot make the design tonnage, either because the initial ore is too hard or the design was not done properly. In these cases, the owner must retrofit his plant with either pre-crushing or pebble crushing to make the plant work. This further extends the lost production period because retrofits take more than one year to implement in most cases and the capital cost is not included in the budget.

SAG milling deserves to be considered the best technology for reliable, cost effective production and should not be replaced by other technology which may in fact be worse. Also of great importance is the environmental consideration of less dust which a wet SAG circuit offers.

Looking at the need to reduce grinding energy, research into alternate technologies is justified. However, at the same time, there is a need to make SAG milling do what it is supposed to do – make money for producers by giving them the revenue from day one that results from operating the plants that they have paid to build. They expect us to give it our best shot, including starting-up at design tonnage and holding it steady until maintenance requires a shutdown.

RECOMMENDATIONS

Do adequate test work to allow proper mill sizing and throughput analysis to be assessed. The criteria to be considered include size of the deposit, configuration of the ore zone(s), and mining method by which the ore will be mined.

The test work required is also a function of what stage of study is being done, as discussed in detail at the SAG Conference in 2011. (² Starkey, Meadows and Scinto, 2011)

Also recommended in that conference is the need to use power based ore hardness measurements as one of the design alternatives. (² Starkey, Meadows and Scinto, 2011)

Purchase grinding mills that allow design tonnage to be met at all times even when hardest ores are processed, either alone or as a blend if required.

Do not blindly apply pre-set criteria for designing a SAG mill. While 80th percentile design is usually safe, there will be situations where some other value is more appropriate. If ore hardness is increasing with depth, or if the hardest ore is the highest grade zone in the mine, the hardest ore may be more appropriate.

If a leach plant is being built, the recovery is not closely related to grind, the open pit uses two or more shovels, and the hardness variability is not large, the average ore hardness may be more appropriate for the SAG mill design. Every case is different and needs its own design criteria.

REFERENCES

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