Keys To Best Practice Comminution

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ABSTRACT

Comminution circuits are composed of multiple unit operation, with the objective of reducing mined rock to a size where valuable minerals grains are liberated from gangue. Optimal comminution is critical to achieve efficient mineral separation.

There are three reasons for writing this paper. For operators to manage good operations; for designers to produce workable designs; and for educators to provide useful education for mineral process engineers. In all cases, understanding of the transfer size (T_{80}) between the SAG mill and the ball mill is critical to achieve best economics in a semi-autogenous mill (SAG) grinding plant.

T_{80} is important to operators because when the SAG energy and the Bond Ball Mill Work Index on SAG ground ore are measured, accurate prediction of future throughput in any SAG circuit is possible. Without knowledge of the plant T_{80}, it can take many months to figure out how to correct what is really a SAG mill grinding problem, because that problem is hidden if the T_{80} is not measured.

Best Practice Comminution means running a SAG mill under optimal conditions, and avoiding overloading, overspeeding and using excessive steel additions, both during the design and operating stages of the plant. When normal limits for these parameters are exceeded in the design stage, production shortfalls will result, and operating costs will be high. While extra SAG mill capacity is a bonus, lack of capacity is a disaster.

This paper shows how to design workable grinding circuits on a particular ore, using either single stage SAG milling, SAB grinding, SABC grinding, or HPGR pre-crushing followed by ball milling. There are many ways to set up a SAG plant, and future expansion should always be considered at the design stage. This opportunity can be overlooked if the designer does not understand the options available.

INTRODUCTION

The choice of title for this paper is an old one. How many times have you read an author who claims to have the most up-to-date, ground-breaking, cutting-edge, accurate, innovative technology in the world to design SAG mills and SAG mill comminution circuits? In fact, the phrases "Best Practices" and "Best Practice Comminution" are so over-used that in the year 2021, when we should know exactly what Best Practice looks like, we shrug and say – here we go again, another paper or report based on private mill design technology where design secrets are hidden as 'proprietary' to prevent the scrutiny required to understand the most important equipment design exercise that has ever been required of a mineral processing engineer.

Make no mistake. A correctly sized SAG mill is the heart and soul of every new mining project where SAG milling will be used to grind the primary crushed ore. Revenue to pay for the mine and concentrator construction costs is derived from the tonnes (and grade) of ore processed in the SAG mill. Shortfalls in revenue and reduction of profit margins by high operating costs, affect the net present value of the mining project. Yet, in the last 10 years in Canada alone, there have been four projects built which suffered massive losses in the early operating years because the SAG or AG mill could not produce the annual tonnes that had been nominated in the feasibility studies for the respective projects. In any other industry, there would be known expertise available to prevent these losses and the losses would not have happened. That massive production short falls still happen in a mineral processing plant is a measure of where we are as an industry. Our ability to attract new, sharp, well-educated young engineers is contingent on our success in using the skill and creativity of these young engineers to create value for their employers.

The anecdotes, technical analyses and new developments which this paper presents, are based on true stories and life experience of the author, starting in the 1960's, and include technical discussions based on a SAG hardness measurement system that has been invented in the 21^{st} century. Patents granted and applied for allow this technology to be taught openly in universities and practiced in every mineral processing operation in Canada where there is an interest to do so. Specialist users of proprietary technology based on private information and software programs of unknown content will not solve the problems we face. We must base SAG mill designs and performance predictions, on accurate ore hardness measurements, and understandable, first principles design methods, practiced by a client's own in-house metallurgical staff. To do this, SAG mill design technology must be simplified and taught in a practical way to every person who has chosen ore comminution for their career. Best practice SAG mill and comminution design demands an immediate upgrade in the way this technology is taught to mineral processing students and plant metallurgists. The SAG mill is the single most important and expensive piece of equipment on a mine site, and because of this, it needs to become the best-understood and operated piece of equipment in a concentrator.

Best Practice Comminution is what the industry wants but there is not universal agreement about what it looks like. As this paper is written, it is realized that choices need to be made. Will this paper talk about myths, unproven theories, and preferential choices, or will it talk about facts? The desired result of building a mine and a concentrator, is to grind and beneficiate the ore, in the way, and at the intended throughput, to make a defined profit. This is the important goal, so facts, progress and success will dominate this discussion. If a mine owner's goal is not aligned with the goals outlined, then please study what is being presented in this paper for guidance. Until every mineral processing design engineer knows how to design a SAG mill, mistakes will continue. The future and success of our industry depends on our understanding of this simple concept. SAG milling is the only comminution method that works on every ore ever discovered. It must not be ignored because we did not do enough research to understand how it works. Some ores will work better using other comminution methods, from an economic point of view, but SAG milling must be part of every new project evaluation.

CHOOSING THE TESTING AND DESIGN METHOD

The starting point for any new milling project is a series of questions which need to be asked even before any design work is started on a newly defined ore reserve. To be considered Best Practice, the answer to every question should be yes. Many will be surprised by this. Get used to it. The future is now.

1. Does the comminution design method have a track record of always meeting the specified tonnage design criteria in the Feasibility Study - and will the plant be capable of achieving design production on day 1 without modification to the grinding equipment?
2. Is the comminution circuit designed on the 80^{th} percentile of hardness variability measurements in the client's own ore body? Do not introduce other factors, such as comparisons with other nearby and similar ore bodies, or similar sized SAG mills treating similar ores as has been done in the past.
3. Will the grinding tests done use a method that allows kriging of the hardness values into the mine plan for the ore, and is drill core used for the grinding tests? There are big advantages for predicting future tonnage when design hardness values can be kriged into the mine plan.
4. Will the comminution circuit be capable of easy, low-cost expansion if the ore reserves and the plant capacity are increased? Very large capital savings can be gained if this concept is understood.
5. Can pilot plant beneficiation be done using diamond drill core as feed for the pilot plant? This is important for deposits that will be mined by underground methods. It can now be done.
6. Is the goal of the metallurgical testing to find the process that yields the highest recovery of the valuable metals contained in the deposit, based on pilot plant testing of SAG ground ore? It is important that the water chemistry that is developed in a SAG mill be tested at the pilot plant process testing stage.
7. Has high confidence flotation testing been chosen as the design tool if flotation is being used to concentrate mineral values?
8. For flotation plants, will the comminution circuit selected be capable of running at steady tonnage? There is a penalty to be paid for instability, if constant design tonnage has not been considered for a flotation plant.

FACTS TO BE CONSIDERED

In this section, some relevant historical information is introduced as guidance for new plant design and establishing what has been achieved in the area of Best Practice Comminution.

1. When the author ran the 5.5 ft (168 cm) diameter Nordberg Pilot Plant SAG mill for Art MacPherson's new SAG mill design projects in 1964-1965, the standard loading was "2 inches (51 mm) below the lip of the feed trunnion", or 26% load (Rexnord, 1976). It was known then to be the best and proper load at which to run a SAG mill and this has not changed. The Nordberg Pilot SAG mill had a fixed speed drive and ran at 75% of critical speed. This has also not changed as being the best speed at which to run a SAG mill (Rexnord, 1976).
2. The Kidd Creek Concentrator was a start-up (1966) to be emulated because of what was achieved. It was not a SAG plant. It had primary crushers at the mine, and secondary and tertiary crushers at the mill site. For grinding it used rod mills, and primary, secondary and tertiary ball mills to reach the

secondary copper flotation size P_{80} of 44 µm, and two regrind mills per circuit for copper and zinc flotation middlings, respectively. On start-up, Line A, treating copper zinc ore, produced design tonnage on the first shift, made saleable concentrates of copper and zinc on the first shift, and did not shut down for 30 days. This proves design tonnage from day 1 is possible and should be the design objective for every plant, including those plants using SAG mills. This can be done if the designer knows how to do it, by correctly sizing the SAG mill and motors to drive it.

3. The McNulty curves were developed based on the analysis of the start-up performance of 41 plants, including concentrators, chemical plants, smelters and hydrometallurgical plants (McNulty, 1998). Plant start-up performance (percent of design capacity achieved vs months of commissioning) was grouped into four performance categories (Series 1-4), and the performance of the categorized plants was correlated with the level of technology maturity, the size of the plant relative to its predecessors, the degree of pilot testing completed, and the quality of the engineering design. Series 1 projects, characterized by the use of mature technology, equipment of a similar size and duty to that used in previously successful projects, thorough pilot testing of any potentially risky unit operations (SAG mills were specifically mentioned), and a complete and professional job of the engineering design, were noted to achieve above 90% production capacity after 6 months. McNulty's analysis has often been incorrectly interpreted to suggest that it is acceptable to underproduce for up to 6 months in a new SAG plant. But the brutal mistake is that the McNulty curves apply to the whole plant, including the mine, and if the SAG mill is not capable of producing the design tonnage every day starting on day 1, the rest of the plant cannot be properly commissioned. This can only happen when the grinding chamber is correctly sized and the proper motor power is provided. It should be noted that McNulty Series 2-4 plants never achieved 100% of the design capacity. The purpose of McNulty's analysis was to show the value of complete and professional engineering design, and the adequate pilot testing of new technologies and/or flowsheet configurations. (McNulty, 1998).
4. Good engineering ethics are part of Best Practice Comminution. A SAG mill must be designed using ore samples from the owner's own mine. Simulations relating production and mill sizing decisions to other 'similar' properties, may have been practical before SAG mill hardness could be measured accurately in kWh/t, but the successful development and measurement of required SAG energy in kWh/t to achieve a defined grind and capacity, has rendered simulation without adequate hardness measurement obsolete for the purpose of SAG mill design, in the author's opinion. Common sense and best practice show that measuring a client's own ore is the best way to design a SAG mill.
5. Recent project execution practice, and previous Starkey co-authored publications, confirm that some senior designers want to check the sizing of new SAG mill A against the size of SAG mill B, across the road from plant A, and SAG mill C 10 km away because it had similar hardness measurements compared to ore body A. Unfortunately, this practice allows downward step changes to be propagated into the design system, because if mills B and C were undersized, Mill A will also be undersized.
6. There is another powerful reason to upgrade mill design methods. Not everyone has access to the data required to do simulation design. Engineers in remote locations need to use fundamental first principles and data that is available to everyone, and which does not need to be regularly updated for completeness and best accuracy. To continue with simulation-based design means that mill

design is restricted to the elite, and so it is good for the organizations who can do the simulations, but not for the entire industry. Engineers in every plant in the world need to be empowered to do mill design work on the day they need it done. This is a matter of equity.

7. Best practice ore hardness measurement requires measuring the SAG hardness to grind the ore from a feed size F_{80} of 152 mm to a transfer size T_{80} of 1.7 mm, using the most accurate test available, in kWh/t and measuring the Bond Ball Mill Work Index on SAG ground ore. These measurements harmonize well with SAB grinding circuits which use a transfer size T_{80} in the range of 1 mm to 3 mm. Using this approach, the design SAG energy to grind to the target T_{80}, is calculated by adjusting the measured SAG energy to 1.7 mm P_{80}, using the Bond Ball Mill Work Index on SAG ground ore for the adjustment.
8. From 1977 to 1989, the author worked for Kilborn Limited and was responsible for flowsheet selection, and equipment design and purchase on many projects. Engineering practice in those days for the comminution circuit in a new plant included lessons that have been discarded with the advent of SAG milling. In those days, 3 stages of crushing, and rod and ball mill grinding, were common in comminution flowsheets. Bond's Rod Mill Work Index (RM Wi) and Ball Mill Work Index (BM Wi) tests provided good designs for grinding mills. If the design was 1,200 t/d, each stage had to be able to produce 1,200 t/d or (54 t/h at 92.6% availability). There was a further obligation, not stated, that the new grinding circuit must be able to process more than the target t/h. This was the way to ensure that stage bottlenecks would not cause under-budget performance.
9. Today in SAG mill design, it has become apparent that instead of creating a little extra capacity in each successive stage, resulting in the possibility of ~10% extra production, that tight sizing and under capacity in the SAG mill of about 15% are now somehow okay with some designers. Starkey does note that best practice includes acceptance of the fact that over capacity is an asset while under capacity is a disaster. It makes a lot of sense to be in the former mode rather than the latter. That is Best Practice Comminution, because when a SAG mill is too big (say 10%) the amount of SAG steel used can be reduced, along with operating costs, so the extra size of mill is partly paid for by the reduced operating cost. A common misconception is that a SAG mill cannot be expected to produce more than 85% of design capacity on an annual basis. This is nonsense. The real value of extra size has not yet been evaluated, but will be the focus of future university research.
10. A consulting project was done to find the problem in a large SAG operation in the province of Quebec. The situation was tricky in that pre-crushing had been added and the SAG mill, which was longer than normal (D/L < 2), was not able to process the design tonnage. Studies of the DCS data were done to try and find what the problem was. In studying the data it appeared that the SAG mill speed control was part of the normal control strategy. Knowing that 75% of critical speed is often the best, Starkey isolated all the data involving a mill speed at 75% of critical. When that was done, the relationship between the other variables, including feed tonnage, percent solids in the SAG discharge, mill power draw and percent load in the mill were seen to move in an orderly and predictable way. The conclusion was that by varying the mill speed, the stability of the seasoned charge in the mill was altered in a way that took many hours to stabilize. Whenever the mill speed was changed, it overpowered all the other more quickly responding variables, leaving the SAG mill uncontrollable until the new speed-related variable had stabilized. Since this took many hours of operation, the controllability of the mill was lost whenever the speed was altered. Operating a SAG

mill at a fixed 75% critical speed corresponds to the operational strategy adhered to in the 1960's and 1970's.

11. Little has been said about the impact of under-sizing a SAG mill, on the operators who are trying to operate it, and on the management team that must instruct the operators what to do. Workplace stress is the only way to describe the situation. A first-hand view reveals some of the results. High turnover of middle management and senior operators. Never meeting production targets. Actual loss of more production while trying to achieve something that is not possible. No mid-morning coffee breaks where management can share a comfortable review of the last 24 hours of effort to achieve best performance possible. In short, job insecurity, lack of self-respect, and lack of motivation occur.

12. Wrapped up in all of this is the practice of Professional Engineering. An engineer, whose lawful duty it is to protect the financial interests of their client, is obliged to pick the right SAG mill. If the engineer does not know how to do that job, and vouch for the accuracy of the design, then they must recuse themselves from project decisions. Unless professional engineers step up to the plate to do their duty, mistakes will continue. There could be jobs lost because of this problem. But close scrutiny will show that a mine owner needs to either hire employees, or consultants, who know how to design a best practice SAG mill and include that size in the SAG mill request for quotation sent to the manufacturer.

INDICATORS OF GOOD SAG MILL PERFORMANCE

In consideration of the above items relating to Best Practice Comminution, the following techniques should be used to evaluate the actual physical and financial performance of a new process plant.

1. The capital estimate will be met at start-up and injection of additional cash investment to achieve design capacity will not be needed.
2. Operating costs will be as predicted, or lower than predicted, in the Feasibility Study. If pre-crushing must be added later, more capital is needed, and high operating costs become a burden for the entire life of the mine. If pre-crushing needs to be added to a plant, the operating cost will likely rise as well.
3. Feasibility study design tonnage will be produced every day. This allows monthly production targets to be met by only needing to control the grade of ore mined, without adjusting the cut-off grade. Cut off grade changes affect the size of the deposit and so are not helpful in a new start-up.
4. Annual tonnes produced during the year will be equal to, or greater than, that shown in the Feasibility Study. Failure to meet annual production budgets greatly compromises the Mine Manager's ability to get head office support for in-house improvement projects.
5. Fineness of grind in comminution, going to a beneficiation plant, will be at the liberation size chosen based on measured liberation and experimental pilot plant confirmation test work.
6. The environment in the control room will be comfortable. Excellent performance days, when production targets are exceeded, will be celebrated. Management goals will be met, resulting in feelings of self-respect and positivity for all employees associated with the operation of the SAG mill.

THE ROLE OF T_{80} IN SAG MILL DESIGN AND OPERATION

Many SAG grinding circuits are built today where the SAG and ball mill discharges are mixed in the same pump box, feeding the final grind classification cyclones. Many times, the SAG mill discharge passes though a trommel or a horizontal vibrating screen with 12.7 mm slotted openings which allow coarse hard scats to be passed from the SAG mill to the ball mill for further grinding. That this may be right on the edge of being too coarse for efficient ball milling is true, but common use shows that this approach is not a serious problem per se.

One problem with this configuration is that this design does not permit sampling of the SAG mill discharge to see what is actually going on in the SAG mill. This can only be determined by looking at a sample of the SAG mill discharge leaving the SAG mill trommel as undersize. If it is too coarse for efficient ball mill grinding, the problem can go undetected for many months. If the mills are tightly sized this could be the difference between making production targets or failing to do so. Fast optimization of the SAG mill demands that a measured T_{80} for the SAG mill discharge product be available within 24 hours of taking the sample.

Best practice design methods will allow any reasonable transfer size to be used in a SAG mill circuit plant design from 0.1 to 3.35 mm. There are many reasons why this is an asset for a project. It will now be shown, by means of an example, what the scope of alternate designs look like for a typical ore.

This is important because sometimes there are existing ball mills remaining from the brownfield expansion project, and sometimes there is valuable preowned equipment available that would be perfect in the new flowsheet. These examples, (summarized in Table 1), show the scope and variability that can be used with confidence in selecting mills for a new grinding application. This knowledge opens the door to what can be possible in a new project. It is not necessary to only use a configuration that someone else has already used. Modern up-to-date mill selection can use creativity and new initiative to design a plant that will best match the ore body being mined, and within the budget of the client who needs to buy the equipment.

In this example the SAGDesign (SDT) ore hardness is 10 kWh/t (to grind the ore from F_{80} 152 mm to T_{80} 1.7 mm) and the SAG ground Bond Ball Mill Work Index is 15 kWh/t. Table 2 shows alternate equipment selections that will produce 471 t/h, (10,400 t/d and 3.8 million tonnes per annum) at 92% availability. This Table is based on normal design parameters which need to be included in the selection of SAG and ball mills and the drive motors for each mill. For good SAG operation, the SAG mill D/L ratio should not be less than 2 in normal circumstances. Similarly, the ball mill L/D ratio should not exceed 1.65.

Each of the SAG/ball mill pairs shown in the various cases in the Table 1 example, will do the required grinding job and produce the specified tonnage of 471 t/h at a finished grind of 80% passing 75 microns. As in any trade-off study, there are also reasons to favour one configuration over another.

TABLE 1 – CIRCUIT DESIGN EXAMPLE - EFFECT OF T_{80} ON SAG AND BALL MILL SIZE

Case	Mill Type	Diameter (ft)	Effective Grinding Length EGL (ft)	RPM at 75% Critical	Mill Motor Power (MW)	Circuit Motor Power (MW)	T_{80} (µm)	Remarks
1	SAG	36	17.8	9.6	14.9	14.9	75	5 mm Screen + Cyclones
2	SAG	36	14.0	9.6	11.7	14.1	150	5 mm Screen + Cyclones
	Ball	15	24.2	15.1	2.4		75	Very fine T_{80}, Large SAG
3	SAG	34	14.5	9.9	10.5	13.7	212	5 mm Screen + Cyclones
	Ball	16.5	25.7	13.7	3.2		75	Fine T_{80}, Large SAG
4	SAG	32	13.9	10.2	8.6	13.1	425	1.3 mm Screen + Cyclones
	Ball	18	28.9	13.1	4.5		75	Good Choice fo SAG
5	SAG	30	13.8	10.6	7.2	12.6	850	2.5 mm Screen
	Ball	20	26.1	13.0	5.4		75	Normal Best Choice
6	SAG	30	12.0	10.6	6.3	12.3	1700	5 mm Screen
	Ball	20	29.4	13.0	6.0		75	Good Choice
7	SAG	28	12.7	11.0	5.6	12.1	3400	10 mm Screen
	Ball	20	31.6	13.0	6.5		75	Smallest SAG

Normal best practice is to select Case 5. Cases 4 and 6 are also good choices, because both of these options use 30 or 32 ft diameter SAG mills, and also use coarse vibrating screens to separate the fine fraction (screen undersize) for further grinding in a ball mill. 32 ft diameter SAG mills are desirable as they are commonly available, having been selected for many key plants with twin pinion synchronous drives.

Case 7 would probably only be selected if a 28 ft diameter SAG mill was available with a short delivery period. For this case, the ball mill feed size of minus 10 mm is at the limit allowed for grinding in a ball mill without a coarse feed factor penalty, to ball mill power. Without this correction, tonnage (t/h) would be lost.

Similarly, Cases 2, 3 and 4 would probably not be selected except to use existing and available SAG mills. SAG mills consume higher power than the ball mills for these options and so the total power cost will be higher than if a smaller SAG mill were to be selected.

Case 1 (single-stage SAG milling) is the least commonly selected of the cases shown. An example is Lake Shore Mine, in Timmins, Canada, which used a converted ball mill as a single-stage SAG mill to grind the ore from a feed F_{80} of 152 mm to a final cyclone overflow product P_{80} of 75 µm, the liberation size recommended for downstream separation. The single stage grinding option should be evaluated for every new project where the target grind is 75 µm or higher because this choice is likely to be the lowest capital cost and the lowest operating cost. Furthermore, if a short SAG mill D/L = 2 or greater is chosen, the tonnage can be doubled by simply adding a ball mill. If this expansion is planned from day 1, the ore bins, chutes and conveyors may not require modification to handle the increased tonnage. This represents a large bonus for the owner if an expansion is needed early in the mine life following initial cash flow generation. However, if the SAG mill is too long, this simple expansion strategy will not work, as the long SAG retention time will always produce a fine grind.

Case 1, in Table 1, is an example for providing for this expansion at start-up. The SAG mill has a D/L ratio just over 2 and so is eligible to be upgraded by making a coarser grind and adding a ball mill to do the incremental grinding required in addition to the design power provision. The Lake Shore example was a long SAG mill and cannot be easily expanded but, at this plant, the goal was to get into expansion quickly and a large unused ball mill was available to meet the quick start-up requirement after the addition of grates to convert it to a SAG mill.

It is important to note that SAG mills of any D/L ratio, from short to square to long can be run as a single stage SAG mill to do the size reduction that is required for good liberation. In fact, a SAG mill is the most versatile and forgiving class of equipment that is available in the mill comminution equipment class. As far as is known today, the provision of the required power and the chamber size to draw that power, will give the required production, regardless of the dimensions selected, within reason of course. These limiting dimensions will be discussed below.

There is another fundamental mill design property that perhaps is not well known, and that is the Starkey B Factor or SAG mill loading factor. The Starkey equations, described in a conference paper presented by Starkey & Associates Inc. and entitled "Sizing SAG Mills Using Nordberg Data, With Starkey Load Factor", to calculate the power draw at any mill diameter, are valid (Boucher et al., 2021). The original Nordberg ball mill table for the A factor, which is related to the mill diameter, started at 8 ft inside the liners and went up to 20 ft., probably because that was the largest diameter of ball mill used at that time in the 1970's when the information was published by Nordberg (Rexnord, 1976). Starkey extended those ball mill sizes down to 1.6 ft. and up to 40 ft. by extrapolation of the existing factors (Boucher et al., 2021). It has been found by benchmarking, that the A factor extrapolation is valid at 40 ft diameter and at 1.6 ft in diameter, the latter is the internal size of the Starkey SAGDesign test SAG mill. The A factor equation, $W = f(D^{2.5})$ has also been found to be valid for all sizes from 1.6 to 40 ft in diameter. The other equations for loading and speed are similarly relevant to all diameters studied. While not necessary to calculate required power in a SAG mill or ball mill, this information is very relevant to choosing the correct size of SAG mill to deliver the required power to the tumbling charge in a SAG mill. Per force, this information is part of using best practice engineering to design a SAG mill that will work as intended.

BEST PRACTICE OPERATION

SAG mill grinding has proven over the years to be an attractive and preferred technology and highly effective for grinding ore in a concentrator. It is perhaps the only technology that works on every ore to which it is applied; there is no ore in the world that cannot be ground using a SAG mill. While water shortage on a mine site, or extreme hardness up to 30 kWh/t just to reduce the particle size from F_{80} 152 mm to a P_{80} of 1.7 mm, may make it more economically attractive to use another approach for the final plant design, SAG milling, and where possible single stage SAG milling, must always be considered as one option for a new design, until something else is proven to give better economic return.

Achieving best practice comminution requires a basic understanding of what is normal and what is not with respect to SAG mill operation. Certain rules need to be applied to new mill designs to ensure they will work. The following points, if implemented during the design stage, will avoid some of the problems that have been observed in Canada and other countries in recent years.

1. Rules for sizing grinding chambers are very different for soft ores needing less than 5 kWh/t, and hard ores, requiring more than 15 kWh/t, to reduce the size of primary crushed feed from F_{80} 152 mm to T_{80} 1.7 mm. In addition, liberation size plays a key role in deciding whether a long or a short mill is required. A difficult case is a soft ore with a coarse liberation (or target) size. Experience shows that making a coarse grind on a soft ore in a long mill will not work as smoothly as desired, and maybe not at all. A long mill has a long path for the ore to flow through the entire length of the mill. Careful thought is needed to decide if the D/L (Diameter/Effective Grinding Length) limit should be reduced below 2 for the SAG mill under design in this case.

2. Limiting the D/L to a minimum value of 2. An expert SAG mill designer should be consulted before this minimum D/L is further reduced. Some of the easiest SAG mills to operate, and work horses of the industry which perform very well on any ore, are the sizes where the D/L is about 2.5 or greater, such as the 22' diameter x 8' EGL SAG mill selected for the Red Dog and Voisey's Bay operations. Another common size is the 32' Diameter x 13.5' EGL AG mills that were installed at Carol Lake and Mount Wright, and at Clarabelle, all in Canada, and at SarCheshmeh in Iran and many other plants, as SAG mills.

3. When single-stage SAG milling is used and the grind target is finer than 100% passing 100 mesh (149 µm), practically any dimensions for a SAG mill will work because high flow from the cyclone underflow ensures that the retention time for slurry in the mill will be low, and the transport velocity very fast. But as the final product size increases over 500 µm, as occurs in iron ore concentrators in the Labrador Trough (Canada) for example, a short mill with D/L = 2 or greater, will work better than a longer SAG mill.

4. AG and SAG mills use very different grinding mechanisms to grind the ore. In an AG mill the grinding is mostly done by abrasion, so it is nearly impossible to make a product size other than about 80% passing 500 µm, plus or minus 250 µm. Additionally, an AG mill shell should always be purchased for 15% steel, not 5%.

5. SAG milling however, when run at 26% load and 75% critical speed, produces maximum impact breakage and in general, a coarser product as the steel ball load in increased. A fact not usually recognized is that the MacPherson test using an air swept mill, normally runs a load of ~ 45% of mill volume. This is why every MacPherson test gives rounded pebbles and calls for a pebble crusher to be used in a plant.

PILOT PLANT TESTING OF UNDERGROUND ORES

Since the start of SAG milling about 70 years ago, it has not been feasible to do pilot plant SAG grinding and beneficiation testwork on unexploited ore deposits because it was virtually impossible, considering cost and accessibility to the ore, to mine up to 50 tonnes of minus 152 mm feed to run pilot plant tests in a 5.5 ft or 6 ft diameter pilot SAG mill. The feed rate to such mills ranges up to about 1 tonne per hour and a 1-week test easily requires 40 tonnes or more of sample. Since a representative sample of underground ore is the only ore a SAG mill will never see, it is pointless to try to do 6 ft diameter SAG mill pilot plant tests on unexploited deposit. The East Kemptville example proves that to be the case.

At East Kemptville Tin in 1980, a ‘proper’ effort was made to do SAG mill pilot testing with a sample from deep in the ore body. An adit was driven, and a portion of each blasted round was placed into a bin as a sample. About 45 tonnes was set aside for pilot testing at Lakefield Research in a 6’ diameter Cascade pilot SAG mill. Because the project was fast tracked, pilot plant results were not presented to the engineering company until one month prior to the issue of the Feasibility Study. This study was completed using the information from testing with two rod mills and a grate discharge ball mill to grind the ore. Not only was the SAG pilot result too late to be used in the design of the plant but it was later discovered after mining about 19 million tonnes of ore, that the ore quality at the horizon of the adit was very different to the ore above and below that horizon. The lesson learned was the design of a SAG mill must include a detailed knowledge of the hardness variability for the ore body. Having engineered Rio Algom’s design of the process plant, the author realized that many small-scale hardness tests would be the only way to properly measure the ore hardness variability in a deposit and to design a SAG mill to properly match and process this deposit.

The pilot plant metallurgical evaluation of a new ore deposit has been accepted for more than 100 years as the best approach to find out what flowsheet is best to concentrate the ore and what chemistry is developed in the comminution circuit so it can be evaluated for the downstream performance of the concentrator. When flotation is used as the main beneficiation method, it is imperative that the flotation response to SAG ground ore be tested, including the type of ball charge. Since SAG milling started, underground mines could not do economical pilot testing. The result is that many plants were built with the only pilot testing completed on minus 2 mm crushed ore. Ball milling was as close to plant operation as could be done for a new plant. However, it could not show what flotation performance of a SAG ground ore would look like.

The introduction of the SAGDesign test (which includes a Bond Ball Mill Work Index test on SAG ground ore) in 2004, for measuring ore hardness, has been successful in creating the most accurate test in the world for SAG mill design. It is now true that a laboratory scale test has replaced pilot plant SAG mill testing as the best way to determine the size of a required commercial SAG mill. However, the need to grind ore continuously in a SAG mill is still required to do meaningful beneficiation testing of flotation processes so that the pulp chemistry created in SAG grinding in a plant can be tested at pilot plant scale. This helps to prove what recovery can be achieved by duplicating the commercial flotation process at an affordable pilot scale.

With the completed development of the continuous laboratory scale Starkey Mini Pilot SAG Mill (MPSM), at the end of 2019, and its sale to the University of Toronto Mineral Processing Group, the possibility to use core from regular exploration for pilot plant testing is now possible. The breakthrough idea that has allowed this to become a reality was presented at the 2019 SAG Conference in Vancouver. The graph that shows this is now a possibility is reproduced here as Figure 1.

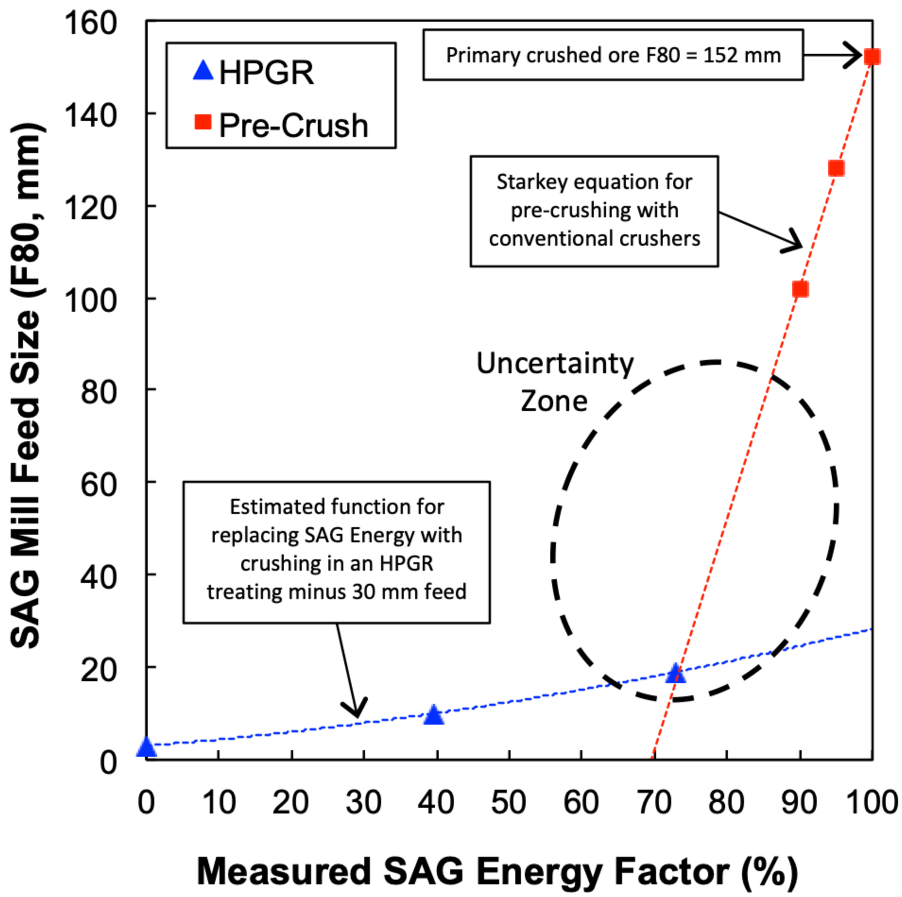

Figure 1 – Factor for measured SAG energy to grind from F_{80} 152 mm to T_{80} 1.7 mm as a function of pre-crushed Feed size (F_{80}), (Starkey et al. 2019).

It was not realized at the time this graph was first published in 2019, that the SAGDesign test feed lies (almost) on the extreme right of the graph, describing energy reduction as a function of pre-crush size. Since we already have proved beyond doubt with benchmark testing on commercial plants, that SAGDesign results can be extrapolated to any commercial size of mill treating ore crushed to F_{80} 152 mm, it is assumed that pilot plant testing of feed 80 % passing 19 mm (100 % passing 25.4 mm) should give representative results. The new Starkey Mini Pilot SAG Mill has the same grinding chamber dimensions as the laboratory SAGDesign test mill which has treated the same size standard drill core and which has been used successfully to size commercial SAG mills for the last 17 years. It is predicted that the MPSM will grind approximately 10 kg/h of ore on average hardness ore.

Everything is now in place to do the required experimental research demonstrating the advantages of using the Mini Pilot SAG Mill to develop a full process plant flowsheet for the comminution and beneficiation of a new underground or open pit ore body, at a reasonable cost.

A PATH FORWARD

This paper is only a first step in achieving what the mining industry in Canada, represented by CIM (Canadian Institute of Mining, Metallurgy and Petroleum) and PEO (Professional Engineers Ontario) in Ontario, must do to restore confidence in the way mining projects are designed and built.

An industry decision was made many years ago, to offer research funding and support through the JKMRC in Australia, to fund research projects that were aimed at optimizing the performance of AG and SAG mill grinding plants to produce better results from existing grinding plants. Funding in the millions of dollars was made available through industry support in paying for well organized research programs. This work was very successful and has been used by major mining companies to add great value to existing operations by using results from the Drop Weight Tester to measure ore hardness as a parameter A x b.

The astonishing part of this story is that with the successful invention of power-based measurements to determine the kWh/t required to grind an ore, first presented at the 1996 SAG conference in Vancouver as the SAG Power Index Test, it was realized that the JK SimMet software optimization program was locked into a system where the measured operating parameters of existing mills were needed to fully use the optimization program. In a classic statement by a senior Barrick executive after presenting a talk at CMP Toronto meeting about 8 years ago, where optimization of 23 plants were shown to have created enormous additional values for Barrick, the audience was told that the presenter "Would never use the same (optimization) program to design new SAG mills". The missing parameters did not allow that to be done. A second problem was that the JK SimMet software did not require a transfer size as input. Therefore, all the value that T_{80} control could add, is missing from that approach.

To date power-based measurement of required SAG energy has been focussed on empirical results. Is it not time to do the research work necessary to connect what works in practice with existing software, which has cost millions to develop? This is not a project for one person to sort out. A consortium of talented people and industry funding is needed.

As the one person who invented both the SPI and SAGDesign tests, Starkey recommends that industry spend the required research money to sort out the obvious shortcomings in existing ways that SAG mills are designed. Combining the SAGDesign test results with computer software optimization would support the accuracy of what is already available and allow everyone to participate in upgrading a broken system.

We have watched as governments spend freely to make sure every citizen is able to participate in a COVID-19 free economy. Bond created a marvelous system when he taught the whole industry how to design ball mills by publishing his work. Why cannot we do the same for SAG mills if for no other reason than to prove we are interested in making the Canadian Mining industry the world's best - and that we are really looking after the financial health of our clients. After all, that is our duty and there is still work to do.

ACKNOWLEDGEMENTS

Two significant developments need to be mentioned in this paper to acknowledge, and to show what plans have been made, to ensure how the transition and communication of these ideas to future generations of mineral process design engineers will occur.

The first is the undertaking by the Universities of Toronto, and Alberta, under the guidance of Professor Erin Bobicki, to teach the methods described in this paper to the next generation of mineral process engineers. Without this support, the claim to know what best practice comminution looks like would be presumptuous, because the path to understanding and acceptance of a technology needs to be supported by research and teaching of relevant, reliable information to students. Professor Bobicki has undertaken to do both of these things. First by purchasing for the two universities, the laboratory SAGDesign test mills for both locations and next, by requesting the design for, and then purchasing, the world's first Continuous Laboratory Scale Semi Autogenous Grinding (SAG) Mill (aka the Starkey Mini Pilot SAG Mill). As a result, the next generation of students will have the opportunity to study and further develop best practice, which will be of great benefit for the Mining industry, in Canada and world-wide.

The second development is the participation of Arkady Senchenko, General Manager and co-owner of Institute TOMS in Irkutsk, Russia, in the use of the patented SAGDesign technology, to measure ore hardness and to design SAG mills that do what they are supposed to do. Even before Institute TOMS purchased the second Starkey SAGDesign Laboratory SAG Mill ever made in 2006, Starkey and Senchenko had agreed that Starkey would teach TOMS how to design SAG mills using the patented technology. From the beginning, Senchenko has done the basic mill design work, under the guidance of Starkey and his team of engineers. Now, fifteen years later, it is acknowledged by John Starkey that Arkady Senchenko and the team of engineers of Institute TOMS, are fully qualified SAGDesign Engineers and leaders in the field of SAG mill design and operation for mining projects.

Lastly, the author wishes to acknowledge the support of Dawson Metallurgical Laboratories in 2002 by co-creating the SAGDesign test procedure, and Outotec in 2004, by patenting the way the SAGDesign test results are used to design SAG mills. Those supporting activities were critical to the test being accepted as a valid way to design SAG mills in the early years of its introduction to the field of AG and SAG mill design. The author is also grateful that Outotec chose to sell the Patent back to Starkey in 2019 for due consideration. This acquisition by Starkey and the filing for a Patent on the newly invented Starkey Mini Pilot SAG Mill in 2020, has allowed consolidation under one roof, of all the SAG mill design and operating technology that has been developed by Starkey in the 21st century, under the name of SAGDesign testing.

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