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Impact on Grinding Mill Design of Recent New Discoveries

ABSTRACT

At the 2009 CIM conference in May 2009, previously unseen differences between macro and micro grindability relationships contained in the SAGDesign database were presented. This database included SAG and ball mill design energy measurements on many samples. These were compared with the extremes of SAG hardness variation from two recent projects. These extremes demand very different methods to design the SAG and ball mills needed for these ores respectively.

Based on those findings it is now evident that historic grindability measurements do only reveal the information that the tests were designed to reveal. Bond Rod Mill, Ball Mill, and Crushing Work Index tests have been massaged for years trying to find how to get a good SAG mill design from these (and other) measurements. These efforts have been partially successful, but not always.

Other researchers have used breakage parameters to develop SAG mill design data. These are not grinding tests but do give a good estimation of the relative point hardness in an ore body with respect to SAG hardness. These breakage tests do not include ball mill grinding data. Based on the 2009 CIM paper, the ratio of macro to micro grindability is an important key to achieving a reliable SAG mill design because that ratio reveals the best split for SAG and ball mill energy on that ore.

The reason why the SAGDesign test gives an acceptable grinding design result is now evident. It relates to the 19mm F80 of the ore charge fed to the SAGDesign test and to the test procedure which includes a Bond Ball Mill Work Index test on SAG ground ore from the first stage of the test. The ratio of SAG pinion energy to Bond BM Wi is a key parameter in a SAG mill grinding circuit design, because this ratio controls the power split between SAG and ball mills at the target T80 (transfer size).

INTRODUCTION

Recent major projects have identified that no two consulting firms will predict the same throughput in a chosen SAG mill even when they use the same breakage test data. Sometimes, different tests are used for mill design, which also provide conflicting results. These inconclusive results are unacceptable to the clients, and the professional organizations in the mining industry, that we serve. This paper will show how the new discoveries summarized here, have identified new grinding mill design procedures which will lead to meeting production schedules for every new project.

The CIM paper (Starkey and Samuels, 2009) was written to analyse the SAGDesign database and show the results from 5 years of SAGDesign™ testing. 232 tests on 35 different projects are included. Grinding mills were designed for each project, so every project in a sense, was a trial of how well the testing/calculation method suited the ore. The results showed that in all cases there were no problems in sizing the grinding mills, even for the hardest ores.

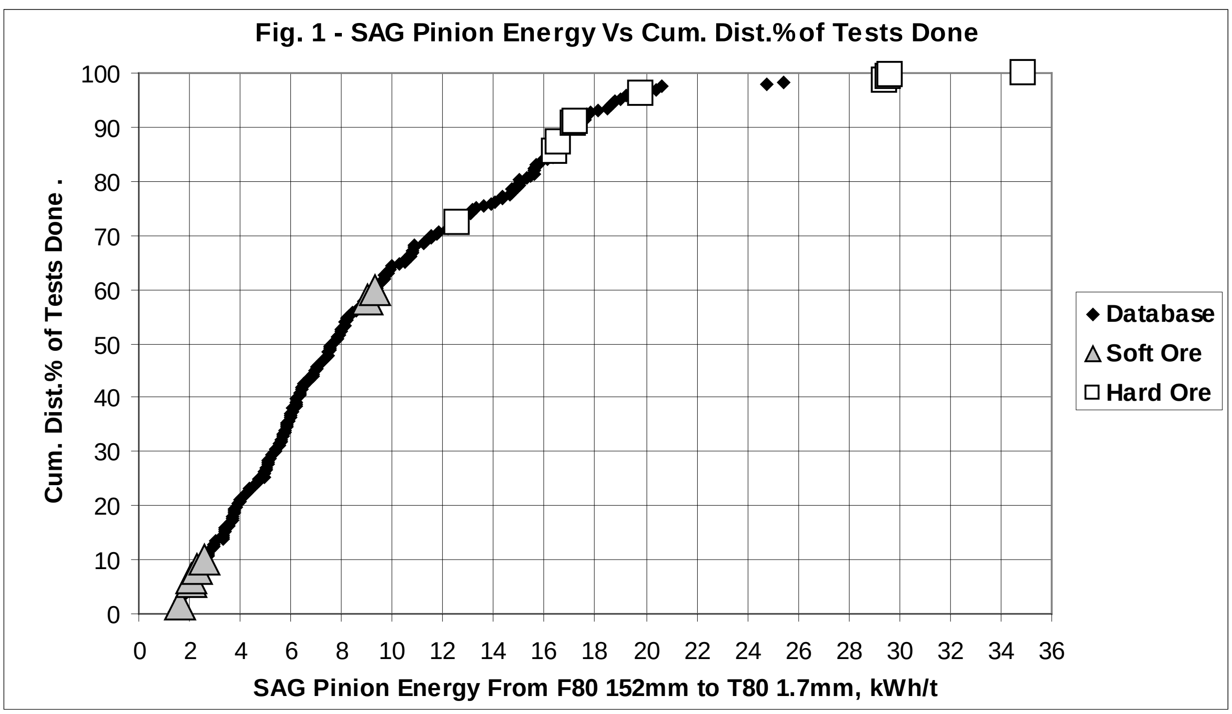
There are three key elements in a successful SAG mill grinding circuit design. First is the sampling because without proper samples no proper design can be achieved. Second, the tests done need to generate meaningful data. And third, the mill sizing procedure needs to be standardized to a point where the design calculations relate the empirical measurements made to the proper prediction of mill performance. Until every plant metallurgist understands how to do these calculations, mistakes will continue. Because SAGDesign technology is patented we are prepared to teach this method to our clients.

This paper was also written to show that in spite of the surprising new discoveries, the testing and analysis methods we use did not require change or adjustment. The SAGDesign test was conceived to measure the required design information on every sample. The calculation method was set up to use these measurements in a mathematically correct way to size the grinding mills required to grind the ore. This method does not require a computer program or a data base. It is based only results derived from testing the client's ore and the mill design is specific to that ore.

By using these methods, two large areas for mistakes have been avoided. First, the problem of designing for hardest ores has been eliminated because a SAGDesign test identifies SAG hardness up to over 30 kWh/t. Second, the use of calculation instead of simulation with other ores, has eliminated mistakes caused by comparing ores with different macro/micro hardness ratios. This is the biggest impact from this work because the hardness ratio has not been routinely measured before as a fundamental property that is crucial to achieve a good design. These standard measurements from SAGDesign testing are being viewed for the first time. It is therefore not surprising that the conclusions have not been noticed before.

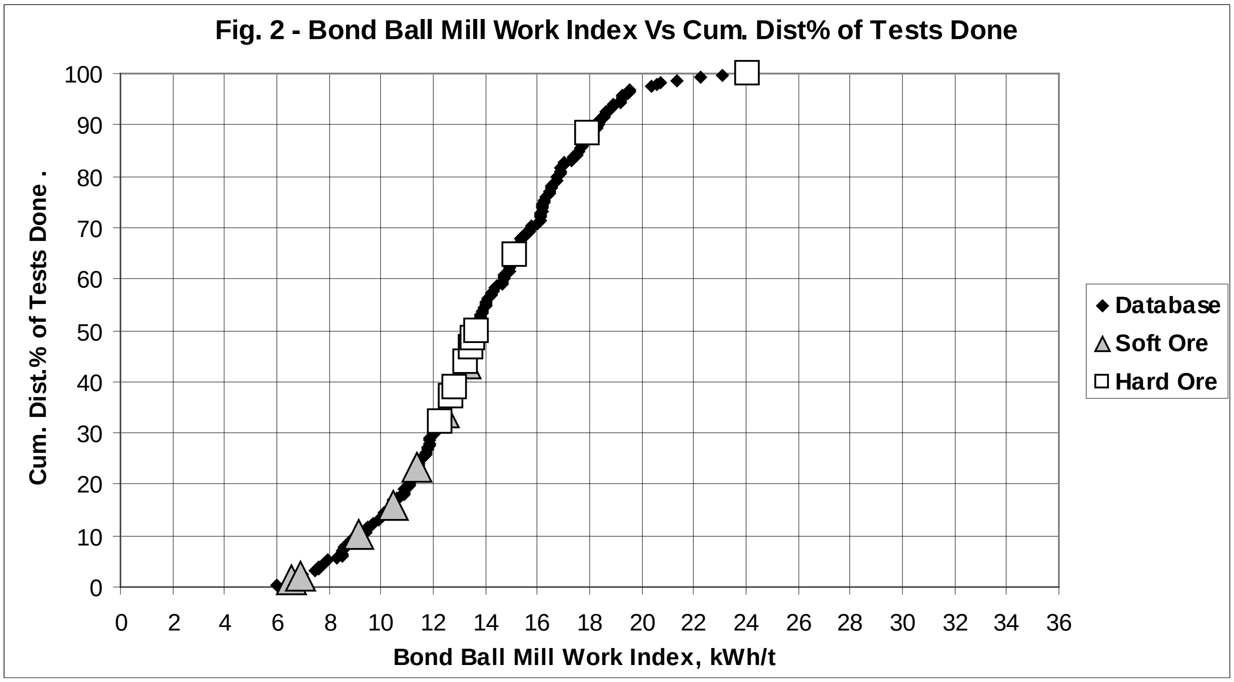
SAGDESIGN DATABASE

One standard way to present SAG hardness variability is to consider the SAG pinion energy (to grind to T80 1.7mm) plotted against the cumulative dist. % of the samples tested. Please see Figure 1 below.



These test results demonstrate several important things. There are many samples that are very soft to grind in a SAG mill, and second, there are ores that are harder to grind than any seen to date. The ability of the SAGDesign test to identify extremely hard ores is shown in this graph. No other SAG test has identified ore that is more than double the 80% percentile hardness. Another point is that hardness is random at the low energy end of the curve. Compared to Fig. 2, this is the difference between grinding in a heavy steel chamber and grinding in a semi-autogenous environment. The results are totally different.

The corresponding Bond Ball Mill Work Index data from the same tests is plotted in Figure 2.



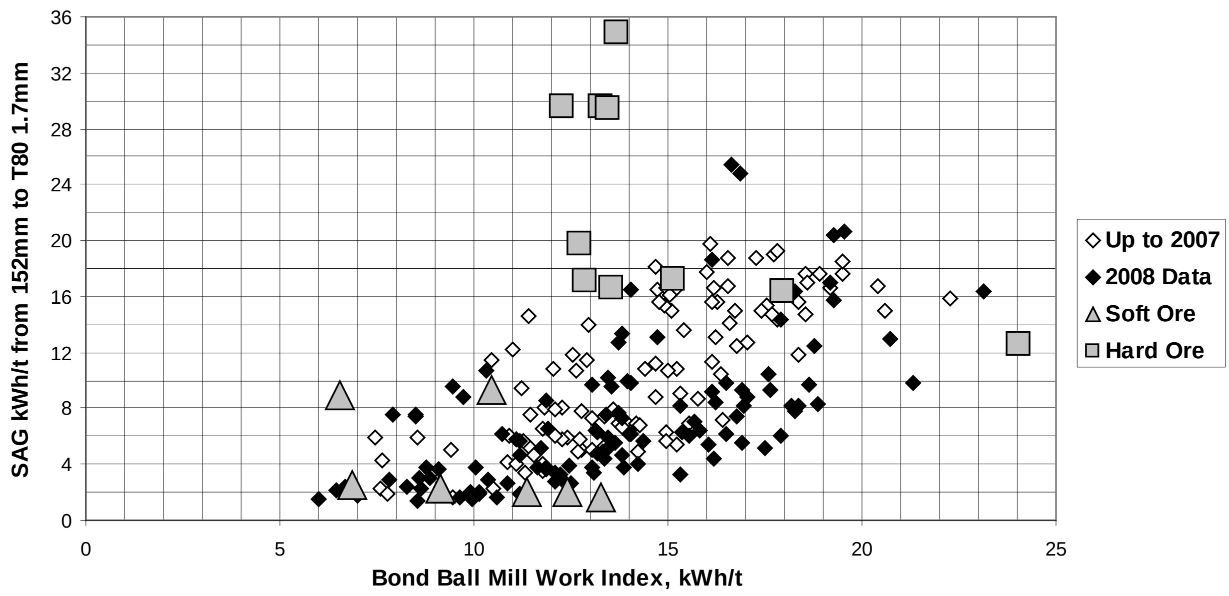
Here both the hard ore and the soft ore (in the SAG mill) overlapped other hardness ranges for the Bond BM Wi database. Because the shape of these curves are so different proves that the data generated for each sample can only be used in the context of both measurements together. When the Bond Rod Mill Work Index is used instead of the SAGDesign measurement, the Rod Mill Wi variability graph will look more like Figure 2 (McKen et al., 2006) than Figure 1 because the Rod Mill Wi test is done in an even heavier steel environment than the Ball Mill Wi test. This is why the Rod Mill Wi test should not be used for designing SAG mills. There are other reasons as well that are discussed below.

The graph of SAG pinion energy (to 1.7mm) Vs Bond BM Wi is given in Figure 3. Excluding the very soft and very hard projects, shows that the database in general does support a broad correlation between SAG and ball mill hardness but that the function is too ill-defined to be useful in sizing a SAG mill from a Bond BM Wi measurement. When the hard and soft ores are added, the correlation is invalid and it has therefore been concluded that a SAG mill cannot be designed from a Bond BM Wi result alone.

It is also seen from Figure 3 that for a constant Bond BM Wi, the SAG hardness can vary from 2 to 34 kWh/t. This new discovery is the reason to recommend that SAG hardness measurements cannot be used alone but only in conjunction with the corresponding Bond BM Wi (done on SAG ground ore as part of a SAGDesign test).

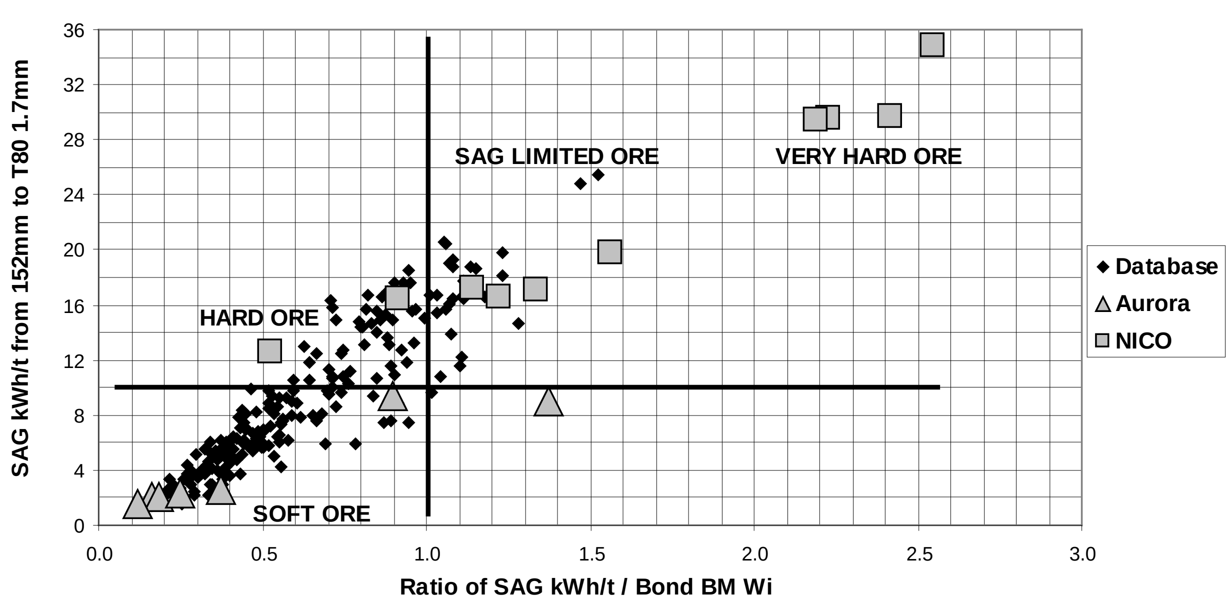
It can be seen from this work that simulation modeling that does not allow for the different ratio of SAG hardness to ball mill hardness cannot work on all ores. It will only work when the hardness ratio (SAG /ball mill) is the same in the new ore as that in the database. This perhaps explains why major companies are still struggling to understand why different simulations give different design results.

Fig. 3 - Database SAG and Bond Data by Year - Aurora and NICO Added



To emphasize this point, Figure 4 has been prepared. Here the SAGDesign database is presented differently with SAG kWh/t being plotted against the ratio of SAG kWh/t to Bond Ball Mill Wi. Looking at the data this way shows the extreme differences between ores at the same ball mill hardness.

Fig. 4 - SAG Pinion Energy Vs Ratio of SAG / Bond BM Wi, with NICO, Aurora

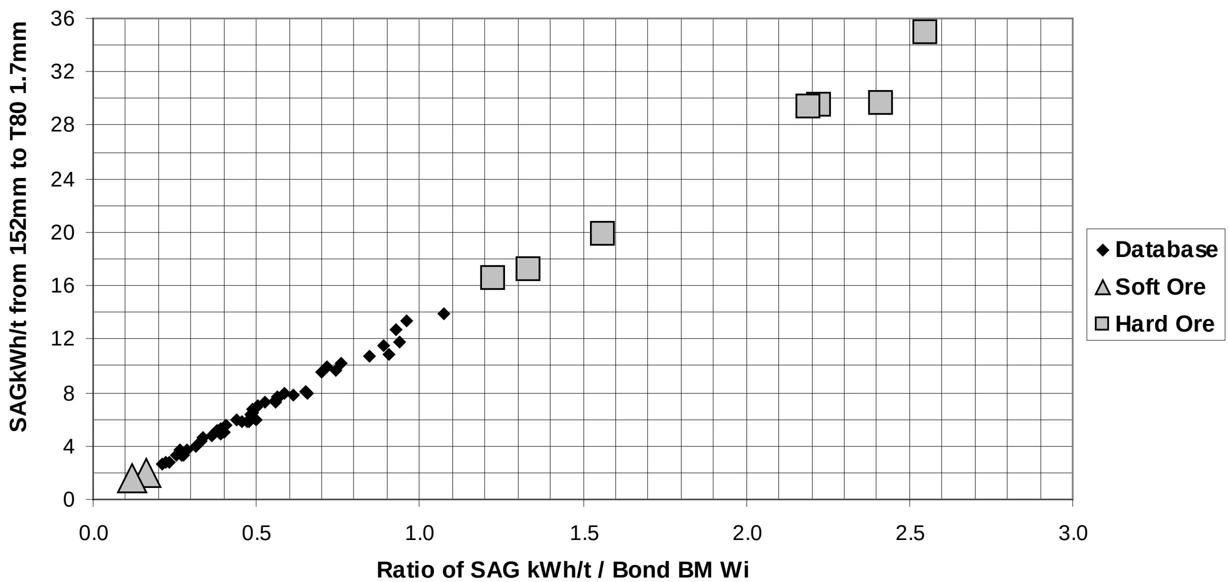


The division of this graph into 4 quadrants shows the main areas to be considered in design. 10 kWh/t for SAG grinding to 1.7mm, is considered the division line for hard and soft ores. Hardness ratios below 1.0 are also considered to be favorable to basic SAG milling. For ores with SAG kWh/t to Bond BM Wi ratios greater than 1.0, the ore is considered to be hard and SAG limited and pebble crushers should be used. Other more conventional methods should also be considered for ores in the top right hand quadrant.

NEW DISCOVERIES

The new discoveries are highlighted in the following graph which plots all samples from the database that had Bond BM Wi values between 12 and 14 kWh/t. The surprising observation was that samples from both the very hard and very soft projects appear on this plot. Clearly new methods are required to deal with this situation. The corollary is that SAG mills cannot be designed from a BM Wi value alone.

Fig. 5 - SAG kWh/t to 1.7mm Vs Bond BM Wi, 58 Samples with Bond Wi 12 - 14



The new discoveries therefore include the wide variance in SAG mill pinion energy from 2 to 34 kWh/t for constant measured Bond Wi values of ~13 kWh/t, and the need to use the ratio of SAG/ball mill hardness as a key factor in designing a SAG mill circuit. Of all methods in use today, SAGDesign technology is the only method that properly considers these factors in the design of new grinding mills.

It has taken 5 years to gather enough data to fully understand SAGDesign test performance on a variety of ores, but a clear picture is now emerging. Coupled with the success of every plant benchmark test done to date, we are now confident that we offer to clients a design procedure that will work for every ore encountered. This explains why Outotec, after doing their due diligence review in 2004, decided to patent the test and to guarantee throughput and grind for any mills designed by Starkey using SAGDesign technology, and supplied by Outotec. It is also obvious that any mill of similar dimensions and power supplied by a reputable supplier, will work just as well to accomplish the design criteria for the project. But the guarantee is provided only by Outotec. Hopefully, this will change in the future.

COMMINUTION TESTS

A brief summary of the most common comminution tests are listed below. First listed are the tests that do not use steel in a grinding mill environment. Their function in designing a SAG mill is briefly described. These tests are included to show enough information for readers to judge which tests are likely to give a useful and reliable result for SAG mill design. There are other tests available that are not included here.

- Bond Crushing Work Index Test, CWi, kWh/t. Used by some designers as one of the factors affecting SAG mill power.

- Abrasion Index Test, Ai. Measures wear in g/t. Not used directly in SAG mill design, only for liner wear and operating cost determination.
- JK Drop Weight Test, t_a, A and b parameters. These are used as inputs to the JK SIMMET program which predicts mill power by simulation and comparison with operating plants. Mill sizing is derived from these simulations. This method is usually good for ores up to ~15 kWh/t for SAG pinion energy but not above that because of a lack of operating data on hard ore. The SAG/ball mill hardness ratio is not considered as a prime input, so errors are possible.
- SMC Test or Drop Weight Index, DWi, A and b parameters. This is a smaller scale test to develop the same parameters as the Drop Weight Test. It is used to cut the sample weight required from 100 kg for the DWT to less than 20kg.
- JKRBT, A and b parameters. This is a highly automated rotary breakage tester that was developed to rapidly generate A and b parameters on a large number of samples by treating sized particles in a controlled environment.

The JKRBT is not considered as a rotating grinding mill because it develops breakage information similar to the Drop Weight Test and the SMC Test. It does not grind the ore, it breaks it piece by piece.

The following list includes rotary grinding tests that use steel balls. These mills simulate large scale operating mills and use similar steel loads, and dry ore as feed. They are considered to be more reliable for scaling up of the results.

Table 1 – Rotating Mill Grinding Tests Using Steel Balls

TEST	F80, mm	MILL SIZE	SAMPLE	REMARKS
Bond BM Wi, kWh/t	2	12" dia x 12"	10 kg	Constant volume, BM design
Bond RM Wi, kWh/t	10	8" dia x 20"	20 kg	Constant volume, RM design
SPI, Minutes	12.7	12" dia x 4"	5 kg	Constant wt. 2kg, scoping test
MacPherson AWi, kWh/t	19	18" dia x 6"	200kg	Continuous, air swept pilot scale
SAGDesign, kWh/t & kWh/t	19	19.2"dia x 6.4"	15 kg	Constant vol., SAG/BM design

Includes Bond BM Wi on SAG ground ore (as above).

The difference in hardness indicated by the Bond BM Wi test and the Bond RM Wi test was the first indication that there is a significant macro/micro grindability ratio for every ore. This has been known for 50 years and relates to hardness above and below 2mm. Both of the Bond tests are done in a high steel environment. For the Rod Mill Wi test this means that soft ores having a hardness of less than 5 kWh/t are rare because the steel demands a significant power input even for the softest ores.

The other fact of significance here is the F80 for the test concerned. There is a shift in hardness for many ores between macro and micro grinding done in a SAG and ball mill respectively. After noting that the Rod Mill Work Index test on the hardest ore tested did not pick up the SAG hardness of 29 kWh/t, (Starkey and Samuels, 2009) it is now realized that the 10 mm F80 for the Rod Mill Work Index tests is probably the reason because the Bond BM Wi was 12.7 kWh/t (at 2mm), the Rod Mill Wi was 19.7 kWh/t (at 10mm) and the SAG pinion energy was 29.6 kWh/t (at 19mm). Obviously the macro hardness is not measured properly in tests with feed sizes of 10mm or less.

This raises a whole new concept in that comminution tests do a good job determining the hardness in the comminution device for which the test was designed. To use a test for other purposes is an approximation at best and can lead to significant errors as noted above.

From Table 1 above one might conclude that the SAGDesign and MacPherson tests should give similar results. In practice however the SAGDesign test uses a 26% load and stops at 80% passing 1.7mm. The MacPherson test produces a much finer product with a P80 of about 0.4mm and the mill is often operated with as much as 45% load as determined from actual test reports. The results are therefore nearly impossible to correlate and the AWi value overlaps Bond in the range of 2mm to 0.4mm so the mode for interpreting the data is very different. Very few people know how to use the AWi because it is not a constant and is only valid at the transfer size generated in the test.

MILL SIZING CALCULATIONS

A typical SAGDesign calculation sheet is presented below. Shaded cells in Table 1 are the input numbers, taken from the testing program. Usually the 80th percentile is utilized as the design point for a project but he client, given the distribution data, can elect to use hardest ore, median ore or any other point that represents what the mine can deliver to the mill on a consistent basis. This table is presented to show the precision of the mill sizing calculations once the ore testing data is complete and analysed. By fixing the input values, the case report sheet can be copied. Other cases are then examined to look at balancing the power by changing the transfer size or making other adjustments that are appropriate to the ore body, the hardness distribution, the ratio of SAG to ball mill hardness and future expansion.

This is design by calculation not design by simulation. It is understandable and can be examined for accuracy by the client and/or the engineering company responsible for the work.

CASE 1 - No pebble crusher. Fixed rpm new SAG and ball mills. 80th% ore.

A - Calculation of Unit Pinion Energy for SAG Mill and Ball Mill ***Reduction for pebble crush*** ***0%***

Item	Units			80th%
SAG Mill to 12 mesh US Std.	kWh/t		***design SAG pinion energy***	**29.5**
Adjust SAG Energy to "T80"µ	**1700**	***SAGDesign test T80***		**0.0**
Total SAG Shell Energy	kWh/t			**29.5**
B Mill Pinion Energy to "P80" µ	**74**	***design P80***		**12.3**
SAGDesign Bond BM Wi	*kWh/t*		***design Bond Wi***	***13.4***
Total Grinding Energy	kWh/t			**41.8**
Design SAG Feed - mt/h	**215**	***design t/h***	***Measured Ratio, SAG/BM***	***2.2***

B - Calculation of Unit Motor Energy for Fixed speed SAG Mill and Ball Mill (Metered Energy)

Item	Factors		80th%
SAG Energy kWh/t * @	1.06	** SAG Motor - corrected for efficiency loss with synchronous motor & clutch*	**31.3**
BM Energy kWh/t ** @	1.06	*** BM Motor - corrected for efficiency loss with synchronous motor & clutch*	**13.0**
	0.88	*BM diameter correction factor - see Table F*	**11.4**

C - Calculation of Unit Motor Sizing for Fixed Speed SAG Mill and Ball Mill

Item	Factor***		80th%
SAG Motor kWh/t*@	1.10	*SAG Mill operating allowance factor*	**34.4**
BM Motor kWh/t**@	1.05	*Ball Mill operating allowance factor*	**12.0**
		Installed unit energy	**46.4**

*Note *** Includes for SAG operating margin and for ball mill operating margins.*

D - Motors Required for Fixed Speed SAG Mill and Ball Mill **215 t/h**

		80th%
SAG Mill Motor, kW		**7,394**
Ball Mill Motor, kW		**2,576**

E - Mill Dimensions, Motor Specification, Fixed Speed SAG Mill ***Adjust mill D & L to provide req'd kW***

Mill	Speed	Dia, Ft	A	B	C	EGL	Calculated Motor		Instal	Mill Dimensions	
	% Crit	(ID Shell)	ID - 0.5'	26% Load	75% Crit	Length	HP	kW	HP	Dia, ft	EGL, ft
	fixed			*10% steel*							
SAG Mill	75	32.00	986	4.17	0.1838	13.12	9,916	**7,394**	**10,000**	**32**	**13.1**
Ball Mill	75	16.00	167	5.02	0.1838	22.37	3,454	**2,576**	**3,500**	**16**	**22.4**

IMPACT OF NEW DISCOVERIES ON THE MINING INDUSTRY

The impact of these new discoveries on the mining industry is up to those charged with responsibility for designing the mills for the new large tonnage grinding circuits. Given that the cost of a single 40ft diameter SAG mill is now more than $55 million US, it is imperative that the design procedures used be carefully reviewed for accuracy, at the testing stage and at the mill sizing stage. Until the mill metallurgist understands how the results were obtained and calculated, to the point where he or she can design the mills, uncertainty will remain leading to disagreements and future throughput problems.

Careful coordination of the sampling with the mine plan is required. Meetings with the geologists and mine engineers are imperative because a SAG mill is chosen to match an ore body and the mill designer must understand the ore body in sufficient detail to properly design a SAG mill grinding circuit.

But the goal here is to resolve the disagreements in what tonnage a mill will produce, with solid technical expertise, accurate measurements and clear thinking. Sadly, these factors have escaped the grasp of many professionals who through no fault of their own have not had the experience required to deal with the complex problem of designing a SAG mill circuit for variable hardness ore. Given the new discoveries presented in this paper, a challenge is before us. Upgrade design procedures - and give our clients the quality of mill design that they expect and deserve. Throughput shortfalls are unacceptable.

CONCLUSIONS AND RECOMMENDATIONS

SAGDesign testing should be used for new large tonnage projects where failure to achieve design tonnage and grind will cause severe financial distress to the owner. SAGDesign testing is accurate, fast and affordable for any client, large or small, and invariably gives the best answer in the shortest time.

Grindability tests produce results that are valid for the purpose intended. Bond tests are excellent for designing rod mills, ball mills and crushers. SAGDesign tests are suitable for designing AG/SAG mills.

Rotating grinding mill tests are best for grinding hardness measurement because they duplicate the action of commercial grinding mills and the results can be scaled up.

Conventional impact breakage parameter measurement methods do not adequately deal with hard ores because this kind of test does not give a measure of required SAG pinion energy for hard ores, to achieve a stated size. There are also no operating mills to which the hard ore data can be compared.

The Bond BM Wi cannot be used alone to design a SAG mill. A proper measurement of SAG mill pinion energy is needed for good SAG mill design.

The ratio of SAG pinion energy to Bond BM Wi is helpful when selecting the SAG/ball mill power split for a new grinding circuit. We recommend that this ratio be included in the measurements needed for any new SAG/ball mill circuit design and used as a guide in deciding what power split will be chosen.

The shape of the database variability graphs is different for SAG mill pinion energy and Bond BM Wi. This shows that to achieve a good design, SAG mill data should be used with the corresponding ball mill data from the same samples. Other SAG tests that have a different variability distribution cannot replace the proper measurement of SAG pinion energy.

Previous assumptions that conclude that SAG kWh/t varies with Bond BM Wi kWh/t are correct for some ores, but the relationship is not accurate enough to use for SAG mill design purposes. In addition, there are exceptions noted in this paper which make this approach unworkable as a standard procedure.

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