IMPACT ON GRINDING MILL DESIGN OF RECENT NEW DISCOVERIES

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ABSTRACT

At the 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 different considerations to be used in the design of the SAG and ball mills needed for these ores. The term 'new discoveries', relates to the wide variation revealed by the new measurements.

Based on those findings it is now evident that historic grindability measurements only reveal the information that the tests were designed to reveal. Bond Rod Mill, Ball Mill, and Crushing Work Index tests have been studied for years to find how to get a good SAG mill design from these (and other) measurements. These efforts have been partially successful.

Other researchers have used breakage parameters to develop SAG mill design data. These are not rotary 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 (Starkey and Samuels, 2009), the ratio of SAG to ball mill grindability is an important factor in achieving a reliable SAG mill circuit design because that ratio reveals the best and most practical split for SAG and ball mill energy for the ore being tested.

The reason the SAGDesign test gives an acceptable grinding circuit design result for any ore relates to the 19mm F80 of the ore charge fed to the SAGDesign SAG mill 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 grind to T80 1.7mm) 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 design T80 (transfer size).

INTRODUCTION

Three recent major projects involving a review and testing by Starkey & Associates, have shown that consulting firms can predict different throughputs in a chosen SAG mill. In one case the same grinding test data was used. In two other cases, different tests were used for mill design, which also provided conflicting results. This paper will show how the new discoveries summarized here, have confirmed that the grinding mill design procedures developed by J. Starkey (JS) in 2004, that were introduced with the commercial use of SAGDesign testing, have worked for every new project. In the author's opinion these design procedures, and the use of results from SAGDesign testing, will lead to client's meeting production schedules for every new project, including those where the SAG hardness is 'off the charts' when compared to existing operations.

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 needed, even for the hardest ores.

There are three key elements in a successful SAG mill grinding circuit design. First is the sampling because proper samples are needed for a proper design. Second, the tests done need to generate meaningful data. And third, the mill sizing procedure should to be standardized to a point where the design calculations relate the empirical measurements made to the proper mill design or prediction of mill performance. Simplicity of sample preparation, total cost of the testwork, and the time required to do the tests are also important. Because SAGDesign technology is patented we are prepared to teach this method to students, engineers and clients.

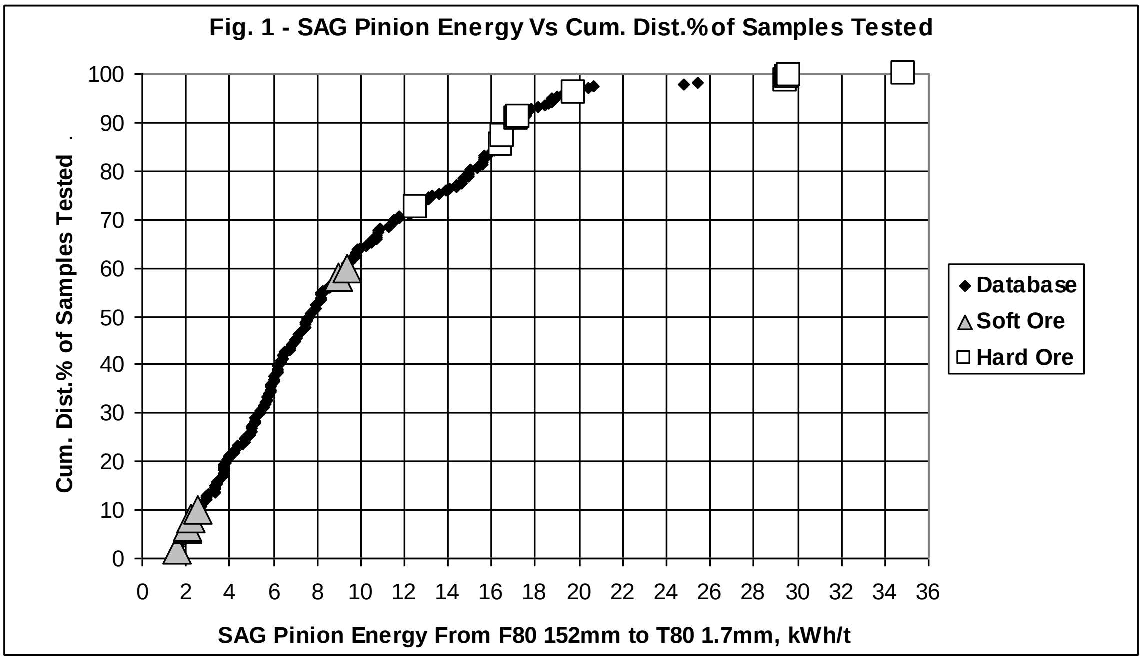
The SAGDesign test was conceived to accurately measure the required design information on every sample, for SAG milling and ball milling. The calculation method was set up to use these measurements in a mathematically correct way to size the grinding mills required to grind the ore. This method does not require a computer program (other than Excel) or a data base. It is based on 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 34 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 finding 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 seen and reviewed for the first time. It is therefore not surprising that the conclusions have not been noticed before.

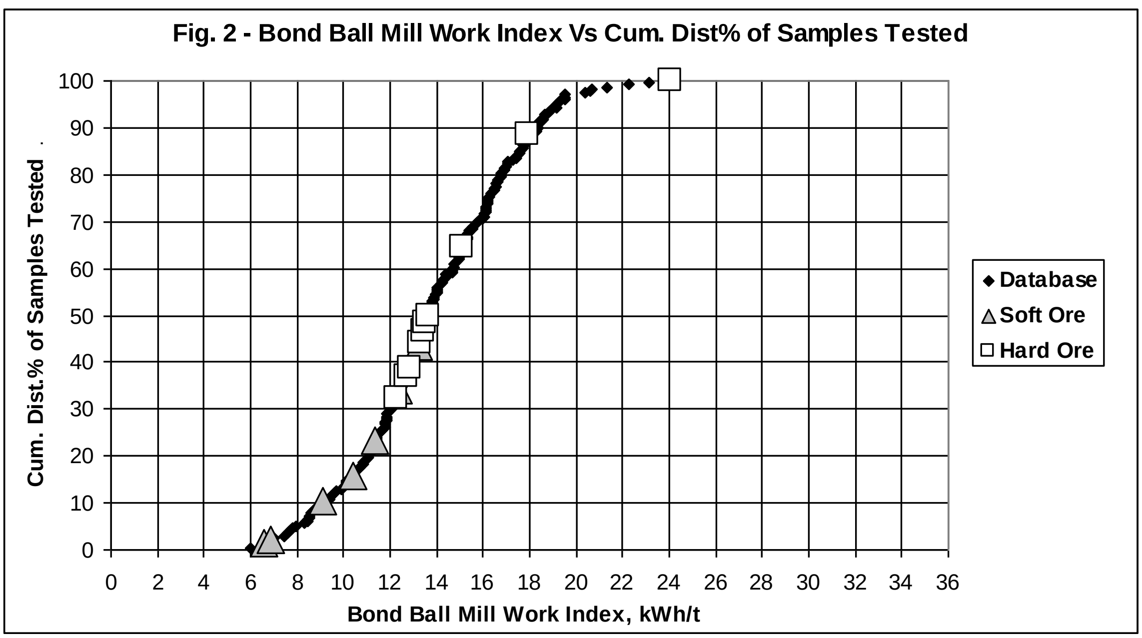
SAGDESIGN DATABASE

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 distribution % of the number of 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 samples 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 laboratory SAG test has identified ore that is more than double the 80th percentile hardness. At the low energy end of the curve the hardness increases steadily with no apparent minimum other than the lowest value recorded. Compared to Fig. 2, this is the difference between grinding in a heavy steel chamber and grinding in a semi-autogenous environment. The shapes of the graphs are quite 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 it 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 data from 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 only a Bond BM Wi measurement. When the hard and soft ores are added to the database, the correlation is invalid. To those who ask if we can design a SAG mill from only a Bond Ball Mill Work Index measurement, we firmly say “no”.

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 (preferably done on SAG ground ore as part of a SAGDesign test).

Based on this work we recommend that simulation modeling should consider similar ratios of SAG hardness to ball mill hardness when designing a SAG mill for a specific ore. If the ratios of SAG/ball mill hardness for the new ore are the same as the ores in the database, the design should work. But if the new ore has different ratios (SAG/Bond BM Wi hardness) the design probably will not work well and direct calculation of required mill sizes from the test data should be done instead of using simulation modeling.

Fig. 3 - Database SAG and Bond Data by Year - Soft and Hard Ore Added

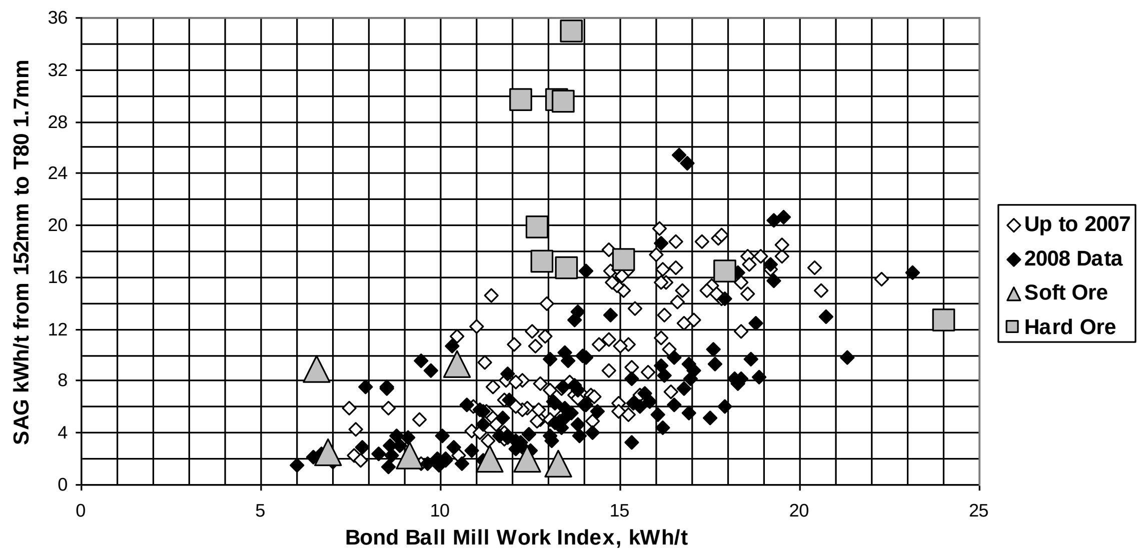
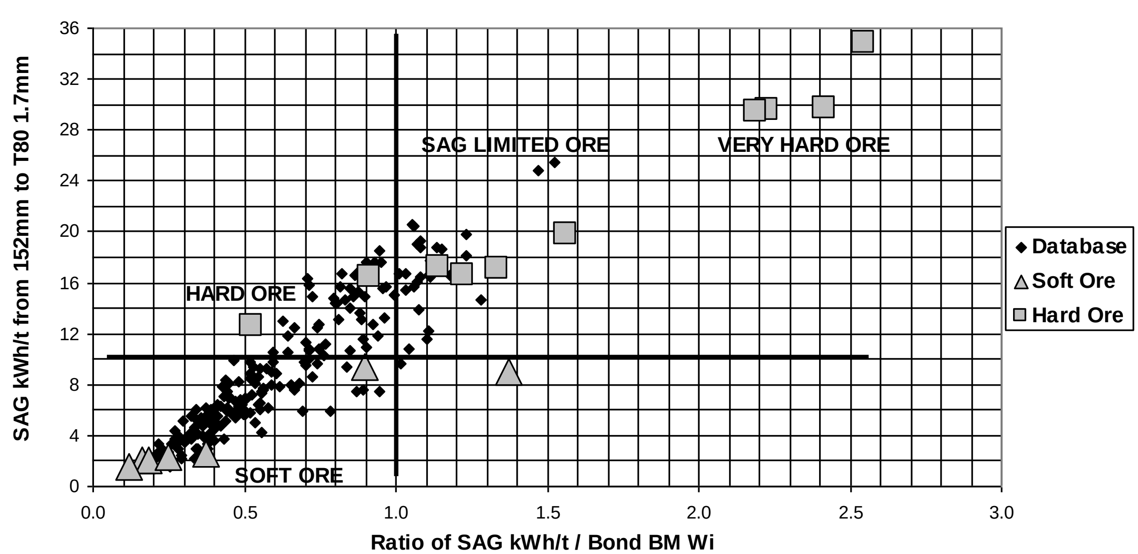


Fig. 4 - SAG Pinion Energy Vs Ratio of SAG / Bond BM Wi, c/w Soft & Hard Ore



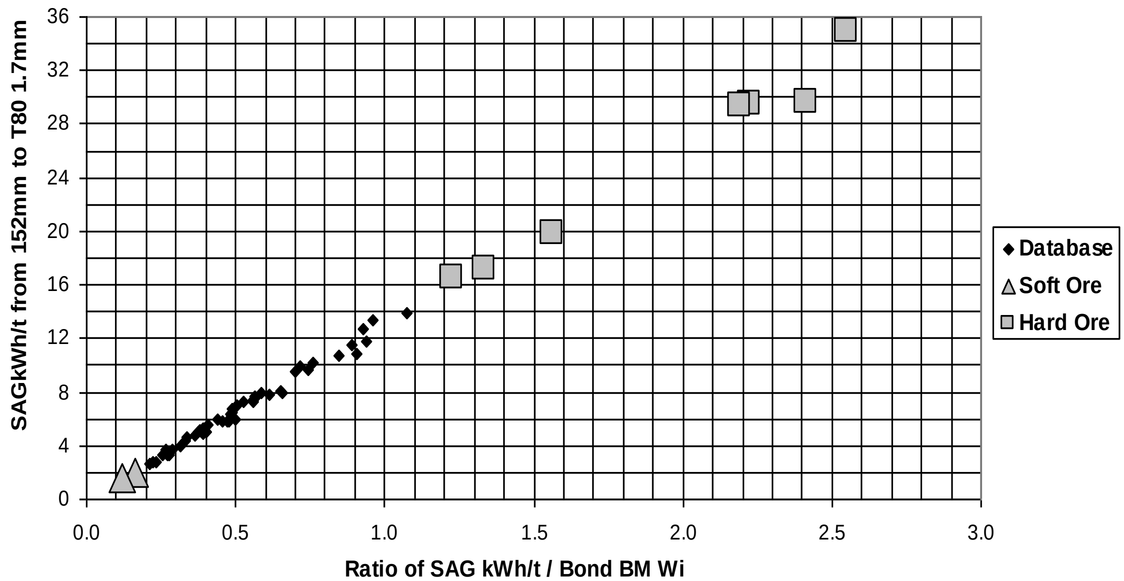
To emphasize this point, Figure 4 has been prepared. Here the SAGDesign database is presented differently with SAG kWh/t being plotted against the ratio of SAG kWh/t to Bond Ball Mill Wi. Looking at the data this way shows the extreme differences between ores at the same ball mill hardness.

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 dividing 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 probably be used. Other methods to mitigate the requirement for high SAG energy should also be considered for ores in the top right hand quadrant.

NEW DISCOVERIES

The new discoveries are highlighted in the following graph (Figure 5) which plots all samples from the database that had Bond BM Wi values between 12 and 14 kWh/t. Samples from both the very hard and very soft projects appear on this plot. In the writer's opinion a calculation method, not simulation is required to properly deal with this situation.

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. To the best of the writer's knowledge of the laboratory methods discussed in this paper, SAGDesign technology is the only laboratory and calculation method that accurately measures and 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. A clear picture is emerging. Coupled with the success of plant benchmark tests done to date at 6 and 15 kWh/t, we are confident that the SAGDesign test and procedure will work for every ore encountered.

A brief summary of the most common comminution tests are listed below. First listed are the tests that do not use steel in a rotating 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 results 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.
- JK Drop Weight Test (DWT), 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. SAG Mill sizing is derived from these simulations. This method is usually good for ores up to ~18 kWh/t for SAG pinion energy but not above that because of a lack of operating data on harder ores. 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 DWT and the kWh/m^3 for each sample tested. Its use allows the sample weight required to be reduced from 100 kg for the DWT to less than 20kg and is excellent for scoping and geometallurgy.

- 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. This is a new test and the author is not familiar with the results.

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, use similar steel loads and dry ore as feed. They are considered by the writer to be more reliable for scale-up.

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 weight 2kg, scoping test
MacPherson AWi, kWh/t	19	18" dia x 6"	200kg	Continuous, air swept, pilot scale
SAGDesign SAG, kWh/t	19	19.2"dia x 6.4"	15 kg	Constant vol., SAG/BM design
Includes SAG Test and Bond BM Wi on SAG ground ore.				

The difference in hardness indicated by the Bond BM Wi test and the Bond RM Wi test was the first indication 50 years ago that there is a unique macro/micro grindability ratio for every ore. This has been known since Bond published his methods for mill sizing and relates to hardness above and below a feed size F80 of 2mm. Both of the Bond tests (rod mill and ball mill) are done in a high steel environment. Since the SAGDesign test is done in a much lower percentage steel environment (11 % by volume of steel), it follows that the distribution function of the data will have a different shape. Figures 1 and 2 confirm this fact as noted above.

The other fact of significance here is the F80 for the test concerned. There is a shift in relative hardness for many ores between the 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). It is concluded that the macro hardness relative to SAG grinding is not measured properly in tests with feed sizes of 10mm or less.

This raises a new concept in understanding comminution hardness measurements. 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. Because a SAGDesign test includes a Bond Ball Mill Work Index test on SAG ground ore, the SAGDesign SAG test result and its Bond BM Wi result give the required grinding design information.

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. Since the AWi value overlaps Bond in the range of 1.7mm to 0.4mm the method required for interpreting the data from SAGDesign and MacPherson tests is, and needs to be, very different.

MILL SIZING CALCULATIONS

A typical SAGDesign mill sizing calculation sheet is presented below. Shaded cells in Table 1 are the input numbers, taken from the testing program and the design criteria. Usually the 80th percentile is utilized as the design point for a project but the 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 input values, the Case 1 data 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.

These calculation procedures were chosen to take advantage of the design measurements (for SAG and ball milling) the SAGDesign test program. Bond's diameter correction factor is used by Starkey & Associates because it has been judged to be conservative by determining benchmark operating work indices at Escondida and Candalaria. (Classification efficiencies were not considered). Not all engineering houses use this correction factor. For a 24 ft diameter ball mill, the operating Wio diameter correction factor is 0.8 times the energy calculated from the Bond Wi.

This is design by engineering calculations, 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. The various factors used are shown and can be adjusted if not appropriate for the duty intended. By avoiding simulation techniques, the quality of the assumptions and algorithms used in the computer program are not a factor in sizing the mills.

Table 2 is an example of how mill sizes are calculated using SAGDesign technology. The SAG pinion energy (80^{th} percentile) required to grind the ore from F80 152mm to T80 1.7mm is used as input. The equation used to calculate the SAG pinion energy can be found in the reference paper below (Starkey et al, 2006). The Bond Ball Mill Work Index on SAG ground ore is also used as input. Note that all 5 inputs to this calculation spreadsheet including T80, P80 and t/h are shown as shaded cells in Table 2. Required SAG and ball mill motor kW are given in the D section of this example and mill dimensions in section E are chosen to provide the exact amount of energy required. The method is precise and only requires selection of suitable mill dimensions to match the grinding to be done.

Table 2 – Typical Mill Design Calculations

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 GRINDING MILL DESIGN

The impact of these new discoveries on grinding mill design is clear to the author. But the way forward to use this information may not be easy for others to accept because of the wide array of methods currently used to design SAG mills and SAG grinding circuits. Therefore comparisons of SAGDesign testing with other methods, benchmarking, and field experience using these design techniques, are recommended as an urgent priority.

To date, benchmarking tests at a producing mine in Canada gave a predicted energy requirement of 6.0 kWh/t Vs a measured plant hardness for the ore fed to the mill of the same value. For a hard magnetite ore tested in a 5.5 ft diameter SAG pilot mill in Hibbing, Minnesota, both the observed SAG pinion energy and the measured value to produce 80% passing 1.7mm were 15 kWh/t. It is also known from direct comparison with drop weight test results that the SAGDesign measurements are comparable on a relative basis. (Starkey and Meadows, 2007). On another project, SAGDesign measurements have matched the relative drop weight SAG hardness results on the same hard ore samples.

Given the cost of a single 40ft diameter SAG mill, it is imperative that the grinding mill design procedures used be carefully reviewed for accuracy at the testing and mill sizing stage for every project, and especially the large scale ones. Careful sampling by working with the mine engineers and geologists to generate composite samples that match the early mine production by year, should be done. These samples should be tested using SAGDesign. The advantage of using SAGDesign is that the mill sizing calculations can be checked. This is mill design by calculation from empirical measurements, not simulation based on other ores that may not have the same macro/micro hardness ratio.

CONCLUSIONS AND RECOMMENDATIONS

1. SAGDesign testing should be used to design the mills for new large tonnage projects where failure to achieve design tonnage and grind will cause severe financial distress to the owner. It is accurate, fast, and affordable.
2. If a client requires confirmation of SAGDesign testing and mill sizing, benchmark testing of a similar grinding circuit should be done by taking a feed sample and comparing the SAGDesign result with plant performance. Other tests can also be done for confirmation if deemed to be necessary.
3. Properly chosen samples are at the heart of any grinding mill design project and are the first requirement for a successful grinding operation, regardless of the tests used. Taking samples is part of the full SAGDesign program.
4. Rotary mill grindability tests produce results that are valid for the purpose intended. Bond tests are good for designing rod mills and ball mills. SAGDesign tests are suitable for designing AG/SAG mills.
5. Conventional impact breakage parameter tests do not measure the SAG pinion energy in kWh/t needed to achieve a stated product size. For ores harder than treated in existing operating plants, this is a problem.
6. 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 required data for any new SAG/ball mill circuit design and used as a guide in deciding what power split will be chosen.
7. The Bond BM Wi cannot be used alone to design a SAG mill.

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