SAG kWh/t Measured Using a Standard Test

53 Projects in 6 Years

COMMINUTION '10

Capetown, SA

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1. ABSTRACT

At SAG 2006, the SAGDesign^{TM} Test was introduced. After 6 years and 50 successful mill design and 3 accurate benchmark projects, this technology has emerged as a proven mill design method based on the direct measurement of SAG pinion energy in kWh/t using standard commercial grinding conditions for the test in a 0.5 m diameter SAG mill.

In the 2009 database, SAG pinion energies (to grind from F80 152 mm to T80 1.7 mm) vary from 1.4 to 34 kWh/t and Bond ball mill work index values vary from 6 to 24 kW/t for the same ores. Project design tonnages varied from 200 to 150,000 t/d, SAG mill sizes varied from 10 ft to 40 ft diameter in multiple SAG mills, and ball mill sizes varied from 7 ft to 27 ft in diameter.

Calculated SAG pinion energy for full scale plant benchmark tests were within 3% of actual plant power consumption when SAG feed samples are tested using the SAGDesign test. The test method reproducibility is also 3%. As a result, this technology should therefore be considered for every new SAG milling project prior to mill purchase.

2. INTRODUCTION

Previous papers discussed the 2008 database of 232 SAGDesign samples in context to 35 mill design and sizing projects. This paper is a formal update with regard to the 2009 SAGDesign database of 320 samples that now covers 53 grinding circuit analysis and mill sizing projects.

Several key things have emerged from the projects mentioned above. The new discoveries reported last year included big variability in SAG hardness. Two projects having the same Bond ball mill work index (13 kWh/t) had SAG hardness as low as 1.4 kWh/t in one case (Aurora) and up to 34 kWh/t in the other case where NICO data was reported in January 2010 at the CMP in Ottawa. This proved that a Bond BM Wi alone must never be used for designing a SAG mill.

The ratio of SAG hardness (to grind from F80 152 mm to T80 1.7 mm) divided by the Bond ball mill work index was defined as a key factor in the design of a new SAG/ball mill circuit. Simulation techniques that do not consider this ratio may produce erroneous results.

A clear picture is emerging as the SAG mill comminution literature expands with the inclusion of this technical report. The NICO project was unique and no other projects have been encountered to date with similar properties. This proves that it is important to use a test like SAGDesign that measures ore hardness at the coarse and fine ends of the comminution size spectrum. It also clearly shows that simulation techniques will not yield a robust design when no other similar ores exist in the database.

The technical development of the SAG mill design process has lagged far behind the use of industrial SAG grinding technology and the use of undisclosed or private technology has not helped. SAGDesign is the first method introduced in the last 50 years that teaches engineers how to use it without proprietary software. SAGDesign is based on a simple concept: measure the coarse and fine hardness variability on every sample tested in an ore body and design a SAG/ball mill circuit to match that ore body by first principle calculations.

3. PROJECTS

Table 1 – List of All SAGDesign Projects Completed to Date

JOB	TESTS	ORE	DESCRIPTION	Av Ratio	SAG Mill(s)		BALL Mill(s)		DESIGN
				SAG/BWi	Dia. ft	EGL ft	Dia. ft	EGL ft	Fd (t/h)
S 1	2	Fe	ROM crushed ore	0.46	20.7	17.4	-	-	366
S 2	5	Au	Gold ore	0.63	16.0	20.0	-	-	75
S 3	8	Au	1/4 cut drill core	0.89	34.0	14.5	24.0	31.8	651
S 4	10	Au	ROM and 1/2 cut core	0.80	18.0	27.6	-	-	100
S 5	13	Fe	1/2 cut drill core	1.11	40.0	20.0	24.0	35.0	6561
S 6	4	Cu, Mo	ROM crushed ore	0.44	28.0	12.0	18.0	25.5	661
S 7	1	Fe	Crushed feed - pilot plant BM	0.90	5.5	2.8	-	-	0.95
S 8	7	Co, Cu	ROM crushed ore	0.32	20.0	9.4	14.0	18.8	315
S 9	10	Zn, Pb, Cu	ROM crushed ore	0.48	22.0	8.0	14.0	21.8	225
S 10	4	Mo	ROM crushed ore	0.59	36.0	15.0	22.0	31.0	1150
S 11	4	Au	ROM crushed ore & drill core	1.11	22.0	11.0	14.0	22.0	134
S 12	10	Mo	Split diamond drill core	0.51	34.0	17.0	22.0	35.5	1150
S 13	3	Au, Ag	2" ROM crushed ore & 2" core	0.40	20.0	9.3	-	-	82
S 14	6	Cu, Ni	Diamond drill core	0.92	38.0	18.4	22.0	36.3	1046
S 16	5	Au	ROM crushed ore	0.58	16.4	6.4	10.5	11.6	45
S 17	6	Au	ROM crushed ore	0.61	23.0	7.5	14.8	19.7	103
S 18	3	Pb, Zn	Drill core	0.86	32.0	12.7	24.0	38.3	744
S 19	6	Au	ROM crushed ore	0.74	23.0	6.1	11.8	13.1	154
S 20	6	U	Split diamond drill core.	0.48	26.0	10.5	16.5	27.0	456
S 21	1	Au, Ag, Zn	Diamond drill core composite	0.45	24.0	11.3	16.5	23.5	217
S 22	1	Au, Ag, etc.	ROM crushed ore to 3"	0.53	10.0	3.5	7.0	8.0	9
S 23	4	Au	2.5" split drill core	0.46	24.0	9.5	16.5	23.0	186
S 24	1	Cu, Zn	ROM blasted ore	0.48	22.0	7.0	15.0	21.1	181
S 25	23	Cu	Drill core, oxide and sulphides	0.48	24.0	10.1	17.0	23.0	362
S 26	38	Co, Cu	Drill core	0.33	22.0	23.5	-	-	452
S 27	1	Au	ROM crushed ore	0.58	16.4	6.4	11.8	13.1	95
S 28	12	Ni	Drill core	0.78	40.0	21.3	26.0	36.4	1329
S 29	7	Cu, Ni	Drill core composites	0.88	40.0	23.0	26.0	40.0	2003
S 30	3	Au	Drill core	0.74	18.0	8.2	10.5	18.0	76
S 31	1	Ag	1/2 cut drill core	0.46	18.0	5.9	11.8	13.1	37
S 32	5	Au	Diamond drill core	0.77	24.0	10.2	15.0	27.3	274
S 33	10	Fe	1/2 cut diamond drill cores	0.53	26.0	12.0	-	-	493
S 34	10	Au, Co, Bi	Include porphyry/dike waste	1.61	26.0	10.1	14.0	21.0	139
S 35	1	Cu	Crushed feed, ore from belt	0.34	16.5	5.0	10.5	12.0	93
S 36	1	Cu	Crushed fd, ore from belt BM	0.33	16.5	5.0	10.5	12.0	140
S 37	5	Cu	Drill core	0.38	22.0	8.8	10.5	12.0	226
S 38	2	Cu Ni Pt Pd	ROM crushed ore	0.81	22.0	10.4	14.0	21.9	124
S 39	2	Au, Cu	Drill core	0.50	18.0	7.6	12.0	17.6	82
S 40	1	Au	Split diamond drill core	0.67	28.0	11.2	18.0	31.5	266
S 41	6	Au	Drill core	0.38	32.0	15.3	22.0	31.7	926
S 42	4	Au	Drill core	1.14	38.0	17.0	26.0	33.9	1019
S 43	16	Au	1/4 cut drill core	0.72	26.0	10.9	16.0	23.0	200
S 44	7	Au	Drill core	0.81	26.0	12.3	15.5	24.3	181
S 45	8	Au, Cu	1/2 drill core composites	0.74	40.0	23.0	26.0	40.0	1848
S 46	5	Rare earths	1/2 drill core composites	0.70	20.0	7.5	12.0	17.0	91
S 47	1	Sn	1/2 drill core composite	0.75	36.0	14.8	17.0	22.0	453
S 48	1	Cu	ROM crushed ore	0.25	24.0	10.5	20.0	24.9	579
S 49	8	Au	1 ROM, 7 1/4 cut NQ cores	0.94	22.0	9.7	13.0	23.3	125
S 50	14	Ni	12 PQ cores, 2 crushed ore	0.37	-	-	-	-	Tests only
S 51	6	Au	ROM crushed ore OP/UG	0.64	38.0	18.7	27.0	42.7	1283
S 52	1	Au	ROM crushed ore UG	0.68	18.0	8.2	11.8	18.5	53
S 53	1	Mo	Crushed feed, belt-cut ore BM	0.46	28.0	14.0	-	-	324

Table 1 above lists all of the projects done to date. Three of these projects highlighted within the table, namely S7, S36, and S53 are plant benchmark tests and are discussed in Section 3.2 below.

3.1 Mill Design Projects

50 projects involve mill design work and include new mill design and predicting throughput in existing mills. For a number of Russian projects the ability to forecast tonnage in existing mills was important because a number of projects had stopped mid construction in 1991 when the economic transformation in Russia commenced. At that point, only the plants with profitable production forecasts were allowed to continue operation. Meanwhile other plant construction projects were put on hold while economic reviews (feasibility studies) were conducted.

Russian colleagues (at TOMS and Irgiredmet) have received SAGDesign technology with great enthusiasm because the technology comes with training in how to use the test data to size the grinding mills. The Russian designers could generate laboratory data, perform mill sizing calculations and generate mill reports, all in their own language.

New design projects have been discussed in various presentations at recent conferences. The first plant to operate based on SAGDesign results is the Tenke Fungurume Project in the Democratic Republic of Congo. The first phase of the testing is shown as S8 in Table 1 while final work to check all of the ore zones is shown as Project S26 where 38 samples were tested.

New mills were purchased for the Climax Molybdenum plant in Colorado based on SAGDesign testing. At the time, delivery for new SAG mills was 3 years and the only way to get the mill order in the queue in less than 3 months was to do SAGDesign tests on 10 samples, the number required for a manufacturers' guarantee of throughput and grind from Outotec. (Outotec holds the patent on SAGDesign testing). Outotec mills were not purchased in this case but the client knew the results were correct and purchased the SAG and ball mill needed based on Starkey & Associates Inc.'s design.

The most significant feature to emerge from Table 1 was the results for the NICO project, listed above as project S34. The results were presented at the annual CMP Conference in Ottawa in January 2010. The NICO ore body is unlike any tested before or since and was classified at the 98th percentile in the SAGDesign hardness database. The ore has extreme hardness in the SAG mill even though this hardness was not detected in a corresponding Bond Rod Mill Work Index test. This raises serious questions about design techniques which use tests other than SAG tests to design SAG mills. It is worth noting that JK dropweight and MacPherson tests on the same ore, also classified NICO ore at the 98th percentile level of hardness in the respective databases. (Starkey & Samuels, 2010).

In the NICO case, the client decided to use three stage crushing and rod milling to prepare ball mill feed because this was shown to save energy. Since simulation techniques do not work for ores that are harder than A*b = 27, SAGDesign testing can be used to properly compare SAG mill costs with HPGR when trade-off studies are done. The work done to date clearly shows that SAGDesign and JK Dropweight give similar results for ore hardness and that SAGDesign results allow the sizing of required mills for any ore including the 98th percentile or hardest ores.

3.2 Benchmark projects

Among the 53 grinding circuit analysis and mill sizing projects, three are benchmark projects. The objective of each benchmark project was to compare the SAGDesign test work results with the observed plant performance. The first benchmark project (S7) was performed with a pilot plant mill and the other projects (S36 and S53) were with industrial sized SAG mills; refer to Table 1 for mill sizes. Table 2 presents a summary of the benchmark project results.

Table 2: Benchmark sample SAGDesign results

Project	Source	Type of Feed	Feed t/h	Total kW	Spec. W kWh/t	F80 mm	T80 mm	REMARKS
S7	Lab	Three inch pieces from the belt			14.97	152	1.7	Standard pinion energy for 6" feed
					15.44	127	1.0	Adjust lab to pilot plant sizes
	Pilot mill	Continuous feed belt with fines	0.95	13.55	14.26	127	1.0	Error is about + 8.2% for lab result
					14.98	152	1.0	Adjust pilot plant for six inch feed
S36	Lab	Three inch pieces from the belt			5.52	152	1.7	Standard pinion energy for 6" feed
					3.85	51	2.6	Allow 20% for fine feed, 6% for motor
	Plant	Continuous feed belt with fines	140	525	3.75	51	2.6	Error is + 2.7% for lab result
S53	Lab	3 m belt cut crushed and split			14.15	152	0.16	Standard pinion energy for 6" feed
					14.74	94	0.16	Allow for fine feed & 10% for motor
	Plant	Continuous feed belt with fines	318	4613	14.52	94	0.16	Error is + 1.5% for lab result

Note: The S7 pilot plant power was adjusted for tare and power factor and so may not be accurate.

For each analysis, grind size requirements and ore feed rates were equated so that the comparison between SAGDesign results and observed SAG mill plant performance was based solely on the reported specific grind energy (kWh/t) and mill power draw (kW). The relative error between the plant data and SAGDesign results for the pilot plant mill and two industrial SAG mills were 8.2%, 2.7% and 1.5% respectively. The results from the 2 full scale plant benchmark projects indicate the accuracy of the SAGDesign test results and mill sizing calculations.

3.3 Test reproducibility

Consistency of test work results is an issue in data analysis for comminution circuit design. The quality of the SAGDesign test result is dependent on the SAGDesign Test Standard Operating Procedure, a descriptive test method that is set up to treat both crushed run-of-mine ore and/or any commercial drill core, each suitably crushed to 80% passing 19 mm. SAGDesign tests are accurate based on the above benchmark studies. In terms of precision, the reproducibility of the SAG test results has been verified on 5 occasions.

Table 3 describes the SAGDesign test reproducibility studies, where the repeat SAG test is identified. With reference to the table, the average absolute difference, or relative error, was calculated to be 1.2%. As defined by Starkey & Associates Inc., the acceptable relative error on any SAG test is 3.0%.

Starkey & Associates Inc. strives to maintain the highest quality of test work results. In order to extract further information about the test result reproducibility, a full study is currently underway to evaluate and compare the reproducibility of the SAGDesign test with other comminution test methods. Comparisons of duplicate samples, tested at the same and other laboratories are also being done.

Table 3 - SAGDesign test reproducibility

Project	Lab	Sample Identification	SAG Mill Charge wt. grams	No. of Revs	Calc SAG W to 1.7mm kWh/t	Relative Error
S3	Dawson	1	7427	2210	15.59	
		Repeat Test	7013	2130	15.63	**0.3%**
S5	Dawson	1	8380	2527	16.43	
		Repeat Test	8443	2561	16.58	**0.9%**
		2	8162	2830	18.73	
		Repeat Test	8268	2863	18.79	**0.3%**
		3	8620	2450	15.65	
		Repeat Test	8600	2523	16.13	**3.0%**
S46	Starkey	1	7572	1573	10.95	
		Repeat Test	7456	1531	10.77	**-1.6%**
SAGDesign Equation for Pinion Energy:				**Total no. of Repeat Tests**		**5**
W = Revolutions * (grams+16000)/(447.3*grams)				**Average Abs. Difference**		**1.2%**

4. DATABASE

The SAG design test reproduces commercial SAG mill grinding conditions on 4.5 L of ore. The SAG mill test determines the SAG mill pinion energy requirement to grind ore from 80% passing 152 mm to 80% passing 1.7 mm by testing the sample at 80% passing 19 mm. The SAG mill product is then crushed to 100% passing 3.35 mm and is subjected to the standard Bond ball mill work index (BWi) grinding test to provide the total pinion energy at the specified grind size for mill design purposes. The full SAGDesign test reports SAG pinion energy in kWh/t, the Bond BWi in kWh/t, as well the ore specific gravity. When the ore variability is considered by doing a number of tests, the information is complete to design the grinding mills for any project. No other test work or computer program is required.

In the past 6 years, starting in 2004 when the SAGDesign test was patented, the SAGDesign test work database has grown to include 53 projects and 320 samples on ores of all kinds as shown in Table 1 above. Table 4 summarizes the database of all SAGDesign test work results recorded up to and including 2009.

Table 4: Database summary of SAGDesign test work results

Item	Ore SG				SAG kWh/t to 1.7 mm				BM Wi kWh/t				RATIO SAG / BWi			
	'07 data	'08 data	'09 data	DB	'07 data	'08 data	'09 data	DB	'07 data	'08 data	'09 data	DB	'06-'07	'08 data	'09 data	DB
Count	113	119	88	**320**	113	119	88	**320**	113	119	88	**320**	113	119	88	**320**
Min	2.53	2.47	2.38	**2.38**	1.61	1.37	2.20	**1.37**	6.55	6.01	7.92	**6.01**	0.12	0.16	0.19	**0.12**
Max	4.73	4.47	4.71	**4.73**	19.82	34.89	22.49	**34.89**	22.28	24.06	21.05	**24.06**	1.37	2.55	1.22	**2.55**
Median	2.82	2.81	2.82	**2.81**	9.03	6.45	10.86	**8.52**	14.17	13.47	15.61	**14.27**	0.69	0.45	0.67	**0.59**
Avg.	3.03	3.00	3.00	**3.01**	10.06	8.54	10.33	**9.57**	14.01	13.71	15.52	**14.31**	0.69	0.60	0.66	**0.65**
Std dev.	0.49	0.46	0.52	**0.49**	5.24	6.69	4.66	**5.72**	3.20	3.64	2.67	**3.32**	0.29	0.45	0.26	**0.35**

Ore specific gravities vary from 2.38 to 4.73. SAG pinion energies vary from 1.37 to 34.9 kWh/t and Bond ball mill work index values vary from 6.0 to 24.1 kW/t for the same suite of ores. The SAG kWh/t to Bond BM Wi ratios vary from 0.12 to 2.55.

SAG hardness variability is considered by plotting the SAG pinion energy against the cumulative distribution % of the number of samples tested. Figure 1 presents the SAG kWh/t variability by year and Figure 2 presents the SAG kWh/t variability of the entire SAGDesign database.

Whether the test results are analyzed on an annual or overall basis, the database demonstrates several important aspects. As illustrated by the shape of the curves in Figure 1, there are many samples that are very soft to grind in a SAG mill. 20% of the samples tested are less than 6 kWh/t and 80% are less than 16 kWh/t. Secondly, the ability of the SAGDesign test to identify extremely hard ores is shown in Figure 1. The test has identified ore that is more than double the 80th percentile hardness. The hardest SAG pinion energy recorded to date is 34.9 kWh/t.

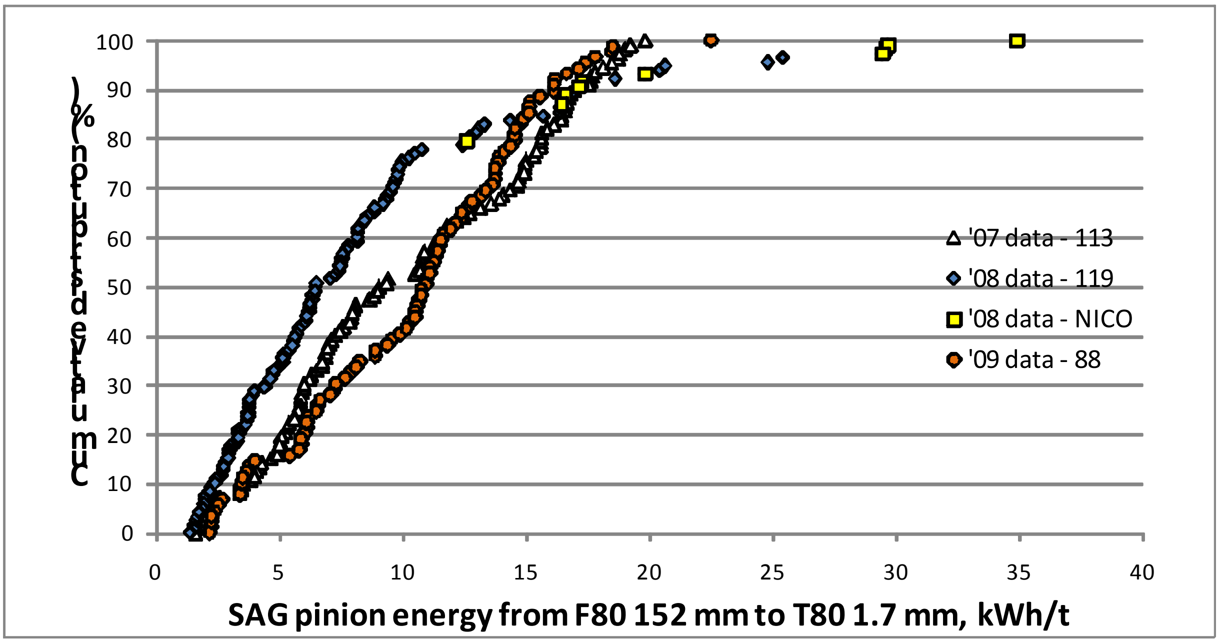

Figure 1 - Cumulative distribution % of SAG kWh/t by year

Figure 2 presents the Bond ball mill Wi variability by year. As illustrated by the 2008 data in Figure 1, hard ore (in the SAG mill) can possess variable Bond BM Wi. Because the shape of the SAG kWh/t and Bond BM Wi curves are so different, it proves that the data generated for each sample can only be used in the context of using both measurements together.

The graph of SAG pinion energy vs. Bond BM Wi is given in Figure 3 below. The database supports a general trend between SAG and ball mill hardness for the majority of the test work data but the correlation is too low to be useful in sizing a SAG mill from only a Bond BM Wi measurement. Macro SAG hardness measurements cannot be used alone but only in conjunction with the corresponding micro hardness measurements of the Bond BM Wi.

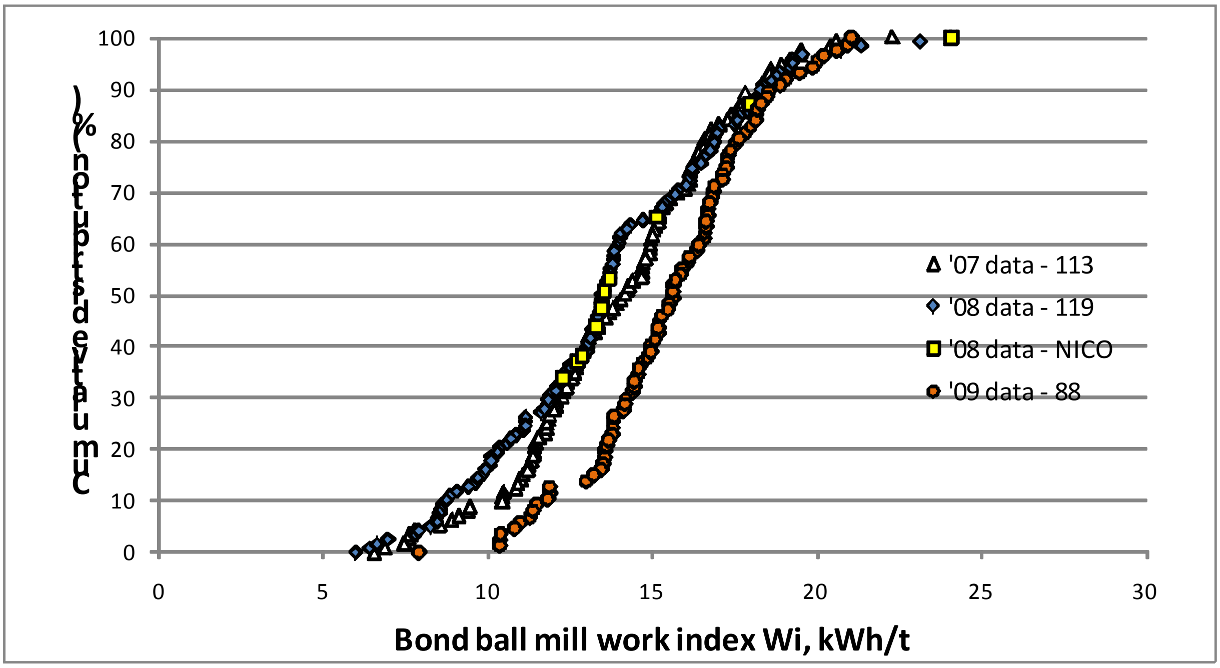

Figure 2 - Cumulative distribution % of Bond BM Wi by year

Figure 3 also shows the unusual nature of NICO ore. No other similar ores were seen in the data base. The one sample from NICO that showed a high BWi and a low SAG energy requirement was actually the waste sample that would be mined as dilution. It is customary to include a waste sample to show the effect of over-break in the mine because that waste will go to the mill.

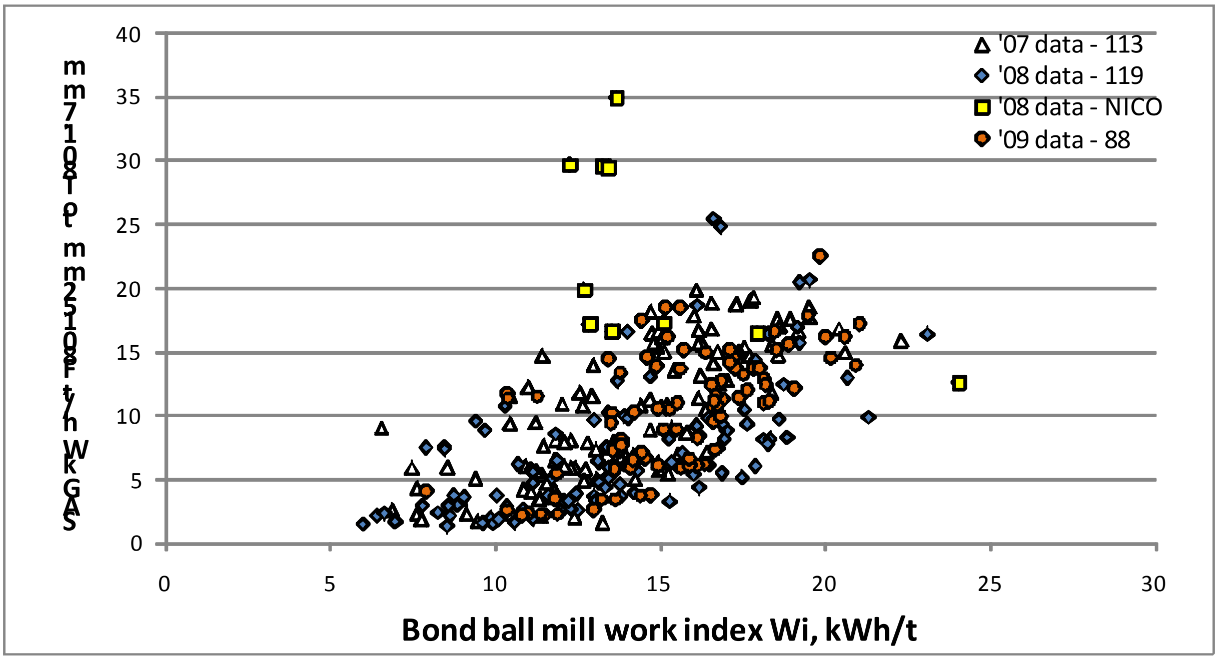

Figure 3 - SAG kWh/t Vs Bond BM Wi by year

Figure 4 shows the SAG kWh/t being plotted against the ratio of SAG kWh/t to Bond BM Wi. The graph is divided into 4 quadrants, each of which represents different considerations for grinding circuit design. 10 kWh/t for SAG grinding to 1.7 mm is considered the dividing line for hard Vs soft ores. Hardness ratios below 1.0 are considered to be favorable to SAG milling. The top right hand quadrant is characterized by ores with SAG kWh/t to Bond BM Wi ratios greater than 1.0. These are considered to be hard and SAG limited. In these circumstances, pebble crushers and other methods to mitigate the requirement for high SAG energy should be studied.

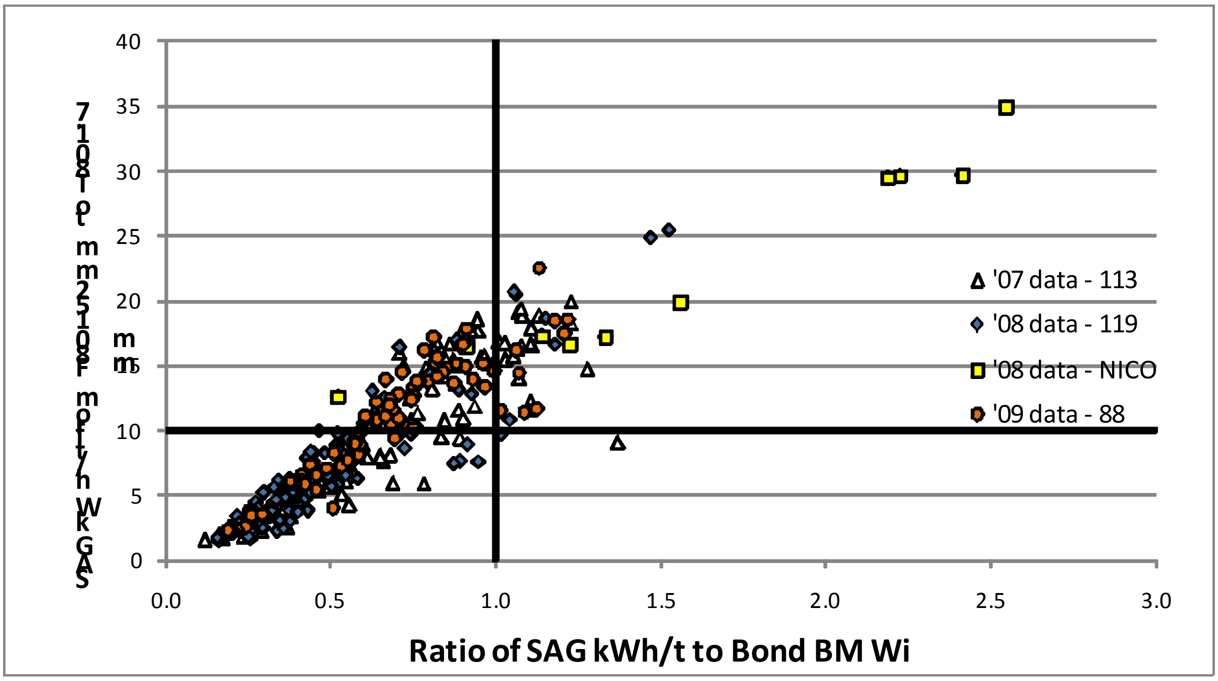

Figure 4 - Ratio of SAG kWh/t/Bond BM Wi by year

The database is a unique suite of information because this data has not previously been available. The discovery of the true variance of macro hardness for SAG mill design, and micro hardness for ball mill design, and the relationship between the two, opens a new door for accurately sizing the mills required for SAB, SABC and fully autogenous grinding circuits.

5. CONCLUSIONS

The database analysis proves that SAGDesign methodology is robust, reliable and very helpful in determining what mills are required to grind a client's ore.

Based on the NICO findings, it is not helpful to compare one ore with another unless the measured hardness is the same for both SAG and ball milling size ranges.

Direct calculation for designing new mills is preferable to simulation because there are no restrictions at the hard end of the spectrum when using SAGDesign.

SAG mills can be designed in all situations and for any ores. Capital Vs operating cost trade-offs should be examined to be sure that the most economical circuit is selected.

When HPGR trade-off studies are being done, SAGDesign tests will be very helpful to determine if HPGR, or energy mitigation in a SAG mill circuit will be more economical.

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