PAPER 3

Comparison of Ore Hardness Measurements for Grinding Mill Design for the Tenke Project

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ABSTRACT

As part of the ongoing project development for the Tenke Fungurume Copper-Cobalt Project in the Democratic Republic of Congo, Phelps Dodge Corporation has examined methodologies for determining the size of grinding mills to support a 7000 mtpd operation. Six samples were tested by Hazen Research, Inc. (HRI) to obtain the JK parameters using the JK Drop Weight Test, standard Bond crushing, and rod mill work indices, abrasion indices and by Dawson for Bond Ball Mill Work Index tests using crushed feed, and Standard Autogenous Grinding Design (SAGDesign) Tests, patented by Outokumpu. (See reference 8 below).

The comparison of these results gives context to how the various measurements relate to each other and how they can be used to obtain an accurate design for the grinding mills required for the Tenke Project. This is the first published direct comparison between JK Drop Weight, standard bond work indices, and SAGDesign test results. The SAGDesign test includes a SAG test followed by a Bond BM Wi test done on SAG ground material.

INTRODUCTION

After the presentation of the paper "SAGDesign Testing – What It Is and Why It Works" at the recently concluded SAG 2006 Conference in Vancouver, a question was asked about how SAGDesign ore hardness measurements compared with other comminution tests, specifically the JK Drop Weight Test and the parameters that are derived from such testing. At that time it was noted that a paper was being prepared for the CMP Conference in January to show how various ore hardness measurements compare with each other when done on the same samples.

This paper will therefore present the first such comparison using test results from the Phelps Dodge Tenke Fungurume Project where six composite samples were examined by the tests noted below. A seventh sample was tested at Dawson but not at other labs. The tests were done at four different laboratories listed below and included the tests shown.

Hazen Research, Inc.

- Bond Rod Mill Work Index
- Bond Abrasion
- Specific Gravity, 2 methods
- JK Drop Weight Tests – Data Analyzed by Contract Support Services, Inc.

Phillips Enterprises, LLC

- Bond Impact Crushing Work Index
- Specific Gravity

Advanced Terra Testing, Inc. (ATT)

- Unconfined Compressive Strength ASTM D 5731
- Specific Gravity, ASTM D 854

Dawson Metallurgical Laboratories, Inc.

- SAGDesign (SAG to T_{80} 12 M followed by Bond BM W_i on SAG ground ore)
- Bond Ball Mill Work Index (Crushed Feed)
- Specific Gravity (part of the SAGDesign test).

The results from this work are presented below and are discussed in this paper. The SAGDesign results were compared to JK Drop Weight analysis of results by analyzing the SAGDesign Database for all tests done to date for SAG Pinion Energy (to T_{80} 1.7 mm) and Bond Work Index on SAG ground ore. To data 63 SAGDesign tests have been done and this allowed the Tenke results to be ranked with respect to all the samples tested to date.

Critical issues with regard to the various tests done are reproducibility of the test result in duplicate tests, and the deliverable from the test. As far as the SAG portion of the SAGDesign test is concerned, it was the only SAG test done that had as a deliverable, the unit SAG pinion energy required which in this case was to grind the ore represented by the samples, from a feed size F_{80} of 152 mm to 80% passing 1.7 mm, and a simple adjustment procedure in case the SAG product size needed to be adjusted. Bond rod and ball mill work indices are readily converted to pinion energy for rod and ball mills but not for SAG mills.

Reproducibility, while not studied in this paper is clearly a part of the meaningfulness of the data presented. It was clear from the data that there are large variances between the various results that stem from the imprecision of the test measurement and/or the selection of the sample tested.

TEST RESULTS

Test results have been summarized in the following tables and analyzed in Figures where appropriate. Table 1 gives the particulars on the composite samples that were tested at the four laboratories.

Table 1: Samples Received

Composite	Remarks
1	Composite of 5 special samples
2	Composite of 12 special samples
3	Composite of 1 special sample
4	Composite of 2 special samples
5	Composite of 3 special samples
6	Composite of 1 special sample
Original	600 kg grab sample tested at Dawson only

Specific Gravity Tests

Specific gravity tests were done at all four laboratories by 6 different methods. The results are presented in Table 2 below.

Table 2: Summary of Specific Gravity Tests

Specific Gravity Method	**Tested By**	**Composite Number**						**Avg of 6**
		1	**2**	**3**	**4**	**5**	**6**	
Average of 2 pycnometer methods	Hazen	**2.93**	**2.91**	**2.74**	**2.85**	**2.86**	**2.75**	**2.84**
Average of 3 ASTM Method D 854	ATT	**2.86**	**2.82**	**2.68**	**2.78**	**2.81**	**2.71**	**2.78**
SAGDesign - Water displacement	Dawson	**2.76**	**2.82**	**2.54**	**2.81**	**2.75**	**2.82**	**2.75**
Phillips Enterprises Wax coated	Phillips	2.76	2.18	2.25	2.33	2.26	---	2.36
Weigh in/out of water (mean of 25)	Hazen	2.56	2.35	2.37	2.35	2.40	2.42	2.41

The first three results shown in Table 2 are in reasonable agreement with each other. Wax coating clearly yields the most accurate result with regard to the real density of ore in-situ in the mine or in a dry crushing circuit, but for grinding calculations where the ore is in continuous contact with water, the pycnometer, ASTM D 854 and Dawson methods are more relevant.

Standard Comminution Tests

These are tests which up to the present have been an integral part of many comminution studies. This is important data when comparing with JK Drop Weight and SAGDesign results. Results are shown in Table 3. Headings for each column are composite sample numbers, defined above.

Table 3: Summary of Usual Comminution Tests

Standard Tests	**By**	**1**	**2**	**3**	**4**	**5**	**6**	**Avg of 6**
Bond Crushing Wi, kWh/t	Phillips	9.0	11.1	5.0	7.1	7.6	--na--	8.0
Bond Rod Mill Wi, kWh/t	Hazen	12.7	13.5	7.0	10.1	11.9	12.5	11.3
Bond Ball Mill Wi, kWh/t (Crushed ore)	Dawson	8.3	10.4	6.6	6.5	8.0	10.7	8.4
Bond Abrasion Test A_i , grams	Hazen	0.01	0.06	0.08	0.10	0.09	0.39	0.12
UCS, psi (average of 3 subsamples)	ATT	7260	4343	890	860	1913	1970	2873

It is clear from these results that Composites 3, 4 and 5 are the softest of the 6 because all 5 of the methods used indicated the same trend of softness for these three composites. Considering that the Bond CW_i and the standard Bond BM W_i both recorded average values of 8 kWh/t, it was surprising that the Bond Rod Mill W_i average was 11.3 kWh/t. Since the ore is unusually soft, the Rod Mill W_i is probably irrelevant in determining required power for the SAG mill.

Drop Weight Tests

Drop Weight tests were done at Hazen and analyzed by Contract Support Services, Inc.

Table 4: Summary of 6 JKTech Drop Weight Tests

JKSimMet Parameters	**By**	**1**	**2**	**3**	**4**	**5**	**6**	**Avg of 6**
A (maximum breakage)	CSS	42.5	63.5	68.1	61.1	57.3	60.5	
b (relation energy vs impact breakage)	CSS	2.28	1.58	2.30	2.38	2.18	2.03	
A x b (overall AG-SAG hardness)	CSS	96.9	100.3	156.6	145.4	124.9	122.8	
t_a (abrasion parameter)	CSS	1.48	1.35	2.00	2.27	1.66	2.02	
Relative to JKSimMet Database								
A x b Database Rank %	CSS	85	85	94	93	90	90	89
t_{10} @ E_{cs} = 1 kWh/t Database Rank %	CSS	69	89	97	94	89	91	88
t_a Database Rank %	CSS	93	91	96	97	95	96	95

The three Composites 3, 4 and 5 were again the three softest. The A x b factors were the highest for these three samples. The average results are all in the softest 12% of all samples tested by JKTech. Composites 1 and 2 were the hardest with respect to abrasion breakage resistance.

Tenke results are compared to the JKSimMet Database in Figure 1 below. This Figure is not an original but a recreation to show the comparison of Tenke samples with the JKSimMet Database.

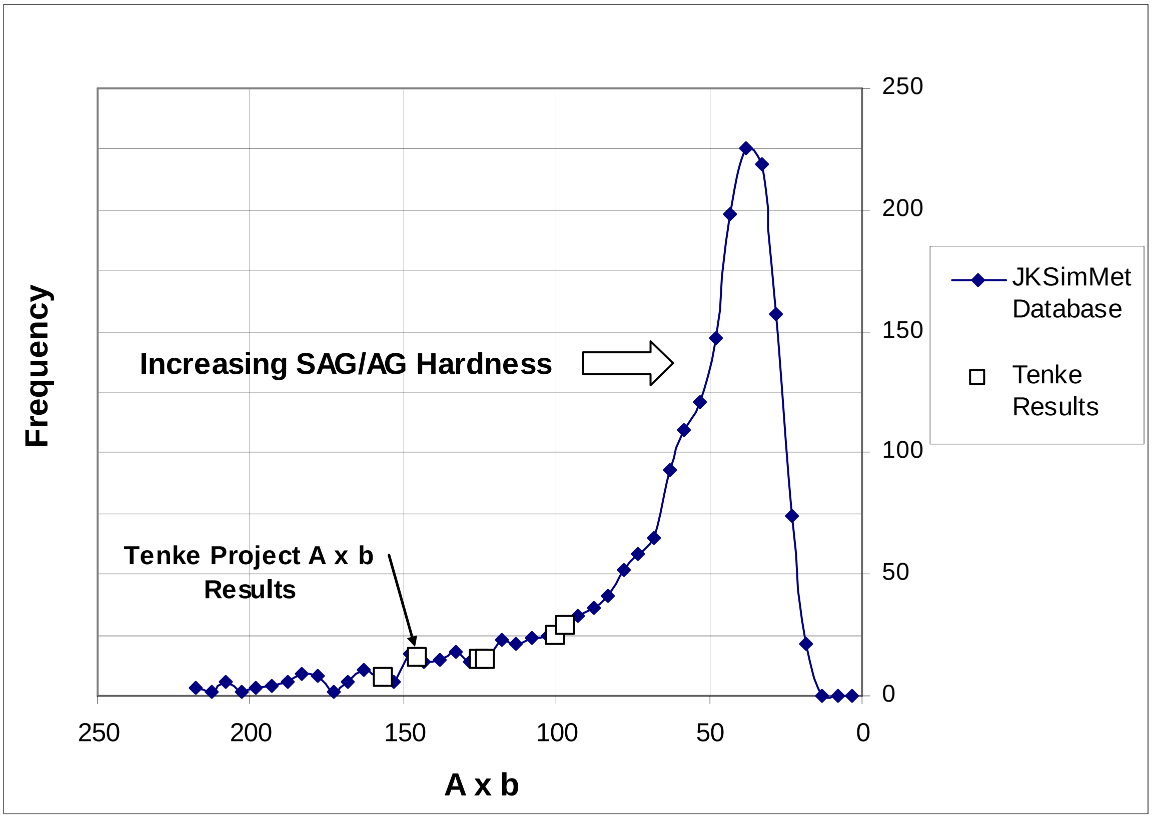

Figure 1: A x b - JKSimMet Database (approximation)

Values for A x b are all close to or above 100 and this corresponds to ores that are "moderately to very soft with respect to impact breakage resistance and are very soft with respect to abrasion breakage resistance". (See Table 4 above). This is a quote from the Hazen report of testwork.

SAGDesign Tests

SAGDesign results are given in Table 5 below. Here again composite samples 3, 4 and 5 showed the lowest requirement for SAG pinion energy. Then, in order to understand the relationship between these results and other samples that have been tested, all of the SAGDesign tests to date were listed and sorted in order of decreasing SAG pinion energy required to grind from F_{80} 152 mm to T_{80} 1.7 mm. Since only 63 tests have been done to date the results are not as statistically representative as the JKSimMet Database but nevertheless, the results ranged from 85 to 99 % of the softest ores tested to date.

Table 5: Summary of 7 SAGDesign Tests

SAGDesign Results	**1**	**2**	**3**	**4**	**5**	**6**	**Original**	**Avg of 7**
sg - water displacement	2.76	2.82	2.54	2.81	2.75	2.82	2.91	2.77
Revolutions (to achieve T_{80} 1.7mm)	450	449	302	260	229	465	574	390
Weight of ore in mill, grams	6739	6608	6921	7359	7087	6634	6889	6891
Pinion kWh/t to T_{80} 1.7mm	3.39	3.43	2.24	1.85	1.67	3.55	4.27	2.91
Bond BM Wi, kWht (SAG ground ore)	8.91	11.33	7.61	7.77	9.46	11.75	8.32	9.31
Pinion kWh/t to T_{80} 200 microns	4.14	5.27	3.54	3.61	4.39	5.46	3.87	4.32
SAG + BM Pinion kWh/t	7.53	8.70	5.77	5.45	6.07	**9.01**	8.13	7.24
Relative to SAGDesign Database								
kWh/t to T_{80} 1.7mm D'Base (63) Rank %	93	91	96	98	99	90	85	93
Bond Wi, kWh/t - D'Base (60) Rank %	91	83	98	96	88	76	94	89

These results from Table 5 are analyzed in Figures 2 to 5 below.

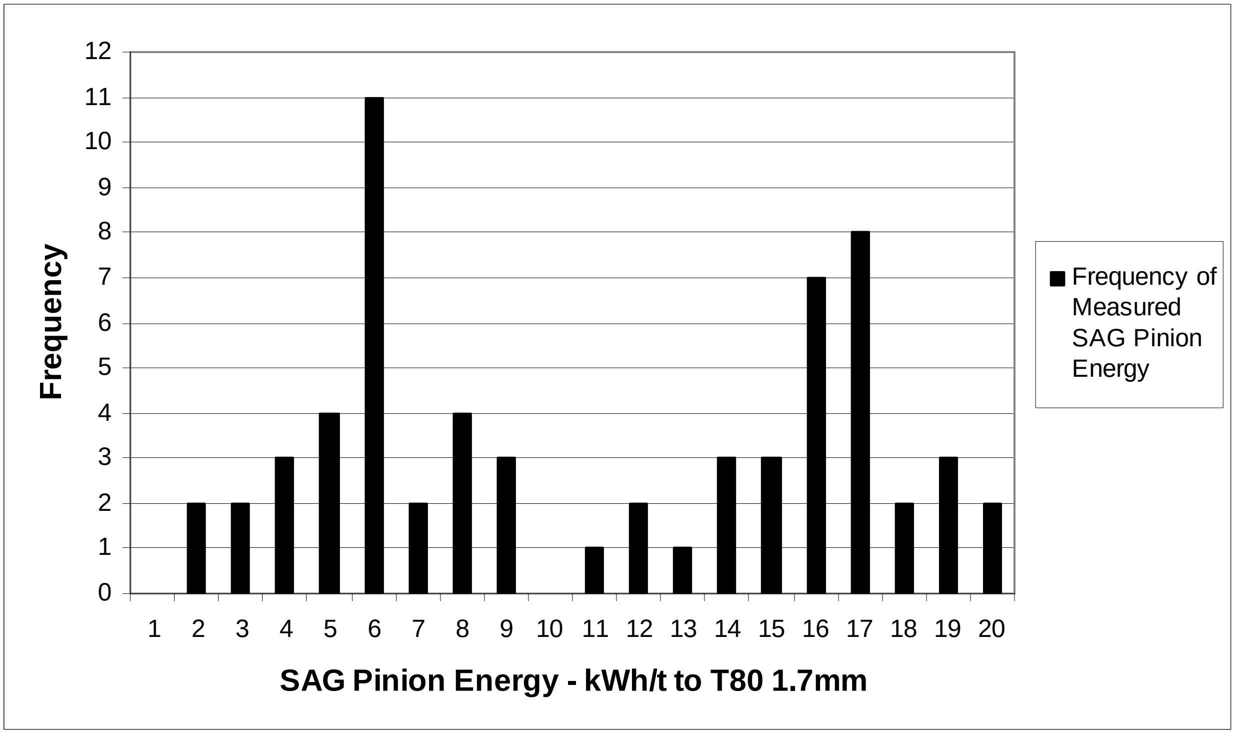

Figure 2: SAG Pinion Energy - SAGDesign Database

Figure 2 is very interesting with regard to what is being measured in the SAG mill phase of the SAGDesign test. The energy levels are spread evenly over the entire hardness range. Unlike the Drop Weight Test, the SAGDesign test also measures abrasion grinding that is being done in the SAG mill. Since a large portion of the energy in a SAG mill is consumed by abrasion grinding, from a design perspective SAG mill design energy is very useful information to have.

It is also worth noting that the hardest ores required up to 20 kWh/t to grind from F_{80} 152 mm to a product size of 80% passing 1.7 mm. The Tenke samples required between 1.7 and 4.3 kWh/t to do the same size reduction.

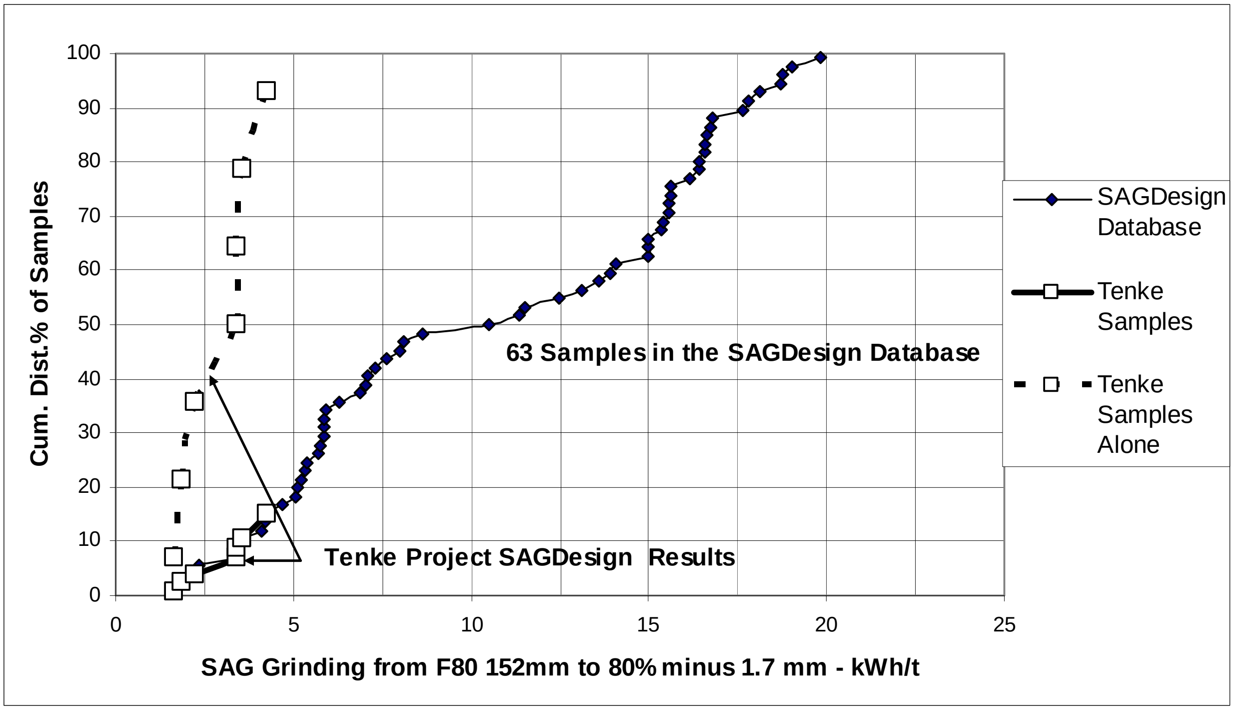

Figure 3: SAGDesign Database Variability of Measured SAG Pinion Energy

Figure 3 clearly shows the relation of Tenke samples to the SAG pinion energy database by plotting pinion energy against cumulative sample distribution for increasing hardness.

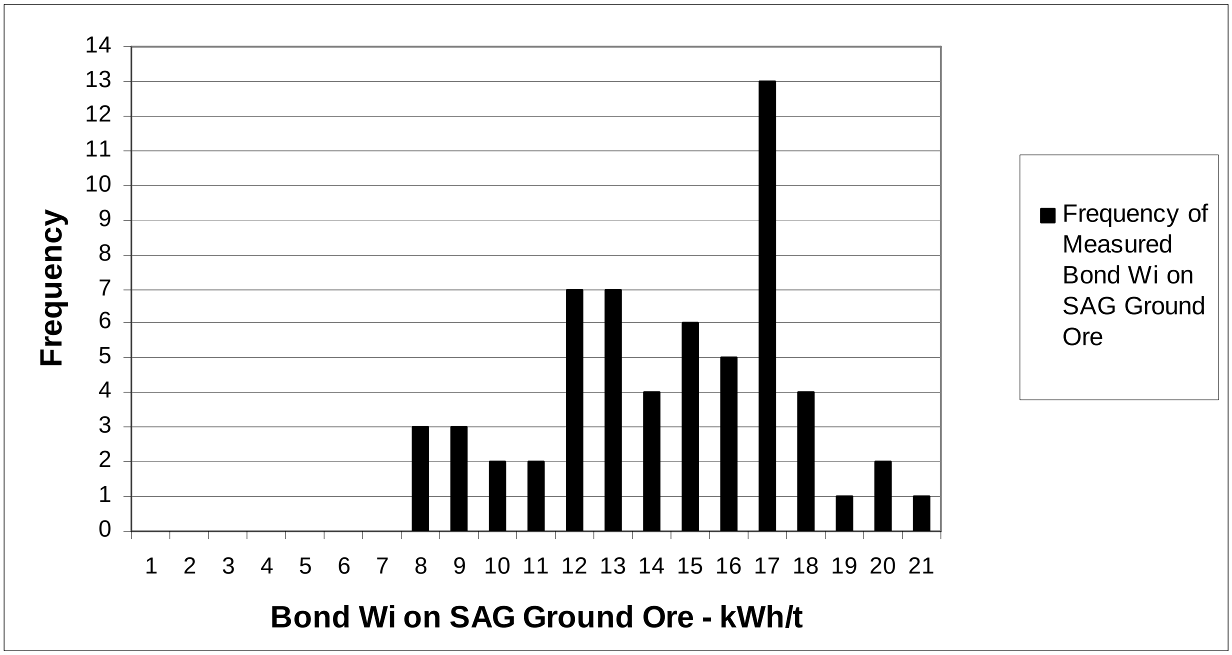

Figure 4: Bond BM Wi - SAGDesign Database

Figure 4 examines the Bond BM Work Index data from the SAGDesign tests. This data is all obtained from doing Bond BM W_i tests on SAG ground ore. In Table 6 below it is seen that the Crushed Bond Ball Mill W_i test gives a lower result than when the ore is ground in a SAG mill. For Tenke samples the average difference was 0.9 kWh/t higher for the SAGDesign Bond test. The reason for this is that a SAG mill quickly grinds the soft material and so naturally the coarse particles remaining represent the harder fractions in the feed. It is therefore submitted that the SAGDesign Bond result is the proper one to use when designing a ball mill for SAG ground ore.

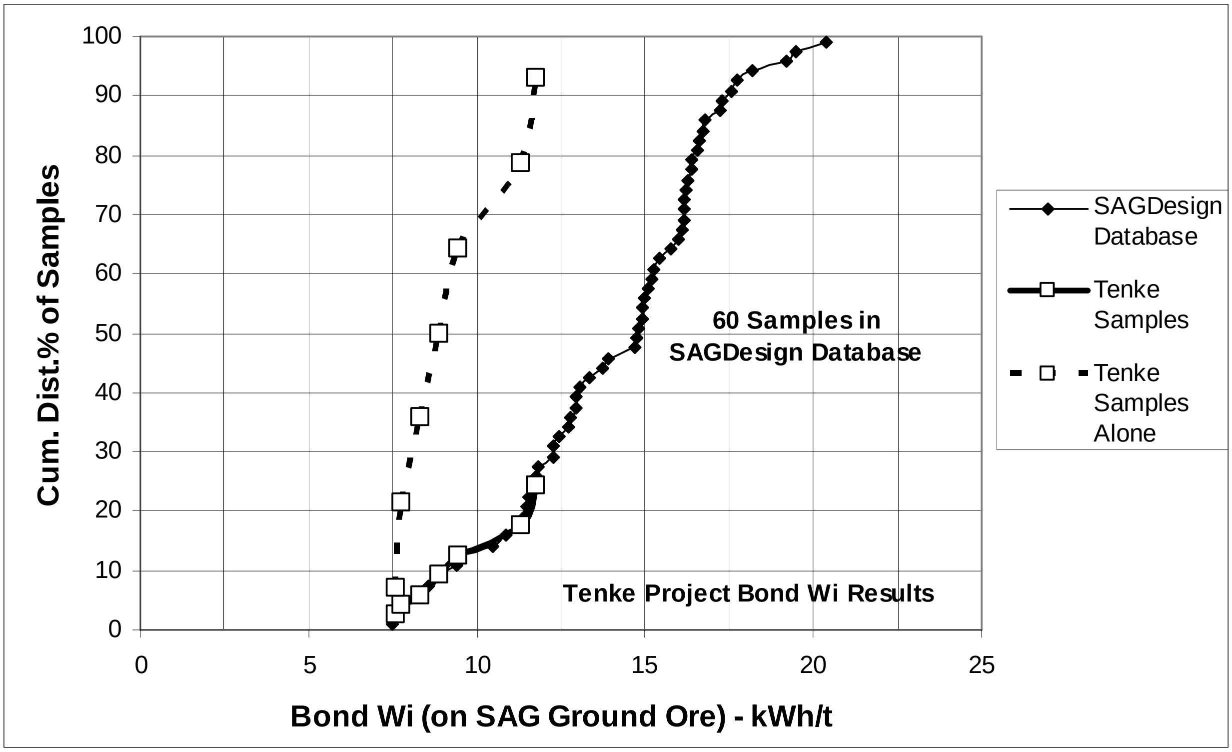

Figure 5: SAGDesign Database Variability of Measured Bond Wi

Figure 5 gives the variability of the Bond Wi measurements for Tenke compared to the SAGDesign database. This again clearly shows that the Tenke samples are among the 15% of the softest samples tested to date. Only 60 samples have corresponding Bond data.

SUMMARY AND COMPARISON OF ALL TESTS

In order to have a second look at how these various tests compare, the following Tables (6 and 7) and Figures (6 and 7) have been prepared. This data has all been presented above but for clarity it has been organized and sorted according to increasing Bond BM Wi as measured by the SAGDesign test. The SAGDesign test is known to give good SAG results. (This refers to the previously reported reproducibility when duplicate SAG tests are done). The Bond BM W_i is a standard test that yielded the best comparison with other tests when the data was sorted this way.

Table 6: SAGDesign Pinion Energy Variability Analysis - Equal Wt.% of Ore per Sample

Composite Sample Description	***Original***	**SAGDesign Results**			**Specific Energy**			**Wt. %**
	Comp.No.	**Bond BM Wi-kWh/t**		**SAG**	**SAG Mill**	**Ball Mill**	**Total**	
		Crush	**SAGD'n**	**kWh/t***	**kWh/t***	**kWh/t****	**kWh/t**	
Upper Ore Zone Trench	1	8.3	**8.9**	3.39	3.39	4.14	7.53	8.3
Lower Ore Zone Trench	2	10.4	**11.3**	3.43	3.43	5.27	8.70	8.3
Intermediate Ore Zone Trench	3	6.6	**7.6**	2.24	2.24	3.54	5.77	8.3
Upper Ore Zone Adit	4	6.5	**7.8**	1.85	1.85	3.61	5.45	8.3
Lower Ore Zone Adit	5	8.0	**9.5**	1.67	1.67	4.39	6.07	8.3
Intermediate Ore Zone Adit	6	10.7	**11.8**	3.55	3.55	5.46	9.01	8.3
Original Sample - Upper Zone Grab	*1st test*	*6.5*	*8.3*	*4.27*	*4.27*	*3.87*	*8.13*	*not incl.*
Average of 7 samples		8.4	9.3	2.91	2.91	4.32	7.24	
	**grinding from F_{80} 152mm to T_{80} 12M*				*** grinding to P_{80} 200 microns*			

Figure 6 plots the sample distribution % against SAG ground Bond BM W_i, SAG pinion energy, and standard Bond BM W_i when sorted by increasing SAG ground Bond BM W_i. This clearly shows the difference between SAG ground feed and crushed feed for the Bond work index tests. There is a lack of correlation in these results that could relate to the tests or to the sub samples used. This information is used again in Fig. 8 where the mill design parameters were selected.

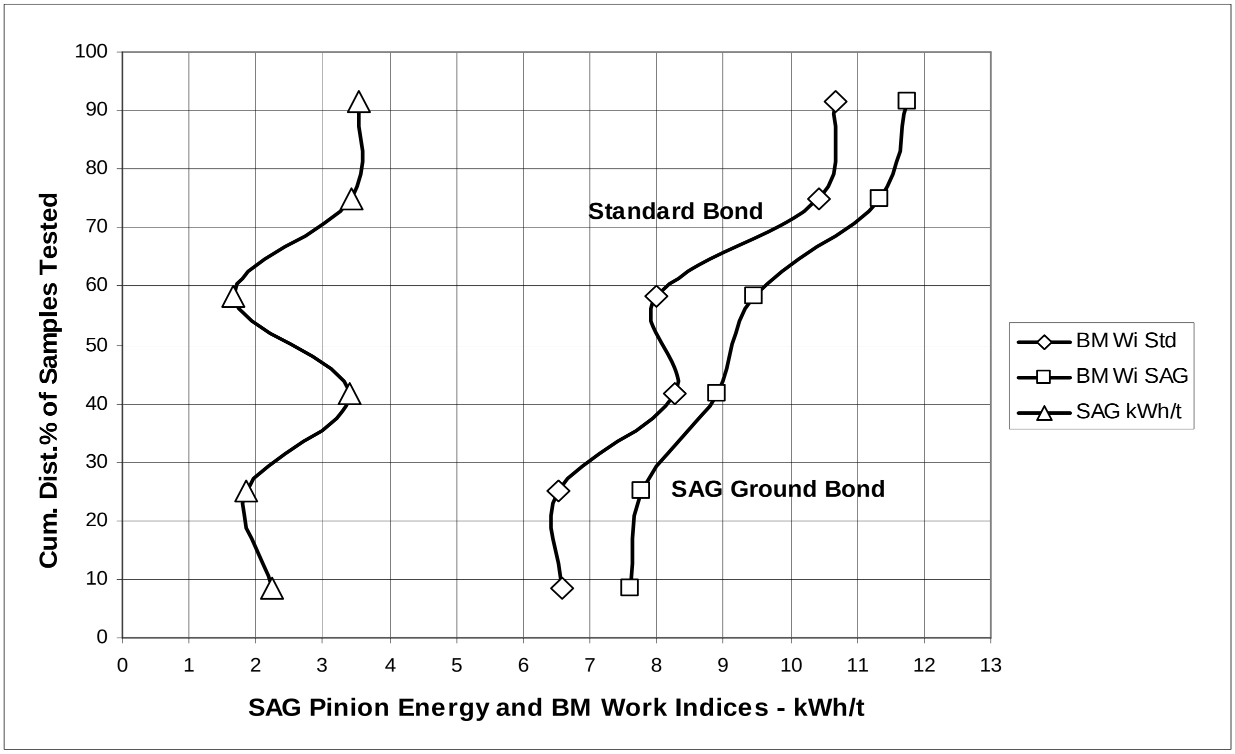

Figure 6: Data Sorted by Increasing SAGDesign Bond W_i (SAG Ground ore)

Table 7 and Figure 7 related to it, compares the other parameters against each other when sorted by increasing SAG ground Bond BM Wi. The apparent contradiction in the (A x b)/10 factor in Figure 7 is explained by the fact the for the JKTech parameters, increasing hardness is related to a decreasing value for this parameter. So the apparent lack of correlation is not real. In order to use the JKTech data the JKSimMet software package is also required – and this in turn can be used to simulate the grinding circuit for a specific mill sizing and configuration.

It is suggested however that since the coarse breakage parameters are not the major power consumer in many SAG mills that other data is required to accurately estimate the abrasion energy needed to grind the ore tested and correctly size the mills.

Table 7: Other Comminution Tests on the Same Samples

Composite Sample Description	***Original Comp. No.***	**RM Wi kWh/t**	**A x b**	**UCS psi**	**SG, g/cc Dawson**	**Wt. %**
Upper Ore Zone Trench	1	12.7	97	7260	2.76	8.3
Lower Ore Zone Trench	2	13.5	100	4343	2.82	8.3
Intermediate Ore Zone Trench	3	7.0	157	890	2.54	8.3
Upper Ore Zone Adit	4	10.1	145	860	2.81	8.3
Lower Ore Zone Adit	5	11.9	125	1913	2.75	8.3
Intermediate Ore Zone Adit	6	12.5	123	1970	2.82	8.3
Original Sample	*1st test*	---	---	---	*2.91*	*not incl.*
Average		11.3	125	2873	2.77	

The above information is compared in Figure 7 below. The imprecision of these measurements is evident by the irregular fluctuations when compared to each other. It is noted that the ore SG also increases with Bond BM W_i and perhaps SG plays a role in mill design for these ores.

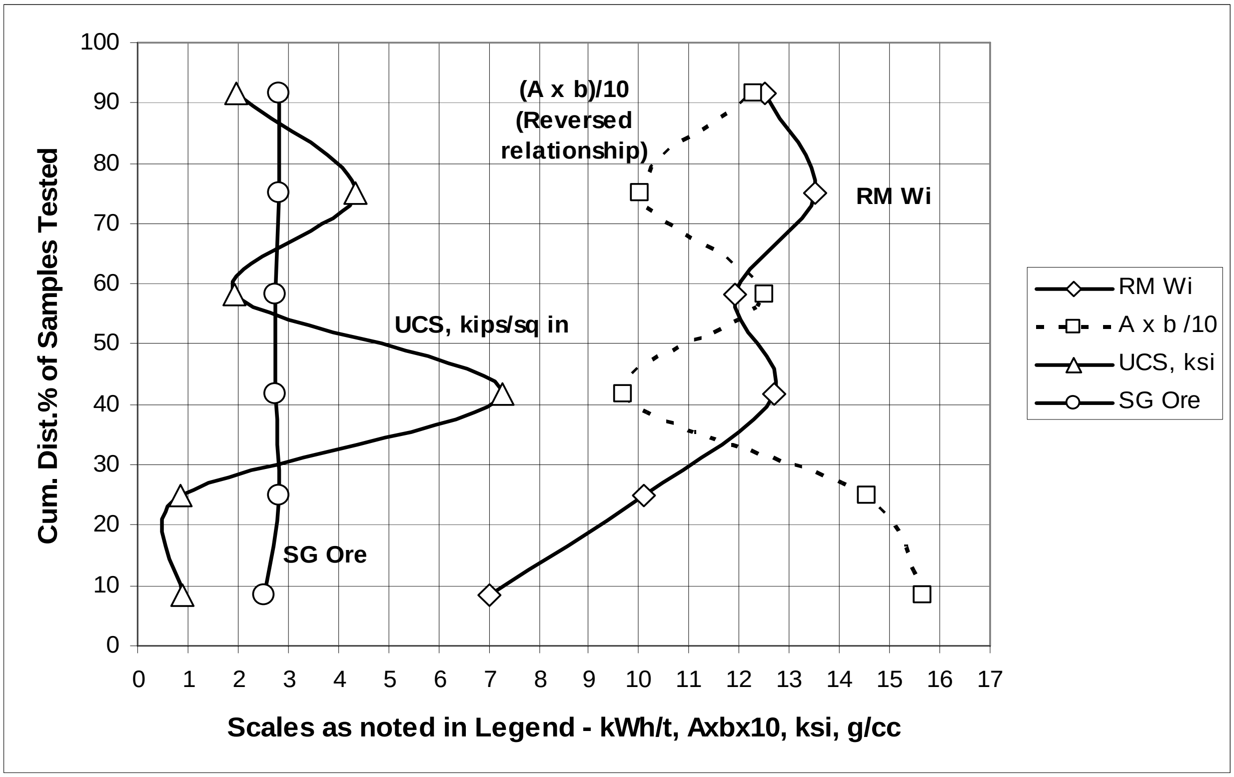

Figure 7: Data Sorted by Increasing SAGDesign Bond W_i (SAG ground ore)

USING THE DATA

The purpose for doing this comminution test work was to determine the power requirements for the grinding circuit and the required mill sizing for the Tenke Project and to offer the client the assurance that this work has been done correctly. Obviously the cost of getting the final result is a factor and the time required to do the tests and complete the design is also important.

In this case, the SAGDesign results were used to design grinding mills for the project. Figure 8 shows how the design energy level was selected.

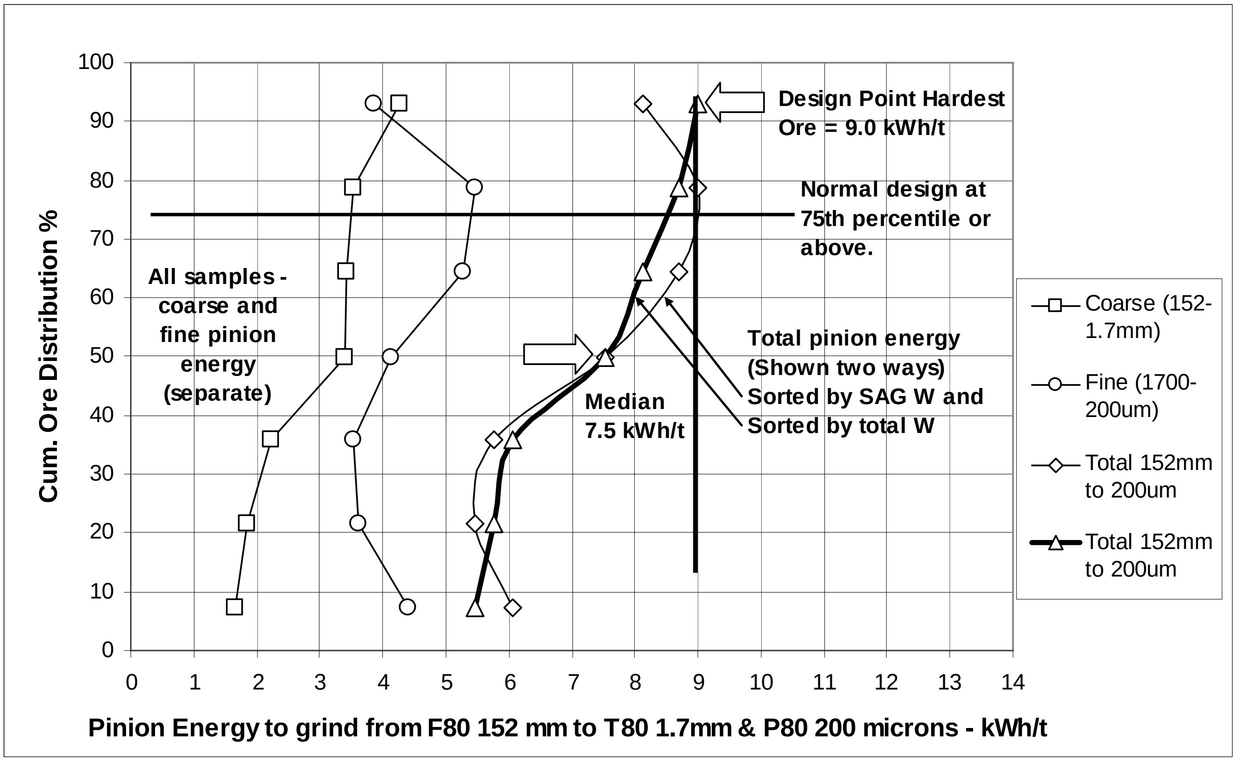

Figure 8: Tenke Project Ore Hardness Variability in Coarse and Fine Stages

By selecting the pinion energy level equal to 9.0 kWh/t and the Bond BM Wi = 11.5 kWh/t the design was done. Using this data the recommended mills can be (were) selected.

The SAGDesign work is of a reasonable cost. The duration of the testing and compilation of the results can be done in a timely manner allowing a firm result to be achieved.

The cost, duration and quality of the mill design are not well known if this approach is not taken. But one thing is clear and that is that the SAGDesign program is the only method that has the support of a leading grinding mill manufacturer as a basis for grinding performance guarantees for grinding equipment purchased from that supplier.

CONCLUSIONS

Considering the databases involved in comparing JKSimMet and SAGDesign results, both methods gave results in the same comparative range, that is, that the Tenke ore samples were among the 10% softest of all ore samples tested to date.

From the above and the correlation with other hardness measurements it is therefore concluded that the SAGDesign tests correctly identified the real grinding hardness of the ore samples tested.

Based on the shape of the SAG pinion energy versus frequency graph in Fig. 2, the SAGDesign test is measuring much more that just the impact breakage energy. It measures design energy.

Impact breakage energy is not the main factor in selecting power required for SAG grinding. It is well known that the combination of impact breakage and abrasion energy is needed.

In SAG Mill design often there is too much emphasis placed on Drop Weight tests. In most cases the provision of required impact breakage is a secondary result of providing enough total power to grind an ore. Controlling the ball size and ball charge level usually provides for the impact breakage.

The lack of reproducibility in comminution test measurements is a problem that demands many more measurements. The best and most cost effective way is to use the most accurate test.

The SAGDesign Test is such a test and does a good job of measuring required SAG pinion energy level and the Bond ball mill work index. (See reference 8 below).

High testwork costs and lack of samples for testing have, and will in the future discourage the use of more samples and ‘usual’ grinding tests, especially for small mining companies.

The Bond Rod Mill work indices were much higher than the Bond Ball Mill work index values. Because the ores were so soft, the effect of these Bond RM W_i results on required SAG grinding energy should probably be ignored for the Tenke project.

The use of Bond equations to calculate pinion energies in ranges where the mill feed size exceeds normal rod mill feed is a mistake and leads to lower than required SAG pinion energy. Fred Bond did not envision the use of these equations for other sizes than he had data to support.

A common problem here is that using former technologies, a client’s design engineer cannot accurately design a SAG mill from basic measured parameters.

Judging by the number of design errors that have been made in the last ten years alone is reason enough to state that a more fundamental approach is required for SAG mill design.

It is important that we all understand the fundamentals of SAG mill design. Otherwise mistakes will continue to happen.

RECOMMENDATIONS

Continue doing evaluations like the one detailed in this paper. If the conclusions presented above are correct, the results and observations noted will be reproducible on other projects.

Include MacPherson Autogenous Work Index Tests in future evaluations in order to understand how these results compare to SAGDesign testing.

Evaluate the reproducibility of every comminution test that is used and follow up with benchmarking of actual mill performance versus predicted from test work results. If we don't know how accurate the result, it will be difficult to make good judgments in designing new mills.

When time and budget constraints exist, include the SAGDesign Test in the test work program. It is fast, accurate and the program costs less overall than many of the other methods. It also carries a throughput/grind guarantee for mills designed by Starkey using the SAGDesign program, when the mills are purchased from Outokumpu Technology. Other reputable mills of the same size will perform equally well.

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