ACCURATE, ECONOMICAL GRINDING CIRCUIT DESIGN USING SPI AND BOND

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ABSTRACT

The development of the Minnovex SAG Power Index (SPI) Test in Canada has created a new and accurate way to measure ore hardness in a SAG environment. Coupled with the standard Bond Ball Mill Work Index Test it is now possible to determine from these two relatively inexpensive laboratory tests, the amount of energy required to grind an ore from the primary crushed size to the desired liberation size. By testing multiple samples to discover where the hard and soft ore zones are located, the representative hardness distribution for the ore body can be determined and grinding equipment selected that is capable to meet production targets for all mining areas of the deposit.

In the last century, it was deemed prudent to select up to 50-tonne samples of ore for Semi Autogenous Grinding (SAG) pilot plant tests and a second 5-tonne sample for metallurgical pilot plant work. The methods outlined in this paper show how the 50-tonne sample is no longer required for SAG design because it is better to measure the representative hardness distribution of the ore body than the hardness of a "chosen" representative sample. This is demonstrated to be true by the fact that the lower horizons of an ore zone cannot initially be accessed to recover 150mm pieces, and the bulk samples taken, rarely represent the desired design hardness of the ore. Median hardness will not yield a good result in most cases and a clear understanding of the location and extent of the hardest zones is imperative to achieve a truly successful grinding circuit design.

This paper discusses two plants (Kubaka and Agnico Eagle) that have been designed using SPI and Bond with no pilot plant test backup. Both have been very successful in that they can grind design tonnage on the hardest ores in the mine. This guarantees that the mine's profitability is protected in any mining sequence. It also allows the extra power to be converted to higher throughput on softer ores if additional cash flow is needed. The advantages from the owner's point of view are dramatic. This procedure will be attractive as well when considering the costs for test work, and the samples for testing. Existing diamond drill core is normally used and this allows the inclusion of data from the deepest regions of the mine. In addition, it is also clear that the decision to use a crusher can now be made at the design stage of a project based on measured parameters and the estimated capital costs of alternative designs.

Keywords: Grinding, SAG, Design, Bond, SPI,

INTRODUCTION

The purpose of this paper is to describe a new method that has been used successfully in Canada, to design SAG/ball mill grinding circuits. This new method was developed to allow design engineers to create meaningful grinding circuit designs early in the project development cycle at or before the feasibility study stage so that any problems or uncertainties could be addressed as part of the feasibility study. Previous experience has shown that if the grinding mill sizes are not accurately determined at this time, it can lead to production problems or project delays while the correct information for grinding design is developed.

It has been evident for many years, and agreed to in principal by renowned SAG experts including the late Art MacPherson, that SAG design test work needs to be done at a number of points in the ore body in order to understand hardness variance. Now that there are two successful SAG operations based on this technique, it will be helpful to look at the theory behind these designs, to discuss the results and to offer constructive guidance for achieving continued success and improvement in the application of these principles. We also suggest that it is the responsibility of the Senior Consulting and Design Engineers to become involved in the selection of samples that are to be used for plant design. With this involvement, they have the opportunity to offer performance guarantees for the process being created.

There have been two plant designs completed, built, and reported in the literature to date. They are Kubaka[1] and Agnico-Eagle[2]. Kubaka was a new grassroots project in the Russian Far East while Agnico-Eagle was a plant expansion in north-western Quebec where a new SAG mill was added to an existing ball mill grinding circuit. Both plants were designed using SPI (SAG Power Index) and Bond (Ball Mill Work Index) tests. Both of these projects have also been written up as technical papers. Kubaka's performance was reported in January 2001 at the Canadian Mineral Processors Conference in Ottawa, while Agnico-Eagle was written up for the Vancouver SAG Conference held in October 2001.

GRINDING POWER MEASUREMENT THEORY

It is interesting to trace the development of the tests used for grinding power measurement dating back to Bond's Third Theory of Comminution. In a paper written for British Chemical Engineering in 1961, Fred Bond stated in the opening paragraph, "Comminution theory is concerned with the relationship between energy input and the product particle size made from a given feed size. It continues to be a rich field of controversy." That this remark is still valid today after 40 years is no surprise to those who have been involved in grinding circuit design. It happened that just as Bond was concluding his work to define how to design rod and ball mills in an accurate, economical manner, the concept of dry autogenous grinding (AG) was being introduced. Not far behind was dry semi-autogenous grinding (SAG), as engineers and operators quickly learned that adding steel to an existing AG mill would often significantly increase the throughput. The addition of water to the milling process and the removal of slurry by slotted grates to retain the charge, allowed wet grinding to replace the dry air swept mill as the grinding method of choice. At the same time dusting problems in the dry mills were eliminated.

Bond's three main tests, still used today for sizing mills and crushers were: the Bond Impact Work Index Test, The Bond Rod Mill Work Index Test and the Bond Ball Mill Work Index test. All of these tests are done in a dry environment and are empirically calibrated against many actual plant measurements including feed and product sizes and power consumed. The results of this work produced empirical equations that related energy requirements directly to the hardness of the ore, and inversely to the square root of the product particle diameter minus that of the feed particle diameter in the case of the rod and ball mill work index tests. The "energy register" (or Work Index) for any product was set to be the energy required to reduce a particle of infinite size to 80% passing 100 microns, a common product size in mineral processing applications. By considering the energy input of any finite feed size and deducting it from the energy of the comminuted product, the input energy to grind the ore is calculated by difference. The basic Third Theory equation is:

$$W = 10Wi/P^{0.5} - 10Wi/F^{0.5} \quad (1)$$

Where Wi is the work index, W is the work input (motor output) and F and P are the 80% passing sizes of the feed and product respectively, in micrometers.

This relationship between feed and product energies and the calculation by difference of the required grinding energy is the basis for the two Bond Rod and Ball Mill Work Index Tests. Both were confirmed by empirical tests in industrial plants where feed and product sizes and consumed energy could be measured. (Benchmarking).

Art MacPherson was a pioneer in the introduction of AG and SAG mills to industry. Through strength of character and a keen perception of improving grinding economics he was able to convince corporate directors to purchase large and larger SAG mills, matching industry's need to process lower grade ores at higher tonnage. At the same time MacPherson developed a dry SAG test using an air swept 457mm (18 inch) diameter by 152mm (6 inch) long test mill. Starting with minus 1.25 inch crushed ore and 16% by volume of steel in the test mill, the ore was ground in continuous mode to its natural grain size, or a product that could vary between 200 and 500 mircometers, depending on the sample tested. Then using measured power and Bond's equations an autogenous work index (AWi) for the sample was calculated. This measurement and calculation is valid at the product size produced.

Subsequent work by Minnovex Technologies Inc. showed that the AWi value is a variable, depending on the product size produced in a semi-autogenous mill [3]. MacPherson must have known this and corrected the AWi to reflect the "real" value at the design size used. But controversy exists with regard to the validity of these calculations. The perceived validity requires the acceptance of two things. First, that the equations developed for grinding ore in a predominantly steel environment, are still valid in an environment that is predominantly ore at a much coarser size, and second that the judgement factors applied (unpublished or explained) represent an accurate picture. It is easy to demonstrate that measurement of ore hardness variance as the AWi, is not a sensitive measurement because large SAG mills routinely produce product T80's that are greater than 2 mm while the test AWi is measured at about 350 micrometers. In simple terms, a large portion of the test energy measured in the autogenous grinding test is not applicable to the grinding done in the plant at a much coarser size.

It was felt from a practical perspective that by determining the SAG energy required to grind ore to a transfer size (T80) of 10 mesh (1.7mm), that the total grinding energy could be calculated by adding the energy calculated from the Bond Ball Mill Work Index measurement. It was no coincidence that the Bond test started with feed prepared to all passing 6 mesh (or about F80 = 10 mesh). Expressed as an equation:

$$W_{\text{Total}} = W_{\text{SAG}} + W_{\text{Ball Mill}} \tag{2}$$

Where W is the grinding mill work input in kWh/t.

For the above reason, the Starkey SAG mill was built in 1991 to measure the energy required to grind ore to a size of 80% passing 10-mesh or 0.17 mm (T80) by grinding small drill core samples to precisely that size. The SAG Power Index (SPI) Test was then co-developed by Starkey and Minnovex Technologies Inc. of Toronto into a commercially acceptable way to measure required SAG energy by benchmarking SAG and AG mills in a large number of plants. One outstanding achievement of this program (commercial development), was the discovery that in the range of ~0.4 to ~3mm T80, the energy consumed in either a SAG mill or a ball mill to make a size reduction in this range would be equal and could be estimated using Bond equations.

Other investigators have contributed greatly to the understanding of SAG and AG energy requirements, notably JK Tech with the Drop Weight test and those involved with the modeling of grinding process variables. Modeling is an excellent way to improve the performance of existing mills. This paper however is focussed on those tests (SPI and Bond) that are used for new plant design in the context of getting the right answer at an affordable price. It needs to be stated here that at the time grinding test work is done, there is no cash flow from the property and there is uncertainty as to whether or not there is a mine.

ENGINEERING DESIGN PRINCIPLES

There are an increasing number of investigators and designers who accept that a representative hardness distribution function for an ore body is required for the best design of a grinding circuit. Previously, representative samples for pilot plant testing were considered the norm. But if one considers the depth of most ore bodies and the requirement to test minus 200mm ore samples, it is immediately clear that either a great deal of money will be spent to get the samples or the sample tested will not be representative. The latter is the more common scenario and most failures of SAG or AG grinding circuits can be traced directly to a non-representative sample or one that is softer that a large part of the orebody.

As professionals in the business of grinding design we must accept more responsibility in becoming involved in the selection of the samples. If necessary, a knowledgeable mining engineer should be hired – one who understands geology, ore reserves and milling. This is one job that cannot be left to others without peril to the very objective of the exercise.

Once the representative hardness distribution function has been defined, several points immediately become obvious. For example, maximum hardness (kWh/t to grind the hardest ore to T80 10 mesh or other selected transfer size), median hardness, average hardness, 90th percentile of hardness variability (top decile), 75th percentile of hardness variability (top quartile). By selecting the design hardness point from this data several beneficial considerations can be introduced. First, by designing for maximum hardness, the plant can be assured it will grind design tonnage at all times. This will eliminate periods of reduced cash flow that can severely hamper a mine's ability to meet financial obligations and jeopardize required exploration programs. Second, it becomes possible to identify marginal ore at the extremities of a zone that will result in reduced throughput and really is not ore because of marginal grade. Third, the prior location of hard ore will allow mine planning to be done to avoid these zones at start up or at other times when financial commitments require extra, not reduced cash flow.

The decision on how to balance grinding capacity with the ability to overproduce is really not difficult when the relevant facts are known. What has not been fully understood in the industry is that hardness variability in most ore bodies ranges to plus or minus 50% from the median hardness with respect to the SAG grinding stage of the operation. Knowing that this variability is "normal" it stands to reason that it must be defined for good grinding design. Also of relevance is the relationship of ore grade to hardness. A number of sulphide ores exhibit softness in the higher-grade portions. But some gold ores on the other hand show that the hardest ore is the highest grade. In this situation it would be devastating for the plant to be designed for median power. Another key consideration in the engineering design of a grinding circuit is the likelihood of the ore reserves changing with changes in the metal price. While being "not part of the study" is the official engineering position, the client probably wants or needs to know what lies ahead in the "what if" world of changing economics.

It is also clear from the new method of designing grinding circuits that the decision to use a pebble crusher in the SAG/AG circuit is a technical and reasonably well-defined decision. In view of the potential to increase SAG throughput by up to 20%, and overall circuit capacity by about 10%, the decision to defer putting in a crusher at the start can be used for insurance (if grinding data is limited) or for expansion if slightly higher tonnage is forecast.

The firm conclusion to the foregoing discussion is that grinding circuits need to be designed from reasonably detailed laboratory data that can be quickly won from existing core, drilled to assess the grade of the deposit. Pilot plant work is an excellent way to confirm the design hardness of a given sample but the pilot plant sample should be selected because its hardness is known before it is mined.

In the case of the Kubaka and Agnico-Eagle designs, both plants were designed for maximum power and to always meet production schedules. Kubaka has done this and Agnico-Eagle will do so as well, based on the published data when harder ores are processed.

The decision to design the grinding plant to use maximum required power, or the top quartile of hardness variability, or to the median or some other level, is a decision for the client's selected design team. We do however suggest that the investment in grinding capacity is usually a good one in terms of the value of the additional throughput possible versus the cost of the extra capacity. The ability to produce design throughput at all times is usually appreciated by owners and shareholders alike.

SAMPLING

How many samples are required and where should they be taken are two questions at the top of every project manager's or owner's list. The more common situation is the case where budgets are limited. But the responsible management of the client's money leads to the conclusion that there needs to be a balance between sampling, testing, analysis of results and design engineering. It is indeed the designer's responsibility to produce the best possible design at the most reasonable cost. This paper has been written to demonstrate how this new method for grinding design meets these criteria.

Samples for SPI and Bond testing need to explore the point hardness variability of the ore body. In the case of open pit mines, one sample representing one bench blast is an ideal data point because that unit of ore could easily become feed for the plant during one or several days of operation. The development of detail at this level is important if the plant is to function in the intended way. The purpose of the sampling also has a bearing on what samples to take. For example, if the objective is simply to define the maximum hardness in the ore body, less samples will be required than to develop the full spectrum of hardness variability. Kubaka was designed on 6 samples because of the great difficulty in obtaining samples from the Russian Far East. Clearly, the representative hardness distribution was not well defined and the decision to design for maximum power was proper under those circumstances. In Agnico-Eagle's case, the design was based on 18 samples, carefully selected to represent as well as possible, the silicious gold and the sulphide base metal zones. Drilling was still underway when the samples were taken so again, it was proper, based on the data available, to design for maximum hardness.

In taking samples for SPI/Bond testing, special considerations need to be used for the different styles of ore zones being sampled. For example, small lenses need to be studied for variability across entire intersections so that the true hardness variance is understood. In the case of massive ore zones a grid approach may be better in order to understand ore hardness variability during the first 3 to 5 years of the mine's life. But also here there is good value to look at entire intersections, taking samples from consecutive core runs down the length of the drilled hole. In one case, an 800m long drill hole (all in ore) was sampled to produce 15 individual samples for SPI/Bond testing. Breaks were made when the obvious geology/mineralogy changed but it is also useful to break off each sample at one bench height intervals in order to meet the point hardness criteria mentioned above. Being practical is the main objective of the sampling engineer and the overall objective and budget in the end, governs the sampling decisions made.

Sample quantities are 2 kg for an SPI test and 10 kg for a Bond test. By doing Bond tests on every three SPI tests (classified to match hard, medium, and soft SPI results) the size of the SPI samples can be kept down to about 5 to 6 kg each. A better method would be to submit 12 kg for each sample so the testing program could be more flexible.

LABORATORY TESTING

The SPI Test

The main points involved in these laboratory tests are well described in previously published papers. The SPI test is available only at Minnovex Technologies Inc. in Toronto or at one of their licensed labs at AARL in Johanesburg or in Brazil.

The SPI test is done on 2 kg samples of carefully prepared ore to a specified size of 100% passing 19mm and 80% passing 12.7mm. The sample and steel charge are repeatedly ground and removed from the 305mm (1 ft) diameter by 102mm (4 inches) long Starkey SAG mill, until the ore portion has reached a fineness of at least 80% passing 1.7mm. The time required to accomplish this size reduction is the SPI, measured in minutes.

Benchmark tests in many plants have allowed the calibration of the SPI test to convert minutes into required energy to grind the ore to any specified size using the empirically derived equations to give energy at the SAG mill shell. The form for that equation is:

$$W = a * f(SPI/P^{0.5})^{b} \qquad (3)$$

Where a and b are empirically derived constants and P is the product 80% passing size as above.

Because many SAG and AG plants use primary crushed feed to about 80% minus 152mm, and the test itself uses a fixed feed it is not surprising that the resulting equations are a function of only the plant product size desired and not the feed. Obviously feed size is important and the calculated energy is adjusted to match the feed size. However in the case of new plant designs, unless there are specific plans to use fine blasting in the pit or finer than 152mm feed by crushing, the required SAG energy is best designed using the base data representing F80 152mm feed.

The Bond Ball Mill Work Index Test

The Bond Ball Mill Work Index test has been an industry standard for more than 40 years. It has worked well and energy requirements are calculated as motor output or pinion energy. Bond did this because there were so many different styles of drives in his data base that the drive efficiency had to be removed to get at the actual grinding energy. Bond tests are available at any well equipped ore processing research laboratory.

Care needs to be taken to preserve the accuracy and validity of the Bond test. Engineers sometimes take liberty with the beauty and apparent simplicity of the calculations. Some of the most common errors or omissions that can lead to erroneous results are noted here. Drying the sample before starting is important. And stage crushing to minus 6 mesh is important. Screening of the sample after grinding in the Bond mill needs to be thorough and accurate. Overloading the 100-mesh screen or using too short a shaking time on the rotap (or other device) can be a problem in achieving stability. Final screening of the product to obtain the P80 value must be done on 100 grams of the material, not the entire sample of up to 350g. When the entire sample is screened the result is that the P80 is more than 5 micrometers too high. It would be better instead to use the default P80 of 114 micrometers for the 100-mesh screen test. Another common problem is to use the 100-mesh closing screen for the Bond test (114µm P80) when the intended P80 for the plant to be designed is finer or coarser than 114µm. The test P80 should match as closely as possible the final design P80 for the plant. There have been cases involving special minerals such as mica, where the measured work indices at different closing screen sizes are dramatically different.

There are a number of correction factors that need to be applied to the Bond Wi to get the proper result. The two most important are the diameter factor and the fines factor. The diameter factor is becoming more important and with the advent of larger and larger mills that factor has become a larger and larger number. Specifically it is:

$$W \text{ (to calculate Wi) } = W_{input} \times (D/8)^{0.20} \quad (4)$$

It is also important to use the fines correction factor when grinds finer than 70µm are required.

$$W_{corrected} = W(P+10.3)/1.145P \quad (5)$$

Where P is the product which is finer than 70 micrometers and W is the power input.

These (and any other relevant) correction factors should be included in detailed assessments of ball mill grinding power using the Bond equations.

TYPICAL RESULTS

Agnico-Eagle and Kubaka were ores of fundamentally different hardness. The following tables give the basic design data that was used for each plant design. The data shown here differ slightly from the originally reported values because the two projects were done early in the development of the commercial SPI test, before the final calibrations were completed. For consistency the original SPI data in minutes has been used and design calculations redone to reflect the current values as they would appear today.

Other calculations are now done differently. Original SPI tests were calibrated to show the required power to be consumed at the motor. Different styles of drives including wrap around motors, are now used so the SPI values are calculated to show shell power (very nearly the same as pinion power). This standardizes the SPI power calculations with Bond Work Index power values where power is calculated and expressed as motor output (or pinion) power. Other factors used in this present analysis represent a solid basis for using the SPI/Bond grinding design technique. Synchronous motors, commonly used in North America, are shown as a 7% addition to required grinding power and an operating allowance has been included to acknowledge the fluctuations that occur during normal grinding operation. This allowance has been set at 10% for SAG mills and 5% for ball mills. A SAG mill should not be run above 90% of the nameplate load because today, motors normally have a 1.0 safety factor, whereas 1.10 is really required. Ball mills run with less fluctuation and the allowance is reduced to 5% or a safety factor of 1.05.

Basic grinding laboratory results are given in the following four tables along with the design calculations used to confirm the required power for these two plant designs.

Table 1. Kubaka SAG Grinding Test Results - Updated

Sample No.	Description	SPI Minutes (Sorted)	Pinion En'gy T80 1200um (F80 150mm) kWh/t	Gross Energy T80 1200um (at Motor) kWh/t	Required Motor Unit Energy kWh/t	Required Motor[1] for 81 t/h HP
7	Open Pit	58	7.3	7.8	8.5	922
12	Underground	92	9.3	10.0	10.9	1188
8	Open Pit	115	10.6	11.3	12.4	1343
10	Open Pit	120	10.8	11.6	12.7	1375
11	Open Pit	120	10.8	11.6	12.7	1375
9	Open Pit	152	12.3	13.2	14.4	1566

Note [1] – Allow 10% for operating safety factor.

Table 2. Kubaka Ball Mill Grinding Test Results

Sample No.	Description	Bond BM Wi kWh/t (200 mesh)	Pinion En'gy P80 53um[1] (From Bond) kWh/t	Gross Energy P80 53um (at Motor) kWh/t	Required Motor Unit Energy kWh/t	Required Motor[2] for 81 t/h HP
1	Underground	15.1	15.5	16.6	17.4	1887
2	Underground	13.8	14.2	15.2	15.9	1724
3	Open Pit	15.5	15.9	17.0	17.8	1936
4	Composite #1	15.0	15.4	16.5	17.3	1874
5	Composite #2	15.5	15.9	17.0	17.8	1936
6	Open Pit Comp.	17.6	18.1	19.3	20.2	2199
	Average	15.4	15.8	16.9	17.7	1926

Note [1] – Includes fines and diameter correction factors.
Note [2] – Allow 5% for operating safety factor.

Table 3. Agnico-Eagle SAG Grinding Test Results - Updated

Sample No.	Description	SPI Minutes (Sorted)	Pinion En'gy T80 238um (F80 150mm) kWh/t	Gross Energy T80 238um (at Motor) kWh/t	Required Motor Unit Energy kWh/t	Required Motor[1] for 202 t/h HP
11	DD Core	9.9	4.3	4.6	5.0	1356
14	DD Core	11.7	4.7	5.0	5.5	1487
7	Initial Samples	14.4	5.3	5.6	6.2	1667
6	Initial Samples	18.0	5.9	6.4	7.0	1884
4	Initial Samples	23.4	6.9	7.3	8.0	2177
1	Initial Samples	30.3	7.9	8.5	9.3	2509
9	Stock Pile	45.8	9.9	10.6	11.6	3149
8	Stock Pile	48.6	10.3	11.0	12.0	3254
5	Initial Samples	48.9	10.3	11.0	12.1	3265
17	DD Core	53.6	10.8	11.6	12.7	3434
12	DD Core	53.7	10.8	11.6	12.7	3437
13	DD Core	56.2	11.1	11.9	13.0	3524
2	Initial Samples	59.5	11.5	12.3	13.4	3637
10	DD Core	62.7	11.8	12.6	13.8	3743
16	DD Core	64.7	12.0	12.9	14.1	3808
15	DD Core	73.0	12.8	13.7	15.0	4070
18	DD Core	83.5	13.8	14.8	16.2	4382

Note [1] – Allow 10% for operating safety factor.

Table 4. Agnico-Eagle Ball Mill Grinding Test Results

Sample No.	Description	Bond BM Wi kWh/t (200 mesh)	Pinion En'gy P80 74um[1] (From Bond) kWh/t	Gross Energy P80 74um (at Motor) kWh/t	Required Motor Unit Energy kWh/t	Required Motor[2] for 202 t/h HP
1	Shaft 1	12.5	6.1	6.5	6.8	1847
2	Shaft 2	12.0	5.8	6.3	6.5	1773
3	Shaft 3	11.8	5.7	6.1	6.4	1744
	For Design	12.5	6.1	6.3	6.8	1847

Note [1] – Includes diameter correction factor.
Note [2] – Allow 5% for operating safety factor.

The SPI hardness variability functions, as defined by this test work are plotted together on the same chart below as Figure 1. This demonstrates two things. First that the ores are remarkably different in hardness and second that the variability function takes a similar form for the majority of ore bodies.

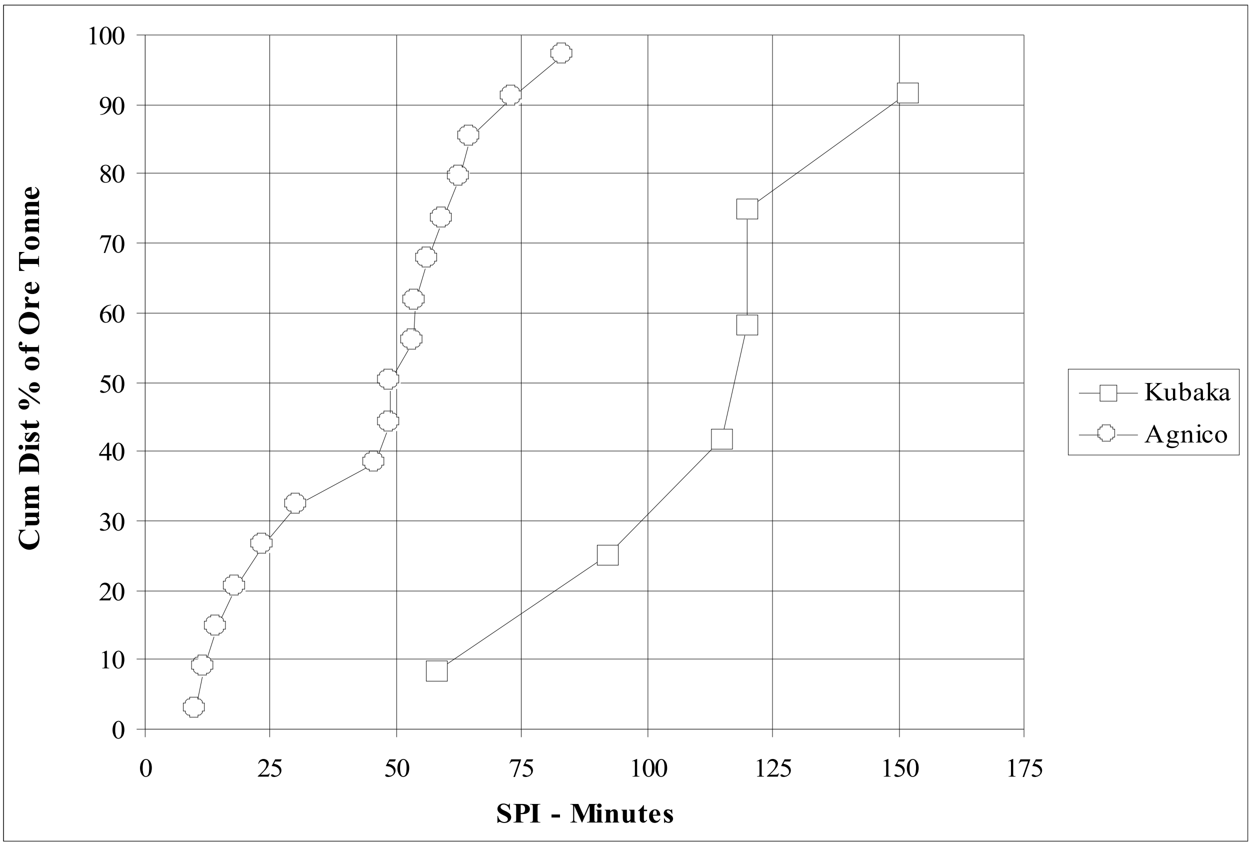

Figure 1. SPI Variability Vs Dist. % of Ore Tonnes

GRINDING EQUIPMENT SPECIFICATION

The selection of the grinding equipment is perhaps the most critical part of this exercise. The SPI measurement and calibration curve (equation) was based on mills that operated efficiently, probably in the region of 30 by volume and turning at about 75% critical speed. For these power design projections to be correct, the new mill must draw the stated power at an efficient operating condition. It is not adequate to say that the mill will draw the power by increasing the load above 30% and the speed above 75%. There is now evidence available from pilot plant tests that the mill throughput is reduced under these conditions and the extra power is not effective. The reason, visually observed is simple. Maximum grinding rate occurs when the cascading charge hits the shell at about 5 o'clock in a clockwise rotating mill. This occurs at the speeds near to 75% critical and at loads in the 25 to 30% range. Above this the charge hits the shell at 4 o'clock and the grinding rate falls off dramatically. More work will be done on this phenomenon in the near future.

With regard to SAG mill varispeed drives, a related problem can occur. If the drive will deliver its rated power at say, 80% of critical speed, then when the speed is cut back to 75% the available power is cut back as well. This downgrades the mill's ability to deliver the design power at the most efficient conditions. It is therefore recommended that the maximum speed for a varispeed drive be set at about 76% of critical speed. This drive is used principally to cut back speed and prevent liner wear on very soft ores so this function is not detrimental to the purpose. In fact the opposite is true because the slower the top speed, the more useable power is available at 55% speed.

Similar considerations need to be used in the design of a new ball mill. Here the performance is better understood and the operating conditions such as charge level are more easily measured and monitored. The norm is also to use fixed speed drives running at speeds in the range of 72 to 75% of critical. A common choice is to set the speed of the new mill at about 72% so that one additional tooth added to the pinion will result in an increase to 75% of critical speed.

Naturally, the grinding chamber and the motor for any new SAG or ball mill must match. The design engineer must check the power draw at 75% of critical speed for both SAG and ball mills to be sure that the specified motor power will be drawn at the design conditions. It is easy to back off on load to save power if it is not needed but the important point noted above is to draw the full required power at the best and most efficient conditions.

At Kubaka the SAG chamber selected was 6096mm (20 ft) diameter by 2286mm (7.5 ft) long (EGL) with a 1500 HP motor. At Agnico-Eagle the SAG chamber chosen was 7315mm (24 ft) diameter by 3658mm (12 ft) long (EGL) with a 4500 HP variable speed drive. From the data shown in Tables 1 and 3 and Figure 1, it is clear that both of these mills were designed to process the hardest known ores at design tonnage.

TIMING AND COST CONSIDERATIONS

The best part of having a reliable laboratory test to design a SAG mill is that the waiting period for collecting 50-tonne bulk samples and testing them in a 1.8m diameter pilot mill is virtually eliminated. There are now enough SAG mills in operation to be comfortable with the concept that any ore can be ground in a SAG mill. The only challenge is to find out how much power is required. We believe that this paper has shown how this can be done, quickly, accurately and at a surprisingly low cost.

As noted above, when the initial test work is being done on a new mine, in many cases it is not known whether there is an ore body or not. It is not the same as doing an expensive research program for an existing mine where there is cash flow to pay for the test work. It is therefore recommended that grinding design for new plants be done on laboratory sized samples and that these should be selected to represent as a minimum the hardest zones in the mine. If a complete hardness distribution function can be developed then the mill can be sized more precisely to meet production limits that are preset.

That the cost of sampling and test work to find out proper mill sizes needs to be reduced, is evident. The owners and managers of the new mines need to convinced that the procedures described here are not only much less expensive but also are accurate. We do not hesitate to point out that the choice of a SAG and ball mill circuit can now be selected to meet maximum and minimum throughput criteria, to keep the capital cost to a minimum. This is important for a mine with limited ore reserves, but the capability to overproduce is an asset while production shortfalls are a severe liability.

CONCLUSIONS AND RECOMMENDATIONS

- The SPI and Bond grinding design procedure described in this paper is now a proven, reliable and accurate way to design a new grinding circuit.
- The cost of obtaining the grinding design information is far less than the pilot plant method.
- Pilot plant testing should be restricted to confirmation of the design hardness and to metallurgical objectives by doing beneficiation work on the SAG ground material, particularly the effect of SAG ground fines on metallurgy.
- When the number of samples is restricted and the full hardness distribution function cannot be defined, it is important to have included samples of the hardest ore. Hard zones for sampling can be identified by UCS measurements, slow diamond drill rates or other geologic classification method.
- When the hardest ore has been identified, a choice can be made to add a crusher or not to the SAG milling circuit.
- If the design is for less than maximum hardness, a crusher can be used to make up the difference. In this case other options include stockpiling the hard ore for blending in later, or simply leaving the hard ore behind in the underground mine or on the low grade stockpile for the open pit mine. There is a danger in this case that the design tonnage may not be achieved on the hardest ores due to operating logistics.

- Control of the SAG milling circuit is easier when the new feed to the ball mill circuit can be sampled. This sample allows direct measurement of the T80 or transfer size.
- Always design new plants from laboratory tests. They are less expensive and more accurate than pilot plant or other SAG tests because more data points are generated.
- When calculating grinding power, leave proper allowances for motor safety factor and for electrical and mechanical drive losses.
- Size the SAG grinding chamber to draw the required power at efficient grinding conditions.
- The purchase of a SAG mill sized to grind the hardest ores is a good investment if the downstream parts of the process can handle the excess tonnage when soft ores are being milled.

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