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A NEW TOOL FOR SAG HARDNESS TESTING

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A NEW TOOL FOR SAG HARDNESS TESTING

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ABSTRACT

A practical new test has been developed for SAG hardness determination. Using two kilogram samples of minus one inch diamond drill core or crushed muck samples, the Starkey SAG Test has been shown to give accurate predictive information which directly relates to on-stream SAG mill performance. Typical results and test criteria are discussed in the paper.

Achievements to date include:

- Identification of hardness profiles and the location of hard and soft zones in a large ore body.
- Accurate prediction of the hardness of a bulk sample by using an adjacent diamond drill hole.
- Derivation of a plotted curve relating pilot plant power to laboratory relative hardness.
- Demonstration that for every test done to date, the Starkey SAG Test produced a product size distribution identical to that produced in a pilot plant or full scale plant SAG operation.

This test can now be used for blast hardness monitoring and short term control of mine production in existing plants and for identifying the proper locations for bulk samples in new projects. In addition, new SAG mill design can now be rationalized in a low cost way to eliminate unforeseen production shortfalls.

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INTRODUCTION

This paper is presented to introduce the Starkey SAG Test, a practical new laboratory tool for measuring the relative hardness of small ore samples in a semi-autogenous grinding (SAG) environment. The test was first designed for use on diamond drill core samples during the prefeasibility stage of new mining projects, to provide new information about the ore body at reasonable cost. It is a new tool and does not replace existing pilot plant test requirements.

The test will also be useful for throughput prediction in existing SAG plants by assisting in short and long term mine planning, where forecasting of metal grades and milled tonnage is used to control mine profitability. Because in-plant hardness testing has previously been unavailable on small samples, this test offers exciting possibilities for SAG mill operations where hardness variation is or could be a problem.

The Starkey SAG Test provides the following benefits to the mining industry:

For Existing SAG Operations

- Feed forward control of day to day mill production to increase metal units recovered, using both grade of drill cuttings and hardness of blasted muck samples.
- Long range mine planning using the best possible model to maximize productivity, based on hardness (converted to mill throughput) and grades from diamond drill core samples.

For New SAG Plants

- Determination of hardness variability profile for the ore body using diamond drill core, for integration into the mine block model and to optimize mine planning as noted above.
- Definition of the best place to mine bulk samples for pilot plant scale SAG testing. This is based on knowing the exact location of hard, soft and average hardness ores.
- Approximation of the SAG product size distribution and size distribution variance. This data can be used for preliminary ball mill sizing, in conjunction with Bond Work Index tests, long before pilot plant tests are completed.

As with any new development, the concept of knowing accurate ore body SAG hardness values at the prefeasibility stage will take time to be integrated into the accepted and usual system for developing a property for SAG production. It is hoped that mine head office management will study this technology carefully to understand its validity as outlined in this paper, and support and encourage its use. This development will only succeed if geologists, miners and mineral processors work together to unravel the web which has led to disappointing SAG mill performance at too many plants in recent years because this information was not available.

BACKGROUND

Since the development of semi-autogenous grinding in the mid 1950's, the mining industry has experienced difficulty in obtaining the representative bulk samples which are required for grinding testwork, SAG mill sizing and design. Even when bulk samples do represent the overall ore body, they are often very costly to obtain. In addition, it often happens that changes in ore hardness during normal mining cycles create periods of wide mill throughput variance, especially in open pit operations. When these fluctuations are large, or when hard ore reduces mill throughput, significant cash flow shortfalls can occur. If this happens during the early years of a mine, severe problems can result.

Traditionally, two solutions are used to cope with hardness variation and/or unusually hard ores. The first is to install massive blending facilities to eliminate the effect of short term variations. The second (for unreasonably hard ore), is to install conventional crushing equipment in the SAG circuit to prevent build up of critical size material in the mill, which is the prime cause of reduced throughput. In both of these instances capital and maintenance costs are increased in order to deal with the problem. In plants where the crushing must be added later, the capital cost is even higher than if installed initially.

The cost of obtaining bulk samples and the cost of testing them using "best technology", can lead to difficult planning decisions for a project where SAG milling is intended to be used. The bottom line for many clients is therefore to defer spending large amounts of money on a bulk sample until a clear picture of the deposit emerges from a prefeasibility study which determines in general terms that the project may be feasible. Clearly, for low grade SAG projects the very essence of the prefeasibility study depends on early knowledge of the approximate power required to grind the ore and the size and complexity of the grinding circuit required.

Regarding the design of new SAG mills, it is interesting to note that process engineers to date have been unable to obtain early, accurate, and low cost information relating to SAG hardness and the effect of SAG grinding on metallurgy. Indeed, the number of errors and problems which many operators have suffered through are testimony to the shortcomings of existing methods. In fairness, it must be stated that this is the logical outcome of applying SAG technology to the ore processing industry before the development of a suitable small scale test to determine what now appears to be required information.

Ore testing plays an important part in all project planning studies. Preliminary diamond drilling has normally been done to delineate the ore zone based on assays which give an accurate appraisal of metal grades. Metallurgy is then studied in the context of lab crushing to about minus 6 mesh and ball mill grinding of 1 or 2 kg samples to the chosen liberation size. Ball mill power is determined from Bond testing of 5 to 10 kg samples of drill core.

For low cost budget situations where the project will not be viable unless the SAG process can be used, prefeasibility studies have been carried out by doing the SAG test work on samples of about 50 to 200 kg of ore. These samples are normally a composite of several diamond drill holes representing average hardness. This is done because larger scale pilot plant SAG work would be premature and costly at this stage. Required SAG power is then estimated from the data and initial costing is done. If an open pit is involved, the hardness variance from blast to blast has not been determined, yet it is this variance which can cause unpredicted mill tonnage swings in a large open pit operation.

To conduct a proper prefeasibility study for a SAG operation, the following guidelines and concerns should be dealt with by the design engineers or consultants:

1. Use the initial diamond drill core for prefeasibility assaying, SAG hardness determination, Bond ball mill grindability, and metallurgical bench scale ore testing.

2. Determine that the SAG ground ore is amenable to the flotation, leaching and/or ball mill grinding process which will follow, and that the power consumption is reasonable.

3. Investigate the variation in hardness and throughput, from blast to blast, or stope to stope, based on the actual mining plan so that a realistic appraisal of SAG power can be made.

4. Plan to mine (drill) the chosen bulk sample(s) for pilot plant testing with due regard to depth and accessibility limitations, making adjustments if necessary, based on timing and cost.

5. Plan the pilot plant SAG grinding and on stream metallurgical test work which will be required to properly design the optimum process flowsheet for the project.

6. Ensure that the pilot plant SAG grinding data and metallurgical information will be available in time to properly integrate it into the feasibility study.

7. Confirm that the best way to get design information for the SAG project has been chosen.

This latter consideration can now be redefined, because of the development of the Starkey SAG Test. It does not replace existing larger scale tests. Rather, it adds a low cost, missing link to the tools which design engineers have available to them in performing the critical task of designing a SAG process flowsheet.

CRITERIA

The difficulty of obtaining material for 50 kg tests to determine hardness variation has led to a number of attempts to find a smaller scale test. To be fully effective the test must be able to process one inch diamond drill core as well as much coarser samples and still use the same standard grinding procedure. This is important because the database relating one ore to another will often play an important part in interpreting test results and having confidence in the data.

The Starkey SAG Test was designed to specifically address the problem reported from several SAG operations that tonnage fluctuations and inability to grind design tonnage were occurring. It was also obvious that plants were being built without adequate design information, and that operators for ores with varying hardness were surprised at their inability to predict and control SAG mill grinding throughput.

The SAG test which will have the widest appeal will be simple to do and capable of being used in any and all circumstances. The following criteria and objectives were therefore considered for the Starkey SAG Test and incorporated into its design:

1. The test must be simple enough that unskilled labour can easily do the work.
2. The test must simulate SAG grinding on a small scale which is reproducible and accurate.
3. The test mill must be a scaled down 6' Cascade SAG mill with a 3:1 length/diameter ratio.
4. The diameter should be the same as the Bond mill so that operators will accept scale up.
5. The speed of the mill must be 70% of critical at the shell to match commercial installations.
6. Top size of the feed must not exceed 1" so that small diamond drill core can be used.
7. The SAG test product size must be equal to or coarser than Bond feed size with no overlap.
8. The test should use 2 kg of ore, the sample size normally used for low grade flotation tests.
9. To minimize sampling problems, the test must be batch, with no new ore added later.
10. A steel charge must be used to reduce test time and to simulate true SAG grinding action.
11. Ball size and ore size should be a direct scale down of pilot plant conditions.
12. By making size reduction constant, grinding time in the mill will be proportional to power.
13. The mill to do the test should be affordable so that anyone can buy it or do custom tests.

The above criteria have been followed with the result that all tests done to date relate to constant test conditions. The first mill built ran on a standard laboratory rolls. The second bolted on to an existing horizontal drive assembly. The third generation, built by Minnovex Technologies Inc., has its own drive and stand and is a model of simplicity and practicality. In each case the speed and mill dimensions were the same. The success of this program is therefore directly attributed to the choice of the parameters listed above.

Figure 1 shows the size range relationships between plant SAG grinding, the Starkey SAG Test and the Bond Work Index Test. This figure visually explains point 7 above.

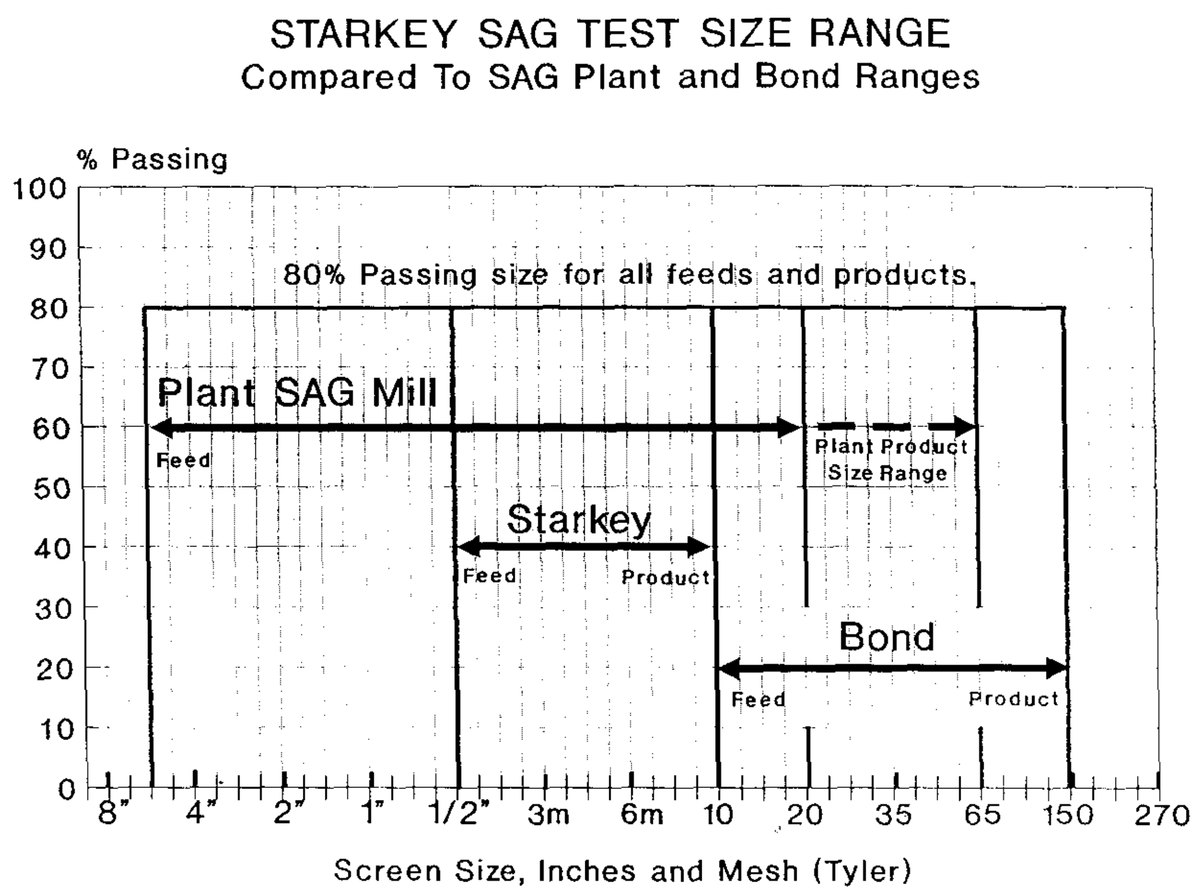

Figure 1 - Starkey SAG Test Size Range

From this chart it is evident that the feed to product size range for the Starkey SAG Test lies in the middle range of sizes when compared to a typical plant SAG mill operation. It also is seen to explore the hardness of particles in a range which is distinctly coarser than those particles tested in a Bond ball mill work index test. The data generated from a Starkey Test is therefore unique and not related to or influenced in any way by information generated from a Bond test.

THEORY

There are several good reasons for assuming that required SAG mill power is proportional to lab test time and that the test procedure selected is valid. First, standard Bond calculations of power required for ball mill grinding are based on the formula:

$$W = 10W_i / P^{1/2} - 10W_i / F^{1/2}$$

Where:
- W = the required mill power in kWh/t
- W_i = the Bond work index in kWh/t
- P = the product 80% passing size in microns
- F = the feed 80% passing size in microns

By making F and P constant, this equation reduces to:

$$W = W_i \times \text{Constant}$$

This means that for this type of calculation, mill power required is a function only of work index or ore hardness. Grinding time in the test is proportional to power used, so its measurement is therefore very relevant to the comparative identification of ore hardness.

Second, the Bond equations were originally developed to "reduce a particle of infinite size" to a size of 80% passing 150 mesh. The empirical data which Bond used, however, always involved ball mills and ball mill feed material which was usually finer than 10 mesh (as rod mill discharge), or finer than 3/8 inch if crushed directly. Clearly, SAG size reduction falls within the range specified by Bond but because the grinding environment is so different, much more test work is required to explore how much of the power is expended reducing the coarse fraction versus the finer fractions. Bond-calculated values of power for coarse size reductions are small because of the equation format. These calculations are not valid for SAG grinding above 10 mesh because the equations are unsupported by empirical data at this size. In addition, the data used to develop the Bond formula involved the use of balls for grinding media where the steel to ore ratio is very high. In SAG milling this ratio is very low (zero for fully autogenous grinding) so power calculations in the coarse sizes (above 10 mesh) will require adjustment based on new empirical data. In this range, the power consumed is not likely to be as efficient as either ball milling or mechanical crushing. For hard ore this can be explained as the result of lifting the charge material (ore and steel) many times before its size is reduced by breakage and attrition.

Third, the Starkey SAG test grind to 80% minus 10 mesh produces a plus 6 mesh fraction with about 19% by weight, and a minus 20 mesh product of about 79% by weight. (See Figure 2). The coarse fraction (plus 10 mesh) is material which must be recycled back to the SAG mill feed in a plant. By making the coarse fraction constant at 20% the test does not have to include estimates of variable circulating loads. There is very little material in the 6 to 20 mesh range, usually less than 2%. It has therefore been observed that the fine fraction (minus 10 mesh) is a good indicator of what the SAG mill will naturally produce as a final product. This means that the coarse fraction determines the time (power), and the fine fraction the predicted product size.

In air swept or grate discharge SAG mills this product size can be adjusted with the classifier, but the natural inclination of an ore to break to a given size is relevant to the prediction of power required for normal SAG grinding.

Typical results for a Starkey SAG Test are shown in Figure 2. Note that two screen analyses and the grinding curve are shown on the same chart. Test details and the explanation of results are presented in the following sections.

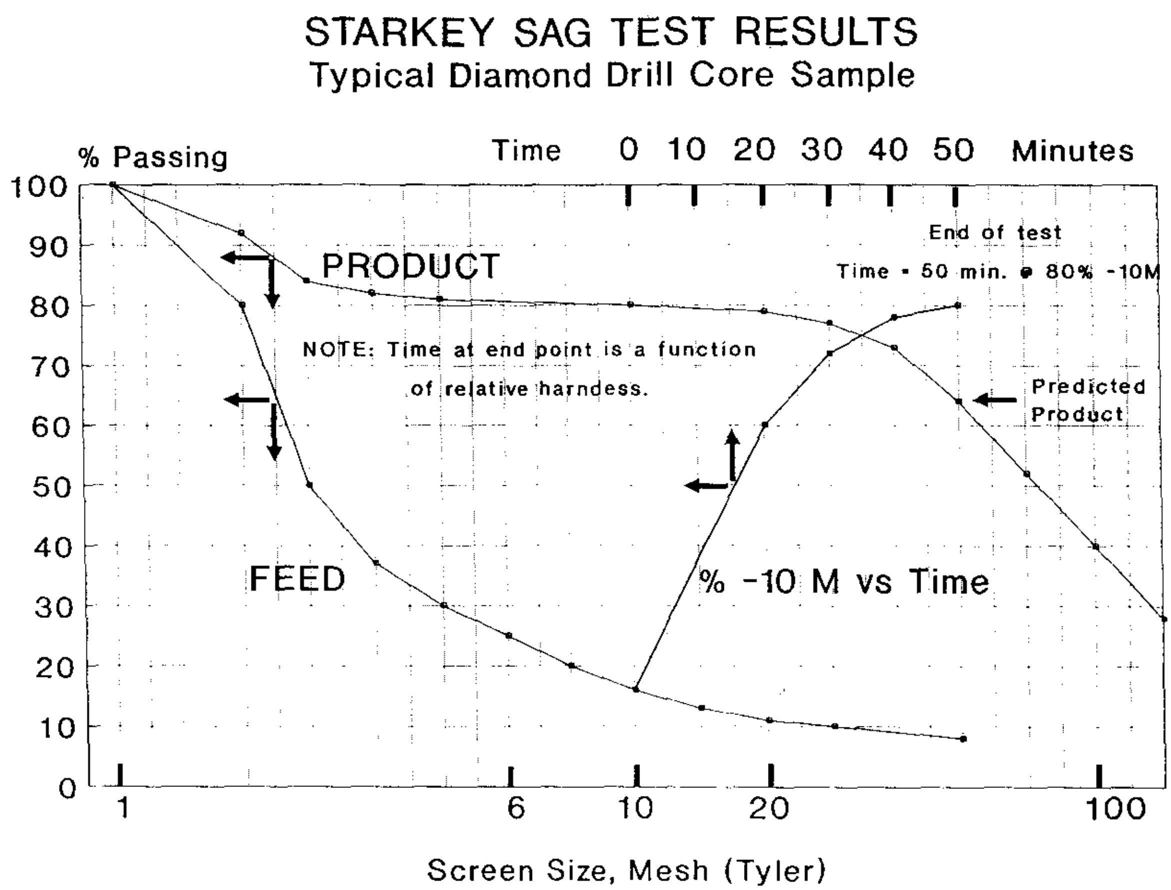

Figure 2 - Starkey SAG Test Typical Results

It is important to define relationships between SAG mill power and final product fineness, because in some cases excess grinding capacity may be available in the plant, which can profitably be used to increase production (as long as satisfactory liberation is achieved). Conversely, for harder ores it will be helpful to know in advance what adjustments to grind should be made to ensure that the best combination of feed rate and liberation is maintained.

SAMPLING

The key to the effectiveness of the Starkey SAG Test lies in the simplicity of the sampling procedures required to obtain the samples for testing. Requirements are quite different for diamond drill and for grab samples from belts or muck piles. Since many samples from both sources have already been tested, these comments are offered with first hand experience as to what results were obtained.

Diamond Drill Core

For diamond drill core which is larger than 2", conventional core splitting produces a very suitable product which is simply crushed to minus 1" in a laboratory jaw crusher and riffled to give all or portions of the 4 to 5 kg of material which is recommended (to include a contingency) for the 2 kg test. Assaying can then be done on the reject portion of the riffled samples in the usual way. For 1 inch diamond drill core, it may be necessary to crush the entire section and riffle out the SAG test sample. In this case also, the other portion of the core would be used for assaying. Note that every section of diamond drill core may not have to be tested for SAG relative hardness. A realistic approach at this time seems to be that the length of core taken for SAG testing should match the mining extraction program (i.e. bench height in an open pit). Also, in order to initially get a clear idea of the real single point hardness variability, a wider grid pattern can be used by testing every second or third hole. If possible, it is a good idea to retain the integrity of the original core logs. It is also important that details on whatever is to be done with the diamond drill core be carefully worked out with the geologists at an early stage in the project.

The key here is to obtain the hardness data from point samples and not composites, because composites tend to mask or average out the variations in the ore while point samples relate directly to the quality of individual blasts in most cases. The relationship of blast spacing to diamond drill hole spacing will usually show that when two or more holes are involved they represent two or more ore blasts in an open pit. It is fair to say that the input of grinding data to an actual mining plan is not usually attempted because of, (a) the cost of obtaining and testing 50 to 200 kg composite samples, and (b) the fact that such samples are usually composites and cannot generate the data required for a single hole. Detailed planning work must be done on small samples to be affordable. The Starkey SAG Test, therefore, is a good way to address the issue of ore hardness variance and work can start as soon as diamond drill core is available.

Muck Samples

The practicality of the Starkey SAG Test is most evident when using muck samples (from a stockpile or a feed belt). Previous work has been done where ore was sampled by taking coarse lumps first, and then a second sample of the same ore including fines. Representative metal grades are not the issue here and were not assayed. The result of this comparison showed that both samples gave virtually the same result for relative SAG hardness. The reason for this is thought to be that the preparation of the mill feed to a constant size allowed the test to achieve the same result because it is the coarse particle response in a SAG mill which determines the throughput, not the fines. With this principal in mind, it becomes an easy task to sample a feed belt or a stockpile, simply by taking approximately 16 to 80 kg of 2 to 6 inch lumps and crushing them as before, to minus one inch, and riffling out the required 4 to 5 kg test sample. The amount of sample taken will be a function of the mineral homogeneity in the ore pile to be sampled. Complex mineral/rock type assemblages will obviously need larger samples to ensure reasonable representation in the sample taken for the SAG test.

Test Mill Feed

The preparation of the actual 2 kg samples which are fed to the Starkey SAG Mill is done in conventional ways to achieve a tightly controlled size structure (much like the Bond test which is set as 100% passing 6 mesh with multiple recrushing of the oversize). It is believed that part of the success of the Starkey SAG test is the result of a clearly defined (and achievable) specification for the test mill feed. Details as to how this is done are contained in the operating manual which is provided with the purchase of the Mill/Technology package.

TEST DESCRIPTION

The Starkey SAG Mill is a 1 ft diameter unit which runs at 70% critical speed. The unit has a TEFC 120V electric motor, a V-belt drive and a Dodge gear reducer coupled directly to the 1" diameter steel drive shaft. Grinding time is controlled by an auto stop timer to eliminate mistakes caused by over grinding. The drive assembly is mounted on balanced swivel bearings which allow the mill to be set in three different positions for charging, discharging and grinding (with the shaft horizontal). The mill is closed with a full diameter cover lid which is beveled to fit the circular chamber wall and is held on using a quick release yoke with a threaded tightening bolt.

The test procedure is a straight forward series of dry grinding and screening steps. After the mill feed sample has been prepared, the entire 2 kg sample is screened down to 10 mesh to give the precise size distribution of the feed. The screen products are then combined and placed in the mill with the proper charge of steel balls. The first grind time is estimated (from experience) at about half of that required for the complete grind. Care must be taken not to over grind a new or unknown sample. After the first grinding period the sample is removed from the chamber and screened on 10 mesh. The time required to complete the grind to 80% passing 10 mesh is then estimated, and the entire sample and the steel charge are returned to the mill. By repeating this procedure several times (if required), the sample is ground to the specified size. When the grind is finished, a complete screen analysis is done on the ground ore to a mesh size which gives, at most, 60% passing. If required, the ground product can be screened to 100 mesh or finer but this is not required for the relative hardness determination. A graph is then prepared to determine the exact time required to reach 80% passing 10 mesh. This time, in minutes, is the relative hardness value. For convenience the feed and product structures are shown on the same graph. The screen analysis plots validate the result when the test has been correctly done.

The predicted 80% passing size of the finished SAG product is determined from the screen analysis of the final product by taking the 64% passing point on the graph (see Figure 2).

If flotation or metallurgical test work is required on the sample, the plus 10 mesh fraction of the SAG ground product is roll crushed to minus 10 mesh and the entire 2 kg sample is reground in a conventional laboratory ball mill to the required size for testing.

This is the test procedure which has been developed to date. In the future the dry grinding test procedure can be followed up with a wet grinding test in the same mill to confirm the dry result or investigate the difference between wet and dry grinding. Indeed there are many potential future test variations which should be tried using the Starkey SAG Mill. These will include the estimation of the limiting ore hardness where crushing is required to give reasonable economics, and the estimation of power required per tonne ground to make a significantly coarser grind than the natural grain size for the ore. Much remains to be done and it is evident that this test mill will provide a basis for doing a great deal of cost effective research in the future.

TYPICAL RESULTS

To date more than 50 Starkey SAG tests have been done on samples from four different properties, including 9 different ore types, one iron slag, and one composite from one of the properties. Much experience has been gained in the execution of this work. The results achieved are summarized as follows:

1. Reproducibility of the relative hardness value has been good for multiple runs on the same material and for grab samples from piles with and without the inclusion of fines.

2. Variance in relative hardness has been measured from 4 minutes to more than 80 minutes for ore and 140 minutes for iron slag (see Table 1).

3. A bulk sample removed from a shaft cross-cut had the same relative hardness as the diamond drill hole which was located close to the shaft.

4. There was good correlation between relative hardness values (minutes) and pilot plant power consumption for three samples taken from the same ore body (see Figure 3).

5. The lab hardness measurement on very soft ore was lower than expected. This seemed to be due to the lab test measuring only the work done on the ore and not the system power to turn the pilot mill with its steel (and ore) charge.

6. By obtaining the hardness frequency distribution for an ore zone (based on data from a regular grid) it was possible to calculate the average relative hardness and show where a bulk sample should be taken to give the desired hardness for design. There is little doubt that for most properties, the SAG mill design power should be greater than the average power for the ore body.

7. The minus 10 mesh product from a Starkey SAG grind has had the same 80% passing size as was achieved in a parallel on stream grind, for all samples tested to date. This includes full scale and pilot plant data (see Table 1 and Figure 2).

The following table summarizes the majority of test results which have been done to date.

Table 1 - Summary of Results

Project	Sample	SAG Test Minutes	k-80 um Predicted	SAG Mill kWh/t	k-80 um Actual	SAG Mill
Ore #1	SAG Feed	31	230	13.6	230	Plant 22 ft
Ore #2	Type 1	47	330	n.a.	n.a.	Not done
	Type 2	45	310	n.a.	n.a.	Not done
	Type 3	80	250	n.a.	n.a.	Not done
	Type 4	28	520	n.a.	n.a.	Not done
	Type 5	55	440	n.a.	n.a.	Not done
	Comp.	69	230	n.a.	n.a.	Not done
Ore #3	Type 1	42	320	n.a.	n.a.	Not done
	Type 2 Soft	36	320	5.3	320	Pilot Plant
	Type 2 Hrd	56	340	7.5	340	Pilot Plant
	Type 3	4	500	2.7	500	Pilot Plant
	Type 3 DD	4	500	n.a.	n.a.	Not Done
	20 DD Grid	4 - 62 (Avg. 26)				
Smelter	Iron Slag	140	150	n.a.	n.a.	Not Done

Individual Starkey SAG Tests and complete interpretation of results are now available from Minnovex Technologies Inc.

From the work on Ore #3, a correlation graph (see Figure 3) was prepared to show the relationship between pilot plant power and Starkey SAG Test grinding time in minutes.

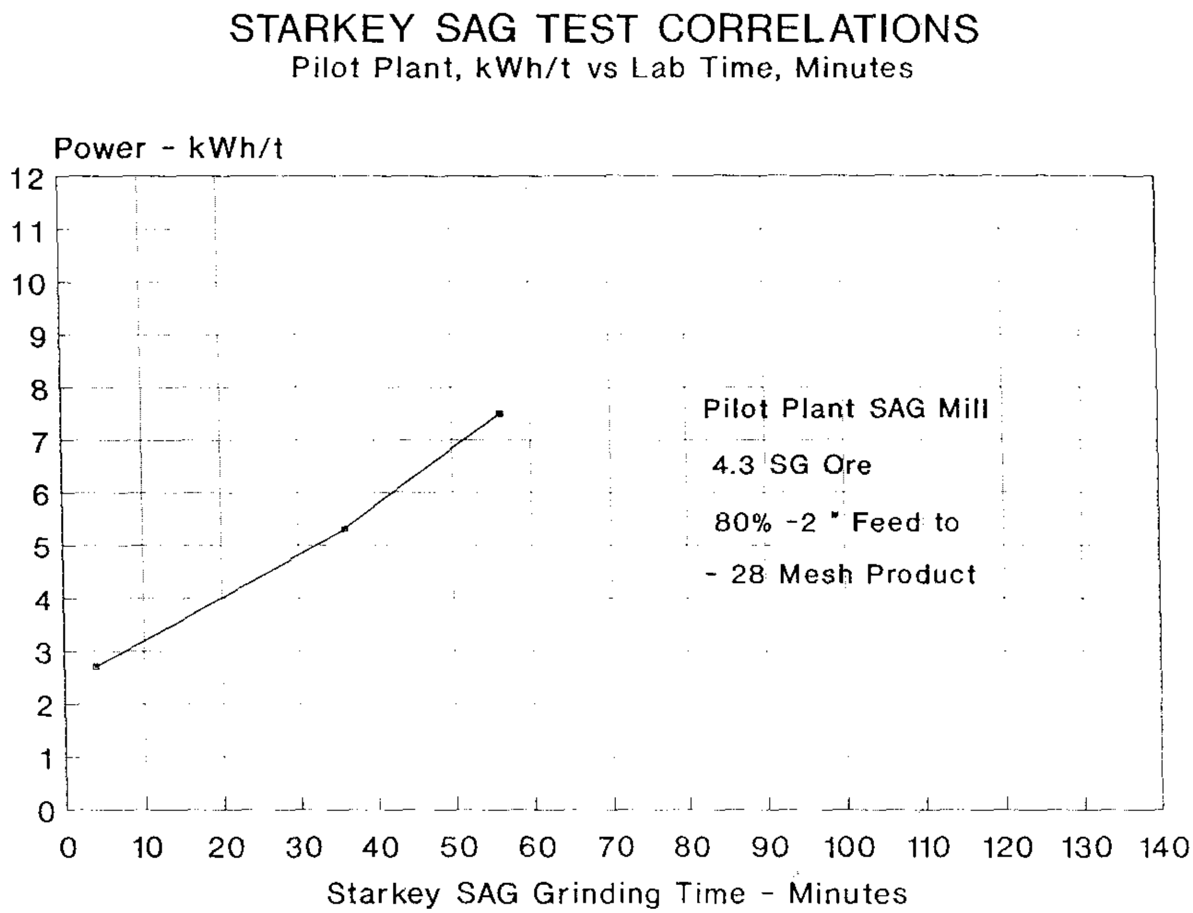

Figure 3 - Starkey SAG Test Correlations for Ore #3, Table 1

OBSERVATIONS

A number of observations have been made from the work done to date.

1. It was possible to accurately predict the relative hardness of a bulk sample from an adjacent diamond drill hole.

2. A reasonable curve of power versus lab relative hardness was obtained using pilot plant power and Starkey SAG Test results (see Figure 3).

3. For every test done to date where comparative data was available, the Starkey SAG Test produced a product size distribution identical to that produced by an on-stream SAG mill, for both pilot plant and full scale plant applications.

4. Grab sampling of 2 to 6 inch lumps has been shown to give a good indication of the relative hardness of the material in a stockpile. Results were reproduced with reasonable accuracy.

5. Point sampling for hardness testing, hole by hole, will predict the relative hardness of blasted ore whenever the diamond drill hole spacing is equal to or greater than the distance between adjacent blast centres. Composite diamond drill samples will not provide this information.

6. Feed forward control of a SAG mill feed is possible for deposits where large variances in ore hardness are encountered.

7. It is now possible to choose the location of a bulk sample for pilot plant testing based on relative hardness as well as metal grades.

8. The hardness variance in two different ore bodies was found to be much greater than previously thought after completion of Starkey SAG Tests.

9. The test procedure as developed is simple to use and workable for the purposes intended.

10. More work on other projects is required to fully develop the interrelationships of grinding time versus SAG power, and the effects of ore specific gravity, different minerals and other parameters on Starkey SAG Test results.

CONCLUSIONS

Existing Plants

- For existing plants, feed forward control using the Starkey SAG Test will allow a mine to be operated on grade and throughput forecasting to achieve maximum metal production.

- The investment in hardness control equipment (Starkey SAG Mill) is insignificant with respect to the benefits which may result from the early identification of hard ores.

- This type of technology will be especially helpful for operations where hardness variance is a problem.

- Mine and mill personnel will require close liaison to achieve full benefits from feed forward production control.

Expansions and New Projects

- The Starkey SAG Test is a viable way to obtain prefeasibility data on SAG relative hardness.

- For plant expansions or feasibility studies, the Starkey SAG Test will allow early identification of ore hardness variance and an order of magnitude estimate of required SAG mill power.

- To take full advantage of the Starkey test, the exploration geologists will have to make certain sections of drill core available for hardness tests. This will be a function of core size and the number of holes which are required to develop adequate variance information. Proper planning and good cooperation will be required.

- By developing hardness variance data as information for the mine block model, the hardness level for pilot plant bulk samples can be chosen to reflect a realistic blend for actual mill feed from the mining plan. It is likely that this hardness will be close to the top quartile of hardness values as opposed to current practice of trying to select an "average" sample.

- The location for pilot plant bulk samples can be chosen with greater certainty and in the most economical location if underground workings are required to extract the sample.