GETTING MORE FROM DRILL CORE

PRELIMINARY SAG DESIGN

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By John Starkey, P.Eng.
Manager - Crushing and Grinding
Minnovex Technologies Inc.
955 Wilson Ave. # 4, Toronto, ON M3K 1G1
Tel.: (416) 633-9400 Fax: (416) 633-2695
E-mail: minnovex@istar.ca

ABSTRACT

SAG 96 presented world wide semi-autogenous (SAG), and fully autogenous (AG) grinding practices, and recommended the coordination of mine and mill operations. Hard ore, when not identified in mine production planning, can cause the selection of a SAG mill which is too small, resulting in losses in tonnage and metal production. Open pit mines are especially vulnerable because mill feed can come from a single blast. The magnitude of hardness variance has often been unknown and this has caused mill design mistakes.

SAG hardness is now being successfully measured on 2 kg core samples to give hardness data during the exploration phase of mine development. The test has worked because it measures the abrasion power component of the SAG grinding process in a precisely scaled down SAG mill. The test is the Minnovex SAG Power Index (SPI) Test and was calibrated to give actual power, by testing hard and soft ores in 4 Canadian SAG plants.

This paper includes examples and a detailed discussion of how this hardness data is used at an early stage in a project, to measure and plan SAG mill power requirements and mill dimensions by studying a range of possible transfer sizes from SAG mill to ball mill, and by making a proper assessment of these related choices when deciding on the power ratio split between the SAG mill and the ball mill.

INTRODUCTION

Autogenous and semi-autogenous grinding has now been used commercially for over 40 years. The last two decades have seen great progress in this field and distinctly different approaches taken by various mill designers. Not all of this experience relates to the gold processing sector but we have no hesitation in suggesting that this experience is directly applicable to gold. However, when processing low specific gravity ores, the effectiveness of fully autogenous grinding will be less and may require the use of steel in the SAG mill.

In North America, designers have preferred to focus on large diameter, short SAG mills, diameter/length ratios in the range of 1.8 to 3.0, with a transfer size to a ball mill in the range of 200 to 3000 microns. Another common design approach has been to keep the size of the SAG mill down, insert in-circuit crushers, and complete the comminution process with large ball mills where total ball mill power can be up to double the SAG mill power. Scandinavian and southern hemisphere SAG mill designers have built grinding plants using low aspect (1/1) ratio SAG mills to produce a finished grind in a single stage. Successful applications in all three styles have been noted and it is suggested that there may not be a large difference in overall economic benefits for one over the other when capital and operating costs are considered.

It is not the purpose of this paper to compare design differences. The use of in-circuit crushers requires extensive study and will be the subject of a future investigation. This paper instead will look at how to get more data from drill core by measuring SAG hardness, using the Minnovex SAG Power Index (SPI) Test, on 2 kg samples of diamond drill core from exploration drilling. By determining the hardness, grade, and sequence of ore to be mined, the mine plan can be integrated with the SAG mill design in a way which avoids production losses and the need to retrofit additional equipment into the grinding circuit. This paper also deals with the way that these hardness measurements are being used to estimate the size of a grinding circuit at the prefeasibility stage of a new project.

The SPI laboratory test has been calibrated in four Canadian SAG plants. A brief history of the development of the SPI test is included below.

Industry readily accepts that metal assays, impurities, and other factors affecting the profitability of a new mine, must be generated on every core sample that is taken from the ground. But because of cost, we have in many cases declined to generate sufficient SAG hardness data. This is not surprising since up until two years ago, the smallest commercial SAG hardness test required 200 kg of material for each test done.

It is worth noting as we begin, that the wide throughput variances which occur in SAG milling have shown how tonnage sensitive SAG mills are with respect to ore hardness changes. In the future it will therefore be more important than ever for miners to take into account metal productivity, not just grade, and for mineral processors to design plants that are complete and practical enough to treat a reasonable blend of hard and soft ores, within the constraints of a well run mine.

BACKGROUND

The International Conference on AG/SAG Technology (SAG 96), held in Vancouver, demonstrated that SAG milling has been accepted as an economical way to grind ore. Authors from many countries presented papers on topics including testing, design, operations and maintenance.

Three previous papers have been published, describing the theory and development of the Minnovex SAG Power Index Test (see References). In order to make this presentation complete, a brief review of previous work is included in this paper.

In SAG mill design there remain unresolved issues, much debate and a variety of opinions. Some of these are listed below.

- In an exploration program, when should SAG hardness data be obtained?
- Is a specific small scale laboratory SAG test required?
- Is it necessary to ensure that a pilot plant sample represent design hardness?
- What is the proper way to define required power in a new SAG mill?
- What is the proper way to determine the SAG/Ball power split?
- Under what conditions of hardness and power cost should a crusher be used ? *
- Is SAG in-circuit crushing better than finer precrushing? *
- What is critical size and how should it be treated?
- To what degree of detail should hardness variance be defined?
- What is a reasonable budget for SAG testing - samples and testwork?

Note: * These will require more study and are beyond the scope of this presentation.

THE SAG POWER INDEX TEST

The SAG Power Index (SPI) Test was developed in 1991 to answer some of these questions. It was evident that unless an inexpensive, reliable, small scale SAG test was developed, some of these questions might never be properly answered.

Four test mills have been built. The protoype was a piece of 12” diameter pipe and ran on a rolls. The second was built in Iran at Gol-E-Gohar, to address a serious hardness variance problem, caused by the underground mining of a very soft 50 tonne sample for SAG testing which was believed to represent 100,000,000 tonnes of high grade iron ore. The third test mill was built by Minnovex and is the industry standard model featuring a quick release lid, swivel mount for easy dumping and auto timer connected to the drive. The most recent one to be built was delivered to a large copper producer in Chile in April 1997. Due to the success of the SPI Test at Gol-E-Gohar, Kvaerner Davy has supported this work and in the Toronto office, the test is being used for all in-house SAG projects.

The commercialization of this SAG test began in earnest when Minnovex become involved in 1993. The theory was described in a paper, presented to the annual meeting of the Canadian Mineral Processors in January 1994 (see Reference 1). This led to a MITEC (Mining Industry Technology Council of Canada) sponsored SAG test calibration project in which testwork was done in five Canadian plants. A report was issued in April 1995, and gave a straight line equation for grinding from F_{80} 6”, to P_{80} 10 mesh, for the high aspect ratio mills in the study, and a second, size corrected equation for finer grind sizes. The reproducibility work was positive and it was evident that the test would be of value to operators and designers. To communicate this data to the broadest possible audience, a paper describing the MITEC calibration work was given at SAG 96 (see Reference 2).

The calibration of the test against actual SAG operations has been the key to predicting with confidence the power required to grind ores from various locations in a mine. Optimization at any plant through the use of expert systems may well improve throughput or power utilization efficiency, but the present data represents a solid design basis for predicting power at the start-up of a new plant.

The SAG Power Index test mill is 12 inches in diameter x 4 inches long and was sized to be the same diameter as a Bond mill and to maintain a 3 to 1 D/L ratio. The mill runs at 70% critical speed, uses 15% by volume of ore and 15% by volume of steel. Two kilogram ore samples are used in each test. This size was chosen because it was a good fit for the mill and because that size of sample is often used for flotation testing.

The selection of the test feed size was chosen to be 80% passing ½ inch because it was felt that at this size, any commercial core could be crushed and used as feed. This was important because once the data base was started it had to be able to include data from any source. The parameter of feed all passing 1 inch in a 1 foot diameter mill also seemed to be a good scale down of the traditional 6” feed in a 6’ diameter pilot mill, which has been used by the industry for over 40 years.

The most interesting parameter to be selected was how fine to grind the ore once it was in the mill. Fred Bond had based the majority of his work on ball mill feed which in his day was rod mill discharge. Since rod mill discharge usually is about 80% passing 10 mesh, it can rightly be concluded that the Bond ball mill work index equations relate to the comminution of this size of product. Mistakes in SAG power requirement and sizing were therefore thought to arise from a misunderstanding of the power required to grind from 6” feed to 80% passing 10 mesh. It was clear that this would be a key parameter in determining SAG power. The determination of total circuit grinding power would then be easy and the power split between SAG and ball mill a matter of choice based on known facts by using the SAG Power Index Test and the Bond Work Index power calculation for the production of fines.

The objective of the SAG Power Index Test is to find how long it takes to grind a sample from 80% passing ½ inch to 80% passing 10 mesh. The only difference from test to test is ore hardness, and the time to accomplish this size reduction has now been shown to be a linear function of required mill power. Consideration was given to a test involving adding make-up sample as the test proceeded but this idea was rejected. The batch test, stage grind was therefore selected, and all of the ore and steel charge is returned to the mill after each grinding period.

OBSERVATIONS RELATING TO SPI TEST RESULTS

When the first ore samples were ground to 80% minus 10 mesh, it was discovered that the Gaudin-Schuman plot of the test mill discharge screen analysis showed that there was plus 6 mesh material and minus 20 mesh material, but very little else. This natural coarse breakage to about 10 mesh seems to be a function of how ore breaks in a SAG mill and should be exploited in planning a SAG grind. When it is also considered that ball milling of minus 10 mesh feed is a more power efficient than grinding coarser fractions, it seems prudent to allow the SAG mill to complete its task and design the mills accordingly.

The 10 mesh SPI Test product is fine enough to predict power required to grind any hard or “critical size” type material. It was clear from pilot plant grinding work done in the 1960’s by the author that any ore can be ground in a SAG mill. The things to be defined for a given feed size are how much power and the corresponding mill size to draw it.

The key point about *“Critical Size”* material is that *there is not enough power installed to grind it.* This definition for critical size will greatly assist designers in understanding how to deal with ore which is significantly harder than average material. By doing SPI tests on a variety of rock types and by doing point hardness measurements within geological structures, the existence of critical size material can now be identified and quantified. The design decision to add SAG power, to crush, or to blend, should now be made depending on how much of the hard fraction exists in the ore body.

A second observation from test results was made. SPI testing on samples which had been tested in a pilot mill, showed that the lab 2 kg test would indicate the normal grain size for an ore by taking the 80% passing size from the minus 10 mesh simulated “product”. Not only does the test predict the relative hardness of the ore, but also the normal grain size that the material will break to in a SAG mill. It is suggested that a SAG mill can readily produce any size coarser than the normal grain size, but a finer grind will require more power and the efficiency may decrease.

It has also been found, that the vast majority of samples break to a normal grain size between 250 and 800 microns. If an ore is hard (Time > 60 minutes), the normal grain size will less than 300 microns. Softer ores also show a direct but variable correlation.

The MITEC study proved beyond reasonable doubt that the test grinding time was a linear function of grinding time in the SPI Test, for each plant. A single calibration equation was derived for grinding to 80% passing 10 mesh (1.7 mm). The Minnovex SAG Power Index (to 10 mesh), expressed in kWh/t, is determined as follows:

SAG Power Index = (0.11 x T + 0.9) kWh/t Where: T = Grinding time in minutes.

SAG grinds finer than 10 mesh can be assessed by using a second, size corrected equation, or by adding a power component calculated using Bond formulas for grinding from 10 mesh to the desired size.

Since only 1 of the SAG mills in the MITEC study had a vari-speed SAG drive and all the mills were usually drawing full power, it was shown that changes in hardness caused changes in mill throughput. Indeed it was the throughput changes that allowed the correlation of kWh/t consumed with measured hardness. In order then to assure mill throughput under all conditions the mined hardness must be known.

Other observations came out of the MITEC work. Most of the plants visited used an autogenous work index (AW_i) value, calculated using the Bond formula, from operating results for power, SAG feed and product sizes. However, MITEC results showed that the calculated value of AW_i is a variable, depending on hardness and the fineness of SAG product produced. The Bond work index, W_i is useful because it is considered to be constant over a broad range of product sizes. AW_i however, only has significance in the calculation of grinding power to the product size for which it was determined. This applies to test and operating results alike and perhaps indicates why so many different procedures have been used for designing SAG power requirements.

Since the SPI Test has been used commercially, a number of ore bodies have had SPI testing done. In all cases examined to date, hardness variance to grind ores to 80% passing 10 mesh, are at least plus or minus 50% from the average. This gives ample cause to recommend that hardness variance be established for new ore bodies and that the choice of installed power should be raised to at least the top quartile of hardness variance. The mine plan must also be checked for the impact of hardness variance on mill capacity.

The reason that this SAG Power Index Test has worked is that the test measures the abrasion power component in the SAG process. This is thought to be the largest power consumer, especially on hard ores. This is not to deprecate the value of the effect of impact forces in a SAG mill, because without the impact availability resulting from steel additions, no SAG mill could be assured of meeting its design throughput. The bottom line is that hard ores require power to grind them and it is incumbent on the design engineers to provide an adequate amount of power and a mill size to draw it. Extra power at the design stage is cheap compared to adding crushers later. But the subject of when it is more economical to use a crusher will be dealt with in a future investigation.

TEST RESULTS FROM DRILL CORE

The data in Tables 1 and 2 have been selected to show the method which is now used to give a preliminary assessment of SAG power from SPI testing of drill core. This example is not an actual case but is typical of results which have been obtained. Since each ore body is different, there are several ways to select samples for testing.

First, a minimum of 20 samples is recommended in order to have statistical significance. Less samples have been used and the results have clearly indicated that 10 data points are far better than two or three composite values because the blending of drill core into composite samples hides the real information which is required to assess variance.

Second, for horizontal massive and flat lying deposits, a grid system for selecting the core samples is needed to cover the entire deposit at several levels. Sample lengths should be selected to match the mining width, so that the point hardnesses measured have significance to the mining operation in a given area. Special attention must also be given to cores drilled in areas which are scheduled to be mined in the first three years.

Third, for vein type and steeply dipping or vertical massive deposits, the recommended procedure is to take at least three continuous intersections through the ore zone in areas selected as typical by the geologist, and test the entire intersection, using bench height or mining width and rock type change as the criteria for selecting each sample.

TABLE 1 - TYPICAL SPI RESULTS

Sample	Hole	From	To	Length	Time	Nat.'l	SPI	Length	Cum.L	Remarks /
No.	No.	m	m	m	Min.	Size,µ	kWh/t	Dist.%	Dist%	Rock Type
1	10	100	107	7.0	25	450	3.65	5.83		Sandstone
2	10	107	113	6.0	30	350	4.20	5.00		Diss. sulphide
3	10	113	117	4.0	44	250	5.74	3.33		Quartz vein
4	10	117	123	6.0	43	300	5.63	5.00		Conglomerate
5	10	123	130	7.0	48	300	6.18	5.83		Quartz vein

6	10	130	131	1.0	10	400	2.00	0.83	Fault zone
7	10	131	140	9.0	40	350	5.30	7.50	Diss. sulphide
8	21	50	58	8.0	20	400	3.10	6.67	Sandstone
9	21	58	65	7.0	39	350	5.19	5.84	Diss. sulphide
10	21	65	70	5.0	60	250	7.50	4.17	Quartz vein
11	21	70	77	7.0	41	350	5.41	5.83	Conglomerate
12	21	77	83	6.0	45	300	5.85	5.00	Quartz vein
13	21	83	88	5.0	35	300	4.75	4.17	Diss. sulphide
14	32	200	206	6.0	33	350	4.53	5.00	Diss. sulphide
15	32	206	215	9.0	53	250	6.73	7.50	Quartz vein
16	32	215	222	7.0	38	300	5.08	5.83	Diss. sulphide
17	32	222	225	3.0	46	300	5.96	2.50	Quartz vein
18	32	225	232	7.0	42	350	5.52	5.84	Conglomerate
19	32	232	236	4.0	70	250	8.60	3.33	Quartz vein
20	32	236	242	6.0	37	350	4.97	5.00	Diss. sulphide

TABLE 2 - RESULTS SORTED BY HARDNESS

Sample / No.	**Hole No.**	**From m**	**To m**	**Length m**	**Time Min.**	**Nat.'l Size,µ**	**SPI kWh/t**	**Length Dist.%**	**Cum.L Dist%**	**Remarks Rock Type**
6	10	130	131	1.0	10	400	2.00	0.83	0.83	Fault zone
8	21	50	58	8.0	20	400	3.10	6.67	7.50	Sandstone
1	10	100	107	7.0	25	450	3.65	5.83	13.33	Sandstone
2	10	107	113	6.0	30	350	4.20	5.00	18.33	Diss. sulphide
14	32	200	206	6.0	33	350	4.53	5.00	23.33	Diss. sulphide
13	21	83	88	5.0	35	300	4.75	4.17	27.50	Diss. sulphide
20	32	236	242	6.0	37	350	4.97	5.00	32.50	Diss. sulphide
16	32	215	222	7.0	38	300	5.08	5.83	38.33	Diss. sulphide
9	21	58	65	7.0	39	350	5.19	5.84	44.17	Diss. sulphide
7	10	131	140	9.0	40	350	5.30	7.50	51.67	Diss. sulphide
11	21	70	77	7.0	41	350	5.41	5.83	57.50	Conglomerate
18	32	225	232	7.0	42	350	5.52	5.84	63.34	Conglomerate
4	10	117	123	6.0	43	300	5.63	5.00	68.34	Conglomerate
3	10	113	117	4.0	44	250	5.74	3.33	71.67	Quartz vein
12	21	77	83	6.0	45	300	5.85	5.00	76.67	Quartz vein
17	32	222	225	3.0	46	300	5.96	2.50	79.17	Quartz vein
5	10	123	130	7.0	48	300	6.18	5.83	85.00	Quartz vein
15	32	206	215	9.0	53	250	6.73	7.50	92.50	Quartz vein
10	21	65	70	5.0	60	250	7.50	4.17	96.67	Quartz vein
19	32	232	236	4.0	70	250	8.60	3.33	100.0	Quartz vein

CALCULATION OF GRINDING POWER VS TRANSFER SIZE

A graph of the above data is given below showing the cumulative distribution of SPI variance. Other design data is required to complete this example. Typical results have been selected to complete this example as follows:

<u>Assumptions</u>

Feed to SAG Mill, F_{80} = 6 inches

SAG product,	P_{80}	=	10 mesh or 1700 microns
SAG Power Index,	SPI	=	6.5 kWh/t (from graph, top decile)
Bond Work Index,	W_i	=	13.0 kWh/t
Final grind size,	P_{80}	=	74 microns
Design tonnage, New feed		=	100 t/h
Range of transfer sizes			1700 microns, Maximum transfer size.
			350 microns, Minimum transfer size.

Calculations

Power Required	=	SAG Power to 10 mesh	6.50	kWh/t
	plus	Bond W_i Component (to 74µ)	11.96	kWh/t
		Total Power required is	**18.46**	**kWh/t**

Note: Bond power calculations are based on the standard formula

$$W = 10\, W_i / (P)^{0.5} - 10\, W_i / (F)^{0.5}$$

Where P and F are the product and feed 80% passing sizes in microns respectively.

Options for prefeasibility power split between the SAG and ball mills lie in the range indicated above. Power required must be useable power in the plant so the actual motors should be sized to include a service factor of at least 1.05. SAG power especially tends to fluctuate from minute to minute by plus and minus 3%. The service factor allows the design power to be drawn with no danger of overload tripping.

Table 3 gives the mill power requirement at five different optional transfer sizes. These have been selected to include the maximum transfer size for a SAG product which can be pumped, two intermediate sizes, the size which gives a 50% power split between SAG mill and ball mill, and the minimum size determined from the SPI testing.

Table 4 shows the scaled up power and mill sizes for the SAG and ball mills required for the same five options described above, based on a design feed rate of 100 t/h.

GRAPH OF HARDNESS VARIANCE

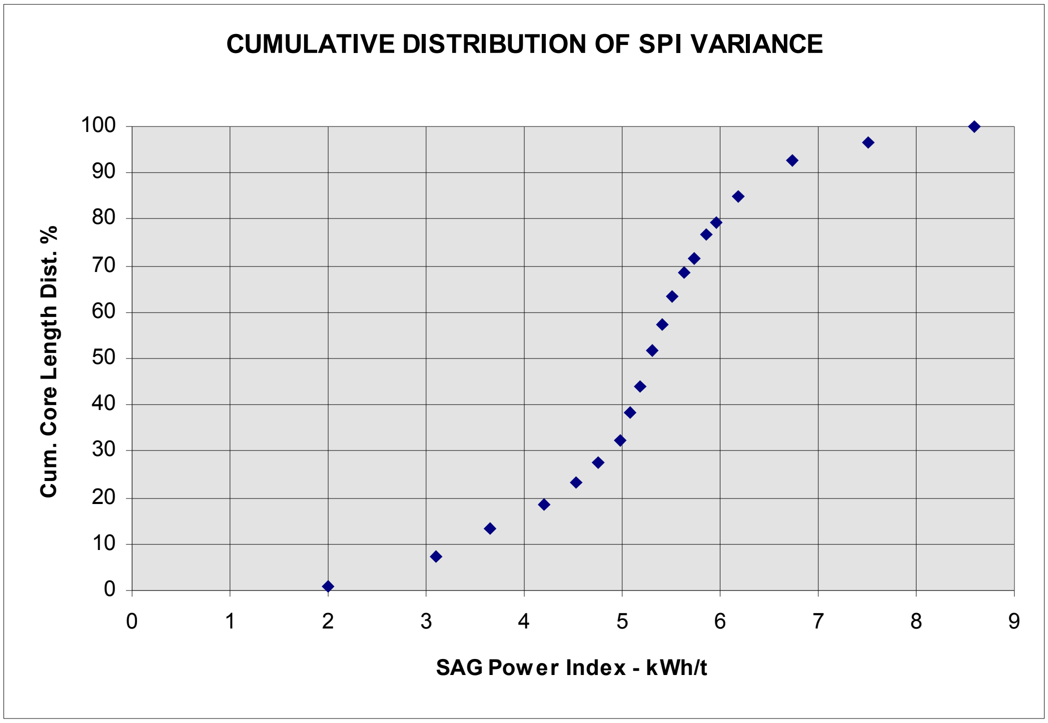

TABLE 3 - MILL POWER REQUIRED AT VARIOUS TRANSFER SIZES

Option	Transfer Size	SAG Mill Power	Ball Mill Power
1	1700 microns	6.50 kWh/t	11.96 kWh/t
2	1000 microns	7.46 kWh/t	11.00 kWh/t
3	700 microns	8.26 kWh/t	10.20 kWh/t
4	489 microns	9.23 kWh/t	9.23 kWh/t
5	350 microns	10.30 kWh/t	8.16 kWh/t

TABLE 4 - ALTERNATE MILL POWER AND SIZE (100 t/h)

Option	Transfer	SAG	BM	SAG - Ft.		BM - Ft.	
	Microns	kW	kW	Dia	EGL	Dia	EGL
1	1700	650	1200	17	6	13.5	16.5
2	1000	750	1100	18	6	13	16.5
3	700	830	1020	18	6.5	13	15.25
4	489	925	925	19	6.5	12.5	15.25
5	350	1030	820	19	7	12	15

Note: Mill sizes are approximate. Manufacturers must be consulted for actual size.

USING AND ANALYSING THE DATA

The simplicity of using SPI data to calculate grinding power is demonstrated by the above analysis. The MITEC project showed that the secondary creation of fines in a SAG mill was done at about the same power efficiency as grinding in a ball mill. This suggests that

SAG plus ball mill power should be the same at any transfer size in the specified range. Since the SPI test gives the power to grind to 10 mesh, the transfer size can be calculated for any configuration of grinding circuit. This is important if there is a need to standardize on one size of motor or, in larger plants, when the SAG grind must be done in one mill.

Some designers have suggested that when fines are produced in the SAG mill that the effective resulting Bond work index value for the ball mill decreases. This may well be true but in order to have a functional circuit, the total installed power must be provided. It is prudent however, to not deduct power, because in reality it is the transfer size which may vary and the gross power is needed for reliable operation.

In the example cited here, the SPI value was selected to be the top decile of hardness variance (6.5 kWh/t). In practice this selection will involve a number of other factors. First, if the hardest fraction also contains the highest gold values, it would favour selection of a high power level. Second, if the mine plan includes SPI data, and hard ore is carefully blended with soft ore, it may be possible to reduce the SAG power to a level equal to the top quartile (5.8 kWh/t). The median SPI value of 5.3 kWh/t should never be selected for design because there is no way to adequately blend hard and soft ores to achieve steady throughput. In addition, there is now evidence that when hard ore is mixed with soft ore that the resultant mix will require power closer to the hard fraction.

It will be noted in the example that when soft ores are being milled the grinding circuit will have available power which is not required. During these periods the steel additions can be suspended to reduce operating costs or the power can be used by treating extra tonnes. These options would seem to be much more beneficial to the project when compared with the result of having insufficient power.

The example shown above and the technical basis on which this discussion is based, assumes that the SAG mill operates in closed circuit with a classification device. The detrimental effect of operating a SAG mill in open circuit outweighs any potential benefit in reducing capital cost by not providing the required pumps and sizing equipment. Since most ores break naturally to 10 mesh, it is unwise to pass coarser material to the ball mill and forego the production of good ball mill feed. Failure to classify SAG mill discharge will result in reduced ball mill efficiency and the unwanted presence of circulating scats.

With the introduction of the SPI Test, it is recommended that new plants manage mill throughput by mining to a planned ore blend. The mine must control metal grade and productivity within specified limits. If this is too difficult, then the provision of extra grinding power will ensure the same end result. Even so, there may be times when only the hardest ore is available, and throughput will suffer. But if this is known at the design stage, the variance can be tolerated and balanced with appropriate grade control.

The SAG process is attractive because it rolls all of the material handling problems of fine crushing plants into a single chamber which holds primary crushed feed until it is ground to about 1 mm. This feature of SAG milling needs to exploited to the fullest.

CONCLUDING REMARKS

Two large mines in Canada are known to practice hardness control at this time. The Iron Ore Company of Canada processes in excess of 100,000 t/d and throughput problems are not tolerated. Hard ores are set aside because the viability of the plant depends on the constant recovery of iron from run of mine ore.

The other property is Highland Valley Copper. They have developed a geological/historical method to predict throughput from various ore blends (see Reference 4). Highland Valley has also done further correlation work using the Minnovex SPI test which was presented at the April 1997, CIM Annual General Meeting.

Fred Bond has long been admired for his keen insight in developing a test which has served the industry well for over 40 years. Today no one questions what data is required to design a ball mill. A Bond Work Index Test. Our goal at Minnovex is to provide the mining industry with a similar small scale service for SAG mill design. We believe that this test now exists as the Minnovex SAG Power Index Test.

It is the managers and owners however who will decide what is best for their companies and projects. They will rely on the collective judgments of their geological, mining and milling specialists in deciding what is acceptable and what is not. At the same time it is clear that to get needed hardness data from drill core that geology, mine and mill staff must work together to get the right mine plan and the right SAG mill for a given property.

A study to define when a crushing plant will pay for itself in terms of reduced power and capital cost is now being planned. This study will consider hardness variance and the local cost of power. It may be that it is cheaper to add extra mill diameter, than to build a separate crushing plant with its attendant operating and maintenance challenges. If a crusher is required, it will be more beneficial to the project to add it first, rather than as a retrofit after start-up.

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