

Choosing a SAG Mill To Achieve Design Performance

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ABSTRACT

A great deal of effort has been expended in the last 11 years by the authors and others to identify the correct power required to grind ore in a SAG mill, by developing ore hardness variability functions for the ore body to be mined. This paper describes the next step in the SAG design process, which is choosing a SAG mill to accomplish the required specified design performance.

At the test work stage, each ore hardness data point is a unique and discreet bit of information that represents the energy required to grind the ore represented by that sample at optimum SAG conditions. When the design criteria are set, it is now considered necessary that the required power draw in the mill chosen be provided at optimum conditions as well.–

Based on actual 3-ft diameter pilot plant results, we can now show that the grinding efficiency and throughput drop when the optimum load limit is exceeded. Future work is expected to show a similar reduction in efficiency when exceeding optimum speed. Providing specified power by exceeding these optimum conditions is not adequate and leads to a lower cost but underperforming SAG mill.

It is possible in some cases to modify a SAG circuit to force it to perform better, but this often takes time, much effort and costly modifications. In most cases the capital spent on a properly sized SAG mill may prevent production losses that would be many times greater over the extended start up period. This is the direct result of choosing the proper SAG mill at the start.

INTRODUCTION

The sequential steps required for the design of any grinding circuit, have changed dramatically in the last seven years. Previously, it was considered necessary to do six foot diameter SAG mill pilot plant tests on representative samples of minus six inch ore (F80), in order to understand design requirements. It can now be shown that this method is costly and not likely to produce the desired result because it is difficult to recover six-inch material from deep within a new mine. The representative nature of the sample is often compromised when the sample is selected.

The development of reliable, laboratory scale SAG testing has opened the door to improved methods for grinding circuit design. The study of ore variability on a blast to blast basis has showed a much higher degree of hardness and throughput variance than was acknowledged when only composite samples were tested in pilot plant facilities or in the mini (1.5 ft diameter SAG mill) pilot plant. Because of this variability, decisions are required at the design stage, to select the power level that will allow orderly and profitable production from the deposit, especially in the first three years when capital is being repaid to investors.

With good definition for the design power level settled the next question becomes how to provide the required grinding chamber and motor to draw the required grinding power. This choice will determine if the mine will struggle for profitability or meet its tonnage production commitments. This choice of the SAG grinding chamber is the subject of this paper and it will be shown that it is not enough to draw the required power, but to draw it at conditions of highest SAG efficiency in the commercial mill. It will also be shown from actual pilot plant results and

capital cost analysis for new SAG mills, what the economic penalty will be for not providing the required SAG mill grinding chamber.

TEST WORK REQUIRED FOR DESIGN

It has been shown in a number of previous publications, the form and nature of a typical hardness variability function for an ore body. (Starkey 1997, Holmes and Starkey 2001, Cousin, Starkey et al 2001). To summarize this procedure a typical suite of laboratory data is presented below to demonstrate the issues that a grinding design engineer must address.

The number of tests required for good design, are related to a number of things as follows:

- Availability of diamond drill core allowing for up to 10 to 12 kg per sample.
- Number and complexity of various ore types in the deposit.
- Potential to expand the deposit with more drilling.
- Number of distinct and different mining areas that will be mined over the life of the mine.
- The sequence of mining that will be followed in extracting the ore (open pit Vs UG).
- Potential for mining methods to change from selective to bulk in later years.
- Shape of the deposit (narrow vein or massive block).
- The likelihood that future expansion of grinding facilities will be needed.
- The future effect on production levels as changes in metal prices occur.
- The importance of producing design tonnage at all times, especially in the early years.

The decision to be made in selecting the number of samples also involves practical considerations relating to the time available to complete the testing and design work, and the budget that is available to do the work. Each design method has its own sequence of activities. It is the consultant's job to assess these factors and methods and recommend to the client a procedure that represents the most responsible use of available funds.

There is a growing consensus among design engineers, that if large sums of money are to be spent on testing (over \$50,000 US for example) that the extra money would be better spent on the SAG mill itself and not on the test work program. Stated another way, money invested in a large SAG mill is an investment that can produce handsome returns if extra production is needed or simply to give the mine the option to mill the hardest ores at design throughput rates.

Typical tests required to define a hardness variability function, are given below in Figure 1. The opinion was published before, (Starkey 1997) that about 20 laboratory tests are required. To date two plants (Kubaka and Agnico) have been designed with less. For simplicity, 10 tests will be used for this discussion so that each sample can be used to represent 10% of the ore in the deposit. Values are selected for demonstration purposes only.

Setting the design criteria can then be done using data that relates to the spatial configuration of the deposit, the value of the ore in situ, the processing rate that will result from treating similar ore to the tested samples and the operating profit margin for typical ore above the cut-off grade.

Table 1: Typical Laboratory Test Results

<u>Test No.</u>	<u>Lab SAG Test Pinion kWh/t</u>	<u>Cum. Dist.% of Ore</u>
1	3.59	5
2	6.13	15
3	7.00	25
4	7.51	35
5	7.88	45
6	8.12	55
7	8.41	65
8	9.00	75
9	10.17	85
10	11.89	95

These data points are shown in graph form below as Figure 1. (Dobby and Starkey 1996).

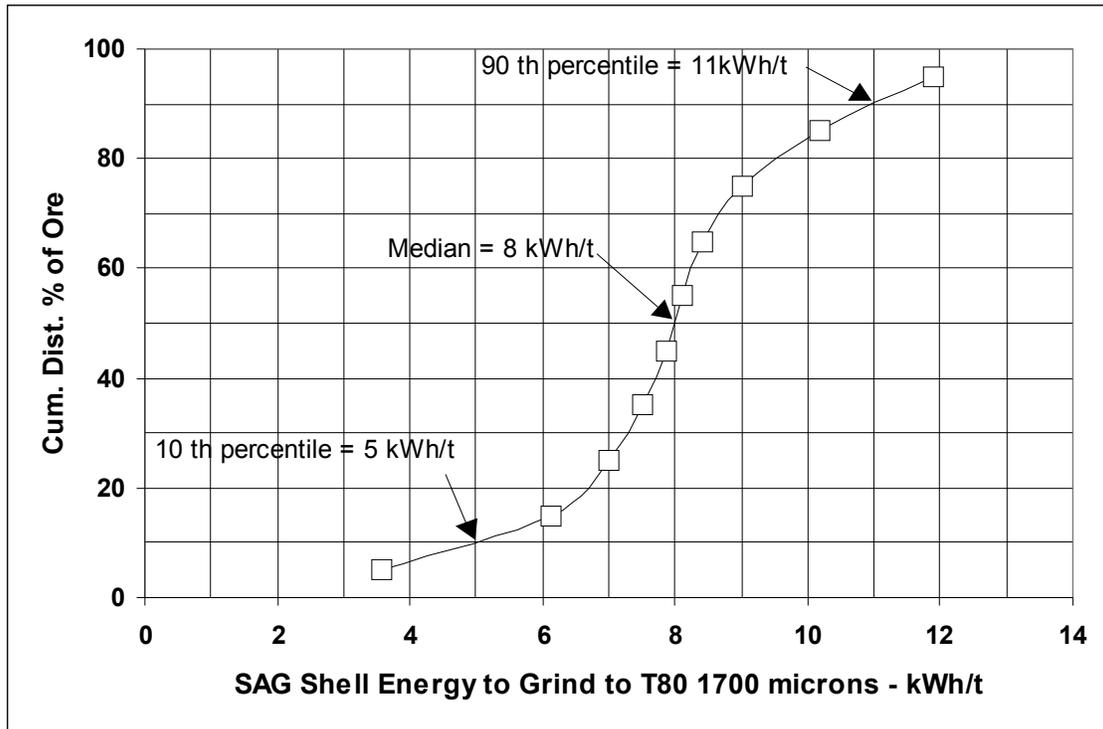


Figure 1: Typical Hardness Variability Function From Laboratory SAG Tests

The design procedures discussed in this paper relate to the above noted sequence of selecting samples for laboratory testing and the performance of suitable laboratory tests to establish the representative hardness variability for the ore body concerned, similar to that shown above. The lab data represents energy requirements at optimum grinding conditions.

OPTIMUM GRINDING CONDITIONS FROM PILOT PLANT RESULTS

A further explanation is required to explain the importance of designing the SAG mill chamber to draw required power at optimum operating conditions of 75% critical speed and less than 30% by volume load. Recent studies in the three-foot diameter SAG mill are instructive. The following graph shows the relevant facts as Figure 2.

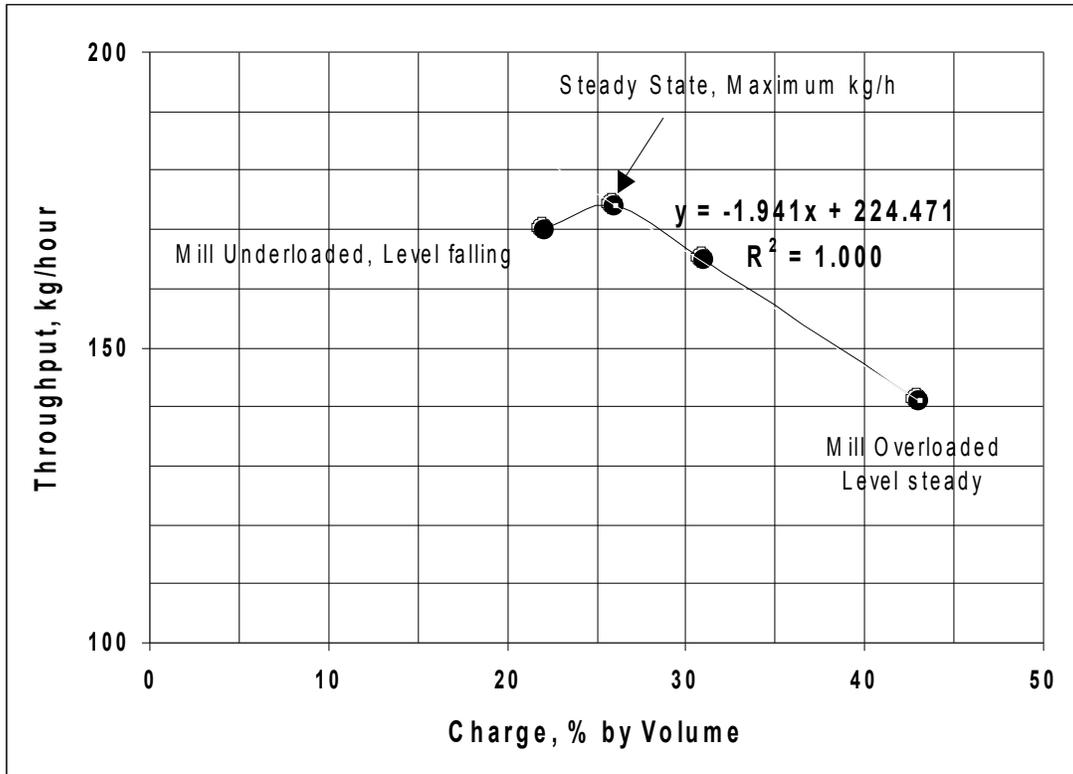


Figure 2: Pilot Plant kg/hr Vs Charge % by Volume

This data is indicative of trends that were happening in the 3-ft. diameter SAG pilot mill. They have not been proven in large commercial scale mills. Because the grinding operation could be viewed through the open end of the SAG mill, it was evident that maximum throughput occurred when the cascading material (for clockwise mill rotation), was hitting the shell at 30° to the right of the vertical diameter (or 5 o'clock). This impact point was normal to the mill shell tangent at that point. It was also easy to show that maximum throughput occurred when the volumetric load (as determined by a quick measurement of the charge level with the mill stopped), was about 26% by volume.

At this level, lower feed rates resulted in falling mill charge volume, while at higher levels the steady state throughput was reduced, by the order of magnitude shown in Figure 2. It was also significant to observe that when the load was allowed to increase above 30% by volume, that the cascading charge started to hit the shell at about 50° to the right of center (4 o'clock) where the distance of free fall for the charge was physically reduced. It is therefore concluded that anything

inside the mill such as increased load, liner shape, mill speed or friction, that causes the cascading ore and steel (in this case 10% steel was used) to hit the shell more than 30° before the vertical diameter will cause reduced throughput. See Figure 2 and equation (1) below. Much more work is required to validate this function in a production environment but the principle of designing the new SAG mill chamber for optimum conditions at the design point is clearly established.

For the operating load range just beyond the optimum performance conditions, a linear model was developed to assess the lost production that would result from running the mill at too high a load level. It is an approximation or a best guess based on limited data. This equation is:

$$y = 225 - 1.94 x \quad (1)$$

Where x = the load in the mill expressed as measured % by volume and y = kg/h of feed.

This information is based on observed throughput reductions caused by loading the 3-ft. SAG mill to over 26% by volume. Using this information, the detriment to throughput, expressed as a % of maximum throughput can be calculated. The results are shown in Table 2.

Table 2: Effect of Load on Pilot Plant Throughput

<u>Load % by Vol</u>	<u>kg/h of Feed</u>	<u>% of Maximum</u>	<u>Remarks</u>
26	174	100.0	Max. feed from pilot plant.
30	166	95.5	
35	157	90.0	10% loss of production.
40	147	84.4	
45	137	78.8	Not valid beyond this load.

This indicates that when the mill was allowed to run in an overloaded condition at 35% by volume, the production throughput loss was 10%. At 40% load the loss was over 15%. If this trend is repeated in full-scale tests it will prove to be essential to monitor and control the load in the SAG mill so that it does not exceed 28% by volume in order to maximize production. In the pilot plant there was the luxury of being able to inspect the load and measure it. In a production plant, frequently calibrated load cells or a more sophisticated method will be needed.

SIZING THE NEW SAG MILL

The task of sizing the new SAG mill is now more clearly defined. The goal should be to provide enough power for at least the 80th percentile of hardness variability so that production losses from a lack of installed power when treating the hardest ore zones will be minimized. The selected power from Fig. 1 would be 9.5 kWh/t to grind the 80th percentile ore and about 13 kWh/t to grind the hardest material. At the 90th percentile from Fig. 1, it is seen that 11 kWh/t are required to grind the ore to T80 1700 microns.

The fact that most ore bodies have zones that are harder than the design hardness is the main reason why it is advantageous to be able to draw design power at optimum conditions. In fact the only way to provide extra useable power for a SAG mill is to increase the size of the grinding chamber because overloading the mill may draw more power but it will not maintain throughput. Another effect may be to generate extra fines at overload conditions but this has not been proven.

The relationships between mill diameter, mill loading, mill speed and length, and power draw are well known by the mill manufacturers. Factors A, B, C and L are used to calculate the power drawn by a SAG mill chamber as shown below in equation (2) (from Rexnord 1975):

$$\text{kW} = A \times B \times C \times L \times 0.746 \quad (2)$$

Where A is the diameter factor, B is the loading factor, C is the speed factor and L is the effective grinding length (EGL) in feet.

Factor A is a function of the mill diameter as approximated by the following equation:

$$\text{Factor A} = 0.17767 \times x^{2.5} \quad (3)$$

Where x = the mill diameter inside the liners in feet.

Factor B for most applications involving silicious ores with specific gravity of about 2.7 is approximated by using the value for Factor B = 4 for design. This value corresponds to about 15% steel in the SAG mill and a load of about 35% and represents the motor power required and the shell is sized to suit that power. Lower steel and charge volume loads draw less power but the chamber will draw power up to this maximum load.

At optimum conditions, (10% steel, 26% load and 75% critical speed) the corresponding Factor B is about 3.48 for silicious ore. Similarly, higher SG ores must use a correction factor to account for the heavier density charge in the mill. First principles are used to calculate this adjustment factor but this will not be discussed here.

Factor C is a function of mill speed and is approximated by the following equation:

$$\text{Factor C} = 0.0378 e^{0.021x} \quad (4)$$

Where x = the mill speed expressed as % of critical speed for the mill.

Critical speed is calculated from the following equation:

$$\text{CS} = 76.63 / D^{0.5} \quad \text{Where D is the mill diameter inside the liners in feet.} \quad (5)$$

Length L in feet is the second last factor and is used as shown above in equation (1). The last numeric factor of 0.746 is used to convert the resultant number to kW from HP.

These factors will give a good idea of what size the SAG mill chamber should be for any given design tonnage and for a selected power requirement, determined as above, from the laboratory test work. The SAG mill size should be checked by the manufacturer for accuracy, and their calculations should be done at the optimum conditions specified. This is the point where errors can be made because a smaller than reasonable chamber will cost less to buy and can look attractive if it is not realized what the penalty in throughput will be.

CAPITAL COST FOR LARGE SAG MILLS

Capital costs for 28, 30, 32, 34 and 36 ft diameter SAG mills have been developed. The basis is single or double pinion design up to a maximum of 10,000 HP per pinion, where each pinion is powered by low speed synchronous motor and an air clutch. Vari-speed and wrap around drives are not included in this analysis because our goal here is to show how important it is to have the right size of grinding chamber and to balance extra production capability with the capital cost to achieve it. Figure 3 below gives the relationship between SAG Mill power in MW Vs US\$ to buy the mill. The design basis used was a 2.4 to 1 diameter to length ratio.

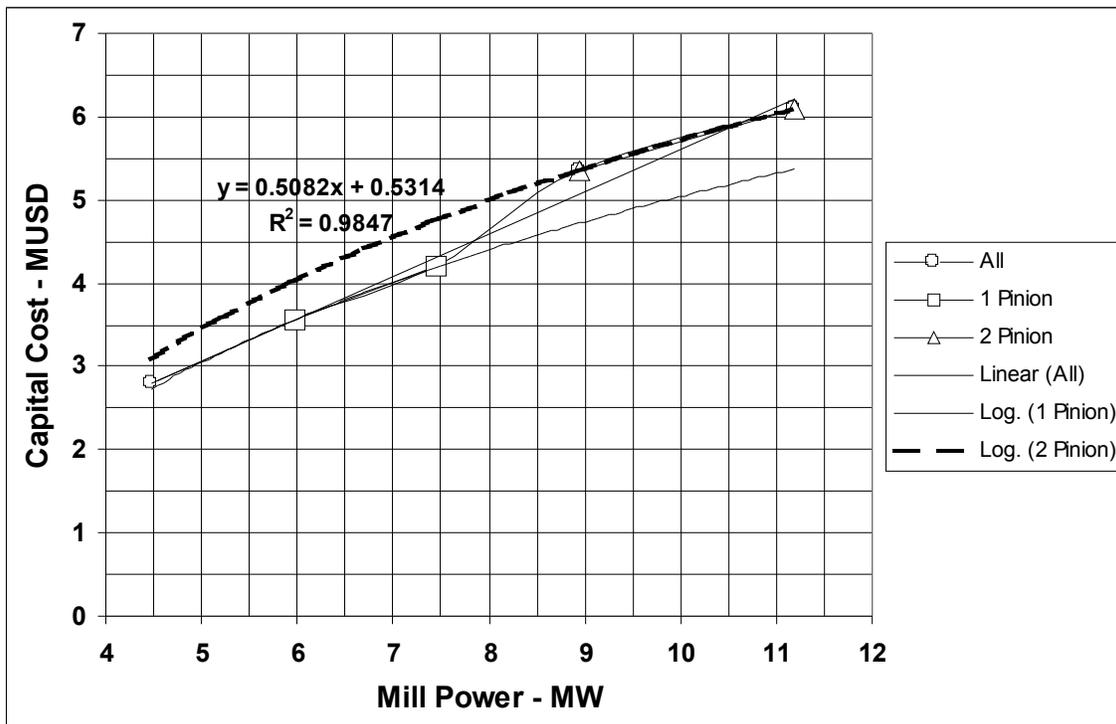


Figure 3: Capital Cost as a Function of Mill Power

The data for this table was derived by using current capital costs for 28, 30, 32, 34 and 36-foot diameter SAG mills with D/L ratios of about 2.4 as stated above. The discontinuity above 7.5 MW is due to the need for a 2nd pinion. The function can be expressed as in equation (6) below:

$$\text{Capital Cost in MUS \$} = 0.5082 x + 0.5314 \quad (6)$$

Where x is the installed mill power in MW (Megawatts).

From Fig. 3 the cost of adding 2 MW of installed power is calculated to be \$1,550,000 US.

Table 3 below shows the results of sizing five SAG mills, matching the power for 2.9 SG silicious ore and determining the capital cost in 4th quarter 2002 US dollars to build the basic mill.

Table 3: Basic SAG Design Data and Costs

Diam.	EGL	HP	Cost MUSD	Delta HP	Delta Cost
28	11.5	6,000	2.79	-----	-----
30	12.5	8,000	3.56	2,000	770,000 USD
32	13.5	10,000	4.20	2,000	640,000 USD
34	14.0	12,000	5.36	2,000	1,160,000 USD
36	15.0	15,000	6.09	3,000	730,000 USD

Using this data the cost of extra capacity can be balanced against the extra production that it will generate. Conversely, the lost production from a mill that is too small can also be assessed and compared to the capital that was saved. Production losses can occur two ways. First by overloading the mill (see Figure 2) and second by setting the design point for the SAG mill too low (see Figure 1). In either case losses of over 10% can occur.

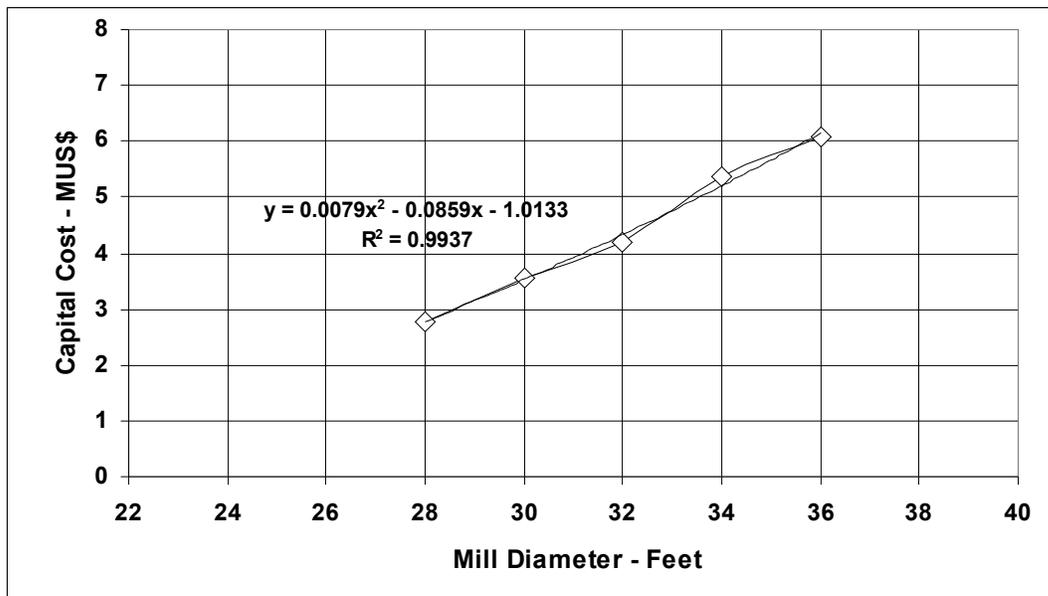


Figure 4: Capital Cost as a Function of Mill Diameter

Figure 4 gives capital cost as a function of mill diameter in the range of 28 to 36 feet, for 2.4 to 1 D/L SAG mills as noted above. This gives a clear indication of incremental capital cost of a larger mill. The same data is presented below in Figure 5 as a function of MW Vs Diameter. As noted above Table 3 summarizes the key data used in this discussion and analysis.

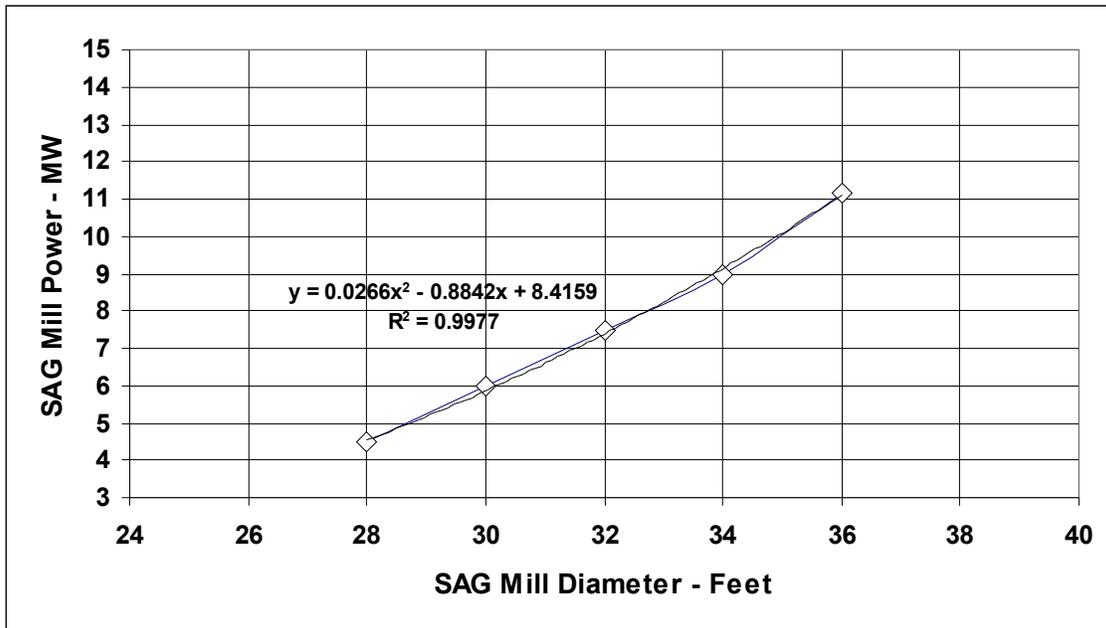


Figure 5: Mill Power as a Function of Mill Diameter

Figure 5 shows the relationship between SAG Mill power and mill diameter from Table 3, again for silicious ore at about 2.9 SG.

INCREMENTAL CAPITAL COST VS PRODUCTION CHANGES

The following typical example is presented to show the order of magnitude of incremental capital costs to increase the size and power of the SAG mill in the range of 11 MW and the relative incremental revenue on an annual basis for lost or increased production.

The data below is based on the typical data from Figure 1 and a typical low grade clean milling copper/gold ore grading 0.60% Cu and 1.0 g/t Au, with a gross value of about \$18 and a Net Smelter Return in the order of \$10 US per tonne of ore milled.

- Design energy requirement from Figure 1 = 9.5 kWh/t (80th percentile).
- Tonnes per hour - design throughput = 1000 t/h (from mill design criteria).
- Required shell energy = 9.5 MW at optimum conditions.
- Required motor (and shell to match) = 11 MW.
- Size of SAG mill = 36 ft diameter by 15.0 ft long (EGL).
- Value of the ore gross in situ - \$18.00 US per tonne.
- Value of the metals recovered NSR = \$10.00 US per tonne.
- Annual Value of NSR = \$80,600,000 US for 92% availability.
- 10% incremental change in annual production is = \$8,060,000 US or \$670,000 US / month.
- Capital cost of a 2 ft. diameter reduction is about \$936,000 (-15%) from 36 to 34 ft. diameter.

- Decreasing the SAG mill diameter by 2 feet from 36 to 34 ft. causes a 2 MW reduction in installed SAG power or an 18% decrease from 11 to 9 MW. This energy can reduce grinding capacity by about 9%, considering the ball mill if it also has 11 MW of installed power.

The impact of these numbers is dramatic and proves conclusively that the cost of undersizing the SAG mill will be detrimental to project economics for this low-grade example. High-grade ores will show even stronger reasons to provide adequate SAG energy at the design stage. Lost production when milling hard ores may not be a problem if the amount of ore that requires more energy than design is low and does not dominate mill feed for long periods of time. It also may not be a problem if the downstream process can handle extra tonnage when the ore is soft.

But it still remains a fact that to give the operators a reasonable chance to meet production targets on a long-term basis, a robust grinding circuit will be needed. Best metallurgy will also be achieved at steady feed rates so there are hidden advantages to having a robust grinding circuit. Saving 15% on the SAG mill (\$936,000 US) can cause a \$603,000 US per month loss in revenue, compared to running design tonnage levels most of the time. It can therefore be demonstrated that providing a SAG mill that is not a bottleneck to production when milling hard ores, is a very good investment for most new mines.

The key to achieving satisfactory and predictable grinding performance results is intimately tied to the provision to draw design SAG power at optimum, not overloaded conditions.

SUMMARY AND CONCLUSIONS

The best design procedure for a new SAG mill involves the stages outlined in this paper.

- Determine from laboratory testing the representative hardness distribution for the ore body.
- Pick the design power for the SAG mill, considering mining production schedules, future expansion plans, future potential changes in metal pricing that affect cut-off grades, and the sizing of the downstream equipment.
- Extra power drawn for loading conditions above optimum is essentially wasted.
- Provide a motor with the capability to deliver design power on a continuous basis by including a suitable service factor, usually 15% to cover any drive losses and normal fluctuations in power demand.
- Size and construct the mill motor to draw full load power at design conditions for load and speed. That is 15% steel, 35% charge and 75% critical speed.
- Check that the SAG mill grinding chamber will draw design power at optimum conditions using the tools and methods described above.
- Request pricing for the specified mill and motor and invite the mill manufacturers to propose their alternative sizes and pricing.
- Evaluate the merits of saving capital in terms of what production capability has been sacrificed if a smaller mill is being considered.
- Always check the power drawing capability of the shell selected. The design engineer is ultimately responsible for confirming the mill manufacturers recommended power draw.

RECOMMENDATIONS

1. Use laboratory tests to develop the hardness variability function for a new ore body and use this data to design the SAG mill.
2. Hire a fully trained mining / process engineer to take the samples for testing. He or his firm will be able to guarantee performance as long as he can be responsible for the samples taken.
3. Select SAG power at a minimum of the 80th percentile of hardness variability, unless other considerations make another choice more reasonable.
4. One such consideration is the decision to use a pebble crusher in the SAG mill circuit. This adds grinding capability to the SAG mill and allows the selection of a smaller SAG mill. This option should be carefully reviewed before implementation because future expansions might make this a poor and restricting choice.
5. Consider extra capital for the SAG mill instead of oversizing the downstream process equipment. It could be money well spent in some cases. Savings for the downstream equipment will result, and better metallurgy will be possible because of steadier feed.
6. Always choose the SAG mill grinding chamber to deliver the design energy at optimum conditions, that is, 75% critical speed and 26% load by volume of which 10% is steel.
7. Where appropriate, consider the advantages that can result from lower steel additions and/or fully autogenous operation if a larger grinding chamber is selected, to deal with specific parts of the ore body that may be softer than average.
8. Restrict pilot plant SAG mill testing to confirming the design power levels on an ore sample or samples of known hardness. These samples should also be used for metallurgical testing at the same time. The scale of pilot work should be reduced to about 100 kg per hour on 5 tonne samples in order to control the cost of the test work. (Carre, Starkey et al 2002).

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