An Investor's Perspective on Best Practices in SAG Mill Sizing

Spencer Reeves[1](*), John Starkey[1] and Keith Abergel[2]

1 Starkey & Associates Inc., Oakville, Canada and 2 GMP Securities, Toronto, Canada

ABSTRACT

With over 30 years of industrial application, SAG milling is a well understood, mature technology in the mining industry. Despite this, there have recently been several start-ups using SAG technology which have failed to achieve design throughput as a direct result of poorly selected equipment. This paper is intended to evaluate the economic cost of these decisions and their impact on project feasibility/valuation to both operators and investors.

Three different generic mining project models were constructed using data from NI43-101 reports. Each model was developed into a series of comparison cases to calculate plant performance as NI43-101 predicted and measured in operation at start-up. Hypothetical solutions to achieve design tonnage were then developed including: a retrofit of existing equipment, and an appropriate SAG mill.

This analysis indicates that under-sizing the comminution circuit has a significant impact on the economic performance of a mine, primarily by limiting throughput. The capital cost savings achieved by under-sizing are far outweighed by the long term effect on revenue streams. In some cases, had this information been known to investors, the project may have even been shelved or cancelled.

Selecting an appropriately sized SAG mill increases overall capital costs, but also significantly improves project rate of return relative to the undersized case, as it allows for the initial throughput target to be achieved. This capital cost increase is still much less expensive than the installation of additional comminution equipment, such as pre-crushing after plant commissioning.

This paper has found that the under-sizing of a SAG mill has a significant impact on an investor's ability to properly evaluate mining project economics. The tools to accurately forecast SAG mill performance are available, and can be used to design comminution circuits that meet or exceed the expectations and demands of investors.

Keywords: SAG, Sizing, Valuation, Cost Estimation, Best Practices

INTRODUCTION

With over 30 years of industrial application, SAG milling should be a well understood, mature technology in the mining industry. Despite its long history of industrial application, there have been several recent mineral process plant start-ups utilizing SAG technology which have failed to achieve design tonnage and/or final grind size, specifically due to the installation of an undersized SAG mill.

A brief analysis of this frequent undersizing reveals a likely cause: the need to reduce capital costs. This is certainly a valid goal, and is essential to any successful project. However, when taken to its extreme, capital cost reduction can compromise the ability of the project to meet its design targets. AG/SAG mills are often prime targets for this type of cost reduction due to their very high unit cost, which typically numbers in the tens of millions of dollars per mill, plus engineering, transport, ancillary equipment and installation costs, which can push the total cost of a grinding circuit well into the hundreds of millions (CIM, 1998).

This paper is intended to evaluate the economic cost of such extreme capital reductions as they apply to SAG milling, and their effect on project feasibility and valuation to both operators and investors. This is accomplished through a series of case studies which were created based on three different operating projects. The case studies were developed to mimic the perspective of a public investor, using only publicly available data as published on SEDAR[1]. Mill resizing was performed using publicly available tools, as published on the Starkey & Associates Inc. website[2] to coincide with this work.

METHODOLOGY

Three case studies were developed to analyse multiple instances of undersized SAG mills. Each case study was developed from only public data available prior to construction as published in NI43-101 compliant feasibility studies. This was done to limit the amount of bias imparted by the author as each of the projects studied has since been commissioned and additional data is now available. Furthermore, the economic assumptions stated in each study including metal prices and operating costs were also adhered to, regardless of their current realism, to mimic the best available data at the time the decision to proceed with the project was made.

Each case study was divided into four discounted cash flow scenarios, summarized in Table 1.

[1] The System for Electronic Document Analysis and Retrieval (SEDAR) is a system provided by the Canadian Securities Administration to allow for public dissemination of Canadian securities information, including NI43-101 technical reports. See www.sedar.com.

[2] www.sagdesign.com

Table 1 Summary of Case Study Scenarios

Scenario	Description
1	Expected base case from NI43-101
2	Capital renovation (Assumed pre-crushing)
3	Predicted performance without renovation
4	Revised mill sizing

The use of four scenarios per case study facilitated the comparative analysis of each potential decision to achieve design throughput and grind relative to the expected base case presented to investors. The first scenario defines the expected base case value of the project as presented in the NI43-101. The second scenario allows for an additional capital expense after an unsuccessful commissioning to achieve the initial design target. This was defined as the addition of a pre-crushing plant. Capital costs for these facilities were estimated based on the cost estimation handbook (CIM, 1998), scaled for inflation.

Pre-crushing is frequently the only recourse available to mining companies when their SAG grinding circuit falls significantly short of its design target. Some additional throughput can be generated by optimizing mill operating parameters but is typically not sufficient to achieve the large increase required to compensate for the undersized SAG mill. Pebble crushing is also an alternative, but is frequently already included in the initial design to trim SAG mill dimensions. Scenario Three presents the predicted performance of the grinding circuit without any modification whatsoever. This results in a lower overall throughput rate and a longer life of mine but maintains the initial capital budget.

Finally, Scenario Four presents a revised mill sizing as calculated using the SAGDesign Mill Sizing and Throughput Calculators, publicly available from the S&A website. This mill would be able to achieve the initially selected design throughput target, but includes increased capital costs. The new capital cost was estimated using data kindly provided by a major international mill manufacturer. Mills were selected using the stated ore grindability measurements in kWh/t, or when unavailable, estimated using the conversion between "Axb" ore hardness as predicted from SMC or JK DWT test data to kWh/t as presented in Bailey *et al.* (2009). Such an estimation should not be used for actual engineering design work but was suitable for this exercise as it was intended to replicate public perspective.

A constant discount rate of 5% was used for all Net Present Value (NPV) calculations. This discount rate is a reasonable assumption for copper-gold and gold projects.

It should be noted that the selection of discount rate will have a material impact on the results of this analysis as the undersizing of a SAG mill effectively delays revenue into a later discount period. As such, the calculated value of each project is somewhat subjective. Very low or zero discount rates favour no renovation under the assumptions made for calculating NPV. At very high discount rates, the addition of pre-crushing would always prove to be the most favourable scenario. However both of these very high and very low discount rates are unrealistic for use in this analysis.

Case Studies

The following SAG mill data and economic assumptions were used to construct each case study and subsequent scenarios. Also presented are the re-evaluated mill sizes. Grindability in the report is defined as specific energy in kWh/t measured at the pinion to grind from the stated F80 to the planned T80.

Case Study One: 35,000 tpd Copper/Gold

Table 2 Case Study One SAG Mill Selection

Sizing	No. of Mills	Diameter (ft)	EGL (ft)	Inst. Power / Mill (HP)	Tot. Charge (% Vol)	Steel Load (% Vol)	Speed (% Crit.)	Grindability (kWh/t)
Initial	1	34	17.5	17,000	30	12	77	7.27
Revised	1	36	16	18,500	26	10	75	7.27

Tables 3-5 Case Study One Economic Assumptions

Parameter	Years 1-5	Years 6-10	Years 11-17
Mill feed (total kton/period)	70,405	70,409	91,973
Feed Grade (%Cu)	0.43%	0.41%	0.27%
Cu. Recovery (%)	89%	89%	89%
Copper Price (C$/lb)	2.25	2.25	2.25

Parameter	Years 1-12	Years 13-17
Op. Cost (C$/t)	8.27	4.66

Parameter	Value
Total Capital Cost (MC$)	438

Case Study Two: 60,000 tpd Copper/Gold

Table 6 Case Study Two SAG Mill Selection

Sizing	No. of Mills	Diameter (ft)	EGL (ft)	Inst. Power / Mill (HP)	Tot. Charge (% Vol)	Steel Load (% Vol)	Speed (% Crit.)	Grindability (kWh/t)
Initial	1	40	22	29,500	26	10	75	11.25
Revised	2	38	17	23,500	26	10	75	11.25

Table 7 Case Study Two Economic Assumptions

Parameter	Value
Operating Cost (C$/t)	6.96
Total Capital Cost (M$ CDN)	915
Exchange Rate (US$/C$)	1
Copper Price (US$/lb)	2
Gold (US$/oz)	800
Silver (US$/oz)	11

Feed grade and recovery vary by year, presented in Appendix A.

Case Study Three: 55,000 tpd Gold

Table 8 Case Study Three SAG Mill Selection

Sizing	No. of Mills	Diameter (ft)	EGL (ft)	Inst. Power / Mill (HP)	Tot. Charge (% Vol)	Steel Load (% Vol)	Speed (% Crit.)	Grindability (kWh/t)
Initial	1	38	21	26,000	26	10	75	7.86
Revised	2	36	14.5	15,000	26	10	75	7.86

Table 9 Case Study Three Economic Assumptions

Parameter	Value
Operating Cost (C$/t)	8.43
Total Capital Cost (M$ CDN)	760
Exchange Rate (US$/C$)	1
Gold (US$/oz)	775

Feed grade and recovery vary by year, presented in Appendix A.

RESULTS

The NPV of each scenario is presented in Table 10 while the relative change to NPV from the base case is summarized in Figure 1. Cash flow models are presented in Appendix A.

Table 10 Summary of Calculated Project NPV, in Millions C$

Case/Scenario	1	2	3	4
35,000 tpd	1,400.8	1,329.3	971.3	1,386.2
60,000 tpd	968.2	920.6	779.7	965.1
55,000 tpd	952.4	861.7	769.1	935.1

Figure 1 Relative Change in NPV from the base NI43-101 Scenario One

In the scenarios of capital renovations, the expected value of the project decreased significantly, primarily due to the operating costs associated with the new equipment. On average, NPV decreased by 6.51%.

As expected, when corrective actions are not taken, an undersized SAG mill will limit the performance of the entire plant over its lifetime and have a severe negative impact on project NPV. In the 35,000 tpd project, this impact was particularly great as the SAG mill was significantly undersized and increased the project duration by over 60%.

Finally, when a larger hypothetical SAG mill was selected, NPV did decrease slightly from the initial base case due to the larger initial capital expenditure but not to the extent of the other two possible scenarios.

DISCUSSION

The analysis indicates that the undersizing of a SAG mill can have significant impacts on project valuation. It is not the purpose of this paper to determine if the mills selected were or were not the best available engineering choice. To draw conclusions on that subject based on this analysis would disregard a great deal of other extraneous factors which may have influenced the engineering decision making process. It should be noted however that each of the selected mills was incorrectly presented to the public as though it could achieve the design tonnage. The mill sizing calculations performed as part of this paper predicted the actual average operating throughput of each project within 3,000 tpd. Rather than criticize this decision, this analysis was intended to evaluate the resulting cost and to provide a cautionary warning for future SAG mill sizing exercises.

Of all the potential scenarios examined, the most positive economics were generated when the correct SAG mill was selected to achieve the initially specified design criteria.

The least economic scenario was the undersized SAG mill without renovation. In reality, this scenario is unlikely as an operator would choose to install additional comminution capacity. This would happen in all but the most marginal economic situations when the payback for additional capital revision could not be justified. All three of these no-renovation scenarios had a large negative impact NPVs at a 5% discount rate relative to the expected NI31-101 value. The analysis showed all plans still remained profitable but may have been shelved or passed over in favour of other alternatives such as the other scenarios presented here. If no such solution were to be found due to other factors, the entire project may have been shelved.

The use of capital revision to compensate for an undersized SAG mill is a less favourable alternative than the larger revised sizing, except at very large discount rates (>50%) which reward the delay in expenditure despite the larger total capital cost. The use of such extreme discount rates is not expected, except during periods of hyperinflation, and is not a reasonable basis for evaluation. In practice, the NPV calculated in these scenarios are likely higher than would be expected as it does not include a delay in throughput to account for construction of pre-crushing facilities and does not include an additional operating cost allowance for pre-crushing, either temporary or permanent. Both of these factors would negatively influence NPV. Furthermore, it is unlikely that the revision could be paid for out of operating profit so a second round of capital funding would be required. Securing this capital could be challenging if the company has incurred large debts as part of the initial project.

As part of this paper, two other trends were also identified in the reporting of mill sizing which made the data difficult to interpret and are described below.

Insufficient test results and mill sizing validation

In two cases, the mills selected were chosen based on the results of relatively few samples taken for SAG grindability (or breakage parameter) measurement. More samples and testing is required to represent the hardness of an entire mine's worth of production. Without further data on the variation of ore hardness within the deposit, it is difficult to assess the validity of the selected design grindability values. Furthermore, due to the lack of standardization in SAG mill grindability measurement, it is generally agreed that secondary/multiple methodologies be used to validate the mill sizing.

Unclear qualification of information

Many of the SAG mill design parameters in these feasibility studies were poorly qualified, particularly in reference to specific energy in kWh/t. This value was often defined as a work index, rather than an operating work index, and as such should have been described with calculation inputs and the location at which the index was to be measured, either at the pinion or at the motor.

CONCLUSIONS

This paper has found that the selection of the correct SAG mill size and power plays an important role in determining the economics of a mining project. The large unit cost of a SAG mill makes it a common target for capital cost reduction leading to the purchase of an undersized mill. In each of the three case studies examined, an incorrect SAG mill size was chosen and severely limited overall plant throughput.

Mill sizing and required power were checked using publicly available tools and only the data in the NI43-101 reports. In each project, the calculated throughput of the NI43-101 selected mill fell short of the design target. These results were then confirmed to correlate within 3,000 tpd of the actual plant performance of the installed mills. While this accuracy is not sufficient to design a new mill with confidence, it is certainly sufficient to indicate to the public that the selected mills are undersized.

The analysis indicated that when the potential cost of capital revision of an undersized SAG mill to meet design tonnage is compared with the cost of the correct, larger mill size, on average, an undersized SAG mill reduced project NPV by 5.61% percent.

Several other factors were also identified as part of this analysis relating to unclear reporting in the data used to select the appropriate SAG mill due to both insufficient testing and reporting of ore grindability measurements, and the unclear qualification of information.

Ultimately, these factors compromise an investor's ability to independently evaluate a project which utilizes a SAG mill. The tools to accurately forecast SAG mill performance are available, and can be used to design comminution circuits that meet or exceed the demands of investors. It is recommended that similar analysis should be performed on future NI43-101 reports prior to their publication to confirm that the true cost of undersizing the SAG mill is understood.

NOMENCLATURE

F80	Feed size, 80th percentile of the SAG feed particle size distribution
T80	Transfer size, 80th percentile of the SAG product particle size distribution
NPV	Net Present Value
AG/SAG	Autogenous or Semi-Autogenous grinding
EGL	Effective grinding length

REFERENCES

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APPENDIX A: Base Case Cash Flow Models

Case Study 1: 35,000 tpd

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	Total
Mill Feed (kT)		14,081	14,081	14,081	14,081	14,081	14,082	14,082	14,082	14,082	14,082	13,139	13,139	13,139	13,139	13,139	13,139	13,139	232,787
Grade		0.43%	0.43%	0.43%	0.43%	0.43%	0.41%	0.41%	0.41%	0.41%	0.41%	0.27%	0.27%	0.27%	0.27%	0.27%	0.27%	0.27%	
Cu (kt)		54	54	54	54	54	51	51	51	51	51	32	32	32	32	32	32	32	
Revenue		267,231	267,231	267,231	267,231	267,231	254,816	254,816	254,816	254,816	254,816	156,571	156,571	156,571	156,571	156,571	156,571	156,571	3,706,225
Operating Cost ($/t)		8.27	8.27	8.27	8.27	8.27	8.27	8.27	8.27	8.27	8.27	8.27	8.27	4.66	4.66	4.66	4.66	4.66	
Operating Cost		116,450	116,450	116,450	116,450	116,450	116,456	116,456	116,456	116,456	116,456	108,660	108,660	61,228	61,228	61,228	61,228	61,228	1,687,990
Operating Profit		150,781	150,781	150,781	150,781	150,781	138,359	138,359	138,359	138,359	138,359	47,911	47,911	95,343	95,343	95,343	95,343	95,343	2,018,236
Capital Cost	438,476																		438,476
Cash Flow	-438,476	150,781	150,781	150,781	150,781	150,781	138,359	138,359	138,359	138,359	138,359	47,911	47,911	95,343	95,343	95,343	95,343	95,343	
Cumulative Cash Flow	-438,476	-287,695	-136,915	13,866	164,647	315,427	453,786	592,146	730,505	868,864	1,007,223	1,055,134	1,103,045	1,198,388	1,293,731	1,389,074	1,484,417	1,579,760	

Case Study 2: 60,000 tpd

Year	0	1	2	3	4	5	6	7	8	9	10	11	12
Throughput (kt)			19,817	21,900	21,900	21,900	21,900	21,900	21,900	21,900	21,900	21,900	21,900
Mass Con. (t)			168,213	161,240	146,566	151,999	139,559	136,913	153,990	139,552	130,069	121,478	123,646
Cu in Con. (t)			47,117	43,959	38,798	40,810	36,818	35,841	41,573	36,658	33,288	30,832	31,282
Au in Con. (oz)			276,477	272,027	245,845	240,244	257,415	280,896	223,506	213,345	197,693	198,615	211,296
Ag in Con. (oz)			371,127	307,004	338,097	469,952	380,657	324,887	304,788	329,446	356,759	270,666	299,602
Revenue			432,956	414,770	371,417	377,255	372,413	386,278	365,411	335,888	308,812	297,777	310,223
Op Costs			137,926	152,424	152,424	152,424	152,424	152,424	152,424	152,424	152,424	152,424	152,424
Capital Cost	915,000												
Cash Flow	-915,000		295,029	262,346	218,993	224,831	219,989	233,854	212,987	183,464	156,388	145,353	157,799
Cumulative Cash Flow	-915,000	-915,000	-619,971	-357,625	-138,632	86,199	306,188	540,042	753,029	936,493	1,092,882	1,238,234	1,396,034

Year	13	14	15	16	17	18	19	20	21	22	23	24	Total
Throughput (kt)	21,900	21,900	21,900	21,900	21,900	21,900	21,900	21,900	21,900	21,900	21,900	1,475	481,192
Mass Con. (t)	121,972	122,838	127,238	139,358	121,846	146,125	142,654	138,674	129,744	139,072	144,933	8,912	3,056,591
Cu in Con. (t)	30,335	30,647	32,746	37,268	31,378	39,536	38,349	37,285	34,476	37,562	39,516	2,377	808,451
Au in Con. (oz)	200,246	209,546	155,739	149,856	138,984	141,859	151,928	138,302	129,563	127,640	123,197	8,726	4,292,945
Ag in Con. (oz)	281,608	344,564	319,199	358,764	430,415	438,264	479,508	405,104	357,559	352,289	340,024	24,083	7,884,366
Revenue	297,011	306,519	272,447	288,109	254,236	292,583	295,859	279,450	259,554	271,560	276,484	17,724	7,084,736
Op Costs	152,424	152,424	152,424	152,424	152,424	152,424	152,424	152,424	152,424	152,424	152,424	10,266	3,349,096
Capital Cost													915,000
Cash Flow	144,587	154,095	120,023	135,685	101,812	140,159	143,435	127,026	107,130	119,136	124,060	7,458	2,820,640
Cumulative Cash Flow	1,540,621	1,694,716	1,814,739	1,950,423	2,052,235	2,192,394	2,335,830	2,462,856	2,569,985	2,689,122	2,813,182	2,820,640	

Case Study 3: 55,000 tpd

Year	0	1	2	3	4	5	6	7	8	9
Total tonnes milled (kt)			20,075	20,075	20,075	20,075	20,075	20,075	20,075	20,075
Gold Grade (Oz/t)			1.02	1.13	1	0.82	0.74	0.65	0.76	0.83
Gold Production (kOz)			556	615	544	447	403	354	414	450
Revenue			430,575	476,893	421,658	346,519	311,985	274,415	320,838	348,529
Operating Cost			-172554	-170612	-173554	-171162	-175550	-177090	-177221	-179143
Operating Income			258,021	306,281	248,104	175,357	136,435	97,325	143,617	169,386
Royalty			-7,959	-7,153	-6,325	-5,198	-4,680	-4,116	-4,813	-5,228
Income			250,062	299,128	241,779	170,159	131,755	93,209	138,804	164,158
Capex	-250,000	-510,000	0	0	0	0	0	0	0	0
Sustaining Cap			-9,880	-175	-20,025	-175	-7,425	-295	-7,010	-11,715
Closure			0	0	0	-1,000	-2,000	-2,000	-2,000	-2,000
Working Cap			-30144	-462	483	1,134	-128	82	-327	-455
Cash Flow	-250,000	-510,000	210,038	298,491	222,237	170,118	122,202	90,996	129,467	149,988
Cumulative Cash Flow	-250,000	-760,000	-549,962	-251,471	-29,234	140,884	263,086	354,082	483,549	633,537

Year	10	11	12	13	14	15	16	17	18	Total
Total tonnes milled (kt)	20,075	20,075	20,075	20,075	20,075	20,075	6,647			287,697
Gold Grade (Oz/t)	0.9	0.76	0.76	0.81	0.87	0.87	0.39			0.84
Gold Production (kOz)	486	411	413	438	474	473	70			6,548
Revenue	376,910	318,892	319,750	339,131	367,094	366,738	53,916			5,073,843
Operating Cost	-181814	-160289	-161089	-162468	-164472	-150789	-36,891			-2,414,698
Operating Income	195,096	158,603	158,661	176,663	202,622	215,949	17,025			2,659,145
Royalty	-5,654	-4,783	-4,796	-5,087	-5,506	-5,501	-809			-77,608
Income	189,442	153,820	153,865	171,576	197,116	210,448	16,216			2,581,537
Capex	0	0	0	0	0	0	0			-760,000
Sustaining Cap	-500	-235	-605	-295	-425	0	0			-58,760
Closure	-2,000	-2,000	-2,000	-2,000	-2,000	-3,000	-9,000	-10,000	-11,000	-52,000
Working Cap	-572	2,784	-90	-334	-512	1,376	13,814	13,353	0	
Cash Flow	186,370	154,369	151,170	168,947	194,179	208,824	21,030	3,353	-11,000	1,710,779
Cumulative Cash Flow	819,907	974,276	1,125,446	1,294,393	1,488,572	1,697,396	1,718,426	1,721,779	1,710,779	