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Power-based modelling of single-stage AG and SAG mill circuits

Alex Doll[1]* and Miguel Becerra[2]

1. *Consultant, Alex G. Doll Consulting Ltd, Canada*
2. *Technical Specialist, Processing group T&S, Anglo American, Chile*

ABSTRACT

Comminution circuit design and geometallurgy is normally performed using the power-based class of models. Many models of this type exist and all of them are empirically based, meaning they are calibrated to fit a specific set of laboratory results to a database of mill surveys. Most empirical comminution models are calibrated to two-stage AG/SAG mill and ball mill circuits -- this work compares the performance of several commonly used power-based models to surveys conducted on single-stage AG/SAG circuits.

Survey data was collected from Anglo American's El Soldado mine and from published works by others and the operating specific energy consumption of circuit was computed. Ore grindability measurements were collected, allowing model predictions of specific energy consumption to be computed using models proposed by Jorquera & Becerra (at El Soldado), Morrell, Barratt and Amelunxen. The actual operating specific energy consumption is finally compared to the predictions.

The more complex ores required more complex models to obtain reliable predictions; whereas, the simple ores can be modelled by any of the models. A complex ore, such as Palabora, requires grindability measurements be made at three size classes, such as the three Bond work indices. A simple ore, such as El Soldado, can be reliably modelled with a single grindability measurement, such as the SAG Grindability Index. A quick diagnostic of whether an ore is "complex" or "simple" is to compare the three Bond work indices: "simple" ores generally have the same value for all three work index values, whereas "complex" have dramatically different values for all three.

INTRODUCTION

The single-stage autogenous grinding (AG) or semi-autogenous grinding (SAG) mill is a low-cost option for milling relatively low tonnages. Such circuits consist of an AG or SAG mill that is fed directly from a primary crusher, and the mill product is then classified through a hydrocyclone (or fine screen) and oversized material is returned to the mill for further grinding. The product of the single-stage mill is finished material suitable for flotation or leaching, usually in the size range of 80% passing 200 µm to 100 µm.

The design of such circuits is complicated by the typical power-based models used for conceptual design being calibrated to a two-stage circuit with AG or SAG mill product being passed to a pebble mill or ball mill stage for finished grinding. The two-stage circuit includes a "transfer size" of AG/SAG product that becomes the feed to the closed-circuit ball mill.

This work is compares the existing El Soldado single-stage model (Jorquera & Becerra, 2016) to two-stage models by Barratt (1979), Morrell (2004) and Amelunxen (2013) where the two-stage models include internal "phantom" transfer sizes (for modelling) that are not present in the operating circuit.

METHODOLOGY

Operating data from the single stage SAG mill at Anglo American's El Soldado mine in Chile was evaluated and compared to four published power-based comminution models. Case studies from literature for other single stage SAG or AG mills were then evaluated in the same four models.

Power-based comminution models are used to predict the specific energy consumption (CEE) of a comminution circuit, E, as kW·h/t, where a laboratory measurement of grindability is input. In the case of a multi-stage grinding circuit, the specific energy consumption of each stage can be considered, such as a primary SAG and secondary ball mill circuit where the individual stages would be E_{SAG} and E_{ball}, and the combined total circuit CEE would be E_{total}. In all cases, the specific energy consumption is defined as the motor power consumed relative to the shell of the mill (a.k.a. power at the pinion output) divided by the fresh feed rate in dry tonnes per hour.

The simplest models use a single grindability measurement to estimate the specific energy consumption across the whole size range observed in the industrial circuit (going from feed size to product size); the El Soldado model is this type. The more complicated models break the sizes range into intervals and estimate the specific energy consumption for each interval with a different grindability measurement; the Morrell Mi model (2-intervals), Amelunxen SGI model (2-intervals) and Barratt model (3-intervals) are of this type.

Grindability measurements

Laboratory tests are conducted on ore samples that give measurements of ore grindability suitable for use in one or another of the models. Relevant to this work, we consider the following grindability indices grouped into the following families. Certain conversion equations between families are provided for compatible tests.

The Bond work index series:

- **Wi_{BM}**, the Bond ball mill work index (conducted at an appropriate closing mesh size), unitless (but relative to either a metric tonne or Imperial short ton basis).
- **Wi_{RM}**, the Bond rod mill work index (conducted using a wave-liner mill and a fourteen mesh closing size), unitless (but relative to either a metric tonne or Imperial short ton basis).
    - $Wi_{RM} = 115\ (A\times b)^{-0.57}$ [based on reinterpretation of Doll, 2016]
    - $Wi_{RM} = 1.35\ (SGI)^{0.51}$ [Doll, 2016]
- **Wi_C**, the Bond crushing work index, unitless (but relative to either a metric tonne or Imperial short ton basis). This parameter also goes by the acronym LEIT (Low Energy Impact Test).

Results derived from drop-weight tests (could be a JK DWT™, SMC Test™ or a generic drop-weight):

- **A×b**, the slope at the origin of a t_{10} versus E_{CS} chart describing a drop-weight test.
- **Mia**, the "coarse" size class grindability measurement in a Morrell Mi equation. Related indices are **Mic** for crushers and **Mih** for high pressure grinding rolls.
    - $Mia = 390.87 \times (A\times b)^{-0.81}$ [based on reinterpretation of Doll, 2016]
    - $Mia = 1.4 \times (Wi_{RM})^{0.95}$ [derived from Doll, 2016]
- **Mib**, the "fine" size class grindability measurement in a Morrell Mi equation. Based on Morrell's re-interpretation of the results of a Bond ball mill work index test.

Results from a bench-scale SAG test:

- **SGI**, the SAG Grindability Index, the time (in minutes) to reduce a 2 kg ore charge to 80% passing 1.7 mm in a standard-sized SGI mill. The proprietary SPI Test™ should be functionally equivalent to, and interchangeable with, an SGI result.
    - $SGI = 8882.72\ (A\times b)^{-1.24}$ [Doll, 2016]

Power-based models

El Soldado SGI model: Becerra and Jorquera (2016) published a single-parameter model, Equation (1) fitted to the El Soldado single-stage SAG mill to the SAG Grindability Index (SGI). The equation was fit neglecting the power consumed by the mill's pebbles that are discarded from the SAG circuit (transferred to a parallel crushing circuit and not returned to the SAG). Equation (1) includes a correction to make the specific power consumption relative to the pinion output (a.k.a. the mill shell).

$$E_{SAG} = 5.494 \left(\frac{SGI}{\sqrt{P_{80}}}\right)^{0.563} \times 0.96 \times 0.985 \tag{1}$$

where: *SGI* is the SAG Grindability Index, minutes,

P_{80} is the SAG hydrocyclone overflow 80% passing size, µm.

Amelunxen SGI model: Amelunxen et al. (2014) published a two-parameter model, Equation (2) originally fitted to data published in Canada and corroborated with measurements to a number of (mostly) copper porphyry mines in North America and South America. The same paper publishes the dimensions and experimental method of the SGI test. Amelunxen's original method is based on power measured at the motor input; this is corrected to the pinion output for compatibility with the other methods. The ball mill correction factor (*CFnet*) is empirical and one way of estimating it was presented by Amelunxen at the Procemin 2013 Short Course by Doll & Amelunxen.

The SGI equation uses a transfer size between a SAG and ball mill; it is proposed that a synthetic transfer size of 2100 µm be used to model single-stage SAG mills.

$$E_{SAG} = 5.9 \left(\frac{SGI}{\sqrt{2100}}\right)^{0.55} \times f_{SAG} \times 0.96 \times 0.985 + Wi_{BM} \left(\frac{10}{\sqrt{P_{80}}} - \frac{10}{\sqrt{2100}}\right) \times CF_{net} \tag{2}$$

where: *SGI* is the SAG Grindability Index, minutes,

P_{80} is the SAG hydrocyclone overflow 80% passing size, µm

F_{80} is the milling circuit feed 80% passing size, µm,

f_{SAG} is a calibration parameter for pebble crushing and/or fine feed (typically 1.0 for 80% passing six inch mill feed and when no pebble crusher is present).

Wi_{BM} is the Bond ball mill work index, unitless

CFnet is an empirical adjustment to a ball mill circuit [*CFnet* = 2.35 - 0.29 × ln(P_{80})]

Morrell Mi model: Morrell (2008) published a two-parameter model based on two equations (3 & 4) to describe a variety of comminution devices, including single-stage SAG and AG mills. The CEE equation is in two parts, one to characterize the minus 750 µm (80% passing) component of comminution and the other to characterize the plus 750 µm (80% passing) component of comminution.

$$E_{SAG} = 4Mib\left(P_{80}^{f(P_{80})} - 750^{f(750)}\right) + 4Mia\left(750^{f(750)} - F_{80}^{f(F_{80})}\right) \times K \tag{3}$$

$$f(x) = -\left(0.295 - \frac{x}{10^6}\right) \tag{4}$$

where: *Mib* and *Mia* are the "fine" and "coarse" laboratory grindability metrics, respectively,
P_{80} and F_{80} are the milling circuit product and feed sizes, respectively, µm,
K is a calibration parameter of 0.95 for pebble crushing or 1.0 for no pebble crushing

<u>Barratt model:</u> Barratt (1979) published a three-parameter model based on a copper porphyry mine (Island Copper) in Canada. The model uses three Bond work index parameters to characterize three size classes: a "crushing" component to an intermediate 18,850 µm size, a "rod milling" component to an intermediate 2.1 mm size, and a "ball milling" component to the final P_{80} size. A variety of adjustments such as the Rowland EF4 and EF5 factors are included.

$$E_{SAG} = \left[10 \times Wi_C \left(\frac{1}{\sqrt{18850}} - \frac{1}{\sqrt{F_{80}}}\right) + 10 \times Wi_{RM} \left(\frac{1}{\sqrt{2100}} - \frac{1}{\sqrt{18850}}\right) \times EF4_{RM} + 10 \times Wi_{BM} \left(\frac{1}{\sqrt{110}} - \frac{1}{\sqrt{2100}}\right) \times EF4_{BM} \times EF5\right] \times 1.25 \\ -10 \times Wi_{BM} \left(\frac{1}{\sqrt{110}} - \frac{1}{\sqrt{P_{80}}}\right) \times EF4_{BM} \times EF5 \tag{5}$$

$$EF4_{RM} = \left[1 + \frac{(0.907 \times \mathrm{MAX}(Wi_{RM}, Wi_C) - 7)}{(18850/2100)} \left(\frac{18850}{16000(14.33/Wi_{RM})^{0.5}} - 1\right)\right] \text{ (or 1.0 if less than 1.0)} \tag{6}$$

$$EF4_{BM} = \left[1 + \frac{(0.907 \times Wi_{BM} - 7)}{(2100/[P_{80} \text{ or } 110])} \left(\frac{2100}{4000(14.33/Wi_{RM})^{0.5}} - 1\right)\right] \text{ (or 1.0 if less than 1.0)} \tag{7}$$

$$EF5_{BM} = \left[\frac{P_{80} + 10.3}{1.145 \times P_{80}}\right] \text{ (or 1.0 if less than 1.0)} \tag{8}$$

where: Wi_C is the Bond crushing work index, unitless
P_{80} is the SAG hydrocyclone overflow 80% passing size, µm
F_{80} is the milling circuit feed 80% passing size, µm,
Wi_{RM} is the Bond rod mill work index, unitless
Wi_{BM} is the Bond ball mill work index, unitless
EF4 and *EF5* are the Rowland efficiency factors for oversized feed and fine grinding.

Plant surveys

El Soldado

Six plant surveys were conducted at the Anglo American El Soldado mine between 2013 and 2016. The survey data collection included the power draw of the single-stage SAG mill, the fresh feed rate, particle size distributions for circuit feed and product, and the pebble rejection rate (pebbles are discarded from the SAG circuit and treated elsewhere). Grindability testing for SGI and/or a drop weight test was conducted on a feed belt sample taken immediately after the survey. Relationships were established to convert the drop weight A×b and SGI values, and to predict related measures such as Mia, Mib, Wi_{RM}, Wi_{BM}. A constant Wi_C value of 18 metric units is assumed based on earlier testwork..

Table 1 El Soldado survey results

Survey		**2013-03**	**2013-06-05**	**2014-03-26**	**2015-02-04**	**2015-09-23**	**2016-03-23**
Fresh feed F_{80}	µm	104,700	120,000	125,800	92,442	86,024	74,481
pebble size D_{80}	µm	56,600	56,600	57,000	55,400	56,500	57,665
cyclone o/f P_{80}	µm	198	152	205	194	208	210
flow rate of pebbles	dry t/h	186	202	197	226	267	191
flow rate to flotation	dry t/h	387	405	532	548	582	583
motor power at leads	kW	9,786	10,880	10,892	10,077	9,890	9,780
%power used for pebbles		11%	10%	8%	10%	7%	7%
E_{SAG} pebbles	kWh/t leads	2.8	2.8	1.7	1.9	1.3	1.2
E_{SAG} flotation feed	kWh/t leads	22.5	24.1	18.8	16.5	15.7	15.6
mechanical efficiency		0.985	0.985	0.985	0.985	0.985	0.985
electrical efficiency		0.96	0.96	0.96	0.96	0.96	0.96
E_{SAG} of flotation feed	**kWh/t shell**	**21.3**	**22.8**	**17.7**	**15.6**	**14.9**	**14.8**

Table 2 El Soldado grindability and flotation feed model predictions for SGI models

Survey		2013-03	2013-06-05	2014-03-26	2015-02-04	2015-09-23	2016-03-23
SGI fresh feed	min	*103*	*114*	*113*	113	114	99
SGI flotation feed	min	*94*	*109*	*105*	*105*	*105*	*93*
Flotation E_{SAG} by El Soldado SGI equation	kWh/t at motor leads	16.0	18.7	16.9	17.1	16.8	15.6
– corrected to shell	**kWh/t shell**	**15.1**	**17.7**	**16.0**	**16.2**	**15.9**	**14.8**
Difference		-29%	-22%	-10%	4%	7%	0%
hypothetical T_{80}	µm	2,100	2,100	2,100	2,100	2,100	2,100
CFball		0.82	0.89	0.81	0.82	0.80	0.80
Flotation E_{SAG} by Amelunxen SGI equation	**kWh/t shell**	**15.91**	**19.46**	**16.38**	**16.84**	**16.26**	**15.37**
Difference		-25%	-15%	-8%	8%	9%	4%

Italics indicate numbers were not measured directly and are either calculated from other grindability measurements or are assumed.

Table 3 El Soldado grindability and flotation feed model predictions for Morrell and Barratt models

Survey		**2013-03**	**2013-06-05**	**2014-03-26**	**2015-02-04**	**2015-09-23**	**2016-03-23**
A×b of fresh feed		36.35	33.50	*33.82*	*31.00*	*31.70*	*37.00*
A×b of flotation feed		*39.18*	*34.77*	*35.84*	*35.84*	*35.84*	*39.52*
Mia	kWh/t	*19.7*	*21.8*	*21.3*	*21.3*	*21.3*	*19.6*
Mib	kWh/t	*22.4*	*23.6*	*23.3*	*23.3*	*23.3*	*22.3*
$f(F_{80})$		-0.3997	-0.415	-0.4208	-0.387442	-0.381024	-0.369481
$f(P_{80})$		-0.295198	-0.295152	-0.295205	-0.295194	-0.295208	-0.29521
Morrell Mi model	**E_{SAG}, kWh/t**	**16.5**	**19.7**	**17.6**	**17.5**	**17.0**	**15.6**
difference		-22%	-13%	-1%	12%	14%	6%
Wi_C	metric	18	18	18	18	18	18
Wi_{RM}	metric	*14.4*	*15.3*	*15.1*	*15.1*	*15.1*	14.3
Wi_{BM}	metric	*19.0*	*19.8*	*19.6*	*19.6*	*19.6*	18.9
Bond/Barratt model	**E_{SAG}, kWh/t**	**19.6**	**19.6**	**18.07**	**18.29**	**17.45**	**16.67**
difference		-8%	-14%	2%	17%	17%	13%

Italics indicate numbers were not measured directly and are either calculated from other grindability measurements or are assumed.

The power consumed by the discarded pebbles is calculated using a method of mixing grindability results adapted from Amelunxen (2003) and the operating specific energy consumption is adjusted to represent only the power consumed to make flotation feed. The grindability of the flotation feed, as SGI, is also calculated using this mixing method and is less than the SGI of the fresh feed due to rejection of the ~22% harder pebble fraction

Palabora Mining Company

Three plant surveys were conducted at the Rio Tinto Palabora plant in South Africa (Condori et al, 2011a; Condori et al, 2011b; Van Heerden, 1996; and Mainza et al, 2011). The survey data collection included the power draw of the single-stage AG mill, the fresh feed rate, particle size distributions for circuit feed and product, and the pebble rejection rate (pebbles are discarded from the AG circuit in certain surveys).

Table 4 Palabora survey results

		crushed recycle	**uncrushed recycle**	**tap-off (pebble rejection)**
AG F_{80}	µm	133,000	133,000	133,000
hypothetical T_{80}	µm	2,100	2,100	2,100
circuit P_{80}	µm	321	208	249
power at shell	kW	5,930	6,510	5,760
throughput	dry t/d	11,750	12,550	16,049
throughput	dry t/h	544	581	743
pebble discard rate	dry t/h	0	0	120
%power - discarded pebbles (top o/s)		0%	0%	5%
%power - discarded pebbles (bottom o/s)		0%	0%	8%
power, flot feed basis	kW	5,930	6,510	5,011
E_{AG}, flot feed basis	**kWh/t pinion**	**10.90**	**11.20**	**8.04**
Wi_O	metric	20.54	16.83	13.27

Grindability testing for drop weight tests (A×b) and Bond ball mill work index were performed on ore samples from each survey, and allowance for the rejection of pebbles was estimated where appropriate. Crushing work index determinates were made on rock type composites, which were used to estimate values for each survey. Relationships were used to predict related measures such as SGI, Mia, Mib, and Wi_{RM}. The Morrell Mib value turns out to be very sensitive to the closing mesh size used in the Bond ball mill work index grindability test. The details of the Bond test were not published, so it is assumed that the tests were conducted at 300 μm closing screen size to generate a test P_{80} of 225 μm and the Mib is calculated on this basis.

Mainza et al (2011) noted that the grinding efficiency of the "crushed recycle" case was low, and all four models had difficulty making accurate predictions for this case. The Morrell model was run with *K*=1.0 to account for Mainza's observation. The allowance for energy consumed in the "tap off" pebble case is somewhat dubious, but Mainza et al. suggested that the main difference only appears in the +50 mm size range. This observation makes the modelling problematic, so the large difference between survey and models is not unreasonable.

The Barratt method comes the closest to estimating the observed Palabora CEE. The very high crushing Wi (versus the rod and ball mill Wi) causes a large penalty to the CEE in Barratt's equations, and the rod mill EF4 factor is very high at 1.33. None of the other models consider a coarse grindability measurement (in the 50+ mm size range), suggesting this feature of Bond-type calculations is necessary to accurately model Palabora.

Table 5 Palabora grindability and model results

		crushed recycle	uncrushed recycle	tap-off (pebble rejection)
Wi_C	metric	*18.0*	*18.0*	*16.2*
Wi_{RM}	metric	*7.5*	*7.5*	*7.7*
Wi_{BM}	metric	12.6	12.6	12.1
Barratt model	**kWh/t pinion**	**9.44**	**11.14**	**9.88**
difference		-13%	-1%	23%
SGI	minutes	*23*	*23*	*25*
El Soldado SGI	**kWh/t pinion**	**6.0**	**6.8**	**6.7**
difference		-45%	-40%	-16%
CFball		0.68	0.80	0.75
Amelunxen SGI	**kWh/t pinion**	**6.77**	**8.68**	**7.83**
difference		-38%	-23%	-3%
A×b, flot feed basis		121	121	*114*
Mib	kWh/t	12.5	12.5	11.9
Mia	kWh/t	*8.03*	*8.03*	*8.43*
Mic	kWh/t	*2.51*	*2.51*	*2.66*
Morrell Mi model	**kWh/t pinion**	**6.36**	**7.61**	**7.16**
difference		-42%	-32%	-11%

Goldfields Ghana – Tarkwa

A survey of the single-stage autogenous mill at Tarkwa is described by Mainza et al. (2011). Grindability results include the Bond work index series; the laboratory where the tests were performed is not described, but a likely location is Mintek who are known to have a proper Bond rod mill with a wave liner.

Table 5 Tarkwa survey results

		Feb 2005
SAG F_{80}	µm	150,000
circuit P_{80}	µm	140
power at dcs	kW	11,314
mechanical efficiency		0.97
electric efficiency		0.96
power at shell	kW	10,535
throughput	dry t/h	605
E_{SAG}	**kWh/t shell**	**17.41**

The model predictions in Table 6 demonstrates that the low ball mill work index (relative to the crushing and rod mill work index) confuses the El Soldado model which expects fine size classes to have similar grindability to the SGI size class. Both the 2-parameter models (Morrell and Amelunxen) and the 3-parameter model (Barratt) make reasonable predictions.

Table 6 Tarkwa grindability and model results

		Feb 2005
Wi_C	metric	21.2
Wi_{RM}	metric	20.3
Wi_{BM}	metric	12.6
Bond/Barratt model	**kWh/t pinion**	**17.3**
difference		-1%
SGI	minutes	*186*
El Soldado SGI	**kWh/t pinion**	**24.5**
difference		125%
CFball		0.92
Amelunxen SGI	**kWh/t pinion**	**19.3**
difference		11%
A×b		*30.7*
Mib	kWh/t	*13.9*
Mia	kWh/t	*24.4*
Mic	kWh/t	*9.9*
Morrell Mi model	**kWh/t pinion**	**18.4**
difference		6%

Degrussa

Several surveys of the Western Australian Degrussa process plant were published by Latchireddi et al., 2015, and Knoblauch et al., 2015. The grinding circuit consists of a SAG mill in closed circuit with hydrocyclones and a ball mill circuit in closed circuit with hydrocyclones. The operation sometimes operates as single-stage SAG and otherwise operates SAB with the ball mills. Because the SAG mill always operates in closed circuit with hydrocyclones and the transfer size is quite fine, below 200 µm, it is reasonable to model as a single-stage SAG mill even if working in SAB configuration.

The authors describe much of the early operation as being inefficient, and many of the published surveys are discarded from this analysis due to poor operation.

Table 7 Degrussa survey results

		SS SAG Dec 2012	**SAB Oct 2013**	**SAB April 2014**
SAG F_{80}	µm	58,000	77,000	70,000
hypothetical T_{80}	µm	77	169	125
SAG T_{80}	µm	77	169	125
circuit P_{80}	µm	77	49	46
SAG power at pinion	kW	2,616	2,122	2,893
mech efficiency		1	1	1
electric efficiency		1	1	1
SAG power at shell	kW	2,616	2,122	2,893
throughput	dry t/h	187	202	226
E_{SAG}	**kWh/t shell**	**14.0**	**10.5**	**13.2**
E_{total}	**kWh/t shell**	**14.0**	**17.3**	**20.9**
Operator's comment		poor operation	mill better	running well

Table 8 Degrussa grindability and model results

		SS SAG Dec 2012	SAB Oct 2013	SAB April 2014
Wi_C	metric	*8.0*	*8.0*	*8.0*
Wi_{RM}	metric	*11.8*	*10.3*	*10.3*
Wi_{BM}	metric	13.2	13.9	11.3
Bond/Barratt model	**E_{SAG} kWh/t**	**17.1**	**14.1**	**12.1**
difference		22%	34%	-9%
Bond/Barratt model	**E_{total} kWh/t**	**17.1**	**23.1**	**19.8**
difference		22%	34%	-5%
SGI	minutes	*63*	*47*	*47*
El Soldado SGI	**E_{SAG} kWh/t**	**16.7**	**11.3**	**12.3**
difference		19%	8%	-7%
CFball (ignore BM component for E_{SAG})		0	0	0
Amelunxen SGI	**E_{SAG} kWh/t**	**16.5**	**11.3**	**12.5**
difference		18%	8%	-6%
CFball		1.09	1.22	1.24
Amelunxen SGI	**E_{total} kWh/t**	**16.5**	**22.5**	**20.4**
difference		18%	30%	-2%
A×b		54.4	68.8	68.4
Mib	kWh/t	*18.2*	*15.7*	*15.0*
Mia	kWh/t	*15.4*	*12.7*	*12.8*
Mic	kWh/t	*5.6*	*4.4*	*4.4*
Morrell Mi model	**E_{SAG} kWh/t**	**17.3**	**11.4**	**10.4**
difference		24%	8%	-21%
Morrell Mi model	**E_{total} kWh/t**	**17.3**	**17.5**	**17.3**
difference		24%	1%	-17%

These surveys provide two specific energy observations: the CEE of the SAG mill (E_{SAG}) and the CEE of the whole circuit, SAG plus ball mills (E_{total}). In single-stage operation, the two CEE values are equal.

The Amelunxen model gives the best results if the E_{SAG} calculation is performed using the actual transfer size rather than the hypothetical 2.1 mm transfer size described in the model definition section. This is not unreasonable, but does suggest that the use of the hypothetical transfer size for E_{SAG} calculations is not desirable for this mill.

Yanacocha

The Yanacocha single-stage SAG mill in Perú is described by Burger et al., 2011. Two surveys were published and slurry pooling was present in both surveys. Slurry pools are known to cause inefficient mill operation and one would expect the models to predict lower CEE than the survey observations.

Table 9 Yanacocha survey results

		First survey	Second survey
SAG F_{80}	µm	79,100	72,400
hypothetical T_{80}	µm	2,100	2,100
circuit P_{80}	µm	152	154
power at dcs	kW	12,286	13,992
mech efficiency		1	1
electric efficiency		1	1
power at shell	kW	12,286	13,992
throughput	dry t/h	620	779
E_{SAG}	**kWh/t shell**	**19.8**	**18.0**

As suspected, none of the models provide a reasonable prediction of the survey CEE. The models predict CEE of 13 – 15 kWh/t versus observed values of 18 – 20 kWh/t. This is probably due to the slurry pooling identified in the source reference and the models suggest that the Yanacocha mill could improve its specific energy consumption by 5 kWh/t if the slurry pool and any other unpublished operating issues are solved.

Table 10 Yanacocha grindability and model results

		First survey	Second survey
Wi_C	metric	*10.0*	*10.0*
Wi_{RM}	metric	*11.94*	*11.94*
Wi_{BM}	metric	16.55	16.55
Bond/Barratt model	**kWh/t shell**	**15.6**	**15.4**
difference		-21%	-14%
Mia	kWh/t	12.3	12.3
Mic	kWh/t	*4.1*	*4.1*
Mib	kWh/t	18.9	18.9
Morrell Mi model	**kWh/t shell**	**12.7**	**12.6**
difference		-36%	-30%
SGI	min	*44*	*44*
El Soldado SGI	**kWh/t shell**	**11.2**	**11.2**
difference		-43%	-38%
CFball		0.89	0.89
Amelunxen SGI	**kWh/t shell**	**14.3**	**14.2**
difference		-28%	-21%

RESULTS AND DISCUSSION

The average difference between models and the plant observations are given in Table 11. A positive difference indicates that the model predicts a higher specific energy consumption than was observed in the operating plant and a negative difference indicates the model predicted lower.

Table 11 Summary of average difference between model predictions and observed CEE

	Barratt model	Morrell model	Amelunxen model	El Soldado model
Qty of parameters	3	2	2	1
El Soldado	5%	-1%	-4%	-8%
Palabora	3%	-28%	-21%	-34%
Tarkwa	-1%	6%	11%	125%
Degrussa	E_{SAG}: 28% E_{total}: 17%	E_{SAG}: 4% E_{total}: 2%	E_{SAG}: 7% E_{total}: 15%	E_{SAG}: 13%
Yanacocha	-18%	-33%	-25%	-40%

The ore types observed in the surveys can be loosely classified into three types:

- Ores suitable for modelling by one-parameter models. An example is El Soldado.
- Ores suitable for modelling by two-parameter models. An example is Tarkwa.
- Ores only suitable for modelling by three-parameter models. An example is Palabora.

Comminution circuits that were experiencing operating problems, such as the slurry pooling at Yanacocha, will cause the models to predict lower specific energy consumption than was observed. This is reasonable because models used for design should not be calibrated for mills experiencing operating problems, and the model predictions could be a useful indication of performance if the problems are fixed.

No single model worked for all the surveys described, but the Barratt and Morrell models generally are the closest over the whole set of surveys. The ores with more complicated grindability (Eg. Palabora with a high crushing Wi, low rod mill Wi and intermediate ball mill Wi) appear to require the determination of more grindability data in order to model effectively.

CONCLUSION

- A complete ore characterization should be performed before choosing a particular model for single-stage SAG milling. The three Bond work index tests, in particular, should be conducted and the simpler (E.g. 1-parameter) models should be used only if the three work index values are similar (as in El Soldado).
- None of the models was able to predict the specific energy consumption of all the surveys. This suggests that at least two models should be run when designing a single-stage SAG mill design. The Bond and Morrell models were generally the best, and the Amelunxen model is often close behind.
- The Morrell and Amelunxen models worked well when the crushing work index is similar to or less than the rod mill work index. Neither of these models contains a grindability measurement in the +50 mm size range, so they have no way to detect unusual coarse behaviour such as in Palabora where coarse sizes are much harder than medium sizes.

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NOMENCLATURE

AG	autogenous grinding (mill)
CEE	specific energy consumption of comminution, kWh/t
E_{SAG}	specific energy consumption of the AG or SAG mill, kWh/t
F_{100}	feed stream 100% passing size, µm
F_{80}	feed stream 80% passing size, µm
P_{100}	product stream 100% passing size, µm
P_{80}	product stream 80% passing size, µm
SAG	semi-autogenous grinding (mill)
T_{80}	transfer stream 80% passing size, µm

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