OMC POWER-BASED COMMINUTION CALCULATIONS FOR DESIGN, MODELLING AND CIRCUIT OPTIMIZATION

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ABSTRACT

Orway Mineral Consultants Ltd (OMC) as a consultancy has specialized in comminution circuit design for over 30 years. The OMC Power Model is OMC's in-house software for specific grinding energy power-based circuit calculations. The model uses ore hardness parameters from testwork, circuit configuration, equipment geometry and operating conditions as inputs. The model combines proprietary and published power models to predict the total specific energy and the specific energy for each of the components of the comminution circuit. This makes the software a valuable tool for the design and validation of JKSimMet modelling or actual plant performance. Proprietary calculations have been developed and reconciled with over 100 plant benchmark projects encompassing a variety of comminution circuit configurations.

This paper describes the OMC approach for determining power requirements for the design of grinding circuits. The accuracy of the OMC Power Model software is confirmed through plant survey benchmark performance and comparisons are made with other power modelling techniques. Practical examples are presented, showing applications for single stage SAG (SS-SAG), SAB and SABC circuit configurations.

KEYWORDS

Grinding specific energy, comminution circuit power modelling, design and optimization

INTRODUCTION

Conventional low throughput grinding options, consisting of multi-stage crushing followed by rod and ball mills, have almost become obsolete in the move to higher milling rates required to process lower metal grades. Grinding circuits with fully autogenous (AG) or semi-autogenous (SAG) mills, often combined with ball mills are now the standard to meet the high capacity requirement for processing ores with lower metal grades. Simulation software and power-based equation methodologies have been established for designing AG/SAG based grinding circuits and predicting their energy requirements.

Presently, power-based equations remain the principal method for designers to size mills and estimate the power requirement for comminution circuits. The technique is simple and it relies on the design to specify a feed and product size plus a hardness index to produce a specific energy value (kWh/t). The desired throughput of the mill is multiplied by the specific energy to give the mill power requirement, which is used in turn to size a mill for dimensions, internal geometry and loading conditions to match the power draw.

The most frequently used power-based methodologies for calculating energy requirements for comminution circuits using AG/SAG mills are concisely presented in the following section. This paper describes the Orway Mineral Consultants (OMC) approach to determining power requirements for the design of grinding circuits using the OMC Power model software. The accuracy of the OMC Power Model is confirmed through plant survey benchmark performance and comparisons are made with other power modelling techniques. Practical examples are presented, showing applications for single stage SAG (SS-SAG), SAB and SABC circuit configurations for primary and secondary crushed feed material.

DESCRIPTION OF EXISTING POWER MODELS FOR COMMINUTION CIRCUITS

Bond Third Law of Comminution

Comminution theory is concerned with the relationship between energy input and the particle size made from a given feed size. The best known and most widely used power-based equation is that proposed by Bond (1961) and is given in Equation 1. Bond's Third Theory of Comminution is an empirical relationship that relates work input in proportion to the new crack tip length produced in particle breakage.

$$W = 10 \cdot Wi \cdot (P^{-0.5} - F^{-0.5}) \quad (1)$$

Where:

W	=	Specific energy (kWh/t)
Wi	=	Work Index (kWh/t)
P	=	80% passing size for the product (P_{80})
F	=	80% passing size for the feed (F_{80})

Bond's approach consists of determining the ore hardness characteristics, or Work Index (Wi) via standardized laboratory testwork. The full suite of Bond comminution tests provide the Ball Mill Work Index (BWi), the Rod Mill Work Index (RWi), the Crusher Work Index (CWi) and the Abrasion Index (Ai). Over the years, it has been determined that Efficiency Factors (EF1 to EF9) should be applied to Equation 1 to drive the corrected power requirement (Rowland, 1982).

The equation for Bond's Third Theory of Comminution was originally developed for use with conventional crushing and grinding circuits (crusher-rod-ball mill or crusher-ball mill). By the 1970s, the application of conventional circuits tended to be limited to relatively low capacities. The majority of modern grinding circuits include a SAG mill, a ball mill and/or a combination thereof. The use of Bond work indices coupled with other breakage tests, and the application of empirical efficiency factors, has become a standard for determining ore competency to calculate specific energy in modern grinding circuits. Some of the other widely used power-based AG/SAG specific energy models include, but are not limited to: MacPherson (1978); Barratt (1986) and GrindPower (Matthews & Barratt, 1991); SPI (Starkey and Dobby, 1996); SAGDesign (Starkey, Hindstrom & Nadasdy, 2006); Morrell (2004) and SMCC (Morrell, 2011); Ausgrind (Lane, Foggiatto & Bueno, 2013).

MacPherson

MacPherson (1978) created a grinding test conducted in a continuous laboratory mill in closed circuit with an air classifier until steady state was achieved. The main deliverable of the test is the MacPherson correlated Autogenous Work Index (AWi). A particle size analysis of the mill ore charge at the end of the tests provides insight into the build up of critical sized material within the mill. The AWi is used in conjunction with other Bond Work Indices (CWi, RWi, BWi) to determine power requirements using Bond's Third Law of Comminution.

Barratt and Millpower 2000

Barratt (1986) proposed the use of an empirical formula for predicting SAG power involving the use of a combination of Bond work indices over a range of sizes from F_{80} to a defined P_{80}, applying a correction factor to resultant power, and deducting the ball milling component of the power; refer to Equation 2. The approach requires the feed size to the SAG, the SAG mill product size (transfer size) and the final product size. The prediction of the SAG mill transfer size used in the formula is made by comparison with pilot plant data and operating plant data for similar ore types (Barratt, 1989). The approach acknowledges grinding efficiency as the ratio of operating work index to that for a single-stage ball mill. The Barratt approach is the basis of the Millpower 2000 computer-based program (Matthews and Barratt, 1991).

$$E_{SAG} = 1.25 \cdot [(10 \cdot W_{iC} \cdot S_C)+(10 \cdot W_{iR} \cdot S_R \cdot K_r)+(10 \cdot W_{iB} \cdot S_B \cdot K_b)]-(10 \cdot W_{iB} \cdot S_{SB} \cdot K_b) \quad (2)$$

Where:

E_{SAG} = SAG mill specific energy (kWh/t)
$W_{iC,R,B}$ = Crushing, Rod and Ball Mill Work Indices (kWh/t)
$S_{C,R,B,SB}$ = are $(P^{-0.5}-F^{-0.5})$ for the equivalent stage size ranges

Note that for S_B and S_{SB}, the product size 'P' is fixed at 110 µm. Kr is the composite of EF factors for rod milling (Rowland, 1982), excluding EF3. K_b is the composite of EF factors for ball milling (Rowland, 1982), excluding EF3.

SPI

The SAG Power Index (SPI) test (Starkey & Dobby, 1996) uses a bench-scale SAG mill test to determine the specific energy of an industrial SAG mill. The test is operated in closed circuit and the time required to grind the material to a P_{80} of 1.7 mm is used to predict AG/SAG specific energy using Equation 3 and other power-based models available in CEET (Comminution Economic Evaluation Tool).

$$W = K_a \cdot K_b \cdot k \cdot [(\text{SPI mins})/T_{80}^{0.5}]^n \quad (3)$$

Where:

W = SAG mill specific energy (kWh/t)
K_a = Correction factor for feed size
K_b = Correction factor for circuit configuration
SPI = SPI minutes
T_{80} = SAG mill transfer size (µm)
k,n = Empirical constants

SAGDesign

The SAGDesign test was developed to overcome technical limitations of the SPI (Starkey, et al, 2006). The laboratory bench-scale SAG mill reproduces operating conditions of a commercial SAG mill, in a closed circuit dry grinding environment. The ground product for the laboratory SAG mill is then submitted to the Bond ball mill work index test. The number of SAG mill revolutions required to grind the material to a P_{80} of 1.7 mm is used to predict AG/SAG specific energy using Equation 4. Correction factors for feed size and pebble crushing are applied to the AG/SAG specific energy, as well as specific energy adjustment from 1.7 mm to the mill transfer size T_{80} using Bond's Law (Starkey & Larbi, 2012). The Bond equation is used to calculate ball mill specific energy from T_{80} to the final product P_{80} size. The total circuit specific energy is the sum of the SAG mill and ball mill specific energies.

$$W_{SAG} = R \cdot (Ms+16000)/(Ms \cdot 447.3) \tag{4}$$

$$W_T = K_a \cdot K_b \cdot W_{SAG} \cdot [10 \cdot BWi \cdot (T_{80}^{-0.5}-1700^{-0.5}) \cdot EF5] + W_{BM} \cdot K_{BM} \tag{5}$$

Where:

W_{SAG}	=	SAG mill specific energy from F_{80} 152 mm to T_{80} 1.7 mm (kWh/t)
R	=	SAGDesign test mill revolutions (revs)
Ms	=	SAGDesign test mill charge mass (g)
K_a	=	Correction factor for feed size
K_b	=	Correction factor for pebble crushing
T_{80}	=	Mill transfer size, 80% passing (µm)
W_{BM}	=	Ball mill specific energy from T_{80} 1.7 mm to final product P_{80}, using Bond's Law, (kWh/t)
W_T	=	Total grinding mill circuit specific energy (kWh/t)

Note that K_{BM} is the composite of EF3, EF4 and EF5 factors for ball milling (Rowland, 1982).

Morrell and SMCC

Morrell (2004) developed a methodology for predicting specific energy with crusher/HPGR/AG/SAG/Ball mill circuits. The generic power-based equation for circuit specific energy is shown in Equation 6. For total specific energy in an AG/SAG circuit, the method uses two work indices for coarse and fine grinding respectively. "Coarse" in this case is defined as spanning the size range from an F_{80} of the product of the last stage of crushing prior to grinding to a P_{80} of 750 µm. "Fine" covers the size range from an F_{80} of 750 µm down to P_{80} sizes typically reached by conventional ball milling. The delineating size between coarse and fine grinding is 750 µm. SMC test results are used to determine the Drop Weight Index (DWi) and the coarse ore grinding index (M_{ia}). Test data from the Bond ball mill work index test is used to calculate the fine grinding index (M_{ib}). The M_{ia} and M_{ib} indices are used to calculate specific energy for the coarse (W_a) and fine (W_b) components of the total grinding specific energy at the pinion (W_T) according to Equation 7.

$$W_i = 4 \cdot K \cdot M_i \cdot [P^{f(P)}-F^{f(F)}] \tag{6}$$

$$W_T = W_a + W_b \tag{7}$$

Where:

W_i	=	Specific energy (kWh/t)
K	=	Empirical constants
M_i	=	Coarse Work Index 'M_{ia}', Fine Work Index 'M_{ib}' (kWh/t)
P	=	Product size, 80% passing (µm)
F	=	Feed size, 80% passing (µm)
$f(x_j)$	=	$-(0.295+x_j/1000000)$

In 2011, Morrell discussed the appropriateness of SAG mill transfer size in regards to grinding mill specific energy modelling. It was suggested that since AG/SAG mills are mostly operated in very near to open circuit conditions (very low circulating loads) the transfer size is a function of mill performance, which is affected by the feed rate, the operation of the mill and its geometry.

The SMCC approach relies on the total specific energy of the entire circuit first being predicted using the SAG mill feed F_{80} and the ball mill cyclone overflow P_{80} using Equation 6 and Equation 7 (Morrell, 2011). The AG/SAG mill circuit specific energy is predicted using Equation 8 (Morrell, 2011), which does not rely on the T_{80} but relates to mill feed, mill geometry and operating conditions to the specific energy. The ball mill specific energy (W_{BM}) is then found by subtracting the AG/SAG mill specific energy (S) from the total circuit specific energy (W_T), according to Equation 9.

$$S = K \cdot F_{80}^{a} \cdot DWi^{b} \cdot (1+c(1-e^{-dJ}))^{-1} S_p^{e} \cdot f(Ar) \cdot g(x) \quad (8)$$

$$W_{BM} = W_T - S \quad (9)$$

Where:

S	=	Specific energy at the pinion (kWh/t)
F_{80}	=	80% passing size of the feed
DWi	=	Drop-weight Index (kWh/m^3)
J	=	Volume of balls (%)
S_p	=	Mill speed (% critical)
f(Ar)	=	Function of mill aspect ratio
g(x)	=	Function of trommel aperture
K	=	Function for pebble crusher in circuit
a,b,c,d,e,f	=	Empirical constants

Ausgrind

Lane, Foggiatto and Bueno (2013) published details of Ausenco's in-house Ausgrind software, which uses a power-based methodology for predicting specific energy 'Ecs' in AG/SAG circuits. The Ausgrind program calculates the total specific energy for the grinding circuit as a product of the calculated Bond specific energy and the energy efficiency factor 'f_{SAG}' (Lane et al, 2013). The Bond CWi, RWi and BWi indices are used to calculate the total specific energy of a conventional crusher-rod-ball mill circuit to a P_{80} of 150 µm, without the use of the Bond and Rowland EF factors (Lane et al, 2013), as per Equation 10. The base case SAG mill specific energy is calculated as a function of DWi ore competency and multiplied by adjustment factors regarding the mill aspect ratio, ball load, feed size and pebble crusher recycle (Lane et al, 2013), as shown in Equation 11. Pebble crusher specific energy is calculated and vendor data is used for equipment selection. The ball mill specific energy is determined by subtracting the AG/SAG mill specific energy from the total circuit specific energy (Lane et al, 2013), according to Equation 12. Ausgrind efficiency factors and adjustment factors are developed from a database of operating data and grinding circuit types covering a wide range of ore types (Lane et al, 2013).

$$\text{Total Ecs} = [(\text{Bond Ecs to 150 µm}) \cdot (f_{SAG} - F_{80}\_\text{effect})] +/- [\text{Bond Ecs to final } P_{80}] \quad (10)$$

$$\text{SAG Ecs} = [\text{Base Case SAG Ecs}] \cdot [\text{adjustment factors}] \quad (11)$$

$$\text{Ball mill Ecs} = \text{Total grinding circuit Ecs} - \text{SAG mill Ecs} \quad (12)$$

OMC METHODOLOGY AND THE OMC POWER MODEL FOR COMMINUTION CIRCUITS

OMC Capabilities

OMC is a metallurgical consultancy that delivers high quality studies and practical engineering solutions in the areas of comminution, beneficiation and hydrometallurgy. OMC specializes in developing comminution testwork programs, performance and efficiency audits and comminution circuit modeling for the purpose of design and optimization. This expertise encompasses a range of comminution processes through crushing, scrubbing, HPGR, AG/SAG milling, rod and ball milling, as well as fine grinding. With over 30 years of experience in the areas of Crushing and Grinding, OMC has extensive project experience on over 500 projects, 150 plant optimisations and 100 grinding circuits installed based on OMC modelling. Its ore characterisation testwork database comprises over 5000 samples on projects from around the globe.

The OMC approach involves gaining a thorough understanding of the metallurgical characteristics of an ore body using detailed testwork on representative drill core or bulk samples. This knowledge combined with specialised in house modelling techniques, comprehensive database comparisons and extensive project experience provides the building blocks for the consultancy's design, modelling and optimisation processes.

OMC uses a multitude of in-house and commercially available computer software for circuit design and optimisation. OMC's power-based approach and JKSimMet simulations are seen as complementary systems and are used in conjunction to provide separate methods to achieve greater confidence in the design basis. The OMC Power Model is OMC's in-house software for specific grinding energy power-based circuit calculations. The OMC approach is summarized in a block diagram shown in Figure 1, and described in the following sections.

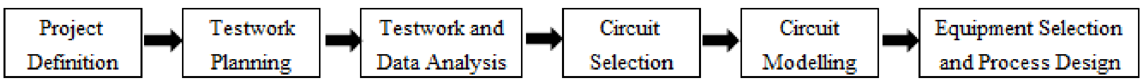

Figure 1 - OMC methodology for comminution circuit design

Project Definition

The project definition is the fundamental activity that drives all other tasks associated with the design of a comminution circuit. Preliminary project definition requires the consideration of the location of the ore body, geology and ore types, water availability and environmental restrictions, as well as access to infrastructure. Knowledge of this information is required for the circuit selection process and modelling activities.

Primary drivers of circuit selection include intended plant capacity as a function of maximum individual equipment capacity limits; the influence of ore characteristics on viable circuit selection and product size requirements (Putland, 2006). Table 1 shows a matrix linking capacity, grind size and ore characteristics (Putland, 2006). This matrix is used as a guideline for preliminary grinding circuit selection. Secondary factors that affect the project definition and circuit selection include the intended mine life and its effect on allowable capital, the variability and constraints imposed by the geology and mining methods used and constraints from downstream process equipment (Putland, 2006). Application of primary and secondary factors should narrow down the circuit options to three or less for further evaluation.

The amount of effort put into the circuit selection and design will depend on the type of study being executed and the extent of information (scoping, pre-feasibility, bankable feasibility) and ore available for testing.

Table 1 - Primary grinding circuit selection matrix

Rock Characteristics	Soft		Medium Competency & Work Indices				High Competency & Work Indices			
Wear Characteristics	Non Abrasive		Non Abrasive		Abrasive		Non Abrasive		Abrasive	
Product Size	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse	Fine	Coarse
Circuit Capacity										
< 4 Mtpa	SS-SAG Scrub BM	SS-SAG Scrub RM	SS-SAG 3C BM SAB	SS-SAG RM	SS-SAG SS-SAG SAB AB ABC	SS-SAG SS-SAG/C ABC	SS-SAG SS-SAG 3C BM SABC	SS-SAG/C SS-AG/C 3C BM SABC 2C SS-SAG RM	SS-SAG AB 3C BM SABC ABC APC	SS-AG/C SS-SAG/C 2C SS-SAG SABC 2C SABC ABC
> 4 < 8 Mtpa	SAB Scrub BM SS-SAG	SS-SAG Scrub	SAB SABC HPGR BM	SAB SABC HPGR BM	SS-SAG SAB SABC SS-SAG ABC HPGR BM AB	SS-SAG SAB SABC AG/C ABC HPGR BM	SABC HPGR BM 2C SABC	SABC HPGR BM 2C SABC	SABC HPGR BM 2C SABC ABC APC HPGR Peb	SABC HPGR BM 2C SABC ABC APC HPGR Peb
> 8 Mtpa	SAB SABC	SAB SABC	SABC HPGR BM	SABC HPGR BM	SABC HPGR BM ABC HPGR Peb	SABC HPGR BM ABC HPGR Peb	SABC HPGR BM	SABC HPGR BM 2C SABC	SABC HPGR BM 2C SABC ABC HPGR Peb	SABC HPGR BM 2C SABC ABC HPGR Peb

Sample Selection

Once the project is defined, a comminution testwork program is required to describe the ore body competency and abrasion properties. An understanding of the geology and mineralogy of a deposit, and the consequent sample selection for testwork, has a significant impact on the effectiveness of the comminution circuit design. Several factors are considered for selecting ore samples. These include, but are not limited to: ore types; the presence of multiple deposits, lodes and/or lenses; rock type variations; depth of deposit; ore grade; mining method and mine plan.

Fresh diamond drill core provides excellent material for comminution testwork. The number and type of drill core samples collected for testing is dependent on the level of the study, the size and complexity of the ore body, the project schedule and budget, as well as the project risk profile. In general, the project testwork program is divided into three stages. The first stage of the testwork program occurs at the beginning of the project (scoping, preliminary engineering assessment), during which composite samples are selected based on the major known rock types. In the second stage (prefeasibility, feasibility), variability sampling and testing is performed. The sample selection can be accomplished by the following guidelines for the Distribution Method proposed by Lotter and Oliveira (2011). In this case, drill core subsamples are selected from the parent drill core population based on the distribution of paymetal and host rock lithology. Optimized sampling must be representative and spatially distributed. The variability testing is performed to determine the relationships between ore competency, lithologies, rock types and mineralizations. This is done to provide mill throughput forecasting and a definitive operating cost estimate. For the third and final stage (EPCM stage), additional testwork is perform to reduce risk for equipment procurement. Samples are collected on the basis of spatial representativeness and/or mine production period. Particular focus is placed on the years of operation up to the completion of the payback period for the project.

It is assumed for this discussion that the final design of comminution equipment to be purchased is done at the completion of the feasibility study stage. In the early stages of the project, it is recommended to spend the necessary money on sample acquisition, testing and variability studies to ensure a robust design. This reduces risk to the client if the project economics are deemed favorable and the project schedule is expedited. Otherwise, the equipment with prolonged lead delivery times (i.e. grinding mills) cannot be ordered on the completion of the feasibility study because the risk may be too high until the final testing is done.

Ore Characterisation Testwork

The key to a successful comminution circuit design is the implementation of a well-structured, comprehensive testwork program. Several laboratory bench-scale tumble mill tests and impact breakage tests are available to characterising ore competency and abrasiveness. The suite of testwork selected will depend on the sample type and the level of study required. Depending on the circuit configuration under evaluation and the amount and size of drill core available for testing, OMC uses the following test methods: Allis-Chalmers Autogenous Tumble Test; Unconfined Compressive Strength Test (UCS); the Bond tests (CWi, RWi, BWi, Ai); SMC test and JK Drop Weight Test (DWT). The full suite of testing is known as the Advanced Media Competency Test (AMCT). SPI and SAGDesign test results are also used for evaluation of soft, brecciated ore types or for heterogeneous ores. For both circumstances, these ores sometimes do not possess sufficient representative coarse material for the SMC and/or the DWT impact breakage testing methods, which can generate biased Axb appearance functions that do not adequately quantify the ore's true competency and variability within the deposit.

The key to characterising the ore is not just testwork but a thorough understanding of the geology. All of the methods discussed above must be manipulated based on the understanding of the geology. A good example is brecciation. Testing can produce identical results for two different ore bodies or the same ore from different parts of an ore body. The difference is that one is brecciated or hydrothermally fractured and the other is not. This is often not identified in the testing as the sample top size tested is below the average fracture spacing within the ore. The only tests that shed light on this phenomenon are the AMCT and CWi, which require large sample masses for the tests and larger diameter whole core samples.

OMC Power Model

The OMC Power Model for grinding circuit modelling and mill sizing is based on a consideration of the total power involved in the comminution process. As such, it is necessary to consider a standard feed F_{80} size and a standard product P_{80} size. For mill sizing and design, typical feed F_{80} values are selected between 100 to 150 mm, whereas production forecasting and grinding circuit modeling is done using calculated F_{80} values, based on ore hardness and crusher closed side setting. Product size P_{80} requirements are defined by the client.

OMC uses an 'f_{SAG}' efficiency factor (Siddall, Henderson & Putland, 1996) for determining total grinding circuit specific energy. The power required for the grinding circuit standardised to an F_{80} of 150 mm and P_{80} of 75 μm is compared to the Bond BWi based power that is theoretically needed to effect comminution from the same size range. The ratio of the two values is referred to as the 'f_{SAG}' efficiency or design factor. The historic importance of using a standard product size in the OMC methodology has often been over looked by others but this standardisation is key to delineate the role of high impact comminution (t_{10}) and abrasion grinding (BWi) in the calculation of total specific energy. To determine the efficiency of an operating grinding circuit, OMC compares the actual f_{SAG} of the plant to the theoretical value calculated using testwork results. The major inputs from laboratory ore characterisation testwork needed to define the f_{SAG} are the Bond BWi (low energy breakage) and the t_{10} parameter from a high energy breakage test. The t_{10} can be determined from DWT or SMC test output or the -6 mm from Allis-Chalmers Autogenous Tumble Test output. The t_{10} can also be back calculated in the model using the SPI minutes (SPI test output) or the W_{SAG} (SAGDesign test output) for use in the SAG mill specific energy modelling component, which is discussed later in the paper.

The OMC Power Model is OMC's in-house software for specific grinding energy power-based circuit calculations. The software includes three models for calculating AG/SAG mill specific energy (E_{SAGi}) and four separate models for total circuit specific energy (E_{TOTi}), as noted in Table 2. For the vast majority of ores, each model tends to give similar results if applied in the appropriate context. At times, combinations of multiple models are evaluated by OMC to ensure accurate comminution specific energy determination for the project. A large discrepancy between E_{SAGi} or E_{TOTi} model outputs is a red flag, which typically triggers a review of the project geology and the samples tested.

Table 2 - Power-based specific energy models in OMC Power Model software

AG/SAG Mill Models E_{SAGi} (kWh/t)	Total Circuit Models E_{TOTi} (kWh/t)
OMC AMCT t_{10} (Energy to First Fracture)	OMC f_{SAG} (AMCT-6mm, t_{10}JKDWT)
OMC Multivariable	SMCC
	SAGDesign/SPI

For two-stage AG/SAG/Ball mill circuits, the primary mill transfer size is not an input for specific energy modelling, but it is rather an outcome of the ore characteristics and performance of the milling circuit given the operating conditions (configuration, feed size, mill speed, ball charge, grate design etc.). For two-stage circuits, the ball mill specific energy (E_{BMi}) is the difference between the total circuit specific energy and the AG/SAG mill specific energy, as shown in Equation 13, and has been the basis of the OMC approach for more than 25 years. In two-stage circuits, the net ball mill specific energy (E_{BMinet}) is obtained by applying the Bond and Rowland EF factors for ball milling (Rowland, 1982) excluding EF3, as shown in Equation 14, using a model output for the 80% passing size of the feed to the ball mill. In most AG/SAG circuits this factor is in fact close to '1' and has little impact on the calculation. In SS-SAG circuits, the SAG mill specific energy corresponds to the total grinding circuit specific energy. Ancillary equipment power, such as crusher no-load, motor/pinion drive train losses and conveying system power, is excluded from the analysis.

$$E_{BMi} = E_{TOTi} - E_{SAGi} \quad (13)$$

$$E_{BMinet} = E_{BMi} \cdot (EF4 \cdot EF5 \cdot EF7) \quad (14)$$

The original OMC power-based models ($E_{SAG(AMCTt10)}$, $E_{SAG(AMCT\text{-}6mm)}$) were based on the AMCT test, classifying the responses obtained from impact testing the products of the Allis-Chalmers Autogenous Tumble Test. The results from the AMCT test were analysed in a number of ways: product distribution and database comparison; calculation of the AG Media Index; survival of +100 mm rocks; the susceptibility of the ore to create a critical size in the +25-100 mm and +12-50 mm sizes classes; as well as the production of fines in the -6 mm size fraction. Due to the large sample mass and drill core size requirement of the AMCT test, the test method and the AMCT power-based models are seldom used. AMCT test results database compilation and subsequent analysis showed that the -6 mm measurement from the AMCT test had a strong correlation with t_{10} derived from DWT tests. This laid the framework for the development of new AG/SAG specific energy models ($E_{SAG(OMCt10)}$ and $E_{SAG(OMC\ Multivariable)}$) and total circuit model ($E_{TOT(OMCt10JKDWT)}$) that use the 'Axb' and 't_{10}' values from the DWT and SMC tests, which are more widely used due to their lower sample mass and size requirements.

The two most commonly used methods for calculating total circuit specific energy are the OMC f_{SAG} ($E_{TOT\ (OMC\ fSAG)}$) and the SMCC (Morrell, 2004) methods respectively. For the OMC f_{SAG} total circuit model, the total specific energy for the grinding circuit is calculated as the product of the Bond specific energy and the f_{SAG}, without the use of the Bond and Rowland EF factors, as described in Equation 15. The f_{SAG} is calculated using an equation with t_{10} and BWi as the inputs. The equation was developed to predict f_{SAG} via testwork and data from operating circuits in the OMC database.

$$E_{TOT(OMC\ fSAG)} = 10 \cdot BWi \cdot [(75^{-0.5} - 150000^{-0.5}) \cdot f_{SAG} - (F_{80}^{-0.5} - 150000^{-0.5}) - (75^{-0.5} - P_{80}^{-0.5})] \quad (15)$$

Where:

E_{TOT}	=	Total grinding specific energy (kWh/t)
BWi	=	Bond BWi (kWh/t)
f_{SAG}	=	Efficiency factor
F_{80}	=	Feed size, 80% passing (μm)
P_{80}	=	Product size, 80% passing (μm)

The most commonly used method for calculating AG/SAG specific energy is the OMC Multivariable Model. In this case, the AG/SAG specific energy is calculated as a function of 'Axb' ore appearance function multiplied by adjustment factors regarding the feed size, ball load, mill speed, mill aspect ratio and pebble crusher recycle, as described in Equation 16. The equation is of a similar form to that published by Morrell (2011), with constants multiplied by functions that were developed from OMC's extensive project database.

$$E_{SAG(OMC\ Multivariable)} = a(Axb)^{b} \cdot F_{80}^{c} \cdot (1+d(1-e^{-gB}))^{-1} \cdot S_p^{h} \cdot f(Ar) \cdot f(K) \qquad (16)$$

Where:

E_{SAG}	=	Specific energy at the pinion (kWh/t)
Axb	=	Appearance function
F_{80}	=	80% passing size of the feed
B	=	Volume of balls (%)
S_p	=	Mill speed (% critical)
f(Ar)	=	Function of mill aspect ratio
f(K)	=	Function for pebble crusher in circuit
a,b,c,d,e,g,h	=	Empirical constants

OMC Power Model software has the capability to compare AG/SAG and total circuit specific energy calculated from impact breakage test results (Axb) to that obtained via bench-scale tumble tests (SAGDesign/SPI). Using published SAGDesign methodology, and applying the OMC approach for two-stage grinding circuits, the ball mill specific energy is the difference between the total circuit specific energy and the AG/SAG mill specific energy. The AG/SAG transfer size is dependent on the ore properties, as well as the circuit configuration (primary crushing, secondary crushing, SAB, SABC etc). Arbitrary selection of a T_{80} value can potentially lead to a gross misrepresentation of the power split between a SAG mill and a ball mill. It is in the view of the authors that mill designers must exercise extreme caution when using methods where the T_{80} must be selected manually.

The abovementioned E_{SAGi} and E_{TOTi} methods developed exclusively by OMC are valid for predicting specific energy on primary crushed feed. For AG/SAG circuits processing secondary crushed feed, a modified method is used for the calculation of specific energy. At secondary crushed feed sizes below an F_{80} of 40 mm a modified Bond method is used to predict total specific energy. This approach has been shown to be extremely accurate in designing secondary crushed feed circuits. The AG/SAG mill specific energy is calculated using the ore characteristics when the feed is coarser than the grate aperture, typically SAB circuits. When the feed is finer than the grate the ore characteristics do not strictly dictate the AG/SAG mill specific energy because the mill operates more like a ball mill.

BENCHMARKING OMC POWER MODEL

OMC Power Model Benchmark With Plant Surveys

OMC's extensive project database was used in the generation of the OMC Power Model software. The specific energy predictions were compared to measured values on over 100 plant surveys. These surveys were performed on multiple AG/SAG circuit configurations, namely SS-SAG, SAB and SABC, which include both primary and secondary crushed mill feed. The OMC Power Model benchmarking results are in good agreement with the plant surveys, with correlation coefficient R^2 values of 0.91 for both AG/SAG specific energy and total specific energy respectively, as shown in Figure 2 and Figure 3.

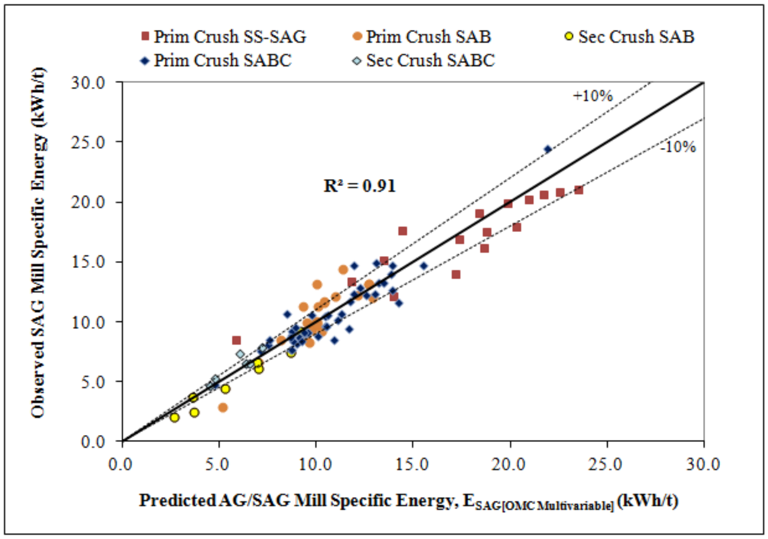

Figure 2 - Observed vs predicted AG/SAG specific energy using OMC Multivariable Model

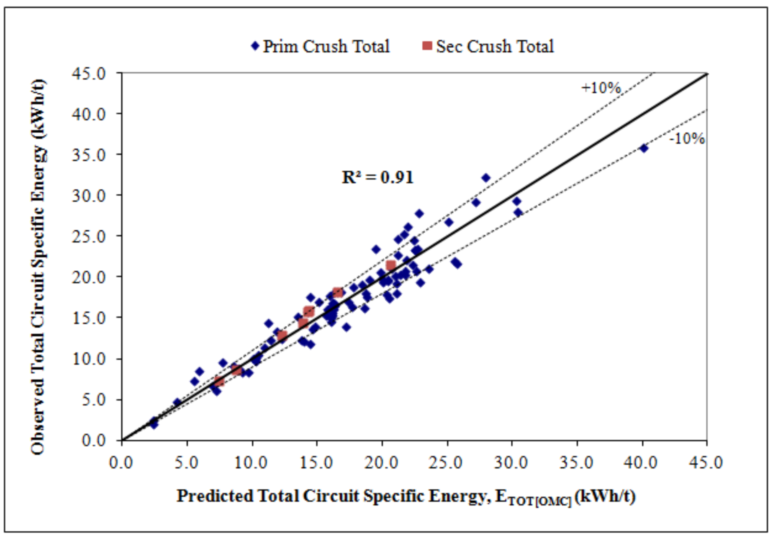

Figure 3 - Observed vs predicted total specific energy using OMC approach

Table 3 describes the range of input and output conditions for the OMC Power Model. The average absolute error was determined to be +/-8.7% for the $E_{SAG(OMC\ Multivariable)}$ AG/SAG specific energy model and +/-8.2% for the E_{TOT} total circuit specific energy model. These results are less than +/-10%, which is considered the accepted margin of error for specific energy predictions in regards to actual plant performance. The OMC Power Model calibration is periodically assessed using new operating data from plant surveys and optimizations. This provides valuable feedback regarding the accuracy of the models for various circuit configurations and ore types.

The OMC Power Model has proven accuracy based on the plant benchmark survey results. This compliments OMC's mill power draw prediction via its torque arm model. This additional piece of software enables the assessment of mill power draw and operating performance via the following parameters: ore hardness (specific energy), milling rate and recirculating load, mill geometry, mill rotation speed, liner profile, ball trajectory, mill loading (steel and total charge), and slurry flow for both grate discharge and overflow mills.

Table 3 - Range of conditions covered by OMC Power Model software

Description	Parameter	Units	Min	Max	Average
OMC Multivariable E_{SAG} Model Inputs	Axb	-	15.0	134.6	42.6
	Bond BWI	kWh/t	7.8	26.5	15.6
	Mill Feed F_{80}	µm	19,500	180,000	96,695
	Final Product P_{80}	µm	50	573	132
	Volume of Balls	%	0	18	11
	Mill Speed	%Nc	66	80	74
	Aspect Ratio (L/D)	-	0.26	1.50	0.49
	Recirculating Load	%	0	49	14
OMC Multivariable E_{SAG} Model Output	Observed Specific Energy	kWh/t	2.1	24.4	10.9
	Predicted E_{SAG} Specific Energy	kWh/t	2.7	23.5	11.1
	E_{SAG} Model Error (+/-)	%	-	-	8.7
OMC Total Circuit E_{TOT} Model Output	Observed Specific Energy	kWh/t	2.1	35.9	17.0
	Predicted E_{TOT} Specific Energy	kWh/t	2.3	40.1	17.0
	E_{TOT} Model Error (+/-)	%	-	-	8.2

Comparison With Other Power-based Models

As several tests have been developed to quantify AG/SAG specific energy requirements, the difference in test methods and the interpretation of their results can produce different outcomes, particularly for competent ores (Bailey et al., 2009). OMC Power Model's AG/SAG E_{SAG} and total circuit E_{TOT} methods were compared to other power-based techniques described in this paper using values published in journal and conference proceedings available to the public. Table 4 compares the specific energy calculations for the SMC worked example along with three existing plants, namely the Kubaka SAB circuit, the Cadia SABC circuit and the Similco SABC circuit.

According to Table 4, each model tends to give similar results for the evaluated circuits. The highest difference was observed when comparing OMC and MacPherson's method for the Kubaka circuit (-3.7 kWh/t, -13% difference). The remaining specific energy predictions for the other examples were less than 10% of the OMC predicted value.

Table 4 - Comparison of OMC Power Model against other power-based methodologies

Example	Circuit Config.	Method	Specific Energy (kWh/t) SAG Mill	Ball Mill	Total	Total Diff.	Source
SMC Worked Example	SABC	OMC	8.6	10.4	19.0	-	-
		SMC	9.6	8.4	18.3	-0.7	(Morrell, 2009)
		Ausgrind	8.1	10.0	18.1	-0.9	(Lane et al., 2013)
Kubaka Circuit	SAB	OMC	12.8	15.7	28.6	-	-
		Starkey	13.0	16.0	29.0	0.4	(Starkey et al., 2001)
		Ausgrind	11.8	14.1	25.9	-2.7	(Lane et al., 2013)
		MacPherson	10.9	14.0	24.9	-3.7	(Lane et al., 2013)
Cadia Circuit	SABC	OMC	9.1	8.3	17.3	-	-
		Ausgrind	8.8	8.8	17.6	0.3	(Lane et al., 2013)
		Survey	8.6	8.0	16.6	-0.7	(Dunne et al., 2013)
Similco Circuit	SABC	OMC	13.2	12.3	25.5	-	-
		Ausgrind	12.0	14.6	26.6	1.1	(Lane et al., 2013)
		FLSmidth	8.0	16.0	24.0	-1.5	(Marks et al., 2011)

CONCLUSIONS

This paper presented some of the most common power-based methodologies for predicting grinding circuit specific energy. The use of Bond work indices coupled with other breakage tests, and the application of empirical efficiency factors, has become a standard for determining ore competency to calculate specific energy in modern grinding circuits. As several tests have been developed to quantify AG/SAG specific energy requirements, the difference in test methods and the interpretation of their results can produce different outcomes.

OMC's extensive project database was used in the generation of the OMC Power Model software, which is used for specific grinding energy power-based circuit calculations. The model uses ore hardness parameters from testwork, circuit configuration, equipment geometry and operating conditions as inputs. The OMC Power Model has proven accuracy based on more than 100 plant benchmark survey results. The average absolute error for the model's AG/SAG and total circuit specific energy predictions were determined to be +/-8.7% and +/-8.2% respectively. The OMC models reproduced specific energy requirement calculations by other methods for various projects within +/-10%. OMC experience and a strong practical understanding of grinding circuits and equipment support the OMC power-based modeling and are contributing factors to its proven accuracy for specific energy prediction in operating plants. Much more than just the calculation of specific energy is required to design a successful comminution circuit. Incorrect circuit selection, mill specifications, limited flexibility in the design or poor control philosophy all result in circuits operating at above predicted specific energy or power utilisation and reduced throughput.

An understanding of the geology and mineralogy of a deposit, and the consequent sample selection for testwork, has a significant impact on the effectiveness of the comminution circuit design. Optimized sampling must be representative and spatially distributed. OMC's experience in the areas of ore sampling and testwork program management, in conjunction with its extensive experience in comminution circuit modelling, design, commissioning and optimisation, places OMC in a strategic position to offer credible and realistic solutions to clients.

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