DEVELOPMENT AND APPLICATION OF AN ENERGY BENCHMARKING MODEL FOR MINERAL COMMINUTION

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ABSTRACT

An energy benchmarking method was developed for mineral comminution and trialed at two SAG mill based operations in British Columbia. The method involves subjecting ore samples to single-particle compression testing to determine the minimum practical energy required to carry out the equivalent comminution duty of site crushing and grinding processes. The minimum practical energy is then compared to the actual energy consumed at the respective mining operation to determine the Benchmark Energy Factor (BEF), an energy performance indicator, of comminution processes at the plant. A key feature of the method is that it is not constrained to one comminution technology, thereby allowing the comminution energy performance of plants comprising different crushing and grinding technologies to be effectively compared. Application of the proposed test to samples prior to and after equipment upgrades provides a method to account for any variation in ore hardness and directly compare the impact of plant modification on energy performance.

Using the BEF metric, the energy performance of two operations treating copper-porphyry ore was determined. Additionally, the energy performance of different comminution technologies was compared. The energy benchmarking method was found to hold considerable potential for representing ore hardness within an Energy Management Information System and as a measurement and validation tool. Furthermore, it was identified as being a potentially valuable metric for inclusion in the TSM Energy and Greenhouse Gas Emissions Management Protocol.

KEYWORDS

Comminution, Energy benchmarking, Energy management, Compression breakage

INTRODUCTION & BACKGROUND

In 2013, an electrical utility, BC Hydro, initiated development of an energy benchmarking method for mineral comminution with the Norman B. Keevil Institute of Mining Engineering, due to a lack of a suitable tool for gauging improvements in energy performance of comminution circuits. Subsequently a benchmarking method was designated as a focus of the comminution research group. The methodology serves as a tool to measure and validate energy conservation efforts, keep track of the energy performance of a process plant and to compare the energy performance of different operations and their associated comminution technologies. The benchmarking method is based on comparing the energy used by comminution process on site to the minimum practical energy required to carry out the same comminution duty; the resulting value is referred to as a Benchmark Energy Factor (BEF). This approach is similar to other benchmarking methods used outside of the mining industry. Rather than targeting the P80 product size or percentage passing of a certain sieve size, models used within the BEF method take into account the actual feed and product size distributions of comminution equipment when calculating the minimum practical energy.

The minimum practical energy required to reduce the size of an ore to a certain product size was nominated as being equivalent to the energy required for crushing particles through single-particle compression. This method of breakage was selected due to its inherent efficiency and the availability of hydraulic piston equipment in material and geotechnical testing facilities. A typical geotechnical laboratory that is equipped for Unconfined Compressive Strength (UCS) testing and sieving can be easily setup to carry out the test regimen. Incorporating piston press testing and adopting models that were originally developed for impact-breakage, a method for determining the minimum practical energy of an ore and comminution duty was proposed by Nadolski, et al, (2014). Further evolutions of the BEF method and case studies on its application to two operations are presented in this paper.

EVOLUTIONS OF THE BENCHMARKING METHOD

Further development of the established method aims at improving model accuracy, reducing time and sample requirements as well as integrating benchmark results with site Energy Management Information Systems (EMIS).

An instrumented MTS piston press unit is used to carry out single-particle compression tests on mineral particles. Particles are compressed between a hardened steel piston and base. The piston is attached to a load cell that has a rated accuracy of +/-325 Newtons. The specific energy consumed during particle crushing, calculated from the area of the force-displacement curve and weight of rock, is monitored online and the test is stopped once a setpoint energy level has been reached. Vertical displacement rates are in the range of 2 to 4 mm/min. This is considered to be slow when compared to the displacement rates of crushing surfaces of comminution equipment.

Narrowly sized particles, ranging from 1.8 to 63 mm in size, are screened from sampled ore and used for compression testing. Usually five to six size fractions are tested at three different energy levels; resulting in 15 to 18 distinct energy-size test results. Reducing the number of individual tests while maintaining a suitable level of model accuracy is a focus of further test development.

Energy-Breakage Equation

Results from piston press testing are used to fit an energy-breakage model, which was developed by Shi et al (2007), shown in Equation 1, on the basis of impact breakage results:

$$t_{10} = M(1-\exp(-f_{mat} \cdot x \cdot k \cdot (E_{cs}-E_{min}))) \tag{1}$$

where t_{10} is the percentage of product which passes through one tenth of the original feed size, M and f_{mat} are material specific parameters which are fitted to experimental results, E_{cs} is the energy in kWh/t consumed, k is the successive number of impacts and E_{min} represents the minimum energy required to overcome the yield strength of the material and achieve breakage, also referred to as mass specific threshold energy. In the case of the single-particle compression test, k is set to 1 as repeated impact is not applied to samples.

A comparison of single-particle compression testing and DropWeight testing was carried out using the same copper-porphyry sample with a particle size of -31.5 +26.9 mm. The similar form of the curves, describing the breakage index t_{10} for a range of energy input levels, supports adoption of the model for slow-compression breakage. The higher efficiency associated with compression breakage is also shown in Figure 1 confirming that compression breakage provides a better estimate of the minimum practical energy required for breakage. This is in-line with publications that focus on comparing comminution energy efficiencies resulting from the application of different breakage mechanisms, such as that of Fuerstenau et al (2002).

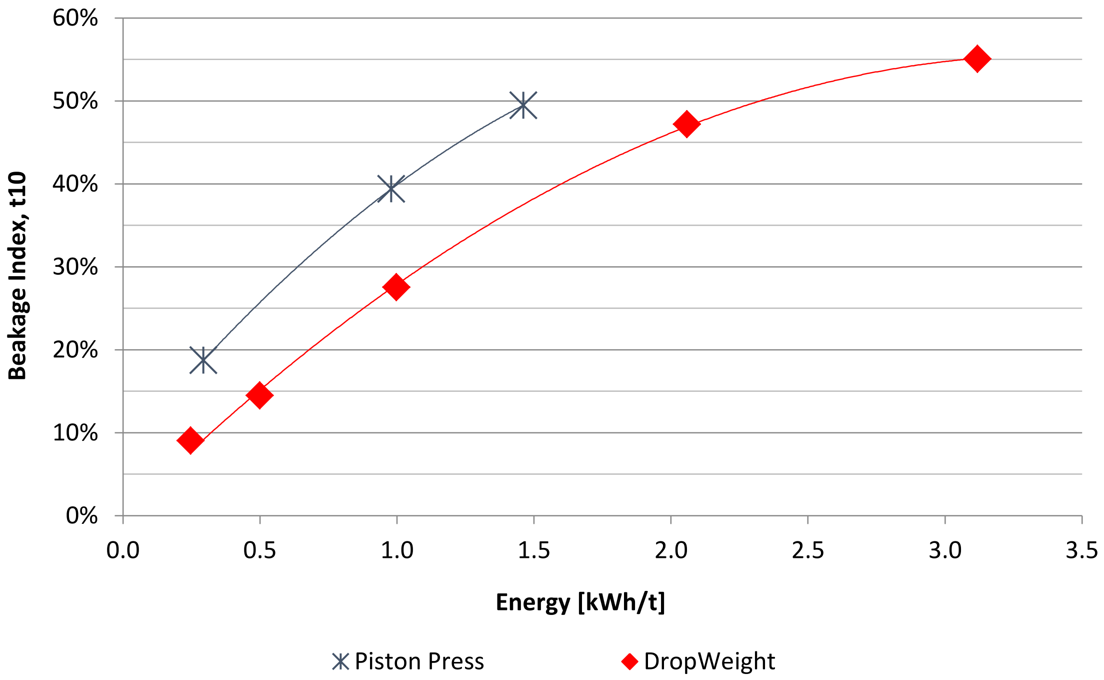

Figure 1 – Comparison of DropWeight & Piston Press results (29.1 mm feed)

The energy-breakage model has, in original and modified form, proven to be quite versatile and applicable to other comminution equipment; a modified form of the model was successfully adopted for fitting results from ball milling (Shi et al, 2015), steel wheel abrasion testing (Chenje et al, 2011) and multi-layer compression breakage (Davaanyam, 2015).

In application to single-particle compression breakage, modification of the exponent of the feed size parameter, x, was found to significantly reduce the standard error. This was also found to be true for multi-layer compression breakage testing (Davaanyam, 2015). The relationship between threshold energy value, E_{min}, and size was determined experimentally for three ores, shown in Figure 2. Each data point represents an average value from approximately 10 to 30 compression tests. The area underneath the force-displacement curve up to the point of bifurcation was calculated and through knowledge of the specimen weight an E_{min} value was calculated. Generation of more data points will show whether a general equation can be used for all ore types or whether the energy-size relationship needs to be determined for each ore.

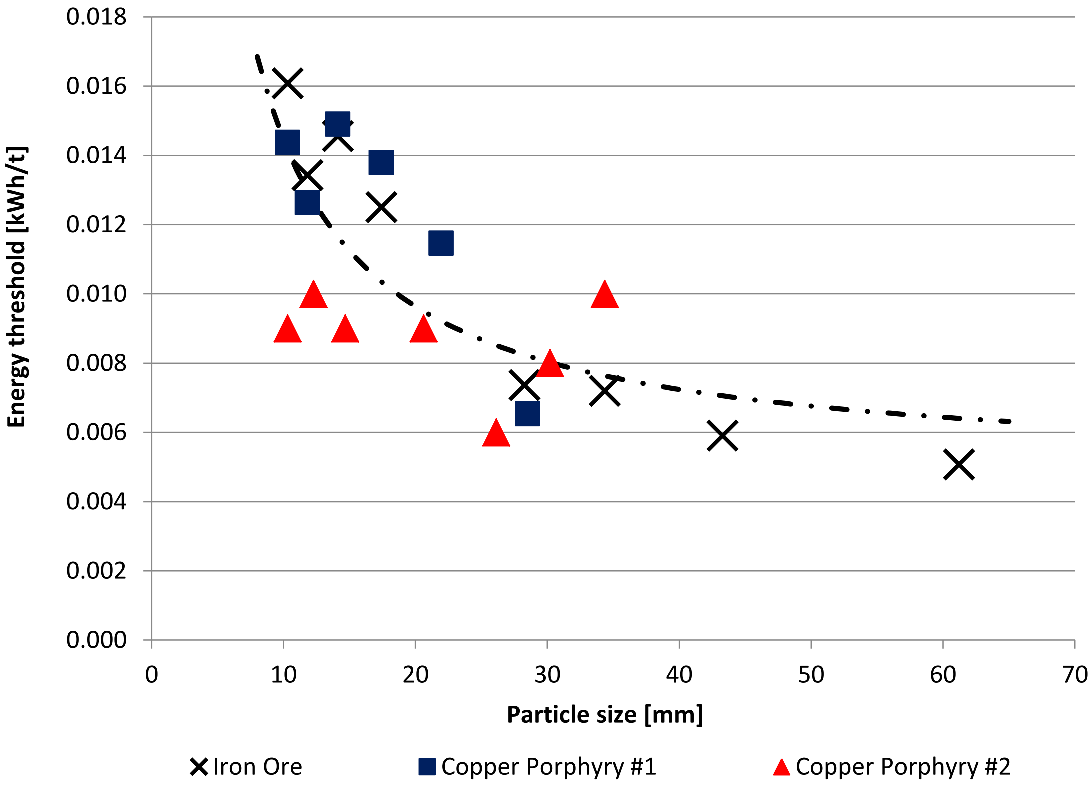

Figure 2 – Energy threshold values for three ores

For some sets of piston press data, fitting of constants for E_{min} or the multiple of E_{min} with size, $E_{min}.x$, results in negative values being determined for the constant representing the threshold energy (yield strength) of the ore. Inclusion of the threshold energy value within the model was found to have little impact on fitting results when considering residuals and the degrees of freedom in the model. Until an appropriate model for E_{min} is developed, the model is used in the following form:

$$t_{10} = M(1 – \exp(–f_{mat} \cdot x^n \cdot k \cdot (E_{cs}))) \qquad (2)$$

For initial applications of Equation 2, a value of 0.5 was used for exponent n, as published by Nadolski et al (2014). However, analysis of additional test data showed that fitting the exponent n to each individual set of results is justified by the significant improvement in residuals. An example is shown in Figure 3, where the model fit resulted in an R^2 of 0.95.

The inputs for the energy-breakage model are determined by carrying out compression tests with a hydraulic piston press using ore collected from site. Samples are separated into narrow size fractions and subjected to piston-press testing as individual particles, for particle sizes above 15 mm, and as mono-layers of multiple-particles, for particles smaller than 15 mm. Mono-layer compression tests are carried out such that the distance between neighbouring particles is less than approximately three times the particle size. Schönert (1996) found that spacing the particles in this way provides energy-breakage results that are equivalent to that of single-particle compression breakage.

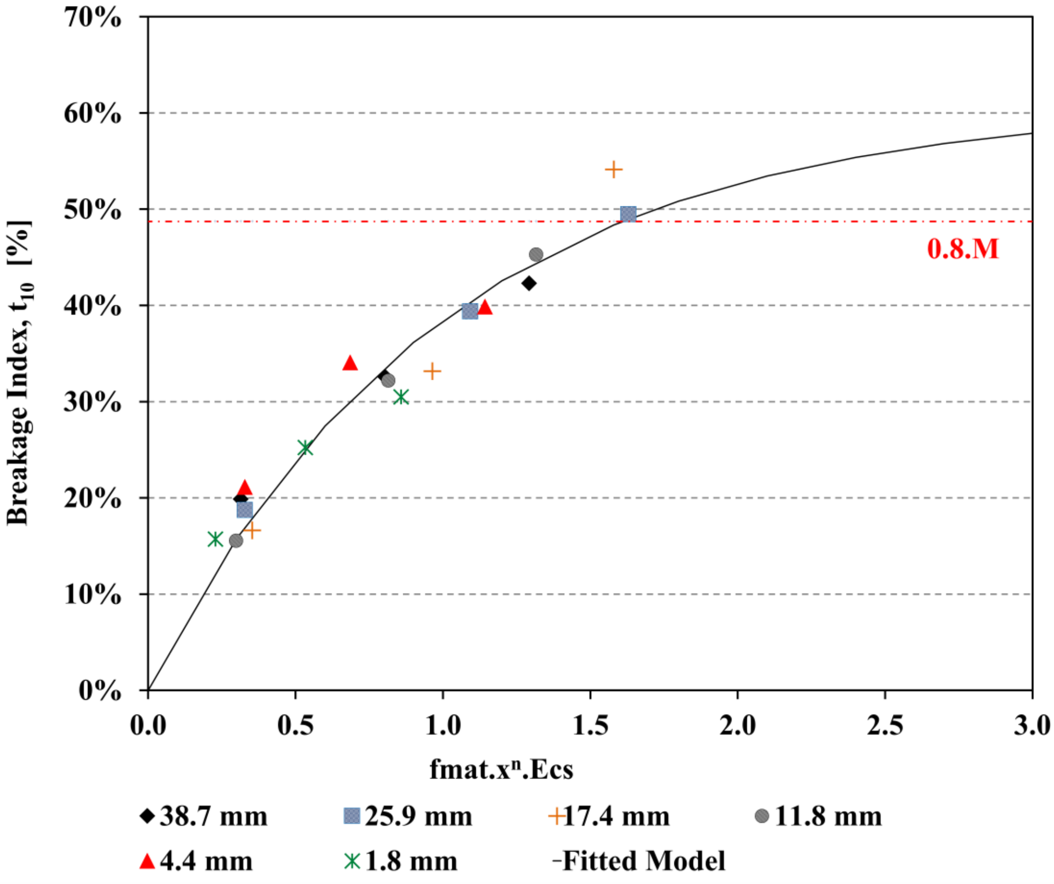

Figure 3 – Energy breakage model fitted to New Afton ore

Figure 4 shows the relation between the t_{10} breakage index and the fraction smaller than 1/n of the original size, presented as t_n. Although the data points were determined from treating three different copper-porphyry ores, the high degree of fit of the trend lines suggests that a master set of curves can be used to describe the product size distribution resulting from single-particle compression breakage.

Using trends which are derived from the plotted data, the percent passing of a certain fraction of the original feed size, represented by t_n, is determined for a nominated value of t_{10}. Hence, the product size distribution for a certain feed sample and energy input is derived by first fitting Equation (2) to find the t_{10} breakage index parameter and subsequently the t_n versus t_{10} curves are referenced to describe the resulting product particle size distribution. This procedure is based on a similar approach used for interpretation of JK DropWeight test results.

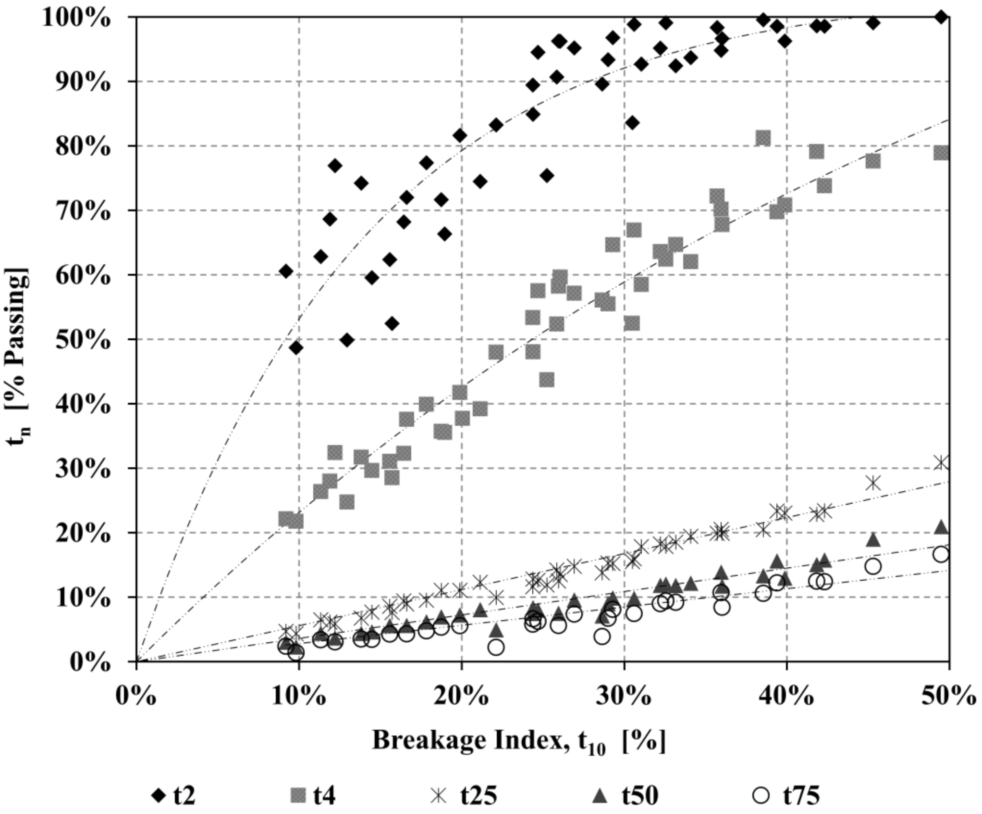

Figure 4 – t10 versus tn curves for three copper-porphyry ores

Calculation of the Minimum Practical Energy

The minimum practical energy is determined for each ore and comminution duty by applying the energy-breakage model in a sequence of virtual comminution stages, starting from the coarsest fractions and working down to the finest size fraction. A schematic of the model is shown in Figure 5. For each size fraction, i, the specific energy input, $E_{cs\text{-}i}$, and proportion of mass subjected to compression-breakage, Si, is optimized such that: 1) the final product size distribution is the same or finer than the product of site comminution equipment 2) a minimum specific energy input results 3) energy input per size fraction, $E_{cs\text{-}i}$, results in at least 80% of the maximum breakage being achieved, i.e. the t_{10} breakage index is at least 80% of the fitted M parameter in Equation (2).

The restriction on energy input results in a lower number of comminution events being required at the cost of higher specific energy expenditure. This is considered to be analogous to lower recirculating loads or a shorter series of classification and comminution steps. This criterion for determining the minimum essential energy was deemed to be important to ensure that the calculated value is practically achievable. Without this restriction, all energy input values, $E_{cs\text{-}i}$, that are equivalent to the energy threshold values, E_{min}, i.e. the energy input at which bifurcation occurs, are selected by the model to minimize overall energy. Therefore, BEF values that are extremely high and consequently not suitable for use as a realistic benchmark value result.

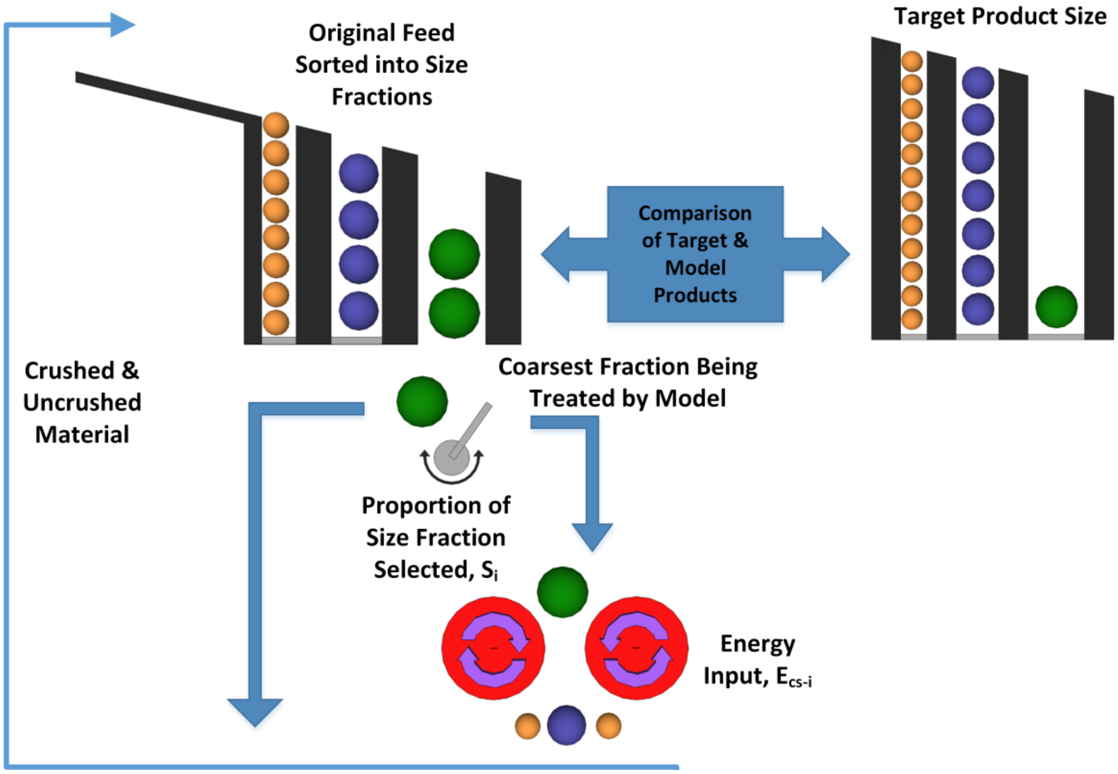

Figure 5 – Schematic of the minimum practical energy model

Comparison to Ball Milling

To investigate the application of the model to fine grinding with ball mills, the minimum practical energy model was compared to the results of Levin testing, an open-circuit batch grinding test, for the same copper-porphyry sample. Levin tests were run at four different energy levels, corresponding to four different grinding times, and the products were sieved and input as the target size for the minimum practical energy model. The resulting comparison is shown in Figure 6, where the deviation between the two models increases with product fineness. These results are consistent with results previously presented where comparisons of Bond ball milling efficiencies and the minimum practical energy were published by Nadolski et al (2014). The comparison showed that energy predictions from the piston press based model are significantly lower than calculated Bond ball mill energy.

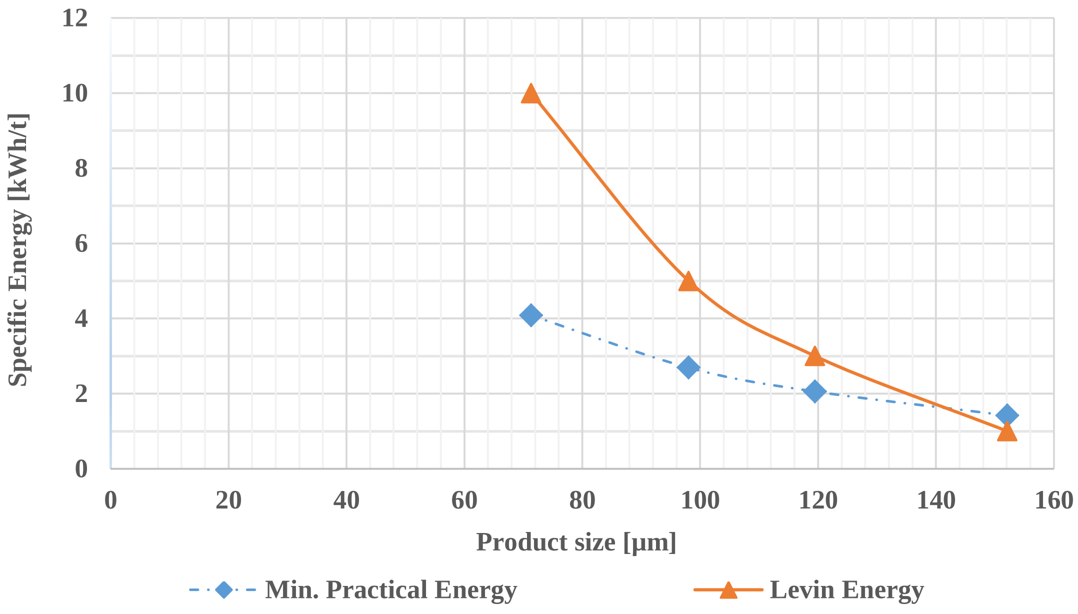

Figure 6 – Minimum practical energy and Levin energy for copper-porphyry sample

CASE STUDIES

The updated BEF method was applied to two operations in BC that treat copper porphyry ore. The two case studies look at the impact of changing circuit configurations and equipment on energy performance.

New Afton Mine

Comminution processes at the New Afton mine, where a SAG mill based grinding circuit is in operation, account for approximately 40% of total site energy consumption with respect to all fuels used. The operation places a great emphasis on energy performance; it was the first Canadian mining operation to achieve certification for ISO 50001 Energy Management System and is active in carrying out energy conservation studies. The extensive use of an Energy Management Information System (EMIS) at New Afton makes it a particularly suitable operation for implementing a regular energy benchmarking protocol. Significant opportunity exists to integrate BEF results with the EMIS, thereby adding a parameter representing ore hardness to the range of parameters being monitored by the system. As a first step towards this goal, BEF values were determined for two operating scenarios.

The battery limits of the energy benchmarking study at New Afton were nominated as starting at the coarse ore stock pile (primary crusher product) and terminating just prior to rougher flotation. A simplified flowsheet is shown in Figure 7. At the time of the study, installation of a VertiMill based tertiary grinding circuit was underway and was included in a separate BEF calculation. During the site survey, SAG mill feed and ball mill cyclone overflow samples were taken for size analyses. Subsequently, SAG mill feed was crushed/screened and a representative sub-sample was taken for piston press testing. The SAG mill feed was found to contain a substantial amount of fines; an F80 size of 35 mm was determined through sieving.

The energy consumption of the VertiMill and slurry pumping equipment was estimated using models based on fine grinding test work and vendor data (Nadolski, 2015). The role of the tertiary grinding circuit is to reduce the size of flotation feed from 220 to 160 µm.

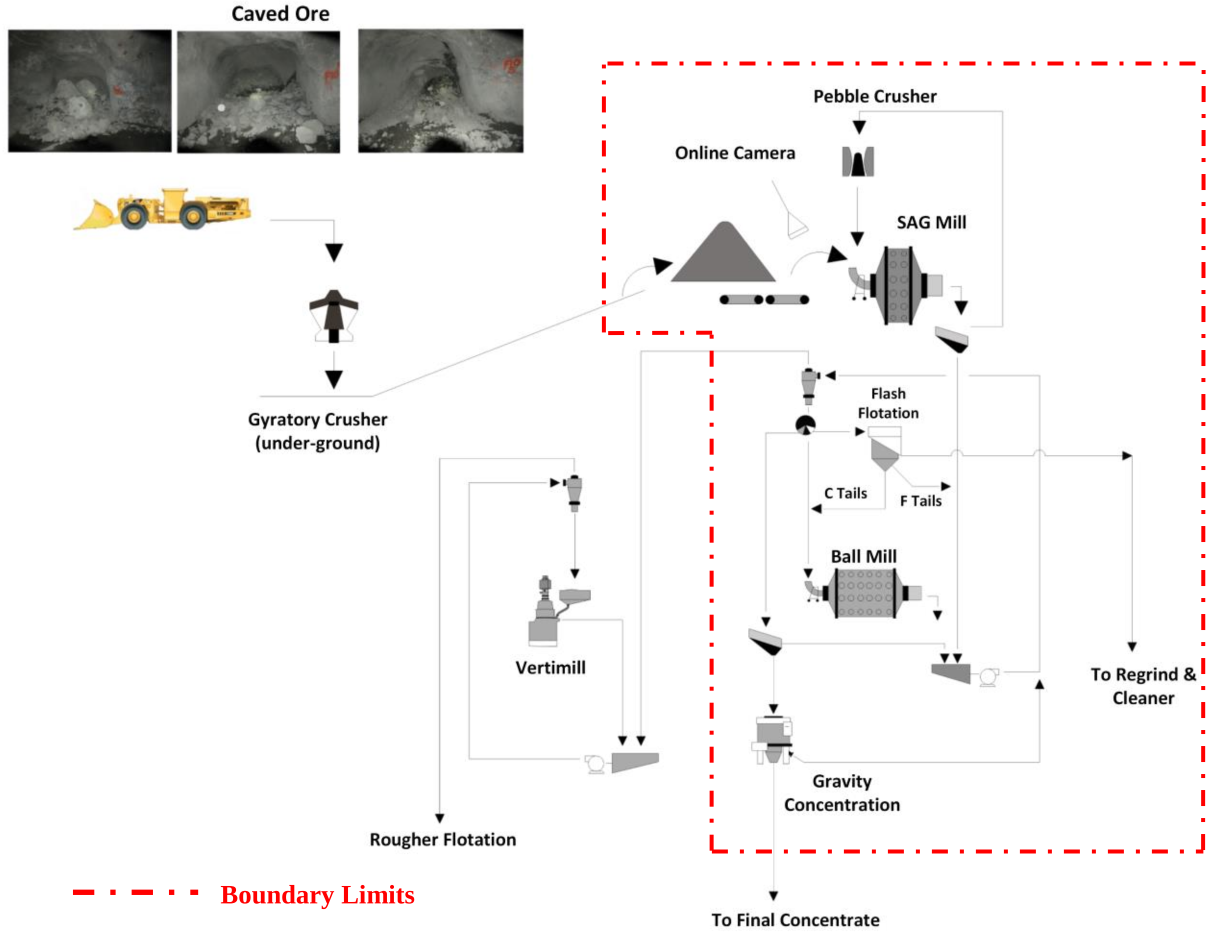

Figure 7 – Simplified New Afton process flowsheet

Piston press testing, outlined in Table 1, was carried out on six different size fractions; three energy levels were applied to each fraction. The resulting fit for the energy-breakage model was shown previously in Figure 3.

Table 1 – Comminution test regimen for New Afton ore

Geometric Mean (mm)	Upper Sieve Size (mm)	Lower Sieve Size (mm)	Number of Tests	Average Energy Level (kWh/t)
38.7	40.0	37.5	15	0.25
38.7	40.0	37.5	15	0.64
38.7	40.0	37.5	15	1.03
25.9	26.9	25.0	15	0.29
25.9	26.9	25.0	15	0.98
25.9	26.9	25.0	15	1.46
17.4	19.0	16.0	15	0.39
17.4	19.0	16.0	15	1.08
17.4	19.0	16.0	15	1.76
11.8	12.5	11.2	10*	0.39
11.8	12.5	11.2	10*	1.07
11.8	12.5	11.2	10*	1.73
4.36	4.75	4.0	15*	0.66
4.36	4.75	4.0	15*	1.38
4.36	4.75	4.0	15*	2.30
1.84	2.0	1.68	15*	0.66
1.84	2.0	1.68	15*	1.55
1.84	2.0	1.68	15*	2.50

* Tests on these size fractions were carried out using a single layer of multiple particles per test

Table 2 shows the parameters that were fitted to the energy-breakage model, Equation 2. The M value of 0.61 indicates that a maximum t10 value of 61% can be achieved per piston press stroke.

Table 2 – Fitted material constants for the energy-breakage model (eqn. 2), New Afton ore.

Parameter	**Units**	**Fitted Value**
M	-	0.61
fmat	-	0.27
n	-	0.43

Using the BEF method, the energy performance of the New Afton circuit was found to improve by approximately 2% with inclusion of the tertiary grinding circuit. Follow up surveys of the circuit after VertiMill installation will confirm the improvement in energy performance.

Table 3 – BEF values for the New Afton circuit

Circuit type	**Specific Energy [kWh/t]**	**Feed Size F80 [mm]**	**Product Size P80 [mm]**	**Minimum Practical Energy [kWh/t]**	**BEF [-]**
New Afton SABC base case	16.32	35	0.225	6.79	2.41
New Afton SABC and VertiMill Tertiary Grinding	18.77	35	0.160	7.99	2.35

Huckleberry Mine

Survey data and sample from a mine-to-mill study for Huckleberry, reported by Nadolski et al (2013), was referenced to calculate the energy performance of individual comminution processes within the circuit. The feed to the primary crusher was estimated from image analysis of the muckpile using WIPFRAG software. Additionally, data published by Wang et al (2013) was used to compare BEF values for circuit configurations that are based on different comminution technologies.

SAG mill feed sample was crushed, screened into narrow size fractions and subjected to piston press testing. Five different size fractions, ranging from 1.8 to 38.7 mm were tested at three different energy levels. The fitted model parameters, shown in Table 4, indicate that tested Huckleberry ore was harder than that of New Afton ore.

Table 4 – Fitted material constants for the energy-breakage model (eqn. 2), Huckleberry ore.

Parameter	Units	Fitted Value
M	-	0.57
fmat	-	0.27
n	-	0.33

Details of the different comminution stages within the Huckleberry circuit are shown in Table 5. A BEF value of 0.31 was determined for primary crushing and suggests that the model used for calculation of the minimum practical energy requires modification in order for it to be used effectively for crushing of coarse particles (+ 50 mm). As discussed earlier in this paper, the current revision of the model places a restriction on energy input to values of at least 80% of maximum breakage. In order to apply the BEF method to primary crushing applications, modification of this restriction on energy input may need to be considered.

Table 5 – BEF values for the Huckleberry circuit. Based on a survey conducted in 2013.

Equipment	**Specific Energy [kWh/t]**	**Feed Size F80 [mm]**	**Product size P80 [mm]**	**Minimum Practical Energy [kWh/t]**	**BEF**
Primary crusher	0.35	260*	51	1.12	0.31
SAG mill, pebble crusher & conveyors	9.82	51	3.11	4.77	2.06
Ball mills (2) & cyclone pumps	9.78	3.11	0.158	5.67	1.72
Total circuit:	**19.95**	**260**	**0.158**	**11.22****	**1.78**

* Determined from image-based analysis of the muckpile
** Not a summation of the individual circuits. A separate calculation for minimum practical energy was carried out for the entire SABC circuit

Table 6 shows the estimated BEF value for each of the considered circuit configurations reported by Wang et al (2013). The updated energy-breakage model, Equation 2, was used to compare the energy performance of each comminution option. Samples taken during a mill survey conducted in 2013 was used for determining the practical energy corresponding to the timing of a survey in 2011; changes in ore hardness may have occurred during the period between recording DCS data and collecting sample for piston press testing. However, the results still show the applicability of the BEF method to gauging plant energy performance for different comminution technologies and product sizes.

Table 6 – Technology comparison. Based on survey conducted in 2011

Circuit type	**Specific Energy [kWh/t]**	**Feed Size F80 [mm]**	**Product Size P80 [mm]**	**Minimum Practical Energy [kWh/t]**	**BEF [-]**
SABC (2011) – Measured baseline	21.5	66.9	0.16	10.65	2.02
HPGR – ball mill	17.1*	66.9	0.16	10.65	1.61
SABC	23.3*	66.9	0.075	12.42	1.88
HPGR – ball mill	21.7*	66.9	0.075	12.42	1.75
Two Stage HPGR – Stirred mill	15.4*	66.9	0.075	12.42	1.24

* Specific energy values were modelled based on pilot and laboratory scale test work as reported in Wang et al (2013).

APPLICATION TO MEASUREMENT & VALIDATION

The BEF method can be easily used to determine the energy and demand savings associated with implementing modifications to comminution circuits. Measurement and validation reports typically require energy and demand savings to be reported in kWh/year and kW, respectively.

In order to measure and validate the impact of plant upgrades, a site survey is conducted prior to implementation to calculate the energy baseline and to collect feed and product samples. Product sampling locations are specified according to the boundary limits of the energy study, as was carried out for the New Afton case study. Size distributions are determined for feed and product samples and are input into the model. Subsequently, feed sample is stage crushed and screened into narrow size fractions and used for piston press testing. Size distributions and ore hardness results are used to calculate the BEF for the baseline period, as shown by Equation 1.

$$\mathrm{BEF}_1 = \frac{Baseline\ SE\ (\frac{kWh}{mt})}{Minimum\ Practical\ Energy\ \#1\ (\frac{kWh}{mt})} \tag{1}$$

Where SE refers to specific energy consumption. Following implementation of plant upgrades, site surveys and piston press tests are carried out for a second operating period and the corresponding BEF value, referred to as BEF_2, is calculated.

$$\mathrm{BEF}_2 = \frac{Post\ implementation\ SE\ \#2\ (\frac{kWh}{t})}{Minimum\ Practical\ Energy\ \#2\ (\frac{kWh}{t})} \tag{2}$$

A BEF_2 that is less than the initial BEF_1 value indicates that some degree of energy conservation has been achieved. The reduction in specific energy consumption and the kWh/year savings are calculated in the following way:

$$Energy\ Savings\ \left(\frac{kWh}{t}\right) = BEF_1\ .Minimum\ Practical\ Energy\ \#2\ \left(\frac{kWh}{t}\right) - Post\ implementation\ SE\ \#2\ (\frac{kWh}{t}) \tag{3}$$

$$Annual\ Energy\ Savings\ \left(\frac{kWh}{year}\right) =$$
$$Energy\ Savings\ \left(\frac{kWh}{t}\right)\ .\ measured\ throughput\ \left(\frac{t}{h}\right)\ .plant\ availability\ (\%).8766\ (\frac{\text{h}}{\text{year}}) \qquad (4)$$

Where measured throughput corresponds to the solids throughput rate that was recorded during the second site survey.

Typically energy savings are determined based on comparisons of implemented technologies to industry standard solutions. Such a comparison may be complex due to lack of reliable models, sample and standardized scale-up approaches. However, determination of BEF values associated with industry standard technologies will simplify the process considerably. For example, based on the New Afton and Huckleberry case studies, it may be said that the BEF associated with SABC circuits in application to copper-porphyry ores is in the range of 1.9 to 2.4. In order to determine the energy savings of a new technology in comparison to an SABC circuit option, the minimum practical energy can be determined for the ore and through knowledge of the specific energy requirements of the new technology, the BEF following implementation can be determined. In this way, the task of quantifying SABC circuit energy requirements through metallurgical testing and modelling is avoided, thereby the procedure of quantifying the energy savings reduces in cost and sample requirements. Further work on determining the range of BEF values associated with comminution equipment is required to supplement future energy studies.

DISCUSSION & CONCLUSIONS

Trials of the energy benchmarking method to two copper-porphyry operations demonstrated how the approach can be used to compare different sites and comminution technologies. Applying the method to primary crushing also showed that refinement of the minimum practical energy model is required to achieve appropriate BEF values for this range of size reduction. Reducing the number of individual piston press tests while maintaining a suitable level of model accuracy is a focus of further test development. Future research also aims to clarify the relationship between size and threshold energy so that energy wasted in elastic deformation of particles during compression is suitably accounted for in the energy-breakage equation.

A frame-work for using the BEF method for measurement and validation of energy conservation efforts has been presented in this paper. An approach to integrating regular BEF measurements with site EMIS systems is currently under development within the research group. Inclusion of minimum practical energy characterization into geometallurgical models for an orebody can be used for ongoing assessment of the BEF in response to changes in operating conditions and/or equipment. This will inevitably improve the tracking of energy performance, forecasting demand and energy consumption, establishment of energy targets and identification of reasons for deviations from energy baselines.

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