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# Optimization of the energy distribution of SABC circuits

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**Abstract:** Improving the energy efficiency of large grinding mills is of great importance to reduce the energy cost of mineral processing. The ratio of SAG mill to ball mill's energy consumption varies greatly among SABC operations. Thus far, very few research studies have been conducted to demonstrate how the SAG mill or ball mill responses to the change of circuit energy distribution in terms of comminution efficiency. The present study investigated the energy performance of an operating SABC circuit at variable circuit energy distributions. An energy benchmarking model was used to assess the comminution energy efficiency of SAG mill, ball mill, and overall circuit. It is found that the target SABC circuit achieves the highest overall energy efficiency when 37.6% of the total circuit energy is distributed to the SAG mill and 62.4% to the ball mill. The maximum energy efficiency of this SABC circuit is approximately 25% when compared to the minimum practical energy required to carry out an equivalent comminution duty. The study also showed that the ball mill is more sensitive to the variation in circuit energy distribution than the SAG mill.

*Keywords:* Semi-Autogenous, energy distribution, energy efficiency, energy benchmarking

## 1. Introduction

Comminution is an important and energy-intensive process in mining operations. It consumes 36% of the total energy use of a gold or copper mine on average (Ballantyne et al., 2012). In comminution, most of the energies are consumed to operate large grinding mills (Musa and Morrison, 2009). SABC (SAG mill-Ball mill-Crusher) circuit is the most widely used grinding configuration in large metal mines. It has been proven that reducing the feed size of the SAG mill can improve the energy efficiency or throughput of SABC circuits (Morrell and Valery, 2001). This can be realized by optimizing blasting design (Jankovic and Valery, 2002) or by using secondary crushing prior to the SAG mill (Castillo and Bissue, 2011; Festa et al., 2014). There is, however, no published information related to the effect of SABC circuits' energy distribution on overall comminution energy efficiency.

Existing SABC operations in the mining industry have a variety of energy distributions due to the differences in ore deposit type and comminution circuit characteristics. The installed power data of 16 SABC operations around the world (Hadaway, et al., 2011; Liu, 2014; Wang et al., 2015) indicate that the ratio of SAG mill power to ball mill power varies from 0.7 to 1.2 with an average value of 0.9 and a standard deviation of 0.13. It should be noted that even for the SABC circuits with the installation of 50%/50% SAG mill/ball mill power, the value of SAG mill/ball mill operating power may differ among operations. For a particular SABC operation, its optimal energy distribution should be determined with a comprehensive consideration of ore properties, mill feed size, required product size, and circuit operating parameters.

In the present work, the energy performance of the SABC circuit at various energy distributions was investigated. An energy benchmarking model was employed to assess the energy efficiency of the overall circuit and the individual mills, respectively. In an SABC circuit, the pebble crusher commonly consumes less than 0.5% of the total energy, and hence this fraction of energy is not considered. It is

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found that the optimal energy distribution of an SABC circuit is closely related to the breakage properties of the feed ore, and the SAG mill and ball mill demonstrate different levels of sensitivity to the variation in circuit energy distribution. The target SABC circuit achieves the highest energy efficiency when 37.6% of the total circuit energy is distributed to the SAG mill and 62.4% distributed to the ball mill.

## 2. Methodology

### 2.1. Design of circuit energy distribution

The SABC circuit at the Huckleberry Mine, British Columbia, Canada, was selected for the case study regarding the present research topic. The circuit configuration is shown in Fig. 1. This circuit processes 792 metric tons of ore per hour. The feed ore is harder than most copper ores with the A*b of 31.3 and the Bond ball mill work index of 21.7 kWh/t.

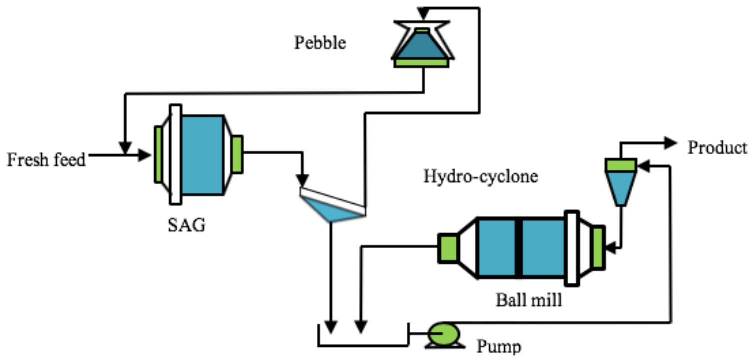


Fig. 1. Comminution flowsheet of Huckleberry Mine

The Moly-Cop Tools Package was used to simulate the performance of the SAG mill and ball mill under variable energy distributions. In the simulation, the net power demands of the SAG mill and ball mill are estimated based on the Hogg and Fuerstenau Model (1972). A base-case model regarding the existing circuit was built and model-fitted against plant survey data using Moly-Cop Tools software. The differences between measured and simulated process data are shown in Table 1.

Table 1. Comparison of measured and simulated process data

| Description | | Unit | Measured | Simulated |
|---|---|---|---|---|
| SAG mill | Fresh feed rate | (mtph) | 792 | 792 |
| | Feed $F_{80}$ | (mm) | 60 | 60 |
| | Product $P_{80}$ | (um) | 3114 | 3316 |
| | Mill motor power | (kW) | 6863 | 6857 |
| | SAG mill specific energy | (kWh/t) | 8.68 | 8.66 |
| Ball mill | Feed rate | (mtph) | 396 | 396 |
| | Feed $F_{80}$ | (um) | 3114 | 3316 |
| | Product $P_{80}$ | (um) | 158 | 157 |
| | Mill motor power | (kW) | 3808 | 3821 |
| | Ball mill specific energy | (kWh/t) | 9.61 | 9.65 |

Measured process data sourced from Wang et al. (2013)

The energy distribution of the SABC circuit can be adjusted by redistributing the comminution duties of the SAG mill and ball mill. This can be achieved by adjusting the circuit transfer size $T_{80}$, i.e. the 80 passing size of the SAG mill circuit product. The value of the $T_{80}$ is determined by ore hardness, mill geometry and circuit operating conditions. It is very difficult to obtain a clear relationship between $T_{80}$ and all circuit operating parameters (Morrel, 2011). Therefore, in this study the SAG circuit classification conditions and the mill throughput were fixed. Under this condition, the mill speed and ball charge of the SAG mill have the most significant influences on the specific grinding energy. Variable circuit energy distributions were designed by simulating different mill speed-ball charge combinations with Moly-Cop Tools (Table 2). The total energy consumption of the SABC circuit also differs as the circuit energy distribution changes, which is discussed in the Section 3.3. The current operating parameters of the SABC circuit at the Huckleberry Mine are shown in the table as Base case. Fig. 2 shows the relationship between the $T_{80}$ and the circuit energy distribution.

Table 2. The operating parameters of the SABC circuit at different circuit energy distributions

| Case No. | $T_{80}$ | SAG Mill | | Ball Mill | |
|---|---|---|---|---|---|
| | | Mill Speed (% Crit.) | Ball Load (%) | Mill Speed (% Crit.) | Ball Load (%) |
| Base case | 3.3 | 73.5 | 15 | 81 | 28 |
| 1 | 1.0 | 90 | 30 | 60 | 18.5 |
| 2 | 2.0 | 85 | 17 | 70 | 28 |
| 3 | 4.8 | 65 | 10 | 85 | 31.5 |
| 4 | 6.2 | 62 | 8 | 85 | 45 |
| 5 | 7.5 | 60 | 5 | 85 | 49 |

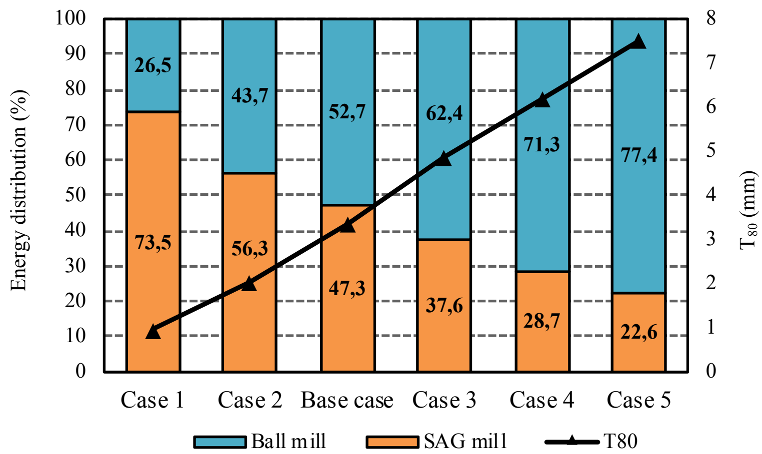


Fig. 2. The relationship between SABC circuit's energy distribution and $T_{80}$

## 2.2. Evaluation of comminution energy efficiency

Energy benchmarking (Nadolski et al., 2014) was used to calculate the comminution energy efficiency. The energy efficiency of a comminution process is represented by the Benchmark Energy Factor (BEF), which is the ratio of the actual energy consumption to the minimum practical energy required to carry out the equivalent comminution duty. The minimum practical energy is the minimum energy required to fulfill the comminution duty in a series of branching-cascading single-particle compression tests, starting from the coarsest size fraction to the finest size fraction.

Single particle compression tests were carried out on variable size fractions of samples from the SAG mill feed. The obtained test results were model fitted to develop an energy-breakage model associated with the sample, and then the minimum practical energy of the SAG mill and ball mill was determined, respectively, based on their size reduction ranges. For each energy distribution shown in

Table 2, the BEFs of the SAG mill and ball mill are calculated by dividing the simulated specific energy to the corresponding minimum practical energy.

## 3. Results and discussion

### 3.1. Minimum practical energy

The minimum practical energy is the baseline energy for assessing the energy efficiency of a comminution technology or circuit. It is determined from the energy-breakage model associated with the sample and the size reduction range of the comminution process. The SAG mill feed size and the ball mill product size are constant when the circuit energy distribution varies, so the size reduction range of each mill is only determined by $T_{80}$.

The energy-breakage model shown in Eq. (1) (Nadolski et al., 2015; Shi and Kojovic, 2015) was adopted for modelling of the compression breakage results. This model is a modified form of the model developed by Vogel and Peukert (2003) and Shi and Kojovic (2007). The parameter 'n' is added to characterize the significance of the particle size effect.

$$t_{10} = M[1 - \exp{(-f_{mat} \cdot x^n \cdot E_{cs})}] \tag{1}$$

Where $M$ is the maximum achievable breakage in terms of $t_{10}$ in a single breakage event, $f_{mat}$ is an indicator of the particle strength, and $n$ is the exponent indicating the significance of particle size effect. The fitted model parameters associated with the sample are shown in Table 2.

Table 4. Fitted material constants for the energy-breakage model (Nadolski et al., 2015)

| Parameters | Fitted Value |
|---|---|
| M | 65.5 |
| $f_{mat}$ | 0.19 |
| n | 0.37 |

Based on the obtained energy-breakage model, the minimum practical energy of the SAG mill and ball mill at variable circuit energy distributions were calculated. The increase of $T_{80}$ means a greater fraction of total circuit energy is distributed to the ball mill to grind a coarser feed (Fig. 2). Thus, the variation of the minimum practical energy against circuit energy distribution can be expressed by the relationship between the minimum practical energy and $T_{80}$, as is shown in Fig. 3. The figure shows that the difference in the minimum practical energy between SAG mill and ball mill becomes significant at a $T_{80}$ greater than 3.3 mm. The SAG mill and ball mill will have very similar minimum practical energy if the circuit transfer size ranges between 1.0 mm and 2.0 mm. It is also observed that the minimum practical energy varies significantly when the $T_{80}$ increases from 1.0 mm to 3.3 mm. This result can be explained by the significant particle size effect at fine size fractions (Hukki, 1962; Shi, 2016). The value of parameter "n" in Table 4 shows that the sample has a medium level of particle size effect.

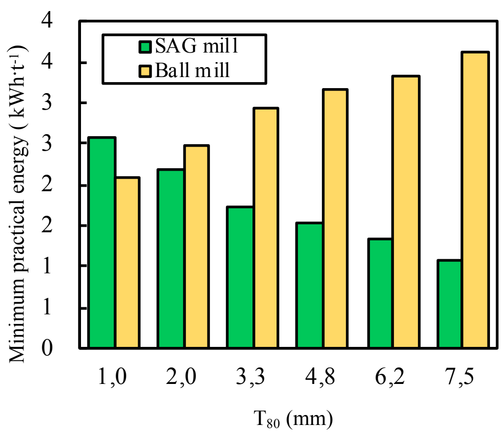


Fig. 3. Effect of transfer size on the minimum practical energy of SAG mill and ball mill

### 3.2. Comminution energy efficiency

The effects of $T_{80}$ on the specific energy consumption and the comminution energy efficiency of the SAG mill are shown in Fig. 4. As illustrated, as $T_{80}$ increases, the specific energy consumption decreases while the value of BEF first decreases then stabilizes around the value of 4. This suggests that the energy efficiency of the SAG mill is more sensitive to the circuit energy distribution when the $T_{80}$ is less than 4.8 mm. The value of $T_{80}$ should be less than or equal to 4.8 mm to keep the SAG mill operate efficiently.

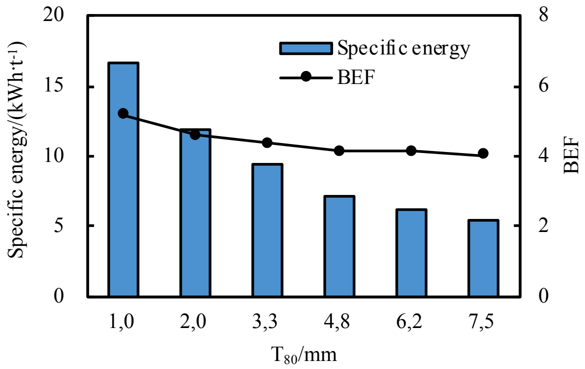


Fig. 4. BEF and specific energy consumption of the SAG mill at different $T_{80}$s

Fig. 5 shows the specific energy consumption and the energy efficiency of the ball mill at different $T_{80}$s. As shown, the specific energy consumption of the ball mill increases as the $T_{80}$ coarsens. However, the BEF of the ball mill stays constant when the $T_{80}$ increases from 1.0 mm to 4.8 mm, and then rises rapidly as $T_{80}$ increases to 6.2 mm. This trend suggests that the ball mill's energy efficiency is only sensitive to the circuit energy distribution when $T_{80}$ is greater than 4.8 mm. The $T_{80}$ should be less than 4.8 mm to ensure that the ball mill operates at an energy efficient state.

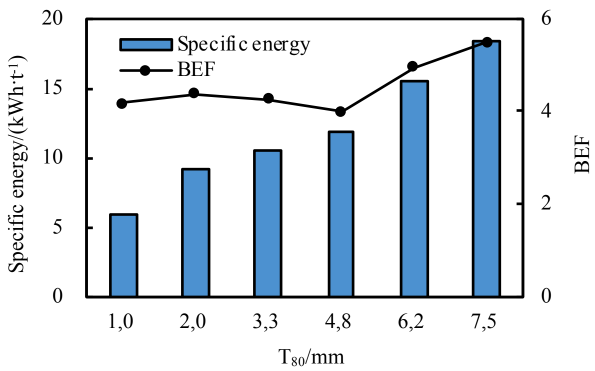


Fig. 5. BEF and specific energy consumption of ball mill at different $T_{80}$s

It also can be seen from Fig. 5 that when $T_{80}$ increases from 1.0 mm to 2.0 mm, the specific grinding energy of the ball mill increases significantly while the BEF is almost unchanged. This result suggests that the minimum practical energy of the ball mill must experience a similar level of increase.

In summary, when $T_{80}$ varies in the range of 1.0 to 10.0 mm, the energy efficiency of the ball mill circuit is more sensitive to the variations of the circuit energy distribution compared to the SAG mill circuit. Only at the $T_{80}$ of around 4.8 mm will the SAG mill and the ball mill operate at their highest energy efficiency at the same time.

### 3.3. The optimal energy distribution of the SABC circuit

The specific energy consumption of the SABC circuit at variable circuit energy distributions are shown in Fig. 6. It is observed that the specific energy consumption of the overall circuit first decreases and then increases, reaching the minimum value of 18.94 kWh·t$^{-1}$ when $T_{80}$ is 4.8 mm. This is consistent with the result obtained in section 3.2 that only at the $T_{80}$ of around 4.8 mm the SAG mill and the ball mill operate most efficiently at the same time. The corresponding circuit energy distribution is SAG mill 37.6%, ball mill 62.4%. If more energy is distributed to the SAG mill, its comminution energy efficiency will decrease. Similarly, the ball mill will run less efficiently if more energy is distributed to the mill.

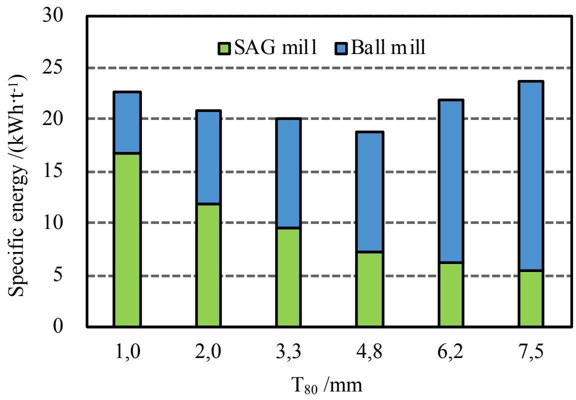


Fig. 6. Effect of circuit energy distribution on specific energy consumption of the SABC circuit

The relationship of the circuit energy distribution on comminution energy efficiency is shown in Fig. 7. The power split ratio between the SAG mill and ball mill is used to characterize the circuit energy distribution, and the comminution energy efficiency is represented by the BEF.

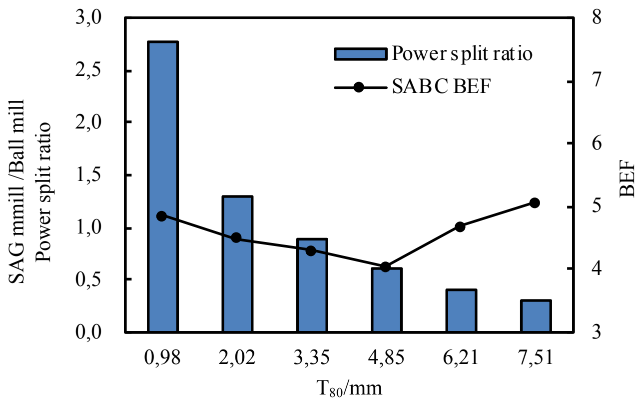


Fig. 7. Effect of SABC circuit 's energy distribution on comminution energy efficiency

The SAG mill/ball mill power split ratio shows a declining trend with the increase in $T_{80}$. The optimum SAG mill/ball mill power split ratio is found to be 6:10. At this point, the BEF of the SABC circuit is 4.05, indicating that the maximum energy efficiency of this circuit is approximately 25% when compared to the minimum practical energy required to carry out an equivalent comminution duty. The SABC circuit currently operates with the specific energy consumption of 20.11 kWh·t$^{-1}$ with the SAG mill/ball mill power split ratio of 9:10. Based on the present research results, an energy saving of 1.17 kWh·t$^{-1}$ can be achieved through the optimization of circuit energy distribution. The Huckleberry mine operates with a daily tonnage of approximately 17,500 metric tons. The present study shows that the optimization of SABC energy distribution has the potential to reduce the daily power consumption of the mine operation by 20,475 kWh.

The optimal energy distribution status of a particular SABC circuit greatly depends on the hardness of the ores it processed. Usually, the designed SAG mill/ball mill power split ratio is determined based on 80 percentile of ore hardness variability (Bueno et al., 2015). However, this energy distribution may not always be the optimal in the long-term operation, especially for heterogeneous mine deposits. The presented method provides the possibility for a dynamic optimization of the energy distribution of SABC circuits.

## 4. Conclusions

This study provides an effective methodology to determine the optimal energy distribution of SABC circuits. The results show that the optimization of grinding circuit's energy distribution is able to reduce the daily power consumption of Huckleberry mine by 20,475 kWh. Future work is required to find out the relationship between ore hardness and the optimal circuit energy distribution.

It is found that the optimal energy distribution of an SABC circuit greatly depends on the breakage properties of the feed ore and the circuit operating parameters. The target SABC circuit achieves the highest energy efficiency when 37.6% of the total circuit energy is distributed to the SAG mill and 62.4% to the ball mill.

It is also demonstrated that the ball mill is more sensitive to the variation in circuit energy distribution than the SAG mill. The BEF of the SAG mill and ball mill within the target SABC circuit varies from 4.01–5.16 and 4.19–5.50, respectively.


### Acknowledgments

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### References


BALLANTYNE G., POWELL M., M. TIANG, 2012. *Proportion of energy attributable to comminution*. 11th AusIMM Mill Operators' Conference, Hobart, Tasmania.

BUENO, M., FOGGIATTO, B., LANE, G., 2015. *Geo-metallurgy applied in comminution to minimize design risks*. Proceedings International Conference on Autogenous and Semiautogenous Grinding Technology, Vancouver, Canada.

CASTILLO G.M., BISSUE C., 2011. *Evaluation of secondary crushing prior to SAG milling at Newmont's Phoenix operation*. Proceedings International Conference on Autogenous and Semiautogenous Grinding Technology. Vancouver, Canada.

FESTA A., PUTLAND B., SCINTO P.,2014. *Shedding light on secondary crushing*. SME Annual Meeting, , Salt Lake City, UT.

HADAWAY J.B., BENNETT D.W., 2011. *An overview of the design, construction, commissioning and early years of operation of the sag/ball mill grinding circuit at Phu Kham copper gold operation in Laos*. Proceedings International Conference on Autogenous and Semiautogenous Grinding Technology, Vancouver, Canada.

HART S., VALERY W., CLEMENTS B., REED M., SONG M., DUNNE R., 2001. *Optimization of the Cadia Hill SAG Mill Circuit*. Proceedings International Conference on Autogenous and Semiautogenous Grinding Technology. Vancouver, Canada.

HOGG R., FUERSTENAU D.W., 1972. *Power Relations for Tumbling Mills*. Trans. SME-AIME, 252, 418–432.

LIU H., 2014. *The laws of the energy distribution in Wushan SABC comminution circuit and the practical approach*. PhD Thesis. Beijing: University of Science and Technology Beijing.

MORRELL S., VALERY W., 2001. *Influence of feed size on AG/SAG mill performance*. Proceedings International Conference on Autogenous and Semiautogenous Grinding Technology. Vancouver, Canada.

HUKKI R.T., 1962. *Proposal for a solomonic settlement between the theories of von Rittinger, Kick, and Bond*. Trans. AIME 223, 403–408.

JANKOVIC A., VALERY W., 2002. *Mine to mill optimisation for conventional grinding circuits – a scoping study*. J. Min. Metall. 38 (1–4) A, 49–66.

MUSA F., MORRISON R., 2009. *A more sustainable approach to assessing comminution efficiency*. MINER ENG. 22, 593–601.

MORRELL S., 2011. *The appropriateness of the transfer size in AG and SAG mill circuit design*. Proceedings International Conference on Autogenous and Semiautogenous Grinding Technology, Vancouver, Canada.

NADOLSKI, S., KLEIN, B., KUMAR, A., DAVAANYAM, Z., 2014. *An energy benchmarking model for mineral comminution*. MINER ENG, 65, 178–186.

NADOLSKI, S., KLEIN, B., GONG, D., DAVAANYAM, Z., COOPER, A., 2015. *Development and application of an energy benchmarking model for mineral comminution*. Proceedings International Conference on Autogenous and Semiautogenous Grinding Technology, Vancouver, Canada.

SHI F., KOJOVIC T., 2007. *Validation of a model for impact breakage incorporating particle size effect*. Int. J. Miner. Process. 82, 156–163.

SHI F., KOJOVIC T., BRENNAN M., 2015. *Modelling of vertical spindle mills. Part 1: Sub-models for comminution and classification*. Fuel. 143, 595–601.

SHI F., 2016. *A review of the applications of the JK size-dependent breakage model Part 1: Ore and coal breakage characterization*. Int. J. Miner. Process. 155, 118–129.

VOGEL L., PEUKERT W., 2003. *Breakage behaviour of different materials – construction of a mastercurve for the breakage probability*. Powder Technol. 129, 101–110.

WANG, C., NADOLSKI, S., MEJIA, O., DROZDIAK, J., KLEIN, B., 2013. *Energy and cost comparisons of HPGR based circuits with the SABC circuit installed at the Huckleberry mine*. 45th Annual Canadian Mineral Processors Operators Conference, Ottawa, Canada.

WANG P., KOU J., SUN C., WANG C., ZHANG M., KYONGHUN R., 2015. *Operational evaluation of AG/SAG mills in China*. Proceedings International Conference on Autogenous and Semiautogenous Grinding Technology, Vancouver, Canada.