# Addition of MillPebs to a pelletizing grinding mill

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## Abstract

*MillPebs are grinding media ranging from 5 to 12 mm in size and produced by water granulation of molten steel. MillPebs were added to a 5.2-m-diam, 10.4-m-long grinding mill charged with 25-mm balls for processing iron oxide concentrate with a $D_{80}$ of 0.6 mm. A six-month test demonstrated that the addition of MillPebs promoted the production of fine particles. However, a reduction in the quantity of 25-mm balls associated with the charging of MillPebs reduced the rate of breakage of coarse particles.*

Key words: Grinding media, Pelletizing grinding mill, MillPebs

## Introduction

Tumbling ball mills are used to reduce the size of particles to liberate valuable minerals from gangue and/or to maximize the contact surface between the particles and a reacting environment. Grinding is a very energy-demanding process (Fuerstenau et al., 1995) that justifies work to optimize grinding mill operation and design to achieve a maximum throughput and/or size reduction at constant energy consumption.

The selection of grinding media size and shape has been recognized for decades as a potential avenue for maximizing grinding mill efficiency (Arentzen, 1993; McIvor, 1997). It is generally accepted that the larger the particles in a grinding mill feed, the larger should be the grinding media, while fine particle grinding is best achieved with small grinding media. Empirical formula (Dunn, 1982; McIvor, 1997; Rowland and Kjos, 1997) and simulation programs (Austin et al., 1984; Lo and Herbst, 1986; Martinovic et al., 1990; Concha et al., 1993; Napier-Munn et al., 1996) are available to assist in the selection of the optimum ball size to be charged in a mill, but trial and results analysis is the approach preferred by the plant operators.

This paper summarizes the results of a full-scale trial conducted at the pelletizing plant of the Compagnie minière Quebec Cartier, QC, Canada, to assess the potential of mixing small grinding media with the regular charge of a ball mill to obtain a finer ground product. The paper consists of three sections. The first section describes the pelletizing process and the second section reviews the population balance model used to assess the effect of the grinding media. The last section describes the results observed during the test.

## Process description and test work

The mill considered for the test is operated by the Compagnie minière Québec Cartier (Lévesque et al., 1979) pelletizing plant in Canada. The company operates a mine in Fermont in Northern Québec to produce the iron concentrate that is shipped by train to Port-Cartier, Québec for pelletizing.

**Pelletizing process.** The pelletizing process consists of four main steps. The iron oxide concentrate is ground to increase the particle specific surface and is mixed with additives. The mixture feeds rotating discs on which the particles agglomerate to form 10- to 12-mm-diameter pellets. The produced green pellets are heat treated in a furnace to achieve the mechanical and chemical properties required by the steel making plants. The general process is shown in Fig. 1.

**Grinding circuit.** The grinding circuit is shown in Fig. 1. The iron oxide concentrate from the mine is upgraded in a hydrostatic separator to remove silica and increase the iron content of the concentrate by 2% to 4%. The upgraded iron oxide is then combined with the classifier coarse fraction and feeds the grinding mill. The mill discharge is pumped back to the classifier whose overflow contains the fine iron oxide for pelletizing. The 5.2-m-diam, 10.4-m-long (17- by 34-ft) ball mill is charged with 25-mm chromium balls. The average circuit throughput is 200 t/h of upgraded iron oxide concentrate. The maximum mill power draught is 4,900 kW (6,500 hp). The mill rotation speed is 76.5% of critical speed. The slurry density of the mill discharge varies from 77% to 83% solids (w/w). The $D_{80}$s of the upgraded iron concentrate, mill

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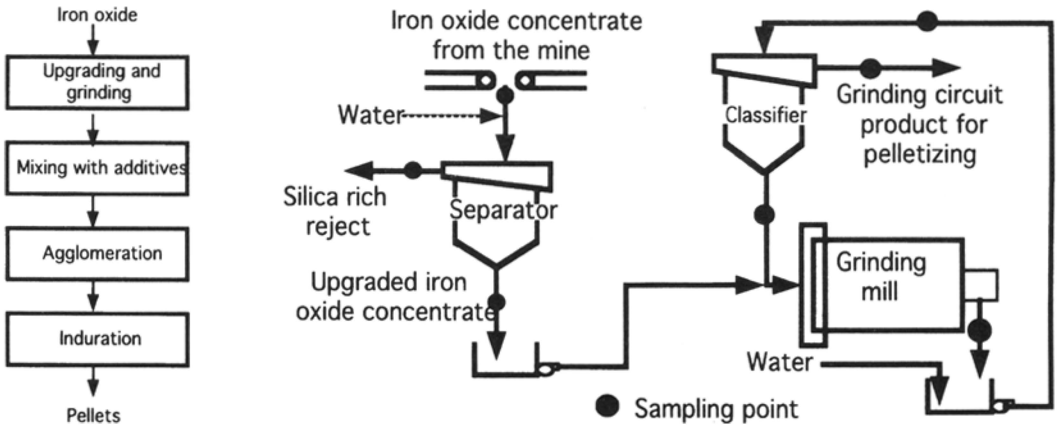


**Figure 1** — Pelletizing plant operations and grinding circuit.

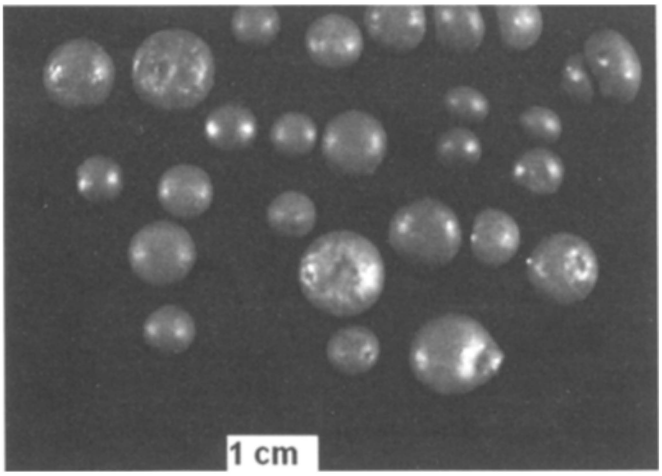


**Figure 2** — MillPebs charged in the grinding mill.

feed and discharge are 0.60, 0.40 and 0.15 mm, respectively. The final grinding circuit product has 55% to 65% passing 0.038 mm (400 mesh).

**Test work.** The study assesses the potential of replacing 20% of the current 25-mm make-up balls with 8- to 12-mm grinding media or MillPebs (Fig. 2) to increase the production of fine particles at no loss of throughput. The plant test was preceded by laboratory and pilot-plant tests to determine a target proportion of MillPebs in the grinding mill charge. Results of these tests indicated that the proportion of MillPebs should be adjusted to approximately 20% of the current mill grinding charge. Because any modification to a ball charge, especially for a large mill, takes a significant time to stabilize, the test was conducted over a six-month period.

Figure 3 shows the chronology of the test. Two sampling campaigns were conducted prior to the MillPebs addition and are used for comparison purpose. Following these preliminary sampling campaigns, the mill was shut down for changing the mill liners. The addition of the MillPebs began after the shut down. During the first month of the test, the proportion of MillPebs added to the mill was 80%. The purpose of the charging strategy was to rapidly increase the load of MillPebs in the mill. However, this strategy led to a deficiency in the 25-mm balls that are necessary for the breakage of large particles. The addition strategy was revised after one month of MillPebs addition to increase the 25-mm balls content in the mill. After three months of 25-mm balls and MillPebs addition, a sample of the mill steel charge yielded a concentration of 15% (w/w) of MillPebs. In addition to daily assessment of the mill operation and sampling of the mill steel charge, sampling campaigns were conducted on a monthly basis to collect the required data for the estimation of the particle breakage rates. The sampled streams are shown in Fig. 1. The slurry solids concentration, the size distribution and the iron and silica content of the collected samples were measured and balanced using a data reconciliation algorithm (Hodouin et al., 1985) to estimate the mill feed that cannot be sampled accurately.

## The population-balance model

The population-balance model (Austin et al., 1984) is a well-recognized approach to study (Cooper et al., 1994; Bazin and Lavoie, 2000) and simulate (Austin et al., 1984; Gupta et al., 1985; Napier-Munn et al., 1996) a grinding mill operation. Using the matrix notation, the size distribution of the mill discharge is linked to the mill feed size distribution by

$$p = Gf \tag{1}$$

where

$p$ and $f$ are matrix columns of the mill feed and discharge weight fractions retained within the considered size intervals and

$G$ is a matrix constructed using the ore breakage or appearance function, the residence time distribution of the particles within the mill and the selection or breakage rate function.

Details on the estimation of the $G$ matrix can be found elsewhere (Austin et al., 1984; Gupta et al., 1985). The effect of the MillPebs addition is studied through the breakage-rate function.

The appearance function characterizes the distribution of the fragments produced by a breakage event in a grinding mill and could be determined by laboratory grinding tests (Austin et al., 1985) or, as discussed more recently, using impact tests (Napier-Munn et al., 1996) to determine the effect of the impact energy on the fragment distribution.

In this investigation, the appearance function is estimated from laboratory grinding tests and adjusted using plant test results to account for the change of scale from the laboratory to the plant. The residence time distribution is estimated using tracer tests conducted on the full-scale mill. Several discussions on the technique used are available in the litera-

**Table 1** — Sampling campaign general results.

| Condition | Campaign | Upgraded concentrate flow rate, t/h | Circulating load % | $D_{75}$ of mill Feed % | $D_{75}$ of mill Discharge % | $D_{80}$ of mill Feed, mm | $D_{80}$ of mill Discharge, mm | Grinding circuit product $P_{37}$, % | Grinding circuit product Blaine |
|---|---|---|---|---|---|---|---|---|---|
| Prior to addition | 0* | 212 | 268 | 22.7 | 58.5 | 0.38 | 0.14 | 62.3 | 1,762 |
| One month of addition | 1 | 193 | 317 | 21.9 | 53.0 | 0.39 | 0.18 | 64.6 | 1,790 |
| Two months of addition | 2 | 215 | 343 | 30.6 | 59.4 | 0.40 | 0.18 | 69.0 | 1,880 |
| Three months of addition | 3 | 209 | 287 | 13.5 | 46.4 | 0.39 | 0.19 | 61.1 | 1,584 |
| Four months of addition | 4 | 201 | 297 | 13.2 | 43.9 | 0.40 | 0.17 | 53.7 | 1,538 |
| Three weeks after last add.. | 5 | 210 | 319 | 14.3 | 48.3 | 0.39 | 0.15 | 59.2 | 1,604 |

*Average of two sampling campaigns

ture (Laplante and Redstone, 1983; Austin et al., 1984).

The selection function gives the rate of breakage of the various particle sizes in a grinding mill. Typical breakage rate functions are shown in Fig. 4. The breakage rates produced in a grinding mill increase with particle size up to a maximum value and then decrease for coarser particles. The size of the grinding media influences the position and shape of the breakage rate function. Small grinding media are favorable for the breakage of fine particles but are less efficient for coarse particles, while the trend is reversed for large grinding media. The breakage rates for a given mill are estimated using the mill feed and product size distributions obtained from sampling campaigns conducted during steady state operation of the grinding circuit. The estimation of the breakage rates is described elsewhere (Austin et al., 1984; Gupta et al., 1985).

Figure 4 provides the background for the test. The mill considered for the test should produce the finest size distribution from a fairly coarse particle feed size distribution and, therefore, be efficient for coarse particle breakage as well as for the production of fine particles. If the 25-mm grinding balls are efficient for coarse particles, they are less efficient for the production of fine particles from the broken fragments. The original 25-mm make-up balls may abrade to produce smaller balls, but below 15 mm the spherical shape shifts to ellipsoidal shape and then flat chips that are probably inefficient for grinding. Although mixtures of different make-up ball sizes are used by some operations (McIvor, 1997), it remains that the estimation of the optimum mixture of make-up media is a complex task because of the large number of possible combinations and the time required to stabilize the mill charge. Although mixtures of ball sizes were considered in the past, few papers reported attempts of replacing large grinding media by round media of the size of the steel chips. In practice, large grinding balls are separated from smaller media by compartments (Benzer et al., 2001; Wickens et al., 2003) or kept in separated mills, such as regrind mills (Cooper et al., 1994). The idea of mixing MillPebs with the 25-mm balls assumes that the MillPebs will fill the interstices between the balls and increase the abrasion action associated with the movement of the charge.

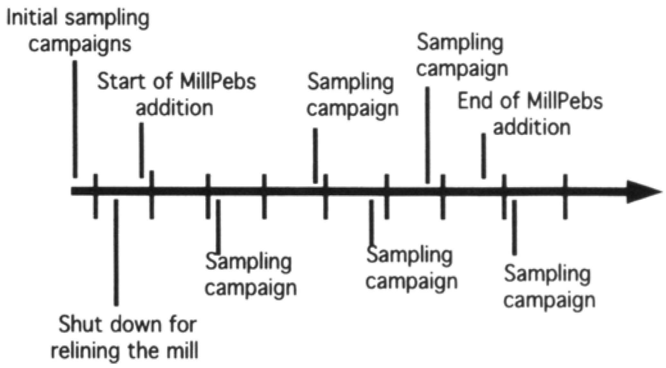


**Figure 3** — Chronology of the test work.

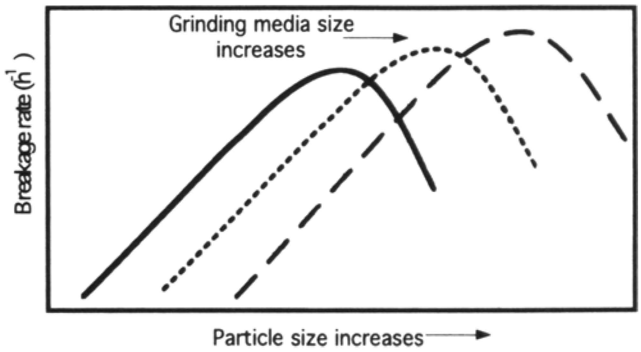


**Figure 4** — Breakage rate functions.

## Results of the test

The test results are discussed in terms of mill throughput, mill feed and discharge size distributions, breakage rates and operating problems observed during the trial.

**General results.** Results of sampling campaigns conducted during the test are summarized in Table 1. The first two sampling campaigns were conducted prior to the MillPebs addition, and the other sampling campaigns were conducted every month following the beginning of the additions. The last sampling campaign was carried out three weeks after the last MillPebs addition. No parallel Bond grinding tests were conducted to assess ore hardness variation during the test period, but in practice the iron oxide concentrate exhibits a fairly constant hardness. The circuit throughput varied between 190 and 215 t/h. Except for Campaign 1, the circuit throughput did not change significantly following the MillPebs addition. The low throughput associated with Campaign 1 is due to the deficiency of 25-mm balls following the aggressive addition of MillPebs with little charging of 25-mm balls at the beginning of the test. The circulating load in the grinding circuit increased following the addition of the MillPebs and remained high for the last sampling campaign conducted with

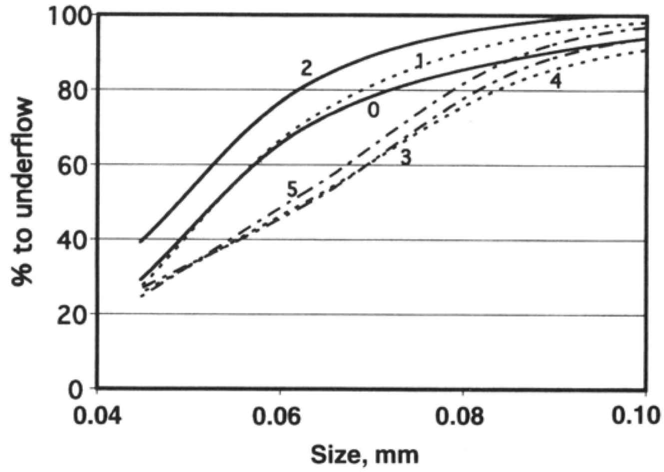


**Figure 5** — Hydrostatic classifier efficiency curves. (Numbers correspond to sampling campaigns.)

**Table 2** — Estimated power normalized breakage rates (t/kW-h).

| Mean geometric size, mm | Sampling campaign* | | | | | |
|---|---|---|---|---|---|---|
| | 0 | 1 | 2 | 3 | 4 | 5 |
| 2.022 | 1.545 | 0.548 | 0.736 | 0.809 | 0.966 | 1.528 |
| 1.430 | 1.063 | 0.432 | 0.556 | 0.617 | 0.709 | 1.056 |
| 1.011 | 0.732 | 0.340 | 0.421 | 0.470 | 0.521 | 0.730 |
| 0.715 | 0.505 | 0.268 | 0.318 | 0.358 | 0.382 | 0.505 |
| 0.505 | 0.348 | 0.211 | 0.240 | 0.273 | 0.281 | 0.349 |
| 0.357 | 0.240 | 0.166 | 0.182 | 0.208 | 0.206 | 0.241 |
| 0.253 | 0.166 | 0.131 | 0.137 | 0.159 | 0.151 | 0.167 |
| 0.179 | 0.114 | 0.103 | 0.104 | 0.121 | 0.111 | 0.115 |
| 0.126 | 0.079 | 0.081 | 0.079 | 0.092 | 0.082 | 0.080 |
| 0.089 | 0.055 | 0.064 | 0.059 | 0.070 | 0.090 | 0.055 |
| 0.063 | 0.038 | 0.050 | 0.045 | 0.054 | 0.044 | 0.038 |
| 0.045 | 0.026 | 0.040 | 0.034 | 0.041 | 0.032 | 0.026 |

* 0: Prior to MillPebs addition
5: Three weeks after last addition

a low content of MillPebs since the addition was stopped three weeks before the sampling campaign.

During the trial, the mill feed $D_{80}$ remained fairly constant at 0.38 mm while the mill discharge $D_{80}$ increased from 0.14 to 0.18 mm. The percentage passing 0.075 mm ($P_{75}$) in the mill feed changed from 22.0% to 14.0%, which caused a decrease in the $P_{75}$ of the mill discharge from more than 57% to 48%. The percentage passing 400 mesh in the final grinding circuit product and the specific surface index (Blaine) varied erratically during the test making it difficult to analyze the effect of the MillPebs on the grinding mill operation.

The classifier separation curves are shown in Fig. 5 and characterize the operation of the classifiers during the test period. In Fig. 5, only the fine particle sizes are shown because the classifier efficiency for particles larger than 0.1 mm is close to 100%. Sampling Campaigns 3 through 5 exhibit a larger $d_{50}$ than the initial sampling campaigns, which could explain the decrease in the $P_{75}$ observed in Table 1. The change of behavior in the classifier operation could be attributed to a modified operating strategy or a temperature effect (Kawatra and Eisele, 1988), because the later campaigns were conducted during the cold season. This result shows that the classifier operation has influenced the circuit operation, and to isolate the effect of the MillPebs it is necessary to estimate the grinding-mill particle-breakage rates.

**Breakage-rate functions.** The breakage rates in the grinding mill are estimated in metric tons per hour (t/h) and divided by the mill power drawn to obtain the breakage rates expressed in metric tons per kilowatt-hour (t/kW-h) for each size interval. Results are given in Table 2. The mill breakage rates observed one month after the first MillPebs addition (Campaign 1) show a significant decrease for the coarse particles due to the deficiency of 25-mm balls in the grinding media charge. On the other hand, the breakage rates for particles finer than 0.1 mm show the increase expected from the theory (Fig. 4). Following this observation, the charging sequence was modified to add the target 20% MillPebs and 80% 25-mm balls. This modification led to an improvement in the breakage of the coarse particles without a significant loss in the breakage rate of fines. Campaigns 3 and 4 continue to show improvement in the coarse particle breakage rates with fine particle breakage rates still above the initial campaigns breakage rate, noted as "0" in Table 2. The breakage rates observed three weeks after the last MillPebs addition fall very close to the initial breakage rates, confirming that the MillPebs have probably been completely evacuated from the mill.

Figure 6 shows the evolution of the ratio of the power normalized breakage rates observed after the MillPebs addition and shows the breakage rates estimated from the sampling campaigns conducted prior to the addition, i.e.

$$R_i = 100\frac{S_{p;i}(k)}{S_{p;i}(0)} \qquad (2)$$

where

$S_{p;i}(k)$ is the power normalized breakage rates for size interval $i$ and sampling campaign $k$.

A ratio larger than 100% indicates an increase in the breakage rates relatively to the pre-MillPebs operation. The normalized breakage rates for sampling Campaign 0 correspond to the average rates for the two sampling campaigns conducted prior to the MillPebs addition. Results show that the addition of MillPebs increases the breakage rate of fine particles. However, to maintain a constant steel load in the mill, it is necessary to reduce the addition of larger balls that negatively impact the breakage rates of coarse particles. It is possible that fine-tuning of the make up grinding media could allow one to maintain acceptable grinding rates for coarse particles while improving the breakage rates of fine particles. Such tuning would require a much longer test program than this study or would require the assistance of powerful simulators that could simulate the mill operation as a function of the grinding media size distribution predicted by a model for the grinding media wear.

**Appearance functions.** The estimation of the breakage rates implies the estimation of the appearance function of the ore. Laboratory tests were initially conducted to estimate the appearance function of the iron oxide concentrate, and the estimated laboratory function was adjusted to account for the change of scale from the laboratory to the plant grinding mill. The results in Table 3 show that the appearance function remains fairly constant despite the time frame of the study and the introduction of MillPebs into the grinding mill. This invariability is rather surprising because the estimation technique provides sufficient freedom to allow changes in the appearance function. This may indicate that for a given mill, changes in the operating conditions could have little impact on the appearance function.

**Operating considerations.** Results of the test show that the replacement of more than 15% of the mill charge by MillPebs did not deteriorate the operation of the mill, as long as a constant addition of large grinding media is maintained to ensure an efficient breakage of coarse particles. The test was ambitious, as small grinding media are usually separated from the coarser ones. However, this preliminary test shows that this option is probably viable and could improve grinding mill efficiency, provided that the correct make-up mixture is identified by plant tests or simulation studies.

Some of the larger sizes of MillPebs exhibit an ellipsoid shape, which is believed to be less efficient for grinding and less resistant to wear than a spherical shape. MillPebs are also sensitive to the flow of slurry, which carries them out of the mill. A relationship between this undesirable entrainment of unworn MillPebs out of the mill, the slurry rheological properties and the flow of slurry through the mill has not yet been established, but would allow for a feasibility analysis prior to a full-scale trial to avoid a situation for which the MillPebs would flow rapidly out of the mill. Ongoing research and development projects aim at improving the quality of the MillPebs and identifying conditions of efficient applicability to industrial mills.

## Conclusion

A full-scale trial of charging a mixture of regular 25-mm balls and 8- to 12-mm grinding media, or MillPebs, demonstrated that more than 15% of the regular ball charge could be replaced by the smaller grinding media without a dramatic loss in production. The addition of the mixture produces a reduction in the breakage of coarse particles with an increase in the breakage of fine particles, as expected from the current understanding of grinding mill operation. The analysis of breakage rates provides an efficient way to evaluate the mill operation itself, excluding external effects due to a change of feed size distribution or classifier operation.

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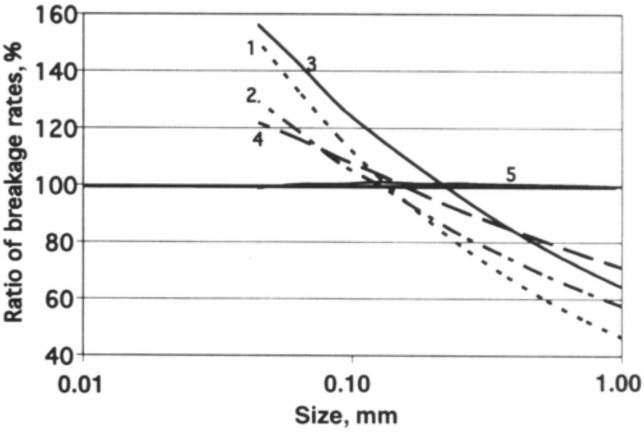


**Figure 6** — Ratio of breakage rates following MillPebs addition. (Numbers correspond to sampling campaigns.)

**Table 3** — Estimated appearance functions.

| Interval top size, mm | Sampling campaign 0 | 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|---|---|
| 1.700 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 | 100.0 |
| 1.202 | 76.6 | 74.7 | 78.9 | 71.3 | 72.2 | 72.0 |
| 0.850 | 58.8 | 55.9 | 62.3 | 50.8 | 52.1 | 51.8 |
| 0.601 | 45.1 | 41.8 | 49.2 | 36.2 | 37.6 | 37.2 |
| 0.425 | 34.6 | 31.2 | 38.8 | 25.8 | 27.2 | 26.8 |
| 0.301 | 26.5 | 23.3 | 30.6 | 18.4 | 19.6 | 19.3 |
| 0.213 | 20.4 | 17.4 | 24.2 | 13.1 | 14.2 | 13.9 |
| 0.150 | 15.7 | 13.0 | 19.1 | 9.3 | 10.2 | 10.0 |
| 0.106 | 12.0 | 9.7 | 15.1 | 6.6 | 7.4 | 7.2 |
| 0.075 | 9.3 | 7.3 | 11.9 | 4.7 | 5.3 | 5.2 |
| 0.053 | 7.1 | 5.4 | 9.4 | 3.4 | 3.9 | 3.7 |
| 0.038 | 5.5 | 4.1 | 7.4 | 2.4 | 2.8 | 2.7 |

## References

Arentzen, C., 1993, "Grinding Takes less Energy with the Right «Grinding Ball» Charge," *Chemical Engineering*, Vol. 100, No. 1, pp. 15-16.

Austin L.G., Klimpel, R.R., and Luckie, P.T., 1984, *Process Engineering of Size Reduction: Ball Milling*, Society of Mining Engineers, New York.

Bazin, C., and Lavoie, G., 2000, "Ball mill rotation speed and rate of particle breakage: Application to a full scale unit," *Trans. Inst. Min. Metall. (Sect C)*, Vol. 109, Nov.-Dec., pp. C161-C164.

Benzer, H., Ergun, L., Oner, M., and Lynch, A.J., 2001, "Simulation of open circuit clinker grinding," *Minerals Engineering*, Vol. 14, No. 7, pp. 701-710.

Concha, F., Magne L., and Austin, L.G., 1993, "Optimization of the make-up ball charge in a grinding mill," *Int. J. Miner. Process.*, Vol. 34, pp. 231-241.

Cooper, M., Bazin, C., and Grant, R., 1994, "Evaluation of grinding media at Brunswick Mining," *CIM Bull.*, Vol. 87, No. 985, pp. 73-76.

Dunn, D.J., 1982, "Selection of liners and grinding media for comminution circuits - Case studies," *Design, Installation of Comminution Circuits*, A.L. Mular and G.V. Jergensen, eds., SME, Littleton, Colorado, pp. 973-985.

Fuerstenau, M.C., Chi, G., and Bradt, R.C., 1995, "Optimization of energy utilization and production costs in mining and ore preparation processes," *Proceedings of the XIX Intern. Mineral Process. Congress*, Vol. 1, San Francisco, SME, Littleton, pp. 161-170.

Gupta, V.K., Hodouin, D., and Spring, R., 1985, "Kinetic ball mill model: Parameter estimation," *The SPOC Manual*, Chapter 7.2, Energy, Mines and Resources, Canada.

Hodouin, D., and Everell, M.D., 1985, "A hierarchical procedure for adjustment and material balancing of mineral processing data," *Int. J. Miner. Process.*, Vol. 7, No. 2, pp. 91-116.

Kawatra, S.K., and Eisele, T.C., 1988, "Rheological effects in grinding circuits," *Int. J. Miner. Process.*, Vol. 22, pp. 251-259.

Laplante, A.R., and Redstone, J., 1984, "Modeling of grinding kinetics at the Sidbec-Normines Port Cartier Pelletizing plant," *Minerals and Metallurgical Processing*, Vol. 1, No. 2, pp. 143-149.

Lévesque, R., Poirier, Y., Morin, G., and Lemay, A., 1979, "Sidbec-Normines Inc. et la production de boulettes à basse teneur en silice et de boulettes à hauts-fourneaux à Port-Cartier," *CIM Bulletin*, Vol. 72, No. 806, pp. 129-136.

Lo, Y.C., and Herbst, J.A., 1986, "Consideration of ball size effects in the population balance approach to mill scale-up," *Advances in Mineral Processing*, SME/AIME, P. Somasundaran, ed., New Orleans, pp. 33-47.

Martinovic, T., Herbst, J.A., and Lo, Y., 1990, "Optimization of regrinding ball mills at Carol Pellet Plant of the Iron Ore Company of Canada," *Control 90*, R.K. Rajamani and J.A. Herbst, eds., SME, Littleton, Colorado, pp. 223-231.

McIvor, R.E., 1997, "The effect of media sizing on ball mill efficiency," *Comminution Practices*, S.K. Kawatra, ed., SME, Littleton, Colorado, pp. 279-292.

Napier-Munn, T.J., Morrell, S., Morrison, R.D., and Kojovic, T., 1996, *Mineral Comminution Circuits: Their Operation and Optimisation*, JKMRC Monograph Series, The University of Queensland, Australia.

Rowland, C.A., and Kjos, D.J., 1997, "Rod and ball mills," *Comminution Practices*, S.K. Kawatra, ed., SME, Littleton, Colorado, pp. 319-338.

Wickens, J., Pekrul, J., and Cole, A., 2003, "Grinding circuit improvements at Barrick Goldstrike's roaster facility," in *Proceedings 35th Annual Meeting of the Canadian Mineral Processors*, January, Ottawa, pp. 71-83.