ENERGY SAVINGS AND TECHNOLOGY COMPARISON USING SMALL GRINDING MEDIA

M Brissette[1]

ABSTRACT

Considering the complexity of minerals, the need for finer grinding is increasing along with the energy cost. However, energy is increasing exponentially when grinding finer with conventional grinding balls. The use of small grinding media represents the best potential to improve energy efficiency. Today, it is possible to use grinding media as small as 1 mm. How do they perform in industrial grinding mills?

The use of small grinding media (5 - 12 mm), called Millpebs, in regrind mills proved that finer grinding can be achieved at lower energy consumption. In ball mills, energy savings vary from 10 per cent to 40 per cent compared to 25 mm media. A regrind ball mill with a mix of small grinding media can be as energy efficient as an Isa Mill charged with 2.5 and 3.5 mm beads. In vertical stirred mills, energy savings vary from 30 per cent to 60 per cent. To carry out the same final grind, a vertical stirred mill with Millpebs will consume at least 60 per cent less energy than a ball mill using 25 mm grinding media. More potential savings were identified.

To achieve those improvements, some operating conditions must be met: 1) feed size should be less than 250 µm; 2) the pulp must be fluid enough; 3) finally, the slurry linear velocity should not be excessive. This paper talks about all those industrial results improvement and operating conditions.

Keywords: fine grinding, small media, energy savings, vertical stirred mill, ball mill

INTRODUCTION

In some mining applications, fine grinding is needed to liberate further the valuable mineral(s). In part because of high prices of small grinding media as well as availability, the most widely used size of grinding ball is 25 mm or bigger. As mentionned by various authors (Jankovic, Valery and La Rosa, 2003; Gao and Holmes, 2007), conventional ball milling was discarded because of its very poor energy efficiency caused by those larger balls. Therefore, new technologies as stirred mills were developed to grind finer more efficiently.

When calculating the recommended top size ball from Bond's formula (1961) for regrind ball mill applications, the required size is less than 25 mm. For the vertical stirred mill, no formula exists to precise which media size to use. As mentionned by McIvor (1997) and Nesset *et al* (2006), the media size is the most important variable affecting the mill efficiency.

As explained by Jankovic (2003), the definition of fine grinding varies from one industry to another. For the mining industry, the conventional ball milling can grind to a final product of 80 per cent passing 75 µm. Regrinding is considered when the final grind is 30 µm and fine grinding at 10 µm. Below that value, the term ultra fine grinding is used. Today, many workers (Pease *et al*, 2006a; Ayers, Knopjes and Rules, 2008; Burford and Niva, 2008) are extending the ultra fine grinding technology to fine grinding and regrind applications.

What is more important? The grinding technology, the size of grinding media or both? This paper resumes industrial results comparison of using smaller media into existing technologies.

OPERATING CONDITIONS FOR SMALL MEDIA

During first attempt of using small media (4 - 8 mm), Jankovic (2008) reported that high flow rates and high slurry densities have caused the discharge of those small media from an 800 HP Vertimill. Bazin (2004) has reported the same phenomena in ball milling. Since, Wheelabrator Allevard has conducted and supervised more closely many industrial trials. After investigation, it was found that small media can stay in the mill when some operating criteria are met.

1. Grinding Process Specialist, Wheelabrator Allevard, 201-7272 boul. Maurice-Duplessis, Montréal, Québec H1E 6Z7, Canada. Email: mbrissette@waenam.com

Pulp density

Table 1 shows that the ejection of small media, monitored at many plant sites, depends mainly on pulp density, expressed in percentage solids by weight. A difference of 2 per cent to 4 per cent is enough to cause the discharge of the media. Below a critical value, the small media are staying in the mill. Diluting the pulp with water at mill's inlet stops the ejection rapidly.

TABLE 1

Pulp density value causing discharge of small media in ball mills.

% Solid by weight	Goldstrike tertiary	QCM regrind	IOC regrind	Duck pond secondary
Ore type	Au	Fe	Fe	Cu-Zn-Pb
Millpebs ejected	67%	81%	78%	78%
No ejection	64%	77%	76%	76%

Ball fraction of mill volume

Table 2 shows that for nearly the same filling, measured physically, the mill power with smaller media is significatively reduced. Therefore, if the power is kept on target when adding small media, the charge will increase and may cause mill's overcharging, specially if the charge is already at the trunnion level. One should be careful to reduce the power target when converting a charge from larger to smaller grinding media.

TABLE 2

Power reduction in ball mills using small media at the same charge volume of 25 mm balls.

Mine	Gold-copper mine		Brunswick			
Mill type	Regrind		Secondary		CuPb regrind	
Media	30 mm	Millpebs	25 mm	Millpebs	25 mm	Millpebs
Volume fraction	16.5%	16.7%	33.0%	30.4%	36.8%	37.4%
Power	50 Amp	41 Amps	900 kW	630 kW	550 kW	470 kW

Flow rate

There is a limit on the flow rate of slurry that a ball mill can handle, specially when processing extremely high tonnage. McIvor (1990) recommends that the linear velocity of slurry in a ball mill should be less than 5 m/min to avoid mill overloading and balls be washing out of the mill. So far, small media have stayed in industrial mills for velocities up to 3.3 m/min when operating at the proper pulp density.

Small media were introduced in one 800 HP and two 1250 HP Vertimills without any media discharge incident. As shown in Figure 1, feed rate of one of the 1250 HP was as high as 830 TPH with a pulp density varying between 40 per cent and 60 per cent solids by weight.

To be noted that the reduction ratio calculated at the mill is almost constant above 400 TPH regardless of the ball size (Millpebs, 12 mm and 25 mm), the ore type (Cu-Mo vs Zn-Pb ore) and the feed size (below 140 µm versus above 350 µm). This can be easily explained by an extremely low residence time. It might also indicate that the equipment's capacity is exceeded. When grinding is not needed, it is an excellent solution for creating surface, commonly called refresh milling.

Feed size

The most important parameter to determine the required size of grinding media is the feed size. In Figure 2, the specific breakage rate was calculated by Bazin, Parent and Chevalier (2004) and Bazin (2008a) for two industrial ball mills. The specific breakage rate of Millpebs are higher than the 25 mm media when the particle size is less than 250 µm regardless of the ore type (Fe and Cu-Zn-Pb), the Bond Index (12 and 23 kWh/t) and Millpebs' proportion (20 per cent and 100 per cent).

The selection of the ball size is already summarised by McIvor (1997). Table 3 shows that energy efficiency is improved from 10 per cent to 40 per cent when Bond is recommending balls smaller than 12 mm and the feed size is less than 150 µm.

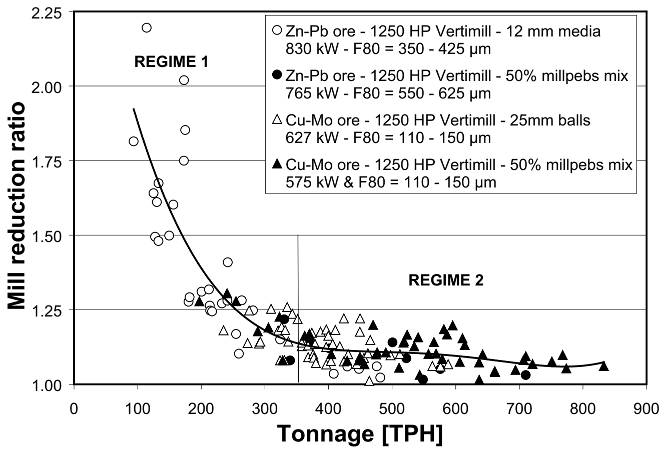

FIG 1 - Influence of feed rate on mill reduction ratio in 1250 HP Vertimills.

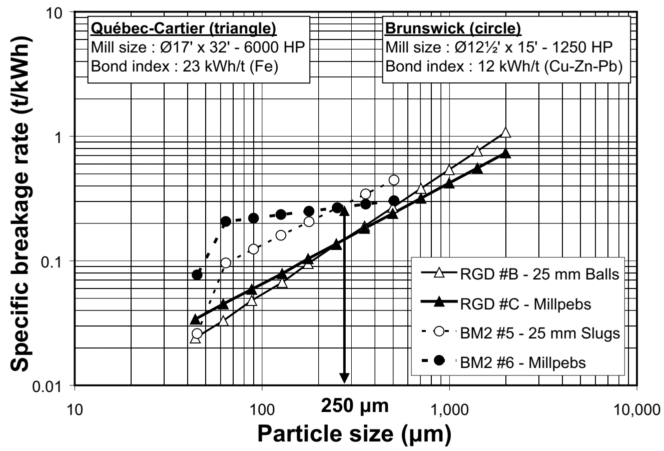

FIG 2 - Specific breakage rate of Millpebs versus 25 mm media in ball mills.

SMALL MEDIA IN INDUSTRIAL MILLS

When all three operating criteria are met and the feed size is appropriate, small media can be added to the mill to reduce energy consumption or grind finer. The most common methodology to evaluate grinding efficiency is the Operating Work Index (Bond, 1961). A second method is to calculate the breakage rate using the perfect mixing ball mill model but it does not take into account the mill's power. That variable is introduced in the specific breakage rate, expressed in t/kWh (Bazin, 2008a).

For small mines, resources are sometimes limited to perform extensive surveys. The feed rate in regrind circuit is rarely measured and much often, unknown. It is much easier to monitor the P80 of the cyclone overflow and adjust the mill's power accordingly. No extra resources are needed and existing production data can be used. When multiples mills are operating in parallel, the power of

TABLE 3

Energy efficiency improvement in ball mills with small media.

Application	Ore Type	BWI kWh/t	F80 µm	Bond Ball Top Size	% Millpebs	Energy Savings	Finer Grind
Secondary ball mill	Cu-Zn-Pb	12.0	93	8 mm	100%	-36%	Same
Regrind ball mill	Cu-Pb	12.0	30	5 mm	100%	-37%	Same
Regrind ball mill	Cu-Zn-Pb	10.0	40	5 mm	100%	-40%	Same
Regrind ball mill	Au-Cu	9.5	90	6 mm	100%	-39%	Same
Regrind ball mill	Au	18.0	130	8 mm	30%	-10%	+5%
Regrind ball mill	Cu	N/A	130	N/A	30%	-15%	+10%
Secondary ball mill	Fe	N/A	125	N/A	30%	-15%	Same

the mill containing the tested media is adjusted to have both the same discharge product. All regrind process flowsheets are available in previous papers (Brissette, 2009a; 2009b).

Ball mill

Case 1 – secondary and regrind ball mills in copper-zinc-lead mine

The choice of grinding media size to achieve fine grinding efficiently in the range of 15 to 25 µm has always been a concern at Brunswick Mine (Staples *et al*, 1997). Because the recommended Bond size of 8 mm was considered below practical limits, the use of a corrected make up size formula by Azzaroni (1981) and breakage function were chosen as methodology to optimise ball sizing. Cooper *et al* (1993) chose the 25 mm slug because they were more cost effective than balls even if Herbst and Lo (1989) demonstrated that balls are generally 10 per cent to 15 per cent more efficient than conical shape (slugs).

Because the K80 of the cyclone underflow was 112 µm for the secondary ball mills and 44 µm for the CuPb regrind mill, a charge of 100 per cent Millpebs was tried in one mill of both grinding circuits. Bazin (2008a; 2008b) showed that power was reduced by 36 to 37 per cent in both cases to achieve the same grind product.

Case 2 – regrind ball mill in gold-copper mine

Flotation laboratory test demonstrated that if the grind target was changed from 40 µm to 20 µm, more gold would be liberated. The idea was to test different sizes of grinding media to get the best grinding efficiency.

In Table 4, the 19 mm and the 25 mm slugs led to the same gold rejection of 1.90 gr/ton at the cleaners tails as the 30 mm balls (Brissette, 2009a). It shows that all those media sizes were not efficient enough to grind finer. When the mill was shutdown for almost one month, the gold rejects increased to 2.69 gr/ton. Therefore, the regrind mill was necessary to improve gold recovery.

TABLE 4
Industrial results of Millpebs in a regrind ball mill of a Au-Cu mine.

Parameter	Unit	Balls	Millpebs			Slugs		No
		30 mm	5 - 12 mm			19 mm	25 mm	Regrind
Motor amperage	Amp	50	41	36	31	50	50	-
Filling degree	%	16.5%	16.7%	14.7%	10.9%	N/A	N/A	-
Overflow P80	µm	43	27	41	42	N/A	N/A	N/A
Overflow Blaine	cm^2/gr	2015	4713	3096	2116	N/A	N/A	N/A
Cleaner tail Au	gr/t	1.91	1.14	1.42	1.77	1.85	1.85	2.69

The best result was achieved with Millpebs when the P80 of the cyclone overflow was 27 µm. At lower charge, the gold contents at cleaners tail were still lower for nearly the same P80 as the 30 mm balls. In fact, the particle size distribution from the small media contained more fines, better measured by the Blaine number. Commonly used in the cement and the iron ore mining industries, the Blaine measures the ore's particle surface per unit of weight in cm^2/g. The lower gold content of the cleaner's tailing was directly linked to the higher amount of fines.

Vertical stirred mill

Case 3 – regrind mill in copper-molybdenum mine

To decrease the grinding cost, a mix of 50 per cent Millpebs and 50 per cent 25 mm balls were introduced in one of the two parallel vertical mills. The average power draw was 625 kW with a mill's throughput varying between 270 TPH and 650 TPH. The tonnage was calculated from a flow and density meter installed at the outlet of each feed pump.

When all the operating parameters taken at the mill are combined together (kW, TPH, F80 and P80) in Figure 3, the Millpebs mixture requires much less energy (1.0 kWh/t vs 1.6 kWh/t) to obtain the same reduction ratio as the 25 mm balls. When both mills were operating at the same power,

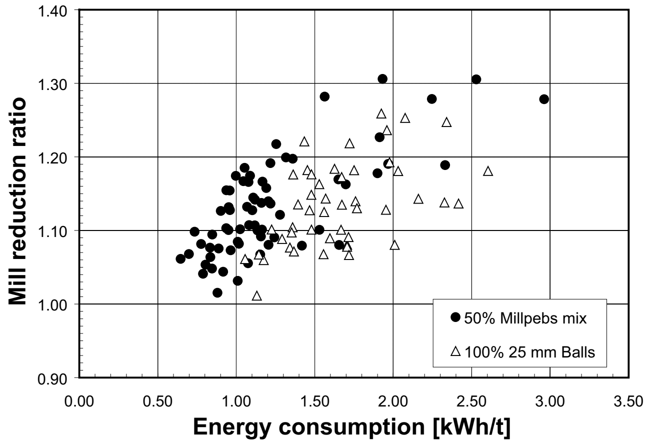

FIG 3 - Energy consumption versus the mill reduction ratio.

the mill containing the Millpebs mix was performing with a 31 per cent higher throughput (498 vs 380 TPH).

Case 4 – regrind mills in copper-gold mine

A new charge of Millpebs was entirely introduced into a 800 HP Vertimill by Brissette (2009a) to replace the existing 25 mm balls charge. In Table 5, power was reduced by 33 per cent to have the same grind of 75 per cent passing on 44 µm at the cyclone overflow. However, the surprise come from the fact that having a coarser grind of 53 per cent passing on 44 µm was leading to the same grade in the final concentrate with higher gold recovery. Total energy savings was 61 per cent. Being even coarser was decreasing gold recovery. However, further investigation is needed to better understand what happened.

TABLE 5

Industrial results of Millpebs in a 800 HP Vertimill of a Cu-Au mine.

Media		25 mm	Millpebs		
Number of days		31	6	7	10
Power	kW	588	395	225	185
Energy consumption	kWh/t	2.22	1.49	0.85	0.70
% 44 µm at overflow	%	75.4	74.3	53.4	42.8
Final Cu concentrate grade	%	31.1	30.9	30.9	30.4
Gold recovery	%	72.9	68.0	77.9	63.7

INDUSTRIAL TECHNOLOGY COMPARISON WITH SMALL MEDIA

Ball mill versus vertical stirred mill

No industrial ball mill was ever replaced by a vertical stirred mill in the past. In the previous case, the mine is operating two production lines having both similar primary grinding and flotation capacity. The difference resides in the regrind mills. A 2500 HP ball mill was installed in the first production line when the concentrator was initially built and a 800 HP Vertimill was installed in the second line when the concentrator capacity was increased. Both mills were using 25 mm balls with similar operating conditions (265 TPH at 75 per cent -44 µm) with the same ore.

Figure 4 shows that with 25 mm balls, the 800 HP Vertimill is drawing 44 per cent less power than the ball mill (587 kW vs 1045 kW). This value corroborates with previous studies of Stief, Lawruk and Wilson (1987) and more recently, Nesset *et al* (2006). Since, the ball mill was replaced by a second Vertimill of 1250 HP and commissioned with 25 mm balls. Surprisingly, that mill is performing like the 800HP Vertimill with Millpebs. More saving can be expected when small media will be added in the newer 1250 HP Vertimill.

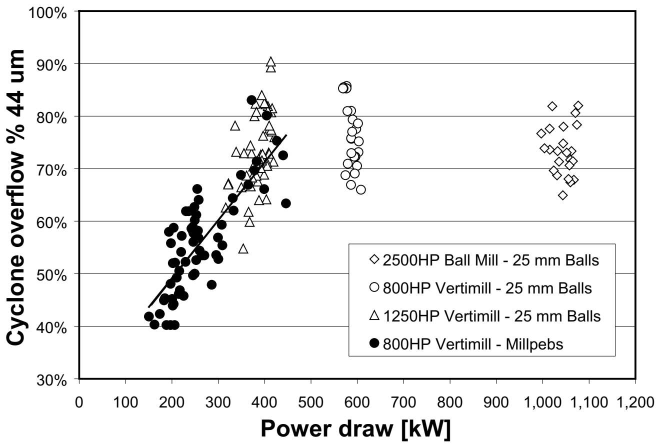

FIG 4 - Power Comparison between mill technology and media sizing.

Ball mill versus ISA mill

In March 2006, extensive maintenance was conducted on the 4.1 MW regrind ball mill at Kumtor Gold Mine of Centerra Gold, located in Kyrgyz Republic. To continue production, the IsaMill was used instead during four weeks for a coarser grind duty: the F80 was 135 µm instead of 20 µm. Although results were inconclusive because of different product size, Pease *et al* (2006a) and Shi *et al* (2008) showed some potential for this technology in regrind applications because the energy efficiency decreased from 40 kWh/t with a P80 of 18 µm to 24 kWh/t for a P80 of 60 µm. No optimisation was conducted although the media appeared too fine for this coarser duty.

In October 2008, Millpebs were introduced by Brissette (2009b) in Kumtor regrind mill in order to provide a finer feed (>90 per cent – 20 µm) to the IsaMill. Tonnage is directly measured at the regrind cyclone overflow feeding the Isa Mill. The Millpebs proportion reached about 25 - 30 per cent before running out of on-site inventory and lack of control in mill's pulp density. In Table 6, a fraction of small media in the 25 mm balls charge decreased the energy consumption from 42 kWh/t to 25 kWh/t by maintaining the final grind target at 18 µm. Based on the Operating Work Index, the use of small media gave the best efficiency. The higher circuit tonnage was attributed to the higher plant feed rate but the fact that the grind had kept the target of 90 per cent can only be attributed to the smaller media. After the trial, the grind target was not reached even at higher power and lower feed rate.

TABLE 6

Industrial results of 25 per cent Millpebs in a regrind ball mill versus an ISA mill at Kumtor mine.

Mill	Media	kW	TPH	kWh/t	F80 µm	P80 µm	Overflow % 20 µm	WOI kWh/t
Regrind before	25 mm	3717	88.2	42.1	129	18	88.0	28.5
Regrind trial	25% Mpbs	3333	135.0	24.7	130	<18	90.1	16.7
Regrind after	25 mm	3895	119.0	32.7	-	-	87.8	-
Isa mill	2.5 - 3.5 mm	1885	80.0	23.4	135	60	N/A	54.7

Vertical stirred mill versus ISA mill

So far, no vertical mill has been replaced by an Isa Mill. Both technologies were compared at Mount Isa by Gao, Young and Allum (2002). The Isa Mill showed a sharper particle size distribution than the Tower mill but efficiency (kWh/t) is not shown, neither a Operating Work Index comparison.

Since 1999, as reported by Pease *et al* (2006b), the 520 kW Tower Mill of Mount Isa is in operation to prepare the feed of the two 1.1 MW Isa Mills to grind from a F80 of 37 µm to a P80 of 12 µm. The total installed power is 2720 kW. Before the process changes for the new George Fisher ore body, the total power of the previous grinding configuration to grind from 37 to 12 µm was 1270 kW by using a conventional ball mill: 750 kW; and Tower Mill: 520 kW (Young *et al*, 1997; Young, Pease and Fisher, 2000). From an energetic point of view only, the older configuration consumed less than half of today's energy. The feed rate is not mentioned in either case. Recently, Olson and Dixon (2009) have installed a vertical stirred mill prior to the ISA mill at Goldcorp Peñasquito to grind from 125 µm to 30 µm.

DISCUSSION

When larger grinding balls are ejected from a ball mill, it is caused by the operating conditions. So does the small media. Their ejection can be overcome. The first and main cause remains the pulp density. As mentionned by Klein and Hallbom (2009), as the particle size in slurry gets finer and solids concentration increases, the non-Newtonian effects become more pronounced. For the moment, diluting the pulp is one solution. Viscosity modifiers can be a second alternative. When adding more water, the flow rate is increased. As stated by McIvor (2009), every extra unit of water can lead to significant improvement in the circuit classification system efficiency, over grinding and energy efficiency. So far, small media has stayed in ball mills for slurry linear velocity less than 3.3 m/min. Studies should be conducted to better understand the rheology effect of both concentration and flow on media sizing.

Feed size dictates media sizing. Bond top size ball formula gives a good indication if the mill needs smaller media as shown in Table 3. When finer grinding is not needed, significant energy improvement can be achieved. Unfortunately, that formula can not be used in vertical stirred mills, which accepts balls size up to 30 mm. Stirred pilot mill can now be related to industrial performance by using the same size of small grinding media. More studies are needed to correlate feed size to top media sizing. It is also important to mention that in all those industrial cases, no circuit optimisation was conducted.

CONCLUSIONS

To use small media into industrial mills, two identified operating criteria must be met. The most important factor is the pulp's density which must be fluid enough. The second is the media volume must be kept below the trunnion level. The power target need to be lowered when converting a mill charge. Flow rate is important but the critical value still need to be found. For energy improvement, the maximal feed size range to use small media like Millpebs (5 - 12mm) is 250 µm. Therefore, both fine grinding and regrind applications required media size smaller than 12 mm.

The first benefit of using small media is energy savings. Compared to 25 mm media, small media reduces the energy consumption by 36 per cent to 40 per cent in ball mills and 33 per cent in vertical stirred mill. A vertical stirred mill reduces further the energy by 43 per cent versus a ball mill. The combination of small media in a vertical stirred mill requires at least 60 per cent less power than conventional ball mill using 25 mm balls. More savings were identified.

For a feed size greater than 100 µm, small media in a regrind ball mill showed a better energy efficiency than the Isa Mill based on the Operating Work Index (16.7 versus 54.7 kWh/t). None of those trials were final and optimised. Further investigation is needed. To grind from a feed size of 37 µm down to 12 µm, the use of a ball mill and vertical mill combination was requiring less power than the Isa Mills and vertical mill combination.

Finally, both technology and media size are important. A vertical stirred mill with small media represents the best potential to decrease the energy consumption in the fine grinding and regrind application. The Isa Mill might not be as energy efficient due to very small grinding media. The limit between the fine and ultra fine grinding should be found as they required different size of grinding media (1 - 3 mm versus 5 - 12 mm). The operation of vertical stirred mill needs further investigation through process optimisation, which should results in both lower energy and media consumption. The sizing of this equipment with small media will become more important in the future.

ACKNOWLEDGEMENTS

The author wishes to thank all the concerned mining companies and all the personnel who collaborated for their support during those industrial trials, especially Curtis Deredin and Mark Furlotte from Brunswick Mining, Claude Bazin from Laval University and Serge Parent from Wheelabrator Allevard.

REFERENCES

Azzaroni, E, 1981. Mill Grinding Media Size and Multiple Recharge Practive, paper presented to *2nd Asian Symposium on Grinding*, Manilla, September.

Ayers, C, Knopjes, L and Rule, C M, 2008. Coarser Feed Applications of MIG Isa Milling, paper presented to *Communition 2008*, Falmouth, United Kingdom, 17 - 20 June.

Bazin, C, 2008a. Traitement des Données du Circuit de Broyage Secondaire à Mines Brunswick et Calibrage des Fonctions de Broyage et de Sélection, *Wheelabrator Allevard Technical Report by Laval University*, Québec, Canada, 27 September.

Bazin, C, 2008b. Traitement des Données du Circuit de Rebroyage de la Flottation CuPb à Mines Brunswick et Calibrage des Fonctions de Broyage et de Sélection, *Wheelabrator Allevard Technical Report by Laval University*, Québec, Canada, 25 November.

Bazin, C, Parent, S and Chevalier, G, 2004. Addition of Millpebs to a Pelletizing Grinding Mill, *Mineral & Metallurgical Processing*, 21(4):193 - 197.

Bond, F C , 1961. Crushing and Grinding calculations Part I, *British Chemical Engineering*, 6(6):378 - 385.

Brissette, M, 2009a. Paper 35 – Energy Savings and Improved Recovery with Small Grinding Media, in *Proceedings 41st Canadian Mineral Processors Conference*, pp 587 - 608 (The Canadian Institute of Mining, Metallurgy and Petroleum: Ottawa).

Brissette, M, 2009b. Energy Savings and Technology Comparison using Small Grinding Media, in *Proceedings of the VI International Mineral Processing Seminar*, pp 135 - 143 (Gecamin: Santiago).

Burford, B D and Niva, E, 2008. Comparing Energy Efficiency in Grinding Mills, in *Proceedings MetPlant 2008 - Metallurgical Plant Design and Operating Strategies* [online], Australasian Institute of Mining and Metallurgy: Perth) , pp 45 - 64. Available from: <http://www.isamill.com/index.cfm?action=dsp_content&contentID=21> [Accessed: 4 March 2009].

Cooper, M, Bazin, C, Grant, R and Tessier, R, 1993. Paper 10 – Grinding Media Evaluation at Brunswick Mining and Smelting, in *Proceedings 25th Canadian Mineral Processors Conference*, pp 347 - 358 (The Canadian Institute of Mining, Metallurgy and Petroleum: Ottawa).

Gao, M, Young, M F and Allum, P, 2002. Isa Mill Fine Grinding Technology and its Industrial Applications at Mount Isa Mines, in *Proceedings 25th Canadian Mineral Processors Conference*, pp 171 - 188 (The Canadian Institute of Mining, Metallurgy and Petroleum: Ottawa).

Gao, M and Holmes, R, 2007. Developments in Fine and Ultrafine Grinding Technologies for the Mineral Industry, CSIRO Minerals, Institute of Materials, Minerals and Mining. Available from: <http://www.iom3.org/features/615+1902> [Accessed: 23 March 2008].

Herbst, J A and Lo, Y C, 1989. Grinding Efficiencies with Balls or Cones as Media, *International Journal of Mineral Processing*, 26:141.

Jankovic, A, 2003. Variables Affecting the Fine Grinding of Minerals using Stirred Mills, *Mineral Engineering*, 16:337 - 345, paper presented to MEI Conference 2002, Perth, Australia. Available from: <www.sciencedirect.com> [Accessed: 23 March 2008].

Jankovic, A, 2008. A Review of Regrinding and Fine Grinding Technology – The Facts and Myths [online]. Available from: <http://www.metso.com/miningandconstruction/mm_proc.nsf/WebWID/WTB-041206-2256F-02070?OpenDocument> [Accessed: 23 March 2008].

Jankovic, A, Valery, W and La Rosa, D, 2003. Fine Grinding in the Australian Mining Industry [online], paper presented to *3rd International Conference on Recent Advances in Materials, Minerals and Environment*, Penang, Malaysia, 20-22 October. Available from: <http://www.metso.com/miningandconstruction/mm_proc.nsf/WebWID/WTB-041206-2256F-02070?OpenDocument> [Accessed: 1 March 2006].

Klein, B and Hallbom, D, 2009. Rheology in Mineral Processing, in *Proceedings Recent Advances in Mineral Processing Plant Design* (ed: D Malhotra, P R Taylor, E Spiller and M LeVier), pp 406-418 (The Society for Mining, Metallurgy, and Exploration: Littlelon).

McIvor, R E, 1990. Module 18 – Evaluation of Circuit Classification, in *The Metcom Engineering and Management System for Plant Grinding Operations*, GPD Co Ltd and Metcom Consulting LLC, Rev 4 (2005).

McIvor, R E, 1997. The Effect of Media Sizing on Ball Milling Efficiency, in *Comminution Practices* (ed: S Komar Kawatara), pp 279 - 292 (The Society for Mining, Metallurgy, and Exploration: Littleton).

McIvor, R E, 2009. The Importance of Water Utilization for Maximizing Grinding Circuit Classification System Efficiency, in *Proceedings 41th Canadian Mineral Processors Conference*, pp 573 - 585 (The Canadian Institute of Mining, Metallurgy and Petroleum: Ottawa).

Nesset, J E, Radziszewski, P, Hardie, C and Leroux, D P, 2006. Assessing the Performance and Efficiency of Fine Grinding Technologies, in *Proceedings 38th Canadian Mineral Processors Conference*, pp 283 - 309 (The Canadian Institute of Mining, Metallurgy and Petroleum: Ottawa).

Olson, B and Dixon, S, 2009. Goldcorp's New Peñasquito Mill, *Mining Engineering*, 61(9):16 - 19.

Pease, J D, Anderson, G, Curry, D C, Kazakoff, J, Musa, F, Shi, F and Rule, C, 2006a. Autogenous and Inert Milling using the IsaMill, in *Proceedings 4th International Autogenous and Semiautogenous Grinding Technology Conference* (eds: M J Allan, K Major, B C Flintoff, B Klein, A L Mular), II:230 - 244 (University of British Columbia: Vancouver).

Pease, J D, Curry, D C, Barns, K E, Young, M F and Rule, C, 2006b. Paper 16 – Transforming Flow Sheet Design with Inert Grinding – the Isa Mill, in *Proceedings 38th Canadian Mineral Processors Conference*, pp 231 - 249 (The Canadian Institute of Mining, Metallurgy and Petroleum: Ottawa).

Shi, F, Morrison, R, Cervellin, A, Burns, F and Musa, F, 2008. Comparison of Energy Efficiency between Ball Mills and Stirred Mills in Coarse Grinding, paper presented to *Communition 2008*, Falmouth, United Kingdom, 17 - 20 June.

Staples, P, Woodcock, F, Cooper, M and Grant, R, 1997. Evaluation of Grinding Media Shape and Size in a Pilot Plant Ball Mill, in *Proceedings 29th Canadian Mineral Processors Conference*, pp 13 - 26 (The Canadian Institute of Mining, Metallurgy and Petroleum: Ottawa).

Stief, D E, Lawruk, W A and Wilson, L J, 1987. Tower Mill and its Application to Fine Grinding, *Mineral and Metallurgical Processing*, *AIME Transactions*, 4(1):45 - 50.

Young, M F, Pease, J D, Johnson, N W and Munro, P D, 1997. Developments in Milling Practice at the Lead-Zinc Concentrator of Mount Isa Mines Limited from 1990 [online], in *AusIMM 6th Mill Operators Conference*, Madang, Papua New Guinea, pp 3 - 12, 6 - 8 October. Available from: <http://www.isamill.com/index.cfm ?action=dsp_content&contentID=21> [Accessed: 27 July 2008].

Young, M F, Pease, J D and Fisher, K S, 2000. The George Fisher Project to Increase Recovery in the Mount Isa Lead/Zinc Concentrator, paper presented to *AusIMM 7th Mill Operators Conference*, Kalgoorlie, Australia, 12 - 14 October.