PAPER 35

Energy Savings and Improved Recovery with Small Grinding Media

Michel Brissette, M.Sc.A., Grinding Process Engineer

Wheelabrator Allevard
7272 boul. Maurice-Duplessis Suite 201
Montreal, Quebec, Canada
H1E 6Z7
TEL: 514-353-1655
FAX: 514-353-1768
E-mail: mbrissette@waenam.com

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ABSTRACT

To recover more valuable ore and considering the complexity of minerals, the needs to grind finer is increasing. To reach the desired fine grinding targets, using the existing grinding media size, the energy consumption is increasing exponentially. As already proved at this conference, small grinding media represents the best potential to improve grinding efficiency. How do the small grinding media perform in industrial grinding mills?

The use of small grinding media in regrind mills proved that finer grinding can be achieved at lower energy consumption. In ball mills, smaller grinding media versus 25 mm media generate a power saving from 10% to 44%. In vertical stirred mills, the power saving increases from 20% to 60%. More potential savings have been identified.

For the same operating conditions, how a vertical stirred mill is performing compared to ball milling? In regrind application, a vertical stirred mill with small media (5-12 mm Millpebs) will require at least 62% less energy than a ball mill charged with 25 mm grinding media.

INTRODUCTION

In some mining applications, fine grinding is needed to liberate further the valuable ore. The purpose of regrind mills is to achieve the last stage of grinding before final flotation stage: the cleaners. In part because of high prices of small grinding media as well as availability, the most widely used size of grinding media is 25 mm.

When calculating the recommended ball top size from Bond's formula (Bond, 1961), the size for regrind applications is much lower than 25 mm. Today, the barrier for small grinding media is broken. They are best suited in regrind application. The size of grinding media is one of the most important variables affecting the mill efficiency (McIvor, R., 1997; Nesset, J.E., Radziszewski, P., Hardie, C. & Leroux, D.P., 2006).

Conventional ball milling was discarded for fine grinding because of its very poor energy efficiency (Zheng, J., Harris, C.C. & Somasundaran, P., 1994; Yan, D.S., Freeman, M. & Dunne, R., 1995). Therefore, new technologies as stirred mills were developed to grind finer more effectively. Three fundamental questions should be asked. What is the best fine grinding technology? What should be the best media size to use? Is it possible to grind finer by using less energy with the existing regrind equipment?

LABORATORY BATCH MILL AND PILOT TESTS

Ball Milling

In the past, Wheelabrator Allevard conducted many unpublished laboratory batch tests in order to evaluate the impact of small media on grinding efficiency. The answer was always leading to the same conclusion: a finer product (P80) was obtained for a same grinding time. Moreover, energy consumption was decreased whenever power draw measurement was available. At that time, these results could not be transposed to industrial scaling.

In 2004, a mix of Millpebs (30%) with 25 mm balls (70%) was tested in a pilot station by Companhia Vale de Rio Doce (CVRD), consisting of a small ball mill with discharge overflow running in closed circuit with one hydrocylone (Alves, V.K. & Lacoste-Bouchet, P., 2005). The mixture showed benefits in every aspect: reduction of power draw, increase of productivity and increase in product's fineness. The grinding efficiency, as calculated by the Work Operating Index (WOI), was improved by 16%.

Most of laboratory testworks are using one or two sizes of media to compare energy efficiency. They result in efficiency different from the industrial mills often explained by the fact that they are operating with a graded charge (Kalra, R., 2002). Recently, small media graded charge with different top size was tested using the Bond Ball Mill Work Index methodology (Partyka, T. & Yan, D., 2006). The most energy efficient media was obtained with the smallest top size (5,5 mm) when the feed size F80 was finer than 100 µm. The larger top size balls (19 mm and 36.8 mm) were just consuming more energy. Small balls were not efficient when the feed size (F80) was coarser than 500 µm.

Vertical Stirred Milling

When evaluating coarse grinding in laboratory scale using the Bond Ball Work Index procedure, small balls (11 mm) in a stirred mill was as efficient as ball milling (Jankovic, A. & Cervellin, A., 2004). In fine grinding, testwork in a Vertimill pilot mill showed the better efficiency of Millpebs compared to 12 mm balls and cylpebs (Kalra, R., 2002). When comparing grinding efficiency between pilot and industrial scaling, results indicated that further improvement could be achieved by the introduction of small media (4-5,6 mm) versus the 15 mm media used in the industrial Vertimill (Jankovic, A. & Morrell, S., 2002).

Fine Grinding Efficiency

The fine grinding technology has been an issue for the past 10 years. The subject has been well summarized by others (Gao, M. & Weller, K., 1994; Gao, M. & Holmes, R., 2007; Kalra, R., 1999; Kalra, R., 2004; Jankovic, A. & Valery, W., 2004; Jankovic, A., Valery, W. & La Rosa, D., 2003; Lichter, J. & Davey, G., 2002).

All the grinding technologies, including ball milling, were compared together with different media size chosen on a very narrow size fraction in both batch and pilot units with power draw measurements (Nesset et al., 2006). Whatever the technology used, the media size distribution selection was a key to achieve the highest energy efficiency. Figure 1 shows the best results obtained for each technology. The most energy efficient combination was the use of 5 mm media (Millpebs) in a vertical stirred mill, which was requiring 43% less energy than the other technologies.

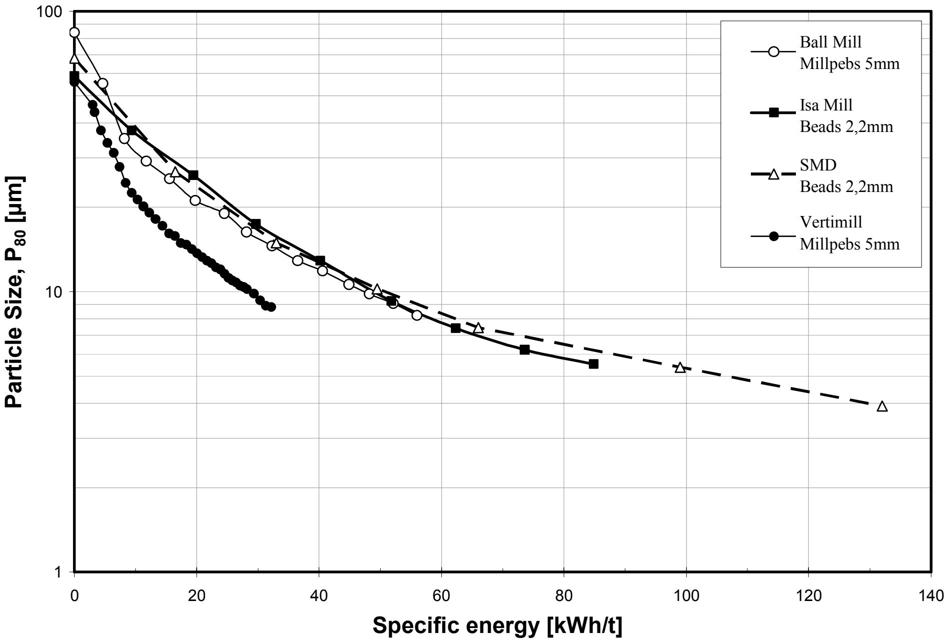

Figure 1: Best energy efficiency by grinding technology and grinding media size
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Can we evaluate fine grinding efficiency by using the P80 only? Usually, if the P80 are similar, we conclude that the grinding efficiencies are the same. Figure 2 shows the laser size distribution of two samples. Both P80 are at 57,5 µm. The size distribution is different only when the particle size is less than 30 µm.

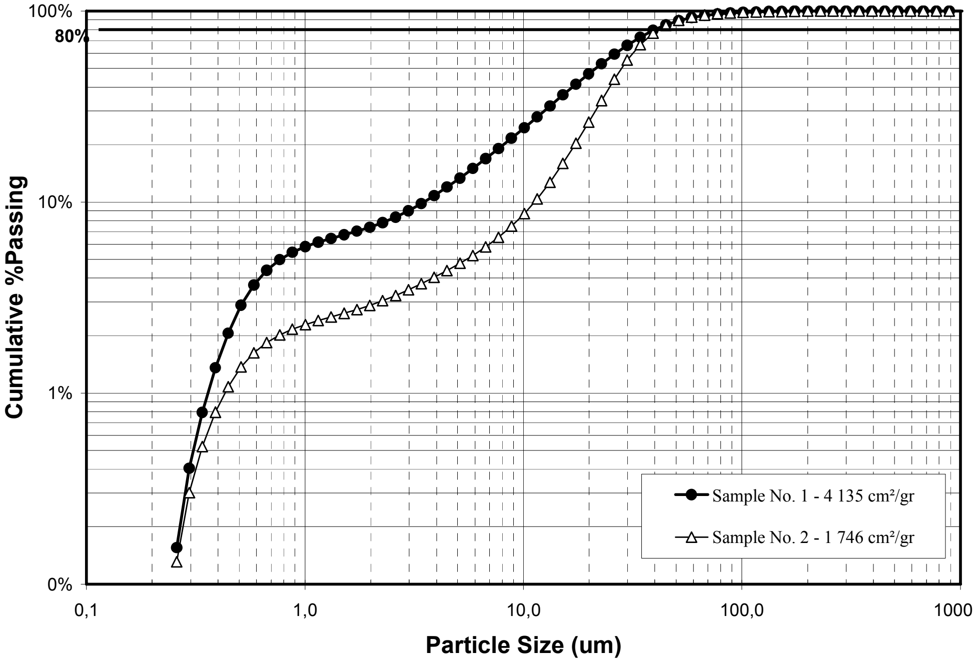

Figure 2: Size distribution and surface measurement of ore sample with the same P80

The Blaine, commonly used in the cement and the iron ore mining industries, measures the ore's particle surface per unit of weight (in cm²/g). From the two samples above, the Blaine of the first sample is almost three times higher than the second sample (4 135 vs 1 746 cm²/g) showing grinding improvement. Therefore, the Blaine gives a better representative value of the fine particles than the P80 and should be used in fine grinding efficiency evaluation.

SMALL CAST STEEL MEDIA – MILLPEBS

Millpebs are a mixture of small media ranging from 5 to 12 mm with a hardness of 64 HRC shape from spherical to oblong as shown in Figure 3. The Millpebs provide the grinding surface necessary where the main grinding mechanism is attrition.

Figure 3: Picture of a 100% Millpebs charge in a regrind ball mill

MEDIA SIZE SELECTION VERSUS FEED SIZE

One of our first industrial trials in the iron ore mining industry confirmed us that the feed size is one of the main criteria (Bazin, C., Parent, S. & Chevalier, G., 2002). As shown in Figure 4, the breakage rate of the 20% Millpebs mixture becomes much higher when the particle size is less than 250 microns. The F80 was 680 microns, making the 25 mm balls more effective for that application. It is important to mention that the Bond Index for that iron ore was 23 kWh/t, which was very hard.

The selection of the ball size has been already summarized by McIvor (1997). A first start is to use the Bond's equation to determine the recommended top size of the grinding balls. In the trial discussed earlier, Bond was recommending the use of 26 mm media, which the mine was already using. It confirmed that the Millpebs were simply too small for that application.

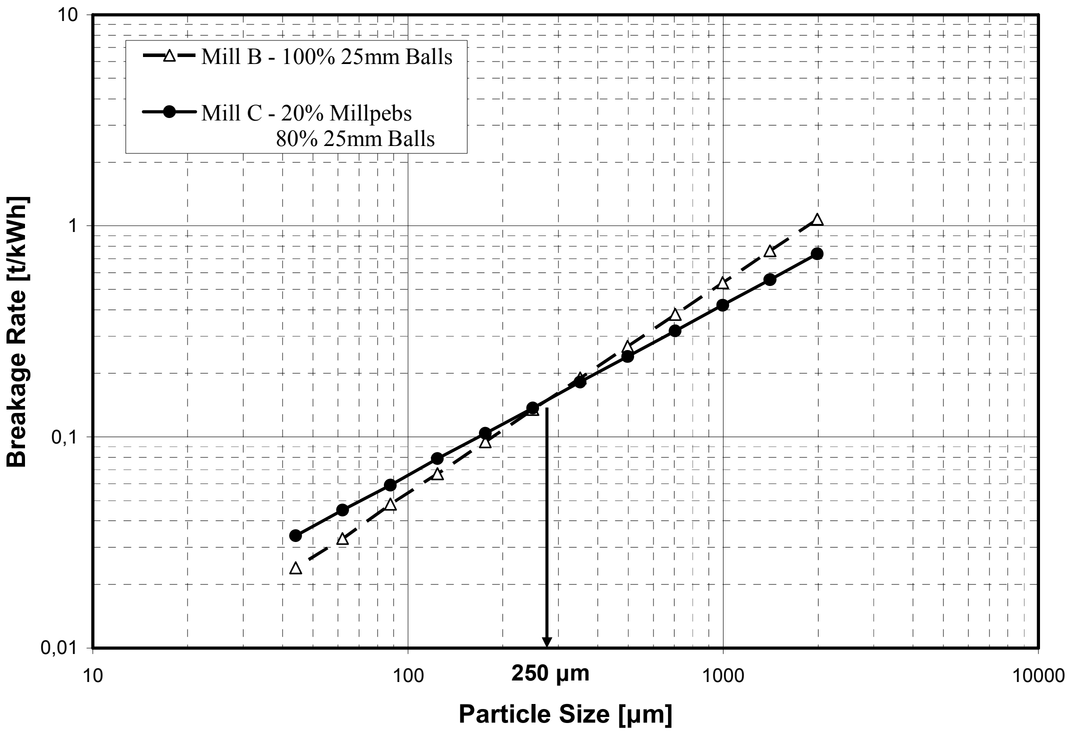

Figure 4: Breakage rate of a 20% Millpebs mixture in a 17' x 34' industrial mill

Once the F80 criteria has been defined of being less than 250 μm, WA has focused its search on regrind application. In 2005, one of our first successful trial has come out because finer grinding (P80= 16 μm vs 25 μm) was obtained in a CuPb regrind mill with 10% less power (Orford I., Lacoste-Bouchet, P. & Cooper M., 2006). Since, the mine was not able to retrieve the finer ore at the cleaner flotation cells because more water addition was needed. Unfortunately, the water recycling plant was already running at full capacity, unable to handle that extra water demand. Today, the power draw has been decreased by 33% in order to be at the same grind.

This paper is presenting 4 new cases listed in Table 1 where Bond was recommending media size less than 12 mm with their corresponding improvement.

Table 1: Millpebs performance results in industrial fine grinding mills

Case No	Ore Type	Technology	Application	Bond Ball Size	Power Savings	Increase TPH	Finer Grind
2002	Fe	Ball Mill	Regrind	26 mm	Same	Same	Yes
2004	Cu-Pb	Ball Mill	Regrind	5 mm	-10%	Same	+56%
					-33%	Same	Yes
1	Cu-Pb-Zn	Ball Mill	Secondary	8 mm	-44%	Same	Same
2	Au-Cu	Ball Mill	Regrind	6 mm	-30%	Same	Yes
3	Cu-Mo	VertiMill	Regrind	N/A	-20%	+25%	Same
4	Cu-Au	VertiMill	Regrind	N/A	-60%	Same	Same

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SMALL MEDIA IN INDUSTRIAL BALL MILL

Case 1 – Secondary Ball Mill in Copper/Zinc/Lead Mining

The choice of the 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., P., Woodcock, F., Cooper, M. & Grant, R., 1994). The recommended size of 8 mm for the secondary ball mills was considered below practical limits. The use of a corrected make up size formula (Azzaroni, E., 1981) and breakage function (Austin L.G., Shoji, K. & Luckie, P.T., 1976; Lo, Y.C. & Herbst, J.A., 1986; Morrel, S., 1990) were chosen as methodology to optimize ball sizing. Although balls are generally 10% to 15% more efficient than conical shape (slugs) in primary grinding (Herbst, J.A. & Lo, Y.C., 1989), the 25 mm slug was found to be more efficient and cost effective than balls in the finer particle size fraction (Cooper, M., Bazin, C., Grant, R. & Tessier, R., 1993).

Because of the grinding efficiency improvement in their CuPb regrind circuit (Orford, I. et al., 2006) and the recommended ball size in the secondary balls mills was still at 8 mm, Millpebs were finally introduced in June 2006. The mill was sampled at its feed and discharge only to compare the performance to a similar parallel ball mill as shown in Figure 5. The cyclone underflow K80 is 105 µm and the mill's discharge, 80 µm. The charge was progressively converted to 100% Millpebs over time, which was reached after two years. In Figure 6, the power decreased from 930 kW to 525 kW to have the same grind as before. This corresponds to a 44% decrease from the initial power.

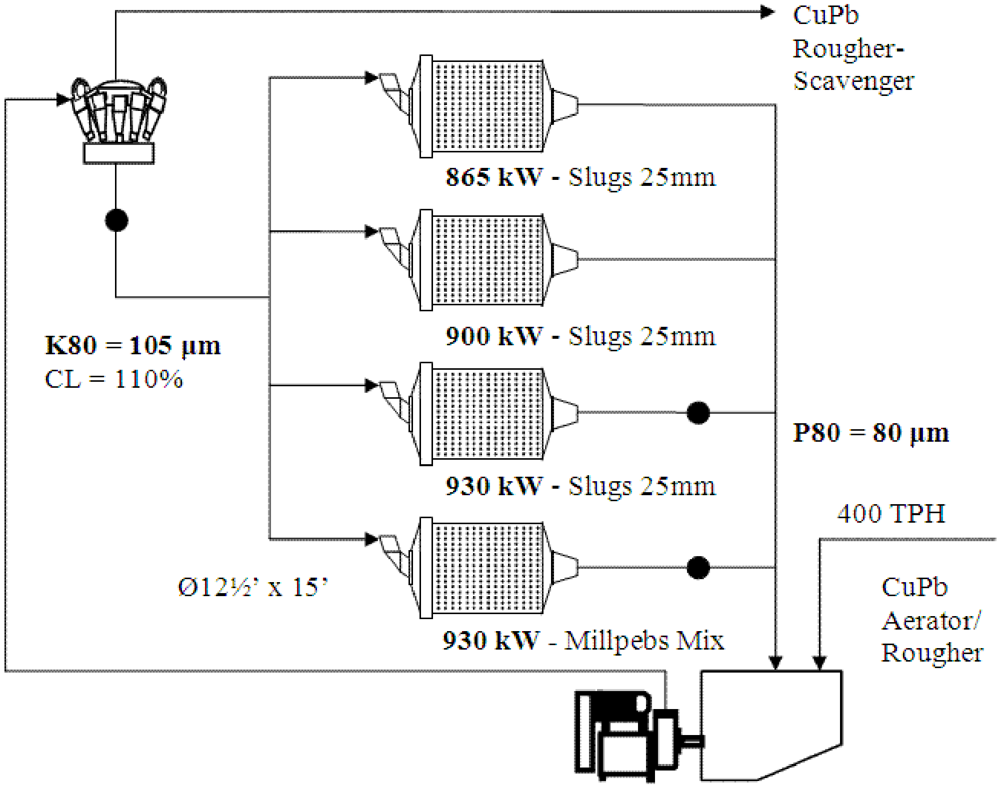

Figure 5: Case 1 – Secondary ball mill circuit flowsheet

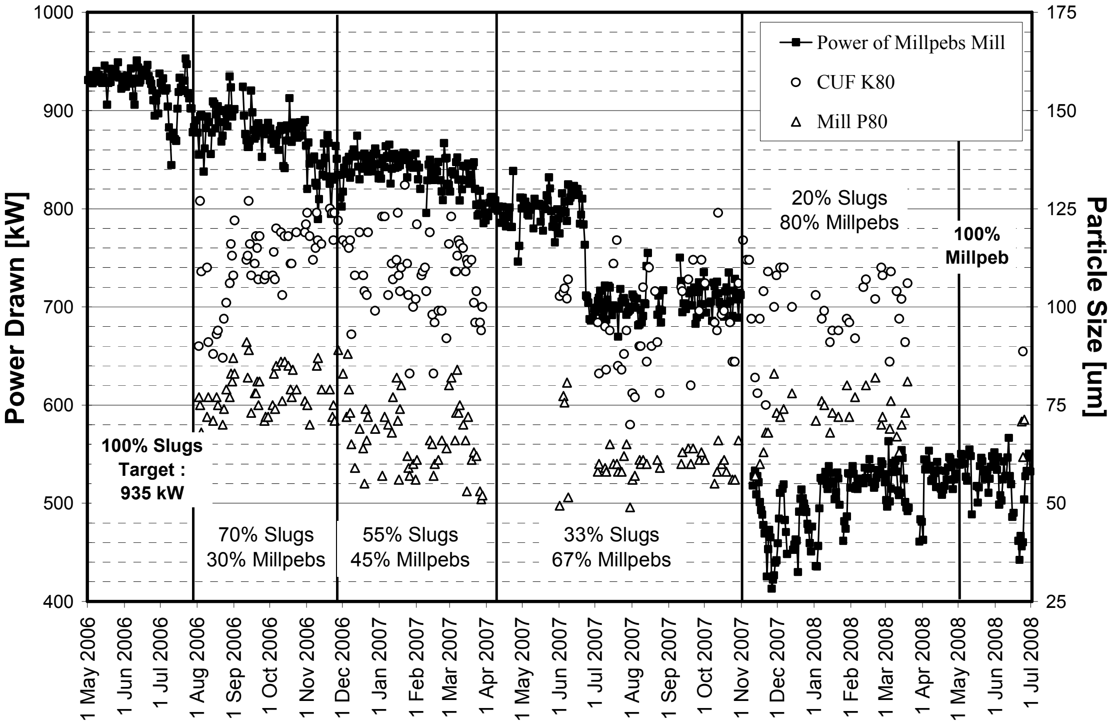

Figure 6: Gradual charge conversion to 100% Millpebs in a secondary ball mill

Case 2 – Regrind Mill in Gold Mining

Flotation laboratory test demonstrated that if the grind target was changed from 40 µm to 20 µm, more gold would be liberated leading to an increase in gold recovery. The idea was to test different sizes of grinding media to assess the best efficiency. Because the regrind mill did not have any power meter installed, the power is expressed in motor amperage only.

Figure 7 shows the flowsheet of the regrind circuit which is processing approximately 200 TPD. The complexity of this circuit lies in the feed streams: two streams from the rougher going into the pump box and two streams from the column and the flash cells going directly into the mill's inlet. The mill's F80 is estimated around 95 µm and the P80 is 75 µm at its discharge.

In Figure 8, the average gold content was lower only with Millpebs. Statistical analysis in Figure 9 indicates that all gold values are different from each other with a confidence level of 90%. Both, the 19 mm and the 25 mm slugs led to the same gold rejection as the 30 mm balls, showing that all those media sizes were not efficient enough to grind finer. The mill was shutdown for almost one month and led to a gold rejection up to 2,69 gr/ton and more at the cleaner's tailing. Therefore, the regrind mill was necessary to improve the gold recovery.

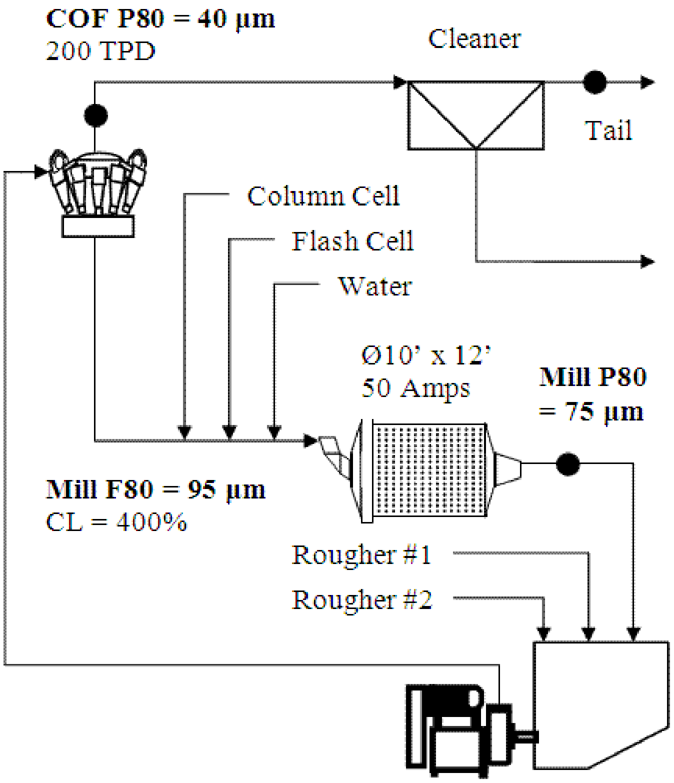

Figure 7: Case 2 – Regrind circuit flowsheet

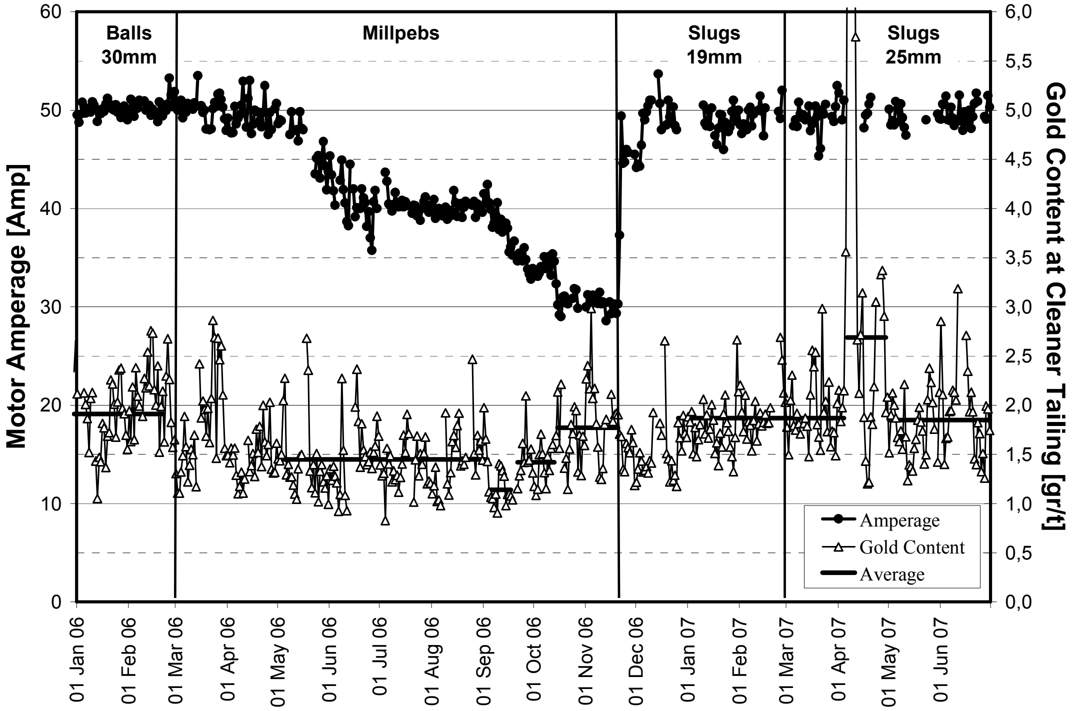

Figure 8: Regrind mill's performance with different grinding media

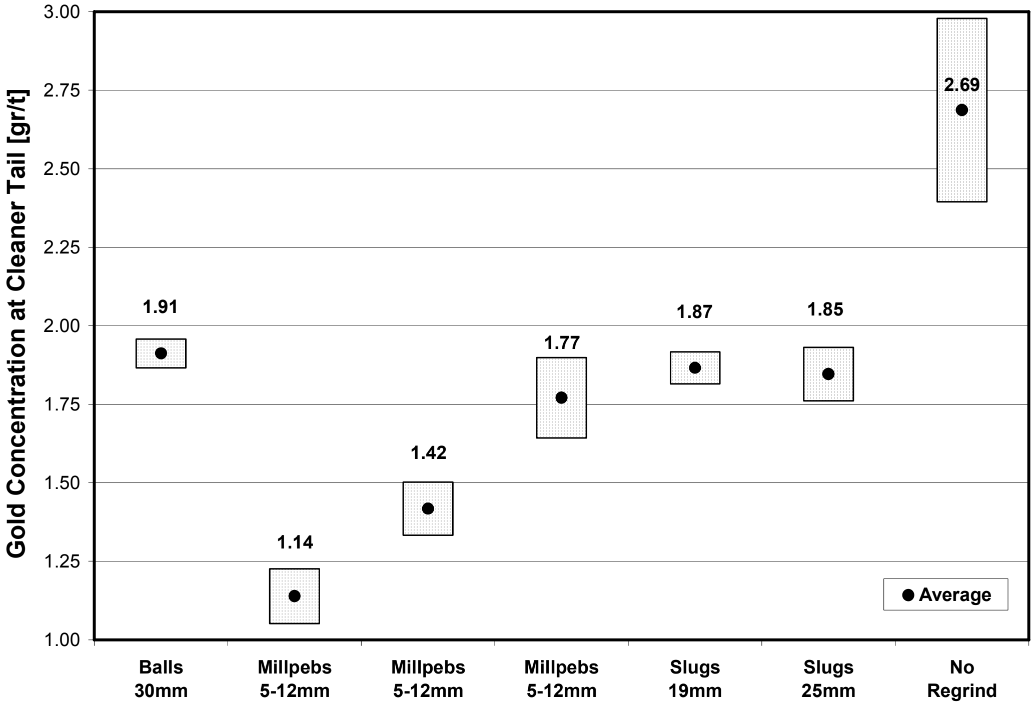

Figure 9: Statistical analysis of the gold content at the cleaner's tail

From Figure 8 and Table 2, the best result was achieved with a charge level of 16,5% of Millpebs as much less gold was rejected from the cleaner cells (1,14 gr/t vs 1,91 gr/t). The P80 of the cyclone overflow was 27 µm. This improvement was also possible by changing the apex diameter from 50/60 mm to 40 mm. Unfortunately, it was not possible to keep those operating conditions as the cyclone capacity was exceeded. Half of the apex were changed back to 50 mm diameter. It is interesting to note that for a same charge level (~16,5%), Millpebs were drawing 20% less power than the 30 mm balls. The charge level was then decreased progressively until more gold was loss, which happened to a very low filling degree (10,9%).

Table 2: Influence of Millpebs' charge level on grinding efficiency and gold's reject

Parameter	Unit	Balls 30mm	Millpebs 5-12mm		
Motor Amperage	Amp	50	41	36	31
Filling Degree	%	16,5%	16,7%	14,7%	10,9%
Mill P80	µm	76	57	66	72
Overflow P80	µm	43	27	41	51
Overflow Blaine	cm²/gr	2015	4713	3096	2116
Cleaner Tail Au	gr/t	1,91	1,14	1,42	1,77

The compromise was found when the filling degree was about 14,7%, drawing 30% less power. The gold reject was 1,42 gr/ton. Although the P80 at the cyclone overflow was very close to the initial P80 value (41 vs 43 µm), the Blaine was 50% higher. Therefore, more fines were sent to the cleaners explaining the better gold recovery. When the Millpebs' charge level was decreased to 10,9%, the Blaine was similar to the 30 mm balls with a coarser P80 (51 vs 43 µm). The gold rejection was still slightly better at 1,77 gr/ton. From Figure 9, that value is not statistically different from the cones media, regardless their size. At that time, the potential net increase in revenue was evaluated at 600k USD/year with a gold price of 620 USD/oz.

SMALL MEDIA IN INDUSTRIAL VERTICAL STIRRED MILL

Case 3 – Vertical Regrind Mill in Copper Mining

The objective was to decrease the grinding cost by comparing the grinding efficiency of 25 mm grinding balls to a mix of 50% Millpebs and 50% 25 mm balls in two vertical mills operating in parallel as shown in Figure 10. The average power draw and mill's throughput were 625 kW and 365 TPH. The tonnage is calculated from a flow and density meter installed at the outlet of the vertical mill feed's pump. To simplify the grinding efficiency evaluation, both mills were surveyed at the feed and discharge only. The average cyclone underflow K80 is 142 µm and the mill's discharge, 125 µm leading to a reduction ratio of 1,15 in the mill.

The difficulty encountered was the feed size variation from 110 µm to 180 µm. The strong relationship ($R^2 = 0,84$) of Figure 11 shows that the product size can almost be predicted with a constant reduction ratio (P80/F80) of 1,15, regardless of the feed size. Therefore, the reduction ratio was the more appropriate parameter for the evaluation than the P80.

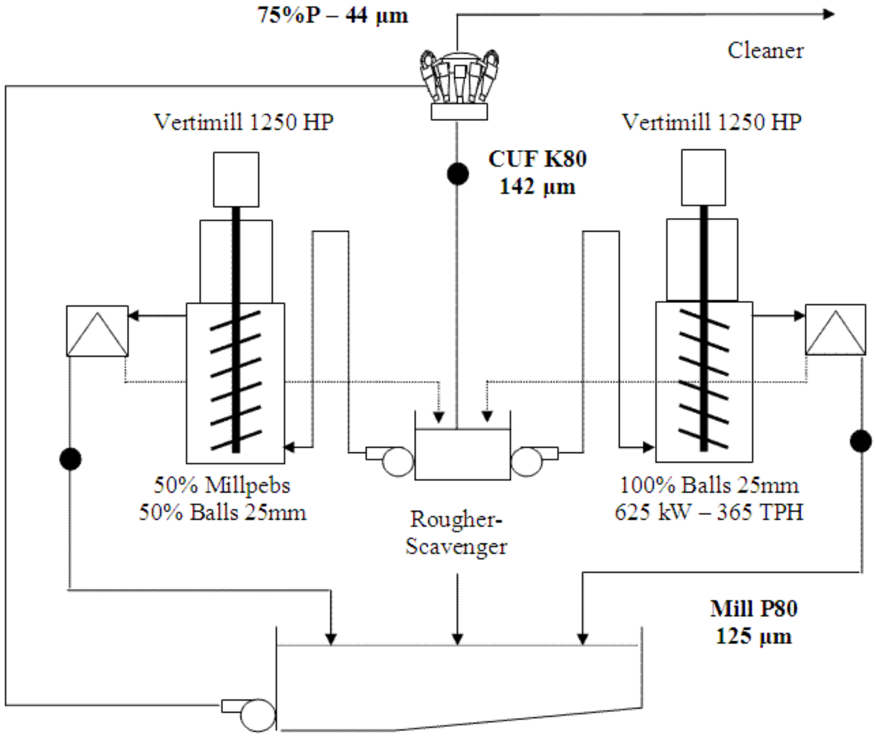

Figure 10: Case 3 – Vertical mill regrind circuit flowsheet

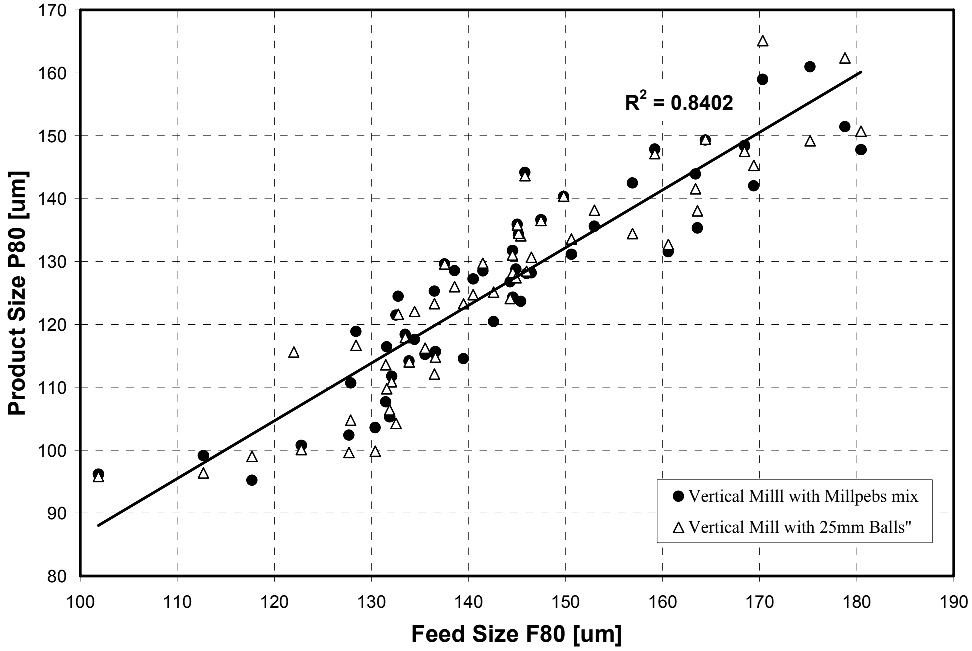

Figure 11: Product size (P80) relationship versus the feed size (F80)

When all the operating parameters are combined together (kW, TPH, F80 and P80) in Figure 12, the grinding efficiency is much better with the Millpebs' mixture as it requires much less energy (1,0 kWh/t vs 1,6 kWh/t in average) to obtain the same reduction ratio. When both mills were running at the same power target of 625 kW as shown in Table 3, the mill containing small media was performing with a 31% higher throughput.

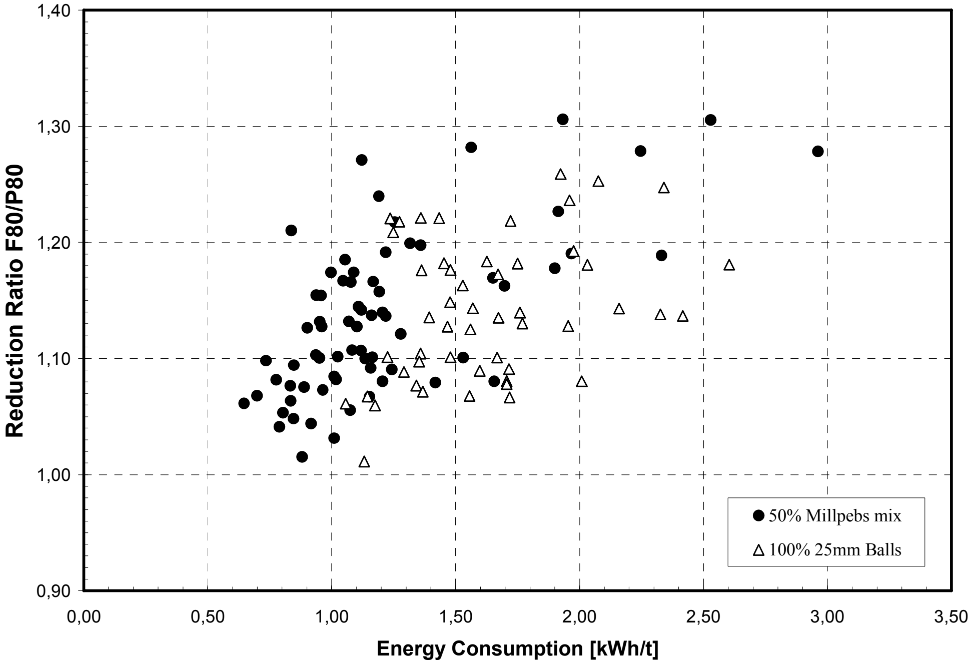

Figure 12: Energy consumption in function of the reduction ratio

Table 3: Vertical mills' performance at the same power target

Media		Power Target = 625 kW Balls	 Millpebs Mix	Difference %
Power	kW	627	624	< -1%
Throughput	TPH	380	498	+31,0%
Energy Efficiency	kWh/t	1.65	1.25	-24,2%
F80	µm	145	144	< -1%
P80	µm	125	125	Same
Reduction Ratio		1.17	1.16	< -1%

In respect to the initial goal, the total grinding cost can only be achieved when lowering the power to the same productivity level. Consequently, the lower charge will decrease the media consumption. Both the lower energy and media consumption will decrease the grinding cost. To remove the ore change effect out of the equation, efficiency was evaluated during the same period of time.

Unfortunately, from Table 4, the power was not decreased at the same throughput level. Still, the power was 20% less and the mill's throughput was 25% higher for a same reduction ratio. Further investigation did not take place to understand those results. Regardless of the data used, the Millpebs mixture was always operating at higher throughput (25 to 32%), leading to better energy efficiency (24 to 36%) than the 25 mm balls for an approximately same reduction ratio.

Table 4: Vertical mill's performance at lower power target

Media		Cost Effective Balls	 Mpbs Mix	Difference %
Power	kW	671	535	-20,3%
Throughput	TPH	415	520	+25,3%
Energy Efficiency	kWh/t	1,62	1,03	-36,4%
F80	µm	143	146	+2,1%
P80	µm	131	135	+3,1%
Reduction Ratio		1,09	1,08	< -1%

Case 4 – Vertical Regrind Mill in Copper Mining

In November 2007, a charge of 100% Millpebs was introduced into a vertical mill to assess the performance versus the 25 mm grinding balls. The ball's charge was dumped to get faster results. The throughput of the mill was not available as the previous case.

The flowsheet will be discussed in the next section along with the shaded period of Figure 13 (December 24th, 2007 to February 7th, 2008). The power was varied from 150 kW to 450 kW to see the effect on the grind, Cu grade of the final concentrate and gold recovery.

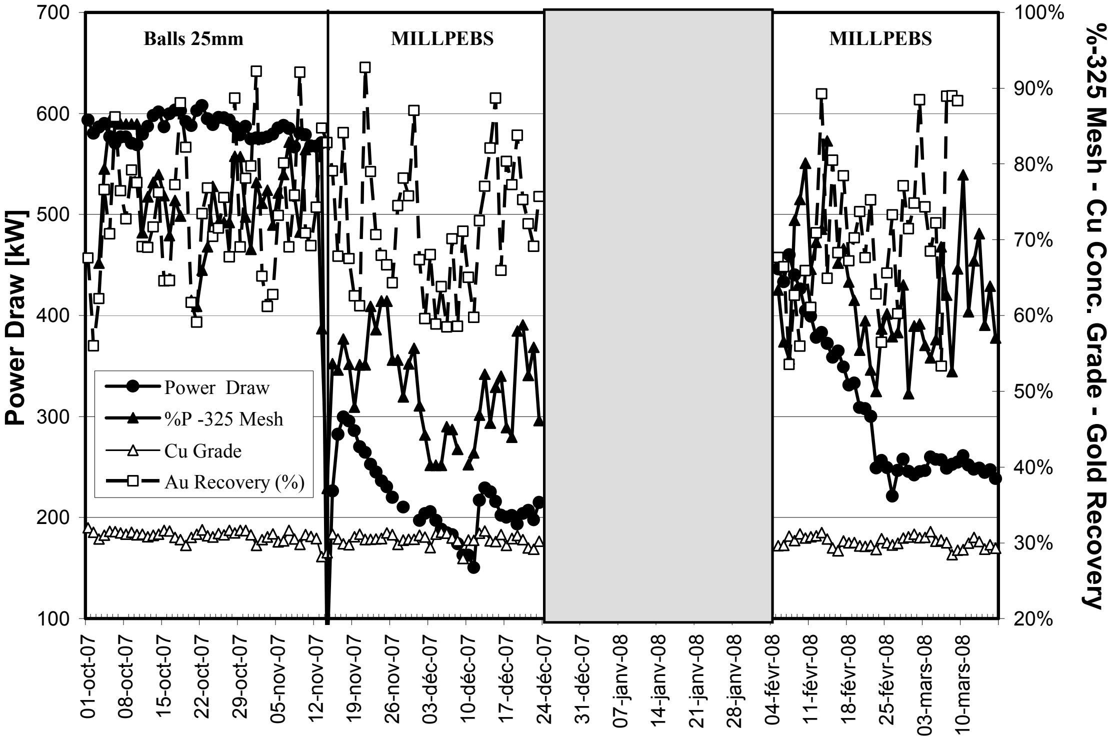

Figure 13: Vertical mill's performance with 100% Millpebs

In Table 5, to be at the same grind of 75% passing on 325 Mesh, the new power with the Millpebs was approximately 400 kW. It corresponds to an energy saving of 33% of the initial power compared to the 25 mm balls. The surprise comes from the fact that at 225 kW, the final copper grade was the same with a much coarser grind of 53% passing on 44 µm with an improvement of 5% in gold recovery. The energy saving was 62%. Lowering more the power to a much coarser grind was leading to a slightly lower copper grade and more important, a loss of 9% in gold recovery.

Table 5: Vertical mill's performance between 25 mm balls and Millpebs

Grinding Media	Power kW	No Days	Cleaner Feed %P –325M	Cu Grade %	Au Rec. %
Balls	588	31	75,4%	31,1%	72,9%
Millpebs	394	6	74,3%	30,9%	68,0%
Millpebs	223	7	53,4%	30,9%	77,9%
Millpebs	183	10	42,8%	30,4%	63,7%

Today, investigation and optimization of the regrind circuit are on-going on as it seems that the copper grade can be over 32% if ground finer than 100% passing under 44 µm.

HORIZONTAL BALL MILLING VERSUS VERTICAL STIRRED MILLING

Ball milling technology was discarded for fine grinding because of very poor efficiency caused by balls larger than 20 mm (Gao, M. & Holmes, R., 2007). Althought Vertimill was successfully introduced in secondary grinding (Jankovic, A. & Valery, W., 2004), no industrial ball mill was compared neither replaced by a Vertimill in the past in order to compare energy efficiency with the same ore and operating conditions.

In the last case, the mine is operating two production lines having both similar primary grinding and flotation circuit capacity. The difference resides in the regrind mills as shown in Figure 14. A 2500 HP ball mill was installed in the first line when the concentrator was initially built and a 800 HP Vertimill was installed when the concentrator capacity was increased by adding a second production line. Both mills were running with 25 mm balls with similar operating conditions (265 TPH at 75% passing on 44 µm) with the same ore grade. The ball mill's charge level was very low (5% to 8%) and the vertical mill was fully charged.

From Table 6, which shows both mills' performance one month prior to the introduction of the Millpebs, the Vertimill drawn 44% less power than a ball mill. This value corroborates with previous studies (Stief, D.E., Lawruk, W.A. & Wilson, L.J., 1987; Nesset, J. et al., 2006). Unfortunately, no circuit survey was conducted

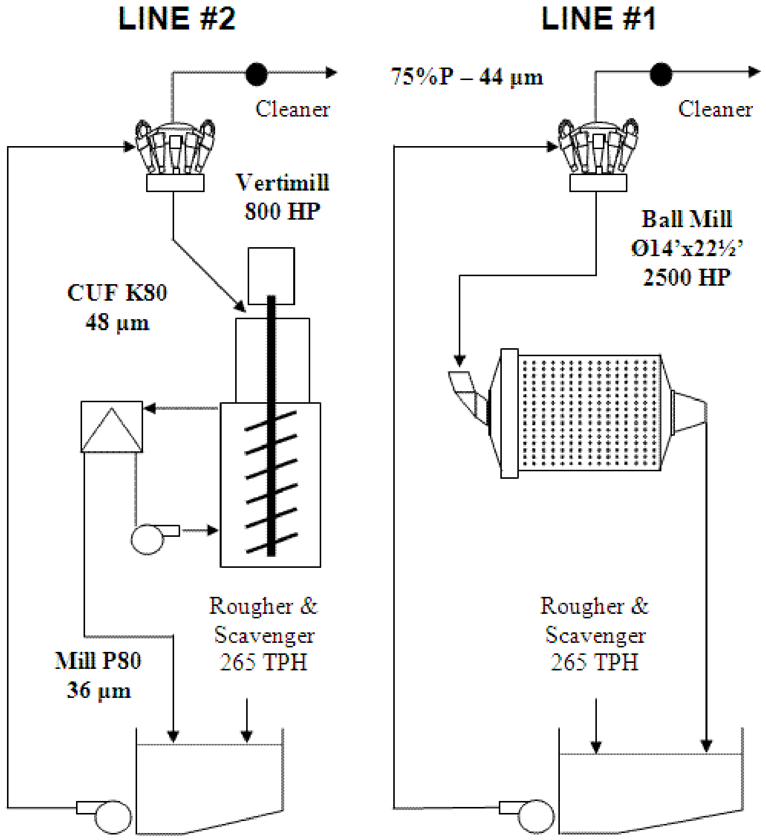

Figure 14: Case 4 – Vertical mill regrind circuit configuration

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Table 6: Power comparison between an industrial ball mill and a vertical stirred mill for the same regrind application

Balls 25mm	Days of Operation	Power kW	Cleaner Feed %P – 44 µm
Ball Mill 2500 HP	28	1045	73,5%
Vertical Mill 800 HP	29	587	75,2%

In fact, the ball mill from line #1 was removed to be replaced by a 1250 HP Vertimill. During the construction phase and due to the good performance of the 800 HP Vertimill filled with Millpebs, 70% of the flow coming from production line no. 1 was added to the second line. Adding more than 70% would have been exceeding the 800 HP Vertimill's flow capacity. The remaining 30% was bypassing the mill and sent directly to the cleaners. Figure 15 shows the missing shaded portion of Figure 13.

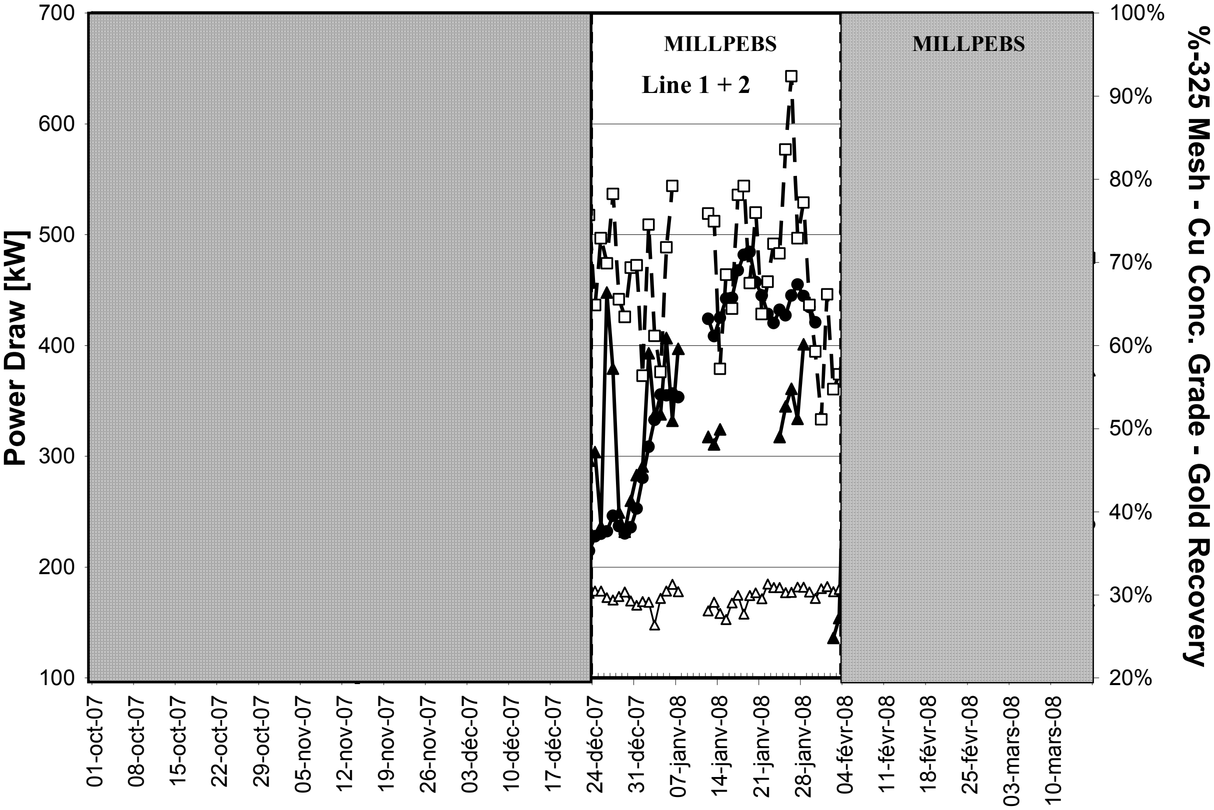

Figure 15: Vertical mill's performance with combined production lines

In Table 7, althought a coarser grind was obtained with the Millpebs, the copper grade remained almost the same and the gold recovery declined slightly. This can be explain by the fact that 80 TPH was bypassing the mill and going directly to the cleaner cells without being reground. The total power requirement represents 73% of the initial total power. There was still power available (160 kW) to increase the charge of the Millpebs in the Vertimill and consequently the grind if it would have been needed.

Table 7: Regrind circuit's performance at total productivity level (530 TPH)

Mill Configuration	Grinding Media	Total Power kW	Cleaner Feed %P –325M	Cu Grade %	Au Rec. %
Ball Mill + Vertimill	25mm Balls	1620	75,4%	31,1%	72,9%
Vertimill Only	Millpebs	439(1)	53,6%	30,6%	68,0%

(1): Power requirement for 85% of the total flow rate from both lines (450 TPH)

Today, the second 1250 HP Vertimill was commissioned with a 25 mm ball's charge. The mill is drawing 400 kW with a final grind of 75% passing on 44 µm. Investigation is on-going to have a better understanding of the vertical mill's operation since that the mill is drawing the same power as the 800 HP Vertimill when fully charged with Millpebs. More potential saving is expected when the 1250 HP Vertimill will be charged with 100% Millpebs.

MEDIA CONSUMPTION

There is several ways to evaluate the grinding media consumption: kg/t or g/kWh. The main problem in regrind circuits is that the feed rate is rarely available and must be calculated from mass balance. Surprisingly, many regrind ball mills do not have a power meter installed leaving the kilowatt unknown. Media consumption of regrind mills need to be compiled differently.

Since that power measurement is available for Case 1 and 4, Table 8 shows that the consumption expressed in g/kWh, g/h and kW. One should be careful before jumping to an early conclusion. Based on g/kWh only, the 25 mm media is wearing much less than Millpebs. In fact, using in g/h, the wear rate of both media is nearly the same. The difference is Millpebs will draw significantly much less power than 25 mm media.

Table 8: Media consumption in g/kWh

	Case 1			Case 4		
	g/kWh	g/h	kW	g/kWh	g/h	kW
Millpebs	168	86,2	515	138	31,0	223
25 mm	95	86,2	905	55	31,9	587

The easiest way is to compile the total quantity added per month. In all cases, the small media were added for a period of 30 days of operation in order to have a representative consumption. The wear rate, in kg/h, can also be used since that the total operating hours is usually known. In Table 9, three of the four cases illustrate the consumption of small grinding media are the same of 25 mm grinding media.

For Case 3, the higher consumption was caused by the higher charge giving more grinding surface and leading to a 25% higher productivity. This proves the importance of being in the same operating conditions (same tonnage and same grind) when evaluating the consumption of small media. For Case 2, the consumption at higher charge level (35 amps) was 26 tons per month in order to have more fine particles. That increase was easily paid off by the higher gold recovery. It also shows the inefficiency of the 19 mm slugs which had a higher consumption.

Table 9: Total grinding media addition comparison per month

	Millpebs 5-12 mm	50% Mixture Millpebs-Balls	Balls 25 mm	Slugs 25 mm	Slugs 19 mm
Case 1	53 t	-	-	53 t	-
Case 2	19 t(1)	-	20 t(2)	23 t	28 t
Case 3	-	25,3(3)	19,8	-	-
Case 4	22 t	-	23 t	-	-

(1) : Estimated consumption to be at the same final grind
(2) : Consumption for 30 mm media
(3) : Consumption at higher productivity

DISCUSSION

Due to the ball charge make up (80% > 19 mm), the Bond Ball Mill Work Index Determination cannot be used to calculate the required fine grinding energy. These larger balls are not efficient to grind fine particles (Partyka, T. & Yan, D., 2006; Gao, M. & Holmes, R., 2007). It may explain why some regrind ball mills are oversized in regrind circuits as presented in the last case. In both vertical stirred mill and ball mill, laboratory testworks confirms the energy efficiency improvement of small grinding media in the size of 5 mm. Since media size distribution is a key to improve grinding efficiency (McIvor, R., 1997; Nesset, J. et al., 2006), a graded media addition should be considered. The lack of correlation between laboratory and industrial scale might be related to the use of the P80, which can lead to erronous conclusion when calculating the energy efficiency. Even if the P80 is the same, the size distribution can be totally different in the range of 1 to 30 µm. The Blaine measurement should thus be used to assess energy efficiency.

To calculate top size balls in ball milling, the Bond formula gives a good indication. In all presented cases, the Bond calculated top size balls fell well below the ball size used. The mill was always drawing less power (10 to 44%) when the charge was converted to small grinding media, leading to a much better energy efficiency, especially if finer grinding was not needed. Unfortunately, the Bond formula can not be used in vertical stirred mills.

Vertical stirred mill is as efficient as ball mill for coarse grinding application when applying the Bond Ball Mill Work Index procedures (Jankovic, A. & Cervellin, A., 2004). In industrial fine grinding application (Case 4), a vertical mill with larger media (25 mm) draws 44% less power than conventional ball mill with the same operating conditions. When replacing the 25 mm balls with small grinding media, the energy efficiency of the vertical mill was greatly improved (25% to 60%), confirming the improvement obtained in pilot testworks (Karla, R., 2004; Nesset, J. et al, 2006). Stirred mill pilot result can now be related to industrial performance by using the same small grinding media size.

The use of smaller grinding media, less than 12 mm, often encountered problems because the media was overflowing out of the mill during operation (Jankovic, A. & Valery, W., 2004; Gao, M. & Holmes, R., 2007). In the conducted trials, even though one of the Vertimill was fed from the top instead normally bottom feed, that phenomenon has not been observed. There are three reasons why small grinding media will be ejected from the mill; 1) high pulp viscosity; 2) high slurry velocity; 3) very high filling degree. First, viscous pulp can be solved by adding more water at the mill's feed, leading to lower pulp density. If higher percentage solids gives better grinding efficiency (Laplante, A. & Redstone, J., 1983; Jankovic, A., Valery, W. & La Rosa, D., 2003), the gain of using small media with pulp dilution is even bigger. Second, decreasing the circulating load will lead to lower throughput, thus, lower velocity. However, because of large balls inefficiency in fine grinding, regrind mills in some mines are operating at a much higher productivity level. Those mills need to be carefully monitored to make sure that the small grinding media are staying in. So far, small media has stayed in ball mill with slurry linear velocity up to 3,2 m/min. Finally, the charge level for small media must be kept under the overflow outlet at all time. It goes without saying that small media does not require high charge load because of much better grinding efficiency.

Vertical mills can operate at higher volume load (85%) than conventional ball mills (45%), leading to higher productivity capacity. Because the best combination for fine grinding was found to be the vertical stirred mill technology with small grinding media (Nesset, J. et al., 2006), sizing this equipment with small media will become more important in the future.

CONCLUSION

To clearly answer one of the main concern of the fine grinding area: can we really grind with less energy? Yes. Small media can decrease the energy from 10% to 60% depending of the final ore grind. Results are coming from five industrial regrind mills in the mining industry. Those results were obtained by changing the grinding media only. For a same grind, the small media consumption will be the same as all other 25 mm grinding media. No capitalisation requirement is needed. More potential savings are possible if an optimization of the mill's operating conditions is conducted in parallel with the cyclones and the flotation circuit.

To evaluate grinding or energy efficiency in fine grinding, the Blaine measurement should be used along with the P80 as it gives a better measure of the fine particle size distribution. Today, on-line Blaine measurement is available in the cement industry. This tool, if adapted to the mining industry, will lead to further development for new empirical and simulation modelling in regrind circuit optimization.

For regrind ball mills, the energy savings with Millpebs versus the 25 mm media are ranging from 10% to 44%. The actual product size limit is 15 µm and the use of 5 mm size was justified from laboratory testworks. If the Bond Ball Mill Work Index Determination cannot be applied in fine grinding, the Bond formula to calculate the top size media seems applicable for industrial mills .

For regrind vertical mill, the energy savings with Millpebs versus 25 mm media are ranging from 20% to 60%. More potential power savings have been identified. An empirical formula to calculate the recommended top size should be developed like the Bond formula as vertical mills can accept ball size up to 30 mm. With 12 mm media, the product size is limited to a P80 of 15 µm. This limit is the same as conventional ball mill, which is 43-44% less efficient. Can that limit be broken with smaller media?

In fine grinding, the future relies in the combination of vertical stirred mills charge with small grinding media. That combination will require at least 60% less power than a conventional ball mill charged with 25 mm media (1045 kW vs 400 kW). The small grinding media opens doors for new territories to explore ultrafine grinding with the vertical mill in the mining industry since Millpebs can be produced to smaller size (1 mm) if required.

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