Regrind Mills: Challenges of Scaleup

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Abstract:

As ore deposits become finer grained the requirements for regrinding before cleaning or leaching have increased substantially. Despite this increasing need, there is no standard test to predict grinding energy requirement below 70 microns. The standard Bond Mill test applies for coarser ball milling, but is not appropriate for stirred milling with fine media grinding to 70 microns. With no industry -standard test, the energy requirement is often made on the basis of supplier estimates or benchmarking against similar applications. Yet suppliers use vastly different scale-up methods which result in widely different energy estimates. Estimates can differ by 100-300% even for similar mills. This must result in serious errors to install either too much or too little grinding power. This paper explores this by comparing the actual performance of full scale regrind mills against their original design estimate. It confirms that serious scale-up errors have been made, and have then been perpetuated by "benchmarking".

The test conditions to achieve accurate power estimation are discussed. The essential test conditions are: continuous (not batch) tests, ensure steady state (no coarse fraction retained in test mill), correctly account for classification, measure energy directly (not inferred), and using the same media size as the full scale installation. Failure to correctly address even one of these factors can bias results by 40%; failure to address several multiplies the error.

Introduction:

The requirement for regrinding mills has increased as ore deposits have become more complex and fine grained. This increased requirement has not yet been matched with accurate industry design tools for fine grinding. There is no industry-standard test for fine stirred milling. The Bond test and other scale-up tests designed for coarser grinding do not apply below for stirred milling with fine media to sizes below 70 microns. Using these coarse grinding techniques for finer regrinding underestimates energy requirement because of the different ball sizes, different trajectories and different ball–particle and ball-shell interactions in small mills. Modified Bond tests such as the Levin test are more accurate but are often regarded to be too time consuming and requiring too much sample. As a result, regrind mill suppliers have developed their own scale-up methodologies. Yet in recent experience these different scale-up methods result in 300-400% variations in estimated energy for the same duty. In several recent cases, estimates for the same mill from different manufacturers have varied by over 100%. Clearly they can't all be right. Plant designers need a standard technique to select the correct energy, and need rigorous data on *actual* operation performance (not *design* performance) for benchmarking. Without such a standard, the temptation is to choose the lowest energy estimate, perhaps supported by benchmarking against other *designs* rather than *performance*. This approach could perpetuate incorrect designs, and will lead to project failures.

This paper compares actual regrinding performance with design performance. The poor design record is explained by inadequate laboratory procedures. Different procedures and interpretations are reviewed, and the conditions required to achieve accurate scale-up for any regrinding technology are described.

Scale-up Procedures for IsaMill™

MIM developed the IsaMill™ in the early 1990's in response to fine regrinding needs of its ore bodies. Because they were also the operators, the MIM engineers required accurate scale-up. Also, they were able to calibrate predictions against operating mills. As a result they developed procedures for accurate 1:1 scale-up from laboratory to plant, and achieved this with both the MIM George Fisher and the MRM 1.1 MW, 3,000 liter IsaMills (M3,000s) (Figure 1). In this scale-up procedure, an M4 (4 liter horizontal) IsaMill™ is operated in multiple pass mode where the product from one continuous pass becomes feed for the next pass to develop a "signature plot" of energy versus different product sizes. This mill is filled 80% with media of the same size as final application (typically 1-3 mm), and agitated at 1500 RPM. The mill configuration and operation – discs, disc speed; media size, media type and media filling; and mill discharge classifier – are all very similar to the full scale operation. Therefore the feed particles "see" the same grinding and classification mechanisms as they do at full scale. Because the grinding media is small relative to the test unit, mill shell effects are minor, as demonstrated by the 1:1 scale-up performance.

MIM and MRM M3,000 Scale-up

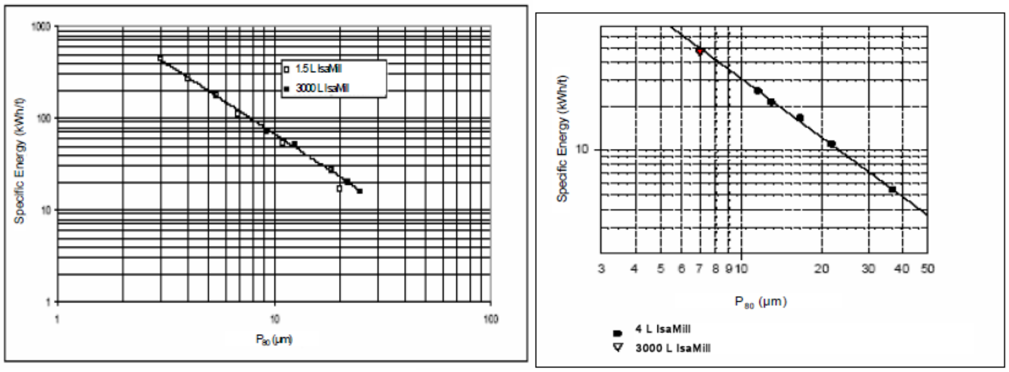

Figure 1. Scale-up of MIM(left) and MRM M3,000 IsaMills (Barns K, Curry D; 2006)

The reasons for the accurate direct scale-up from the laboratory to full size IsaMills are:

- Using the same size and type of grinding media as full scale - no correction factors are needed.
- The mill configuration and mechanism is the same – horizontal mill, similar grinding discs with similar tip-speeds, and closing the mill with an internal classifier similar to full scale. Therefore the mechanisms, velocities and physics within the laboratory mill are very similar to the full scale mills.
- A large test mill relative to particle and media sizing, so shell effects are minimal.
- Testing with the same slurry feed size and density.
- Ensuring enough feed material is processed to reach steady state. Each point on the "signature plot" results from a continuous pass through the mill, during which the mill reaches steady state. The mill contents must be displaced several times in each pass, as retention of even a small amount of coarse particles will seriously underestimate full scale steady-state power. This is a crucial point that simply cannot be achieved in a batch test, because it does do not continuously add new material and can't ensure steady state. This requirement to achieve steady state is crucial for fine regrinding – fortunately it is also possible with relatively small samples (15 kg).
- Direct measurement of energy consumption from the agitator shaft, in the same way that energy is measured for full scale mills. This also done to accurately subtract the no-load power ensuring the lab mill will scale-up to any size mill.

Having developed this procedure for internal MIM operations use, it has now been successfully applied in other installations. Figure 2 demonstrates the scale-up performance for the 2.6MW (3500 hp) M10,000 IsaMill for Anglo Platinum.

Western Limb Tailings Retreatment Scale-up

IsaMill Model	Installed Power (kW)	Chamber Volume (L)	Specific Energy (kWh/t)	Pulp % Solids	P_{98} (µm)	P_{80} (µm)
M4	4	3.5	37	39	47.5	16.0
M10,000	2,600	10,000	37	42	42.5	16.5

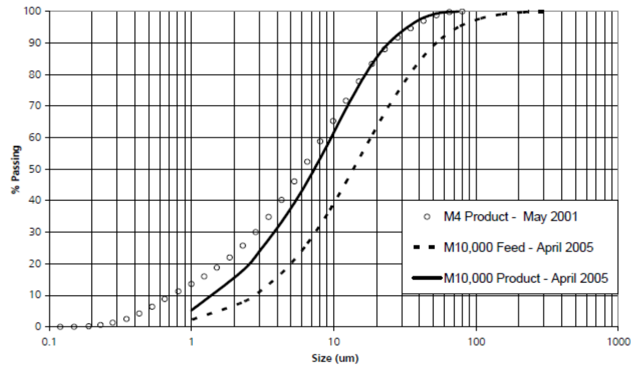

Figure 2. Western Limb M10,000 Scale-up (Curry D, Clark L, Rule C; 2005)

SMD Scale-up:

The scale-up performance of stirred mill detritors (SMD's) at the Century mine has been reported. (Gao M, Reemeyer L, Obeng D, Holmes R; 2007). The duty at Century is fine lead-zinc regrind, very similar to the George Fisher and MRM duties reported above. However for Century, an error of 20% was reported from the 0.55 kW lab mill to the full scale 355 kW mill- that is the full scale mill was less efficient than predicted from testwork. This may be attributed to measuring laboratory power draw by grinding chamber reaction torque rather than by direct measurement (Nesset J, Radziszewski P, Hardie C, Leroux D; 2006), but the power measurement had been corrected to be a direct power measurement and there was still a 20% error from the 0.55 kW lab mill to the full scale 355 kW mill, so this error may be due to not reaching a steady state operating condition in the mill.

SMD Scale-up

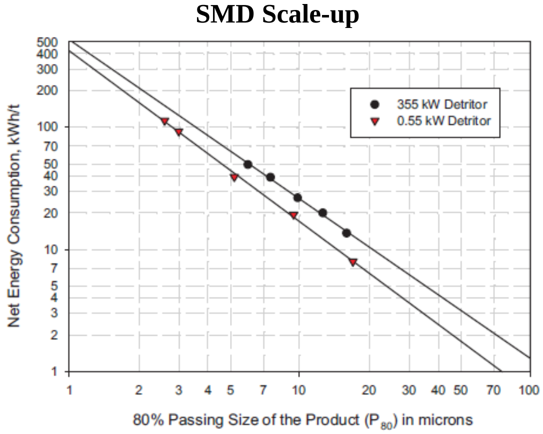

Figure 3. SMD Century scale-up (Gao et al, 2007)

The scale-up procedures developed for the IsaMill were then compared against the full scale Century SMD's. The IsaMill M4 procedure accurately predicted the full scale Century performance on a P_{80} basis. This is intuitively correct – though the mills have different designs (horizontal versus vertical), essentially they stir the same media at similar speeds, so should be expected to have similar energy requirements for gross size reduction. The only difference between the tests was the finer P_{98} (sharper size distribution) from the IsaMill, attributable to the internal product separator and the bypass losses that occur in the full scale SMDs.

Industrial SMD vs. Lab Scale IsaMill

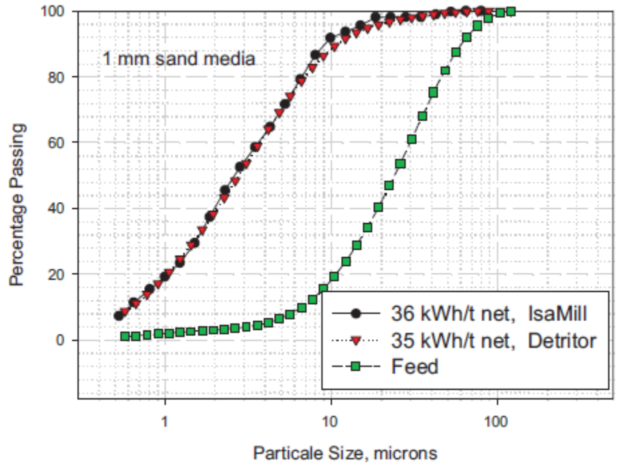

Figure 4. Full Scale SMD vs. 4 Liter IsaMill Comparison (Gao et al; 2007)

Errors Caused by Inadequate Top Size Breakage

A continuous test that simulates full scale grinding mechanism should give accurate scale up. However rigour is required to ensure coarse particles do not accumulate in the mill, and are adequately broken during the test. The importance of avoiding build up is discussed later – using too small a sample to reach steady state will *underestimate* energy. But failure to break top size particles can *overestimate* grinding power. If grinding media is too small to break the largest particles they will accumulate in the mill and displace grinding media. This reduces grinding efficiency while increasing power draw (analogous to “critical size” build up in a SAG mill). This reduction in grinding efficiency is not always evident if the particles are retained in the mill.

This was almost certainly the cause of the analogous data reported by Farber et al. This work compared two different media types, A and B. The smaller media appears to be more efficient but the results are misleading because of coarse material holdup in the mill. When this coarse material is taken into account the energy requirement is much higher. The first graph in Figure 5 demonstrates the lower friction of Type B media, leading to lower power draw on water. As expected, for any media type, smaller particles need less energy to mix than coarser ones. (it is easier to push your hand through a bucket of 3mm balls than a bucket of 12 mm balls). The same effect should be seen when operating with slurry, yet the second graph in Figure 5 shows the opposite effect – both media types are reported to consume more energy using fine media in ore grinding (“UG2” platinum ore). This almost certainly indicates the tests were in error – the fine media (1.7mm Type B and 2 mm Type A) was too small to break the top size, causing reduced grinding efficiency and holdup of coarse material in the mill. Therefore the resulting signature plots (Figure 6) are incorrect.

Media Power Draw

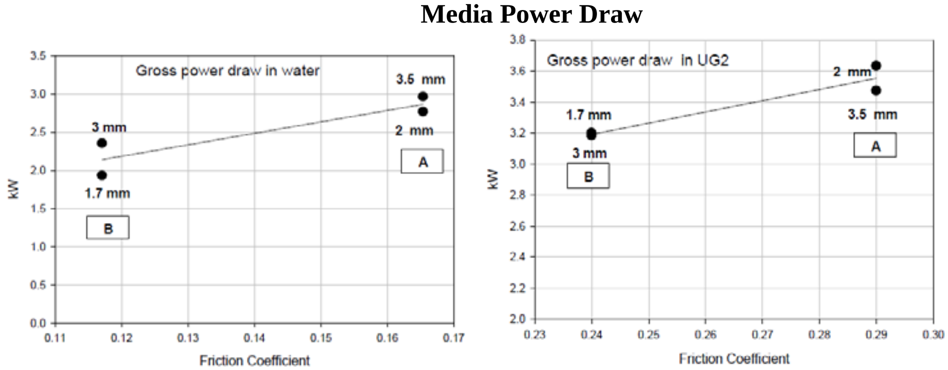

Figure 5. Power draw in water (left) and UG2 slurry (right) for first pass of Signature Plot test. (Farber et al; 2010)

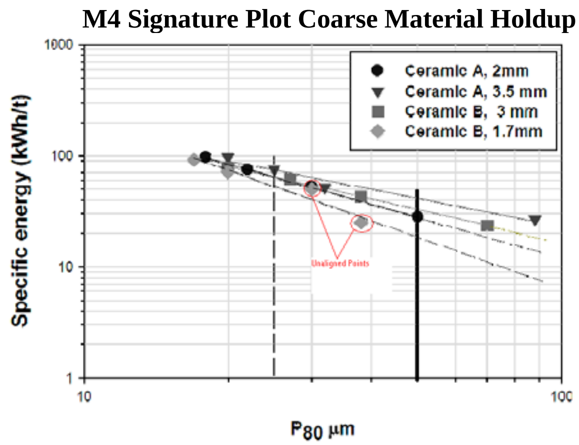

Figure 6. UG2 signature plot with different media size and media SG (Farber et al, 2010)

Indeed, there is a "fingerprint" of this error in Figure 6: the first point for 1.7mm Ceramic B does not fall on the same line as the other 3 points, rather it is finer than expected. This is a clear indication that coarse material was held in the mill in the first pass, that steady state had not been reached, and so the test is invalid. Note that this point's deviation does not "look" very significant on the wide log-log scale used in Figure 6. However it is a large deviation that would be much more apparent if the graph was redrawn with a better scale (10 to 100 kwh/t rather than 1 to 1000 kwh/t). Beware of the dangers hidden by log-log scales in fine grinding!

Similar investigations which correctly ensured top size breakage and steady state were conducted by Larson. Different sizes and types of media were compared in water and grinding copper ore. This yielded the expected results – smaller media is more efficient, drawing less power in both water (Figure 7) and copper ore (Figure 8), ***so long as*** it breaks top size particles.

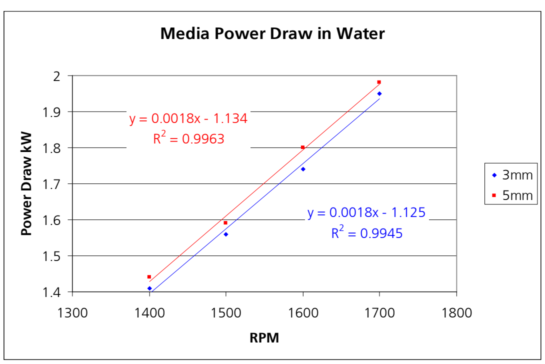

Figure 7. Hira media size vs gross power draw in water. (Larson M; 2010)

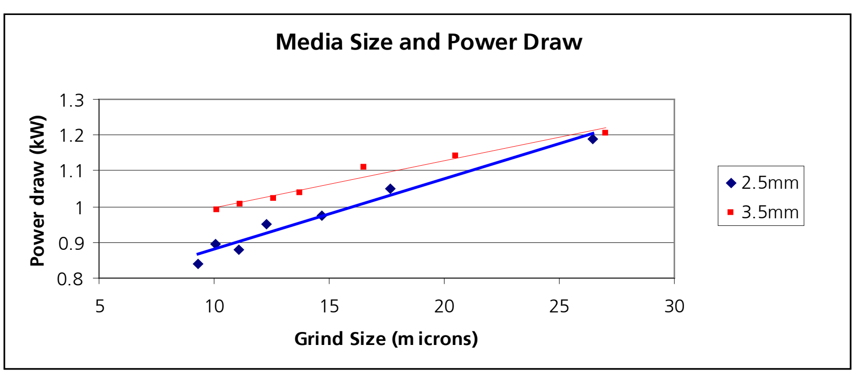

Figure 8. Media size power draw in copper concentrate slurry. (Larson M; 2010)

Figure 9 shows the difference in net power draw between the same two media charges but across different grind sizes. These were taken from individual signature plot tests on the same ore under the same operating conditions. Both media were capable of breaking the top size. The 5mm media resulted in a slightly smaller P_{98}/P_{80} ratio. It was 2.6 compared to 2.7 for the 3mm.

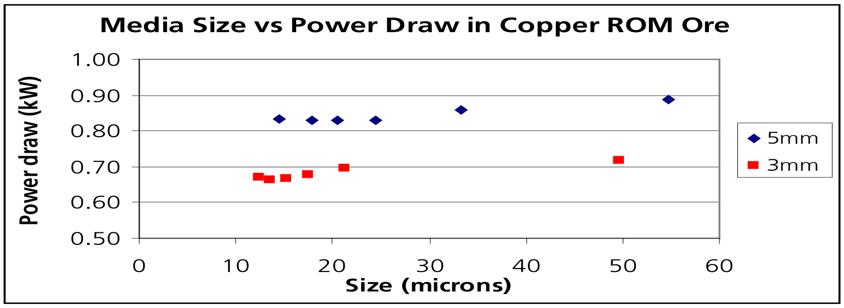

Figure 9. Hira media size vs. power draw in a copper ROM ore. (He M; 2010)

Again, as shown in Table 1 and Figures 8 & 9 the smaller MT1 media will also draw less power under the same slurry conditions. Further, as the slurry is ground finer the power draw will decrease. In Figure 8 the first points at 1.2 kW are almost the same power draw. At these points the 2.5mm media produced a P_{98} of 95µm and the 3.5mm media produced a P_{98} of 63µm. The finer points had closer ratios as the 2.5mm media was more capable of grinding the top size in these passes.

Net Mill Power at Different MT1 Media Sizes			
Media Size	1.5 mm	2.5 mm	3.5 mm
Net Mill Power	.80 kW	.98 kW	1.07 kW

Table 1. Average net mill power draw for copper concentrate varying only media size (Larson M; 2010)

Morenci M10,000 Scale-up:

The design of the Morenci M10,000 is described below and in Table 3. Though the M4 IsaMill test accurately predicted energy requirement to achieve P_{80}, it demonstrates other important factors required for accurate prediction of the P_{98}, as explained below (Cole J, Wilmot J; 2009)

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The design was for a P_{80} of 7 micron and a P_{98} of 15 micron. Actual feed sizes were P_{80} of 11 micron and a P_{98} of 34 micron with the Morenci concentrates. The Morenci concentrates contained variable amounts of pyrite which is more difficult to grind than a relatively pure chalcopyrite. Due to the mineralogy of Sierrita concentrates, containing approximately 85% chalcopyrite, a switch was made to process Sierrita concentrates. Sierrita concentrates were less variable in composition and softer than Morenci concentrates. Sierrita concentrates are also similar to the Bagdad concentrate which was used to size the IsaMill. The P_{80} and P_{98} from the Sierrita concentrates were finer than the Morenci concentrates, at 7.4 micron and 25 micron respectively, but were still not at the design criteria.

The design pyrite level in the concentrates was 22.5%, the actual varied from the low teens to as high as 55% on Morenci concentrates.

Morenci concentrate leach plant design criteria.

Morenci MT-DEW-SX	
Design Criteria	
Feed Rate, mtph	26.4
Super Fine Grinding	
Feed Rate, mtph	32.0
P80, µm	7.0
P98, µm	15.0
kWh/t	68.0

Table 2. Morenci M10,000 design criteria (Cole J, Wilmot J; 2009)

Even with the difference in ore mineralogy, this inability to achieve the P_{98}/P_{80} ratio as designed from the original testwork suggests that a small fraction of coarse, hard material was not fully ground and remained in the test mill. Though this is the only case so far when P_{80} scaled but the P_{98} did not, it suggests that if the objective of the testwork is highly accurate prediction of P_{98}, then the standard 15 kg of sample for an M4 may be insufficient.

Centerra Gold’s Kumtor Mine has a similar duty with M10,000 IsaMill grinding gold/pyrite feed from 20µm to a P_{80} of 10µm prior to cyanide leach. Figure 10 shows this scale-up was successful, including the predicted P_{98} (in fact, the full sized mill produced a slightly better size distribution than predicted).

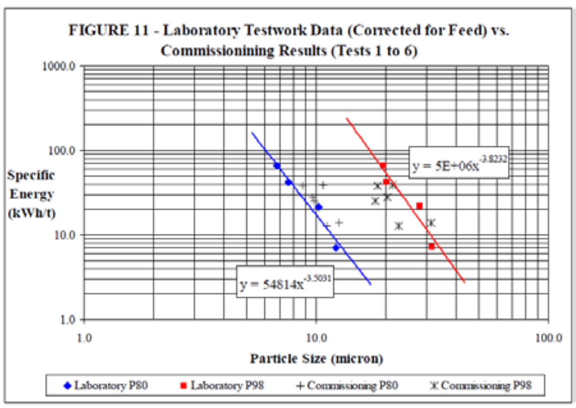

Figure 10. Kumtor M10,000 scale-up (Kazakoff J, Mortimore A, Smith S, Curry D; 06)

Tower Mill Procedures:

The test conditions for the Nippon Eirich Tower Mill are shown in Figure 11. These procedures raise several questions when compared with the requirements described above. Firstly, recirculating mill discharge directly to the mill feed pump means that steady state can never be reached – mill feed is almost instantly contaminated with fines from the “first pass” (in contrast, the M4 IsaMill tests passes the sample continuously from the feed tank through the mill into a separate product tank, reproducing full scale grinding).

Figure 11. Nippon Eirich Brochure; March 2009

Secondly, these tests appear to use a sample size far too small relative to the size of the test mill. Mill void volume must be replaced at least 3-4 times to achieve steady state and avoid hold-up of coarse particles (which causes serious underestimation of energy). Table 3 indicates this Tower Mill testwork uses about half the volume required to reach steady state.

Mill Type Test Feed vs. Void Space Ratio

Mill Type	Mill Open Volume(L)	Solid Volume(L)	Ratio (recommended above 3)
M4 IsaMill	1.35	5.0	3.70
NE008 Tower Mill	2.35	3.33	1.42
KM-5 Tower Mill	35.2	50.0	1.42
3.0 SG Solids, .66 Media Bulk Fill Ratio and .88 Mill Operating Volume Based on Geometry			

Table 3. Grinding test solids/open volume ratio comparison

The impact of too small a feed volume is demonstrated in Figure 12 from tests on a pilot Tower Mill. The signature plot shifts significantly from 50 liters of feed (0.7 times mill open volume) to 150 liters of feed (2 times open volume). Clearly the mill is not at steady state with the smaller volume. In this case the energy estimate to grind to a P_{80} of 70μm increases by 30% at the higher feed volume. In fact, the feed volume needs to be even higher than this, so the true error is even higher.

Combining too small a sample size with the error of diluting new feed with mill discharge compounds the error further, and is likely to lead to serious underestimation of true power requirement in a plant situation.

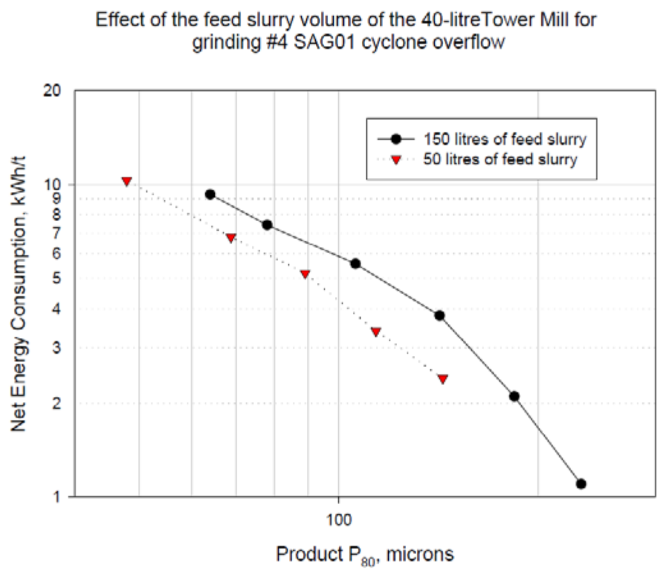

Figure 12. Effect of varying feed solids mass in a pilot tower mill (Gao M)

Extensive testwork has been done to ensure this is not a problem with the standard 15 kg M4 IsaMill testwork. One example is shown below comparing the signature plots generated with masses of 15 and 35 kg of common iron ore concentrate. In this case both tests consisted of a magnetite concentrate with a F_{80} of 65 microns being ground with 3.5mm media. The 3.5mm media was selected for its energy efficiency and ability to better break the top size than would happen with a smaller media. The resulting steep size distribution would show an improvement in final concentrate grade of 2-3% depending on the target grind. Both the P_{80} and P_{98} plots fall within the margin of error for the M4 test. The iron ore had a solid SG of 4.2. This is on the high side of what is normally tested. Anything lighter will take up more volume so the conclusions from this testwork will apply to those samples as well.

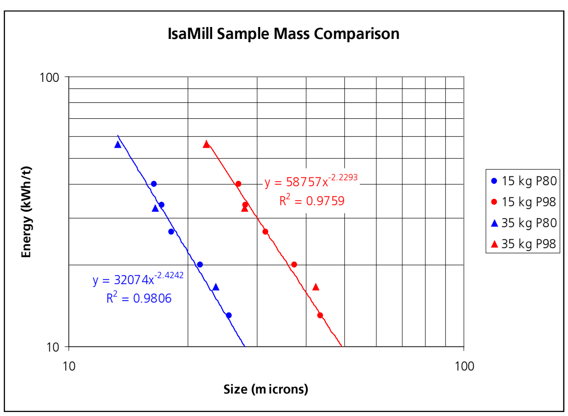

Figure 13. Effect on signature plot of varying feed mass in an M4 IsaMill (Larson M, Villadolid V; 2010)

The two tests resulted in respective points at 16.5 and 16.7 µm P_{80}'s at just over 40 kWh/t. A comparison of those two size distribution curves is given below. The shape is nearly identical. This would also indicate that at both sample masses the mill is discharging the same steady state sample with no segregation effects.

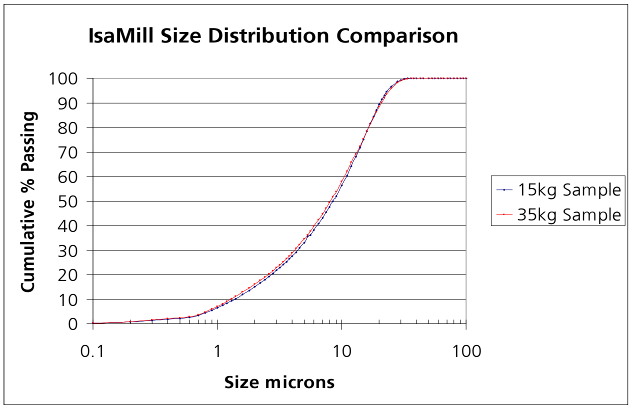

Figure 14. Effect of varying feed mass on M4 IsaMill product size distribution (Larson M, Villadolid V; 2010)

Nesset Regrind Comparison:

The 2006 paper by Nesset et al compared the grinding efficiency of a ball mill, IsaMill, SMD and Vertimill. It concluded that the SMD procedure of measuring power by reaction plate torque would underestimate energy requirements by 32% and 39% for the two media types that were tested. Once the SMD power was measured from the motor there was little difference in energy requirement between the IsaMill and SMD on a P_{80} basis, though there were differences at the P_{98} level. This supports the findings reported above. However, Nesset's paper also concluded that the laboratory Tower Mill was 43% more energy efficient than either the IsaMill or SMD, for the finest media tested in the Tower Mill. Since both the IsaMill and SMD were specifically developed and determined to be more efficient than Tower Mills for fine grinding, and this has been demonstrated consistently at plant scale, this conclusion needs further examination. It demonstrates another potential source of error in laboratory testing – using different size media than full scale.

Media size is crucial for fine grinding efficiency – the need to use finer media to increase energy efficiency drove the development of both the IsaMill and SMD. Nesset's Tower Mill tests used 5mm media, a size which is never used in plant installations, and the coarser media that were tested in the Tower Mill were much less energy efficient. The finest media practically used in operating Tower Mills is 12 mm (otherwise media floats from the mill). Per cubic metre, 5mm media has 2.4 times the surface area of 12 mm media – a huge difference for attrition grinding in a stirred mill. Nesset et al report the most efficient media sizes for different devices in Table 4. Though 5 mm media is most efficient in the ball and Tower Mill, the key point is that it cannot be practically used at large scale, both in terms of media retention and energy intensity (size of installation). This is precisely why the high speed stirred mill technologies (IsaMill and SMD) were developed – to practically achieve the energy efficiency benefits of fine media.

Efficient Media Size

Technology	Media Type	Media Size (mm)
IsaMill	Ceramic beads	2.2
SMD	Ceramic beads	2.2
VertiMill	Steel shots	5
Laboratory Ball Mill	Steel shots	5
Brunswick Zn Regrind Mill	Steel slugs	16

Table 4. Most efficient media sizes (Nesset et al; 2006)

Even the inappropriate media size does not fully explain the unusual Tower Mill efficiency reported by Nesset. It is likely that the Tower Mill testwork also failed to reach steady state and retained coarse particles in the mill. Not enough experimental information is available to confirm this, but based on reported sample size and number of tests, it appears that the Tower Mill feed may only have been 1.5 times mill void volume, not enough to reach steady state. This suspicion is supported by a graph (Figure 15 below) comparing product size distribution for three different media sizes. This reports that the 5mm media improved both P_{80} and P_{98} compared with coarser media. This is unexpected – usually coarse media breaks coarse particles more effectively (especially in stirred milling). This counter-intuitive result strongly suggests that coarse particles were retained in the Tower Mill in the test procedure, which would cause serious underestimation of energy requirements as described in earlier sections.

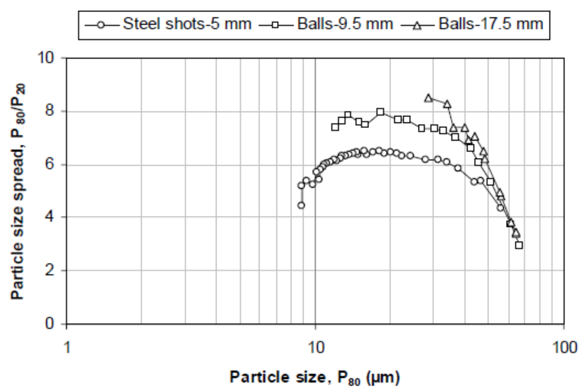

Figure 15. Vertimill product sharpness and media size (Nesset et al; 2006)

Comparison of Tower Mill Design and Operating Data

A short list of Tower Mill design and actual data is included in Table 5. This was compiled by publicly available data (Vendor installation list), AMIRA P336/P9 projects and Xstrata's own operating data.

Tower Mill Design vs. Operating Data

Application	Energy requirements for a target product size		Design/ Actual
	Vendor Design	Actual*	
Cu regrind	6 kWh/t for 45µm	13 kWh/t for 45µm	48%
Pb secondary grind	4.4 kWh/t for 63µm	7.9 kWh/t for 63µm	57%
Pb tertiary grind	7.1 kWh/t for 45µm	12 kWh/t for 45µm	63%
Zn regrind	5.7 kWh/t for 30µm	9.4 kWh/t for 30µm	61%
Zn regrind	19.4 kWh/t for 20µm	25.5 kWh/t for 20µm	76%
Pb regrind	16.7 kWh/t for 20µm	31 kWh/t for 20µm	54%
Ni regrind	11.7 kWh/t for 60µm	13.5 kWh/t for 60µm	84%
Fe regrind	9.4 kWh/t for 30µm	13.8 kWh/t for 30µm	68%

*Actual energy requirements were calculated using operating work index from plant surveys

Table 5. Tower Mill design and actual comparison

The operating work index was also calculated for all available full scale mill data and is shown in Figure 16. There is no design data included in this but it should serve as a guide as to what the mills are actually capable of. Recent regrinding designs falling in the lower area of the graph have significantly under quoted actual operating mills.

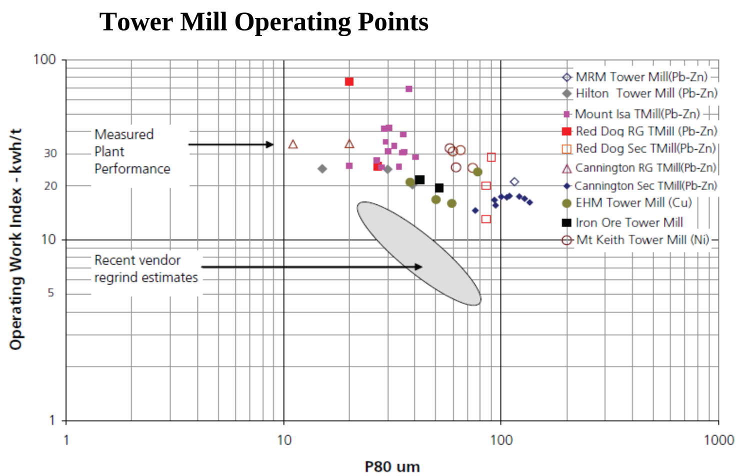

Figure 16. Tower mill operating work index summary (Pease J; 2010)

Modified Bond and Levin Tests:

The Levin test appears to be underused for sizing regrind ball mills. Examples of the results are shown in Table 6. The requirement of 20-30 kg may be a prohibitive factor. The Levin test is a modified Bond Ball test, but makes use of finer screen sizes, and finer feed sizing. In the Levin test the lab ball mill is run at varying lengths of time (energy). At the end of each interval the entire mill contents are emptied and screened at that intervals size. Any undersize is replaced with new top size to maintain a constant volume. This is completed from 75, 53, 45 and 38 microns. With 4 tests each requiring about 2 liters of material this could result in a requirement for more material than is possible to produce in a small pilot plant run given that it will likely be a rougher concentrate. However, if the material mass is possible it would appear that the test will give more accurate results than many of the alternatives.

COMPARISON OF PLANT DATA WITH RESULTS OF THE GRINDABILITY TEST

	kWh/t	
Materials and Origin	Plant	Grindability test for fine material
GOLD ore, East Driefontein	14.4	14.8
Gold ore, Libanon	10.8	11.3
Gold ore, Western Deep Levels, VCR Reef	14.7	13.8
Gold ore, Western Deep Levels, Carbon Leader	17.6	16.4
Fluorspar, Chemspar	4.3	3.3
Copper-lead-zinc ore, Black Mountain	12.8	11.1
Copper-zinc ore, Prieska	13.6	12.8
Sand tailing, Crown Mines	9.3	9.3

Table 6. Comparison of Levin test results with full scale ball mills (Levin J; 1989)

Operating conditions:

When downstream testwork has been done with product produced from one technology it should not be expected to transfer to a different grinding technology. Each will result in a different size distribution curve for a given P_{80}. The ratio between the P_{98} and the P_{80} should be considered for each.

This is important for the recovery in leaching as shown below. The more top size material present the less liberation there will be. Material ground to the same target P_{80} can have three times the top size present. This will also affect the final con grade during flotation as unliberated coarse particles will still float. Potentially these will contribute excess attached gangue minerals to the concentrate.

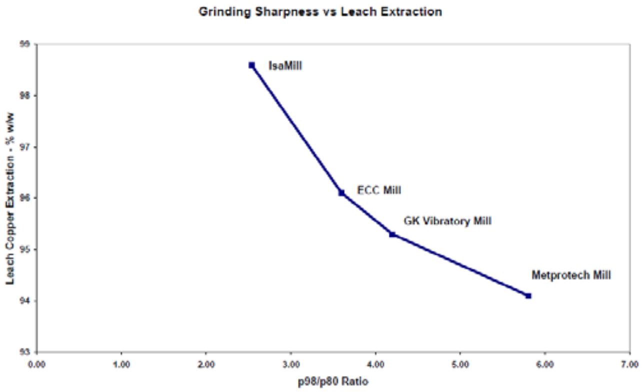

Figure 17. Effect of size distribution sharpness on leaching recovery (Pease J, Young M, Curry D; 2007)

Care should also be taken to do the scale-up testwork at the correct density. The effects of viscosity become more pronounced as the fine sizes common to regrinding are met. At some point depending on the surface area created the slurry will begin to carry the media rather than mixing it to grind. Xstrata Technology currently recommends the use of a Marsh funnel during testwork to control the density to optimize the effects of viscosity on energy efficiency. The Marsh funnel is simply a cone through which the time for the flow of one quart of slurry is measured. The Marsh funnel is not a comprehensive measurement of rheology but does serve to give a quick easy point of measurement ideal for use in multiple lab tests or in the field for site surveys.

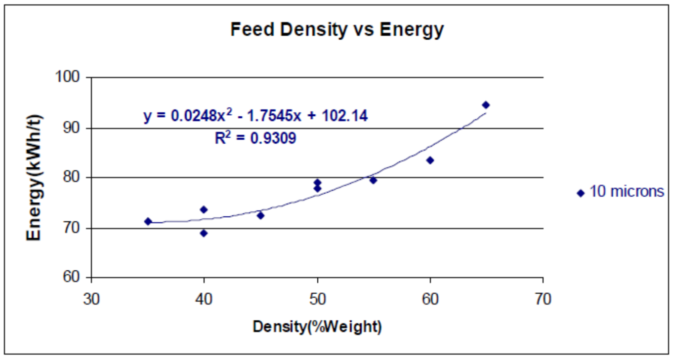

Figure 18. Effect of feed density on fine grinding efficiency (Larson M, Morrison R, Young M; 2008)

The Future:

Xstrata Technology is also striving to improve the scale-up ability of the IsaMill through sponsored and internal research. One of the most recent developments was the development of a JKSimMet model of the IsaMill. The basis of this model is a relatively simple function for predicting the creation of fines. The normal signature plot has one limitation in that the line created does not usually pass through the feed at 0 energy. This limits the signature plot to predicting energy requirements coarser than the band of sizes produced on the plot. It is possible to extrapolate finer however it is always best to actually cover those sizes in the testwork to be sure of the results.

The Squared Function for Fines Production also creates a linear relationship but also consistently passes through the feed at 0 energy. The model itself was inspired by McIvor's work (McIvor R and Finch J; 2007) demonstrating that new production finer than a certain target size is approximately linear for rod and ball mills. Plotting the percent passing a size vs. energy did not work for the IsaMill. It was found though that by squaring that % passing value a straight line through each point including the feed was developed as shown in Figure 19 for a variety of cooper ores. The only constraints are that the size shown has to be measureable in all of the samples. This will likely require a size between the F_{10} of the feed and the P_{90} of the product.

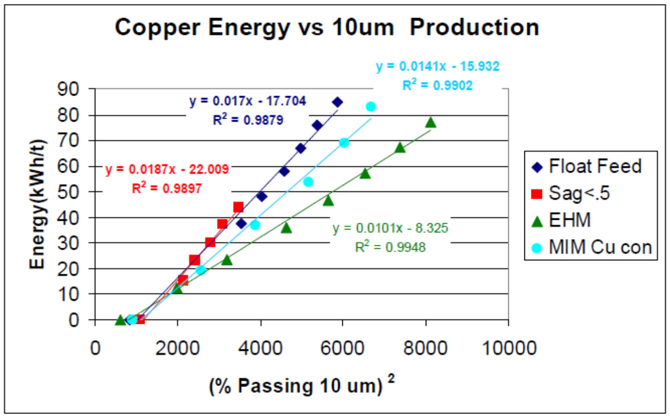

Figure 19. The squared function for fines production applied to different copper ores (Larson et al; 2008)

This method also enhances the ability to properly size a mill if the design feed size changes after testwork. By keeping the slope of the line parallel and changing the feed size a new energy can be calculated. In Figure 19 a signature plot line is plotted as the squared function. A new coarser feed can be plotted by calculating the new squared value and starting the new energy vs. size line at that point to the left of the original feed line. By keeping the new squared function line parallel to the original one a new energy can be calculated to the desired product.

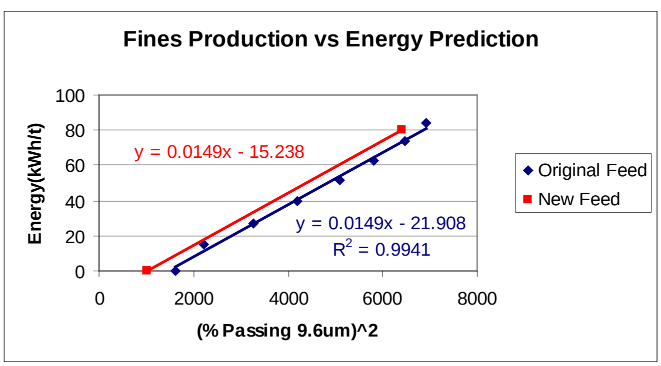

Figure 20. Squared function for fines production energy prediction for coarser feed (Larson; 2010)

The likely reason the squared function works is that the attrition grinding process is creating new surface area in a consistent manner. The IsaMill also results in a rounding of particles. As this should be the same for all attrition grinding processes there is a good probability that the squared function or something similar will apply to those as well.

Conclusions:

Currently a wide range of tests are used to predict regrinding requirements, and they result in enormous variation in predicted energy requirement. Clearly serious mistakes are being made, which will either lead to installing too much power, or too little power and resultant plant underperformance. The industry needs an accepted standard test to reliably predict regrinding energy. An essential part of this is an understanding of actual plant regrinding performance compared with design. The JKMRC Fine Grinding review aims to address these issues. Operators, designers and engineering companies should support a rigorous, independent review to establish industry performance and an industry standard.

Until this happens current scale-up methods have to be rigorously examined to ensure the regrind mills will perform as claimed. Designers should perform reality checks on all vendor estimates – not against other *designs*, but against actual *performance* of other installations.

Acknowledgements:

The authors wish to thank Xstrata Technology and the JKMRC for the research that went into this paper and for the helpful suggestions in writing it.

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