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KNELSON-DESWIK MILL: EVALUATION OF OPERATING VARIABLES

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INTRODUCTION

All ores have an economic optimum particle size (Wills and Napier-Munn, 2006). This optimum value is often a compromise between the need to achieve adequate liberation for the efficient separation and recovery of valuable minerals and the energy consumed by the crushing and grinding process.

It has been recognized for nearly three decades that grinding is the most expensive and least efficient stage in mineral processing (El-shall and Somasundaran, 1984). At that time it was estimated that grinding consumed between 25 and 70% of the total power required in mineral processing. This recognition drove the development of new stirred mill fine grinding technology in the 1990s (Jankovic et.al, 2003; Enderle et. al., 1997; Massey, 2008). These milling technologies have a reduced energy consumption compared to traditional fine grinding using ball mills. In the “coarser” fine grinding applications this improvement is approximately 30%. The benefits increase to above 50% in ultrafine grinding applications (Lichter and Davey, 2006).

Despite these gains, the US Department of Energy reported that an additional energy savings of up to 37% is possible in the minerals industry. They identified continuing research and development and implementing best practices in both grinding and materials handling as the primary avenues for the additional reduction (BCS, 2007).

The best practice in fine grinding using stirred mills will vary from site-to-site and from mill-to-mill. The complex nature of stirred ball milling was made clear as early as 1972 when Molls and Hornle identified 44 different variables which must be considered in wet grinding using a stirred ball mill (Stehr and Schwedes, 1983). Major variables such as mill orientation (horizontal or vertical) and impellor type are generally dictated by the design of a particular machine. However, the optimization of a given stirred mill with respect to specific energy input depends on the complex relationships between a large set of parameters. Examples include mill speed, media size, media loading, slurry density, slurry flow rate, slurry rheology, feed material characteristics, (Sachweh, 1997; Rahal, 1999; Jankovic, 2001; Kwade, 2010). This wide range of variables can be grouped into two classes of significant variables: mill configuration and process state (Figure 1).

The mill configuration variables are those that can be physically changed as part of the optimization process. Of these, mill speed, media size, media loading and media density are the most important. The mills speed determines the power intensity within the milling chamber and often has a direct impact on grinding efficiency. It impacts both the energy input to and frequency of breakage events (Gao and Weller, 1993; Jankovic, 2001).

In addition to the impellor speed, media size, load and density play an important part in determining the optimum specific energy input (Kwade, 2010). The media size must be selected based on the particle feed size. The bead load has an effect on both the number of breakage sites and the energy utilization within the mill (Gao and Forssberg, 1992) and the media density has an effect on both the torque required to drive the impellor (hence power) and the maximum slurry density that can be fed into the milling chamber.

The process state variables are similar to the mill configuration in that they have a significant effect on grinding performance. Unfortunately they cannot be adjusted as easily as the mill configuration. The slurry feed characteristics are largely determined by the ore body and as a result it is intractable. This necessitates laboratory or pilot milling tests over a range of operating conditions to ensure that the correct mill is selected for a given application (Lichter and Davey, 2006).

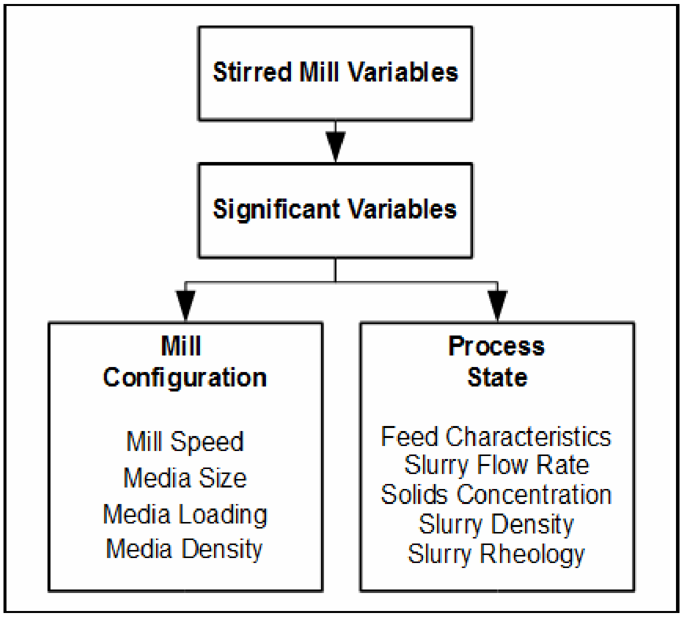


Figure 1. Critical mill operating variables (Rahal, 1999).

Pilot scale testing is preferred to laboratory testing because it allows the investigation of a wide range of operating variables on a continuous basis. On site trials allow a given mill type to be optimized for a desired product size and throughput based on the feed material properties (Gao and Weller, 1993).

Recent pilot studies showed the value of examining different mills types and operating conditions in terms of overall recovery (Jankovic et.al., 2003;Anyimadu et.al. 2006). The first of these studies also highlighted that two mills of the same orientation (vertical) have different optimum stress intensity ranges depending on mill speed, media size, media density and slurry density. They also claimed in related work that the optimum stress intensity can be determined using experiments with one media type and then used to calculate the optimum media size for other media types (Jankovic, 2001).

These results are important both in terms of site specific optimization and in developing precise scale-up procedures for fine grinding applications. The benefits are such that one author has stated that the only reliable method currently available for the selection of mills for ultrafine grinding is a well-planned and executed lab- or pilot-scale test regime (Lichter and Davey, 2006).

The remainder of this paper will demonstrate how a Knelson-Deswik pilot mill can be used to examine the effect of two mill configuration parameters on mill performance. The first of these examines the effect of different media loads and density on power draw. The second shows the effect of mill speed on grinding performance on a copper cleaner product at the Rio Tinto Northparkes Mine (NPM) in New South Wales, Australia.

KNELSON-DESWIK25

Knelson Milling Solutions (KMS) classifies its vertical stirred mill range according to their intended purpose. In broad terms, the mills can be classified as laboratory, pilot or production mills. The current limits for these categories are based on the net mill volume:

- Laboratory, <= 10 liters,
- Pilot, >= 25 and < 100 liters, and
- Production - >= 100 liters

The boundary between these categories is rather loose in that there have been cases where the larger laboratory mills have been used in small scale pilot studies. In the same way, the pilot scale mills have been used as the main production unit in some applications. The pilot mills provide a transition between laboratory and production scale because their size and portability make them well suited to both research and plant trials. The Knelson-Deswik25 is the smallest of the continuous production units that range in size from 25 to 2500 liters.

The Knelson-Deswik mills share a set of operating conditions that are common to the entire product range. The mills have been found to be most efficient when grinding a feed with a slurry density between 1.25 and 1.50 kg/L while operating at a tip speed between 10 and 12 m/s. The Knelson-Deswik25 used in this grinding program has a disc diameter of 195 mm so this translates to an optimum speed range between 980 and 1175 rpm. These operating ranges are important within the context of this paper because it will be shown later that the mill can be operated outside of these design ranges depending on the ultimate goals of the pilot program.

The Knelson-Deswik25 is the smallest of the Knelson-Deswik pilot scale mills. Its nominal operating parameters are summarized in Table 1. The parameters in the table are based on a “standard” grind of an intermediate solids SG and average reduction ratio. The mill capacity will vary from site to site depending on material properties and grinding duty.

Table 1. Knelson-Deswik25 standard operating parameters.

Mill Type	Knelson-Deswik25
Installed Power (kW)	30
Net Volume (L)	25.3
Nominal Media Charge (%)	65
Design Speed (rpm)	980-1175
Design Power (kW)	27
Throughput (kg/h)	500-1000
Volumetric Flow (lph)	300-1200

MILL CONFIGURATION TESTING

The trials described in this paper are divided into two separate parts: media load and density and mill speed. The first of these was carried out in Brisbane, Australia as part of the commissioning of the Knelson-Deswik25. This test work was carried out in “clean” facilities so the effect of media load and density on power draw cannot be directly correlated to grinding performance.

The second section illustrates the effect of mill speed on grinding efficiency. This set of experiments was carried out as part of a larger plant improvement program at the Northparkes Mine.

Media Load and Density

The grinding media used in a stirred ball mill is one of the dominant factors in determining the mill power draw. There has been a shift to higher quality, high density ceramics in an attempt to improve energy efficiency at many stirred milling applications (Burford and Niva, 2008). Media suppliers quote composition, load, density, hardness and roundness as parameters that will influence grinding efficiency. However, the affect of many of these parameters are currently ill defined.

This first mill configuration test illustrates the effect of media load and intrinsic density on the running torque in the Knelson-Deswik25. The tests were carried out with the two media types shown in Table 2. These beads are at the lower and upper ends of the intrinsic density range recommended by KMS. The media sizes and fraction of each size used in each media blend are shown in Table 2.

Table 2. Media specifications.

Media	Keramos	CZC
Composition	Al2O3, 92%	ZrO2, 85%
Intrinsic Density (kg/L)	3.6	6.2
Bulk Density (kg/L)	2.1	3.9
Bead Sizes In Mixture (mm)	3.0, 2.5	3.0, 2.6, 2.2
Blend Fraction	0.5, 0.5	0.2,0.5,0.3

The comparative test was done by the staged addition of media to provide the same media load (volume percent) as shown in Table 3 and Figure 2. At the time of these tests the speed control feedback loop was not fully implemented on the hydraulic drive system. This lack of automated control caused a decrease in impellor speed when the torque increased with media addition. The mill speed set point had to be manually increased to overcome this drop. The result was that the media loads were not all tested at the same impellor speed. Manual adjustments ensured that both media types were tested at similar speeds despite the variation in speed for the different media loads (Figure 3). The increase in speed at addition step seven was intentional rather than an effect of media load.

Table 3. Bead mass for a given media load

Addition Step	Media Load (%)	Keramos (kg)	CZC (kg)
1	17	-	17
2	22	-	22
3	26	15	27
4	31	17	32
5	36	20	43
6	42	23	48
7	47	26	56
8	55	29	65
9	63	35	
10	64	-	32
11	68	38	

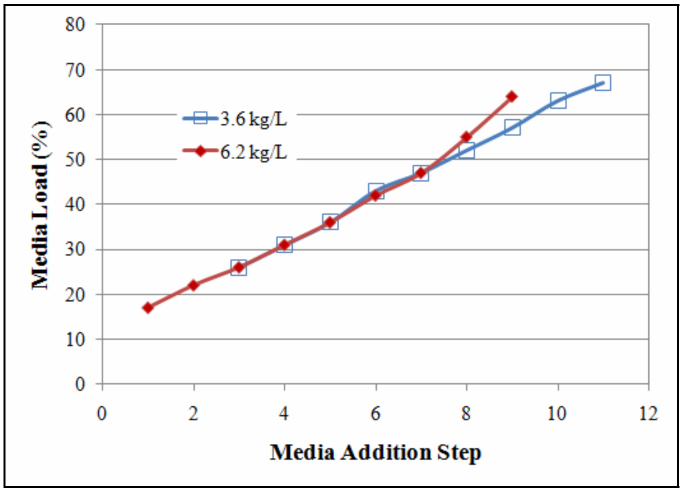


Figure 2. Media load at each media increment.

The effect of media load on mill torque can be seen to the left in Figure 4.It can be seen that at a given volume load the lighter bead produced a lower running torque. The two regression lines for the two media were compared based on a statistical method proposed by Naper-Munn (2003). The torque increased at a slower rate with respect to media load for the lighter bead than for the denser bead (1.05 and

1.85 Nm/% fill respectively). The two regression lines intersected at a media fill of 18 % (vol). This corresponds to the bottom two discs being cover.

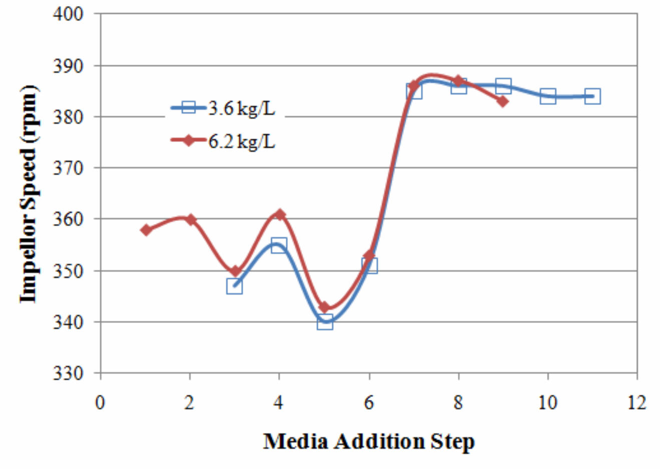


Figure 3. Mill speed at each media increment.

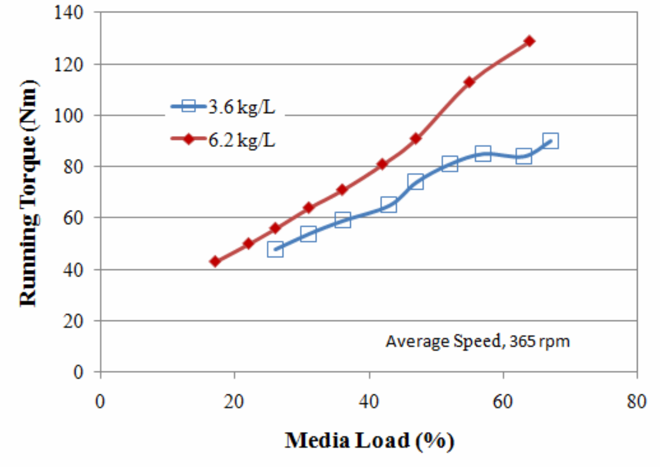


Figure 4. Running torque versus volumetric media load.

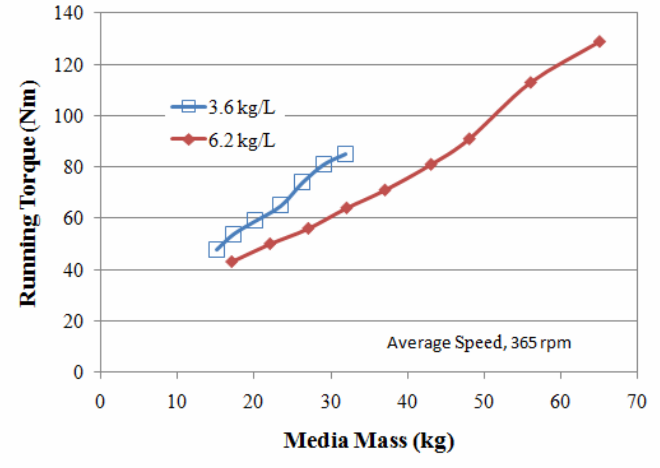


Figure 5. Running torque versus media mass.

Examining the data based on media mass rather than volume fill shows a different effect on running torque. Figure 5 shows that for the same media mass the 3.5 kg/L bead has a higher torque. This effect is driven by more surface area contact between the impellor and media. The same mass of the lighter beads occupy more of the mill volume if the two bead masses are equal.

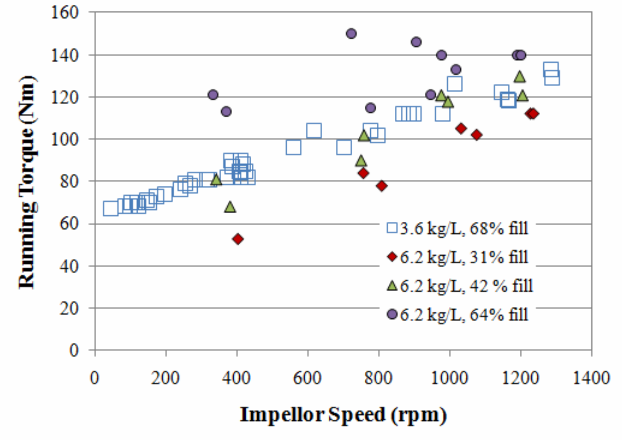


Figure 6. Running torque versus mill speed.

It is interesting to note that the rate of torque increase was the same for both media when related to media mass. There was no statistical difference between the slopes of the two lines (1.9 and 1.8 Nm/kg for the 3.6 and 6.2 kg/L beads respectively). On average the torque was 16 Nm higher for the same mass of the 3.6 kg/L beads.

The last component of the media study was to compare the torque at different media loads across a range of mill speeds (Figure 6). The lighter Keramos bead was tested by randomly varying the mill speed at a bead load of 68%. The data showed that the running torque had a linear response to mill speed (0.05 Nm/rpm). The denser Cenotec bead was then tested by generating a hysteresis loop of torque at three volume loads: 31, 42 and 64%. The speed was increased sequentially from the minimum to maximum speed before being decreased back to the minimum in the same way. In all three tests the torque was higher when the speed was being increased compared to the downward cycle. This effect was most pronounced in the 64% media load test. The difference between the up and down cycles was great enough to prohibit a linear fit of the data. It is included in the graph for completeness but it was not included in the comparative analysis.

The torque response to mill speed was the same for 6.2 kg/L bead at both the 31 and 42% media loads. The torque varied by 0.06 Nm/rpm. On average, increasing the media load from 31 to 42% increased the running torque by 17 Nm.

There was no statistically significant difference between the torque response in the 42% and 68% trials (6.2 and 3.6 kg/L respectively). The higher media load with the 3.6 kg/L bead increased the running torque by 9 Nm on average. However, this increase may be offset by the greater number of potential particle breakage sites within the milling environment. The results from this trial we be revisited in the context of a plant grind in the section below on mill speed.

Mill Speed

The importance of mill speed has been recognized by the mineral industry for many years. During the development and testing of the Knelson-Deswik milling technology in the 1990s it was determined that the optimum milling speed was between 10 and 12 m/s (tip speed). For the Knelson-Deswik25 these values correspond to operating speeds of 980 and 1175 rpm. This section will show that operating at the mill below this range has a detrimental effect on grinding performance.

A Knelson-Deswik25 was leased to the Rio Tinto Northparkes Mine (NPM) in December 2009 for use in a pilot scale study. The main goal of the pilot trial was to determine the flotation response of the copper cleaner streams at different product sizes, milling information was also collected to an attempt to improve grinding performance in subsequent pilot trials.

The original project plan was to have the Knelson-Deswik25 placed within the main plant near the flotation circuit. The mill was to be continuously fed from various process streams and sub-samples were to be taken periodically for batch flotation tests. Due to process constraints this was not feasible. As a result, cleaner feed and tails samples were collected for a series of batch grinding tests. Due to the narrowed scope of work, the flotation response was tested at only two sizes, 40 and 20 microns (P80).

The tests were carried out in what KMS defines as a pendulum test (Figure 7). The feed sample is transferred into the circuit prior to the grinding trial. The slurry is then pumped from one sump to another (e.g. Sump 1 to Sump 2) while passing through the grinding mill. The pass continues until the feed sump is fully emptied. The valves in the circuit are then changed to reverse the flow direction so the slurry is passed back through the mill (Sump 2 to Sump 1). In this way the complete sample is presented to the mill for progressive size reduction.

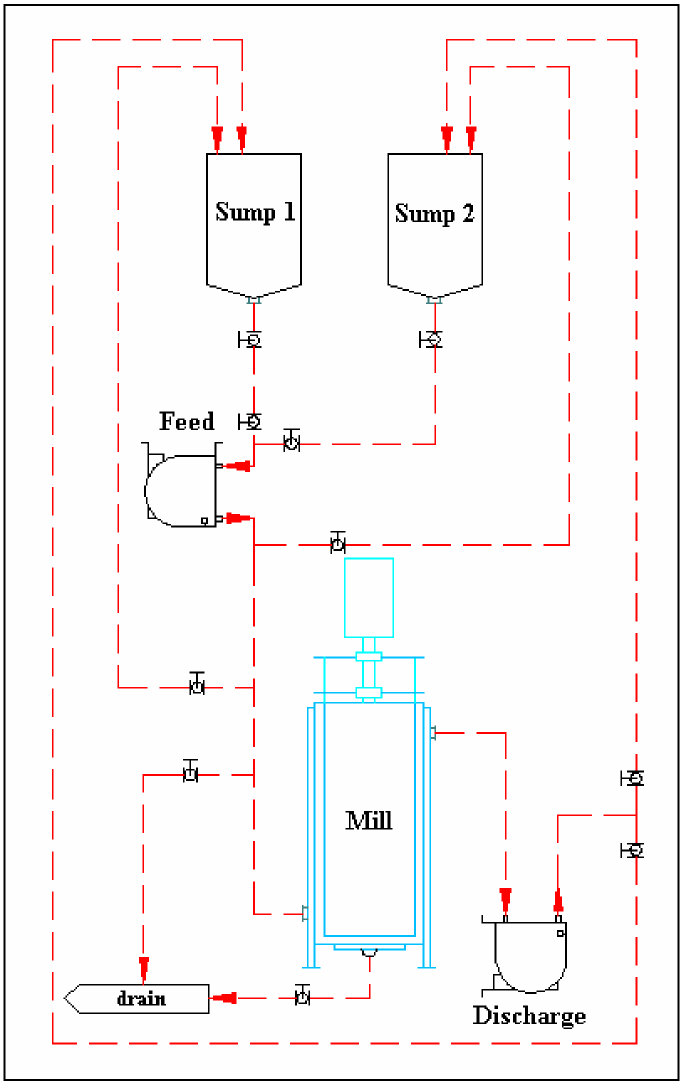


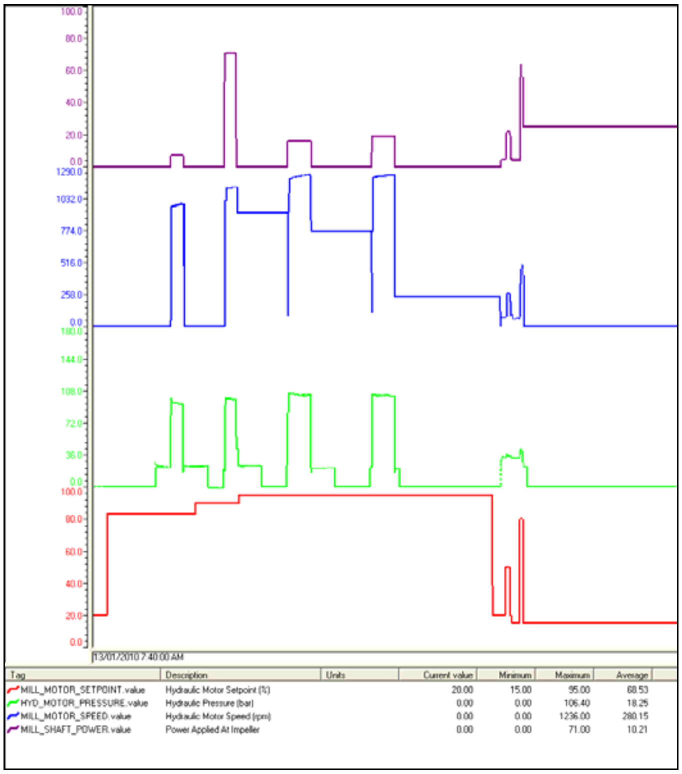
Figure 7. The pendulum testing flow circuit.

The standard test conditions for the NPM trials can be found in Table 4. The media charge of 54 kg was the same CZC media that was used in the media load tests. It was a blend of 3.0, 2.6 and 2.2 mm beads. All particle size distributions were measured using a Malvern Mastersizer 2000E. Milling data was collected both manually and by SCADA software (Figure 8).

A total of twelve grinding trials with associated batch flotation trials were carried out during the Northparkes grinding program. The slurry density and mill speed for tests can be seen in Figure 9 and Figure 10.

Table 4. Grinding test parameter summary.

	Parameter	Value
Mill	Power Supply (V)0	415
	Installed Power (kW)	30
	Motor Type	Hydraulic
	Impellor Speed (rpm)	48-1230
Slurry	Solids SG	3.8
	Solids Mass (kg)	8.9-21
	Solids Density (%)	8-28
	Slurry SG	1.09-1.26
	Pump Rate (lpm)	5-15



Tag	Description	Units	Current value	Minimum	Maximum	Average
MILL_MOTOR_SETPOINT.value	Hydraulic Motor Setpoint (%)		20.00	15.00	95.00	68.53
HYD_MOTOR_PRESSURE.value	Hydraulic Pressure (bar)		0.00	0.00	106.40	18.25
MILL_MOTOR_SPEED.value	Hydraulic Motor Speed (rpm)		0.00	0.00	1236.00	280.15
MILL_SHAFT_POWER.value	Power Applied At Impeller		0.00	0.00	71.00	10.21

Figure 8. SCADA capture of operating variables.

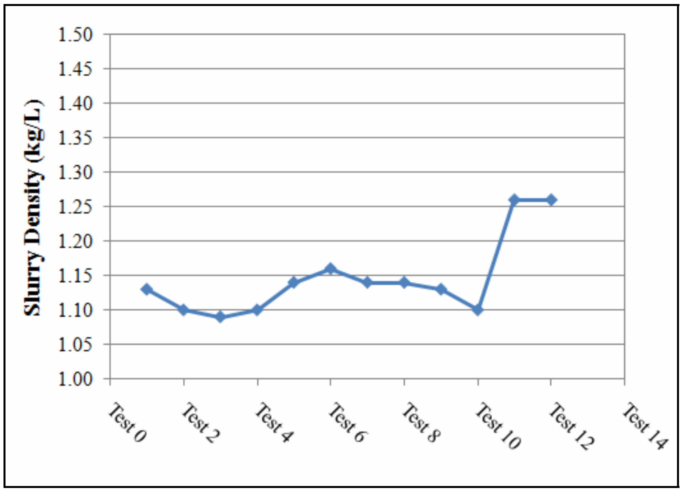


Figure 9. Slurry SG in the NPM grinding trials.

Figure 9 shows that the slurry density was below 1.16 kg/L for the first ten trials. This is below the optimum design range of 1.25 to 1.5 kg/L. The original project plan called for the use of a dewatering hydrocyclone to increase the slurry density to 1.25 kg/L. However the low operating volume for the cyclone circuit did not perform as expected. The decision was made to run at the slurry density of the flotation product rather than to settle and decant the slurry. There were concerns that allowing the sample to stand overnight would bias the flotation results by allowing a change in surface chemistry.

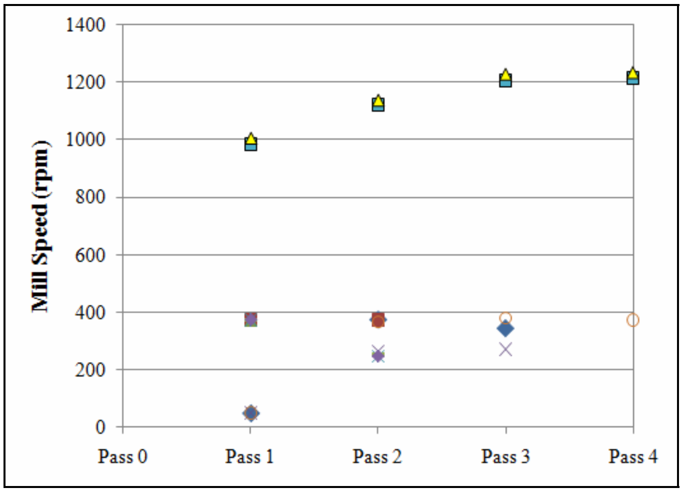


Figure 10. Mill speed in NPM grinding trials.

The feed to the last two tests were allowed to stand overnight and they were decanted to increase the slurry density. There was no flotation testing associated with these grinds.

The decision to carry out flotation tests at two product sizes required careful management of the grinding process. The feed sample was approximately 40 microns in many of the trials and there was the danger of grinding past the terminal product size of 20 microns. Figure 10 shows that the mill was run at low speed for the majority of the grinding trials to either produce a polishing grind or to slowly decrease the product size to 20 microns without the danger of over grinding. The mill speed was generally 48 and 380 rpm (0.48 and 3.8 m/s) for these two modes respectively.

The last two trials in the grinding program were carried out to show the benefits of grinding within the optimum design range for the Knelson-Deswik mills. The slurry density and operating speeds for Tests 11 and 12 are above the minimum recommended values of 1.25 kg/L and 10 m/s (slurry density and tip speed). The mill speeds for the last two grinds are the triangle and square series which range between 1000 and 1200 rpm in Figure 10.

Figure 11 shows the pass-by-pass product sizes for the twelve trials. It can be seen that the Knelson-Milling system offers the flexibility to achieve a target product size by varying mill speed. Most of the grinding trials were terminated with a product size of 20 ± 1 microns. The main exception was the two trials that were carried out to illustrate the effect of grinding at full speed. The Knelson-Deswik25 was able to achieve a sub-10 micron product after four passes through the mill.

The sizing results and mill operating data was used to generate signature plots for the grinding program. It can be seen in Figure 12 that the tests were grouped according to the feed source and mill speed. There was no significant difference between the copper cleaner feed and tails grinds at low speed. However, operating within the mill design range produced a much better specific energy consumption rate (red 'X'). The energy required to achieve different product sizes is shown in Table 5. A statistical comparison of the low speed trials showed that there was no significant difference between the cleaner feed and cleaner tail products when the mill was operated at a tip speed below 3.8 m/s.

The power consumption in the NPM trials can be related to the media testing described in the proceeding section. The mill was loaded with 54 kg of the 6.2 kg/L media blend (3.0, 2.6, and 2.2 mm). This is a 52% media load. It can be seen in Figure 13 that the running torque was the same for both the copper cleaner grinds and the media and water trials.

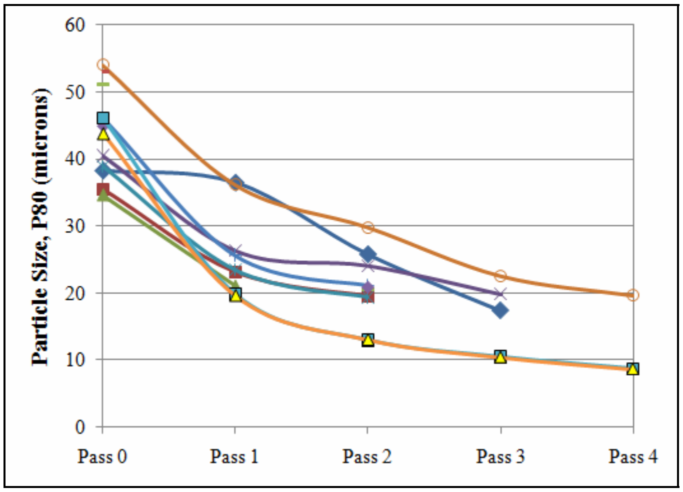


Figure 11. Particle size results from grinding trials.

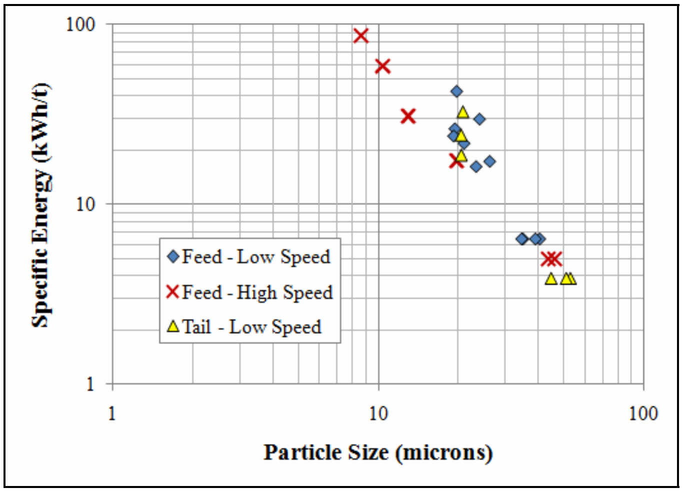


Figure 12. NPM signature plots.

Table 5. Specific energy consumption (kWh/t) at high and low speeds.

Product Size (microns)	Cu Cleaner Feed High, >10 m/s	Cu Cleaner Feed Low, < 3.8 m/s
40	6	6
30	9	11
20	18	29
15	30	56
10	59	145

The similarity between running torque and mill speed observed in the NPM grinding program and the previous 6.3 kg/L torque data highlights the potential optimization of the media load. If the lower density media is able to provide the same grind the power draw, and specific energy consumption would decrease for the same product size.

CONCLUSION

The minerals industry will continue to mine fine grained ore deposits for the foreseeable future. This recognition spurred the development of fine grinding technology in the 1990s. This new processing equipment, namely the stirred media mill, increased energy efficiency in fine and ultrafine grinding. There still remains considerable scope for improving the use of stirred mills through research and development and the subsequent implementation of best practices for fine grinding.

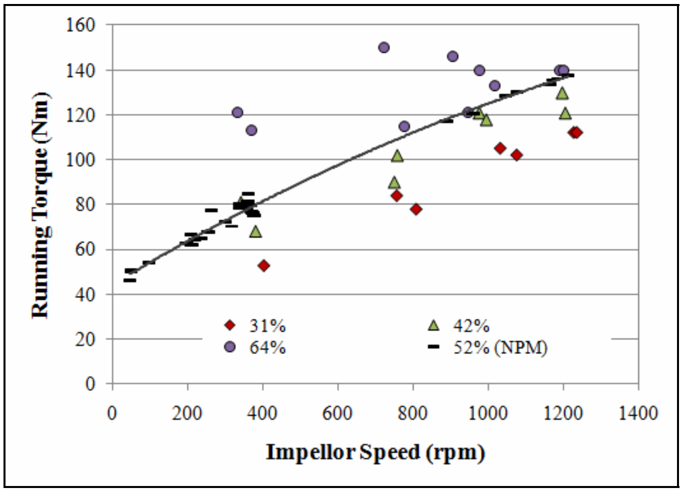


Figure 13. NPM running torque compared to water only media trials.

This work has focused on improving the use of a vertical stirred media mill (Knelson-Deswik25). It has contributed to the general body of research by examining the effect of media load and density on mill torque (power). It also showed that grinding is more efficient if a mill is operated within its optimum design range.

The effect of media density on running torque will depend on whether the media load or media mass is referenced. The 3.6 kg/L bead produced a lower torque per unit mass but a higher torque per unit volume than the 6.2 kg/L media. Operating the mill at a media load of 67% with the lighter bead only increased the running torque by an average of 9 Nm (across a range of 70 to 120 Nm). This increase in torque may be offset by the increase in the number of breakage sites (bead-to-bead contacts) at this higher media load.

The benefits of operating the pilot mill within its optimum design range is shown by the grinding trials carried out at Northparkes Mine. The mill was operated at low speed for the majority of the grinding program to target a specific product size. These tests had a higher specific energy consumption compared to the full speed trials where the tip speed was greater than 10 m/s (980 rpm). The specific energy consumption required to grind the copper cleaner feed to 10 microns was 59 kWh/t when the mill was operated with a tip speed of greater than 10 m/s. This consumption figure increased to 149 kWh/t if the mill was operated with a tip speed below 3.8 m/s

The relationship between media load and mill speed shows potential for further development at Northparkes Mine. The copper cleaner test grinds showed the same running torque versus mill speed trend that was observed in the media and water trials. Northparkes is currently considering a second round of pilot trials at their site using the Knelson-Deswik25. The lower density media may prove to be a better media selection if it can maintain the grinding rate while providing a lower running torque.

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