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Knelson-Deswik Milling Technology: Bridging the Gap between Low and High Speed Stirred Mills

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ABSTRACT

Over the past twenty years there has been an increased emphasis on fine grinding in the minerals industry. This spurred the development of a range of new fine grinding equipment in the 1990s. At that time, the Knelson-Deswik mill was developed in South Africa for the pigments industry.

Knelson Milling Solutions currently offers a wide range of laboratory, pilot and production scale mills. These mills bridge the gap between traditional low speed vertical mills and the high speed horizontal mills (tip speed < 3 and > 15 m/s respectively). They are designed to run at tip speeds between 10 and 12 m/s and are capable of operating with very dense grinding media. The result is a power intensity that is higher than the low speed mills and overlaps that of the high speed mills. This allows the mill to be customized for a wide range of grinding applications.

A case study at Aquarius Platinum's Kroondal Mine shows that the Knelson-Deswik technology can produce a consistent product size despite feed variations. It also shows that the throughput was proportional to the slurry density at Kroondal. The case study identified increasing the slurry density as a process change that can increase throughput and reduce the specific energy consumption.

INTRODUCTION

The increasing complexity and finer grain sizes of modern ore bodies have increased the importance of effective mineral liberation in obtaining acceptable grades and recoveries (Jankovic, Valery and La Rosa, 2003; Lichter and Davey, 2006; Napier-Munn, Morell, Morrison and Kojovic, 1996). This trend has increased the significance of fine grinding technology because the input energy increases exponentially as the required product size decreases from 100 to 10 microns (Gao and Weller, 1993a).

The US Department of Energy recently provided the context for the potential energy savings in the US Mining Industry (BCS, 2007). They reported that grinding consumes approximately 494 TBtu/year. This was over double the consumption of the second highest equipment category, diesel materials handling systems (211 TBtu/yr). The proportion of grinding energy allocated to fine grinding can only be expected to increase as finer ore deposits are mined. It is therefore critical that fine grinding efficiency continue to improve through the selection of appropriate equipment and the development of best practices for existing applications.

The basic principles of stirred ball milling can be traced back nearly seventy years to a description by Klein and Szegvari in 1928 (Napier-Munn et al., 1996; Russell, 1989). The technology was neglected by the minerals industry until the 1950s when the tower mill, a type of stirred mill, was developed by the Japan Tower Mill Company (later renamed the Kubota Tower Mill Corporation). The development of the tower mill was followed by the introduction of the stirred mill detritor (SMD) in the 1960s (Jankovic et al., 2003). It was not until the late 1980s that the changing needs of the minerals industry spurred the development of new higher capacity stirred milling technology (Capstick, 2008; Enderle, Woodall, Duffy and Johnson, 1997; Jankovic et al., 2003). The benefits of these recent developments are such that the stirred mills are now commonly used for fine (15-40 microns) and ultra-fine (<15 microns) grinding applications (Wills and Napier-Munn, 2006).

The most obvious differentiators between the stirred mills are the design of the media agitator (impellor) and the orientation of the stationary shell. The differences between the various stirrer designs are not currently well defined. However, the perforated disc design appears to be more wear resistant than the pin and eccentric disc stirrers. In contrast, the pin and eccentric discs provide a more violent stirring action (Gao and Weller, 1993b). The third major impellor type is the screw agitator found in the tower and Vertimills™. It differs from the other designs in that the screw provides lift in addition to tangential media movement. This screw-type design appears to be restricted to vertical mills while the perforated discs have been used in both vertical and horizontal applications.

The mill orientation is specified as either vertical or horizontal depending on the direction of the grinding chamber centerline (Figure 1). There appears to be debate about the relative merits of the two types within the industry. It has been reported that the horizontal orientation allows a higher energy input due to lower media pressure. This reduces wear and allows operation at higher impellor speeds (Gao and Weller, 1994). Others counter that the lower speed mills are competitive because they are less expensive to construct and maintain (Jankovic et al., 2003). The most appropriate orientation will be application specific because the distribution of media and slurry within the mill also depends on process related parameters such as slurry viscosity, slurry feed rate, the media size, and the media density (Orumwense and Forssberg, 1992; Sinnott, Cleary and Morrison, 2009). As a basic rule, the most advantageous orientation is the one that results in an equal media distribution within the mill chamber (Stehr, 1988).

A more recent trend in stirred mill classification is based on the tip speed (tangential velocity) of the mill impellor. Low speed mills are those with a tip speed below 3 m/s while high speed mills operate at speeds greater than 15 m/s. The effective size reduction limit for these two speeds are quoted as being 15 and 5 microns (80% passing) respectively (Jankovic et al., 2003).

Irrespective of impellor type, mill orientation, and speed classification, all stirred mills have operating variables that can be optimized to reduce energy consumption. Of these, there are a number of critical parameters that have a dominant effect on mill performance (Gao and Weller, 1993a; Orumwense and Forssberg, 1992; Rahal, 1999; Sachweh, 1997). These can be best described as process state and mill configuration variables:

- Process State
    - Feed characteristics, reference particle size and distribution shape,
    - Solids density,
    - Slurry density,
    - Slurry flow rate, and
    - Slurry rheology.

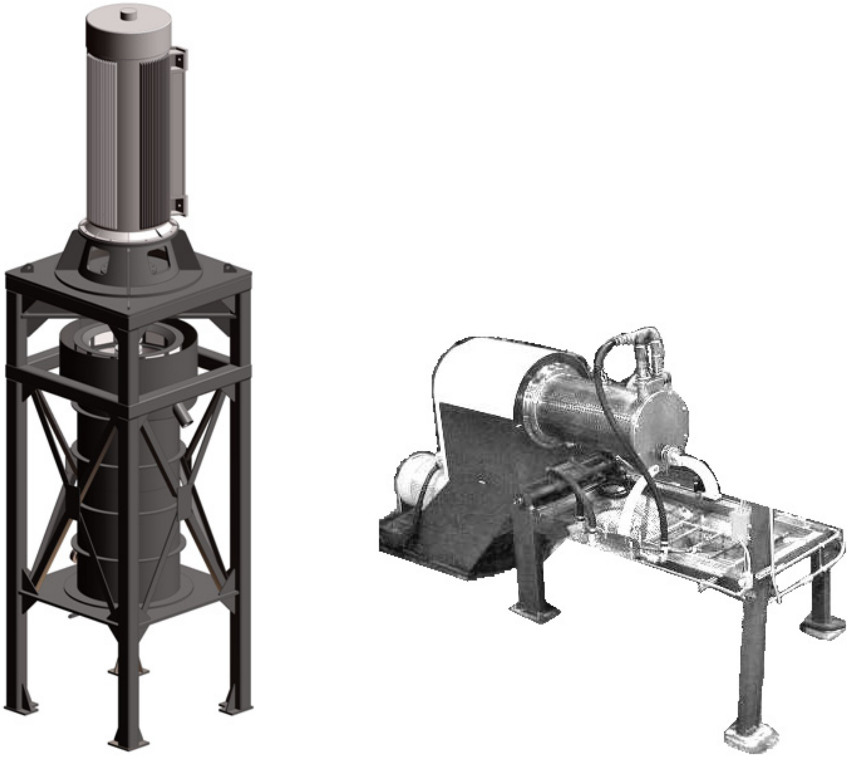

Figure 1: Vertical and horizontal stirred media mill orientations.

- Mill Configuration
    - Impellor design,
    - Mill speed,
    - Media size,
    - Media load, and
    - Media density

The first of these, material feed characteristics, is difficult to control because it is largely determined by the ore body and prior metallurgical processing. Despite the difficulty, there is some scope for manipulating the nominal size and particle size distribution through scalping using screens or hydrocyclones. In a similar way, the solids density (percent solids) can be modified using either hydrocyclones or water addition to vary the solids fraction. This will have a subsequent effect on slurry density because the slurry specific gravity depends on both the solids density and the specific gravity of the (dry) solids. The feed characteristics and solids density will also have an effect on the slurry flow rate. The intensity of the grind required to achieve a target product size will affect how fast the slurry can be pumped through the mill. This can be modified somewhat by increasing the solids density to decrease the total volumetric flow rate. However, there are limits to the solids load that can be sustained due to the rheology of dense, fine particle slurries. Of the process state variables, slurry rheology is the most difficult to measure and control. The rheology of mineral-particulate suspensions is dominated by non-Newtonian behavior (the viscosity depends on shear rate) which depends on a wide range of variables (Cheng, 1980).

In contrast to the process state variables, the mill configuration can be modified to suit a given application. (The mill orientation is not included in the configuration list because it is fixed for a given mill design.) The first two mill configuration variables, impellor design and mill speed, have been described in general terms above. It is unclear in the literature to what extent these variables are manipulated for specific applications. Jankovic et al. (2003) noted that the wear surfaces on the screw assembly can be modified depending on the nature of the material being ground. Gao, Young and Allum (2002) also noted that the number of discs in a horizontal mill could be changed. They found that grinding performance at Mount Isa Mines improved when they increased the number of discs in a horizontal mill from six to eight. The change in the number of discs on the impellor appeared to be part of the product development cycle rather than attempt to customize the layout for a specific feed material. The standard layout for the IsaMill™ was recently reported to still have eight discs (Burford and Niva, 2008). Presumably the screw flight (angle) and disc configuration could be modified as required for most stirred mills. However the effects of these changes have not been fully explored or are not well documented.

Unlike the impellor configuration, it is clear that mill speed is an important control variable for all stirred mill designs (Curry, Clarke and Rule, 2005; Curry and Clermont, 2005; Jankovic, 2001; Jankovic et al. 2003; Kwade, 2010; Rahal, Roberts and Rivett, 2011). The mill speed, by determining the power draft of the mill, also determines the power intensity within the milling chamber. This has a direct impact on grinding efficiency because the maximum power intensity decides the breakage rate of the size reduction process (Gao and Weller, 1993a). In addition, there have been tests carried out that show selective mineral breakage can be achieved by changing the mill speed to vary the power intensity (Parry, 2006). The mill speed also interacts with the impellor design to determine the distribution of slurry and media within the mill (Sinnott et al, 2009).

The final three mill configuration variables all reflect changes in the grinding media. The media size, density and load are varied according to mill type and grinding duty. It has been shown in numerous trials over the past thirty years that there is an optimum media size for a given grinding environment (Conley, 1983; Gao and Weller, 1993a; Mankosa, Adel and Yoon, 1986; Mankosa, Adel and Yoon, 1989; Persson and Forssberg, 1994; Yue and Klein, 2006). This optimum has been most closely related to feed size where ratios between 7:1 and 80:1 have been found depending on operating conditions. This relationship is reflected in the common use of tower mills at the coarser end of the fine grinding spectrum due to their ability to handle larger media (Wills and Napier-Munn, 2006). Higher energy mills typically use smaller media and focus on finer feeds to achieve product sizes below 30 microns (Burford and Niva, 2008).

Lichter and Davey (2006) observed that the grinding media can cause up to a 30% change in the specific energy required to achieve a target grind. This change can be attributed to a combination of bead size, media load (volume %), and the intrinsic density of the media. Increasing the media load provides additional particle breakage sites but increases the running torque (power). A lower bead density decreases the running torque at a given media load (Figure 2).

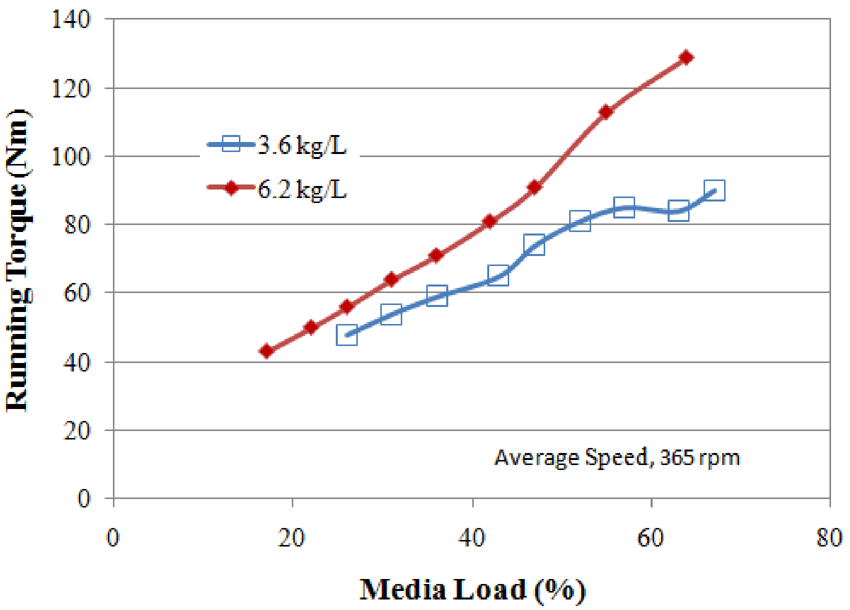

Figure 2: Effect of media load on torque at two media densities (after Rahal et al., 2011).

Taken in isolation, these media trends may lead to the (false) conclusion that the mill should be charged to a maximum fill with the lightest beads possible. However, there is a lower limit to the permissible media density as shown by the grinding media stress intensity relationship proposed by Kwade et al. (1996):

$$SI_m = D_m^3\left(\rho_m - \rho_s\right)v_t^2$$

Where SIm = stress intensity of the grinding media (Nm)

D_m – grinding media size (m)
ρ_m – grinding media density (kg/m3)
ρ_s – slurry density (kg/m3)
v_t = impellor tip speed (m/s)

It is clear in this relationship that the stress intensity approaches zero as the media and slurry density converge. The practical limits on the media diameter are related to the intended feed size while the maximum tip speed is limited by the drive system and wear rate of mill components.

Jankovic (2001) used the stress intensity relationship to compare the efficiency of two vertical stirred mills in grinding calcium carbonate. The author noted that both the tower mill and pin mill had an optimum stress intensity for a specific energy input of 20 kWh/t (combination of media size, tip speed and media density). Although both mills had an optimum value, the pin mill produced a finer product size than the tower mill (approximately 14 and 19 microns respectively). The better performance was attributed to the higher tip speed (2.5 versus 0.74 m/s) generating more media collisions with sufficient stress intensity to break particles. There was therefore less wasted energy. The author further developed this relationship in later work to identify that each grinding application has an optimum stress intensity. If the stress intensity is too low, several stress events are required to break a particle. This causes a reduction in breakage rate. However, if the energy is much higher than required for breakage, it will be wasted (Jankovic et al., 2003).

These media stress and power intensity results are particularly important when considering the fine grinding equipment that has been available to the minerals industry over the past ten year. There is a large gap between the tip speed and power intensity of the low speed vertical mills and the high speed horizontal mills. The Knelson-Deswik mill described below bridges the gap between these two extremes as shown in Table 1 (modified here from Weller and Gao, 1999 as cited in Wills and Napier-Munn, 2006).

Table 1: Power Intensity and tip speed of the various stirred mill types.

Type	*Power Intensity (kW/m^3)*	*Tip Speed (m/s)*
Tower Mill (Vertimill™)	20-40	< 3
Vertical Pin Stirred Mill	50-100	< 3
Knelson-Deswik Mill	240-765	10-12
Horizontal Stirred Mills	300-1000	> 15

KNELSON-DESWIK TECHNOLOGY

The Knelson-Deswik mills are vertical stirred mills which are designed for fine grinding applications across a wide range of operating conditions. They were originally developed in the mid 1990s to provide an economic means for producing fine pigments for the South African manufacturing industry. The technology has progressed from humble beginnings within a family owned milling business to a robust milling system that is manufactured and marketed by a global equipment supplier.

Development History

During the mid 1990s, the problem of iron bearing salts being discharged into the environment came under increased scrutiny. There were concerns that iron salts would contribute to an increase in ground water pollution (e.g. detergents) due to their destruction of the natural algae that would normally break down contaminants. This change in environmental regulation was of particular importance in the manufacture of magnetite pigments in South Africa.

Magnetite pigments are a black iron oxide that is often used for the coloring of ultra violet resistant roofing tiles, paving bricks, rubber and plastics. The conventional method for creating these pigments was to dissolve scrap carbon steel in either sulfuric or hydrochloric acid to produce either ferric chloride or ferric sulfate. Different iron oxide based pigments, such as magnetite, hematite, and limonite, were then created through precipitation by varying the pH of the resulting solution. The disadvantage of this process is that iron salts are a byproduct which has the potential to become contaminants in the local ground water. The tightening of the iron salts regulations led a major South African corporation to request that Des Erasmus investigate new methods for the manufacture of magnetite pigments.

Des was working as an independent chemical engineering consultant at that time so he investigated a wide range of alternate chemical processes for creating magnetite pigments. In each case he found that either iron salts continued to be a byproduct or the high cost of any alternative process rendered it uneconomic. This led to the decision to abandon the precipitation method and to investigate the production of pigment by milling naturally occurring magnetite.

Magnetite is readily available in the South African market because it is a common by-product from copper mining operations. It was readily available in two common size ranges. The dense media separation market commonly supplies 90% passing (d_{90}) 45 micron magnetite for use in the suspension media in coal heavy media separation processes. A coarser magnetite feed, 300 micron (d_{90}), was also available from copper mines such as Palabora. It was believed that the ready availability of two feed stocks would make the direct milling of magnetite a straight forward process. However it proved to be difficult to achieve the mean particle size required for high quality magnetite pigments (50% passing 0.2 microns).

Des carried out grinding trials using various conventional mills available in South Africa as part of this testing program. He discovered that 45 microns was the lower economical limit for milling magnetite with this range of equipment. In an effort to achieve better results, he obtained a conventional bead mill. However, he found that the bead mill had a practical limit of around 10 microns. This led to a development campaign with the goal of producing a bead mill that could economically produce the 0.2 micron product size (d_{50}) required by the pigments industry.

Des and his son Wikus began to experiment with the different milling parameters to determine their effect on grinding performance in a horizontal bead mill. They examined wear materials, impellor types, mill dimension and media types over the course of a year. The result was the development of the Collorox horizontal mill that was used for magnetite grinding in South Africa and the United States. This mill was capable of batch grinding a 75 micron feed down to 0.2 microns (Figure 3). This design was used for two years on a wide range of products which included calcium carbonate, ilmenite, iron pyrites and chrome sands. Over that time, it became apparent that there were shortcomings in the horizontal design. The most important of these were:

- Cavitation at elevated impeller speeds,
- Back pressure in the barrel due to screen blockages,
- Destruction of the mechanical seal,
- Seizure of the impeller due to bead compaction,
- Low utilization due to excessive maintenance, and
- Excessive impeller wear

As a result, Des and Wikus formed the company Deswik (Pty) Ltd. in 2002 and began to experiment with different vertical mill designs (Figure 4). The experience gained during the testing of the original horizontal mill shortened the development cycle for the vertical design. Within a period of six months, the prototype evolved from a five liter paint can on a drill press to a working ten-liter test unit (right image in Figure 4). Over the next three years they made rapid progress in upgrading the mill capacity with the development of a range of laboratory and pilot mills.

The first production mill, the Deswik250, was installed in November 2005 at the Barbrook Gold Mine in South Africa (Figure 5). The Deswik250 was equipped with a hydraulic drive to ensure that there was sufficient torque for starting the impellor with dense grinding media. The advantage of this system was that the mill could be restarted after several hours without removing the grinding media. This was particularly important because the region was subject to frequent power shortages.

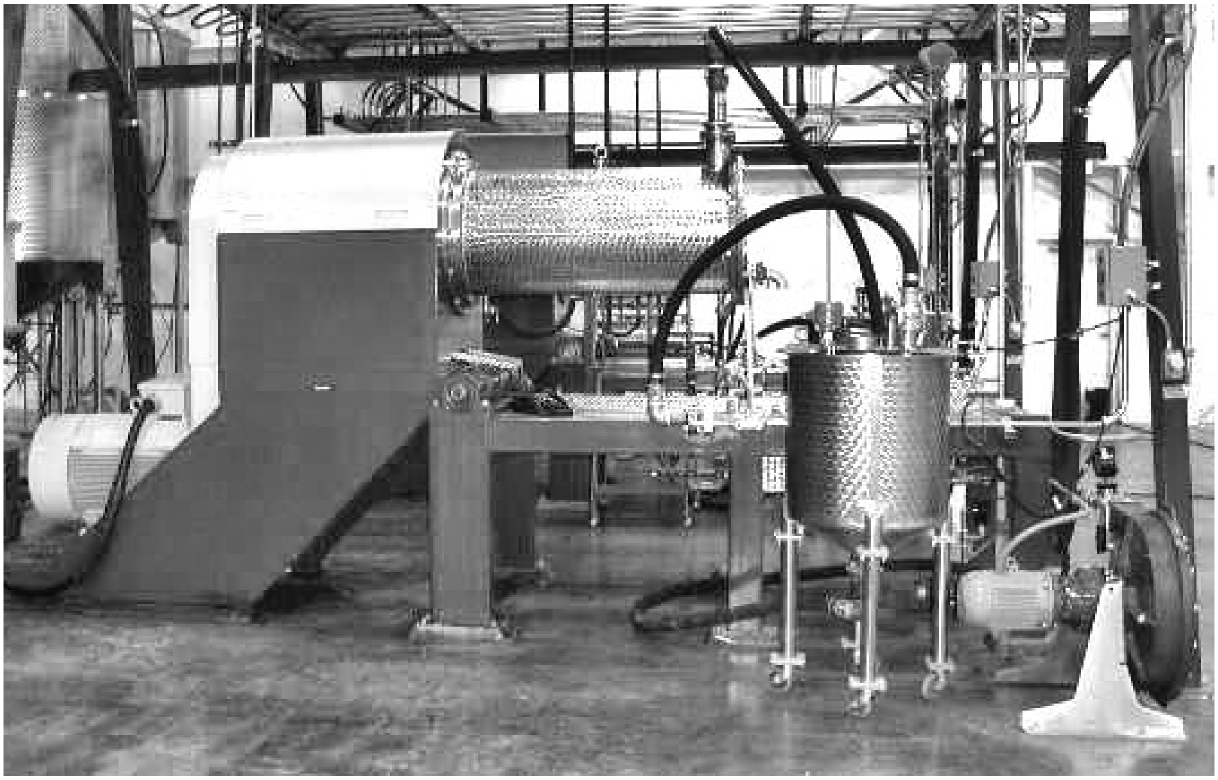

Figure 3: The original horizontal mill used by Deswik for magnetite grinding.

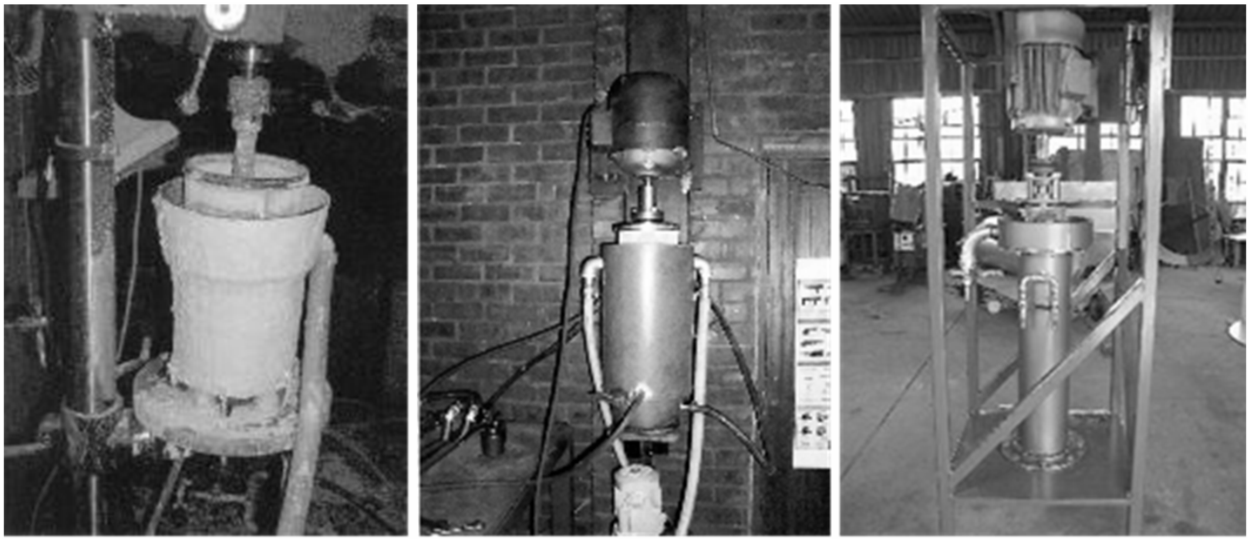

Figure 4: The evolution of the Deswik mill design during the development cycle.

Figure 5: The first Deswik250 vertical stirred mill.

In 2005, the potential of the Deswik Mill was recognized by ACMS (Australian/African/ American Computer Mining Services). ACMS was aware of the developing needs of the minerals industry due to their global activity in mining software development and consulting services. They also recognized the need to expand their business portfolio. As a result, they formed Deswik Mining Consultants as part of their investment in the Deswik technology. The companies were run in parallel until they were merged in 2007 to create Deswik International Ltd.

The merger of the companies saw a period of rapid expansion for the Deswik milling technology. A larger mill was developed for PGM tailings retreatment at Aquarius Platinum's chromite tailings retreatment plant (CTRP) at Kroondal South Africa (near Rustenburg). The Deswik1000 was installed on site in early 2007. Since that time, the mill has been providing a consistent product size in the mid-30 micron range. The recent performance of this mill is presented below in the Case Study.

The success of the Deswik1000 was followed by the development of the Deswik2000 to increase total milling capacity. Two of these larger mills were installed at the Platinum Mile tailings retreatment plant (South Africa) and three were installed at the JSC Vasilkovsky MCC site in Kazahkstan).

In August 2009, Deswik developed an intermediate size production mill for RandGold Resources. Two Deswik500 mills were provided for the Tongon Gold Project in the Ivory Coast (West Africa). These mills are significant in that they were the first production mills to take advantage of the recent developments in motor technology. Both mills were equipped with 220 kW direct-drive high torque electric motors at the request of client. These mills were constructed and shipped to site in early 2010.

The next major step in the evolution of the Deswik milling technology was the formation of a Joint Venture between Deswik International Limited and Knelson (a corporate partnership) in May 2010. The JV, operating as Knelson Milling Solutions, will continue to develop and market the Deswik fine grinding technology. The agreement allows Knelson Milling Solutions (KMS) to take advantage of both the manufacturing expertise and global support network of Knelson and its independent representatives. This allows KMS to provide a better product using updated manufacturing techniques and a higher level of support worldwide.

KMS is already realizing the benefits of this new partnership with the upgrade of the Deswik2000 to the Knelson-Deswik2500. The mill branding has been changed to reflect the changes in both the design and manufacturing capabilities of KMS.

Product Range

The process of continually improving the Knelson-Deswik milling technology has led to a robust milling system that is suitable for the fine grinding of a wide variety of mining ores, industrial minerals and chemicals. The current design improves on previous milling systems by taking advantage of improvements in both wear materials and drive systems. The vertical design also eliminates many of the wear and maintenance problems associated with having bearings in contact with mineral slurry.

The physical advantages of the Knelson-Deswik mill can be summarized as:

- The vertical orientation results in a smaller installation footprint than a comparable sized horizontal mill,
- The mill is open to air so there are fewer problems with back pressure within grinding zone,
- The impellor bearing housing is located above the grinding chamber. This eliminates problems with bearing seal leakage because the bearing is not in contact with slurry,
- Reduced maintenance cost because there are no seals or filters within the mill chamber,
- The mill does not require complex internal product separators because slurry discharge occurs by overflow through a wire mesh screen at atmospheric pressure,
- The vertical design eliminates cavitation in the grinding zone at high speeds, and
- The high torque drive allows the use of grinding media with a wide range of intrinsic density (SG). The ability to operate with a bead density in excess of 6 kg/L increases the media stress intensity that can be achieved in fine and ultra fine grinding applications.

The literature has shown that the grinding efficiency is affected by a wide range of variables. Process parameters such as the feed characteristics, slurry flow rate, slurry density, solids concentration and slurry rheology all affect grinding performance. These variables can often be regulated to fall within an acceptable design range. The mill configuration and/or operating conditions can then be modified to increase the grinding efficiency. The Knelson-Deswik mills are currently offered in a range of sizes that are classified according to their size and intended purpose. The differences between laboratory, pilot, and production ranges of mills will be detailed below along with a listing of some of their current installations. However, there are a number of process and mill configuration variables that are common to the entire range:

Process Design and Mill Configuration

Feed characteristics

The Knelson-Deswik mills are designed for fine and ultrafine grinding applications where the feed size is no coarser than 300 to 400 microns (p_{80}, 80% passing size). In practice the mill performs best when the feed has a normal Gaussian distribution. However, the mill has been used to preferentially grind the coarser "hump" in bimodal distributions without over grinding the finer part of the distribution.

Slurry density

The optimum slurry density for open circuit grinding using the Knelson-Deswik mill has been found to be between 1.2 and 1.5 kg/L. This range was determined through empirical testing on a wide range of materials. The ideal for a given application will depend on the feed characteristics, the target product size, and the rheological characteristics of the slurry.

Finer product sizes are normally run at a lower slurry density due to the large increase in particle surface area and the subsequent increase in flow resistance (viscosity). In some cases a viscosity modifier can be used to overcome this increase. However care must be taken to ensure that this will not have an adverse effect on downstream separation processes.

Solids density

The solids density for a specific site will be limited by the specific gravity of the (dry) solids. Solid materials with a higher density must be processed at a lower solids density to keep the slurry density below 1.5 kg/L.

Slurry flowrate

The nominal flowrate for the different mill sizes are shown below in the sections for each mill type. The flowrate will vary for each application depending on the intensity of the grind (size reduction) and the strength of the material.

Impellor configuration

The Knelson-Deswik mills are designed with a modular impellor that has removable discs and spacers. The system is designed to allow changes to the distribution of media and energy within the mill by changing the number and spacing between the impellor discs. This is normally best done during commissioning. The empirical testing carried out by Deswik (Pty) Ltd indicated that the impellor could be reconfigured for softer materials (e.g. calcium carbonate, talc, and gypsum) to reduce the potential for over grind with no loss of efficiency.

Mill speed

The mill speed is one of the dominant factors in determining the power intensity and media stress intensity within the mill. During the development of the Knelson-Deswik technology, it was found that the mills had the highest grinding efficiency when operated at tip speeds between 10-12 m/s. This design speed is an important differentiator between the Knelson-Deswik and the “low” and “high” stirred mills which operate below 3 m/s and above 15 m/s. The effect of this difference on the power intensity within the milling chamber was shown in Table 1.

It can be seen in the table that the Knelson-Deswik mills bridge the gap between the family of low speed, low energy vertical stirred mills and the high speed, high energy horizontal mills. This offers significant advantage in customizing the media stress intensity. It allows the Knelson-Deswik to be used in applications where the design constraints of other mills limit their ability to operate at the optimum stress intensity for a given application.

Grinding media

The media load, size, and intrinsic density are the main variables for the mill charge. The media load generally varies between 65% and 80% by volume. In a similar way, the media size ranges between 1.5 and 3 mm. The actual size selected for a given application will depend on the expected feed size.

KMS normally recommends that the intrinsic density of the bead be more than triple the expected slurry density. This design threshold is based on the data collected during the development of the vertical mill. It also recognizes the media stress intensity work conducted by Kwade et al. (1996). The media density selection range is based on the slurry density criteria of operating between 1.2 to 1.5 kg/L. This translates to nominal bead density range between 3.6 and 4.5 kg/L for most applications. The maximum bead density currently used in the Knelson-Deswik mills is a 6.2 kg/L Ceria Stabilized Zirconium.

The relationship between the process parameters and mill configuration is complex. It is difficult to predict the mill performance for a given application without carrying out material testing as part of the plant design process. The normal progression is to carry out laboratory-scale testing to confirm the effect of particle size on grade and recovery. Where possible, pilot scale trials are then conducted to provide a better understanding of metallurgical response over a range of operating conditions. The plant designer can then proceed with the installation of a production mill with confidence in both grinding performance and plant recovery over a wide range of operating conditions.

The differences between the Knelson-Deswik mills used for laboratory, pilot and production scale applications are briefly outlined in the next three sections. The sections focus on the nominal design range for each mill and provide a list of some of the current installations.

Laboratory Scale

The laboratory scale mills are designed to confirm metallurgical performance and to provide an estimate of the type of production mill required for a given application. Table 2 shows the two current models offered by KMS. The biggest practical difference between the two mills is the amount of material required to carry out a meaningful batch test across a range of products sizes. Of the two mills, the Knelson-Deswik2 is primarily used for metallurgical testing and the Knelson-Deswik10 is the preferred option for scaling up to a production mill.

A five-liter mill is currently being designed to provide an intermediate reference for both metallurgical testing and mill scale up.

Table 2: Current range of Knelson-Deswik laboratory mills.

Mill Type	*Nett Volume (L)*	*Installed Power (kW)*	*Design Energy Density (kW/m3)*	*Test Mass (kg)*	*Nominal Flow Rate (lph)*
Knelson-Deswik2	3	3	800	5	40-150
Knelson-Deswik10	10	11	890	20	130-600

The following research and testing facilities are equipped with laboratory Knelson-Deswik mills:

- Knelson Milling Solutions, Johannesburg, South Africa
  This is the original testing facility for Deswik (Pty) Ltd. It is equipped with a Knelson-Deswik10. The facility is currently available for both grinding scale up and limited metallurgical testing.

- Mintek, Johannesburg, South Africa
  This facility illustrates the loose distinction between the laboratory and pilot scale classification. They are using both a Knelson-Deswik2 and a Knelson-Deswik25 in a laboratory environment. They are a fully equipped center that can carry out a range of metallurgical testing.

- Ammtec Limited, Perth Australia
  Ammtec has a 10-liter laboratory mill. They are a fully equipped center which is capable of a broad range of laboratory and pilot scale testing. They offer the ability to test metallurgical response for a full range of separation technologies.

- TOMS Irkutsk Siberia
  TOMS is a leading processing and engineering institute that offers fine grinding analysis services to their clients in the Russia/CIS region. Their testing facility is equipped with both a Knelson-Deswik2 and a Knelson-Deswik10.

- Peacocke and Simpson, Harare, Zimbabwe
  PS&A is a research and testing facility which offers a full range services (mineral process testing, flow sheet design and equipment development). They recently acquired a Knelson-Deswik2 to carry out a wide range of metallurgical test work.

- University of British Columbia, Vancouver, Canada
  The Department of Mining Engineering is scheduled to receive a Knelson-Deswik10 in January 2011 The mill will be used to carry out process and mill configuration research as part of an NSERC project. It may be available for independent sample testing.

- Knelson Gravity Solutions, Vancouver, Canada
  The main Knelson facilities will have a Knelson-Deswik2 available for metallurgical testing in early 2010.

Pilot Scale

The pilot scale grinding mills are the next step up in both mill capacity and installed power (Table 3). They are designed to be portable units which can be easily transported to site for short and long term pilot trials. There is a loose transition between the laboratory and pilot scale and pilot and production mill classifications. The Kelson-Deswik25 has been used in laboratory type trials and the Knelson-Deswik50 has been used as the main production unit in low throughput tailings retreatment operations.

The pilot scale mills are the smallest mill class which is normally operated in open circuit.

Table 3: Current range of Knelson-Deswik pilot mills.

Mill Type	*Nett Volume (L)*	*Installed Power (kW)*	*Design Energy Density (kW/m3)*	*Nominal Throughput (dry tph)**	*Nominal Flow Rate (lph)*
Knelson-Deswik25	27	30	1000	0.5-2 [50]	320-1500
Knelson-Deswik50	50	55	1000	2-5	600-3000

* The number in brackets for the Knelson-Deswik25 is the sample size typically required for batch testing (kg).

The pilot-scale Knelson-Deswik mills are available from the following representatives around the world.

- Consep, Sydney, Australia
  A Knelson-Deswik25 is currently available through this agency for pilot testing in the Australasian market. The company offers a wide range of equipment to the mining and mineral processing industry. The Knelson-Deswik mills are latest addition to their product range.

- ZMI, Harare, Zimbabwe
  This associate has a Knelson-Deswik50 that is used for testing platinum concentrates and gold ores throughout Zimbabwe.

- Knelson Milling Solutions (KMS), Vancouver, Canada
  The metallurgical testing facilities at Knelson will be also be receiving a Knelson-Deswik25 in early 2010. This mill will be available for pilot and large scale batch trials.

- Peacocke and Simpson, Harare, Zimbabwe
  Like KMS, PS&A have a Knelson-Deswik25 for pilot scale grinding programs in Southern Africa. This mill is currently available to be used in the field for fine grinding various materials.

Production Scale

The Knelson-Deswik production mill category contains the widest range of mills to cater for a wide range of operating conditions. They are normally operated in open circuit.

These mills were originally equipped with hydraulic drives manufactured by either Bosch-Rexroth or Hägglunds. These drives are still offered by KMS as an optional drive system. However, the latest Knelson-Deswik mill designs are equipped with high torque direct drive electric motors. The original branding used by Deswik International Ltd. (Deswik1000 and Deswik2000) has been retained in the installation listing below to indicate that the units are equipped with hydraulic systems.

Table 4 shows the current range of production mills offered by KMS. A Knelson-Deswik5000 is currently being designed but it has not been included in this paper because some of its design specifications have not been finalized.

Table 4: Current range of Knelson-Deswik production mills.

Mill Type	*Net Volume (L)*	*Installed Power (kW)*	*Design Energy Density (kW/m3)*	*Nominal Throughput (dry tph)*	*Nominal Flow Rate (m^3/h)*
Knelson-Deswik100	110	110	765	4-7	1.3-6
Knelson-Deswik250	290	132	420	6-12	3-21
Knelson-Deswik500	480	220	420	10-20	5-30
Knelson-Deswik1000	910	337	310	15-30	11-57
Knelson-Deswik2500	2425	699	245	30-60	30-160

This summary of the production-scale installations is a partial list. It includes some of the major projects that have been manufactured and installed since the creation of Deswik International Ltd. in 2007.

- Kroondal, Rustenburg, South Africa
  The Deswik1000 installed at Kroondal was the first major installation undertaken by Deswik International. The mill was installed in Aquarius Platinum's CTRP to process PGM tailings. This mill is described further in the Case Study.

- Platinum Mile, Rustenburg, South Africa
  The Platinum Mile installation was completed in 2009. Two Deswik2000 mills were installed to treat PGM tailings. The mills were allocated different duties within the plant. Mill A was configured for a fine grind while the Mill B was a high throughput coarse grind (+ 100 micron feed).

- JSC Vasilkovsky MCC, Kokshetau, Kazahkstan
  The Vasilkovsky site received three Deswik2000 mills for an ultrafine grind on the feed

to a gold leaching circuit. The mills were installed in late 2009. They have been operating for most of 2010.

- Tongon, Ivory Coast, West Africa
  Two Knelson-Deswik500 mills were manufactured and shipped to site in the second quarter of 2010. They are on site and awaiting installation and commissioning in early 2011.

- ZMI Goldwick, Zimbabwe
  This gold dump retreatment will make use of a Knelson-Deswik250 to fine grind the feed to a CIL circuit. The mill is scheduled to be delivered to site in the third quarter of 2011.

CASE STUDY

The first installation of a production mill by Deswik International was a Deswik1000 at Aquarius Platinum's Kroondal Mine (near Rustenburg, South Africa) in 2007. Since that time, the CTRP has been operated by Aquarius's processing partner, Minopex. The original project specification was for the mill to produce a nominal product size of 38 microns to increase the recovery PGM materials. There was no tight specification on mill throughput since the mill is treating tailings streams from three separate feed sources as they become available.

The Deswik1000 was the first major increase in mill size from the Deswik250 manufactured by Deswik (Pty) Ltd. It was equipped with a CA100-40 manufactured by Hägglunds. This hydraulic motor was driven using a PEC803 power unit equipped with two 200 kW electric motors. The specifications for this power system are shown in Table 5. The power system was designed to drive the impellor at 350 rpm (tip speed 12 m/s). The general arrangement of the Deswik1000 is shown in Figure 6.

After the initial commissioning and testing, data collection at the site was sporadic. A limited amount of data was collected in the first half of 2008. This indicated that the mill was operating at a specific energy consumption of roughly 7 kWh/t. This estimate was based on the mill operating conditions and a mean throughput between 30 and 35 dry tph. This production data was not correlated with feed and product size.

In mid-2008, Kroondal began to experiment with a variety of low quality beads in an attempt to cut millings costs. It was reported that the results were mixed at best. The lower quality beads had a lower sphericity and void volume within the media mass. They were also found to have a high breakage rate (note that is the beads, not the feed material) and the high media consumption offset any unit cost benefit. Grinding performance also suffered as a consequence. They persisted with this cost cutting program for nearly a year. In August 2009, the decision was made to return to a higher quality zirconium silicate bead. The specifications for these beads are shown in Table 5. The change to a better quality media coincided with an increase in data collection. The operators were encouraged to fill out daily log sheets which recorded critical mill operating and process variables. They also increased the frequency of slurry sampling for particle size analysis. The data collected in the milling log sheets between August 2009 and February 2010 forms the basis of this case study.

Table 4: Current range of Knelson-Deswik production mills.

CA100-40 with PEC803	*Value*
Specific Torque (Nm/bar)	40
Installed Power (kW)	400
Motor Displacement (cm^3/rev)	2512
Rated Motor Speed (rpm)	390
Maximum Motor Speed (rpm)	400
Hydraulic Pumps (cm^3/rev)	710
Maximum Pump Flow (lpm)	1004
Electric Motor Speed (rpm)	1470
Charge Pressure (bar)	15

Figure 6: Installed Deswik1000.

Table 5: Zirconium silicate grinding media specifications.

CZS	*Value*
Intrinsic Density (kg/L)	4.0
Bulk Density (kg/L)	2.5
Vickers Hardness (HV)	>1000
Roundness (%)	>92
Composition (approximate)	
ZrO2	61.2
SiO2	32.9
Fresh Feed Media Size (mm)	2.8-3.2

Mill Performance

The increased focus on data collection produced a large body of data between August 2009 and February 2010 (inclusive). Over a thousand log sheet entries were made with entries on a total of 97 days. The average daily hydraulic pressure and mill speed is shown in Figure 7. It can be seen that there was a sharp drop in the operating pressure in the third week of September 2009. It is currently unclear what caused this decrease.

Histograms of the hydraulic pressure and mill speed can be found in Figures 8 and 9. These histograms are for total data set rather than the daily average. It can be seen in Figure 8 that the majority of the hydraulic pressure readings (98.6%) lie between 60 and 140 bar. This range can be converted to running torque using the specific torque in Table 4 (2.4 and 5.6 kNm). Figure 9 shows that the mill speed clustered around the design target of 350 rpm. Over 75% of the operating data was with 15 rpm of the design target.

As the data was analysed, it became apparent that data entries were made when the mill was well outside of its normal operating range. For example, the minimum slurry density recorded was 1.01 kg/L. This corresponds to a 2% solids density for the CTRP feed (dry solids SG 3.2 kg/L). Figure 10 shows a histogram of slurry density. It can be seen that a third of the slurry density readings fall below the design threshold of 1.2 kg/L. Operating at this low slurry density is particularly important in terms of specific energy consumption because, as Figures 11 and 12 show, the throughput is proportional to the slurry density. The solids throughput does not show a strong correlation to pump rate.

It is apparent that the average slurry density is at the lower end of the Knelson-Deswik design range. This was taken to be driven by plant process limitations rather than intentional control since the data uniformly distributed around the mean of 1.21 kg/L. However the data needed to be filtered to eliminate the outliers caused by these abnormally low values. The data was filtered to eliminate slurry density values below 1.09 kg/L (solids density below 12%). This eliminated 3.9% of the total data set.

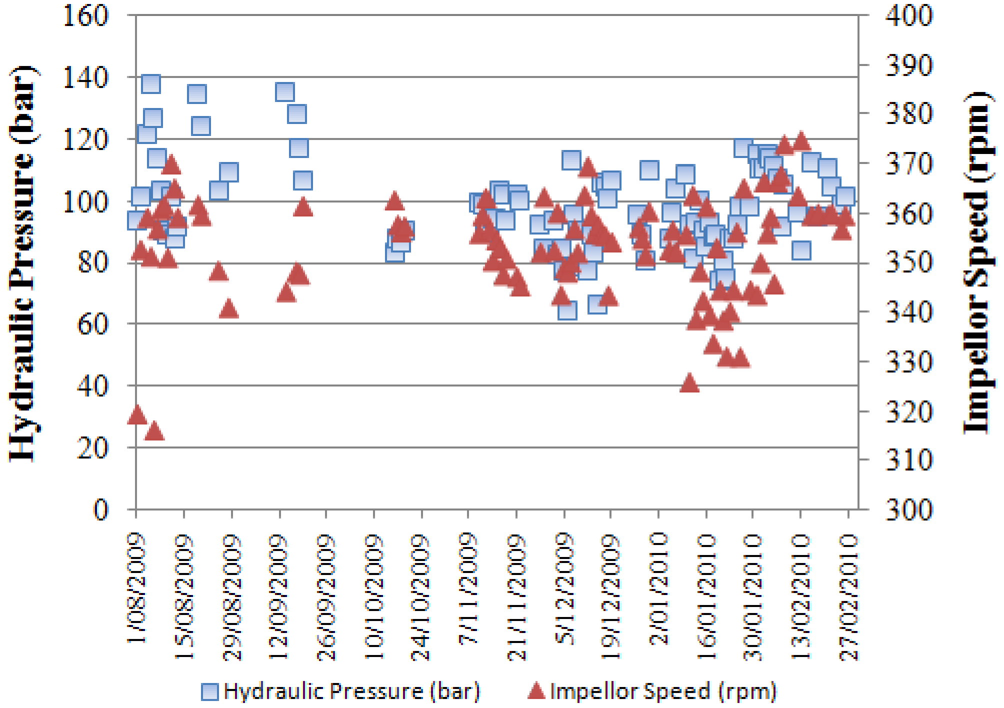

Figure 7: Daily average hydraulic pressure and mill speed.

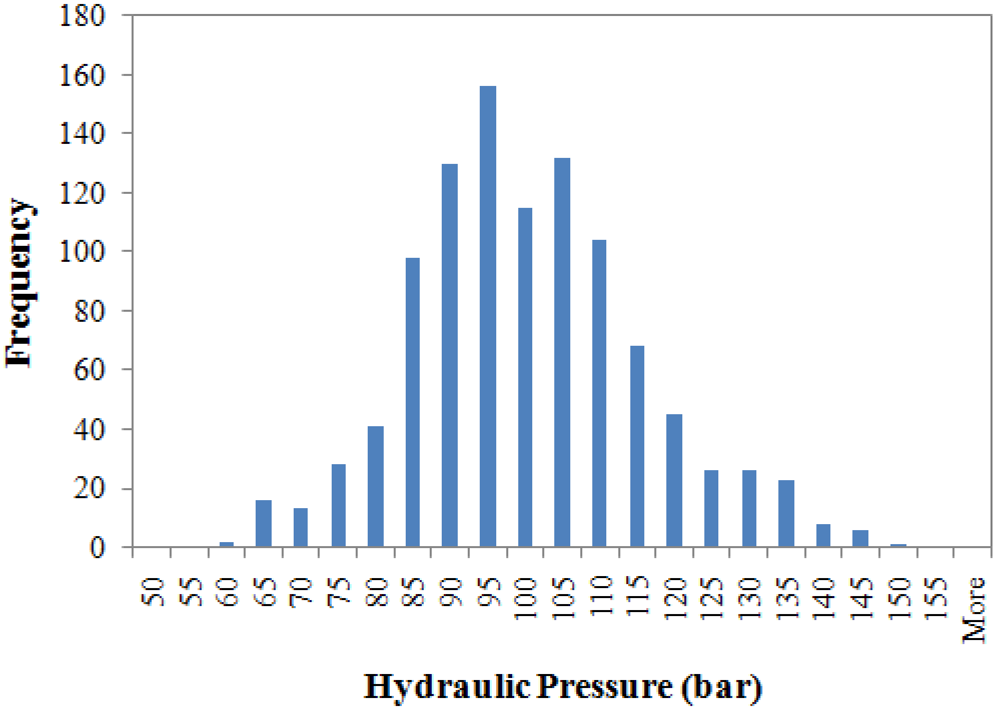

Figure 8: Histogram of hydraulic pressure.

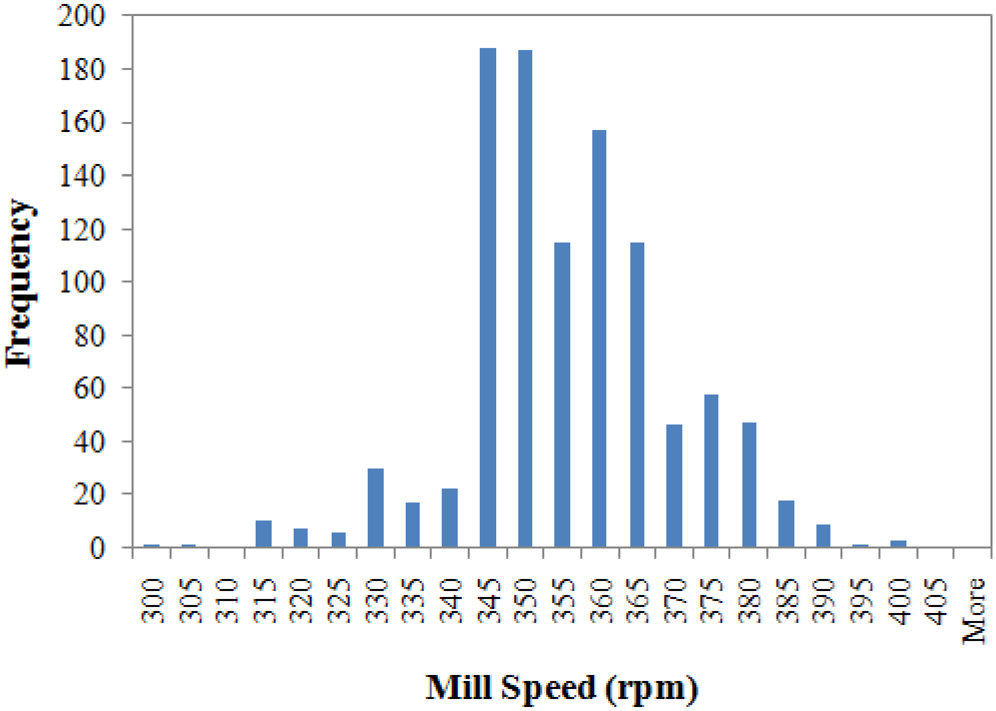

Figure 9: Histogram of mill speed.

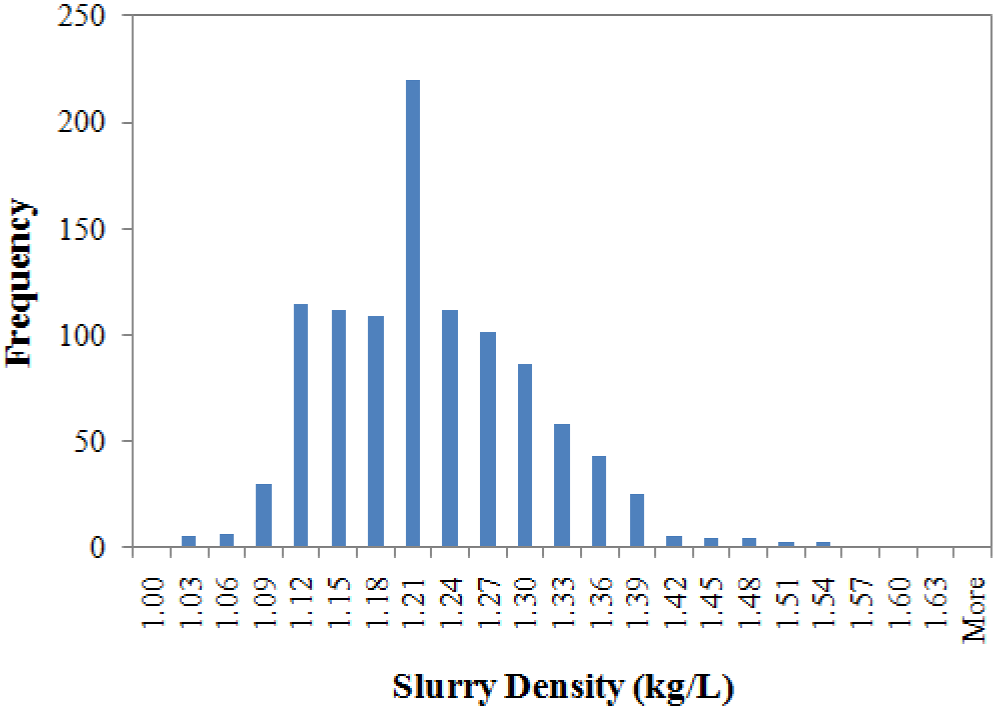

Figure 10: Histogram of slurry density.

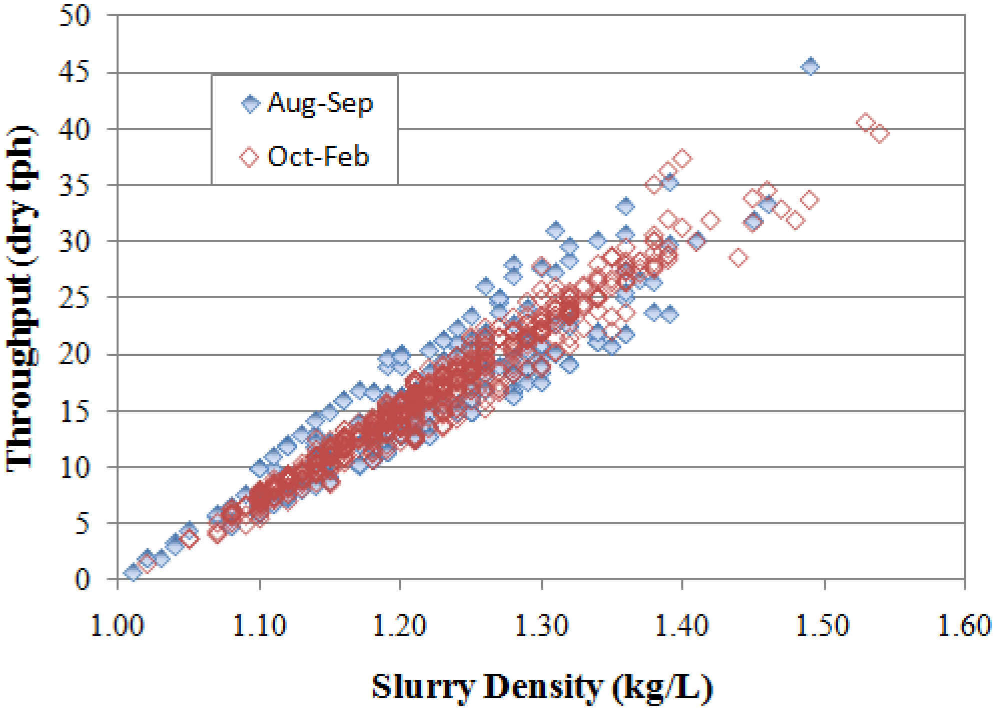

Figure 11: The effect of slurry density on mill throughput.

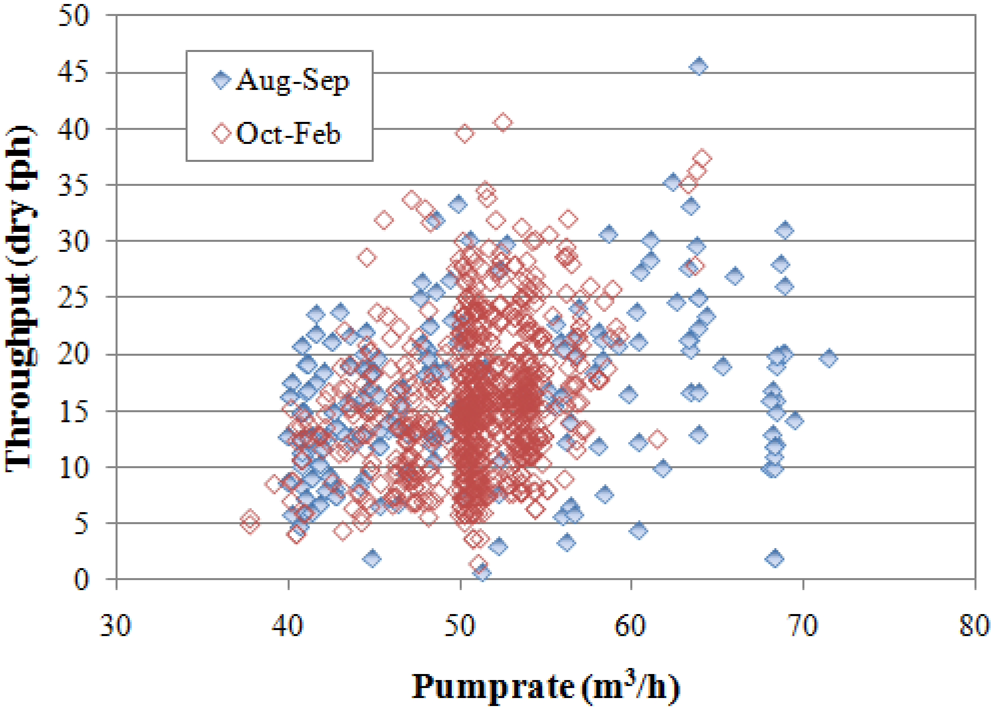

Figure 12: Mill solids throughput versus feed pumprate.

The effect of filtering the data based on a minimum solids density can be seen in Figure 13. The histogram shows that all throughput values less than 4 dry tph and part of the data between 4 and 8 dry tph was eliminated. The dry solids throughput, hydraulic pressure (torque), and mill speed were used to calculate the specific energy consumption (Figure 14). It can be seen that the specific energy consumption decreases with the mill throughput. This trend is expected since the media load and mill speed were the dominant factors determining the power draw (for the same size and density of media). It is interesting to note in the graph that when the throughput was above 30 dry tph, the specific energy consumption was similar to that observed early 2008 when the site was using Ceria Stabilized Zirconium beads (roughly 7 kWh/t).

The final point of interest is that the feed and product size did not show any consistent trends (Figure 15). There was a great deal of scatter when the product size was plotted against the feed size in Figure 16. Over 80% of the product samples had a particle size between 30 and 40 microns. The consistent product size in particularly important when it is compared to the specific energy input (by way of the reduction ratio). Figure 17 shows that the reduction ratio did not increase with the specific energy input. The reduction ratio was generally between 2 and 3 despite the specific energy consumption ranging between 4 and 25 kWh/t. This indicates that as the slurry density drops, energy is wasted in the grinding process because the higher energy input per unit mass does not result in a finer product size. This result makes sense when considering that Figure 12 showed that there was no correlation between solids throughput and pump rate (hence residence time).

The average values for the filtered set of log sheet data are shown in Table 6. The ranges around the mean value were calculated using $p = 0.05$.

The data collected between August 2009 and February 2010 shows that the Kroondal Deswik1000 is able to produce a ± 35 micron product over a wide range of solids throughput. The variation in tonnage could be attributed to changes in slurry density rather than to volumetric feed rate. Kroondal is currently reviewing its CTRP plant in an attempt to increase total throughput to 25 dry tph. This will improve their total PGM output and decrease the specific energy consumption of the mill. The results shown here indicate that increasing the average slurry density of the mill feed should be considered as part of the upgrade process. This will increase the dry solids throughput while maintaining the current pump rate.

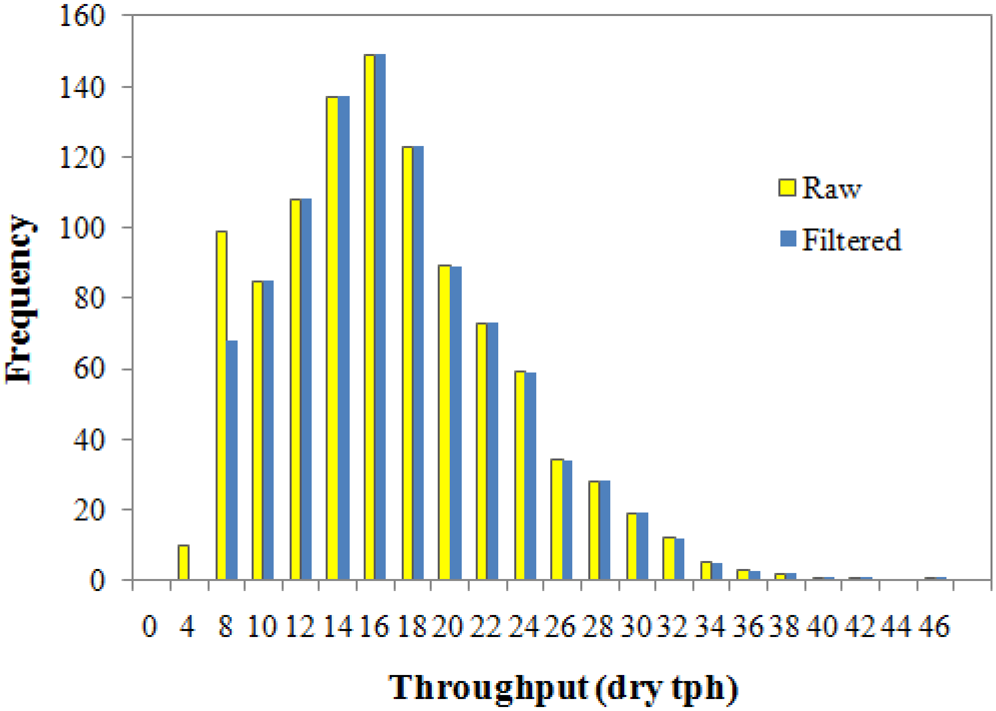

Figure 13: Histogram of mill throughput.

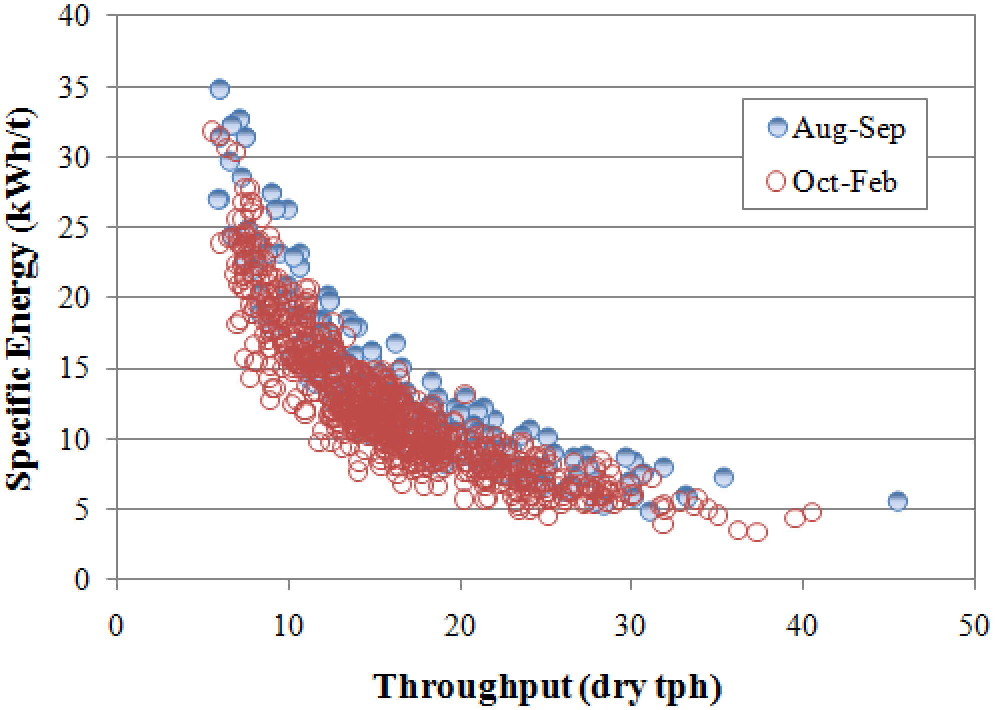

Figure 14: Specific energy consumption versus mill throughput.

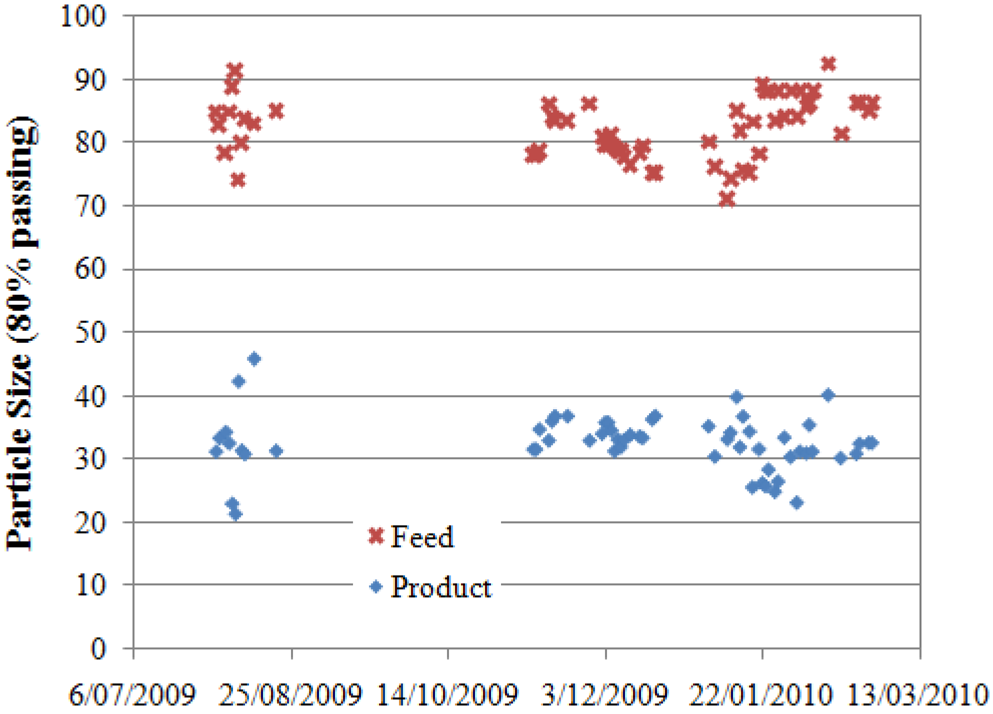

Figure 15: Comparison of feed and product size.

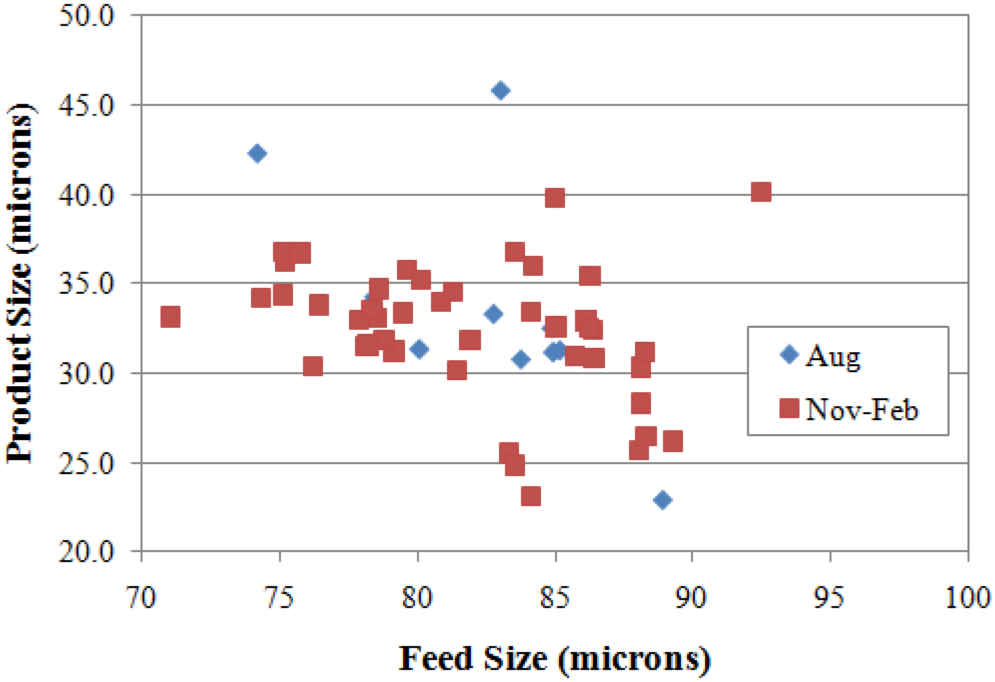

Figure 16: Product size versus feed size (80% passing).

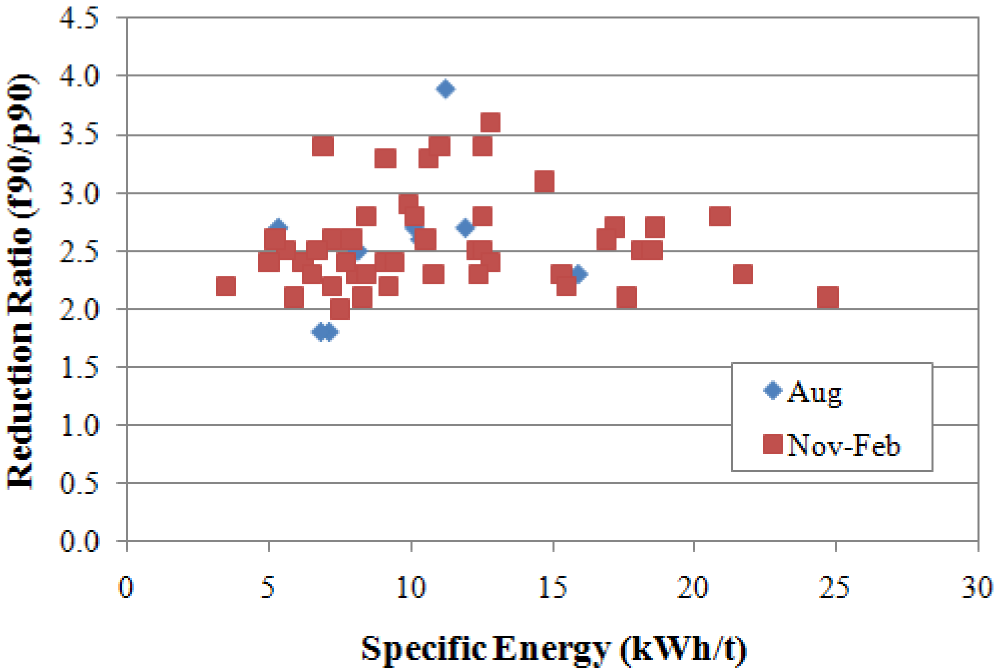

Figure 17: Reduction ratio versus specific energy consumption.

Table 6: Average mill operating and slurry feed parameters for filtered production data.

Parameter	*Mean*	*Minimum*	*Maximum*
Hydraulic Pressure (bar)	99+/-1	59	148
Shaft Speed (rpm)	354+/-1	293	398
Inlet Temp (°C)	17.4+/-0.2	9.7	25.7
Outlet Temp (°C)	37.5+/-0.5	25.9	72.5
Pumprate (m^3/h)	50.6+/-0.3	37.8	71.4
Slurry SG (kg/l)	1.22+/-0.005	1.10	1.54
Throughput (dry tph)	16.2+/-0.4	5.50	45.54
Torque (Nm)	3947+/-38	2360	5920
Shaft Power (kW)	146+/-1	86	219
Estimated Input Power (kW)	183+/-2	108	274
Estimated Current (A)	201+/-2	118	301
Estimated SE (kWh/t)	13+/-0.3	3.4	35
ΔT (°C)	20+/-0.5	3.0	56.3
Product D90 (um)	33+/-1	22.9	45.8
Feed D90 (um)	82+/-1	71.0	92.5
ΔSize (um)	49+/-2	31.9	66.0
Reduction Ratio	2.6+/-0.1	1.8	3.9

CONCLUSIONS

The current trend in the minerals industry has increased the importance of energy efficiency in fine grinding. This recognition spurred the development of a new range of stirred bead mills in the 1990s. These development programs sought to improve existing low speed vertical mills and to develop an alternative high speed horizontal design. Both programs culminated in the well publicized introduction of new stirred media mills for the minerals industry (Vertimill™ and IsaMill™ respectively).

The development of these new technologies was paralleled in South Africa by the development of the Knelson-Deswik mill for the pigments industry. The early focus on this lower throughput, ultra fine grinding application resulted in the mill being less publicized in the wider minerals industry. However, recent literature has shown that grinding performance depends on the feed material and mill operating conditions. All stirred mills will have an optimum operating range which is determined by the process variable (e.g. ore type, size, density, hardness). Although an optimum exists for all mills, the product size that can be achieved by each will often be different. Jankovic et al. (2003) correlated this performance to the media stress intensity and noted that too much or too little energy input would cause a decrease in efficiency.

The media stress intensity depends on the particle size, media density and tip speed of the mill. It is unlikely that the low and high speed (<3 and >15 m/s) stirred mills will be able to produce the most efficient grind for all ore types due to the large gap between their design speed and power intensity. The Knelson-Deswik mill bridges the gap between these designs in that it is designed to operate at tip speeds between 10 and 12 m/s. This, coupled with its ability to use very dense media, allows the Knelson-Deswik to produce a wide range of media stress intensity.

Knelson Milling Solutions offers a wide range of laboratory, pilot and production mills. These mill types can be used as part of the project develop process to ensure that the installed fine grinding system is optimized for a specific application. Laboratory testing allows a confident prediction of full scale performance while pilot trials allow the testing of a wide range of operating parameters. Once a production mill is installed, monitoring of grinding performance is a critical part of mill optimization.

The Kroondal case study showed that chromite tailings could be consistently ground to ± 35 microns. However, the specific energy consumption varied dramatically depending on the slurry density. The slurry density was found to be proportional to the dry solids throughput while the mill power draw did not vary with slurry density. This results in an inverse relationship between slurry density and specific energy. The monitoring program showed that increasing the slurry density is a potential avenue for increasing production tonnage and energy efficiency.

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