The Versatility of Stirred Milling in Innovative Comminution Flowsheets

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Abstract

Stirred milling technology is used extensively in regrinding duties due to its ability to deliver improved energy efficiency and produce narrower particle size distributions when compared to ball mills. Increasingly, stirred mills are also being installed in coarser feed duties. Recent developments in stirred milling technologies have resulted in larger mill shells and higher installed power per unit. These mechanical upgrades include provisions for coarser feed sizes and allow for the use of larger media, thus improving efficiency in these applications.

This paper details the improvements that Swiss Tower Mills (STM) have incorporated in their mill design for coarser feed applications (F_{80} >200 µm) and provides examples of flowsheets that illustrate the versatility of vertical stirred mills in three case studies:

1. Installing a Coarse Particle Flotation (CPF) circuit with concentrate milling to debottleneck a brownfield grinding circuit by coarsening the grind size.
2. Adding a new grinding circuit that includes energy-efficient technologies (High Pressure Grinding Rolls [HPGR] and stirred milling), providing additional capacity to an existing gold processing plant.
3. Secondary grinding of a magnetic separator concentrate with large throughput variations requiring large media for improved energy efficiency and ability to rapidly adjust power draw.

Keywords

Stirred milling, coarse feed application

Introduction

To meet growing demand for sustainable mineral extraction and reductions in carbon emissions, the mining industry is facing increased pressure to use more energy-efficient comminution equipment. Numerous studies have discussed incorporating energy-efficient technologies into comminution flowsheets. Although energy-efficient comminution equipment technologies have been developed and/or adapted for hard rock mining applications, new approaches are needed to achieve significant energy savings.

Valery and Jankovic (2002) proposed that high-intensity blasting, HPGRs, and stirred milling technologies can lead to significant reductions in energy consumption (in excess of 45%). The authors first proposed using a flowsheet featuring HPGR and Vertimill (VTM), discussing the potential reduction in HPGR product's hardness due to micro-fractures caused during passage through the HPGR. However, they did not investigate the effects of coarser feeds on the VTM energy efficiency. Since then, VTMs have been used to process HPGR products in circuits such as the Morenci pilot plant and Boungou operation, where VTMs receive feed from HPGR circuits with a controlled top size (Knorr et al, 2016; Houde & Boylston, 2019; Ballantyne et al., 2021). Houde and Boylston (2019) reported energy efficiency benefits varying between 11% and 17%.

Pease (2007) suggested using an IsaMill in coarser feed applications using ceramic beads to achieve higher energy efficiency and lower steel consumption in comminution circuits. Examples of these circuits included the IsaMill treating the product of a SAG milling circuit at MacArthur River, the product of an HPGR circuit at Anglo Platinum, and HPGR product at Arrium (Larsen et al., 2015). Wang et al. (2013) also investigated the benefits of HPGR and IsaMill circuits at the Huckleberry mine. Pease (2007) raised possible issues with mismatched feed size requirements between HPGR circuit products and IsaMill feed size requirements and suggested the need for a ball-milling stage between the HPGR and IsaMill circuits. If the IsaMill feed is too coarse, coarse particles can build up inside the mill, resulting in lower grinding performance and, in extreme cases, the charge inside the mill locking (Gurnett et al., 2023).

Incorporating stirred mills in comminution flowsheets in secondary or tertiary milling duties, as seen in Cadia, Semafo, New Afton, Raglan, Chino, Cannington, Santa Elena, and Tambomayo, also helps debottleneck the ball mills and stabilize the downstream process feed characteristics (Ballantyne et al., 2021; Mezquita et al., 2022). These applications are coarser than the regrind application for which the stirred mills were originally designed.

Emerging technologies in the coarse particle separation space can also potentially make a step change in energy consumption (Lane et al., 2019). The mining industry has been particularly interested in processing ores at coarser particle sizes due to declining head grades and a tightening regulatory environment around tailings dams. Sulphide flotation using, for example, the Eriez HydroFloat is one emerging technology that allows for improved flotation recovery of sulphide-gangue rock composite particles with low surface liberation when compared with conventional flotation technology (Awatey et al., 2013).

Stirred milling technologies are commonly used for regrinding duties to achieve improved energy efficiency and narrower particle size distributions (lower fines relative to P_{80}) when compared with ball mills. However, limitations in the size of the grinding media can lead to reduced energy efficiency benefit when processing coarser feeds (Huang et al., 2019). Due consideration must be given to the feed slurry density as well as the final product size when selecting the media size for each specific application.

Huang and colleagues (2019) gathered data from VTM operations to investigate the effects of feed size on the mill energy efficiency and found that the energy efficiency of these mills decreased as the feed size F_{80} increased. The authors observed that stirred mills using smaller media performed better when processing finer feed size distributions, leading to a linear drop in energy efficiency with larger feed sizes. Therefore, the use of larger media to effectively break down larger particles is required in coarser feed applications (Paz et al., 2023).

In 2012, STM introduced a new type of stirred milling technology, the Vertical Regrind Mill (VRM) (also known as HIGmill), which is now widely used in fine and ultra-fine grinding applications, and can accept feeds of up to 400 µm. More recently, STM introduced modifications to their stirred mill design to cater for coarser grinding applications, known as the Vertical Power Mill (VPM). Mechanical upgrades provide for coarser feed sizes and the use of larger media, leading to increased efficiency in coarser feed applications.

OBJECTIVES

This paper presents three case studies that demonstrate the versatility of vertical stirred mills:

1. Installing a CPF circuit with concentrate milling to debottleneck a brownfield grinding circuit by coarsening the grind size
2. Adding a new grinding circuit that includes energy-efficient technologies (HPGR and stirred milling), providing additional capacity to an existing gold processing plant
3. Secondary grinding of a magnetic separator concentrate with large throughput variations requiring large media for improved energy efficiency and ability to rapidly adjust power draw.

A comparison of the VRM and VPM mills is also presented, with a focus on the modifications integrated into the VPM mill design to enable the application of this grinding technology in coarse feed duties (F_{80} > 200 µm).

Case Studies

CASE STUDY 1: COARSE PARTICLE FLOTATION

The early commercial adoption of CPF in copper concentrators has been focused on scavenging coarse losses from existing flotation plant tailings. Ausenco designed and built the first CPF plant for base and precious metals at Newcrest's Cadia Valley operation. At Cadia, CPF allowed recovery of coarse composite copper and gold particles that were being lost to conventional flotation tailings without the need for additional up-front power input for particle size reduction (Jaques et al., 2021). At Anglo America's El Soldado operation, the installation of CPF enabled a coarser grind size without a loss in recovery, resulting in higher energy efficiency and water recovery benefits (Arburo et al., 2022).

The HydroFloat technology allows for extending the floatable size range relative to that of conventional flotation cells, which fundamentally shifts the economically optimum grind size. However, the presence of fines in the cell feed can cause performance issues in the HydroFloat. Therefore, efficient pre-classification of the feed is crucial to remove fines (typically particles below 106 µm) prior to the HydroFloat.

The pre-classification stage results in a significant change in the shape of the particle-size distribution reporting to the HydroFloat and, ultimately, the subsequent coarse feed for the regrind stage. When the HydroFloat cells are in a scavenging duty, the pre-classification overflow is typically low grade and can be rejected as fine tailings and, the CPF tailings are also rejected as coarse tailings. The feed to a CPF concentrate regrind stage is coarser than a normal rougher concentrate, and fines deficient.

Case Study 1 is an expansion of a copper concentrator, including a CPF and regrind circuit, as per the flowsheet in Figure 1. Depending on the technology selection for the regrind duty, this circuit can be configured in open circuit, as shown in the process flowsheet. The sizing of the regrind mill needs to take into consideration the fines deficiency of the feed. Ideally, testwork should be performed on a sample from CPF testwork, as the concentrate contains composite particles that will likely not behave like a conventional flotation concentrate.

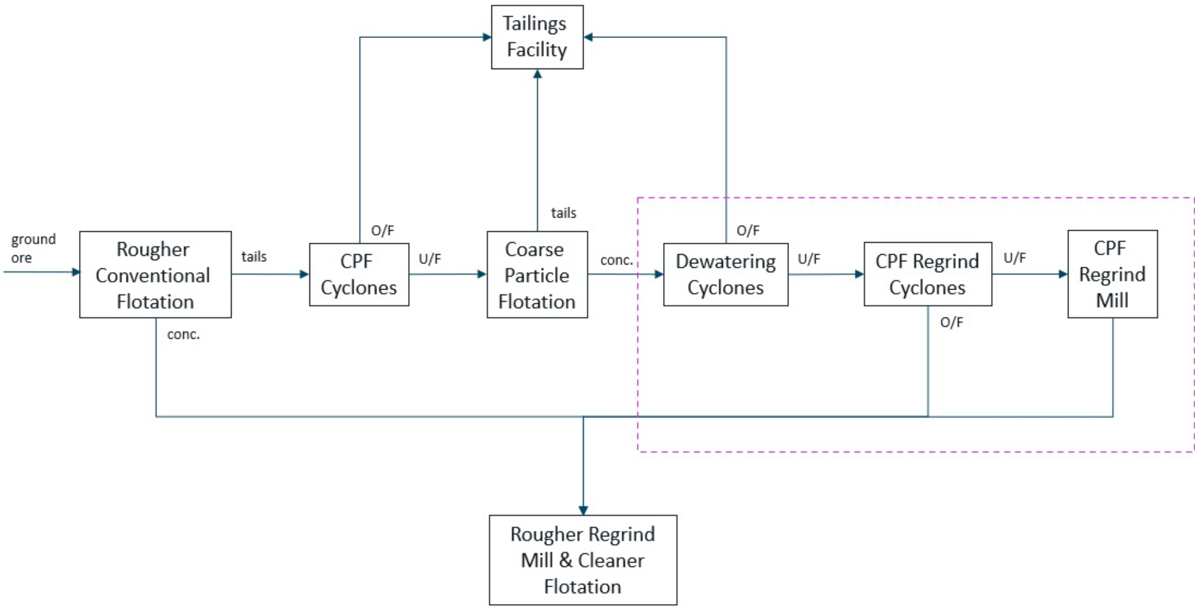


Figure 1—Process Flowsheet—Case Study 1

Laboratory testwork was benchmarked on samples obtained from CPF testing, providing signature plots for the CPF concentrate and for the CPF concentrate after being submitted to a stage of fines scalping. Typically, unscalped products are submitted to regrind tests, but in this instance an additional test was conducted to investigate potential effects of fine particles that would report to tailings (dewatering cyclone overflow) when regrinding coarse composite samples. Tests were conducted using two methodologies (jar mill and VRM tests) and results are presented in Figure 2. The jar mill test used mono-size steel media with 19 mm, the VRM test used graded media with a top size of 10 mm.

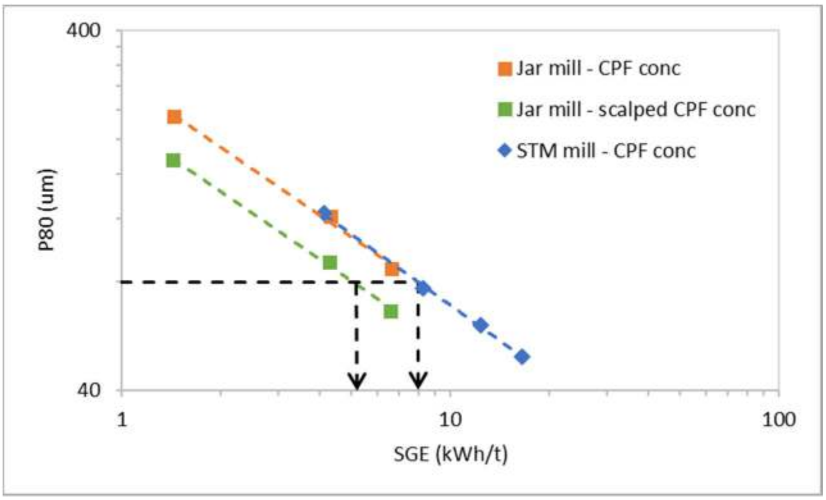


Figure 2—Signature Plot for a CPF Concentrate

Figure 2 indicates a good agreement in energy requirements for the CPF concentrate as measured using different test methodologies (despite the difference in media size). The specific energy measured using scalped CPF concentrate is also coherent, considering the mass split of fines that occur in the dewatering stage. The selected specific energy for the study was 8 kWh/t of regrind circuit feed or 5 kWh/t of dewatering circuit feed. Table 1 shows the design criteria for this case study.

Table 1—CPF Regrind Circuit Design Criteria

Parameter	Unit	Value
Dewatering Cyclone		
Mass Split to Underflow	%	70
Underflow Density	% w/w	60
Overflow Size, P_{80}	µm	67
CPF Regrind Circuit		
Circuit Feed Rate, Nominal (Dry)	t/h	340
Circuit Feed Size, F_{80}	µm	200
CPF Regrind Cyclone		
Mass Split to Underflow	%	80
Underflow Density	% w/w	60
Overflow Size, P_{80}	µm	80
CPF Regrind Mill		
Mill Product Size, P_{80}	µm	80
Feed Density	% w/w	55
Media Consumption	g/kWh	12

Even though feed to CPF is considered coarse, the typical CPF product size can still be processed using small ceramic media. This application considered a VRM with a 23,000-litre shell fitted with a variable speed 3500 kW drive, and filled with ceramic beads with 10 mm top size.

CASE STUDY 2: NEW ENERGY-EFFICIENT GRINDING LINE

Case Study 2 considered an additional comminution circuit to increase processing capacity and deal with a misalignment between mining and minerals processing plant capacities at a gold mine. Various technologies were evaluated to increase processing capacity, with consideration given to power and water requirements, and the overall operating unit cost. The HPGR-like crusher and VPM technologies were found to be suitable due to their power efficiency and ability to deliver an incremental throughput of 160 t/h. Figure 3 shows the process flowsheet, indicating an HPGR-like unit that produces a feed size F_{80} of 800 µm to the VPM circuit.

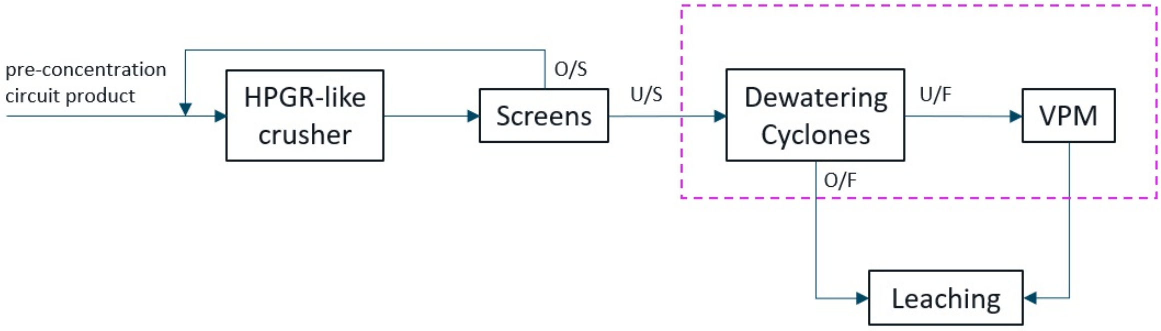


Figure 3—Process Flowsheet—Case Study 2

This HPGR-like crusher has two grinding rollers that are diagonally arranged. The material is fed into the gap between the rolls and is compressed and crushed under high specific grinding force (range of 2–5 N/mm). The crusher is in closed-circuit configuration, with a wet screen with 2 mm aperture. Extensive testwork at STM's test center was undertaken due to this being the first worldwide application of this technology in gold processing. The results from various tests are combined in a single signature plot (Figure 4) (blue points) as well as the design point (orange point). The selected specific energy was 5.0 kWh/t, for a target product size of P_{80} 100 µm (equivalent to P_{70} 75 µm).

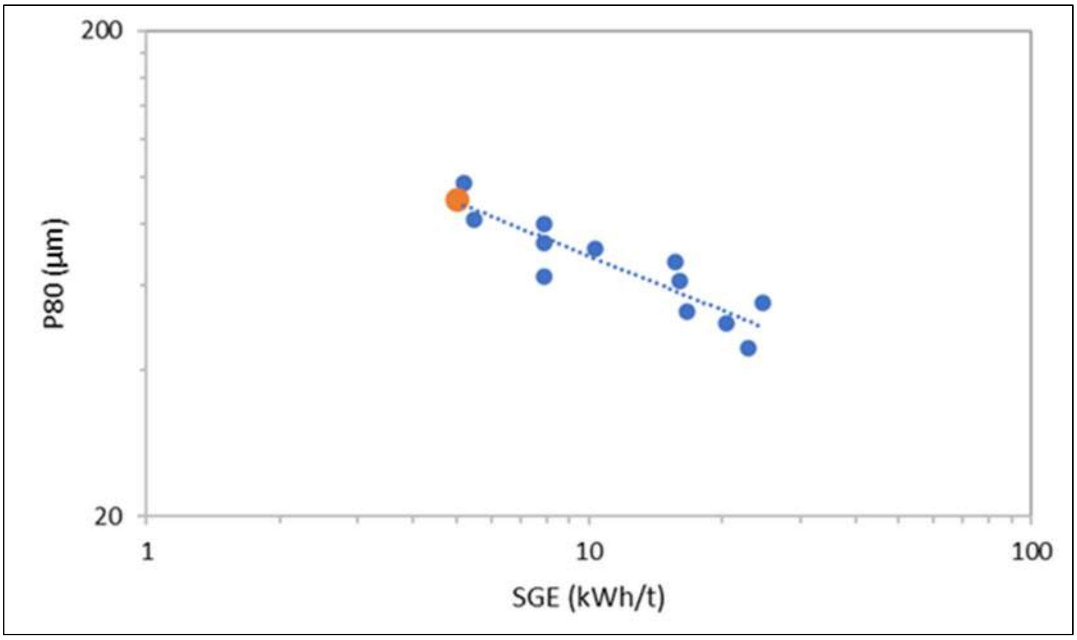


Figure 4—Signature Plot for HPGR-Like Product

The VPM mill was designed and constructed in this duty, and commenced operation in 2022. Operating data have demonstrated the suitability of the testwork methodology, and that the grinding mechanisms of the VPM mill can be successfully applied to grind coarse feeds. The design of this mill was validated through operating data (Figure 5).

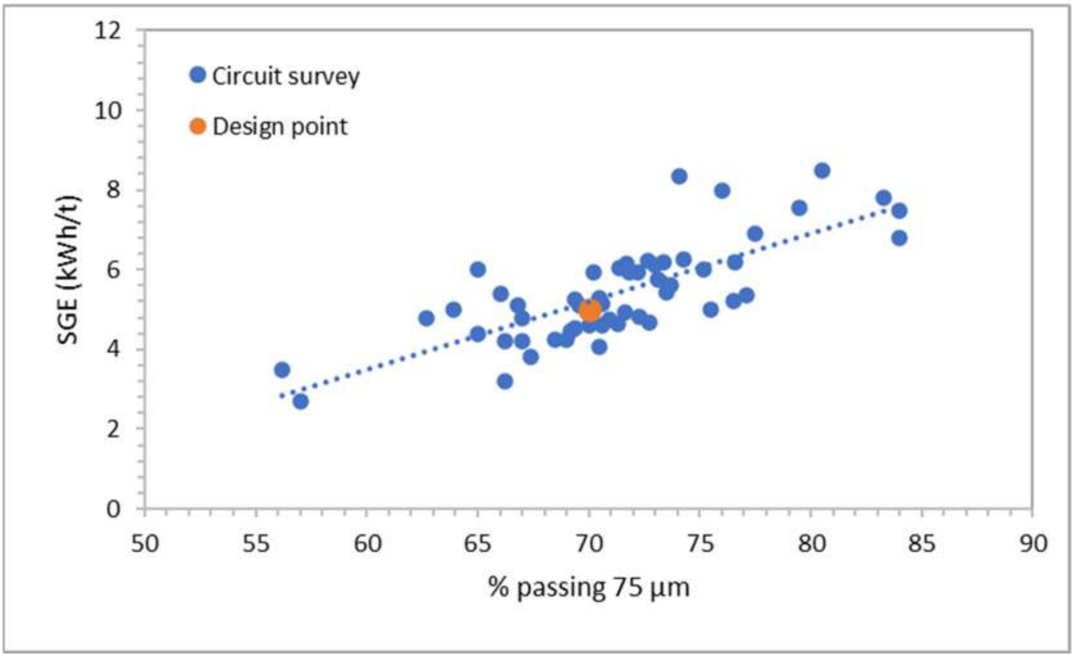


Figure 5—Operating Data for the First VPM10

CASE STUDY 3: VARIABLE FEED RATE

The recovery of magnetite from mining tailings presents an opportunity to extract additional value from tailings materials generated by mining operations. It also has environmental benefits, as it reduces the impact caused by large tailings storage facilities and helps to conserve natural resources by making use of materials that might otherwise go to waste.

Case Study 3 consists of the design of a magnetite recovery circuit, featuring multiple stages of magnetic separation and a regrind circuit. The regrind circuit throughput has a range over 9 times during a 10-year operating period due to the varying sulphur and magnetite grades across the mine schedule. The block flow diagram of this circuit is summarized in Figure 6.

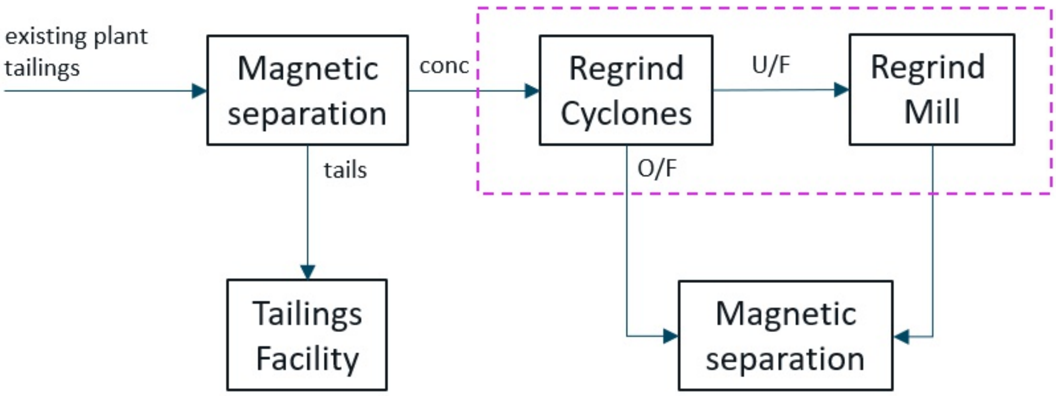


Figure 6—Process Flowsheet—Case Study 3

The regrind circuit design was a particular challenge as overgrinding the material resulted in downstream recovery loss, so the regrind technology needed to be able to achieve sufficient liberation without overgrinding. The design target was to achieve a fixed regrind size (P_{80}) across the throughput range. Ball milling and stirred milling flowsheet options were considered for the project:

- The ball mill option considered adjusting the ball load and mill power draw at the different throughput rates, delivering variable grind size and thus impacting metal recovery. Reducing the ball load in a ball mill can only be used as a long-term control strategy as the reduction is related to the consumption of the balls due to wear. At very low throughput rates, the ball milling circuit would be bypassed, increasing the negative impact on metal recovery.
- The stirred mill range of operation in terms of consumed power is much larger than a ball mill, with tip speed and bead filling being adjusted to ensure the desired power draw is achieved at various throughput rates. Reducing the rotor speed can be used as a short-term control to vary the power from 100% to 30% installed power. Media filling can be used as a medium-term control parameter to reduce the power draw to less than 10% of the installed power. The wide range in feed throughput also required the mill feed valve arrangement to be changed to maintain slurry velocity into the mill and avoid media flow-back.

Figure 7 shows that the operational variability in the VRM mill allows the recovery to be maintained across the wide range of throughput. In comparison, a ball milling circuit would achieve variable recovery dependant on the throughput.

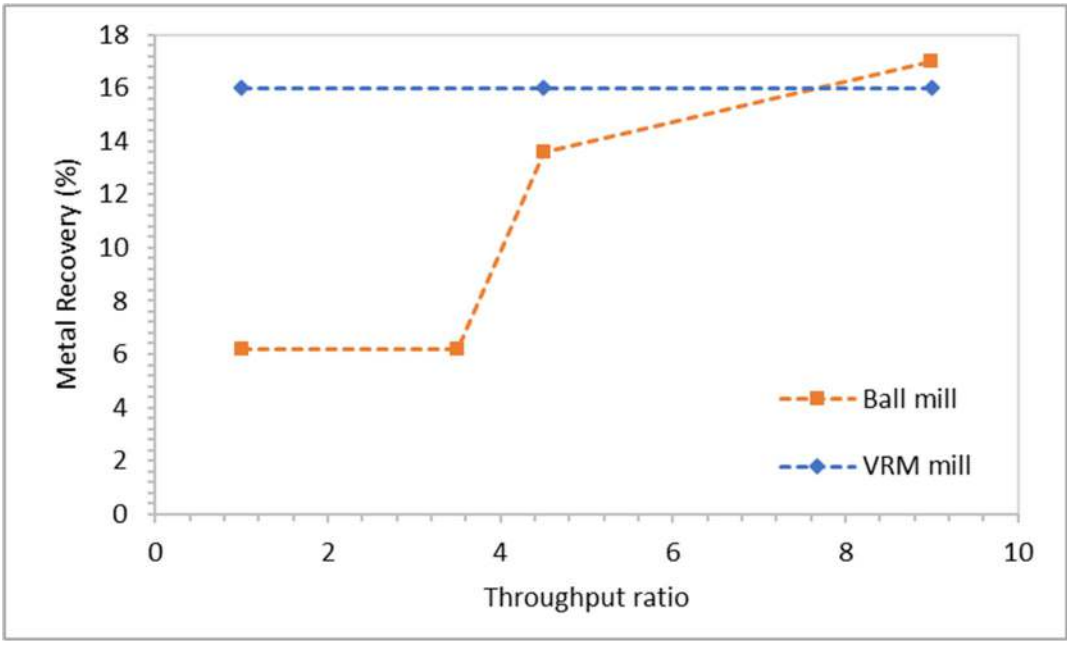


Figure 7—Metal Recovery Across Required Throughput Range for Ball and VRM Mills

Ore characterisation testwork was completed; the signature plot shown in Figure 8. Results indicate an average specific energy of 7.0 kWh/t to grind the ore from a feed F_{80} of 250 µm to a product P_{80} of 75 µm. To allow for variations in feed mineralogical composition and consider the associated change in energy requirements, the mill design was based on a range of specific grinding energy between 6.0 and 8.0 kWh/t.

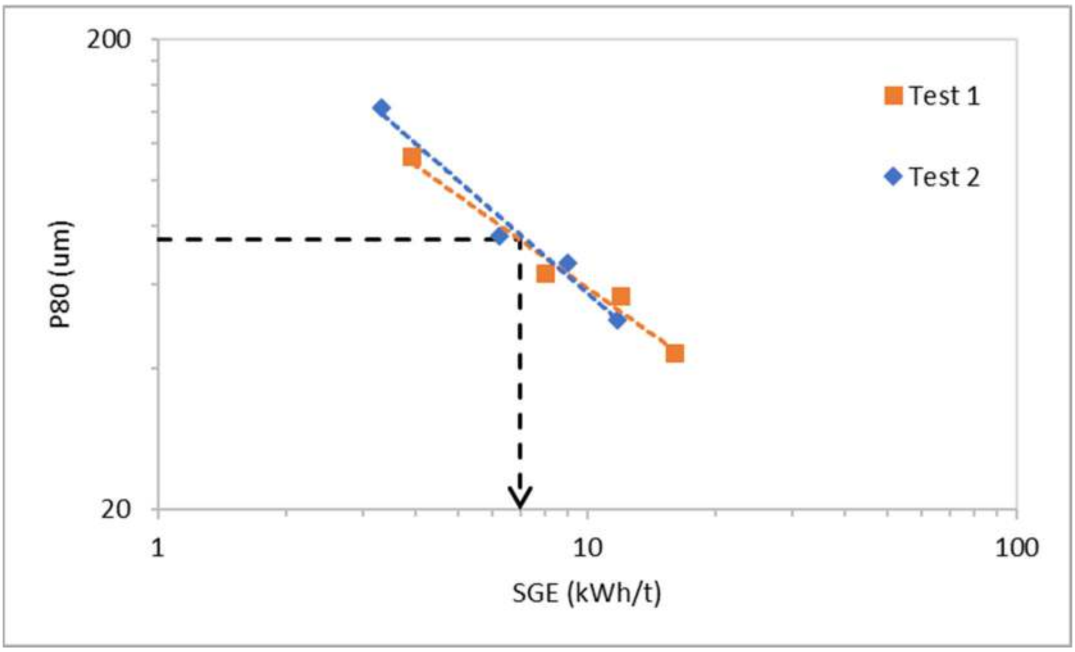


Figure 8—Signature Plot for Magnetic Separation Concentrate

A trade-off study was undertaken to compare ball and vertical stirred milling technologies. The study recommended VRM technology as the preferred stirred milling technology based on its ability to produce the desired product size distribution and operate effectively over a broader range of throughputs. Table 2 presents the key factors impacting the selection of regrind technology for this study.

Table 2—Magnetite Regrind Circuit Technology Comparison

Ball Mill	**VRM**
The ball mill power draw can only be reduced by varying mill speed and ball charge (lowering ball charge can be challenging as it takes significant time), and only allows the power draw to be reduced 35%.	The power draw of the vertical stirred mills can be varied from 100% to 30% of the installed power in the short-term via the variable speed drive (refer to **Error! Reference source not found.** for the VRM's turn-down ratio).
At higher magnetite feed grades, the mill would operate at the maximum throughput and produce a product grind size coarser than target, whereas at lower magnetite feed grades the opposite would occur and finer grind size would be produced.	The media can be changed over the medium term by addition at the top, or removal from valve in the base. Varying the filling can allow the VRM mill to draw below 10% of the installed power.
Multiple ball mill units would be required to achieve the target grind size while covering the range of throughput required for the project.	In the long term, the required feed valve assembly is at two different diameters for high feed rates and low feed rates to maintain slurry velocity.
As the ball mill operates in closed circuit, it is likely that it would produce more fines by both the preferential deportment of high-density minerals to the cyclone underflow and the non-discriminatory breakage mechanism within the mill.	The combination of open circuit operation and the internal classification within the VRM mill reduces the potential production of fines, thereby increasing downstream recovery.

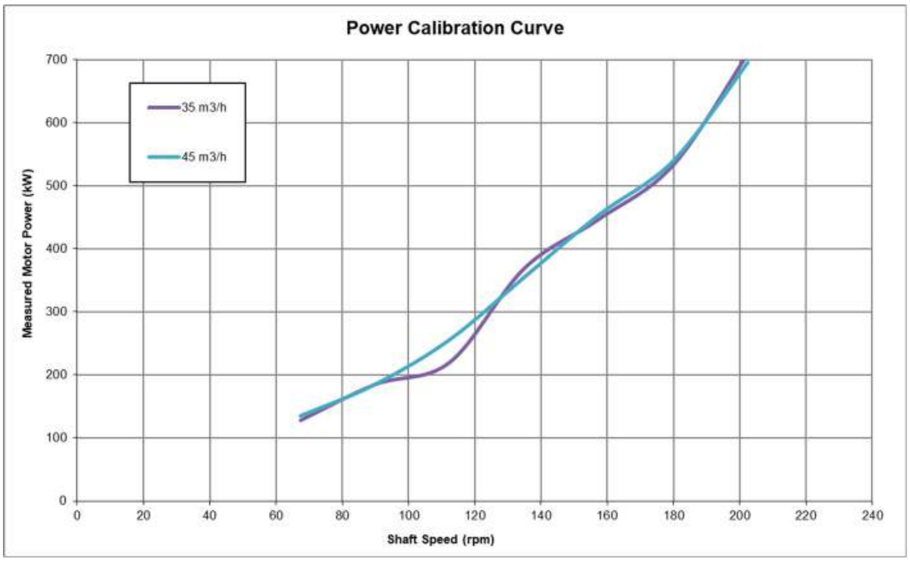


Figure 9—Turndown Ratio of VRM (Swiss Tower Mills, 2023)

The capital cost estimated for a single ball mill circuit was approximately 50% less than the VRM; however, a single ball mill would be unable to achieve the target grind size across the throughput range. The potential recovery losses associated with generation of very fine magnetite particles make the VRM technology the most suitable for this application.

Stirred Mill Design for Coarse Feed Applications

Grinding in stirred media mills occurs by attrition, through the interaction of feed particles and grinding media. Paz et al. (2023) described the principles of operation for STM mills as summarized below and illustrated in Figure 10.

- The feed slurry is pumped from the bottom through a bed of media. The feed inlet and discharge outlet are at opposite ends of the grinding chamber.
- Stator rings installed on the mill shell and rotating rotors create separate grinding chambers around each rotor, promoting plug-flow reactor-like slurry movement through the mill, thereby eliminating short-circuiting or dead zones.
- The grinding rotors create a centrifugal force to push the grinding media and coarser particles towards the high-intensity grinding zones on the chamber's periphery. The fine particles travel upwards closer to the mill shaft, leading to less contact with media and shorter retention time compared with the coarse particles. This internal classification helps prevent overgrinding and ensures that energy is applied mainly to coarser particles.
- The slurry flow path, in conjunction with the selective grinding mechanism, produces a steep product particle size distribution, allowing the target grind size to be achieved in a single mill pass without recirculation.
- Variable speed drives on the mills allow for precise control of the specific grinding energy, enabling consistent and uniform product size distribution, regardless of fluctuations in feed characteristics.

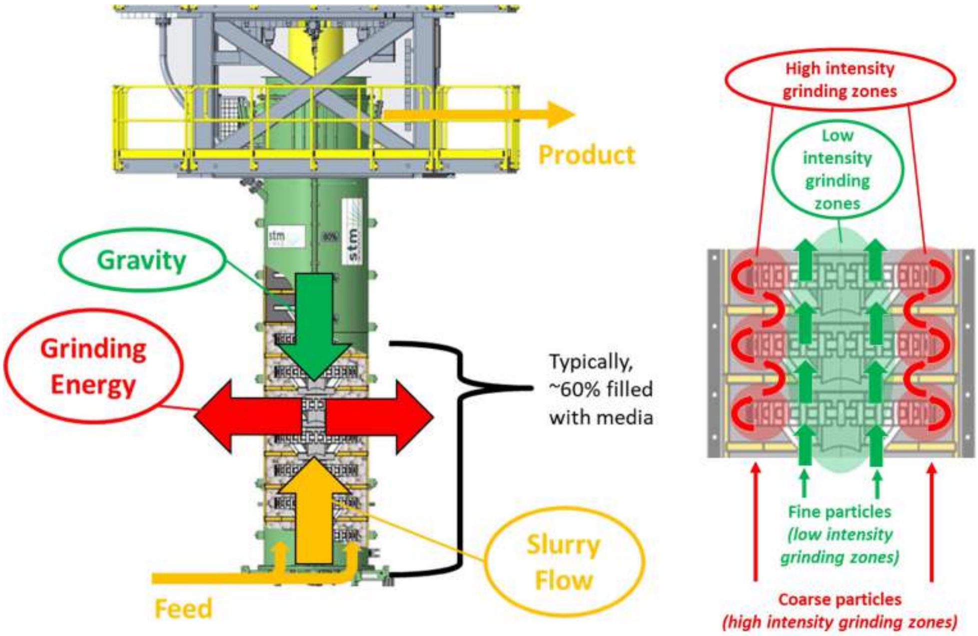
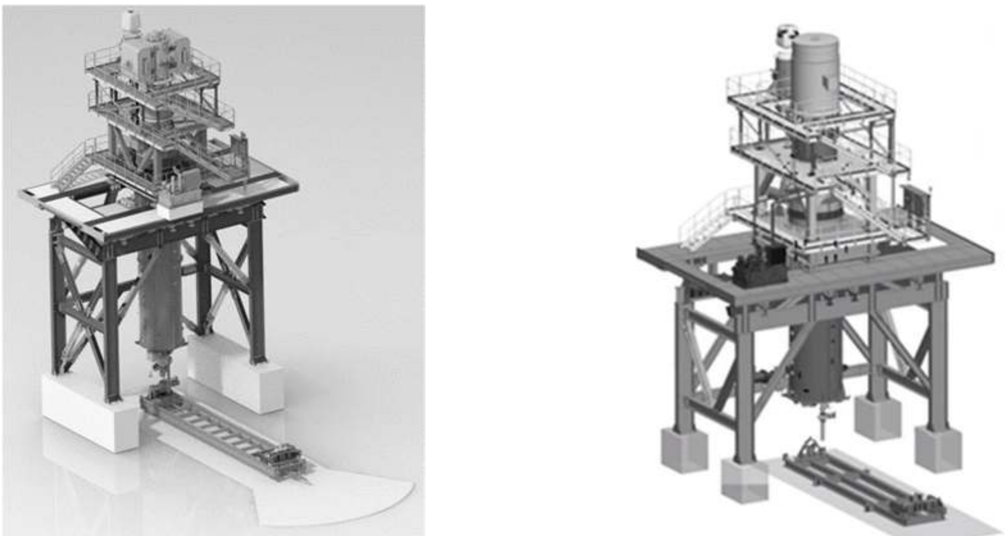


Figure 10—Principle of STM Mill Operation (reproduced from Paz et al., 2023)

To accommodate coarser feeds with a top size of up to 8 mm, and use larger grinding media, the VPM mill has a wider grinding chamber with more space between the grinding rotors and stator rings. Figure 11 provides a side-by-side comparison of a VRM and a VPM with similar volume, and Table 3 presents the main process parameters of these units. The diameter-to-length ratio is a significant difference between the two mills, as the VPM has a wider, but shorter, grinding chamber compared to the VRM.



VRM VPM

Figure 11—Comparison of VRM and VPM Design

Table 3—Comparison of VRM and VPM Process Parameters

Parameter	VRM	VPM
Duty	(Ultra-)fine grinding & regrind	Coarser feed applications
Feed Slurry Density (% w/w)	38–60	50–65
Impeller Speed (m/s)	6–13	8–13
Power Intensity (kW/m^3)	150–300	75–150
Typical Feed Size-Range, F_{80} (µm)	20–400	300–4,000
Typical Product Size-Range, P_{80} (µm)	8–75	>50
Media Size (mm)	1–15	5–32
Media Type	Ceramic	Ceramic or Steel
Largest Unit		
Model	VRM75000	VPM75
Power (MW)	11.5	Current up to 7.5 MW (larger units in development)

TESTWORK AND SCALE-UP

To achieve direct scale-up from pilot testing to industrial mill, STM developed a methodology for continuous and semi-continuous testing. This approach involves replicating equivalent grinding mechanisms, media size, media type, and slurry density used in both the test- and full-scale mills.

The pilot-scale mill operational parameters are chosen for the continuous test to reach the target product size in just one pass through the mill. A sample of the mill product is collected and provides the product particle size distribution. The semi-continuous test requires the slurry to pass multiple times through the mill to generate a signature plot of the grinding specific energy versus the grind size. Small-scale batch tests are not available for coarser duty applications. Table 4 presents the sample mass requirements for the STM mill tests. Currently STM is developing a small sample test for coarse grinding applications.

Table 4—STM Test Sample Mass Requirements

Mill	Batch Test	Semi-Continuous Test	Continuous Test
VRM 5	5–8 kg	30–50 kg	30–50 kg
VRM 25	-	60–90 kg	60–90 kg
VRM 200	-	600–700 kg	600–700 kg
VPM 0.3	-	700–800 kg	700–800 kg

Conclusions

Stirred milling technology has predominantly been used in fine and ultra-fine grinding applications, as these mills offer several advantages over traditional ball mills, including improved energy efficiency and reduced media consumption.

Three case studies have provided examples of the effectiveness of using stirred mills in coarse duty applications. The use of larger media extends the technology application feed size range; however, further work is required to understand the energy efficiency of these mills when compared to ball mills in coarser duty applications.

The case studies presented in this paper show that innovative comminution flowsheets featuring CPF and coarse magnetic separation are now being considered by mining companies that seek to minimize the energy requirement to produce concentrates, use more energy efficient equipment and enable the rejection of coarser tailings.

The design modifications made to the VRM mill have extended the application of the STM mills to coarse duty applications, with the first VPM starting its operation in 2022. The experience at this operation indicates that:

- The VPM mill design allows for the use of larger diameter ceramic media.
- The VPM’s grinding mechanisms can be successfully applied to grind coarse feed size distributions.

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