Flowsheet of the Future: High-Pressure Grinding Rolls, Vertical Stirred Mill, Coarse Particle Flotation, Vertical Stirred Regrind Mill

*M. van de Vijfeijken[1], B. Dierx[2], E. Wasmund[3], J. Concha[4], J. Hernandez[5], & M. Sherman[6]

[1]Swiss Tower Mills Minerals AG
Haselstrasse 1, 5400 Baden, Switzerland

[2]Weir Minerals
Egtenrayseweg 9, 5928PH Venlo, The Netherlands

[3]Eriez
7168 Venture St, Delta, BC V4G 1H6, Canada

[4]Eriez
Av. Manuel Olguín 335, Lima 15023, Perú

[5]Anglo American
650 W Georgia St #620, Vancouver, BC V6B 4N8, Canada

[6]Fluor
1075 W Georgia St #700, Vancouver, BC V6E 4M7, Canada

(*Corresponding author: maarten_vijfeijken@hotmail.com)

Abstract

Mineral processing is immensely energy intensive, and of all the unit processes that comprise a concentrator, the grinding circuit consumes most of that energy. This paper describes a proposed flowsheet of the future that combines established technologies to consume significantly less energy compared to conventional comminution flowsheets, and therefore reduces the operation's carbon footprint and operating costs.

The "flowsheet of the future" uses high-pressure grinding rolls as an alternative to a semi-autogenous grinding mill, and vertical stirred mills in open circuit as an alternative to ball milling. When combined with coarse-particle flotation technology, which allows improved metal recoveries at a coarser flotation feed size, the combination of using more power-efficient grinding technologies with a coarser grind size significantly reduces the total energy consumed. Fluor's process knowledge has contributed by producing a system approach, whereby the grinding circuit and flotation circuit or other downstream recovery process (e.g., gold cyanidation) become a single system rather than an amalgamation of discrete unit operations.

The benefit of the resultant holistic approach for grind–float concentrators is reduced energy demand combined with increased metal recovery by reducing the amount of target mineral lost to over-grinding. For gold plants, the new flowsheet also has the potential to reduce cyanide demands by reducing the mass of steel media consumed by the grinding circuit.

Anglo American, Weir Minerals, Eriez, and STM are performing extensive testwork in support of this flowsheet of the future.

Keywords

HPGR, vertical stirred milling, coarse particle flotation, energy efficiency, recovery, over-grinding

Introduction

The main components of today's typical flowsheet have not changed much over many decades (e.g., using ball mills paired with cyclones to grind target minerals to a size that suits the downstream recovery process). While high-pressure grinding rolls (HPGR) were introduced to the minerals industry approximately three decades ago, and are becoming more common, most concentrators still use tumbling mills for grinding duties (e.g., autogenous grinding [AG], semi-autogenous grinding [SAG], rod, or ball mills). While flowsheets have not changed, the operating environment has changed significantly:

- Reduced head grade and increasing ore hardness compared with a few decades ago (more so with base metals)
- Milling consumable costs have increased significantly (e.g., power and steel media)

Processing harder ore has required applying higher grinding energies to liberate the target minerals. For tumbling mills, the higher grinding-energy demand typically requires the use of more steel media, which significantly increases the cost of milling the ore. Options for reducing the milling cost are:

- Using more energy-efficient grinding technologies (e.g., HPGR and stirred mills)
- Pursuing downstream technologies that allow target-metal recovery at a coarser grind size, e.g., coarse particle flotation.

Given that grinding power demand is inversely correlated to the final grind size, the ability to recover target metals at a coarser grind size may significantly reduce operating costs. As a result, Eriez, Weir, and STM formed a co-operative partnership to evaluate all the ways that their technologies can be synergistically combined to achieve the goal of reduced energy demand. Reducing grinding energy has the potential to reduce the capital cost demand, and using a coarser grind size would also contribute to safer tailings impoundments.

Fluor and others have long recognized that over-grinding target minerals is detrimental to flotation's efficacy, and that applying increasing grinding energy (required by harder ores) has the potential to exacerbate the amount of target mineral lost to over-grinding. These losses would not show up in the metallurgical testing laboratory, due to most laboratory test programs using batch milling and screens to prepare the flotation test feed, whereas the operating circuit uses ball mills operating in closed circuit with cyclones. Increased target mineral losses attributable to over-grinding (directly linked to the choice of grinding technology specified for the flowsheet) will significantly impact the performance of the proposed concentrator, with a more pronounced effect for lower-head grade hard-ore operations.

Given the shared interests of the Eriez, STM, and Weir teams, and Fluor's aim of reducing the cost of ownership of the overall process, this paper presents the results of a holistic approach to designing the "flowsheet of the future." The key element was using a systems approach. In addition to evaluating the role of the energy demands of different comminution technologies combined with a coarser flotation feed size, Fluor considered the impact on flotation performance of the choice of grinding technology, which affects the flotation-feed's particle-size distribution (PSD).

This paper focuses on a copper grind–float concentrator, but the same principles can be applied to other base-metal flotation circuits and industrial mineral circuits where the target mineral is softer than its host rock. While over-grinding is not generally considered detrimental to the operation of cyanidation gold-milling circuits, the impact of steel media consumption on cyanide consumption suggests that the proposed circuit of the future will also consume less cyanide—some operators may find this an attractive option.

Todays Typical Flowsheet

The main features of today's typical flowsheet have not changed much over the last few decades:

- Primary crushing to facilitate transportation of mined ore to a stockpile
- A primary breakage unit (e.g., AG, SAG, or rod mill)
- A ball mill working with a hydrocyclone to perform the final grind to product size.

The main feature of the typical flowsheet (Figure 1) is that an AG–SAG mill's capacity is a function of the ore's feed size-distribution and hardness. Throughput rates, and therefore operating costs, vary as the ore's properties vary.

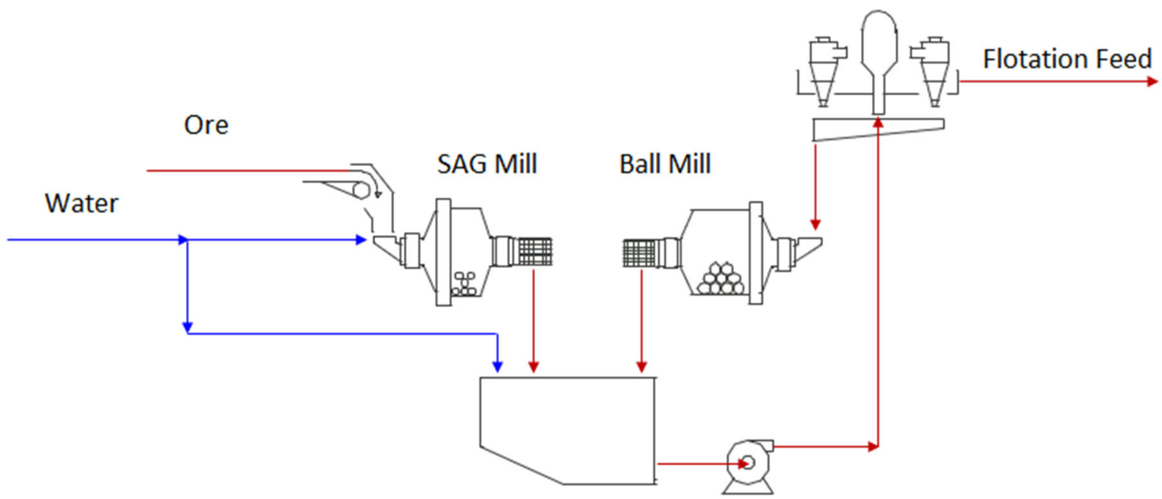

Figure 1—Today's Typical Flowsheet

To reduce the effect of changes in the ore's hardness on plant throughput rate, some operators have chosen to use HPGRs instead of AG–SAG mills.

Available Step-Change Technologies

HPGR

HPGR technology is a well proven and readily accepted machine choice in a wide array of comminution circuits. Its concept derived from Klaus Schönert's research in the 1980s and was adopted in mineral processing due to its energy efficiency when compared to tumbling mill circuits (Burchardt & Mackert, 2019; Burchardt et al., 2011; Morley, 2010). Schönert (1996) discovered that single- or thin-bed particle breakage is most energy efficient, and optimum breakage occurs as particles are compressed between two (nearly) parallel plates with (preferably) unconfined particles perpendicular to the compression forces. Due to the ever-increasing volume of ore to be processed, single-particle crushing has not been scalable; therefore, the HPGR's larger "bed compression" size-reduction mechanism, which results in inter-particle breakage, has become a favourable comminution tool for high-tonnage mineral processing applications (e.g. Iron Bridge, Tüprag Kışladağ and Côté Gold).

Research concluded that specific energy transferred to the ore particles is the dominant driver in fines generation (Lubjuhn, 1994; van Rijswick et al., 2023). As such, HPGRs directly transfer grinding force into the choke-fed particle bed that passes through the gap between two counter-rotating rolls, with the machine consuming negligible amounts of energy in transporting large volumes of ore through the rolls. This is another significant contributor to the overall energy efficiency compared to tumbling mills, where a lot of energy is consumed to lift and rotate the mass of ore and grinding media inside the mill (e.g., for a SAG mill, power is required to rotate the mass of ground product to a height that allows it to flow out of the mill via the pulp discharge assembly).

HPGRs have been included in many comparative techno-economic studies of greenfield projects; in addition, the HGPR's flexibility has also resulted in it becoming the preferred size-reduction equipment of choice in brownfield circuit de-bottlenecking. With global ore grades diminishing, requiring processing of higher throughput rates under increasing energy demands (Calvo et al., 2016), more energy-efficient comminution technologies are sought-after. With ore becoming increasingly competent, HPGR-based circuits have been proven to substantially reduce direct and indirect energy consumption and reduce comminution costs by up to 25%, when compared to traditional SAG mill, ball mill, and crusher circuits, as reported by Daniel, Lane and McLean (2010). For this reason, original equipment manufacturers like Weir have increased the size of HPGRs to effectively process larger volumes of ore in a more energy-efficient manner (Figure 2).

Figure 2—Enduron 2.6 Metre (m) Diameter x 2.6 m HPGR,
Capable of Processing >6,000 tonnes per hour per Unit

Comminution equipment does not operate in a vacuum—it is part of a wider and deeply interlinked mineral processing plant where the comminution circuit's overall performance will significantly influence mineral recovery. This requires a more holistic review of the overall circuit, from rock to recovery. Often, these circuits are prone to increased feed variability, which requires the right combination of size reduction and classification equipment to minimize the fluctuation in product quality, as this will enable greater efficiencies in the recovery circuit. HPGRs can adapt towards changing feeding conditions instantly, as roll speed and grinding force can be changed while in operation, resulting in applying the most-effective, minimal stress-intensity for the particles to break at the given throughput rate. More recently, with grid and energy availability being more heavily scrutinized, comminution equipment that can be ramped up and down swiftly to maximize energy consumption when off-peak energy becomes available during the day offers the owners additional cost savings. This also favours HPGR and vertical stirred mill-based circuits over traditional SAG mill, ball mill, and crusher circuits.

Due to the packed-bed compression-breakage mechanism, HPGRs tend to apply comminution energy over a wide range of feed particle sizes, which results in a higher degree of fines production (Ballantyne, 2023; van der Meer, 2010). However, it is important to underscore that HPGRs can be deployed in several circuit configurations that cater to yielding product at the desirable targeted output PSD. Combined with an adaptive grinding pressure that influences the specific energy, this can result in either a maximization of fines or a reduction in the number of fines, as increased micro-fines production can be undesirable due to reduced recovery or undesirable slimes generation (which affects tailings settling characteristics). Figure 3 shows various HPGR circuit configurations that cater to the most optimal product output for the specified feed conditions.

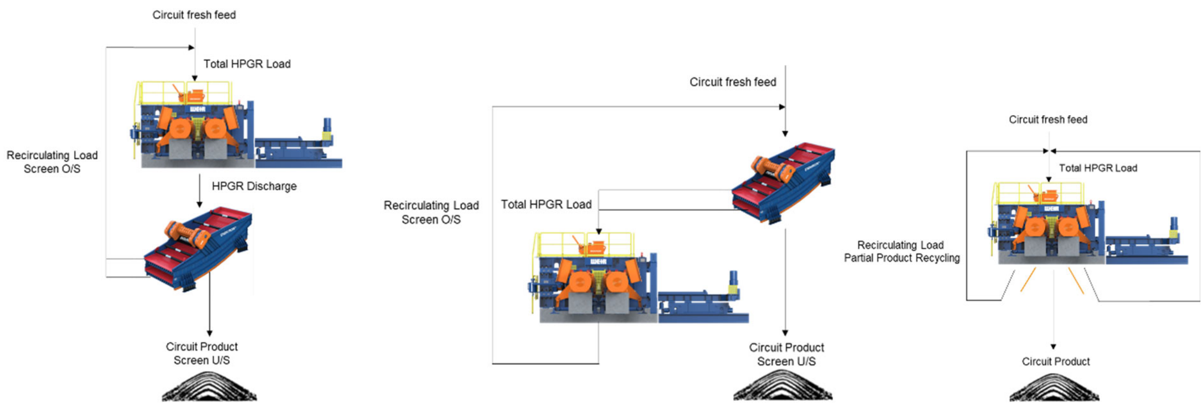

Figure 3—HPGR Circuit Configurations: Closed Circuit with Screen (Left), Truncated Feed (Middle), and Partial Product Recycling (Right) (O/S = Oversize; U/S = Undersize)

Typically, an HPGR is installed in a closed-circuit configuration, with fixed top-feed-size control to produce feed with a maximum PSD-yield below a specified cut size (Figure 3). Alternatively, a truncated or reversed closed circuit configuration can be deployed which contributes to minimizing undesirable (micro) fines production by pre-screening the circuit's fresh feed so that particles already at target grind size bypass the HPGR (Figure 3). Despite slightly reducing the specific throughput, it improves the unconfined particle and bed conditions that Schönert's research revealed.

Lastly, the configuration including partial-product recycle (PPR) (edge recycling), includes an adjustable product-splitter arrangement in which the edge and a portion of the central material is recycled back to the HPGR head feed. This stabilizes circuit output and allows influencing the product PSD, as the position of the splitter plates and the ratio of coarser edge to finer central material can be adjusted without the need for additional classification equipment. The PPR system is frequently deployed in heap leaching applications (Figure 4) or high-moisture fine-particle feed applications such as pellet feed, in which traditional screening is undesirable.

PPR circuits can be successfully deployed when their product feeds a milling circuit (van de Meer & Maphosa, 2012); however, in the absence of fixed-top size control, these circuits have strict feeding requirements to control the 100% passing (P_{100}) to minimize scatting in the mills.

Figure 4—2.4 Metre-Diameter Enduron HPGR in PPR Circuit Configuration Feeding Gold Heap Leaching Pad

In addition to the above-stated HPGR configurations, interest in dry fine grinding has intensified, as more deposits are located in arid locations with very little or no water infrastructure. Combining HPGR with dry-air classification allows micron-sized grinding and classification without any water addition. One recent innovative example is the circuit design (Figure 5) at Fortescue Metal Group's new Iron Bridge Operations magnetite mine. Its flowsheet delivers energy savings by ensuring that energy is not applied to gangue, which is achieved using coarse dry magnetic separation as inter-stage beneficiation between the Enduron HPGRs—this allows rejecting more than 20% of the barren material. By combining HPGRs with dry-air classification, water addition is minimized prior to feeding it into the highly efficient vertical stirred mills. These, in turn, prevent overgrinding by making use of internal classification to minimize mill retention time.

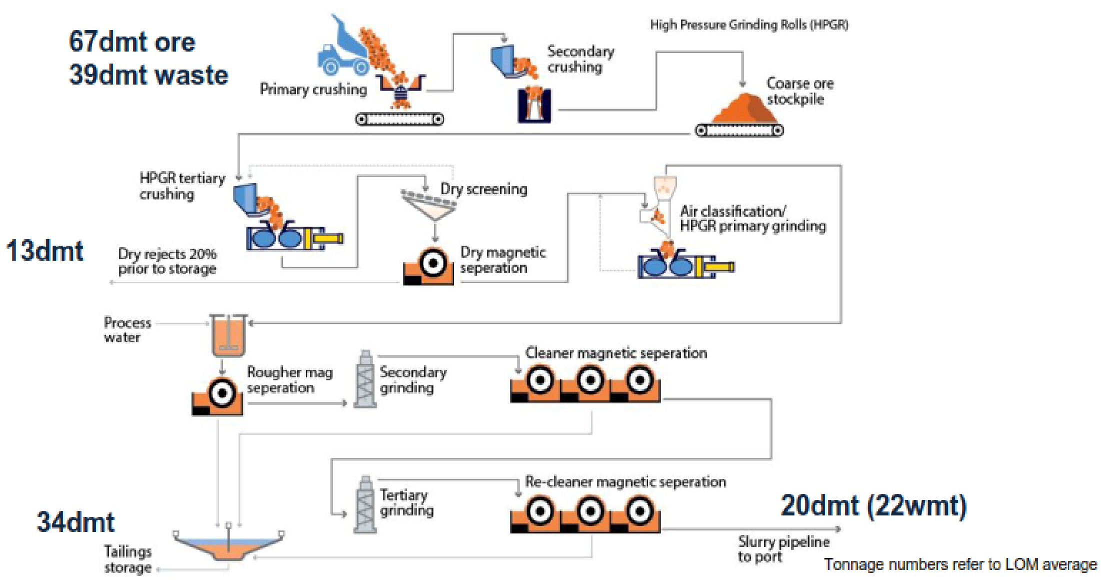

Figure 5—Iron Bridge Process Flow Including HPGRs, Dry-Air Classification and Vertical Stirred Mills

A consistently high recovery rate of the valuable mineral is the apogee of any mineral processing plant. As identified above, HPGR technology combined with flexibility in configuration offers a wide degree of agility to compensate for feed variability, while contributing to reducing overall energy consumption in comminution. Overgrinding, which is usually caused by high recirculating loads and particle residence time in tumbling mills, should be prevented, as this has a profoundly detrimental effect on mineral recovery. Combining HPGRs with vertical stirred mills and coarse-particle flotation (CPF) can further optimize product yield at the lowest possible operational costs.

VERTICAL STIRRED MILL IN OPEN CIRCUIT

Vertical stirred milling technology was developed by a privately owned company operating in the global industrial minerals industry. In 2011 STM obtained the license for this technology, and in 2012 introduced it to the global mineral processing industry. Like the HPGR, there's a demand for vertical stirred mills with higher installed power ratings; currently the largest mill which has been delivered has 6500 kW installed power.

Grinding Mechanism

The STM mill has a vertical mill chamber, with grinding rotors (discs with castellations) installed on the central mill shaft. The mill feed is a slurry, pumped through the bottom of the mill and discharging from top. The mill chamber is filled with ceramic grinding media to approximately 60% of its volume (Figure 6).

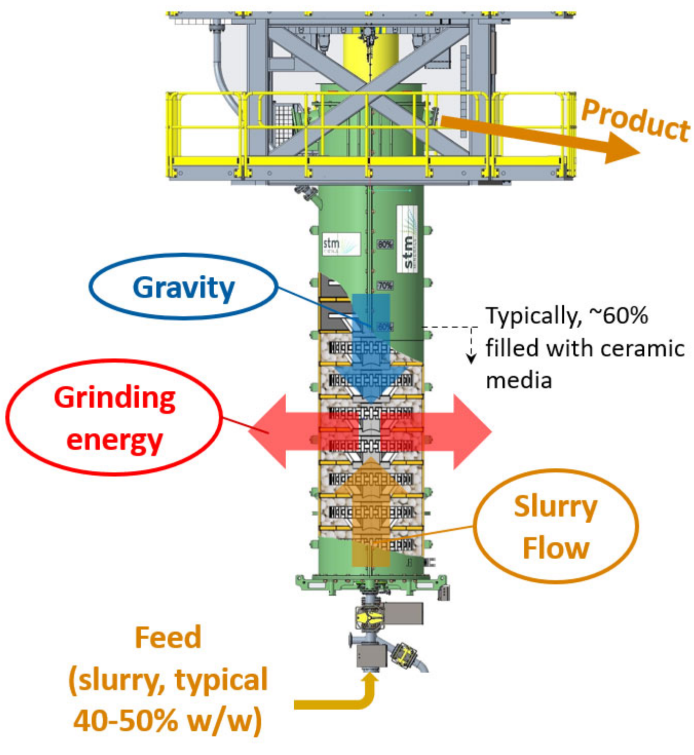

Figure 6—Typical Vertical Mill Cross Section (w/w = solids density concentration by weight)

The grinding media bed moves only in the horizontal plane. This offers the same advantage as with the HPGR of not wasting energy in continuously lifting tons of grinding media. The vertical mill arrangement combined with bottom feed entry and top discharge avoid any possible path for coarse particles to short-circuit the mill.

Energy-Efficient Selective Grinding with Inherent Internal Classification

The mill shell is internally equipped with shell liners and 360° stator rings between each two grinding rotors. This concept generates numerous consecutive grinding chambers. The target is that coarser particles, together with the ceramic media, are pushed by centrifugal forces to the periphery of the chambers, into the high intensity grinding zones, while finer particles tend to travel upwards through the centre of the mill, thereby avoiding any unnecessary grinding. This is called selective grinding, where the energy from the mill motor is applied as much as possible to the coarser particles (Figure 7).

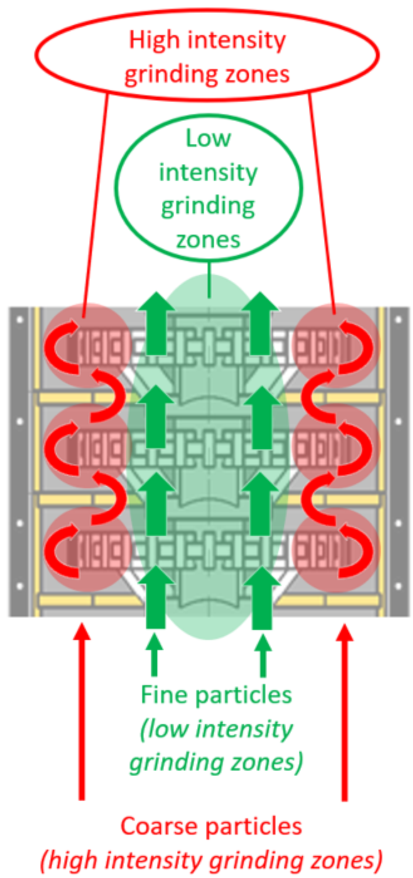

Figure 7—Selective Grinding in the Vertical Mill

Internal classification is achieved by combining the selective grinding feature, variable-speed main motor, and no possible short-circuit path for coarse particles, enables the open-circuit grinding approach. Upstream of the mill there can be a scalping device, typically a cyclone, which can be operated at an optimum feed density of approximately 30% solids by weight (thereby ensuring maximum cyclone classification efficiency) because the mill's optimum feed density (i.e., the scalping cyclone's underflow) is normally around 50% solids by weight range (Figure 8).

This is more advantageous for flotation circuit operators, when compared to ball mill circuits, because a ball mill requires cyclones to be fed at high feed-densities (Figure 9) to ensure that the ball mill receives the correct feed density. Under these conditions, the cyclone's classification efficiency is low, contributing to over-grinding of the target minerals, as shown by Jankovic et al., 2013.

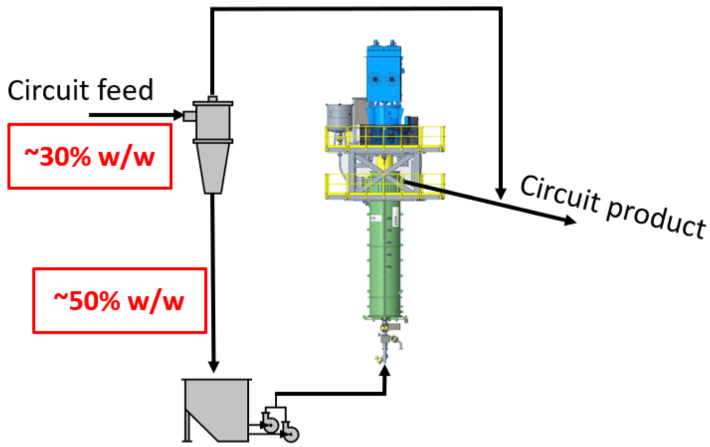

Figure 8—Vertical Mill with a Scalping Cyclone Operating with the Superior Classification Efficiency (w/w = solids density concentration by weight)

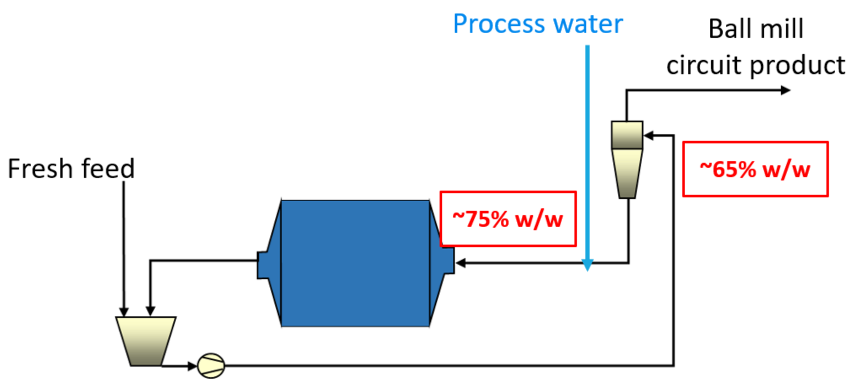

Figure 9—Ball Mill in Closed Circuit with a Cyclone Operating with the Poor Classification Efficiency (w/w = solids density concentration by weight)

When compared to conventional grinding technologies in closed circuit, the combination of the selective grinding action, and the open-circuit configuration with the scalping cyclone operating at an optimum classification feed density, produces a significantly steeper PSD curve (i.e., fewer ultra-fine particles), than that produced by a ball mill operating in closed circuit with cyclones.

Mezquita et al. (2022) demonstrated the energy efficiency gain of the vertical mill in open circuit over a ball mill, describing the expansion installed at the Santa Elena silver concentrator plant in Mexico, where the ball mill cyclone overflow was scalped in a two-stage cyclone concept, with the coarse fraction (underflow of the second scalping cyclone) reporting to a VRM, one of STM's vertical stirred mills. Before the VRM was installed, the ball mill was operating at maximum capacity, with a maximum power draw of 2200 kW, and achieving P_{80} ≈75 µm. Concurrent with the VRM installation, the ball mill was upgraded from fixed speed to variable speed. Figure 10 shows that although the ball mill power draw lessened, installing the additional VRM allowed the expanded circuit to achieve a significantly finer product, P_{80} ≈56 µm at a slightly lower overall power consumption of around 2100 kW (ball mill and VRM combined).

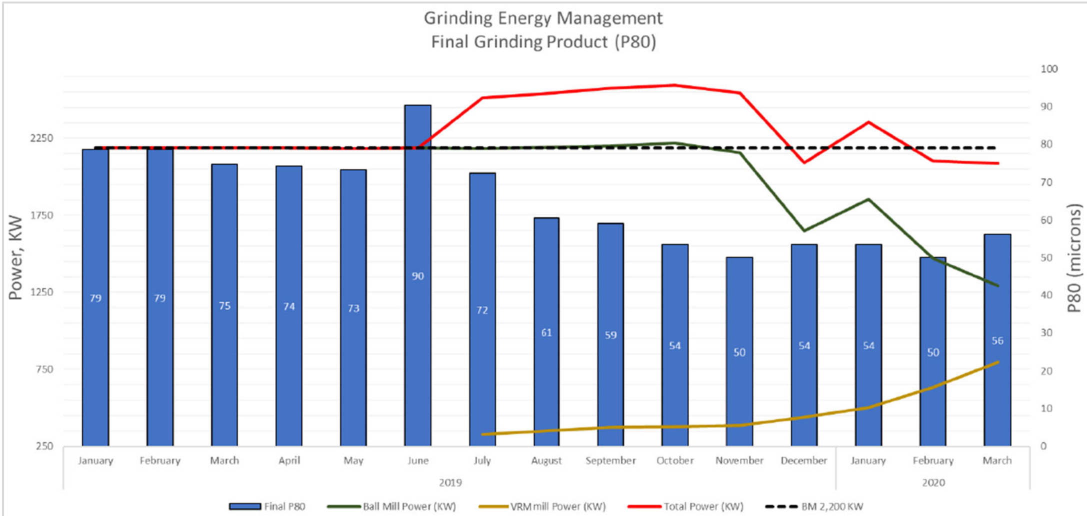

Figure 10—Efficiency Gain of the VRM Over a Ball Mill

Coarser Applications

From the moment the VRM technology was introduced to the global mineral processing industry, STM has been working on developing its technology further towards coarser grinding applications (Erb et al., 2015). In the interim, STM has made significant progress in coarse grinding (Paz et al., 2023) and STM mills are now available for mill feed top-size particles of F_{100} 4 mm At the beginning of 2023 a 1600 kW vertical stirred mill in open circuit was commissioned in a gold mine processing plant with a top feed size of F_{100} 2 mm. STM continues to develop vertical milling technology to enable coarser feed sizes to be milled (Figure 11).

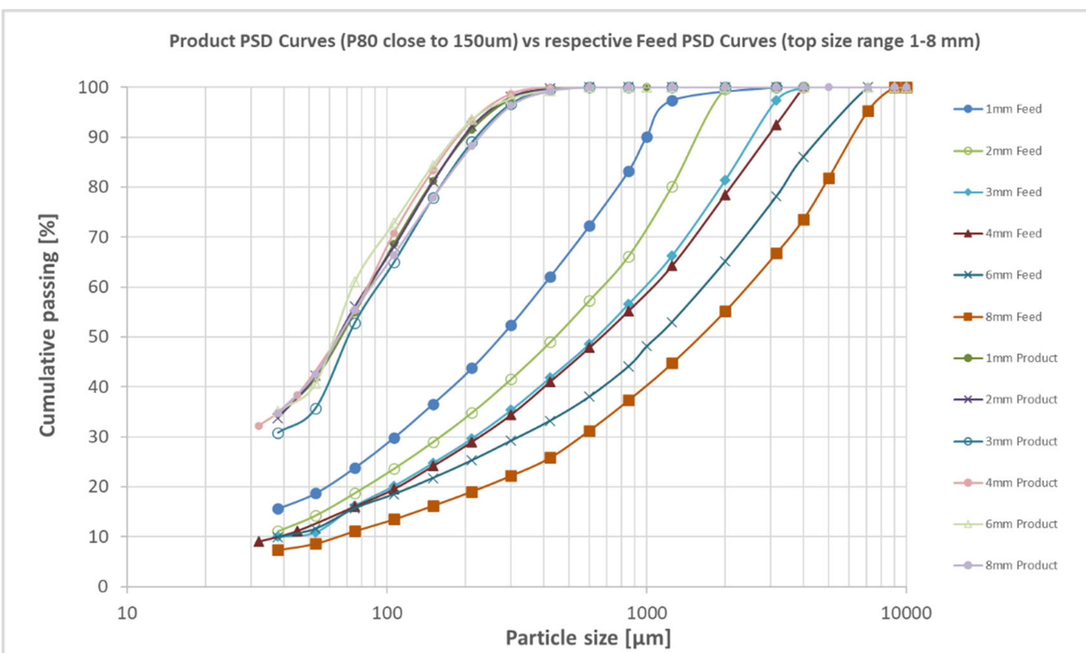

Figure 11—STM Coarse Grinding Testwork on HPGR Product Screened at Different Sizes

COARSE PARTICLE FLOTATION

Among other factors, the recovery or efficiency of conventional flotation is strongly related to the particle size of the ore. The nature of that relationship has been reported in many places over the last seventy years, and Vollert et al.'s (2019) chart for copper producers is reproduced here (Figure 12).

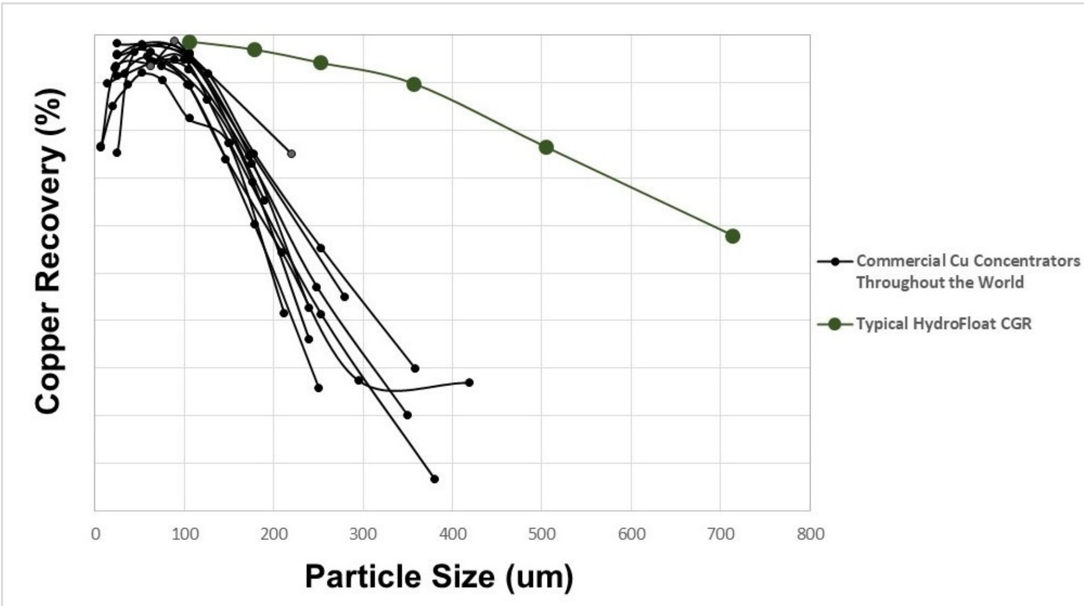

Figure 12—Recovery by Size for Different Copper Concentrator Plants vs. Recovery at HydroFloat CPF in a Coarse Gangue Rejection Application (d_{80} 400 µm) Showing the Extension of Flotation Efficiency in the Coarse Size-Range

The family of curves above represents conventional flotation results published for major producers, as well as a single curve showing experimental results for the HydroFloat CPF machine on the same type of ore. The conventional results show that, on the fine side of the distribution for copper porphyry ore (i.e., typically below 50 microns [µm]), the recovery decreases as the size decreases. Similarly on the coarse side, typically above about 130 µm, recovery is attenuated as particle size increases. Conventional flotation only achieves high efficiency in a narrow interval in the middle of the range, typically 50 to 130 µm. As a result, the tailings (waste product) of these concentrators are enriched in valuable metal units in both the fine and coarse classes of the size distribution (Wasmund et al., 2019), shown in Figure 13, which presents results from two large copper concentrators in the Americas. Therefore, the HydroFloat CPF represents a major step forward in terms of recovery, by extending flotation efficiency over a size range that is two to three times greater than conventional flotation machines' limit.

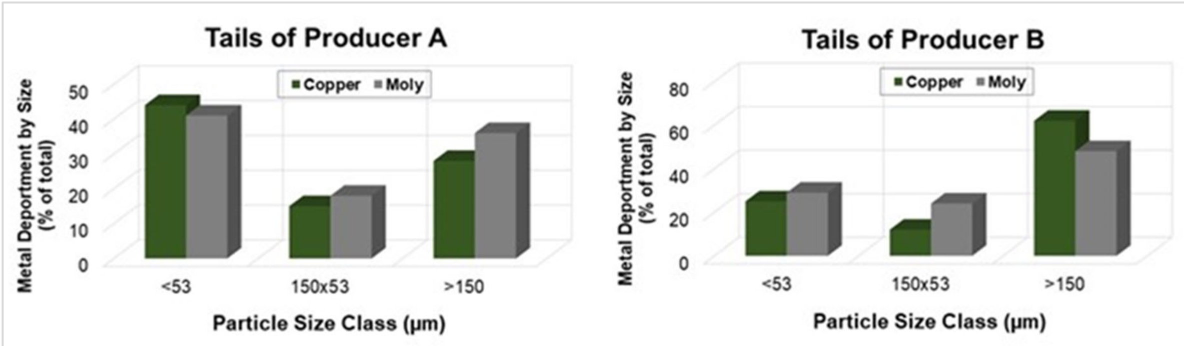

Figure 13—Copper and Molybdenum Deportment by Size for the Final Tailings from Two Copper Porphyry Concentrators in the Americas, Each Greater than 100,000 tonnes per day.

CPF produces this result by combining features that facilitate particle collection and mass transfer including fluidization water to enhance lift, counter-current contacting, a plug-flow residence time distribution, and a zero-order froth (Mankosa et al., 2016). CPF allows the effective flotation size-range for copper to be increased to approximately 400 µm.

A consequence of CPF is that the mill-product size-distribution, as defined by the P_{80} value, can be shifted to significantly coarser sizes. The coarse fraction can be recovered efficiently by the HydroFloat, and shifting the distribution will, in many cases, reduce the volume of fine feed in the distribution, thereby enhancing overall recovery, reducing energy or allowing increased throughput for the same energy, and creating safer, sand-like tailings for disposal. Regino et al. (2020) estimated a 30% to 50% reduction in ball mill energy alone, and Pyle et al. (2022) estimated a 24% decrease in total SAG and ball mill circuit energy by including HydroFloat and coarsening the flotation feed grind-size. The term coarse gangue rejection describes this application, and Anglo American recently reported the first commercial installation at their El Soldado concentrator in Chile (Arburo et al., 2022).

Despite long-standing knowledge and understanding of the relationship shown in Figure 12, until recently scant attention had been paid to designing a grinding circuit to produce a narrow size-distribution customized for flotation.

FLUOR'S APPROACH

The flotation industry has long known that both poorly liberated and over-ground minerals generate a poor flotation response (Figure 14).

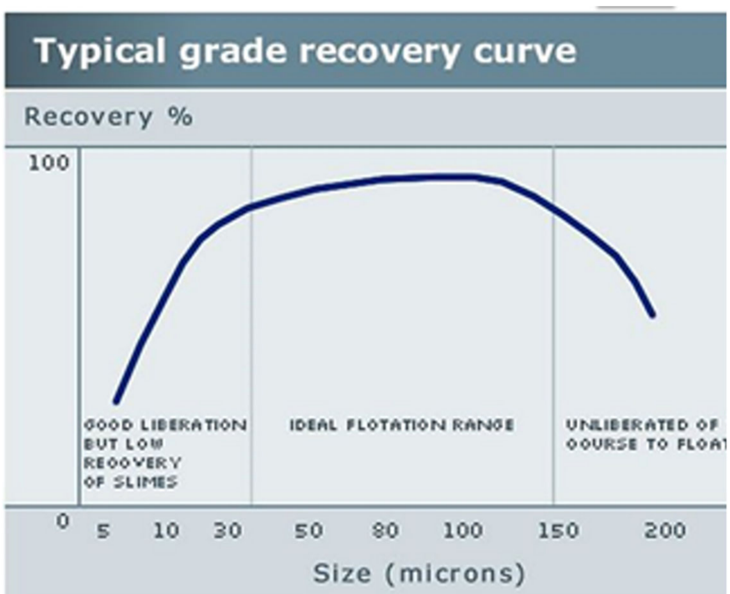

Figure 14—Typical Conventional Flotation Recovery vs. Size (µm) Curve

Instead of approaching this challenge in a "silo" fashion, where grinding, classification, and flotation are separate processes, a system approach was adopted—that is, the three separate processes are one system. What we knew about the system:

- Grinding energy demands are primarily driven by the target grind size.
- Cyclones in a typical concentrator installation operate at poor efficiency (Jankovic et al., 2013), due to the need to produce a high-density underflow that is suitable for feeding to a ball mill.
- Cyclones also classify by specific gravity (SG), not just size.
- Stirred mills are more power-efficient than ball mills.

Fluor's review of the particle size distributions of four ball mill circuits operating since the late 1990s through to today—three processing SAG mill product, the fourth an HPGR product—generated the trend shown in Figure 15, which demonstrates:

- Flotation feed size, F_{80}, is driven by the −38 µm content.
- The finer the flotation F_{80} required, the higher the mass of −38 µm content that reports to flotation.
- In general terms, the amount of material in the optimum flotation feed size (−106 µm to +38 µm) is similar, regardless of the final milling circuit product size.

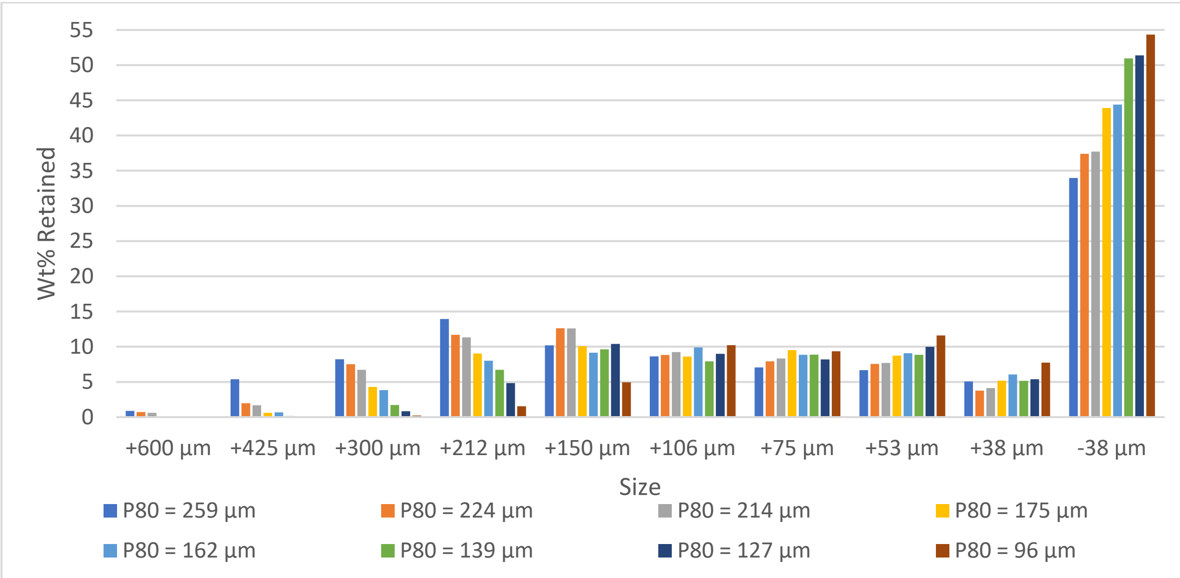

Figure 15—Flotation feed PSDs for Different Copper Concentrators

The data presented in Figure 15 generated the trend in Figure 16, which shows the robust nature of the relationship between F_{80} and the mass of −38 µm produced by the ball mill and cyclone system. Note that the results were collated from copper–gold circuits in different parts of the world, processing ores with significantly different hardness, when expressed as ball mill work indices.

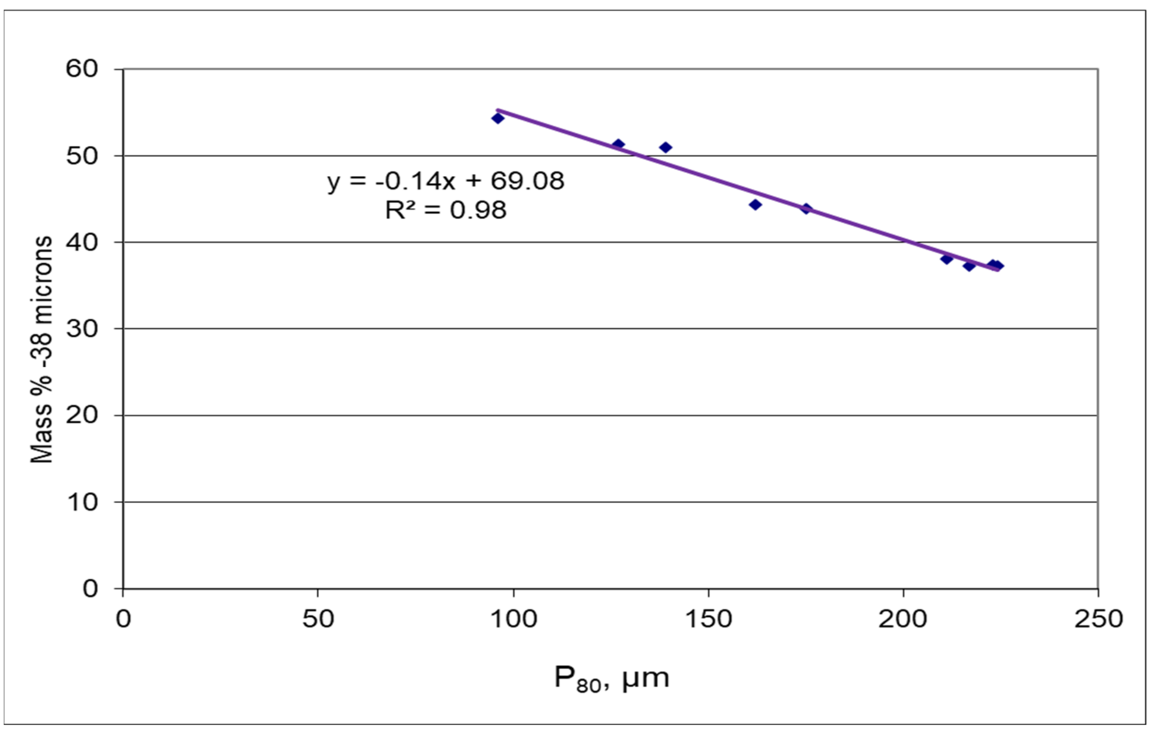

Figure 16—Minus 38 µm Mass % vs. Flotation Feed F_{80}

Figure 17 presents the PSD for the sulphide minerals in a flotation feed (distinct from the non-sulphide gangue) for a different copper concentrator.

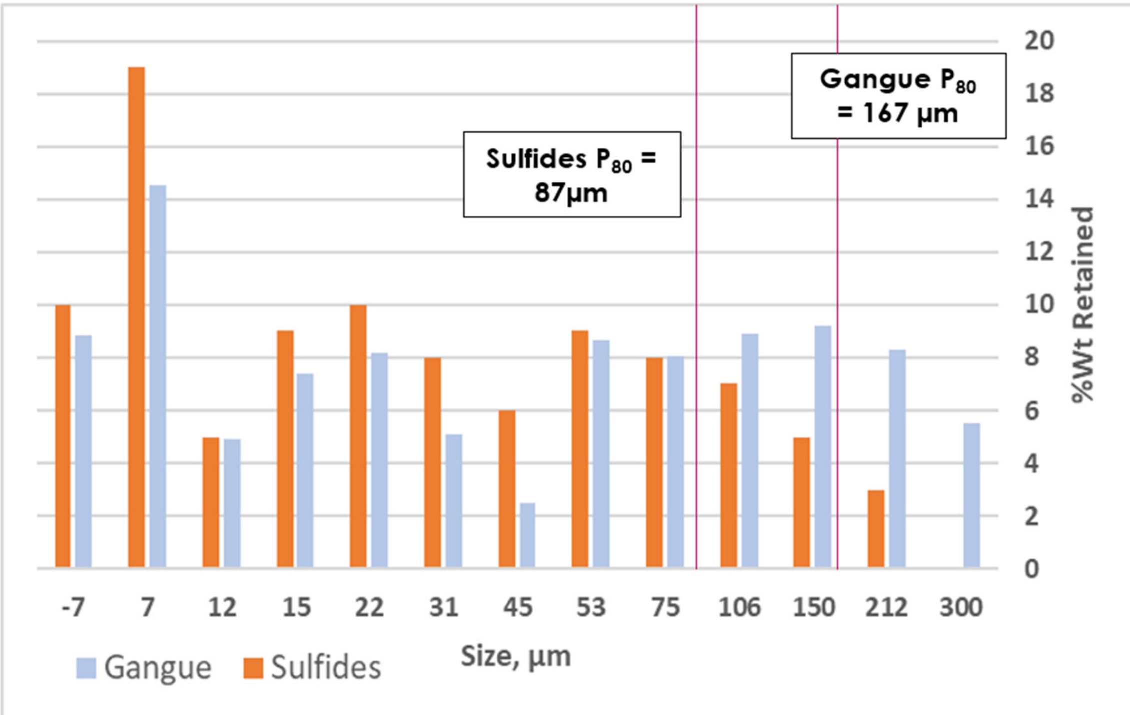

Figure 17—Flotation Feed Gangue PSD vs. Sulphide PSD

Figure 17 demonstrates another outcome of the use of the traditional ball mill–cyclone system—this system grinds the sulphide minerals to a significantly finer product size, P_{80} 87 µm, than the host rock's P_{80} 167 µm. Of specific interest was the sulphide minerals' dominance in the poor flotation recovery size-fractions, material finer than 20 to 30 µm.

This "preferential grinding" phenomenon suggests that harder ores requiring more-intense ball milling energy may be exposed to a greater risk of the target mineral being preferentially over-ground, producing lower-than-expected recoveries. Of greater importance is the potential for the losses attributable to over-grinding sulphides exerting a detrimental influence on the concentrator's performance when head grades are low:

- Host rock hardness determines the installed ball mill's power (i.e., Bond ball mill work index), the flotation feed size target (F_{80}), and the throughput rate.
- For falling head grades, the throughput rate must be high to achieve profitable economies of scale, i.e., high-powered ball mills will be more common in future circuits.
- If the Bond ball mill work index is high (e.g., > approximately 16 kilowatt hours per tonne [kWh/t]), the probability of over-grinding copper sulphides increases because the copper sulphide minerals are softer than the host rock (i.e., operating work index = 12–15 kWh/t).
- However, because cyclones are required to operate inefficiently (to maintain the required feed density to the ball mills), and classify on SG and size, the denser and softer sulphides report back to the ball mill for more grinding.

If the traditional approach to grinding design were maintained, in the future the need to process harder and lower-grade deposits at higher throughput rates will increase the potential for metal losses to over-grinding.

This effect would not be quantified in the pre-feasibility and feasibility laboratory testing programs due to significant differences in the grinding and classification techniques used in the metallurgical laboratory versus the operating circuit. The use of traditional grinding design-approaches for harder, low-grade deposits has the potential for plant recoveries being 2% to 5% lower than laboratory recoveries because of the traditional grinding and classification technologies destroying project value via over-grinding. The higher plant-recovery losses experienced when processing secondary copper sulphides (e.g., chalcocite, digenite) is due to their higher SG when compared to primary copper sulphides (e.g., chalcopyrite).

Given the above phenomena, and considering the options for reducing the mass of slimes and poorly liberated material generated in a typical grinding circuit, Fluor developed a grinding concept that approached the liberation of minerals in the same manner that flotation is generally practiced—that is, by performing a rougher grind followed by a cleaner grind:

- The rougher grind is performed to minimize the over-grinding of the target minerals, i.e., reduced mass reporting to the approximately −30 µm size fraction.
- Flotation is performed on the rougher grind product, with classification performed on the rougher flotation tailings to capture the coarse, unliberated particles, e.g., +150 µm size fraction.
- These coarse particles are then subject to a cleaner grind in a stirred mill to liberate the target mineral for a second flotation step.

While the rougher and cleaner grind concept initially appears similar to the M2F2 flowsheet used by the African Platinum industry, there are significant distinguishing features:

- The M2F2 flowsheet was developed for processing ores that contained two different target minerals, each mineral having a distinctly different liberation size. The ore was first ground to the coarser liberation size to recover the first mineral via flotation, after which additional grinding liberated the second mineral for recovery by flotation.
- Fluor’s circuit design focuses on leveraging the benefits of established grinding technologies via:
  - Use of the “blunt instrument”—the ball mill and cyclone circuit—to do what it does best: process high volumes of material but using the circuit to grind to a much coarser product size. This reduces the amount of damage inflicted on the target mineral via minimizing over-grinding.
  - Use of the more power-efficient stirred milling technology in conjunction with more efficient cyclone classification practice (28%–30% solids cyclone feed density) to reduce the total amount of power required to liberate the target mineral, while also minimizing over-grinding.

This systems-based approach with a two-stage grinding circuit uses specific grinding technologies, classification, and flotation processes to our advantage, and results in energy savings of 10% to 15% when compared to the typical concentrator’s ball milling installation. In addition to the reduction in power demand metal recovery was improved via a reduction in target-mineral lost due to over-grinding and poor liberation.

The benefit of consuming less energy using the two-stage grinding approach is not constrained to the grind-float concentrators. Gold cyanidation plants would benefit from a reduction in steel media consumed in the grinding circuit, because the iron released by the steel media consumes cyanide. Figure 18 presents the results from a gold cyanidation circuit showing the correlation between cyanide consumption and steel-media addition rates.

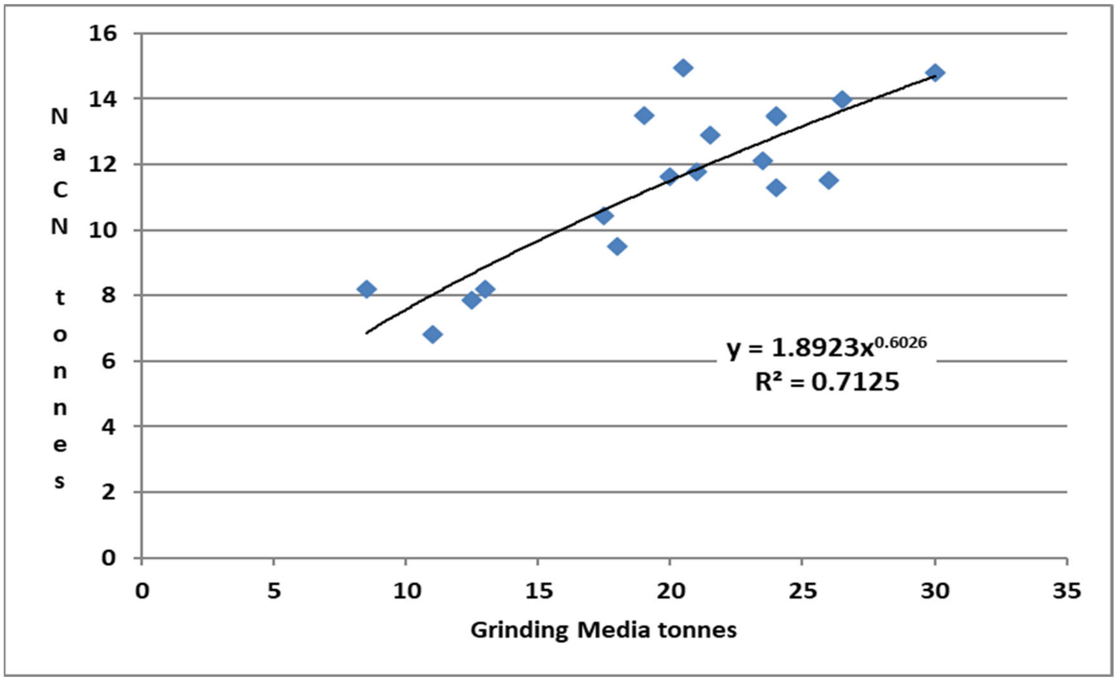

Figure 18—Steel Media vs. NaCN Consumption Rate

Flowsheet of the Future

The availability of HPGRs, the HydroFloat CPF machine, and STM's high-powered stirred mills has made a systems-based approach easier to implement, and therefore significantly more attractive to the industry, through its ability to generate higher metal recoveries while using less energy. This generates a significantly lower carbon footprint per tonne of concentrate produced when compared to the typical concentrator in operation today.

The benefits will be achieved by combining proven technologies in a synergistic manner, rather than as discrete unit processes, to leverage the operating phenomenon associated with each technology:

- Use of HPGRs as a low-energy option for preparing feed to the grinding circuit.
- Use of the two-stage grinding concept, which will minimize the mass of over-ground sulphides via the use of open-circuit stirred milling for the cleaner grind and the use of low solids-density classification feeds:
  - Use of low solids-density feeds for classifying the cleaner grind feed will reduce the mass of liberated sulphides that misreport to cyclone underflow.
  - The stirred mill will consume approximately 20% to 25% less energy for the grinding duty than a ball mill would consume.
  - An open-circuit stirred mill produces fewer slimes than a ball mill operating in closed circuit with a cyclone.
- The HydroFloat CPR technology allows the use of a coarser, rougher grind size, which offers the operator additional reductions in grinding energy-requirements.

Figure 19 presents an example of a flowsheet of the future that leverages all the benefits presented in this paper. Figure 20 presents an option for operators, whose ore may not suit CPF (e.g., fine-grained polymetallic sulphides), but who may still wish to retrofit vertical milling technology into their circuit to increase ball milling capacity while also reducing their losses to over-grinding. The key is to produce a coarser ball mill cyclone overflow product, to avoid overgrinding of the target minerals and have a first pass through the recovery circuit; followed by a second grinding step where the coarse tailings are ground before another pass through the recovery circuit.

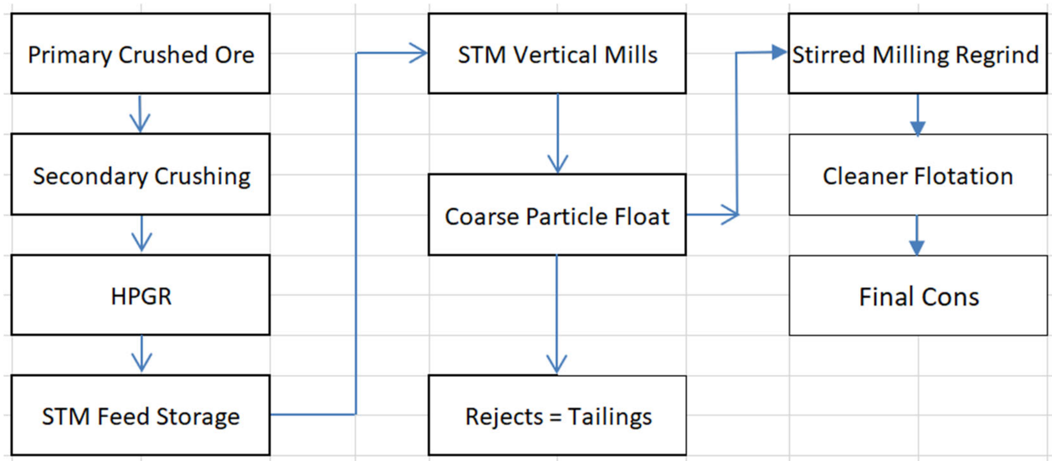

Figure 19—Flowsheet of the Future

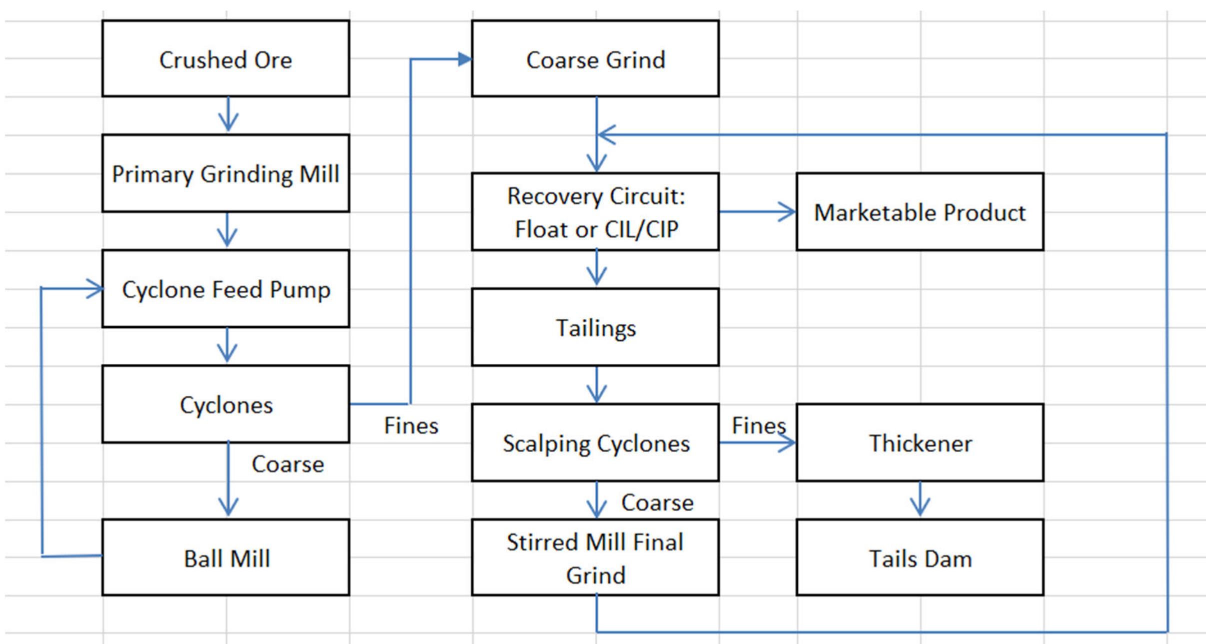

Figure 20—STM Mill Retrofit to Increase Capacity of Existing Ball Mill and Reduce Over-Grinding

Conclusion

The main components of today's typical flowsheet have not changed much over many decades—using tumbling mills paired with cyclones to grind the target minerals down to a size that suits the downstream recovery process. While the flowsheet has not changed, the operating environment has changed significantly, with higher costs, lower head-grades, and harder ores. Some members of the industry have responded to the new operating challenges via the development of HPGRs, vertical stirred mills, and coarse particle flotation machines. The synergy created by these three technologies has led to STM, Weir, and Eriez cooperating to propose alternative flowsheets for the future. Fluor's aim of finding the lowest owner's cost option for processing an ore has resulted in the adoption of a holistic systems-based approach to grinding circuit design where the key design element was the leveraging of operating phenomena associated with the different technologies to produce a lower operating cost circuit.

This paper presented data from several copper–gold grind–float concentrators to demonstrate the effect of the traditional ball mill–cyclone system on flotation feed preparation, and its potential for destroying the value of harder, low-grade deposits due to over-grinding sulphides. The example of the Anglo American El Soldado concentrator provided evidence of the effect of CPF on reducing metal deportment to tailings. The potential benefit of reduced steel media consumption on cyanide consumption was also presented, which some gold miners may find attractive.

Two conceptual flowsheets were also provided: one, a "flowsheet of the future," which combines the benefits of CPF with the low energy-demands of HPGRs and vertical stirred mills; the other, a retrofit option for existing operations that may seek to benefit from an increase in ball milling capacity, decreased over-grinding losses in their flotation circuit, or decreased cyanide consumption in their gold leaching circuit.

Review conclusion and opportunities for future research and discussion:

- Techno-economic review
- OPEX / CAPEX
- Testwork
- Etc.

References

Arburo, K., Zuniga, J., McDonald, A., Valdes, F., Concha, J., & Wasmund, E. (2022). *Commissioning a HydroFloat® in a Copper Concentrator Application*. Paper presented at COPPER 2022. Santiago, Chile.

Ballantyne, G. (2023). *Fractal Energy: Combining fractal dimension of fracture surfaces and Size Specific Energy to describe comminution*. Paper presented at the 2023 Comminution Conference. Cape Town, South Africa.

Burchardt, E., & Mackert, T. (2019). *HPGRs in Minerals: What do more than 50 hard rock HPHRs tell us for the future?* Paper presented at SAG 2019. Vancouver, British Columbia.

Burchardt, E., Patzelt, N., Knecht, J., & Klymowsky, R. (2011). *HPGR's in minerals: What do existing operations tells us for the future?* Paper presented at SAG 2011. Vancouver, British Columbia.

Calvo, Guiomar & Mudd, Gavin & Valero, Alicia & Valero, Antonio. (2016). *Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality?*. Resources. 5 (4). 10.3390/resources5040036.

Daniel, M., Lane, G., & McLean, E. (2010, September 6-10). Efficiency, Economics, Energy and Emissions–Emerging Criteria for Comminution Circuit Decision Making. In XXV International Mineral Processing Congress (IMPC) 2010 Proceedings (pp. 3523–3531). Brisbane, Queensland, Australia. https://www.researchgate.net/profile/Mike-Daniel/publication/325397523_EFFICIENCY_ECONOMICS_ENERGY_AND_EMISSIONS-_EMERGING_CRITERIA_FOR_COMMINUTION_CIRCUIT_DECISION_MAKING/links/5b0bb72f0f7e9b1ed7fa169e/EFFICIENCY-ECONOMICS-ENERGY-AND-EMISSIONS-EMERGING-CRITERIA-FOR-COMMINUTION-CIRCUIT-DECISION-MAKING.pdf

Erb, H., van de Vijfeijken, M., Hanuman, Y., Rule, C. M., Swart, W. C. E., Lehto, H., & Keikkala, V. (2015). An initial review of the metallurgical performance of the HIGmill™ in a primary milling application in the hard rock mining industry. Paper presented at SAG 2015. Vancouver, British Columbia.

Guiomar, C., Mudd, G., & Valero, A. (2016). Decreasing Ore Grades in Global Metallic Mining: A Theoretical Issue or a Global Reality? *Resources 5*(4), 36. https://doi.org/10.3390/resources5040036

Jankovic, A., Valery, W., & Sonmez, B. (2013, January). The Benefits of High Classification Efficiency in Closed Ball Mill Circuits. In *Proceedings of the XV Balkan Mineral Processing Congress, Sozopol, Bulgaria, June 12–16, 2013* (pp. 160–163). https://www.researchgate.net/profile/Alex-Jankovic/publication/283645413_THE_BENEFITS_OF_HIGH_CLASSIFICATION_EFFICIENCY_IN_CLOSED_BALL_MILL_CIRCUITS/links/598056e5aca272d5681dcc5c/THE-BENEFITS-OF-HIGH-CLASSIFICATION-EFFICIENCY-IN-CLOSED-BALL-MILL-CIRCUITS.pdf

Knapp, H., Hannot, S. Meer, van der, F. (2019), HPGR: Why skewing is a requirement for operational applications, Proceedings SAG

Lubjuhn, U., Sander, U., Schönert, K., Druckprofil in der Kompresssionszone de Gutbett-Walzenmühle, Zement-Kalk-Gips, 27. Jahrgang, Nr. 4, 1994

Mankosa, M., Kohmuench, J., Christodoulou, L., & Luttrell, G. (2016). *Recovery of values from a porphyry copper tailings stream*. Paper presented at the International Mineral Processing Council Congress. Quebec City, Québec.

Mezquita, H., Wright, A., Wang F., & Rosario, P. (2022). *Implementation of fine grinding and dual circuit concept at Santa Elena Mine*. Paper presented at the 54th Canadian Minerals Processors conference. Vancouver, Canada.

Morley, C. (2010). HPGR-FAQ. *Journal of The Southern African Institute of Mining and Metallurgy, 110*(3), 107–115.

Paz, A., Zhmarin, E. & Polske, H. (2023). *Recent developments in coarse grinding using vertical stirred mills*. Paper presented at the 2023 Comminution Conference. Cape Town, South Africa.

Pyle, L., Valery, W., Holtham, P., & Duffy, K. (2022). *Pre-Concentration—More than Bulk Ore Sorting*. Paper presented at the International Mineral Processing Council Congress. Melbourne, Victoria, Australia.

Regino, R., Wong, H., Lopez, O., Adams, K., Hobert, A., & Wasmund, E., (2020). *Comparison of two circuit applications for implementation of coarse particle flotation*. Paper presented at the Conference of Metallurgists (COM). Canada (virtual online only due to COVID19 restrictions).

Schönert, K. (1996). The influence of particle bed configurations and confinements on particle breakage. *International Journal of Mineral Processing, 44-45*, 1–16.

van der Meer, F. (2010, September 6–10). *High Pressure Grinding Rolls Scale-up and Experiences*. Paper presented at the XXV International Mineral Processing Congress (IMPC) 2010 Proceedings. Brisbane, Queensland, Australia.

van der Meer, F. P., & Maphosa, W. (2012). High pressure grinding moving ahead in copper, iron, and gold processing. *Journal of the Southern African Institute of Mining and Metallurgy, 112*(7), 637–647.

van Rijswick, R., Onol, S., Oliveira, R., & Dierx, B. (2023). To Flange or not to Flange. Paper presented at the 2023 Comminution Conference. Cape Town, South Africa.

Vollert, L., Akerstrom, B., Seaman, B., & Kohmuench, J. (2019). Newcrest's Industry First Application of Eriez HydroFloat Technology for Copper Recovery from Tailings at Cadia Valley Operations. Paper presented at COPPER 2019. Vancouver, British Columbia.

Wasmund, E., Thanasekaran, H., Yap, N.S., Yan, E., & Mankosa, M. (2019). A high rate mechanical flotation cell for base metal applications", COPPER 2019, Vancouver.