CHAPTER 3.9

Grinding Circuit Flow Sheets

Aidan Giblett and Brian Putland

A significant variety of grinding circuit configurations are used in mineral industries, with a similarly wide range of capacity requirements and grinding circuit product specifications. Grinding flow sheets have evolved and continue to evolve as operators and designers strive to improve plant performance efficiencies and reduce new plant capital costs. This chapter covers the major types of flow sheets in use in mineral processing applications today, while also discussing both common and novel variations on the standard concepts. The main types of flow sheets that will be discussed are as follows:

- Semiautogenous circuits
- Autogenous circuits
- Rod/ball mill circuits
- Conventional crush/ball mill and high-pressure grinding roll (HPGR)/ball mill circuits
- Dry grinding circuits
- Fine grinding and ultrafine grinding circuits

For any given metal recovery process, typically more than one style of grinding flow sheet is viable for the project at the design stage. For very high-capacity operations, several recent projects have demonstrated that multiple grinding lines using HPGRs and ball mills in primary grinding duty can be a viable alternative to semiautogenous milling. These projects are Sierra Gorda in Chile (Comi et al. 2015), Cerro Verde in Peru (Koski et al. 2011), and Boddington in Western Australia (Hart et al. 2011). Fully autogenous grinding (AG) equipment for similar high-processing rates has also been used at the Boliden Aitik copper mine in Sweden, as described by Markstrom (2011). The successful adaptation of the HPGR technology, the increased unit capacity of gyratory and cone crushers, the availability of increasingly larger-diameter ball mills, and the expanded applications of stirred milling technologies ensure a wide range of options for the project engineer to consider at the design stage.

When selecting the most suitable grinding flow sheet, several considerations, which can generally be classified as technical or commercial, can influence the final decision. In commercial terms, capital cost and equipment lead times can become significant factors because of impacts on project schedules and critical financial metrics for the project. Technical factors are often the dominant influence on flowsheet selection and may include the following:

- Equipment unit capacity
- Downstream process requirements, specifically
  - Liberation (grind size)
  - Moisture constraints, for dry grinding processes
  - Pulp chemistry, for wet separation processes
- Material characteristics (abrasiveness, competency, hardness, and material flow properties)
- Safety issues, such as dust generation
- Product specifications (e.g., iron levels)

SAG MILL FLOW SHEETS

Since the 1980s, grinding circuit flow sheets have become dominated by the combination of semiautogenous grinding (SAG) and ball milling technology. This is a direct result of the well-documented decline in average plant feed grades, particularly evident for base metals concentrators (Mudd 2009) and precious metals recovery operations (Mudd 2007). Declining grades necessitate increased plant capacity to achieve sufficient metal production rates for profitable plant operation. Large-diameter SAG mills allow very high single grinding line capacities in comparison to other milling technologies, up to 4,000 t/h (metric tons per hour) when processing low-competency ores. These high capacities per line can generate several advantages in project capital costs, operability, and operating costs.

SEMIAUTOGENOUS, BALL MILL, AND PEBBLE CRUSHER FLOW SHEETS

Over time, the basic semiautogenous/ball mill (SAB) flow sheet has evolved to include pebble crushing (SABC) to increase mill capacity, by either sending crushed pebbles back to the SAG mill (SABC-A configuration [Figure 1]) or sending crushed pebbles forward to the ball mill (SABC-B configuration [Figure 2]), as determined by the relative balance

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of available SAG and ball mill capacity. Early successes in demonstrating the value of including pebble crushing in semi-autogenous milling circuits include the Los Bronces operation in Chile (Vesely and Fernandez 1986) and the Kidston operation in Australia, as described by Bartrum et al. (1988). These authors reported an increase in SAG mill capacity proportional to the tonnage rate fed to the pebble crusher, such that SAG mill capacity increased by 1 t for every metric ton of recycle material crushed. In the case of the Los Bronces operation, this equated to a 10% increase in mill throughput (Suttill 1988).

Grinding circuits that are limited by SAG mill capacity can in some instances be effectively de-bottlenecked by converting to an SABC-B configuration. This requires that some portion of the pebble crusher product be diverted to the ball mill circuit, usually after screening to retain the coarser particles in the SAG mill or pebble crushing circuit. This is an effective, although practically limited, means of increasing the transfer size to the ball mill circuit. Grinding work is consequently transferred downstream from the SAG mill, allowing the SAG mill capacity to be increased. Pilot and industrial testing at the Los Bronces concentrator, reported by Vesely and Fernandez (1986), demonstrated the potential to increase SAG line capacity by 26% under that configuration. After some initial issues with the ball mills handling coarser feed particles as reported by the same authors, the process flow sheet at Los Bronces evolved to an SABC-B configuration (Powell et al. 2006), with pebble crusher product reporting to the ball mill feed. Burger et al. (2006) described the transition of the Batu Hijau (Indonesia) SABC circuit to SABC-B configuration, with pebble crusher product screened and the –10 mm material diverted to the ball mills. Plant trials in this configuration demonstrated an incremental mill capacity increase of 0.5–0.6 t for every metric ton of crushed pebbles bypassed to the ball mill. The SABC-B option is considered where additional ball mill capacity is available or a coarser ball mill circuit product size can be tolerated. Care must be taken to avoid the transfer of excessively coarse particles to the ball mill circuit, because issues with sanding of hoppers and cyclone feed lines, plugged cyclones, high ball mill recirculating loads, charge swelling and reduced power draw, and excessive scat production from the ball mills can result.

Secondary Crush/SABC

The implementation of secondary crushing of the grinding circuit feed has become another common variation on the standard SAG/ball mill flow sheet and is implemented to directly increase the capacity of the SAG mill (Figure 3). This style of flow sheet is a popular post-commissioning retrofit in circuits that are fully using the available SAG mill power but have significant additional ball milling power available, the capacity to readily add more ball milling power, or the ability to tolerate a coarser grinding circuit product size. Early success with this configuration was achieved by operations such as Kidston (MacNevin and Stephenson 1997); Troilus in Quebec, Canada (Sylvestre et al. 2001); and Asarco Ray in Arizona, United States (McGhee et al. 2001); with more recent projects including the Newmont Phoenix operation in Nevada, United States (Castillo and Bissue 2011); Copper Mountain in British Columbia, Canada (Westendorf et al. 2015); Detour

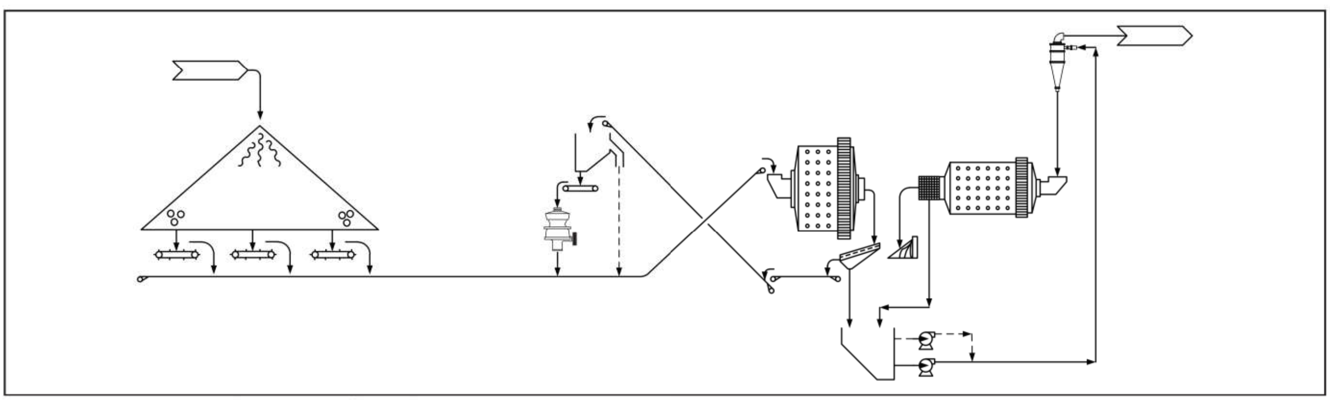


Figure 1 SABC-A grinding circuit flow sheet

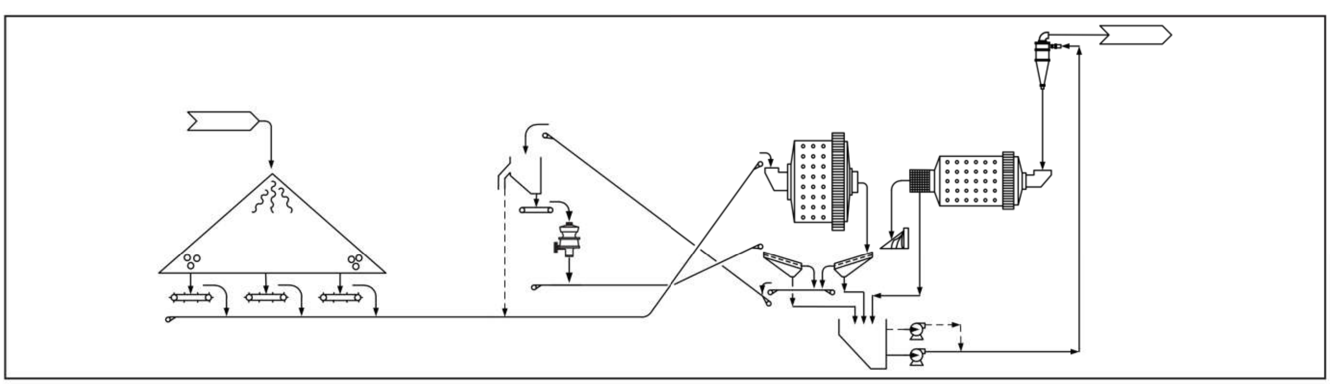


Figure 2 SABC-B grinding circuit flow sheet

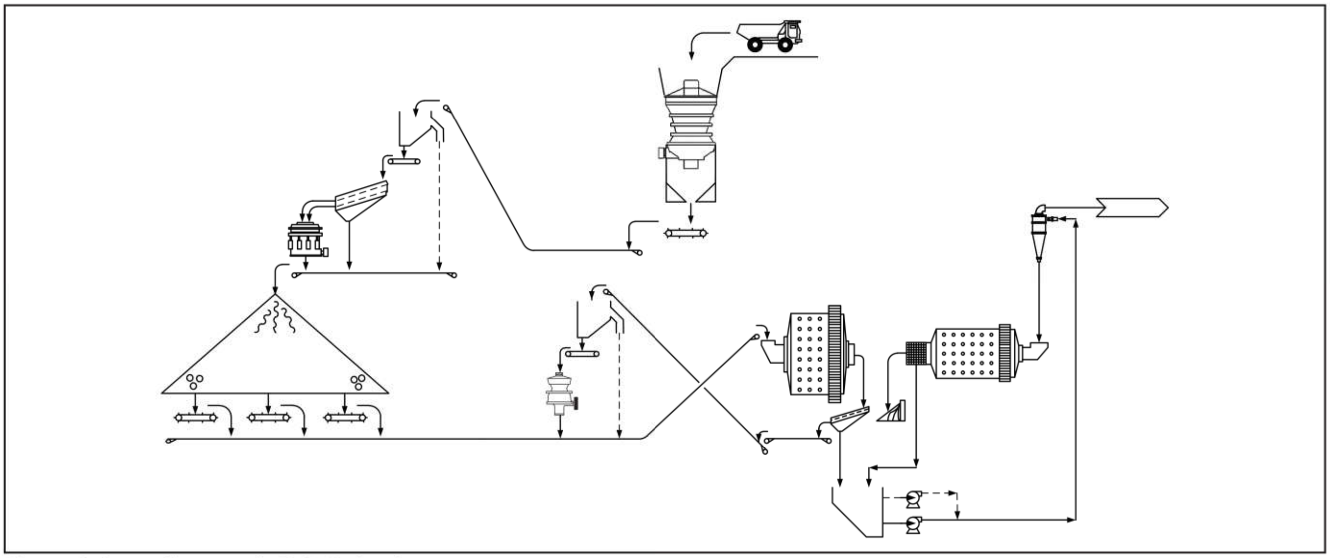


Figure 3 Secondary crush/SABC circuit

Lake in Ontario, Canada (Torrealba-Vargas et al. 2015); and Northparkes in New South Wales, Australia (Sulianto et al. 2016).

Despite early recommendations promoting this comminution flow-sheet configuration for greenfield designs, it is generally well accepted that secondary crush/SAG mill feed flow sheets are best considered for plant expansion or de-bottlenecking exercises where the ability to leverage the underused capital in the secondary grinding mills makes the economics very attractive. A review of several published examples of secondary crush/SAG flow-sheet conversions performed by Siddall and Putland (2007) reflected typical plant capacity increases in the range of 20%–60% for many projects. The extent of the throughput increase is often closely tied to the amount of unused ball mill power that is available or can be readily installed. For greenfield installations, a fit-for-purpose SABC installation will typically have a lower capital cost, and is more amenable to future expansions, than a secondary crush/SABC configuration. Festa et al. (2014) proposed that a secondary crush configuration can become a more practical design option when the design basis exceeds the single-line capacity of the largest available mills or geared drive systems. The Detour Lake project, as described by Torrealba-Vargas et al. (2015), is an example of the successful implementation of this concept for a greenfield installation.

Nelson et al. (1996) provide a thorough account of the operating issues that can occur in secondary crush/SAG mill circuits, based on operating experience at the Kalgoorlie Consolidated Gold Mines (KCGM) Fimiston plant in Western Australia. In this instance, the desire for increased plant throughput rates required a high steel-to-rock ratio in the mill to achieve mill stability. This in turn promotes a coarse transfer size to the ball mill, combined with high metal wear rates and liner breakage in the SAG mill. These issues are particularly evident when the secondary crushers are operated in open circuit, and can be effectively mitigated by closing the secondary crusher circuit with a screen and limiting the mill feed size to 100% passing 1–1½ in. This allows better control of the top size to the SAG mill and allows operation with smaller-diameter grinding media (4–4½ in.) to be considered, in turn reducing the potential for shell liner breakage. SAG mill utilization and operating costs can be further optimized when the mill feed contains a mixture of primary and secondary crushed ore, in what is termed a *partial secondary crush* or *pre-crush circuit*. Examples of partial secondary crushing installations include Porgera (Papua New Guinea), Mount Rawdon (Australia), Geita (Tanzania), and Asarco Ray, as reviewed by Siddall and Putland (2007). Secondary crushing before semiautogenous milling can effectively eliminate the need for pebble crushing because the SAG mill feed contains limited critical size material, and low-operating rock loads in the SAG mill promote effective breakage of critical-size particles.

Single-Stage Autogenous and Semiautogenous Milling

Single-stage autogenous and semiautogenous milling has been widely applied for processing moderately competent to competent ores at small to medium plant capacities in multiple commodities (Figure 4). Applications include St. Ives (Atasoy and Price 2006), Olympic Dam (Alexander and Wigley 2003), Leinster (Fitzmaurice et al. 2000), and Sino Iron in Australia (Tian et al. 2014); and Tarkwa in Ghana (Hothersall et al. 2006). As the grinding is undertaken in a single mill, configuration of the circuit to suit the ore and duty is very important, as discussed by Putland (2011). Configuration options include AG, AG + pebble crusher, SAG, SAG + pebble crusher, high ball charge SAG or run-of-mine ball mill, low ball charge high-speed SAG mill, and partial or full secondary crushed feed. Putland et al. (2011) also noted that the single-stage AG/SAG mill configuration is less suited to grind sensitive ores and high-capacity operations, where two-stage grinding circuits will typically have performance and capital advantages.

There is often speculation regarding the relative suitability of low- and high-aspect-ratio SAG mills for a single-stage grinding duty, although there is no clear demonstration that either style of mill design is any more suitable for the single-stage duty than the other. A notable consideration with single-stage semiautogenous milling duties is the greater exposure to slurry pooling, because of the higher slurry loads associated with the hydrocyclone recirculating load. If not addressed

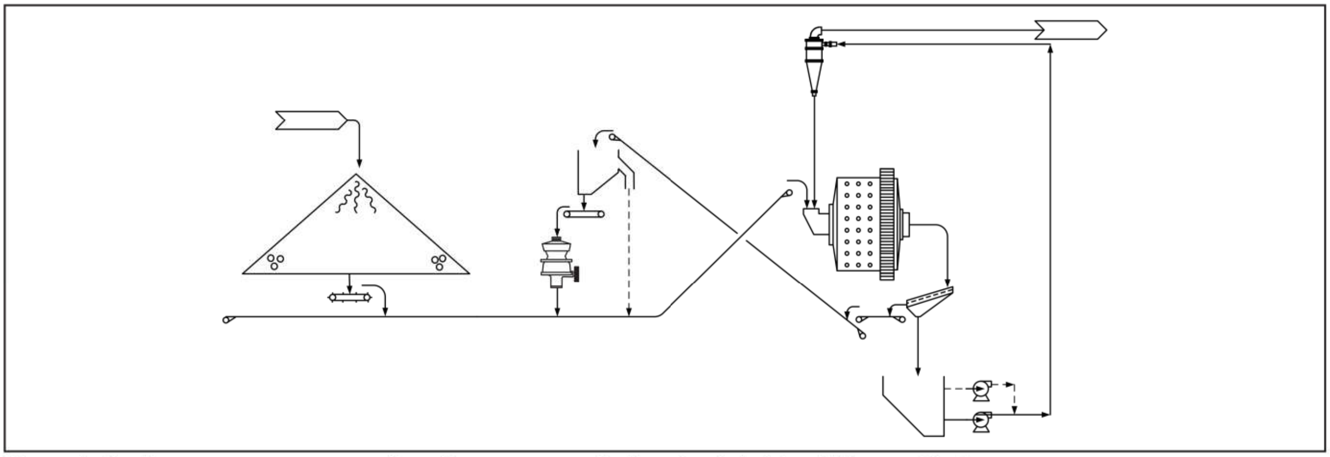


Figure 4 Single-stage autogenous and semiautogenous grinding circuit (with pebble crushing)

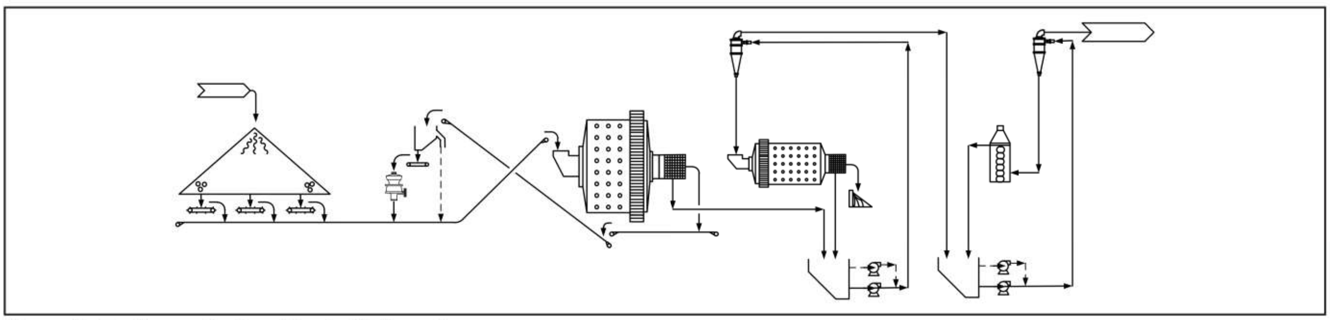


Figure 5 Tertiary grinding/Vertimill flow sheet

when designing the pulp discharge system, resulting impacts can include increased specific energy consumption, reduced grinding efficiency, and high wear rates of grates and pulp lifters. The requirement to have the capacity to move the slurry through the grate and pulp lifters is generally the most important factor in selecting the required mill diameter in single-stage autogenous and semiautogenous milling applications and therefore dictates mill aspect ratio (Putland et al. 2011) as mill length is then selected to achieve the desired power draw.

A major advantage of single-stage autogenous and semiautogenous milling is the low capital cost and flexibility for future expansion (single-stage SAG to SABC), which makes it ideal for starter projects with significant exploration and expansion potential. Another major advantage of the single-stage circuit over the two-stage circuit is the ability to significantly increase throughput by increasing grind size, which is often difficult in two-stage circuits that are constrained by the primary mill (i.e., SAG limited). Alternatively, single-stage mill product size and pulp density are more sensitive to variations in ore properties, and hence are not ideal when downstream metal recovery is sensitive to grind size or viscosity.

MILLING OPTIONS FOR SECONDARY AND TERTIARY GRINDING

Stirred mills have been successfully incorporated into mainstream grinding duties in several base and precious metals flow sheets, after either SAG mills, as shown in Figure 5, or ball mills in the primary grinding duty. An early example of the Vertimill technology in a tertiary grinding duty, as a retrofit to an existing SABC flow sheet, was the Chino operation in New Mexico, United States (Vanderbeek 1997). At Chino, the SABC circuit grind size had coarsened over time to allow increased plant throughput. A tertiary grinding circuit was a practical approach to restore grind fineness and metal recoveries to original target levels while maintaining the higher plant capacity. The incorporation of a VTM-3000 Vertimill into the Ridgeway (Australia) flow sheet in a tertiary grinding duty (Palaniandy et al. 2013) is a more recent example of the same concept.

The Round Mountain operation in Nevada, United States (Henderson et al. 2005), uses a tower mill in secondary grinding duty after a primary SAG mill, fine screening, and a gravity circuit to produce a final grind size of 80% passing 270 mesh. At the McArthur River operation in Australia, described by Anderson et al. (2011), the initial single-stage SAG mill circuit capacity was increased by the addition of a secondhand tower mill processing a bleed of the SAG mill recirculating load. The operation subsequently incorporated two IsaMill M3000s in a similar grinding duty on a SAG mill recirculating load to increase grinding circuit throughput while reducing final grind size.

The economic justification for this style of circuit increases the finer the grind size, with grind sizes below 80% passing 200 mesh viewed as more prospective applications.

An alternative tertiary grinding circuit configuration, consisting of a primary SAG mill and secondary and tertiary ball mills grinding down to 80% passing 500 mesh, is the Sage Mill circuit at the Newmont Twin Creeks operation in Nevada (Yernberg 1996). The 28 ft × 10 ft SAG mill is operated in open circuit, and the 20 ft × 30 ft primary ball mill and secondary ball mill (two 16.5 ft × 29 ft mills) circuits each operate in closed circuit with hydrocyclones. Total grinding circuit specific energy consumption at this grind is nominally 30 kW·h/t and is consistent with the ore hardness properties and the extent of size reduction performed (Giblett and Hart 2016). Specifically, it is an example of fine grinding using ball mills without compromising energy efficiency.

AUTOGENOUS FLOW SHEETS

While the use of autogenous grinding, or autogenous milling, is not as widespread as semiautogenous milling in precious and base metals processing, there are examples of its successful application. The Freeport-McMoRan Bagdad operation in Arizona, United States, is a significant example of the application of an AG, ball milling, pebble crushing (AB/C) grinding flow sheet in base metals concentration, with five grinding lines processing 75,000 stpd of copper–molybdenum ahead of flotation. Because of high pebble loads, circuit capacity is heavily influenced by the utilization of pebble crushers (Clements 1992). The use of 38-ft-diameter AG mills in a copper recovery flow sheet at the Aitik copper concentrator is addressed by Markstrom (2011), where fully autogenous grinding in two AG and pebble mill lines achieves a plant capacity of 33–36 Mt/yr depending on mine production rates. The Palabora copper mine in South Africa (Condori et al. 2011) uses two 32-ft-diameter primary AG mills in an ABC circuit configuration (Figure 6) to process nominally 30,000 t/d of copper ore for flotation, and it is notable for the use of a "permanent bleed-off" to discard pebbles >19 mm in size.

The BHP Cannington operation in Australia (Jankovic et al. 2006) processes silver/lead/zinc ore through a closed-circuit SAG mill, with secondary grinding initially performed by a 1,500-hp Vertimill. In the Cannington case, secondary milling was added to what was initially a single-stage AG mill circuit, to facilitate increased plant throughput at acceptable grind sizes. The primary grinding circuit operates in closed circuit with cyclones, otherwise replicating the flow sheet presented in Figure 5. An expanded secondary grinding flow sheet was later presented by Palaniandy et al. (2014), composed of two VTM-1250-WB Vertimill units.

Typically, the significantly higher mill capacity that results from the conversion of an AG mill to SAG sees semiautogenous milling as the preferred option in the study phase for precious and base metals projects. AG is a rare choice in these instances, where maximum plant capacity per unit capital input is often the critical metric for project success. In the case of the Newcrest Ridgeway concentrator in Australia (Hart et al. 2003), the conversion from ABC to SABC operation resulted in a 25% increase in grinding plant capacity from 4 to 5 Mt/yr, along with an increase in final grind size, reduced pebble recirculating load, and improved primary mill stability.

The use of AG is common in the iron ore industry for grinding magnetite ores because of the high specific gravity of the magnetite, which also generates excellent AG media. In these flow sheets, pebble crushing is not compromised by the presence of steel ball fragments in the mill discharge. The mill product is at a size suitable for primary magnetic separation, which is often employed to reject feed mass before the secondary grinding stage. A recent example of autogenous milling magnetite ores is the massive Sino Iron magnetite operation (Tian et al. 2014). This project has commissioned six grinding lines, each consisting of one 40-ft-diameter × 36 ft effective grinding length AG mill, pebble crushing, and a 26 ft × 44.5 ft ball mill. Powell et al. (2011) describe the use of fully autogenous grinding at the LKAB Kiruna KA3 processing line, with primary autogenous millings and secondary pebble milling to produce a final product of 80% passing 325 mesh. Cleveland-Cliffs Empire mine's Empire IV grinding line (Walqui et al. 2009) applies three lines of 32-ft AG mills with two-stage pebble crushing and dual 15.5 ft × 32.5 ft pebble mills to grind magnetite ore to 90%–95% passing 500 mesh.

ROD MILL/BALL MILL CIRCUITS

In addition to the use of ball mills in secondary and tertiary grinding duties after AG and SAG mills, several other common grinding flow sheets incorporate ball milling: rod mill/ball mill circuits (Figure 7), single-stage ball mill circuits, and two-stage ball mill circuits.

In base and precious metals processing, rod mill/ball mill circuits are often associated with lower-capacity, higher feed-grade operations, and in many cases receive feed exclusively from higher-grade underground mining operations. The use of rod mills in these industries has declined as a result of the widespread use of semiautogenous milling, primarily because of the large difference in unit capacity in favor of SAG mills and the elimination of constraints and costs associated with secondary crushing facilities required to feed rod mill circuits. Rod mills are also useful where the grinding work indices are high and it is necessary to eliminate all coarse particles from

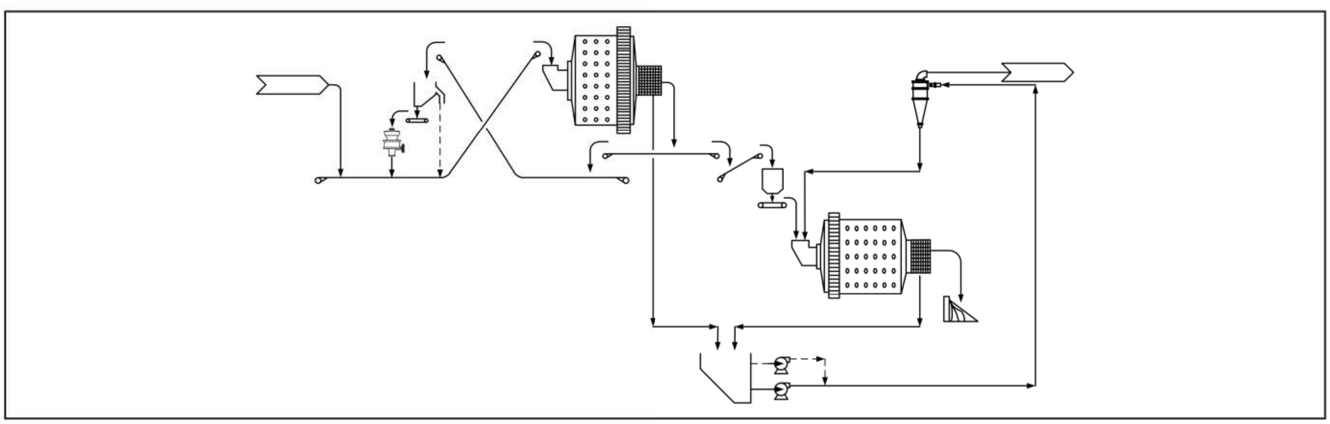


Figure 6 Two-stage AG flow sheet

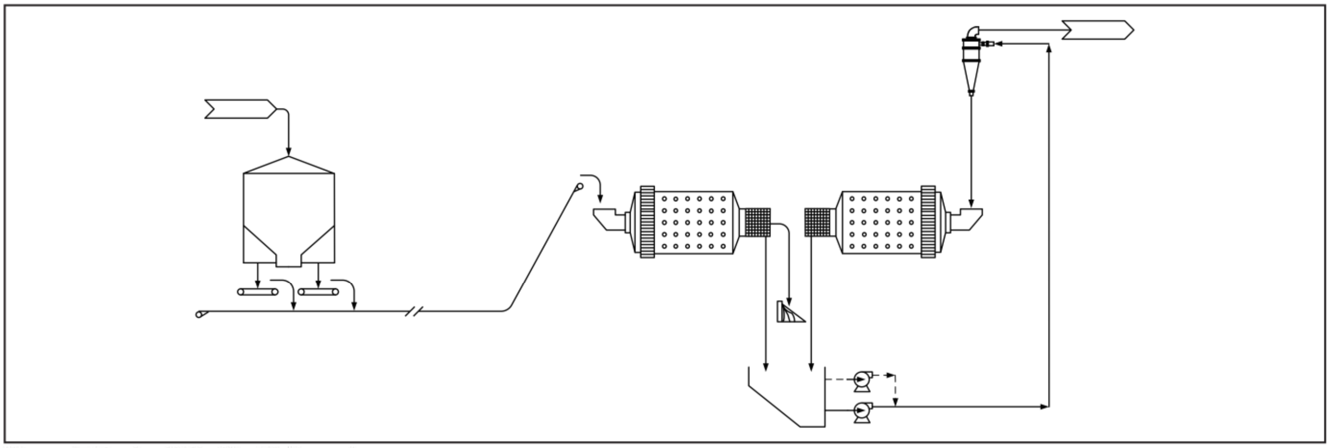


Figure 7 Rod mill/ball mill flow sheet

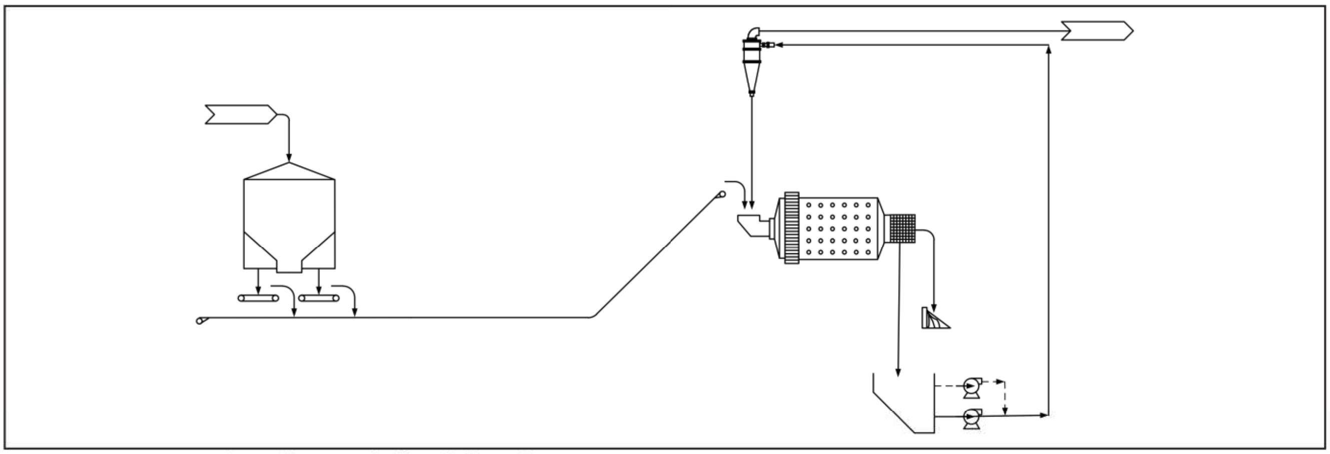


Figure 8 Conventional single-stage ball mill flow sheet

ball mill feed. Eliminating the coarse particles prevents ball mill charge expansion, scatting of oversize from the mill, and associated reductions in grinding efficiency.

Rod mill size is constrained by aspect ratio, rod and mill length, and speed limits required to prevent tangling, bending, and breaking of rods. The largest rod mills are therefore around 15 ft diameter × 21 ft effective grinding length with motor ratings of 3,000 hp or lower, and have significantly lower unit capacity than the average SAG mill. As a function of the mine economics associated with large-capacity, low-grade base and precious metals projects, invariably one or two lines of semiautogenous/ball milling is a more attractive proposition than multiple trains of rod/mill circuits, with the associated crushing and screening plant equipment and plant footprint considerations. Rod tangling is not only a cause of production loss, but it also presents a safety hazard for those tasked with rectifying the issue. However, the conventional rod/ball mill circuit remains a viable option for smaller-capacity operations, particularly those requiring a tight size distribution devoid of excessive fines content. The internal classification performed by the rod mill charge is a recognized advantage over ball mills in reducing the potential for overgrinding, and any recovery increases associated with reduced overgrinding can materially impact project economics, particularly for higher-grade operations.

The use of rod mills is common in the grinding of phosphate ores, where often coarse grinds and low fines content in the flotation feed is advantageous for effective mineral concentration. Van der Linde (1999) and Schmidt (1999) describe the processing of phosphate ores at the Foskor operation in South Africa, where three-stage crushing is followed by 12 8-ft primary rod mills and five 900-hp Vertimill units in secondary grinding duty to produce a flotation feed of 80% passing 370 µm, with <11% passing 400 mesh. The production of apatite concentrate at the Jacupiranga operation in Brazil (Busnardo and De Mineracao 1985) uses four lines of single-stage rod mills to grind 500 t/h of carbonate ore and generate a feed for flotation of 78%–86% passing 50 mesh. Other commodities that often incorporate rod mills in the comminution flow sheet include bauxite, graphite, rare earths, and tin.

PRIMARY BALL MILL CIRCUITS

Single-stage ball mills, conventionally receiving secondary or tertiary crushed feed size of ¼–½ in. (Figure 8), are often used in lower-capacity operations in the 0.5–2.5 Mt/yr range, particularly when processing precious metals. In recent times, the single-stage ball mill flow sheet has been applied on a much larger scale, in the 100,000 t/d range, after tertiary crushing by HPGR technology, at the Boddington gold mine (Hart et al. 2011) and Cerro Verde copper concentrator (Koski et al.

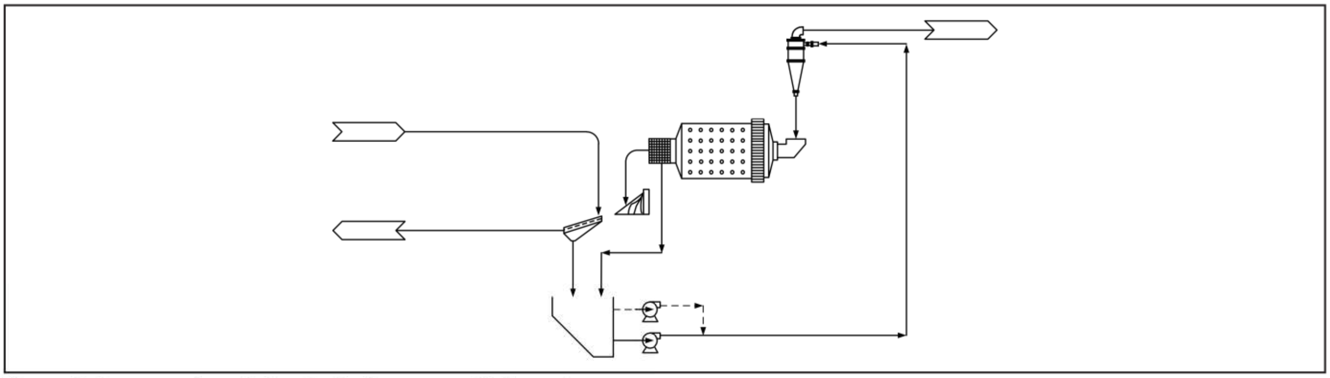


Figure 9 Reverse closed-circuit single-stage mill flow sheet

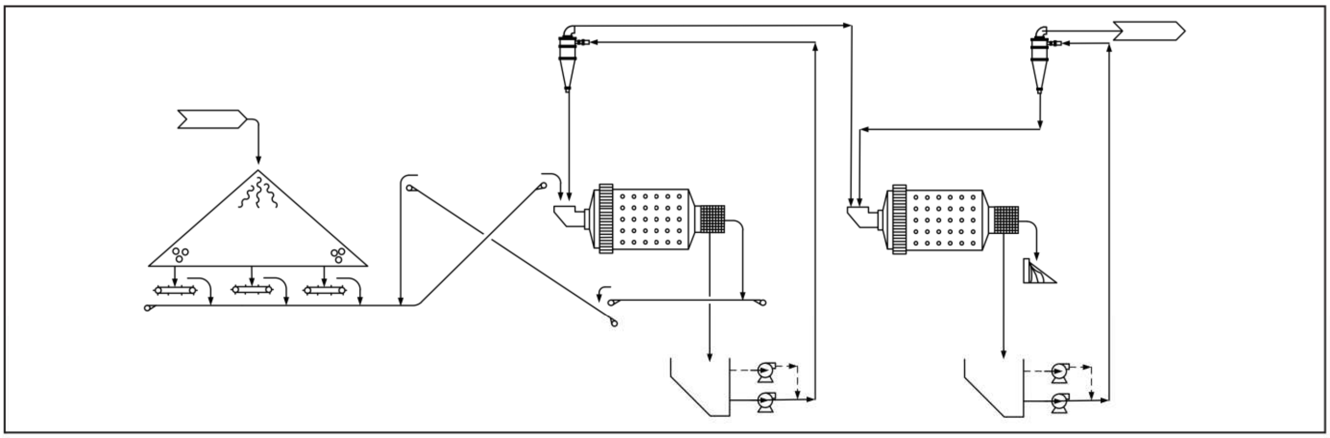


Figure 10 Series ball mill flow sheet

2011). The HPGR/ball mill flow sheet has also been applied at the Sierra Gorda copper–molybdenum project in Chile and the Tropicana gold mine in Australia. These new-generation flow sheets followed from the demonstrated performance of the ThyssenKrupp roll wear protection for hard rock applications at the Newmont Lone Tree operation (LeVier et al. 2004). Furthermore, the availability of very large ball mills and very large-capacity cone crushers in secondary crushing duty are critical requirements for the economic viability of single-stage ball milling in high-capacity applications. Single-stage ball mill applications flowing HPGRs have commonly incorporated a reverse classification configuration (Figure 9) where the HPGR product is wet screened with the screen undersize reporting to the cyclone feed hopper and the ball mill being feed cyclone underflow.

Series ball milling (Figure 10) has been used at several operations, including Sunrise Dam (Nugus et al. 2013), Mount Lyell (Gray and Bisshop 1977), and Marvel Loch (Bird and Briggs 2011) in Australia, with a primary ball operated in closed circuit with cyclones and a secondary ball mill receiving primary cyclone overflow and being, in turn, closed with a secondary cyclone cluster. Series ball milling, with the primary mill receiving secondary or tertiary crushed feed, is a concept more likely to be applied in the fine grinding of gold ores before cyanidation and typically at lower plant capacities (<3 Mt/yr). In the platinum mines of South Africa, it is common to conduct concentration stages between series ball mill grinding stages. The most common circuit of this type is called an MF2, or mill-float-mill-float, circuit as described by Rule (2011).

DRY GRINDING

In specific instances, it is preferable for the downstream recovery process to receive a dry product from the grinding circuit. This is the case in the cement industry where there is extensive use of dry grinding technologies including air-swept SAG mills and ball mills, hammer mills, roller mills, and HPGRs in fine grinding duties, as noted by Burchardt and Brandhoff (2014). Almost all grinding circuits in precious and base metals ore processing flow sheets produce feed for flotation, wet gravity separation, or leaching processes. As a result, there has been limited application of dry grinding technologies in those industries, while the more competent and abrasive nature of these ores also presents challenges for some of the dry grinding technologies. Rowland (1985) stated that "dry grinding requires about 30% more power than wet grinding for comparable size reduction," consistent with the observations of Taggart (1945) and Bond (1961). Rowland (1985) also noted the lower capital cost of equivalent wet grinding circuits, but substantially lower grinding media and liner consumption rates.

Notable exceptions are the use of dry grinding before oxidative roasting of refractory gold ores in Nevada as reported by Tempel (1993) and Thomas et al. (2001), and the use of dry grinding in the processing of nickel laterite ores as practiced at Yabulu in Australia (Stokes 2013). The simplified grinding and classification flow sheet at the Newmont Carlin Trend operation as reported by Tempel (1993) is shown in Figure 11, reflecting the combination of static and dynamic classification of mill products that is common in dry grinding flow sheets.

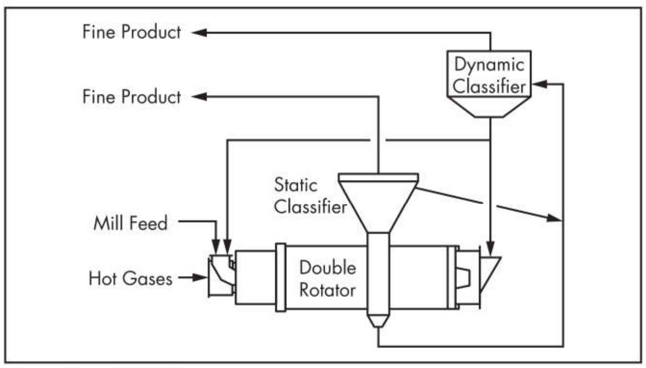
Burchardt and Brandhoff (2014) observe that the cement industry has over time progressed to the use of vertical roller mills (VRMs) and HPGRs in grinding duties down to product sizes of 450 mesh. Significant improvements in energy efficiency have been observed, and these grinding technologies have significant appeal for application outside cement. The standard VRM flow sheet for finish grinding such as applied to grind phosphate ore at Foskor is shown in Figure 12.

REGRINDING AND ULTRAFINE GRINDING

In the context of this discussion, regrinding is considered to encompass the process where a valuable mineral concentrate, most typically produced by flotation or magnetic separation, is reground to further enhance separation, beneficiation, or metal extraction. Regrinding will typically produce a product size down to 80% passing 25–30 µm (450 mesh). Size reduction by grinding down below 80% passing 15 µm (635 mesh) or finer, to as far as below 80% passing 5 µm in some instances, is defined as ultrafine grinding (UFG) in the context of this discussion.

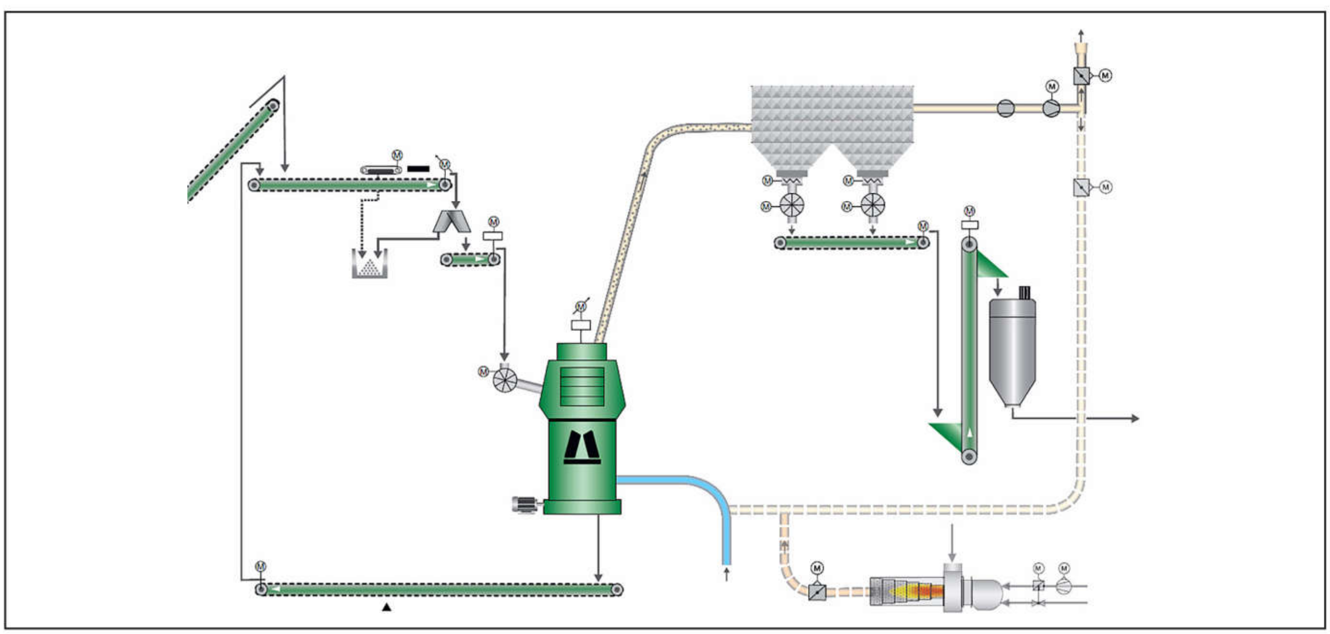
Vertical stirred mills, specifically the Vertimill or tower mill, have become the dominant technology in conventional regrinding applications. The fine media size that can be used in these mills is a great advantage over overflow ball mills, which are typically limited to a minimum grinding media size around ⅞ in. Vertical mills operating in concentrate regrinding applications have been quoted to operate at 30%–50% lower specific energy consumption than ball mills performing in the same duty. Rule (2011) describes the implementation of the horizontal stirred IsaMill technology to effect size reduction down to 80% passing 53 µm (270 mesh) in a tertiary grinding application in platinum ore grinding flow sheets, demonstrating the suitability of that technology in conventional fine grinding duties. Technologies being applied to this duty also include the VXPmill and HIGmill, both of which are vertical stirred mills.

In UFG duties, defined by Lichter and Davey (2002) as sub-15 µm, several technologies have demonstrated suitability for the task. The UFG technologies will typically receive a concentrated feed stream to minimize grinding of gangue minerals, and grind in open or closed circuit depending on the technology applied. The IsaMill technology is used at the Mount Isa lead–zinc concentrator (Pease et al. 2004) to grind lead and zinc rougher concentrates to 80% passing 12 µm, and zinc cleaner tailings to 7 µm. The circuit flow sheet is shown in Figure 13. Ellis (2003) described the use of IsaMills to grind a gold-bearing pyrite concentrate to 80% passing 11–12 µm at the KCGM operation in Western Australia, before cyanide leaching for gold recovery. Anderson and McDonald (2016) described the recent expansion of the Fimiston UFG circuit, eliminating the roasting of pyrite concentrates at the KCGM operations. Many of the platinum operations in South Africa



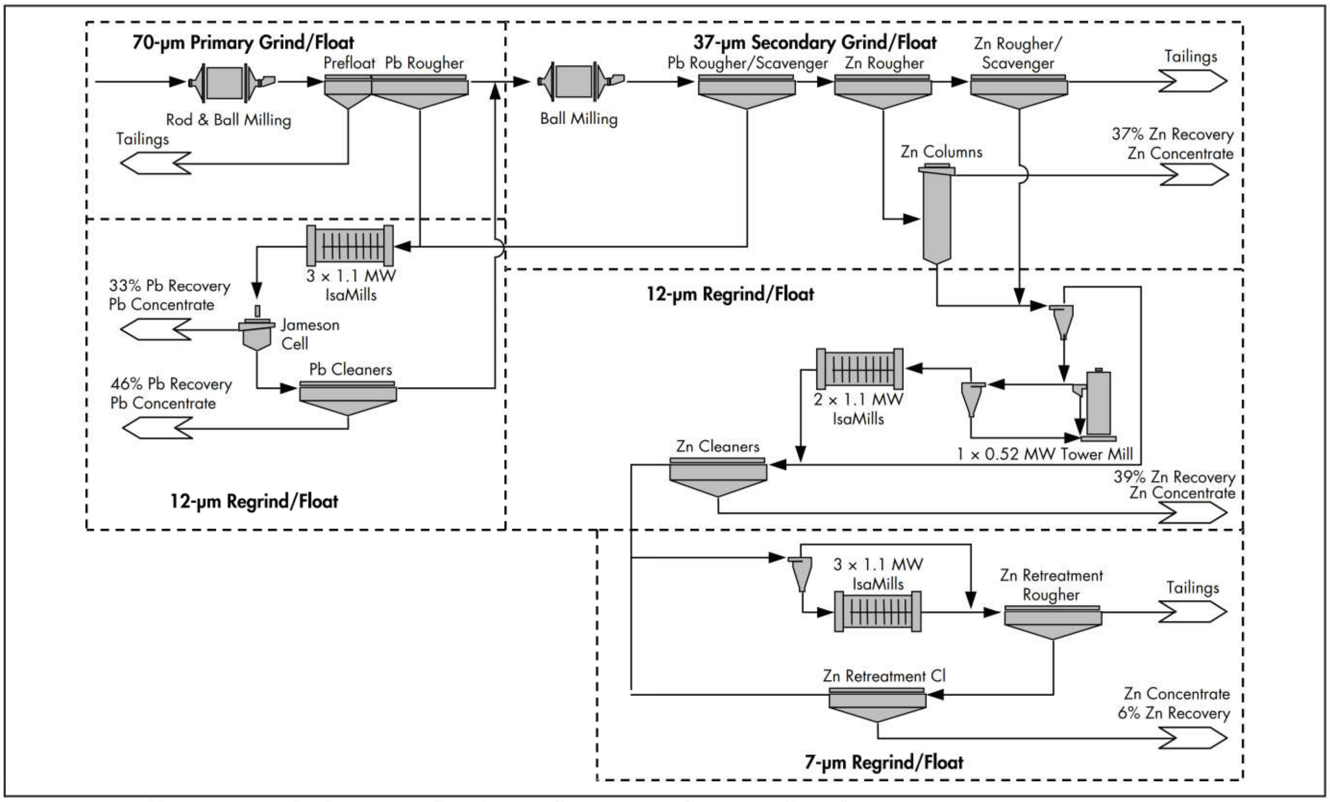
Source: Tempel 1993

Figure 11 Dry grinding schematic for the Newmont Carlin Trend operation



Courtesy of Loesche GmbH

Figure 12 Vertical roller mill circuit flow sheet



Source: Pease et al. 2004, reprinted with permission from the Australasian Institute of Mining and Metallurgy

Figure 13 Mount Isa lead–zinc concentrator flow sheet

have incorporated IsaMills in their flow sheets in the past decade (Rule 2011).

The Metso Stirred Media Detritor (SMD) is a versatile technology that has found application in both regrinding and UFG duties. The use of SMDs in copper concentrate regrind duties at Copper Mines of Tasmania and Thangala copper mine in Australia has been documented by Davey (2003), and a similar application in the Newcrest Ridgeway flow sheet at the Cadia Hill complex in Australia is described by Hart et al. (2005) and Weidenbach and Cesnik (2007). Davey (2002) details the use of the SMD in both regrind and UFG duty at the Century zinc operation in Australia, with 15 SMDs dedicated to UFG duty producing a P_{80} 6.5-µm product size.

GRINDING FLOW-SHEET SELECTION

The importance of reliably determining ore characteristics and how they vary within a deposit at the design stage can never be overemphasized. Too many operations have been forced into expensive plant upgrades and retrofits because of a failure to fully recognize and account for the fundamental nature of the ore during project development. Even the best flow-sheet design optimization efforts will be undone if design criteria fail to accurately reflect the mined ore, or do not fully consider the impact of measured characteristics. Guidance on how to approach ore characterization, using industry best practices to support grinding circuit design, is given in Chapter 3.8, "Grinding Circuit Design." Guidance on how to characterize an ore body in terms of its comminution property variability is covered in Chapter 1.10, "Geometallurgy."

The resistance of an ore to impact breakage is a particularly crucial parameter when evaluating the optimal comminution flow sheet in all cases. Low-impact breakage resistance will likely result in a shortage of AG media, leading to high steel wear rates in a SAG mill. In these circumstances, higher ball charges coupled with high steel-to-rock charge volume ratios will be required to achieve mill power draw targets. While highly competent ores are certainly harder to break in a SAG mill, those same characteristics make the ore resistant to crushing. When hardness is combined with moderate to high abrasive characteristics, particularly high liner wear rates in crushing applications will result. When the ore is hard in one sense or another, there is rarely a clear-cut equipment selection advantage that will serve as a silver bullet for the designer or, indeed, the operator.

Recognizing this and other conundrums that will influence ultimate flow-sheet selection, the selection matrix in Figure 14 is provided to assist in narrowing down the options for the design engineer, by considering common influences on the suitability of the major grinding technologies for a given project. This flow-sheet selection matrix borrows from the tabular representations published by Lane et al. (2002; 2013), Putland (2006), Putland et al. (2011), and Scinto et al. (2015). The matrix is based on the assumption that grinding will be achieved in no more than two stages, which is intended to evade debate around the use of ball mills or stirred mills in a tertiary grinding duty, or similar flow-sheet refinements that are more a matter of final equipment selection and, in some instances, personal preferences. Figure 14 reflects that certain grinding technologies are more tailored to specific ore

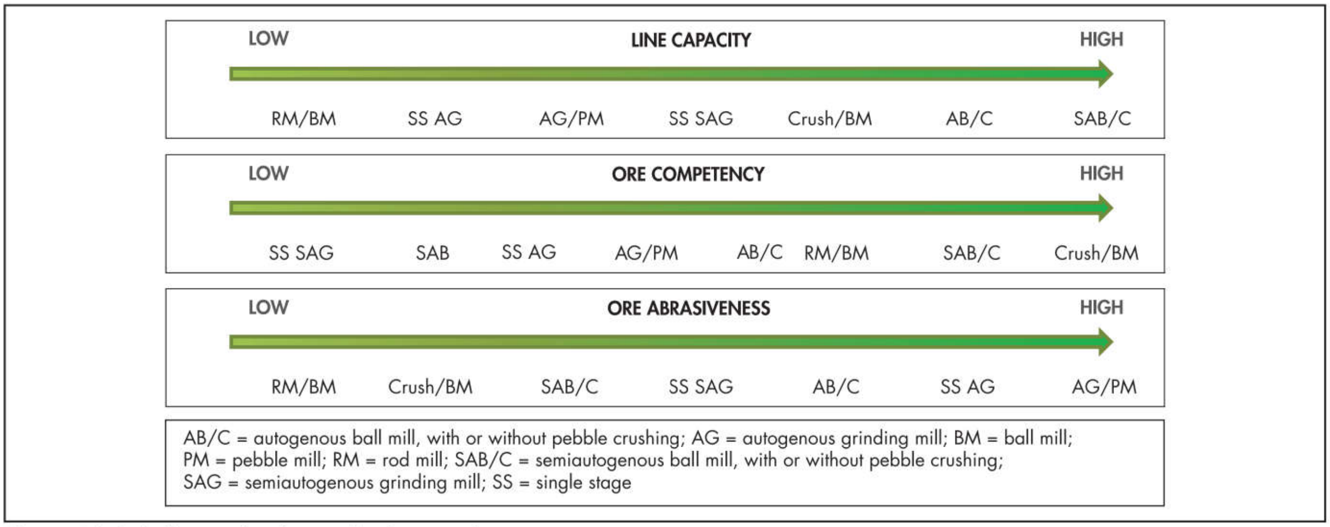


Figure 14 Grinding technology selection matrix

characteristics than others, and that the relative suitability may change based on other project-specific considerations such as life of mine, ore variability, mining method, downstream ore processing requirements, ore density, and clay content.

High specific-gravity ores, such as magnetite, can be more suitable to autogenous milling than others, making that technology a more attractive option in such instances. High-clay-content ores or ores otherwise prone to be problematic in material handling processes have been successfully processed using scrubbers or SAG mills and by minimizing crushing stages before the grinding process. Downstream process requirements can influence grinding technology and flow-sheet selection, as evidenced by the selection of dry grinding technology for the roasting of gold ores in Nevada. If an ore contains hazardous materials (e.g., asbestos or lead), then a wet grinding flow sheet is preferred to dry grinding processes because of the reduced potential for dust generation. Reduced variability in treatment rates and grinding circuit product size can often be achieved by secondary and tertiary crushing before grinding in rod mills or ball mills. Minimizing mineral product contamination with grinding steel can be achieved by the application of AG technologies. Grinding technology selection will be influenced if there is a need for product sizes below the normal operating range of ball mills, and this creates a situation where lower unit capacity grinding technologies such as stirred mills can become viable options. In instances where the minimizing of fines in the grinding circuit product is a critical performance parameter, such as in the flotation of phosphate ores, the use of rod milling technology can be beneficial.

CONCLUSIONS

This chapter has presented several conventional grinding flow sheets and provided references for operations where the many grinding technologies available have been implemented. Some context has been provided in the form of pros and cons of the various flow sheets based on documented operating experience, and guidelines for determining when a particular flow sheet may be applicable have been provided. As was suggested at the beginning of this chapter, there is no single, perfect off-the-shelf flow-sheet solution for a given project; more likely, there will be several flow-sheet variations that can adequately deliver the project's objectives. Similarly, there is no perfect flow-sheet selection guide that can deal with all variables in a desktop analysis, and every project must be considered in detail on its individual merits. Opinions can vary considerably regarding what grinding technologies are better suited to the project and under what conditions. This is largely based on the experience of the engineer, and a significant portion of industry experience and knowledge is unpublished. As a result, there is no substitute for rigorous benchmarking when it comes to final flow-sheet selection and process engineering, ensuring that as much knowledge as possible from others' experience is incorporated in the final design.

The current state of grinding technology is in an interesting position, with established tumbling mill technologies (AG/SAG, rod, and ball mill flow sheets) remaining popular and advanced technologies such as stirred milling and HPGRs establishing a footprint in conventional grinding duties. Worldwide focus on greenhouse gas emissions, increased demand, and rising energy costs support increased focus on grinding circuit energy efficiency during flow-sheet selection. To that end, techniques to define grinding circuit energy consumption using the guidelines described in Chapter 3.12, "Testing and Calculations for Comminution Machines," can be employed. Examples of using these and similar techniques to select more energy-efficient flow sheets have been published by many authors. Notable examples include Parker et al. (2001) and Ballantyne et al. (2016), with both of those assessments supporting the selection of HPGR-based circuits over SAG mills. Other authors have employed similar approaches to promote the use of stirred mills in place of ball mills, and in some publications to promote combining HPGRs and stirred mills as an option for grinding circuits that do not employ any form of tumbling mill technology. How far the industry shifts toward these newer flow-sheet designs will depend on how well the desktop estimates of energy efficiency translate to industrial performance, and to what extent they offset increased capital costs with reduced operating costs.

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