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Review

Guidelines for sulfidic mineral processing practice

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ABSTRACT

By definition, comminution denotes the size reduction of any solid mass into smaller particles. The generic category includes a wide range of equipment consisting of crushing, grinding and pulverising unit operations in either a dry state or enhanced via an aqueous media. Although modern comminution techniques may be applied to a broad range of materials such as ores, coal, industrial minerals, and metallurgical slags, the paper's comments are mainly devoted to the treatment of sulfur-bearing materials. Milling operations are normally in tandem with crushing activities. Albeit that the global beneficiation sector goes unnoticed by the popularity of processes such as smelting and refining, the state-of-the-art in milling and supporting concentration operations plays an important role as the front end of a long list of activities from mine face through to finished product. The paper presents a practical guideline for plant managers and/or business people involved in the mineral processing of base metals such as Cu/Ni/Co and associated platinum group metals. Selected equipment manufacturers and appropriate references comprise a mini-handbook which outlines the areas of concern in business orientation. The principles outlined herein are applicable to any scale of plant operation worldwide. The text is suited to those without a predominantly mining or metallurgical background without endorsement of any particular existing supplier or producer.

Keywords: Comminution; Grinding; Liberation; Mineral processing; Sulfide ores

1. INTRODUCTION

Size reduction has been practiced for many centuries and it has evolved dramatically during the past decades. Some of the first tumbling mills can be traced back to Allis Chalmers (AC) in 1897 which were fabricated at the Gates Iron Works (established 1872) and subsequently purchased by AC (History, 2003). As early as the year 1936, Denver Mining Equipment, USA, advertised its line of crushers, rod and ball mills. Many established companies are engaged in the global marketing of grinding equipment plus ancillary products such as grinding media, pumps, classifiers, and other related equipment. A check list identifies areas of investigation whenever either considering a greenfield site or retrofitting an existing facility in-situ. Over 30 years of practical expertise in the minerals sector were imparted in areas of beneficiation, smelting and refining. The milling aspect in particular became the focus whilst indicating integration of supporting equipment both upstream (e.g., crushing) and downstream (e.g., flotation). Many factors involved in the refurbishment of grinding operations relate to specific characteristics of the ore being processed while a common sense approach is warranted. Guidelines addressing related issues are expected to benefit both the novices and afficionados in the realm of grinding and associated unit operations. Although the list compiled from "hands-on" experience is not meant to be all inclusive, it may serve as a backbone for engineering disciplines assigned to upgrade "comminution" facilities worldwide. It is understood that small scale operations termed "mom and pop shops" such as found in the mountains of Peru and other poorer nations still operate outdated equipment out of necessity.

In contrast, large corporations can afford the luxury of modern high technology equipment which sometimes is dictated by government regulations to address work room environment in areas of noise, heat, and dust exposure to potentially toxic substances. Suppliers of specific equipment and engineering services

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are often linked through the same company. Accepted global practice is arrangement of an EPCM contract (Engineering, Procurement, Construction and Management) with reputable companies such as Fluor Daniel, Bechtel, and others who have proven experience in the operation being considered. Engineering majors may sub-contract various portions to smaller companies (e.g., Minproc) who are best suited to a specific activity such as Cu/Pb/Zn circuits or a SAG circuit. It is the plant's responsibility to source appropriate firms that are qualified to design and implement the task being considered both on time and on budget. Upon preparing a short list, an evaluation must be conducted on the basis of deliverables. Factors such as lead time for design, commissioning, training, and capital costs must be investigated. An engineering feasibility study coupled with an economic evaluation may lead to actual construction of new and/or refurbished facilities. Examination of total direct costs (e.g., labour, supplies) and indirect costs (e.g., taxes, depreciation, insurance) in conjunction with operating costs, transportation, availability of consumables (e.g., water, power, reagents, grinding media) is obligatory for any proposed installation.

Projected operating and maintenance manning levels for staff and hourly personnel may be estimated on a worst case scenario of 365 operating days. Most plants base production on a 330 day operating schedule. Management is expected to determine the return on investment (ROI) or discounted cash flow (DCF) to financially justify the project. A short pay back period provides incentive to proceed with the defined project within set battery limits. The text attempts to assist either the novice and/or seasoned operator in addressing the pertinent factors in any mineral processing activity regardless of country of origin and mineralogy. The paper's mandate was to highlight salient facts regarding mineral processing modes globally and identify applicable sources of information within a single document. The principles expressed herein are similar for treatment of other materials such as industrial minerals (e.g., talc) and nickeliferous laterites. Finch (1998) examined the mineral processing industry and presented his views regarding anticipated changes in comminution, flotation and gravity separation during the next 30 years. Although the paper advertises selected equipment manufacturing facilities and provides references that describe specific problems it is understood that the author has not inadvertently intended to endorse any particular consultant, research laboratory or manufacturer that can solve milling and associated operating problems in a safe manner. The author has drawn on many years of industrial experience to indicate that companies listed within the text are selective to the big ones.

2. CRUSHING

The category hosts a wide array of size reduction equipment such as single and double toggle jaw crushers, cone crushers, hammer mills, and gyratory crushers. Vibrating screens and conveyors are normally combined with crushers in series to provide a product size distribution within a specified range. As a general rule jaw crushers are normally of robust construction due to the heavy service involved. It is an established fact that the comminution process is energy intensive. As a rule of thumb, the front end size reduction requires over six times more energy annually than the contained energy in consumables such as grinding media and liners. According to Jack de la Vergne (McIntosh, 2003) a 6:1 ratio for a jaw crusher and a 5:1 ratio for a cone crusher represent improved design practice with respect to the maximum practical reduction factor. The evolution of jaw crushers was described by WME (1997). Fuller-Traylor was an earlier supplier of crushing and grinding equipment. Current suppliers of jaw crushers are located worldwide such as Thyssen Krupp Födertechnik Mobile crushers manufactured by Krupp Fördertechnik GmbH in the Federal Republic of Germany are employed to crush industrial minerals on the spot immediately after mining operations such as in quarries. Metso Minerals markets a complete line of crushers and includes dry cone crushers in both standard and shorthead arrangements. Nordberg models MP800 and MP1000 are designed to fit onto a 7 foot (2.1m) Symons cone crusher foundation. The MP1000 presently is penetrating the Asian market with short-head cone crushers at mines around the archipelago as well as proving successful at Codelco's Chuquicamata mine in Chile. The Nordberg crusher capacities span a range of sieve sizes from 6-90mm and are grouped in five different categories of closed side setting dimensions which vary from 50-13mm. The cone crusher capacity is easily determined from the chart matrix of sieve size versus capacity. A simplified graph depicting the percent passing a set millimetre size serves as guideline in crusher selection. The unique WaterFlush® cone crusher is available under the trade name of Nordberg who are located in Milwaukee, WI, USA and function as a Metso subsidiary. The wet crushing system employing 250HP and which enables drawing less than two horsepower per ton of ball mill feed has been available since 1994. IMS Engineering supplied crushers in Namibia such as in a wet primary gyratory application (Kawasaki model) and secondary cone crushers used to process material to 20mm by means of a wet system (Pratt, 2003).

Hammer mills are suited for optimal fragmentation of limestone, gypsum, salts, and softer materials such as coke. Equipment such as the Aubema hammer mill directly processes lignite from open cast mines with a capacity of up to 220 tonnes per hour prior to the material entering the drying stage. The unit's capacity approached 1,000tph when crushing hard coal. Aubema Maschinenfabrik GmbH based in Germany also provides jaw and cone crushers, multi-roll crushers, and ball mills. The specialized equipment, which may be used in primary and secondary situations, includes adjustable grates for wear in the beater heads and a magnet to remove tramp metal. Regulations dictate that some applications include an integrated explosion suppression system. This equipment type is currently manufactured by Jeffrey/Dresser in Quebec, Canada. KGHM in Poland employs hammer crushing for size reduction of various copper ores. Although the world standard grain size is 15-20mm the Polish operations result in a concentrator feed of about minus 40mm. The Polkowice concentrator uses primary ball mills to grind the carbonate ore. The different lithological composition of the ore dictates the type of grinding system. Rod mills are used in the Lubin and Rudna concentrators to process the feed comprised of a sandstone and dolomite mixture. Regrinding operations in all concentrators use ball mills (KGHM, 2003). Other downstream equipment in the KGHM Polska Mied_ S.A. plant facilities feature Denver and Outokumpu flotation machines plus Dorr thickeners for dewatering. Lump breakers (e.g., Aubema) are another form of size reduction which is employed in some industries to reduce the physical size of agglomerated material. During inclement weather such as experienced in Canada and the Commonwealth of Independent States (CIS) it is not uncommon to break apart frozen ore and concentrate in order to allow further processing. Australia's benign climate does not create processing hardships such as in the northern regions of the Americas and the FSU.

3. MILLING

Formation of smaller particles may be achieved either in the dry state or provision of an aqueous media (e.g., water) as the carrier. After initial fragmentation into large chunks from underground and open pit operations by means of primary crushers, traditional means of providing finer particles include all forms of grinding such as rod and ball mill combinations, autogenous grinding (AG) and semi-autogenous (SAG) grinding, roller and tower mills plus pulverizing. Each piece of industrial equipment is selected to ensure that its product is amenable to downstream processes such as magnetic separation, flotation, and other related unit operations. The suppliers of grinding mills have changed dramatically over the years. Krupp Polysius Corporation based in CO, USA, supplies a range of mill types for either wet or dry grinding systems, high pressure grinding rolls, and tube mills. The tube mill category include ball mills and semi and/or autogenous mills. Krupp mills have been installed to process refractory gold ores. The Outokumpu Oyj organization (Finland) is a supplier of a full line of milling equipment for either a single supply or turn-key installations (Outokumpu, 2003). It inherited an established lineage of comminution equipment from the Swedish based Morgårdshammer, and Scanmec which spanned 75 years of experience. The original Allis Grinding Division equipment (e.g., the Vertimill) was absorbed under Svedela Industries Inc. which later was absorbed by Metso Minerals Industries, Inc., headquartered in Sweden. Metso Mineral Processing Inc. was formed in 2001 upon combining the Svedala and Nordberg businesses. In order to comply with the US government for approval in the merging of Nordberg and Svedala business portions had to be sold. The Svedala Cone Crusher business was bought by Scanvek while the Nordberg mill business was purchased by Outokumpu (Private communication, 2003). Svedala Grinding has its roots in York, PA, with the founding of the Hardinge Company in 1906. Since the turn of the 20th century a number of mergers, acquisitions and consolidation of business sectors has occurred within the framework of the Svedala organization. Readers may recognize some historic names in the industry such as MPSI, Trelleborg, Dominion Engineering, Sala Companies, Denver Equipment Company, Brenda Process Technologies and Skega. Over many years Metso and its predecessor companies have taken several of these enterprises under their business umbrella such as KVS, Marcy and other manufacturers to become a large international conglomerate.

3.1. Rod and ball mills

These units are the work horses of the global mineral resource industry. It is an established fact that the capacity of a mill operating in open circuit is approximately 80% of the identical mill operating in closed circuit (McIntosh, 2003). Conventional impact mills are the most popular amongst countries requiring a milling stage to process ores. Rod mills historically have been used as the first grinding stage after crushing in treating feedstock as coarse as 38mm albeit that better performance is obtained with feed material less than 19mm. Another rule of thumb is that rod mills are used to grind crushed ore as large as minus 50mm for soft materials and in the range of minus 20-30mm for harder mineralized substances. It is understood that rod mills prepare feed material for secondary ball mills arranged in either open or closed circuit. The overflow product from traditional rod mills ranges in size from 4-16mesh (4.75-1mm) in open circuit whilst 35mesh (425μm) material may be generated in a closed circuit arrangement. Commercial suppliers such as Metso fabricate rod mills in sizes of 0.9 to 4.3m shell diameter while mill length is normally 1.5 to 2.5 times the diameter depending upon the field application. Product is commonly discharged through an appropriate opening in the opposite trunnion. Rod mills may be arranged to discharge the ground contents by (i) trunnion configuration (ii) end peripheral discharge or (iii) centre peripheral discharge (Metso, 2003). The introduction of new feed material results in spreading the rod charge at the mill inlet while a series of wedge shaped slots are created which taper towards the discharge end. Action within a rod mill is analogous to particles being subjected to many sets of rolls in series thereby allowing rod mills to effectively reduce nominal 25mm feed to 10mesh (2mm) or finer in an open circuit. The interstitial space (ie., voids) within a normal rod load are about one half those in a ball mill grinding charge. Consequently, less feed can progress through the voids in the rod mill grinding media as compared to a ball mill. New feedstock is introduced into one of the hollow trunnions by means of a feed chute or drum feeder. The term "trunnion" also denotes the support wheels fitted with bearings upon which the exterior mill riding rings make contact during rotation. A trommel screen, which is the most common, or splitter are usually employed to discharge the hot pulp (ie., slurry) away from the trunnion bearings on both rod and ball mills. Rod mills equipped with trunnion bearings 1016mm (40 inches) diameter or smaller employ hydrodynamic oil lubrication while larger sizes utilize full hydrostatic means of lubrication. Various screen types are employed to protect the sumps and associated pumps from tramp steel and other foreign matter (e.g., wood). The protective screens may be composed of punched steel or wire mesh of suitable gauge and sieve opening, perforated rubber sheets, or polyurethane panels.

Ball mills are employed to grind material to a product size of 35mesh (425μm) or finer. Metso provides bench scale test work in York, PA (USA), Derby (UK), and Sala (Sweden) to evaluate milling parameters in order to design full scale installations. SGS Lakefield Research Ltd. located in Ontario, Canada, provides similar services to determine the power draw and other design criteria. Ball mills are used in primary, secondary, and tertiary grinding circuits. A common practice is to deliver ball mill feed by one of several methods such as (i) single and/or multistage dry crushing combined with screening (ii) a combination of crushing and screening and/or rod milling and (iii) primary crushing followed by AG/SAG grinding. Hard ore feedstock nominally consists of about 80% passing 6mm or finer (1/4 inch) whilst softer ores comprised of 80% passing 25mm serve as typical feed size to a ball mill. Cylindrical mills normally exhibit a length to diameter ratio (L/D) ranging from 1:1 to 3:1 (Metso, 2003). Another rule of thumb states that the ball mill diameter should not exceed 100 times the diameter of the grinding media (McIntosh, 2003). Although a ball mill nominally contains a 40% charge of grinding media a suitable drive system should be designed on the basis of 45 percent.

Ball mills may be designed for either a trunnion or grate overflow discharge arrangement. The pulp gradient between the feed and discharge openings in a trunnion style of ball mill allows product to overflow to the next stage of operations. A reverse helix in the outlet trunnion retains balls within the rotating mill. Grate (ie., diaphragm) discharge is common in some mill sizes. The metal grate serves to retain balls, tramp and coarse feed material. A slotted full diameter or partial diameter grate is fitted in the discharge end of the ball mill. As a rule, a grate discharge on a ball mill will consume approximately 15% more power than an overflow system despite that fact that grinding efficiencies are identical. Vintage mills with grate discharges require manual cleaning of the grate openings to allow passage of ground material. While at Inco Limited, the writer instituted the usage of pneumatic chisels to remove ball chips which clogged the narrow openings of the grates on each end segment. Modern mills include trommel screen discharges to avoid this labour intensive task. Mill support bearings may be comprised of several types such as (i) spherical bearings (ii) journal bearings or (iii) multi-pad type bearings. With the exception of spherical bearings, programs for lubrication design can predict the minimum thickness of the bearing fluid oil film. In general, tube mills feature an L/D ratio of 2:1 or greater. A variation in tube mills is the vibrating ball mill (VBM) sold by Metso Minerals. Although limited to much smaller throughput per hour and end use applications the principles are quite interesting. The unit is based on an intensified impact/shear/attrition environment to provide enhanced grinding action. VBM's provide several advantages compared to standard rotary grinding mills. The motor-driven and bearing supported eccentric shafts impart a circular and high speed motion to the grinding chamber (Metso, 2003). The unit is suited to several commercial applications.

3.2. Grinding media and mill servicing

Grinding media consists of either steel rods, balls, slugs, or billets and varies both in chemical composition and hardness to suit the end application. A different Mohs (Brinell) hardness of the grinding media is essential at primary, secondary ball mill and regrind stages. A charge of balls must cascade and tumble thereby not slide along the circumference as one solid mass. A study was conducted on a pilot scale Marcy ball mill to investigate the shape of grinding media in relation to the feed and pulp temperatures (Staples *et al.*, 1997). The performance of balls and slugs was investigated in Canada using a Cu/Pb/Zn ore. The evaluation concluded that 25mm media provided better grinding efficiency that 29mm media while slugs outperformed balls in both sizes. The consumption of grinding media is usually expressed as kg media/tonne dry ore processed. Norcast located in Toronto, Canada, supplies mill liners and conical shaped grinding media. The diameter of grinding rods and distribution of rod sizes within the mill is important as well as the physical level of charge in a shutdown position. The level of media is normally measured in relation to the centre line of mill. An optimum rod charge occupies about 35% of the internal shell volume in most cases. High carbon steel rods range in sizes from 38 to 114mm (1.5- 4.5inches) to suit the specific application. Nesting of rods, tangles, thin ends or flattened portions create poor contact with adjacent surfaces and result in inefficient milling. Depending upon labour availability and plant size, rod and ball charging may be arranged in either a manual or mechanical mode. Fragmentation of the ore particles depends upon the impact of media to create finer pieces. The mill's critical rotational speed (rpm) is an important variable. A common mill drive system consists of a speed reducer and motor, ring gear and pinion. A rough rule dictates that a dual drive system such as twin motors and pinions driving a single ring gear may be more economical than a single drive arrangement when the mill is designed to draw over 6,000HP (McIntosh, 2003). At present, geared drives are commercially available up to 9,500 horsepower. Without exception autogenous mills rated above 20,000HP require a direct drive ring motor which is actually a gearless drive system. The mill alignment in relation to its longitudinal position on the trunnions dictates the ease of removing ground material to the sump and pump system or discharging by gravity via a launder to the next mill in series. Preventive maintenance is mandatory for components such as ring gear, hydraulic systems, trunnions and thrust idlers. A trommel screen discharge permits removal of tramp steel generated by disintegration of the grinding media and facilitates evacuation of fumes via a hood arrangement. The negative suction of the airborne particulates is hampered with air in leakage to the wet scrubber system since it is impossible to tightly seal a moving object such as mill with the interface components of an exhaust system.

Interiors of modern ball mills are synthetically rubber lined and generally experience a service life double that of steel liners. However, synthetic rubber liners reduce noise but lower output to about 90% of the capacity realized in the same unit fitted with steel liners (McIntosh, 2003). The composition of common mill liners varies according to the application and includes materials such as manganese steel, chrome/molybdenum steel and Ni-hard. Steel liners may be supplied as either a wave type, wedge bar, or lifter bar configuration. The liners are fastened to the shell with large bolts. In the past mechanics employed spent conveyor belts as backing for the expendable liners to provide additional benefit. It is worth noting that periodic inspection of mill interiors is required to determine liner wear on both end and side liners. When lifters are worn smooth they are no longer effective in tumbling the total charge. Inspections will detect cracked and/or worn liner segments, missing liner bolts and other factors that could create a major expense if left unattended. Mill liners, which are regarded as a consumable operating expense, feature a different configuration for rod or ball mills (especially the end liners) whilst the surface contours and shape of each liner segment determines the actual end use. Mill relines are very costly. Operations may choose to provide a standby mill that can be adapted for rod or ball mill usage. Mechanised mill relining is a new practice in some areas. After removal of the trommel screen to permit entry to a mill, which is securely electrically tagged out to prevent accidental start-up, mill inspections are generally labour intensive. On some older mill types it is necessary to remove external hatch covers on the circumference for entry of personnel.

3.3. AG/SAG mills

Both autogenous grinding (AG) mills and semi-autogenous (SAG) mills have been successfully adapted as the primary stage in the processing of sulfitic ores. Ball and pebble mill configurations represent a new era in the treatment of minerals to recover metal values (Finch, 1998). Autogenous grinding employs the feed material in the form of different pebble sizes to facilitate size reduction in the tumbling mill whereas semi-autogenous mills use supplemental steel balls in conjunction with the feed material. Limitation of AG/SAG mill sizes due to gearing constraints has been eliminated by the advances in gearless drive technology since the 1980's. Metso Minerals is recognized as a leading world supplier of gearless mills (Metso, 2003). Metso indicated that a single SAG mill with suitable ball mills can achieve an output of 100,000 metric tonnes per day. Pebble mills are normally employed for secondary grinding applications in which either the contamination of processed material or minimizing running costs due to high liner wear and media consumption are of high importance. Brodie (2003) discussed variable speed SAG milling and related factors affecting mill performance. A SAG mill's effective diameter is quite different when comparing new liners versus worn liners. Relationships between parameters such as ore and media volume, mill speed and power draw were addressed by Barratt (1992). It is important to select a mill speed to suit a change in grind. The nature of the ore must be amenable to forming stable pebbles while the capacity range is similar to ball mills. Research was carried out to evaluate an open circuit versus a closed SAG milling circuit in the processing of gold-bearing ore at the Williams Mine in Ontario, Canada (Barnes *et al.*, 1997). Metso SAG mills at Freeport's operation in West Papua, Indonesia, are supported by cone crushers to process pebble rejects in the C3 and C4 concentrator grinding lines. Sandvik cone crushers are employed to crush oversized pebbles at Codelco's sulfur plant in Latin America (Pratt, 2003). Global suppliers already have the next generation of AG/SAG mills on their drawing boards. Similarly, tower mills are expected to be at the forefront in fine grinding applications.

3.4. Tower mill

It was estimated that 32-billion kWh of electrical power are consumed annually by size reduction equipment in the United States of America. Fine grinding applications represent a large proportion of the industrial power draw. Traditional tumbling mills dedicated to fine grinding create unwanted noise and waste energy as dissipated heat. This particular unit for wet grinding was described by Jones (1985). The unit was first introduced in Japan during the 1950's. Tower mills compete with the IsaMill system in fine and ultra fine grinding applications. By definition, tower mills are essentially a stirred ball mill configuration. The stationary vertical and lined vessel is charged with grinding media which is agitated by a mechanical stirring device. Abrasion is the basic grinding action and the absence of impact limits the feed input to 5mm while the grinding media top size is normally 25mm. The design prevents over grinding which is detrimental to downstream flotation stages and dewatering of tailings. Tower mills are suited for fine grinding at the end of the size reduction spectrum and provide several advantages in comparison to conventional impact or tumbling mills. Fine fractions are prone to over grinding in conventional units. The tower mill is best suited to handling feedstock with a 6mm (1/4 inch) top size in order to produce a product in sizes ranging from 74μm (200mesh) to 2μm or finer. The compact units which occupy very little floor space feature less costs in areas of capital, operating, and maintenance. From an environmental perspective these specialized units generate less noise and vibration than traditional means of size reduction. In contrast, impact mills create unwanted noise and heat thereby affecting the work place environment and threshold limit values for employees. As a rule, wet tower mills operate in closed circuit with a settling type cone classifier but may be physically arranged in either open or closed circuit with top or bottom discharge. Lime slaking is an ideal application for a tower mill. The mill treats limestone to produce grit-free and slow settling slaked lime for pH control in flotation and/or neutralization of waste concentrator tailings. Other potential uses are processing gold-bearing tailings, Pb/Zn ores, metallurgical slags, coal sludges and manganese ore. A modern version of the stirred media grinding mill consists of the Vertimill® (Metso, 2003). Tower mills such as the Vertimill® offer a viable alternative for wet or dry grinding in batch or continuous applications in open or closed circuit as opposed to an impact process within a ball mill.

3.5. IsaMill

Xstrata Technology (formerly MIM Process Technologies) in Australia markets a novel approach to grinding applications within the global minerals industry. The milling principle is intrinsically different from traditional impact grinding in rod or ball mills. The reliable equipment enables materials such as industrial minerals to be economically finely ground on mine sites. The IsaMill utilizes attrition grinding to selectively reduce particles within a sealed and high energy intensity environment. Consequently, the high energy efficiency allows the production of fine and ultra fine grinding without any iron contamination or oxidation of the mineral being ground. A very narrow product size distribution provides another advantage. The IsaMill is a continuously operated and horizontally configured, fine grinding machine which is capable of producing finer than 6μm sized products for large-scale mineral processing and leaching applications. It was developed to grind ores at MIM's Mount Isa and McArthur River operations in the production lead and zinc concentrates. The technology is currently used by other mining companies for gold and platinum production. An IsaMill using coarser inert media could become a real alternative in some applications currently using ball mills, particularly where there are downstream processing advantages from the inert grinding environment. Other associated downstream equipment may include the unique Jameson cell (Xstrata, 2003). This flotation approach is mainly used for recovery of fine coal while SX-EW operations and copper concentrate production are additional proven areas of application. The world's largest fine grinding mill was supplied for Anglo Platinum's Western Limb Tailings Retreatment Project near Rustenburg, South Africa. A 10,000 litre, 2.6 megawatt IsaMill was commissioned in December 2003. The IsaMill was developed as part of a collaborative agreement between Xstrata Technology, Anglo Platinum and Netzsch of Germany, as a scale-up from the existing 3,000 litre, 1.1 megawatt IsaMill. At present, seventeen 1.1 megawatt units are operating in mining plants in Australia and South Africa, treating zinc, lead, gold and platinum concentrates (MEI, 2003a). The parent company, Xstrata plc, is a global mining company with plant operations in Australia, Europe (e.g., Asturiana de Zinc in Spain) and the Republic of South Africa (RSA). Xstrata is a major player in the worldwide vanadium industry in conjunction with recovering other metal values such as germanium. It is worth noting that the Ultrafine Grinding '06 conference will be held in England co-currently with the Hydrocyclone '06 venue described in section 5.

3.6. Roller mills

The physical shape, mechanical action and end use varies considerably for size reduction equipment downstream of crushing systems and listed under the generic category of mills. Roller presses as marketed by KHD Humbolt Wedag are suited for a wide variety of field uses due to a lower energy requirement and higher throughput than conventional comminution methods. Roller presses are capable of 2,500 tph processing rates in coarse or fine grinding applications. The equipment is designed for beneficiation plants treating different grain sizes in ores and minerals. The different feed materials are economically processed upon retrofitting existing plants. Apart from the cement industry, typical applications include gold and phosphate rock, iron ore, and Kimberlite diamond rock. Another manufacturer of roller presses is Maschinenfabrik Köppern GmbK & Co, KG with offices in Germany, Australia, India, the USA and Venezuela. Loesche GmbH has supplied roller mills for grinding cement clinker and blast furnace slag. Roller mills, which are also known as vertical mills, are increasingly used in the cement industry since they enable particularly economical and energy-efficient grinding.

3.7. Pulverisers

It is appropriate to mention dry pulverising and micronising such as employed in the production of titanium dioxide (TiO_2) pigment. Pulverisers incorporate the principles of crushing and disintegration within this specialized equipment sector. The pulverisers produce ultra fine particles of pigment for the global industry due to its whiteness, brightness and opacifying properties. The sub micron non toxic particles are primarily used in the (i) paint/coating industry (ii) plastics industry (iii) paper industry while (iv) other sundry uses include the cosmetics, rubber, printing inks, textiles and pharmaceutical industries. Australia is a major source of supply for ilmenite and rutile feedstock in TiO_2 operations which either use the chloride or sulphate route to produce pigment. Australia is well known for its black mineral sands which contain titanium and other metal values. Monazite is rare earth phosphate [(Ce, La,Y,Th,)PO_4] which is recovered as a component of heavy mineral sands as found in Australia and Madagascar. The high specific gravity of monazite facilitates its concentration by wind and water and it is commonly associated with ilmenite, rutile and zircon as a constituent of heavy mineral sands (Smart, 1999). Thorium is a major constituent of this mineral and imparts radioactive properties to the monazite mineral containing 50-78% rare earth oxides (REO). The yttrium phosphate called xenotime (YPO_4 or $Y_2O_3.P_2O_5$) includes cerium, erbium, and thorium in its 54 to 65% concentration of REO. It is associated with pegmantite and igneous rocks and often is a component of heavy mineral sands which host other valuable materials such as uranium and rutile which is a source for TiO_2 pigment production. Olympic Dam's copper-uranium deposit in Australia contains approximately 0.5% contained rare earth elements (REE) within a fine grained bastnäsite and monazite mixture (Moskalyk, 2003). Other applications of pulverisers include the grain industry, preparation of metallic powders, the coal and foundry industries.

4. FEED SUPPLY

Host minerals include mixtures of bornite, chalcocite, chalcopyrite, heazlewoodite, pentlandite, pyrrhotite, and other species containing both ferrous and non-ferrous metals in conjunction with valuable by-products such as precious metals, indium, gallium, and germanium. Feedstock is normally introduced to the eye of a mill inlet at sufficient velocity to be tumbled with an appropriate charge of grinding media. The subject of dry versus wet milling and optimum size is dictated by the characteristics of the feed material, geographic location, and downstream processing operations. The layout of plant equipment such as storage bins, crushers, conveyors, classification equipment and mills often dictates the chosen approach. Consideration must be given to points of reagent addition for collectors, frothers, and suppressants to condition the pulp prior to rougher flotation and pH adjustment by means of a slaked lime slurry or other method. It is common practice in Cu/Zn and Pb/Zn circuits to increase pH levels in the initial rougher stages then modify the level downwards in subsequent recleaner and/or scavenger stages to optimize the separation of mineralized constituents. It is a fair statement that the finer the initial rod mill feed (e.g., 8mm) or feed to the primary mill the less horsepower is required for the milling operation. At Inco's matte separation plant in Copper Cliff, Ontario, it is necessary to regrind the slow cooled bulk Cu/Ni matte to minus 325 Tyler mesh (45μm) to ensure liberation of the copper fraction from the nickel-bearing fraction and associated metallics portion (Agnew *et al.*, 1997). Plant management must evaluate the overall power requirement for each segment of the process then select the most efficient combination of equipment for crushing and grinding operations. Efficient screening systems are paramount within the initial feed preparation and crushing operation. Circulating loads of oversize material at each stage of the overall process also consume additional electrical power. Unmanageable circulating loads may occur upon wet or dry classification thereby restricting the daily throughput of fresh material. Similarly, plant bottlenecks may occur upon diverting too much oversize back to some crushing stages thereby limiting productivity.

5. CLASSIFICATION

The unit operation of separating a coarse fraction for further grinding and a fine fraction for rougher flotation is well practised over many decades. Traditional rake classifiers (single or multiple) have been used in many countries. In competition, the spiral classifier evolved over the years with some manufacturers (e.g., Humphreys). These auger type units feature spiral rakes in parallel to recover oversize material for additional size reduction (Thompson and Welker, 1990). Eventually, the single hydrocyclone with adjustable vortex became a common site in milling operations. With time these initial prototypes were grouped as banks of cones to adjust to the daily ore throughput. A radial configuration is common for vertically mounted cyclones. Global major suppliers such as Richard Mozly Ltd. (UK), Krebbs Engineers, Humphreys Process Equipment, Linatex (Canada) and others have fine tuned the design to provide efficient separation of ground particles. Major suppliers of commercial hydrocyclone configurations covering a range of applications and capacity number over a dozen. Small diameter hydrocyclones are employed to treat material finer than 50μm in the chemicals, food, minerals, oil and gas, pulp and paper industries. Hydrocyclones are the most widely used separating device in industry. Virtually every mineral processing operation in the world uses this ubiquitous device. The vortex controls the split and consequently the underflow discharge contains the sands for further processing while the overflow contains fine particles likely suitable for flotation or other unit operation. The literature indicates that the ratio of the diameters between the vortex finder (ie., upper overflow exit port) and the bottom underflow exit (ie., apex) must be kept below 2:1 in order to control operations. The ratio of the difference in density of the heavy mineral and the carrier medium (e.g., water) and the difference between the light mineral and medium in an aqueous slurry must be maintained greater than 1.25 in order to facilitate gravity separation (McIntosh, 2003). The majority of wet classification equipment is sensitive to the presence of a slimes fraction which typically consists of minus 400mesh (38μm) particles. It is prudent to avoid slimes content in excess of 5% while levels above 10% can cause serious problems in wet gravity separation units. Cementitious mine backfill and/or pastefill practice classifies mill tailings to remove the slimes fraction before delivery of the mixture underground by means of high pressure positive displacement pumping systems (e.g., GEHO).

Schmidt and Turner (1973) outlined the features of horizontal and flat bottom cyclones. They considered that both types of hydrocyclone were applicable for ball mill grinding circuits producing a product of 80% passing 150μm or coarser (ie., 100mesh). Both types coarsen the physical separation thereby increasing throughput and efficiency. For example, assemblies of 10mm microcyclones can total 35-60 units per stage to process ultra-fine particles. It was concluded that this specialized configuration of small-scale hydrocyclones may provide a viable alternative to conventional centrifuge and filtration equipment within a broad range of applications. Forums such as the Hydrocyclones'03 conference held in Cape Town, South Africa provided participants access to recent advances in equipment and applications. A similar venue for solid/liquid separation was held November 2004 in the RSA. Casteel (2003) described recent advances in hydrocyclone technology as presented by authors such as Jim W.G. Turner. Several papers discussed the application of microcyclone systems which feature reduced capital and operating costs whilst leaving a small footprint in comparison to earlier equipment. Hydrocyclones '06 is scheduled for June 14-16, 2006 at the Falmouth Beach Hotel in Cornwall, United Kingdom. This second symposium is being organized by Minerals Engineering International while the event is sponsored by Krebs Engineers.

6. MATERIAL HANDLING

Proper design of material handling in both the wet and dry states is paramount in any modern beneficiation plant. Engineering groups can apply Internet 3D modelling of the proposed equipment layout to inspect clearances, work space around equipment and other factors. Apart from selecting the diameter and suitable material for wetted pipelines, allowance must be made for adequate slopes of each individual line with straight runs and not excessive loops and curves. The line velocity of each slurry stream must be acceptable over the range of low to high tonnage rate. Provision should be made for maintenance, clean-outs and other features as time savers for operators on each shift. Drainage of the contents of each pipeline should be made to a sump whenever the plant is either in a shutdown mode or is faced with a power interruption and hence emergency measures. Glandless sealed slurry pumps are acceptable to save maintenance gland packing labour. Proven water supply pumps are necessary in any wet operation such as concentrating. It is noteworthy that a concentrator requires up to three tonnes of process water for each tonne of ore processed thereby affecting material handling capacity in many areas of the plant (McIntosh, 2003). Designers of slurry pumps must address abrasion characteristics of each process flow in contact with wetted internals of mechanical pumping components. For example, hardened and wetted surfaces may be coated with Ni-hard. Miller (1973) developed a technique to measure the relative abrasive degree of slurries. The Miller number provided an indication of what metals and alloys to specify for wetted surfaces of slurry transport systems. Ultra high molecular polypropylene linings were used for concentrate storage bins downstream of initial grinding operations. Rather than purchasing all new equipment off-the-shelf it is feasible to use second hand equipment and controls thereby constructing a milling facility in-situ for one half the cost of an all factory new system utilizing state-of-the-art automated monitoring and controls. The mill components may be refurbished either on site or remotely depending upon the machine shop and other maintenance resources of the company implementing the changes.

7. DESIGN CRITERIA

Apart from examining feed supply parameters, a complete mineralogical examination is justified. The physical and chemical characteristics of the material being treated may impact upon the recovery of metal values. Ore composition may be represented over a wide range of components thereby requiring selective grinding and flotation stages to separate each fraction. The economic liberation of one metal-bearing constituent from the host material may be affected by the ore morphology. The optimum recovery process selected thus affects the daily throughput. The ore being processed may either be massive or disseminated ore and exhibit size reduction properties due to variables such as its friability or hardness. In the case of copper/zinc or lead/zinc processes sufficient allowances must be made to optimize recoveries. The final zinc concentrate should contain a minimal amount of entrained copper or lead since these valuable impurities will affect the costs of downstream separation. The recovery of zinc at a later stage may be either a pyrometallurgical operation followed by electrolytic refining or a hydrometallurgical route (e.g., SX-EW). The Bond Work Index (BWI) determination provides a useful tool to evaluate the horsepower required to process a tonne of material from an initial feed composition to a specified size fraction (e.g., 85% passing 325mesh). An empirical formula is used for the BWI to provide a specific energy value (net Hp-hr/t). Ore specific gravity and hardness dictate the type and hardness of grinding media required for efficient size reduction without creating excessive fines. Over grinding may form slimes which load up downstream dewatering equipment. The degree of liberation is important in order to accommodate subsequent separation processes such as flotation stages. Product contamination (e.g., iron) may be attributed to mill liners and grinding media (e.g., Cr, Ni, Mn). It is essential to eliminate potential impurities from flotation operations. The recirculating load in the milling circuit expressed as a percentage of new feed is another important design criteria. A guideline exists that the larger the diameter of the drum hence the more efficient grinding results in a mill. However, this phenomenon ceases to apply when the mill diameter reaches 3.8m (12.5ft). Designers invariably will consider the mill aspect ratio (length/diam.) for custom built units rather than purchasing an off- the-shelf unit in the event that the combination of parameters is not amenable to a conventional commercial unit. Corneille (1987) examined the capital and operating costs of mineral processing plants. Designers currently have the advantage of 3D computer-aided design (CAD) and finite element analysis to predict peak stress levels in the mill's structure. Integrity of the mill's structural elements is an important variable. Engineers can conduct a torsional analysis of the drive train to ensure that the mill operates at speeds away from harmonic frequencies.

The presence of metallics will affect the liberation efficiency of various components. As an example, Inco's matte separation plant in Ontario, Canada, processes bulk copper-nickel matte from the smelter. After casting Bessemer matte into ingots and slow cooling for several days to allow formation of copper and nickel sulfides plus a metallic phase which contains the precious metals, the matte is crushed to essentially 35% plus 13mm. The flow sheet consists of complex circuits involving rod and ball mill grinding, magnetic separation, flotation and thickening, regrinding and further flotation to finally produce several high-grade products for further treatment (Agnew *et al.*, 1997). The plant produces a high-grade chalcocite concentrate (72% Cu), two grades of nickel concentrate for subsequent fluid bed roasting to oxide products for market and the metallics portion which was directed to the TBRC's at the Nickel Carbonyl Refinery. The "tailings" in this plant contain over 70 percent nickel while copper rich material is floated in Outokumpu cells and flotation columns by means of DPG (diphenylguanidine) with lime slurry addition for pH control. The current processing of bulk matte, containing approximately equal amounts of copper and nickel, has an average production rate of 1,300mtpd during a 6.5 day schedule. Inco's Copper Cliff smelter processes its minus 325 Tyler mesh (45μm) chalcocite (Cu_2S) flotation concentrate (called MK) from its matte separation process by forced addition in a modified Peirce-Smith converter shell. The MK reactor features a unique oxygen flash gun that simultaneously injects natural gas and filter cake. Commercial operation commenced in 1993 involving tuyere injection of chalcocite in conjunction with oxygen top blowing and nitrogen stirring to produce blister copper. The mixing action promotes desulfurisation of the molten blister.

8. ASSOCIATED EQUIPMENT

It is anticipated that milling circuits may be integrated with several other unit operations such as dewatering (e.g., thickeners, filters), magnetic separation, flotation and regrind circuits coupled with cleaner and scavenger flotation cells. The category includes all auxiliary equipment not identified under other headings within the text. Sampling equipment, conveying systems, storage bins for products and intermediate materials, supply of potable and process water, supply of consumables such as compressed air plus others represent an extensive list of items to review from the conceptual stage of engineering through to the final plant physical layout and commissioning. The majority of beneficiation plants currently employ agitated and aerated flotation cells ranging from 30-50 cubic meters capacity whilst jumbo cells now are commercially available in 100m^3 capacity. Jameson flotation cells, which feature no moving parts and numbering about 220 globally, represent a novel approach to the separation of different minerals (Xstrata, 2003). The Australian equipment is typically employed in the recovery of fine coal although the principle is used in SX-EW and copper concentrate applications.

Knelson concentrators (KC) from Canada are employed to recover the gold fraction from ore processing, platinum group metals from waste tailings, and in alluvial operations. Knelson units operate on the principle of gravitational enhancement. Feed slurry is introduced into the concentrator's ribbed inner cone rotated at high speed. Particles with the highest specific gravity become trapped within the bed. Injection of water through a series of perforations in the cone's wall prevents compaction of the bed. The bed is maintained in a fluidized state thereby allowing even micron-sized gold particles to be concentrated under the intense "g" force. Knelson concentrators yield an enriched product upon continually trading lighter elements for heavy ones. KC units are employed at the St. Ives gold mines of Western Mining Corporation in Australia. Filter presses present another subject outside the realm of the paper amongst competitors such as Larox, Sala, Denver, Dorr, and Eimco. It is noteworthy that the Centenary of Flotation symposium is slated for June 5-9, 2005 in Brisbane, Australia under the joint auspices of Society of Mining Engineers (SME) and the Australasian Institute of Mining and Metallurgy. The venue will celebrate 100 years of the froth flotation process for the separation of particles (MEI, 2004).

9. INSTRUMENTATION

Operations may choose either a simple "no-frills" or sophisticated system with respect to the degree of instrumentation applied to the milling circuit. Weighing devices are the norm for new dry feed introduced into the primary mill while wet feed transported via pipelines requires mass flow measurement devices. Proven manufacturers are available to measure flow by means of gamma gauges and pneumatically controlled flow measuring devices. Density control is an important parameter that may be addressed with appropriate state-of-the-art instrumentation. A suitable percent solids in the mill discharge slurry provides an indication of the liberation taking place upon treatment of the feedstock. Discharge density may be integrated with the water supply added to wash the feed into the rod mill, ball mill, or semi-autogenous unit (SAG). Operators traditionally used the old fashioned Marcy gauge. The era has now passed when an operator worked at the same job for 15-20 years and could literally feel the grind between his fingers, these skills no longer exist in today's work place culture. The effects of unionized and migrant workers coupled with staff turnover affect the continuity of operations. Workers tend to be quite mobile in current society and keep changing jobs irrespective of pensions and other long-term benefits. Hence, ample instrumentation helps offset the lack of resident experience on the plant floor. In order to ensure acceptable separation of concentrate from gangue material or separation of copper concentrate from a zinc pulp for example, control of all parameters is essential. An example of the latest technology is the tool developed by CSIRO to predict the motion of particles within grinding mills (MEI, 2003b).

It is anticipated that plant management may provide on-stream analysis to control the overall recovery process. Outokumpu Electronics markets the Courier® 40 on-stream XRD/XRF analyser for on-line mineral analysis. The ability of the rugged unit to provide simultaneous X-ray diffraction (XRD) or X-ray fluorescence (XRF) to facilitate the measurement of multi-streams is of tremendous benefit to a milling and grinding circuit. Determination of the stream composition at a regular frequency such as 5-15 minutes is employed in many industries such as Cu/Ni separation, the potash and phosphate industries, talc, and pyrite sectors. On-stream analysis enables operations to quickly detect process changes. Conventional bench analyses every hour coupled with a one hour time delay for the determination does not allow operations to obtain a clear picture of the status of the beneficiation stage. The incorporation of process control and associated management systems provides operations with a unique set of tools for the modern concentrator. Measurements of flotation rougher feed composition, final concentrates and tailings analysis aid the operator of the beneficiation circuit. Readings of pH, reagent addition rates at a preset frequency are useful tools that were not available many years ago. Another useful tool consists of the automatic measurement of particle size from the secondary mill discharge which is expected to be in closed circuit with the primary mill and linked by classification and associated pumping systems. Outokumpu Mintec markets a particle size indicator for single or multiple stream operation thereby providing an accuracy of 1-2 percent on readings taken every 6-8 minutes. The equipment is suitable for on-line particle size distribution of slurries in the range of 28 to 500mesh (ie., 600μm to 30μm). An optional non-nuclear density gauge may be integrated into the unit. It is worth emphasizing that an initial investment in appropriate smart instrumentation from crushing through to metal refining pays dividends by means of improved productivity and plant performance, energy efficiency, consistent product quality, and pollution control. Apart from alkalinity control (e.g., lime addition), temperature measurement is often forgotten by new operators. Although flotation in Australia is subject to evaporation losses, flotation in colder climates such as Canada, the Russian Federation or other countries in the former Soviet Union (FSU) may present problems in the winter season. For example, rougher feed pulp density and temperature become critical during inclement weather as experienced in northern latitudes. A cold pulp introduced in any size of flotation cell will not provide optimum liberation despite the agitation, aeration and reagents employed in the unit operation. Provision of steam spargers integrated with pulp density measurement present one solution.

Australia has applied cone beam tomographs for a much finer 3-D view of the internal structure of an object in a non-destructive method. The tomograph's primary purpose is to scan for material dispersion inside mineral samples, such as the grains of gold inside chalcopyrite. The analytical tool will provide the minerals sector with a powerful new means of understanding mineral associations in ores, thereby enable them to develop strategies to selectively liberate the mineral grains from one another more efficiently than present practice. The tomograph unit uses similar technology to the more widely used medical CAT scanner, but with much more detailed image resolution. Medical CAT scan imaging has a resolution down to a millimeter, whereas the SkyScan 1072 X-ray microtomograph can achieve a two micrometers (microns) resolution. Thermography may be used in heavy industries directly in the production process, plant maintenance and trouble shooting. The measurement of infrared energy serves to monitor and control various stages of a process (InfraRed, 1985). The Societé Le Nickel-SLN nickel electrowinning refinery located at Sandouville near Le Havre, France, employs an automatic infrared system to detect electrical shorts in the electrolysis shop upon scanning every five minutes. Developments for controlling and optimizing minerals processing plants focussed on issues such as degree of sophistication while performance of process control is contingent on reliable data collection and monitoring systems. White (2004) described control principles advocated by (i) Outokumpu's packages (ii) Kennecott Utah Copper Corp.'s use of Metso process technology (iii) application of Citect automation software at Impala Platinum operations in South Africa (iv) Makitron technology packages as applied at KCGM in Australia and (v) Famic Technologies "Automation Studio" software.

10. ENVIRONMENTAL COMPLIANCE AND SAFETY

It is mandatory that designers recognize all safeguards to prevent any injuries to employees by means of appropriate guards over moving components, fences near rotating units, and other suitable measures. A fail safe system ensures good productivity without incurring compensable injuries. Trained safety engineers should critique all drawings in the planning stage to avoid pinch points and other potential accident prone situations in the field under operating conditions during a 24 hour seven day cycle of activity as the worst case scenario. Firms are inadvertently willing to risk lost time injuries by sacrificing safety concerns in order to reduce costs. In the event of a power interruption (e.g., storms, failure of the substation) it is prudent to supply emergency power by means of diesel powered generators to critical units such as mills. A short time is required to discharge the contents of a mill to a sump floor or catch basin once the feed is stopped and only water is added. This step allows a reasonable start-up when operations resume without subjecting the mill motor to an extra power draw for a cold start under load. Mandatory limits for TLV's (Threshold Limit Value) in the work place with respect to heat, noise levels, and dust exposure are set by prevailing regulatory agencies in each state, province, or region. Some governments issue guidelines for the operators that are suggested for compliance albeit that these can not be enforced by law. The noise level expressed in decibels (dba) is normally measured as a time weighted average per employee.

Control of airborne particulates is important since dust particles may contain carcinogens such as nickel and lead. Harmful substances should be contained within process equipment plus upstream and downstream connections. Fine aerosols may contain toxic compounds and escape into the work room environment in the event that sealing of interfaces is inadequate. The evacuation volume may not be satisfactory and thus allow egress of deleterious materials. At present, it is customary to hood both feed and discharge points of a milling unit then evacuate the fumes to a dust collection unit. Dry particles are best directed to a baghouse whilst wet particles are effectively removed by means of a wet scrubbing system. It is recognized that dilution air will be substantial upon maintaining a negative pressure within the shrouded enclosure to ensure entrapment of any particulates. Consequently, the scrubbing unit must be designed to handle a higher volume since it is not feasible to tightly enclose moving objects without risking injury to a passing worker. The collected dust is discharged as a dilute slurry to a covered thickener or sump in order to recycle the material to process and recover any metal values. Venting of transfer points and avoidance of open launders is essential to reduce employee exposure to toxic reagents, chemicals, and potentially harmful substances being treated in a beneficiation circuit. Covering of exposed surfaces of bins and tanks is suggested to reduce the incidence of minute respirable particles.

11. DISCUSSION

Incentives exist for industry, university, and government laboratories to conduct practical research in all phases of mineral processing. Periodically the world experiences an oil crisis (e.g., Iraq) which exacerbates energy costs in heavy industry over the complete range from mine face (underground or open cast), comminution and beneficiation, smelting and refining through to delivery of final product. Artificial intelligence represents a means of improving unit costs in tandem with process control strategies and novel mineral processing techniques. It is a given fact that profitability of most industries in the minerals sector is linked to the efficient use of energy in any form. It is advantageous to tailor equipment to suit the desired result. Analysis of chemical and physical characteristics of the ore body such as specific gravity, ore hardness, composition range, friable or malleable properties in certain size fractions, ease of liberation and other pertinent factors require a thorough study when either initiating a new site or customizing an operation in-situ. Consideration must be given to the morphology of the end product of the size reduction process. The mechanical action(s) employed in the processing stages may affect downstream processing and recovery. For example, the ability to wet a particle is important in flotation whilst the surface area and porosity are relevant parameters if the fine fraction is destined for solvent extraction and electrowinning (SX-EW) following an atmospheric or pressure leaching stage such as experienced in the treatment of laterites (Moskalyk and Alfantazi, 2002). It is apparent that the majority of process equipment is custom designed for a particular application rather than being off-the-shelf as in some industries. It is impractical to identify suppliers worldwide in a major category such as milling equipment since companies are continually either consolidating into larger corporations or simply becoming obsolete. Past sessions on size reduction included the "Comminution Practices Symposium" which was organized by SME (Society for Mining, Metallurgy, and Exploration) and held in Denver, CO during Feb. 24-27, 1997. In conjunction with SME and CIM, a mineral processing design conference provided 2,500 pages in its two-volume set of proceedings (MPPD, 2002). A regular venue is the annual meeting of the Canadian Mineral Processors which is a division of CIM (The Canadian Institute of Mining, Metallurgy and Petroleum). The 36th meeting held January 20-22, 2004 in Ottawa, Canada, featured new developments with respect to process improvements in grinding, flotation, mine backfill and other topics. Another forum consists of the bi-annual International Comminution Symposium organized by MEI (Minerals Engineering International). The 5th conference is scheduled for March 15-16, 2006 in Perth, Australia. The venue will be comprised of sessions concerning all aspects of the comminution of ores and coal.

12. CONCLUSIONS

Optimum mineral processing involves a thorough examination of the physical and chemical characteristics such as mineralogy, ore hardness, specific gravity, friability, malleability, morphology, and an understanding of the complete process from mine face through to shipped product in order to efficiently recover metal values.

Apart from capital and running costs, crushing and grinding equipment design involves factors such as geographic location, desired product throughput and size distribution.

Consideration must be given to compatibility with the next stage of the process. For example, design factors such as surface wetting properties and porosity of fine particles affect the unit operations of flotation and solvent extraction (e.g., SX-EW) respectively.

Toxicology of the feedstock, availability of grinding media and consumables all interact in the design of reliable plant equipment.

Crushing and milling require preventative maintenance schedules and operator friendly state-of-the-art instrumentation for process control. Operating parameters may be programmed to achieve minimal energy consumption with maximized daily output.

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