Introduction to Mineral Processing

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1.0 Introduction

1.1 Mineral Processing and Extractive Metallurgy

Mineral processing is a major division in the science of Extractive Metallurgy. Extractive metallurgy has been defined as the science and art of extracting metals from their ores, refining them and preparing them for use. Within extractive metallurgy, the major divisions in the order they may most commonly occur are, Mineral Processing (or Beneficiation), Hydrometallurgy, Pyrometallurgy, and Electrometallurgy. The last steps in the winning of metals are in Physical Metallurgy where the composition and treatment of metals are varied to provide desired physical and mechanical properties.

In mineral processing, a number of unit operations are required to prepare and classify ores before the valuable constituents can be separated or concentrated and then forwarded on for use or further treatment. The field of mineral processing has also been given other titles such as mineral dressing, ore dressing, mineral extraction, mineral beneficiation, and mineral engineering. These terms are often used interchangeably.

1.1 Ores and Minerals

Ore is a term used to describe an aggregate of minerals from which a valuable constituent, especially a metal, can be profitably mined and extracted. Most rock deposits contain metals or minerals, but when the concentration of valuable minerals or metals is too low to justify mining, it is considered a waste or gangue material. Within an ore body, valuable minerals are surrounded by gangue and it is the primary function of **mineral processing**, to liberate and concentrate those valuable minerals.

1.2 Run-Of-Mine Material and Minerals

Generally, mineral processing begins when an ore is delivered from a mine, to a processing facility. At this point, the ore is called **run-of-mine** material because there has been no treatment performed on it.

There are three primary types of run-of-mine materials:

1. Run-of-mine consisting of useful materials. These could include granites, building sand, limestone, coal and clays. Note that materials in this category are not classified as minerals.

2. Run-of-mine containing useful minerals. The minerals in this category among others include fluorite, apatite, diamonds and gemstones, vermiculite, barite, wollanstonite and chromite and are often referred to as **industrial minerals**. Other examples are i) barite that is used as weighing agent in oil drilling mud and ii) vermiculite, which is used for sound and thermal insulation. The unit value of this class of minerals is low but the purity is high, approaching a chemical grade. The minerals in this class are used directly for industrial applications once they are separated from a gangue content that must be low to start with. The low unit value only allows for marginal treatment costs.

3. Run-of-mine containing value bearing minerals. This class of run-of-mine is similar to the previous descriptions. However in this case, the target mineral obtains its value from the contained metal and these categories of deposits are referred to as **metaliferrous**. For

example, an ore containing the mineral chalcopyrite (CuFeS2) derives its value from the contained copper. Chalcopyrite does not in and of itself have any direct use as a mineral. Once chalcopyrite is concentrated (separated from the gangue), it requires further treatment to extract copper via chemical (hydrometallurgical or pyrometallurcial) methods. A list of some valuable minerals is provided in Table 1.

Table 1. Some Common Metalliferous Ore Minerals

Metal	**Ore Mineral**	**Chemical Formula**
Aluminum	Bauxite	$Al_2O_3 \bullet 3H20$
Chromium	Chromite	$FeCr_2O_4$
Cobalt	Skutterudite	$(Co,Ni,Fe)As_3$
Copper	Chalcopyrite	$CuFeS_2$
	Chalcocite	Cu_2S
	Bornite	Cu_5FeS_4
Iron	Hematite	Fe_2O_3
	Magnetite	Fe3O4
Lead	Galena	PbS
	Cerusite	$PbCO_3$
Magnesium	Dolomite	(Ca,Mg)CO3
	Magnesite	$MgCO_3$
Manganese	Pyrolusite	MnO_2
Mercury	Cinnabar	HgS
Nickel	Pentlandite	$(Fe,Ni)_9S_8$
Tin	Cassiterite	SnO_2
Titanium	Ilmenite	$FeTiO_3$
	Rutile	TiO_2
Tungsten	Scheelite	$CaWO_4$
	Wolframite	$(Fe,Mn)WO_4$
Uranium	Uraninite	UO_2
Zinc	Sphalerite	ZnS

The general focus of this document will be on metaliferrous ores represented by run-of-mine material described in category 3 above. An exception to the above discussion of mineral processing arises when the valuable component of the ore is extracted directly by chemical methods. The most common and notable example of this are precious metal values (gold, silver etc.) where the beneficiation process is applied directly on run-of-mine ores followed by the extraction of gold and in some cases silver as a relatively pure metal within the mineral processing circuit.

Processing Approach and Method

In broader terms, mineral processing consists of two functions. Firstly, it involves the preparation and **liberation**, of the valuable minerals from waste minerals and secondly, the **separation** these values into two or more products, called concentrates. The term separation in this case is synonymous with **concentration**. These functions are carried out within the constraints of the following three rules.

1. The first rule deals with the conservation of mass. The total flow of the material into the process plant equals the total flow out.

2. The second rule relates to the quality or grade of the concentrate product. In practice, it is impossible to produce a concentrate consisting of only one mineral.

3. The third rule is a corollary of the second. It is impractical to recover all of the valuable minerals into the concentrate.

The flowsheet in Figure 1 shows diagrammatically the typical sequence of operations in the process plant. The various unit operations used for liberation and separation will be discussed in the following sections.

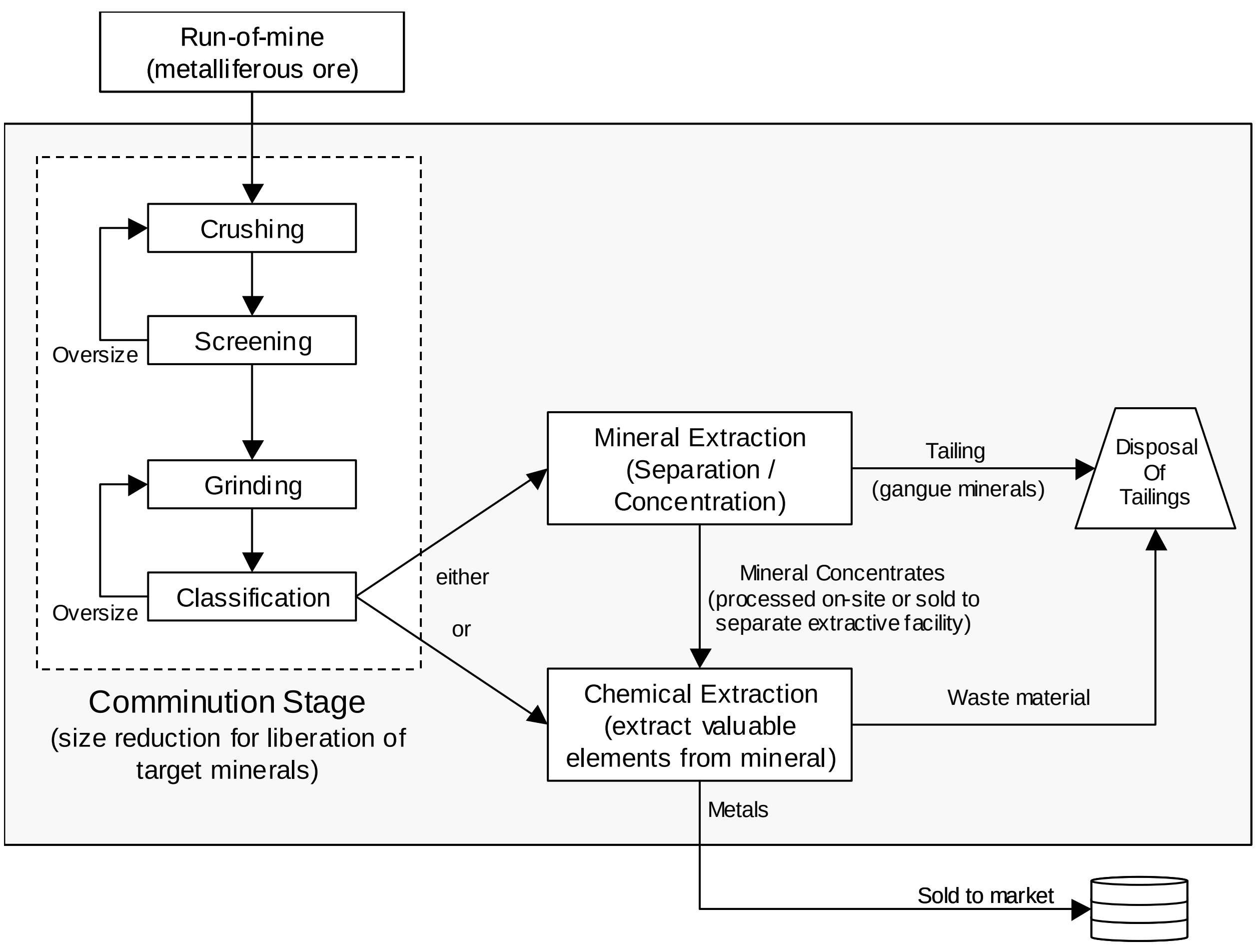


Figure 1. Typical processing flowsheet for metalliferous ores

3.0 Liberation and Comminution

3.1 Liberation

In order to separate the minerals from **gangue** (the waste minerals), it is necessary to crush and grind the rock to unlock, or liberate, valuable minerals so that they are partially or fully exposed. This process of size reduction is called **comminution**. The crushing and grinding process will produce a range of particles with varying degrees of **liberation** (Figure 2). Any particles that exceed a target size required for physical separation or chemical extraction are returned to the crushing or the grinding circuit.

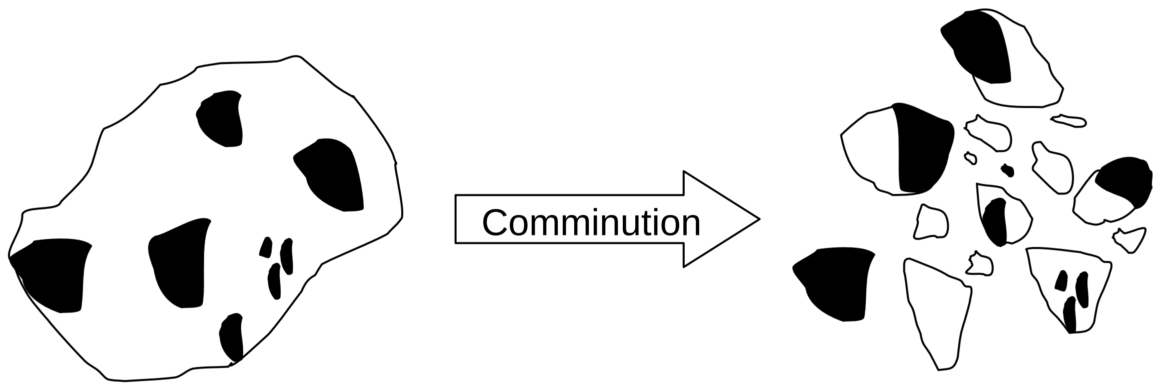


Figure 2. Breaking of larger material to smaller pieces result in particles with varying degrees of liberation. The darker regions represent the valuable mineral.

3.2 Comminution

The comminution process actually begins during the mining stage through the use explosives, excavators or scrapers for softer material. This is necessary in order to generate a material that is transportable by haul trucks or conveyors. Comminution in the mineral processing plant is carried out in a sequential manner using **crushers** and screens followed by **grinding mills** and **classifiers**. The various types of comminution equipment including their general application are described in detail below.

3.2.1 Crushing Equipment

Primary Crushers - Jaw and Gyratory

Within the crushing circuit, a primary crusher reduces material down to a size that can be conveyed and fed to the secondary crushing circuit. The two most common primary crushers used for coarse run-of-mine material are the jaw and gyratory crushers. These primary crushers break rock through compressive forces created by a hard moving surface forcing and squeezing the rocks towards a hard stationary surface.

A Jaw Crusher reduces large rocks by dropping them into a flat “V” shaped space created between a fixed surface and a movable surface. The compression is created by forcing the rock against the stationary plate as shown in figure 3.. The opening at the bottom of the jaw plates is the crusher product size gap. The rocks remain in the jaws until it is small enough to pass through this adjustabe gap at the bottom of the jaws.

In a gyratory crusher, a round moving crushing surface is located within a round hard shell which serves as the stationary surface (figure 3). The crushing action is created by the closing the gap between the hard crushing surface attached to the spindle and the concave liners (fixed) mounted on the main frame of the crusher. The gap is opened and closed by an eccentric drive on the bottom of the spindle that causes the central vertical spindle to gyrate.

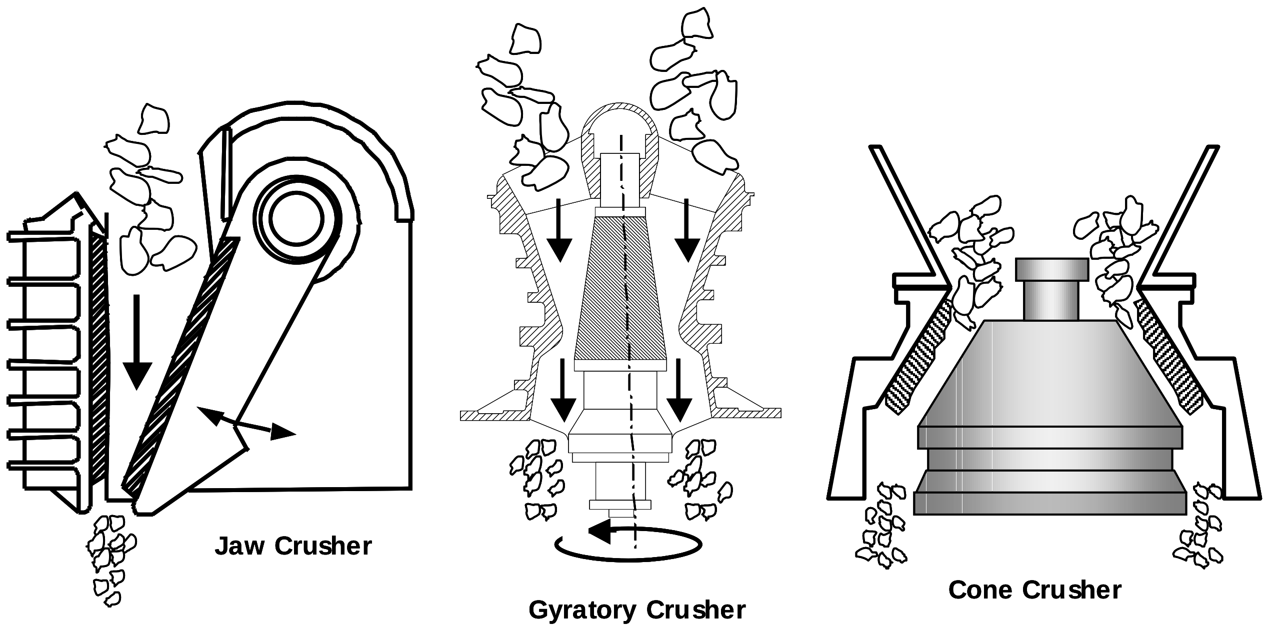


Figure 3 – Primary and secondary crushers

Seconday Crushers - Cone Crusher

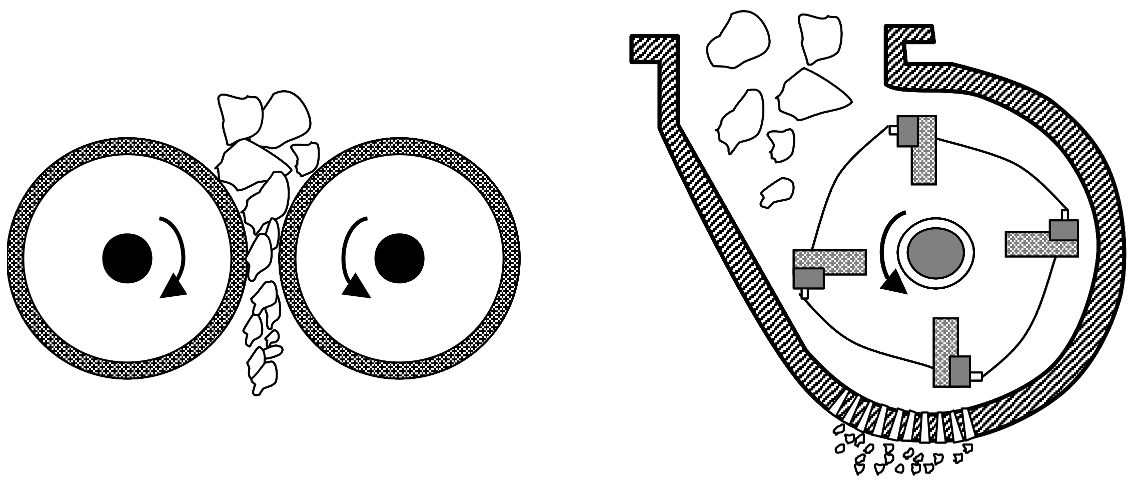
The most common type of seconday crusher is the cone crusher. A cone crusher is very similar to the gyratory but has a much shorter spindle with a larger diameter crushing surface relative to its the vertical dimension. The eccentric motion of the inner crushing cone is similar to that of the gyratory crusher.

Impact Crushers

Impact crushers involve the use of high speed impact rather than compresssion to crush material. They utilize hinged or fixed heavy metal hammers or bars attached to the edges of horizontal rotating disks. The bars repeatedly strike the material to be crushed. Then the material is thrown against a rugged solid surface which further degrades the particle size. Finally, the material is forced over a discharge grate or screen by the hammers through which the finer particles drop while larger particles are swept around for another crushing cycle until they are fine enough to fall through a discharge grid. This type of crusher is normally used on soft materials such as coal or limestone due to the high wear experienced by the impact hammers, bars and inner surfaces. These crushers are normally employed for secondary or tertiary crushing.

Roll Crushers

Rolls crushers consists of a pair of horizontal cylindrical rollers through which material is passed. The two rollers rotate in opposite directions nipping and crushing material between them. These types of crushers are used in secondary or tertiary crushing applications. They are seeing a significant increase in use due to advances in their design and the improved liberation of minerals in the crushed product.



Basic Elements of a Rolls Crusher

Basic Elements of an Impact Crusher

Figure 4 – Elements of a Rolls and an Impact Crusher

3.2.2 Grinding Mills

Grinding, the final stage used in the comminution process, is usually conducted in cylindrical tumbling mills where the particle size is reduced through a combination of impact and abrasion. The primary differences between these mills are in the ratio of diameter to the length of the cylinder and the type of grinding media employed. Grinding media can be steel rods, steel balls, hard pebbles or the ore itself.

Autogenous and Semi-Autogenous Mills

Autogenous (AG) and Semi-Autogenous (SAG) milling has seen increased use in recent years, especially in large mineral processing operations. These mills typically have a large diameter relative to their length, typically in the ratio or 2 or 2.5 to 1. AG mills employ ore as the grinding media. However, one the challenges with AG mills is that properties, such as hardness and abrasiveness, of the ore can vary, resulting in inconsistent grinding behaviour. The addition of steel grinding balls rectifies this situation. This approach is then termed semi-autogenous grinding and the total amount of balls in these mills ranges between 5 and 10 percent of the volume.

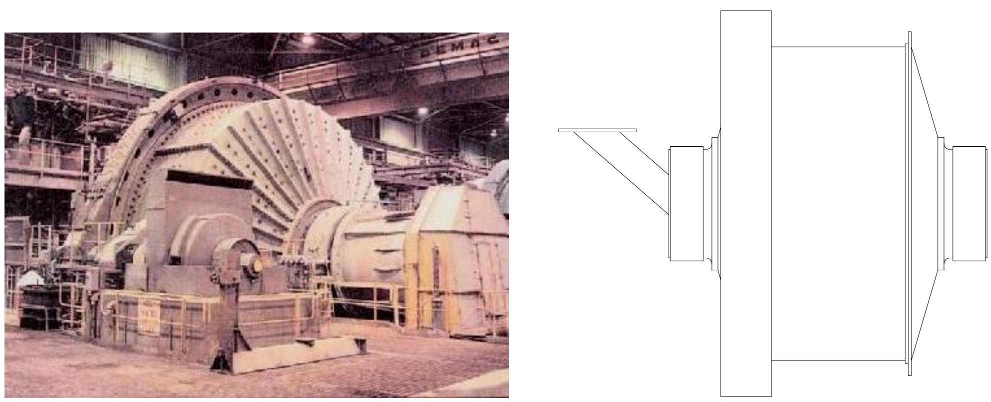


Figure 5 – SAG Mill picture and general shape

Rod, Ball and Pebble Mills

The products from AG or SAG mills typically feed secondary grinding mills with particles that range in size from 5 cm down to below 100 microns (0.1 mm). The final particle size is determined by downstream processing requirements. Grinding is carried out as a wet process with water content between 50 - 70% by weight.

Rod mills are long cylinders filled with steel rods that grind by compressive forces and abrasion. The length of the cylinder is typically 1.5 to 2.5 times longer than the diameter. As the mill turns, the rods cascade over each other in relatively parallel fashion. One of the primary advantages of a rod mill is that it prevents over-grinding of softer particles because coarser particles act as bridges and preferentially take the compressive forces. Rod mills can take particles as coarse as 5 cm. Many of the newer operations tend to install ball mills in combination with SAG mills and avoid rod mills due the cost of the media, the cost of replacing rods and general maintenance costs. Many older operations have rod mills in combination with ball mills.

Ball mills are a similar shape to that of the rod mills except that they are shorter with length to diameter ratios of 1 to 1.5. As the name implies, the grinding media in these mills are steel balls. The particles size of the feed usually does not exceed 2.5 cm. The grinding is carried out by balls being carried up the side of the mill such that they release and fall to the point where they impact the ore particles in trailing bottom region of the slurry. If the mill is rotated too fast, the balls can be thrown too far and just strike the far end of the mill and conversely, if the mill is rotated to slow, the efficiency of the grinding process significantly reduced.

Ball mills are suited for finer grinding as larger particles do not impede the impact on to smaller particle as in rod mills.

Pebble mills are similar to ball mills except that the grinding media is closely sized rocks or pebbles. Pebble milling is a form of autogenous milling as no steel media is used in the process however, the type of rocks used are selected more carefully than in convention AG milling.

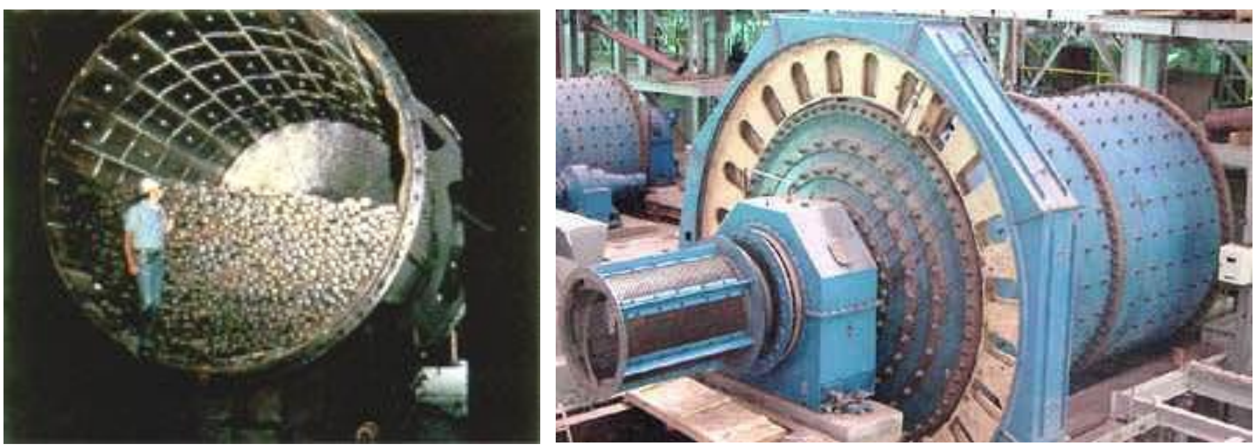


Figure 6 – i) Rod mill (left) opened for maintenance and ii) ball mill (right

4. 0 Size-Separation: Screening and Classification

The size distribution of the particles must be controlled for a number of reasons at various stages of a mineral processing plant:

- To enable undersized material to bypass the crushing or grinding circuit and to retain oversized particles for further size reduction,
- To provide an optimum particle size material for efficient processing in the downstream separation and concentration systems, and
- To prepare product that meets particle size specifications required for the market place.

There are two distinct methods for separation of particles based on size: screening and classification.

Screening: In its simplest configuration, a screen is a hard perforated surface with a matrix of fixed dimension apertures. The material is presented to the screen surface so that material finer than the apertures falls through the screen and the oversize is conveyed to the discharge end of the screen. Screening is generally difficult below 0.5 mm.

Classification: Classification techniques takes advantage of the principle that particles of the same density but of different sizes settle in a fluid at different rates. Exploiting the difference in the settling rates allows for separation based on size. Classification is usually carried out at particle sizes that are considered to be too fine for sorting efficiently by screening methods.

4.1 Screening Equipment

Grizzly

Grizzlies are used for rough screening of coarse materials and are most often found in crushing circuits. A grizzly is basically an inclined set of heavy bars set in a parallel manner. Coarse material slides on the inclined surface of the bars and material finer than the spacing between the bars falls through (figure 7). The grizzlies can be vibrated to improve performance.

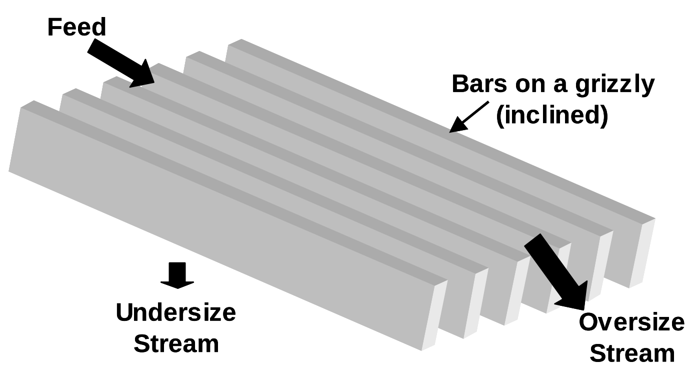
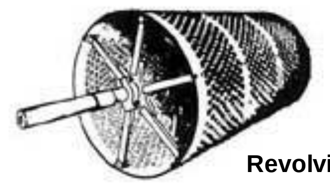


Figure 7 – A grizzly

Revolving Screen (Trommel)

A trommel is a slightly inclined rotating cylindrical screen. The material is fed at one end of the cylinder and the undersize material falls through the screening surface while the oversize is conveyed by the rotating motion down the incline to the discharge end. Although trommels are relatively cheap, they have lower capacities and are susceptible to rapid wear; hence they have been largely replaced by vibrating or shaking screens. A trommel can handle both dry and wet feed material.



Revolving Screen

Figure 8 – Revolving screen used in trommels

Moving Screens (reciprocating, oscillating, vibratory and gyratory screens)

There are various types of horizontally inclined screens such as the reciprocating, oscillating, vibratory or shaking screening. The basic difference in these screens is based upon the motion of the surface and the resulting action imparted on the material being screened. The vibratory screen is probably the most common screening device found in mineral processing applications. Different manufacturers have developed unique vibration and motion systems for the various types of material and particle sizes encountered within mineral processing plants. Many of these types of screens have multiple decks so different particle size products can be obtained from a single feed.

The gyratory screen is supported in a manner that it allows for both a gyratory and slight vertical motion to the screen deck. These types of screens can have multiple removable and replaceable decks. Gyratory screens can be used in wet or dry applications and are usually used for separation of finer particles.

Vibratory Screen **Gyratory Screen**

Figure 9 – Examples of moving screens

4.2 Classification

Sedimentation and Hydraulic Classifiers

Free settling classifiers are essentially large pools, ponds or conical bottomed tanks with a free settling zone. The coarser particles sink and are removed from the bottom of the settling zone. These units are simple in design but often inefficient in sorting and sizing. A hydraulic, hindered bed settler exploits differences in the settling rates of particles. The particles settle against a rising current of water in a series of sorting chambers or conical pockets. The relative rate of settling against the varying up-flow currents in each of the conical pockets provides recovery of the different sized particles in each of the chambers.

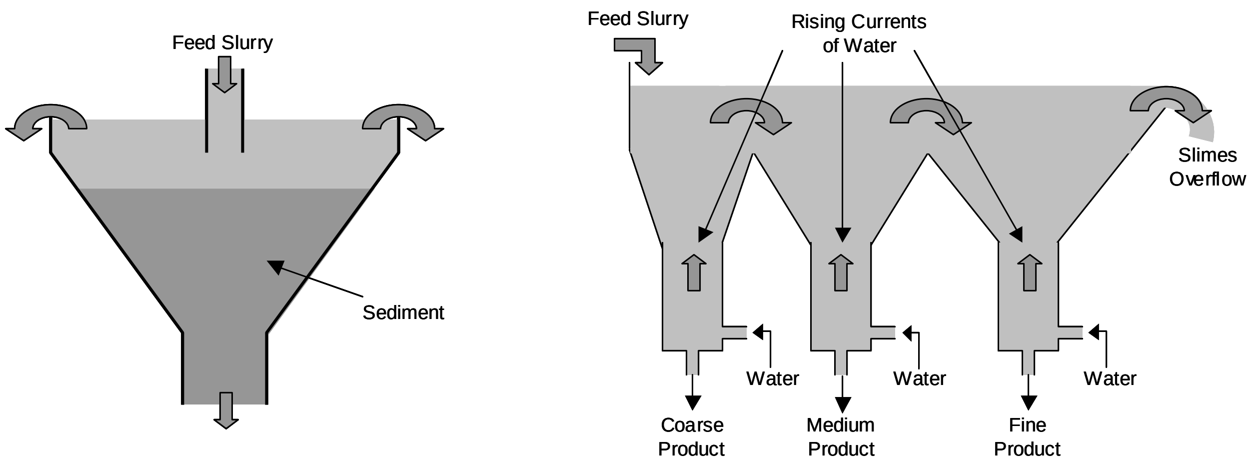


Figure 10 – Elements of a sedimentation (left) and hydraulic classifier (right)

Spiral and Rake Classifiers

Mechanical classifiers such as the spiral and rake classifiers work in a similar fashion in that both drag sediment and sand along the bottom of an inclined surface to a higher discharge point on one end of the settling chamber. The primary difference in the two systems is the mechanism by which the settled material is moved up the inclined surface (see figure 11). Spiral classifiers are generally preferred as material does not slide backwards which occurs in rake classifiers when the rakes are lifted between strokes. This also allows spiral classifiers to operate at steeper inclines producing a drier product. The spiral classifier also produces less turbulence in the settling pool allowing for separation of finer material.

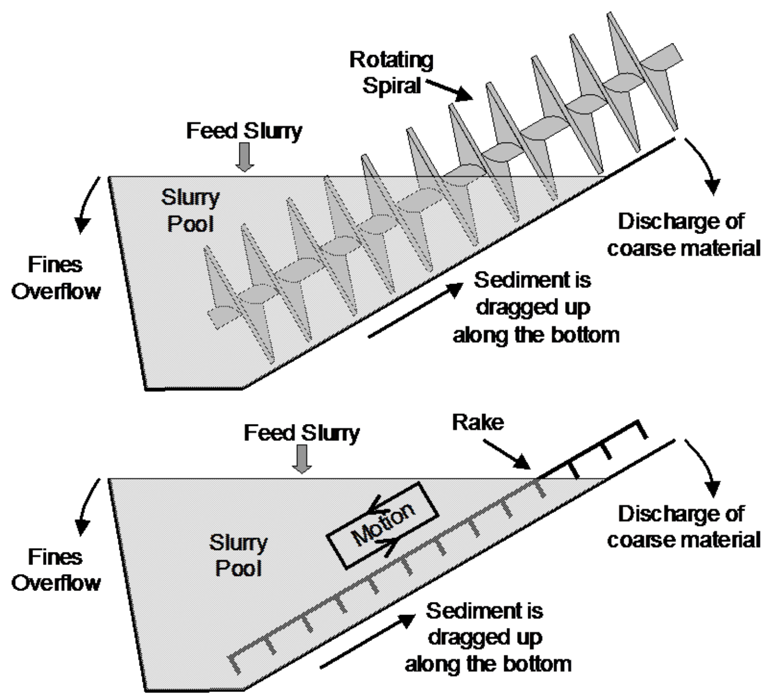


Figure 11 – Elements of spiral and rake classifiers

Hydrocyclones (Cyclones)

Hydrocyclones have become one of the most important and widely used classifiers in the mineral processing industry. They are also used for de-sliming, de-watering, de-gritting and thickening processes. They are most commonly employed in closed circuit within grinding circuits and are used to return coarse material back to the ball or rod mill for further grinding. The main advantages of cyclones is that they have large capacities relative to their size and can separate at finer sizes than most other screening and classification equipment.

The separation mechanism in hydrocyclones relies on centrifugal force to accelerate the settling of particles. The slurry enters the cylindrical section tangentially above a conical section. The velocity of the slurry increases as it follows a downward helical path from the inlet area to the smaller diameter underflow end. As the slurry flows along this path, centrifugal forces cause the larger and denser particles to migrate to the fluid layer nearest the wall of the cone. Meanwhile, the finer or lower specific gravity particles remain in, migrate to, or are displaced toward the center axis of the cone. As the swirling slurry approaches the underflow tip, smaller and lighter material closer to the center reverses its axial direction and follows a smaller diameter rotating path back toward the top overflow discharge pipe.

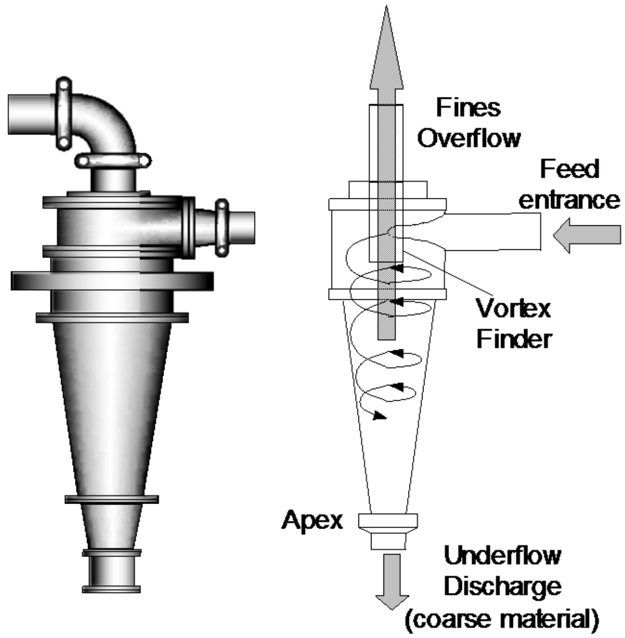


Figure 12 – Hydrocylone picture and elements of operation

5.0 Separation and Concentration Techniques

The separation and concentration of the valuable mineral can take place after the ore is crushed, ground, and classified into the required particle size distribution. There a number of different techniques are employed in concentrating the valuable minerals. These techniques exploit differences in physical or chemical properties of the valuable and gangue minerals.

Separation Methods

i. **Sorting –** based on appearance, colour, texture, optical properties and radioactivity

ii. **Gravity and Dense-Medium Separation** - Separation based on **specific gravity** of the valuable mineral relative to the gangue and the carrying medium such as water. In dense-medium separation, the a carrying medium is a mixture of water, magnetite, or ferrosilicon. The paramagnetic properties of the medium allow it to either remain in suspension at a predetermined slurry density or to be separated from water for cleaning and reuse.

iii. **Magnetic Separation –** separation based upon natural or induced differences in magnetic susceptibility of the minerals within the ore.

iv. **Froth Flotation** - separations based on the surface chemistry properties of a mineral. The natural or modified surface property of the mineral determines its ability to attach to an air bubble and float to the surface.

5.1 Sorting

Sorting by hand has the longest history of all the mineral beneficiation methods and is rarely used today. The method is carried out by visual differentiation of lumps of rocks where valuable lumps are picked out and retained for processing. The cost of labour and being able to economically recover significant quantities of minerals has made this practice obsolete except in the areas of highly valuable minerals such as gems.

Advances in electronics and optical technology have made the automation of sorting techniques an important process in some ore systems. For example, recent advances using optical sorting methods is being employed in the diamond industry using an x-ray beam. Diamonds emit light when hit by an x-ray and the resulting light is picked up by a detector. As a mono-layer stream of rocks and diamonds fall through this beam, the detector activates jets of air which knock the diamond into a separate bin (see figure 13).

Variations of this principle are used on other mineral systems using lasers. The laser light is reflected from a rotating mirror drum which allows the scanning of falling stream of rocks to be scanned at thousands of times a second. A photomultiplier detects the reflected light and activates an air jet at the right instant and intensity to eject the particle from the stream. These systems have been employed in the recovery of barite, talc, wolframite and scheelite to name a few.

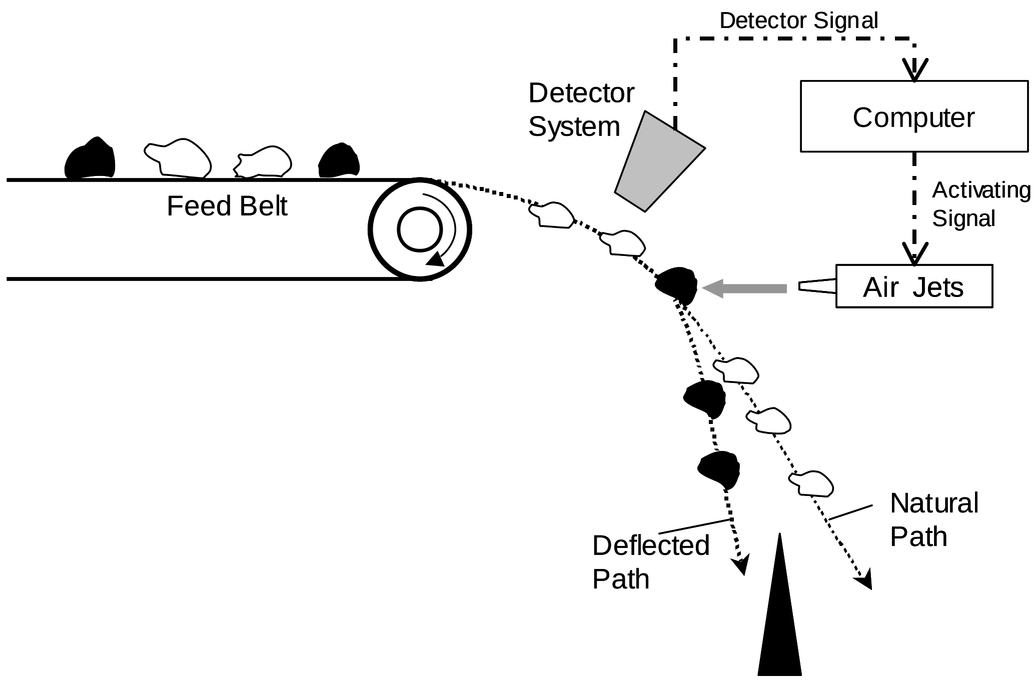


Figure 13. Elements of optical sorting systems

5.2 Gravity and Dense Medium Separation

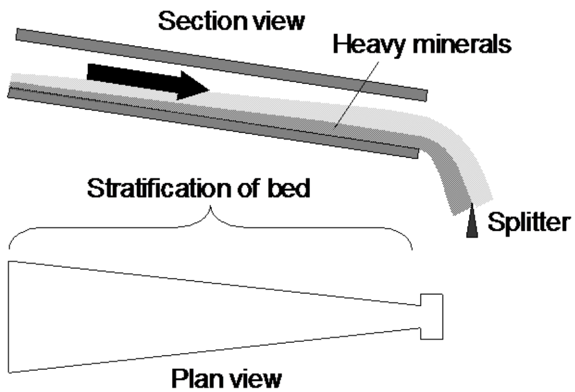
Gravity concentration methods separate particles based on the differences in their specific gravity (SG) values and their relative movement within a natural or applied gravitation force. The relative rate of settling based on the gravitational forces and the counter viscous forces are exploited for effective separation.

Dense medium separation relies not only the difference between the specific gravity of the particles but also exploits the variation in the effective SG of a fluid medium. Particles denser than the specific gravity of the medium sink and are collected as a separate product from the ones that float. For example, a dense medium can be a chemical such as tetrabromoethane which has a specific gravity of 2.96 or a dense medium can be made using very fine particles of magnetite or ferrosilicon suspended in water as a slurry. The SG values of the slurries made from magnetite and ferrosilicon can be as high as 2.5 and 3.2 respectively. Chemicals are often used for lab scale separations while dense medium slurries are used more on an industrial scale. Dense medium separators will not be discussed herein.

Sluices, Reichert Cones and Spirals

Sluices or sluice boxes are commonly found at alluvial operations for the recovery of liberated placer gold. Sluice boxes with riffles are one of the oldest forms of gravity separation devices used today. The size of sluices range from small, portable aluminum models used for prospecting to large units hundreds of feet long. Sluice boxes can be made out of wood, aluminum, plastic or steel. The riffles in a sluice slow and retard heavy material flowing in the slurry, which forms a material bed that traps heavy particles and creates turbulence. This turbulence causes heavy particles to tumble, and repeatedly exposes them to the trapping medium. An overhanging lip, known as a Hungarian riffle, increases the turbulence behind the riffle, is commonly used in these units. Other configurations of sluices may use astro-turf, screens or rubber material with ridges.

Pinched sluices have also been used for heavy-mineral separations for centuries. In its most basic form, the pinched sluice is an inclined trough 60 to 90 cm long, narrowing from about 24 cm in width at the feed end to 3 cm at the discharge end. Feed consisting of 50-65% solids enters the sluice and stratifies as the particles flow through the sluice and crowds into the narrow discharge area. The crowding causes the bed to dilate allowing heavy minerals to migrate and move along the bottom, while lighter particles are forced to the top. The resulting mineral bands are separated by a splitter at the discharge end. Pinched sluices are simple devices and are inexpensive to build and run. Pinched sluices are mainly used for separation of heavy mineral sands. A large number of pinched sluices are required for a high capacity operation, and a large amount of recirculation pumping is required for proper feed delivery. These drawbacks led to the development and adoption of the Reichert cone in many plants.



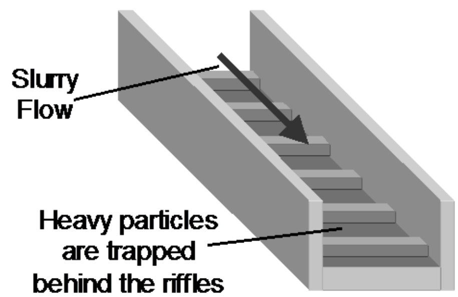


Figure 14. a) Left - Pinched sluice cross section and plan view
b) Right – Sluice box

The ***Reichert Cone*** concentrator is based on the pinched sluice concept but employs an inverted cone instead of a rectangular channel (figure 15). The crowding and dilating effect of the bed is produced by a reduction in perimeter as the material approaches the center discharge point. Reicherts are more efficient than pinched sluices because there are no sidewalls to interfere in the separation process. Reicherts cones are usually stacked to achieve high throughput for a given footprint.

Spiral concentrators are modern, high capacity, low cost units developed for the concentration of low grade ores and industrial minerals. Spirals consist of a single or double helical conduit or sluice wrapped around a central collection column with a wash water channel and a series of concentrate removal ports placed at regular intervals along the spiral. Separation is achieved by stratification of material caused by a complex combined effect of centrifugal force, differential settling and heavy particle migration through the bed to the inner part of the conduit (see figure 16). To increase the amount of material that can be processed by a unit, two or more spirals are constructed around one central column. A variety of designs and modifications have been developed by various manufacturers to improve the general operation of these units.

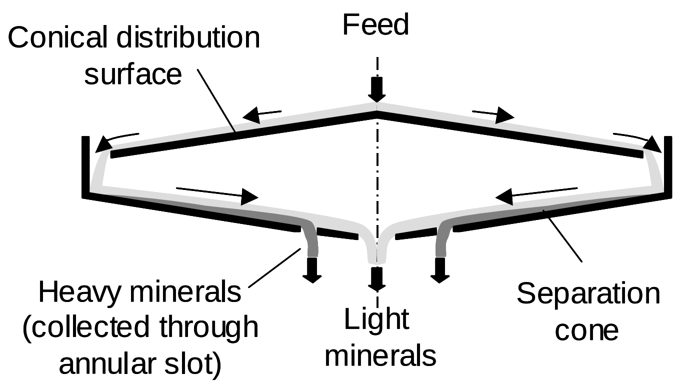


Figure 15. Elements and operation of a Reichert Cone

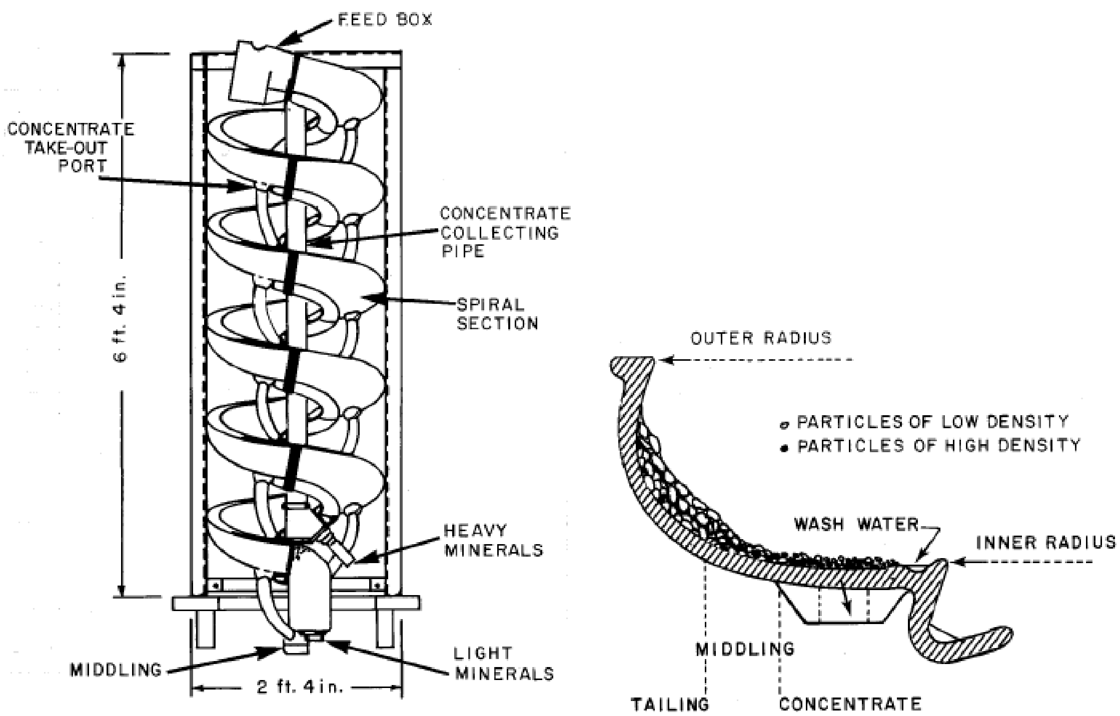


Figure 16. Spiral Concentrator – a cross section of the helical conduit and flow pattern is shown on the right.

Shaking Tables

Shaking tables, also known as wet tables, consist of a sloping deck with a riffled surface. A motor drives a small arm that shakes the table along its length, parallel to the riffle and rifle pattern. This longitudinal shaking motion consists of a slow forward stroke followed by rapid return strike. The riffles are arranged in such a manner that heavy material is trapped and conveyed parallel to the direction of the oscillation (see figure 17). Water is added to the top of the table perpendicular to the table motion. The heaviest and coarsest particles move to one end of the table while the lightest and finest particles tend to wash over the riffles and to the bottom edge. Intermediate points between these extremes provides recovery of the middling (intermediate size and density) particles.

Shaking tables find extensive use in concentrating gold but are also used in the recovery of tin and tungsten minerals. These devices are often used downstream of other gravity concentration equipment such as spirals, reicherts, jigs and centrifugal gravity concentrators for final cleaning prior to refining or sale of product.

Jigs

Jigging, like most gravity concentration techniques, is one of the oldest methods for concentrating minerals based on differences in the density of the particles. The elementary jig is an open tank filled with water with a thick bed of particles, called ragging, supported on a horizontal perforated surface (figure 18). The water is pulsated up and down (i.e. the jigging action) pneumatically or with the use of a mechanical plunger . The jigging action causes denser particles to preferentially trickle down faster and are removed from the bottom of the unit. Numerous types and configurations of jigs have been developed over many years with each type providing some improvement over the other units. But they all rely upon the same principle for separation of the minerals.

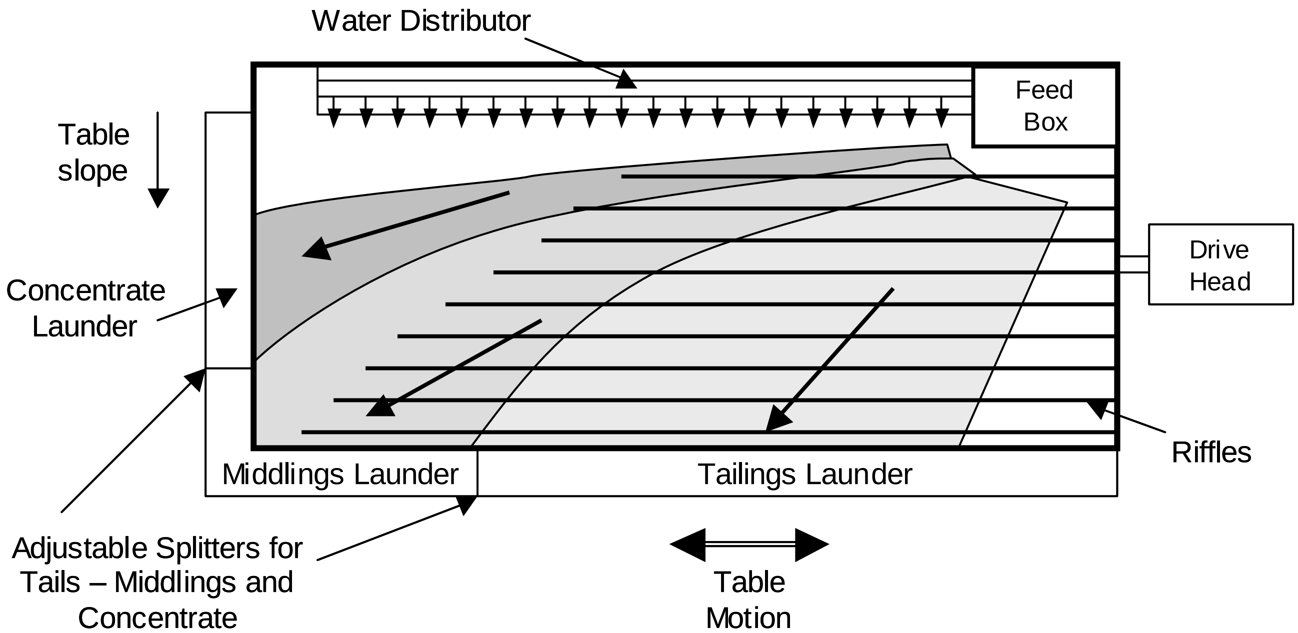


Figure 17. Elements and operation of a shaking table.

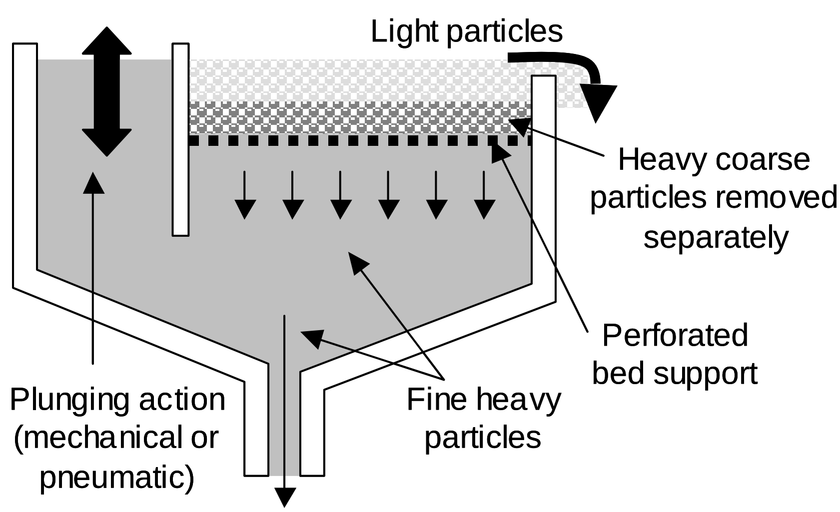


Figure 18. Elements and operation of a jig.

Centrifugal Gravity Concentrators

In the last 20 years, advancements in the design and operation of centrifugal gravity concentrators have made them the predominant method for gravity concentration of gold. Further advances in recent years has expanded the use of this technology for the recovery other heavy minerals. The Knelson and Falcon concentrator companies manufacture the two most common units being used in the industry today.

These units consist of a riffled cone or bowl that spins at high speed to create forces in excess of 60 times that of gravity. Slurry is introduced into the cone; the centrifugal force produced by rotation drives the solids toward the walls of the cone. The slurry migrates up along the wall where heavier particles are captured within the riffles. Injecting water through the holes located in the back of the riffles fluidizes the riffled area. The fluidization process prevents compaction of the concentrated bed and allows for efficient separation of heavy minerals.

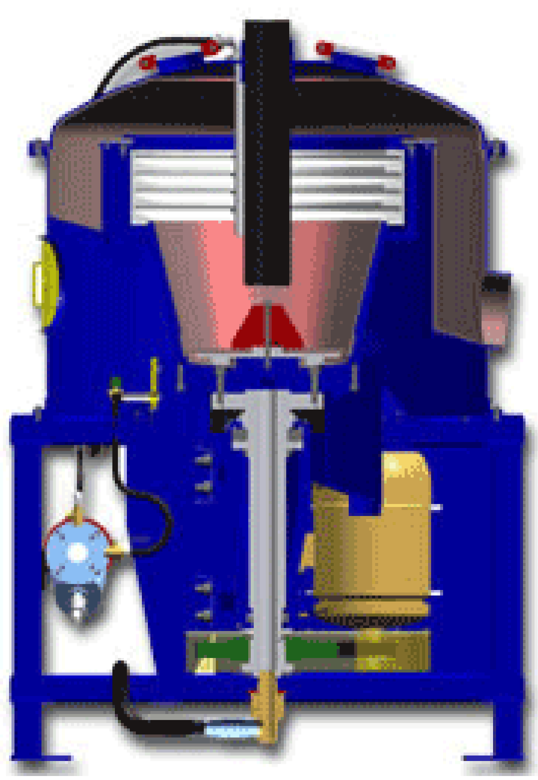


Figure 19. Falcon Concentrator

5.3 Magnetic Separation

Magnetic separations take advantage of the magnetic properties of minerals. All minerals will have one of three magnetic properties: ferromagnetic, paramagnetic, and diamagnetic. Ferromagnetic minerals (i.e., magnetite and pyrrhotite) are magnetic and are easily separated from other minerals, since they will be attracted to the poles of a magnet. Paramagnetic and diamagnetic minerals are not magnetic, but differ in how they interact with magnetic fields. Paramagnetic minerals are weakly attracted whereas diamagnetic minerals are weakly repelled along lines of magnetic forces. Thus, if a mixture of paramagnetic and diamagnetic minerals is passed through a magnetic field; the paramagnetic minerals will be pulled into the field and the diamagnetic minerals will be repelled or separated from the field. Furthermore, paramagnetic minerals have different degrees of paramagnetism that can also be used to effect separations.

Magnetic fields of various intensities can be provided by permanent or electromagnets. Generally, magnetic separators are classified as low or high intensity and whether they work in wet or dry applications.

An example of a concurrent low-intensity wet magnetic separator is shown in figure 20. In concurrent separators, slurry flows in the same direction as the rotation of the drum surrounding the magnets.

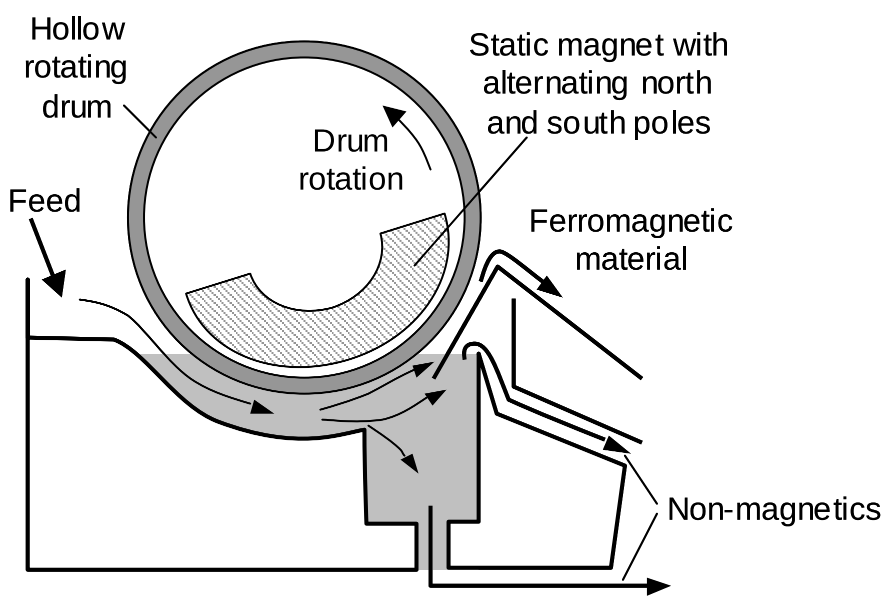


Figure 20. Elements of a wet low-intensity magnetic separator

5.4 Froth Flotation

In terms of daily tonnages of ore that are treated globally, froth flotation is the single most important mineral recovery process. This is driven by its ability to selectively separate minerals. Flotation is considered to be a physico-chemical process. Equipment in the form of mechanically or pneumatically agitated tanks or cells generate air bubbles, which provides the physical aspect. The chemical aspect is provided by reagents, which vary the surface properties of minerals and of the slurry medium for separation of valuable minerals, especially those of copper, lead and zinc sulfides from gangue materials. Advancements in technology have expanded the use of flotation for recovery of oxide minerals such as hematite, cassiterite, malachite, fluorite, and phosphates. The use of flotation for recovery of fine coal is also widely practiced.

The flotation process begins with a modification of the surface properties of the desired mineral. The addition of surfactants renders the mineral surface hydrophobic (water-hating), so that the mineral may preferentially adhere to air bubbles and float to the surface. The unwanted minerals remain hydrophilic (water-loving) and do not attach to air bubbles. The surface of the slurry is modified by other reagents that lower surface tension forces. This allows the air bubbles to form a semi-stable froth. The hydrophobic minerals are recovered by skimming the froth off of the surface, while the hydrophilic minerals remain in the slurry.

Flotation Reagents

The establishment of a hydrophobic surface on a mineral is similar in principle to waxing an automobile or shining shoes to prevent wetting. A hydrocarbon layer is established on the surface because the hydrocarbon surface is not water-wetted. In flotation systems, chemical, rather than mechanical, means are used to establish the hydrocarbon layer selectively on one or more of minerals, and the layer is not complete. There are three main types of surfactants used in flotation: collectors, frothers, and modifiers.

- Collectors are also known as promoters. They are polar reagents with a metal ion on one end joined by an organic ion at the other end. The metal ion adsorbs onto a metal ion in the mineral surface. The organic ion at the other end forms a new surface that is hydrophobic. A common example, potassium amyl xanthate, $C_5H_{11}OCS_2K$ that dissolves or ionizes in water.

- Frothers are surface-active chemicals that concentrate at the air-water interface. They prevent air bubbles from coalescing or bursting by lowering the surface tension of the slurry. Frothing properties can be persistent or non-persistent depending on the desired stability of the froth. Examples of frothers are pine oil and high molecular weight alcohols such as MIBC. There are other proprietary frothers developed by various chemical companies

- Modifiers are sometimes known as regulators, and are used to vary slurry and mineral conditions to assist in the selective flotation of minerals. Modifiers may activate poorly floating minerals such as sphalerite, or may depress certain minerals, so that a differential flotation can be performed on a complex ore. Chemicals that change the pH of the slurry are also used as modifiers. pH modifiers include lime, soda ash, sulfuric acid; can act as activators and/or depressants by controlling the alkalinity and acidity of the slurry. Modifiers can also counteract interfering effects from the detrimental slimes, colloids, and soluble salts that can absorb and thereby reduce the effectiveness of flotation reagents.

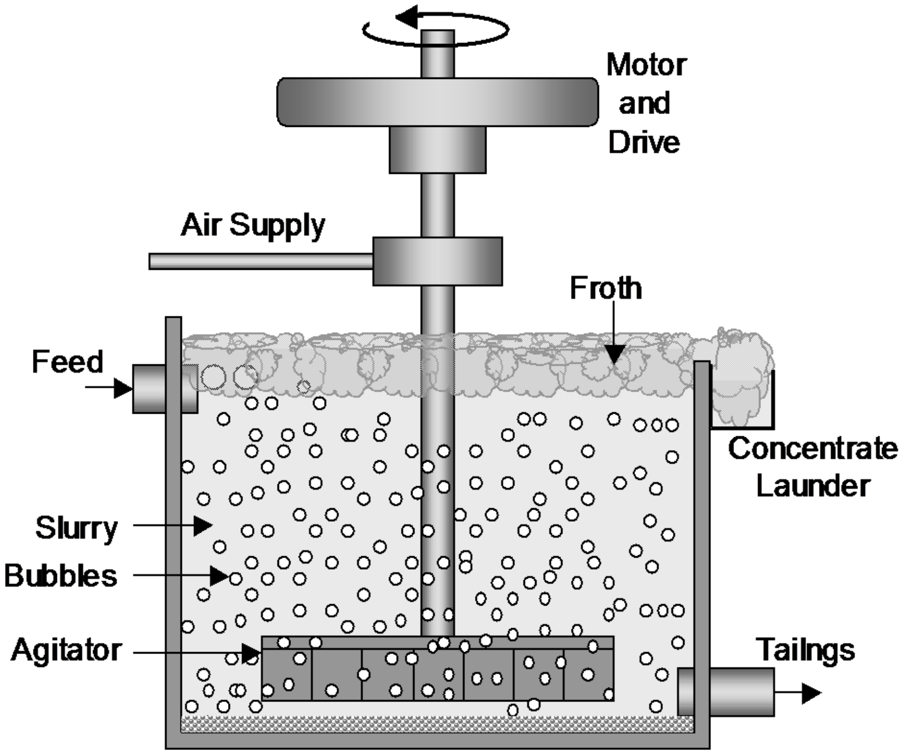


Figure 19. Elements of a conventional flotation cell.