MINE2201

Physical and Chemical Processing of Minerals

Exam Notes

"To transform raw minerals of low value into useful and saleable commodities."

Mineral: A mineral is a naturally occurring inorganic substance (i.e. compound or element) that has a definite or restricted range of chemical composition and a regular arrangement of atoms.

Ore body: An ore body is a mineral deposit that can be economically exploited to become a source of supply of a particular material.

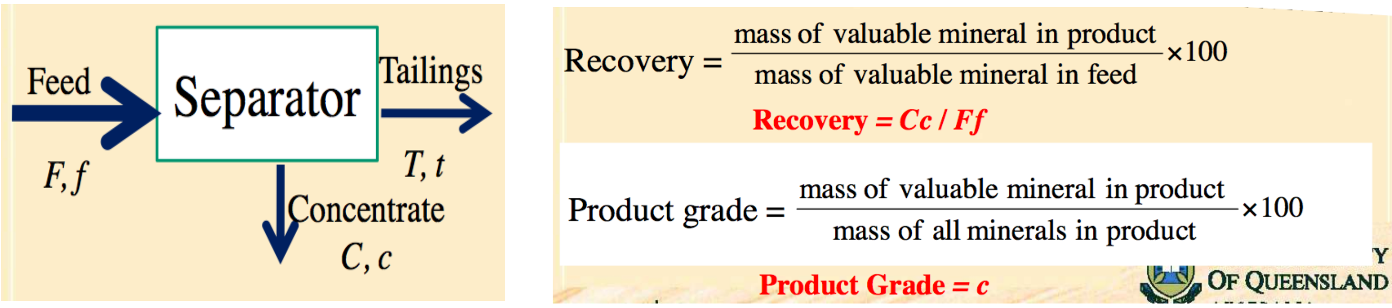


Figure 1: Recovery and Grade

Grade: Weight percentage of a valuable mineral in an ore.

Recovery: Is the percentage of valuable mineral in the feed that is recovered or obtained in the product or concentrate stream.

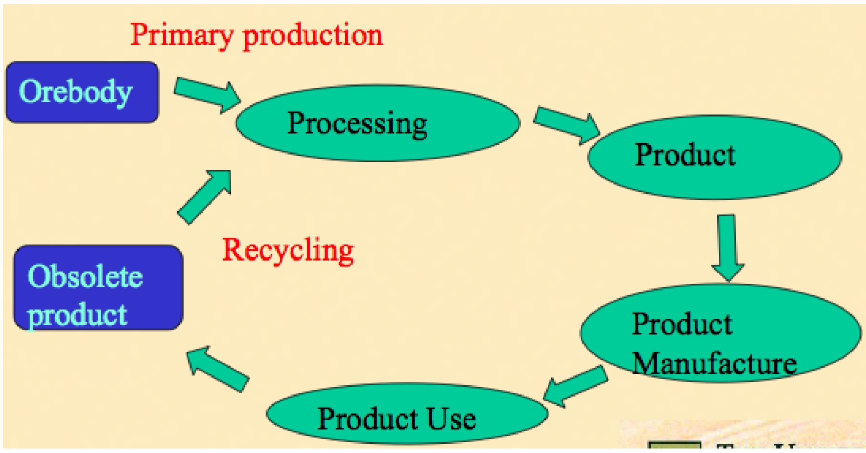


Figure 2: Emerging Paradigm for Sustainability

Sustainability is a key factor in today's society. To design for sustainability we must understand and effectively manage:

- Technology Options
- Economic Factors
- Environmental Impacts
- Social Impacts

Additionally, we must be able to effectively integrate and optimize upstream and downstream processes.

New Technologies:

- Improvements to current processes
- Step-Change (sudden discontinuous change) processes
- Automation

Environment:

- Climate change
- Energy consumption
- Cleaner production

Social:

- Safety
- Impact on communities

Economical:

- Sustainable
- Profitability

The essential starting point in all metallurgical processes is to understand the key physical and chemical characteristics of the raw materials, that is, the ore or obsolete body.

Macro-characteristics:

- Size and depth of the ore body below the surface,
- Orientation relative to the surface
- Integrity/presence of geological faults, and

Largely influences the methods that are required to remove the valuable minerals from the ground, so that they may be further processed.

- Hydrology (i.e. water location and flow)
- Geographical location (i.e. proximity of the source material to existing services such as power, transport and population centers and to markets for the end products)

Meso-Characteristics:

- Variability of ore composition or physical properties with position in the ore body as this can lead to changes in the mine output and in process feeds.

Micro-Characteristics:

"A priori that only one particular mineral or metal is to be produced from the deposit, or that the product will be the most abundant of the minerals present should not be assumed."

- Phases present and their chemical compositions
- The volume or mass fractions of each mineral (e.g. scare phases will liberate at a smaller size than the abundant phase as it needs to be ground finer).
- The grain sizes and size distributions as the grain size can have significant bearing on the choice of processes, which may be used. The grain sizes typically encountered ranges from 1 μm to 1mm; however, smaller grain sizes can be seen and are difficult to recover.
- The shape of the grains as this may make it easier or pose difficulties in trying to separate different phases (e.g. irregular grain shape reduces the particle size required for liberation and separation).
- Microstructure of the grains
- The distribution of grains within the ore

These properties help distinguish the physical and chemical properties of the ore and help to determine what techniques are suitable to recover the valuable minerals.

Liberation: Preparation of particles of a single phase or compound from composite minerals.

"Without liberation we cannot collect the wanted components only."

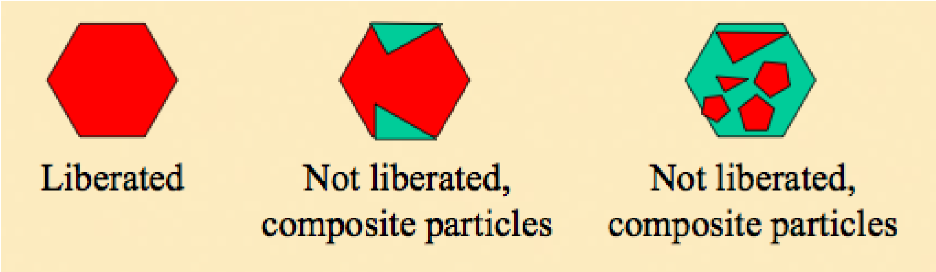


Figure 3: Liberation

Composite Minerals: Particles with two or more phases

Separation: Separation of particles into different phases. Separation is broken into two categories: physical and chemical separation.

Physical Separation: Separation based on the physical properties of the phases. This requires a high degree of liberation.

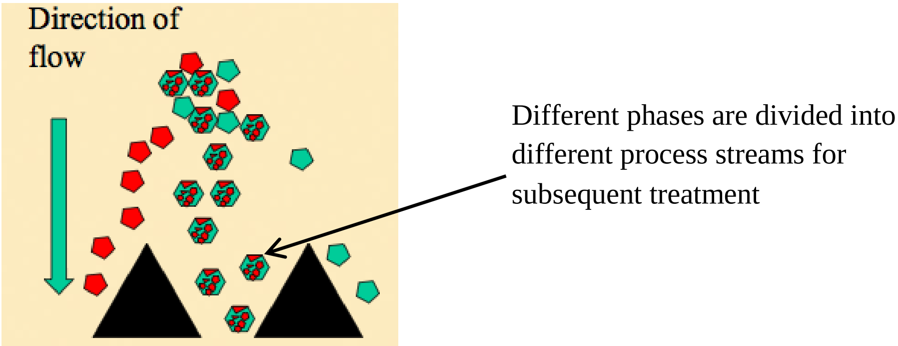


Figure 4: Physical Separation

Chemical Separation: Separation based on the chemical properties of the phases. Certain chemical processes may only require the grains to be exposed.

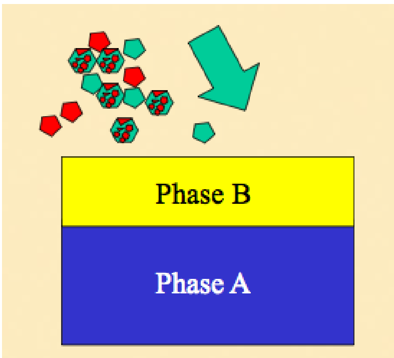


Figure 5: Chemical Separation

"The particle size for efficient liberation and separation of a mineral is principally determined by the minimum grain size at which the mineral is present"

A typical process flow sheet for a metallurgical process is shown below:

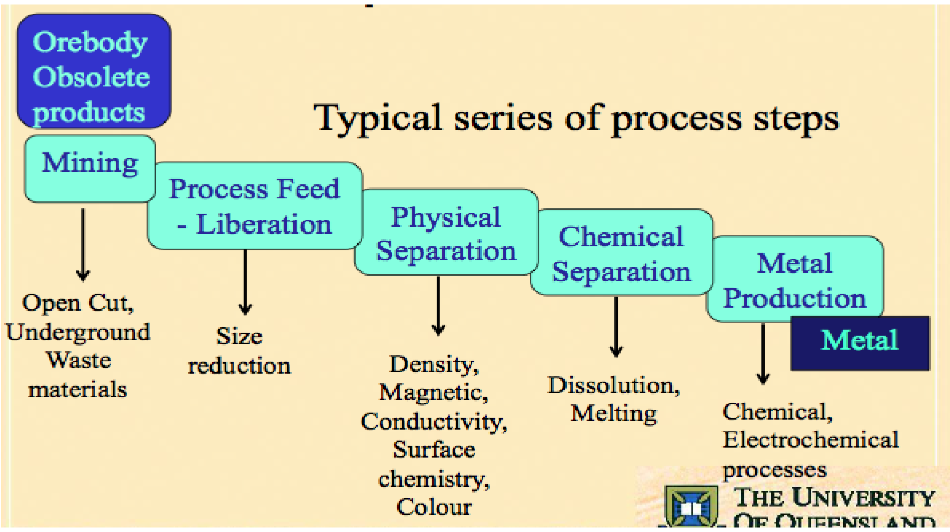


Figure 6: Metallurgical Processes

Run of Mine (ROM): The raw material that is mined and delivered by mine cars or skips prior to any subsequent treatment

Physical Processing: The physical processing of minerals, or mineral processing as it is commonly called, does not result in any change in the physical or chemical properties of the individual phases present in the process streams. The processes are aimed solely at achieving separation of the phases and **to increase the concentration of valuable minerals.**

There are three main techniques used to reduce particle size. These include: slow compression, fast compression or impact and abrasion. These are briefly described below:

Slow Compression: In slow compression, stresses are created throughout the solid material. The stress level is gradually increased until the resolved tensile and shear stresses are just sufficient to propagate through the existing cracks. Fracture only occurs at a few places in the material as larger cracks propagate first. For this reason the particle sizes obtained from this process are relatively large compared to the initial size.

Fast Compression: In fast compression, compressive stress waves are propagated throughout the material. In severe impact the stress level induced are high; however, as they are compressive fracture does not occur immediately. When the stress waves meet the free surfaces of the particle and are internally reflected they form a tensile wave. As this tensile wave moves throughout the material, existing cracks in the structure are extended, new cracks are formed and the fracture of the sample occurs. The new particles are much smaller than the original particles.

Abrasion: In abrasion, particles are abraded with hard neighbouring particles or objects in order to generate shear stresses. As a result fracture is localized at the surface and a bimodal distribution of particles is obtained with one node close to the original size and the other at very small sizes.

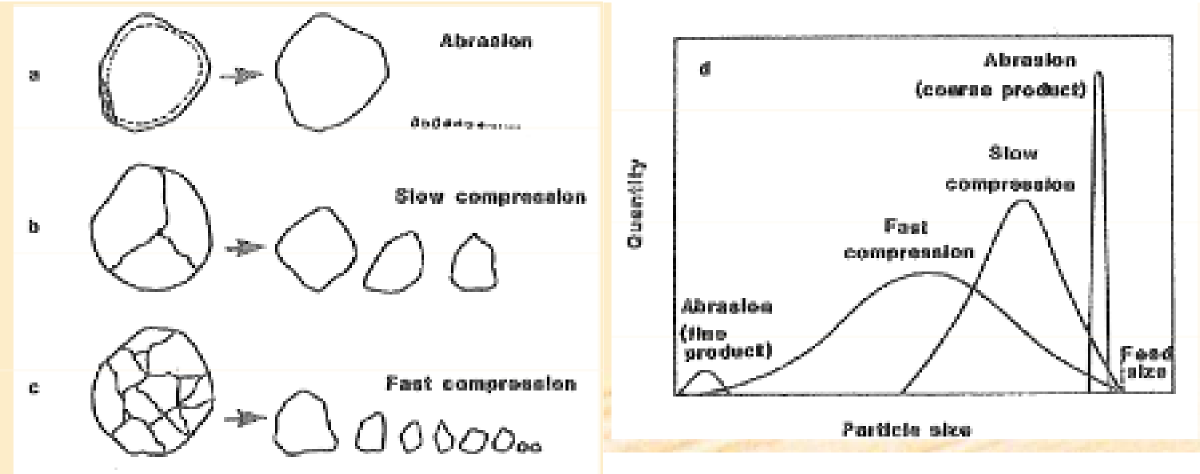


Figure 7: Size Reduction Techniques

"In rocks the tensile strength is only 10% of the compressive strength."

Non-Uniform Compressive loading leads to localised tensile stresses

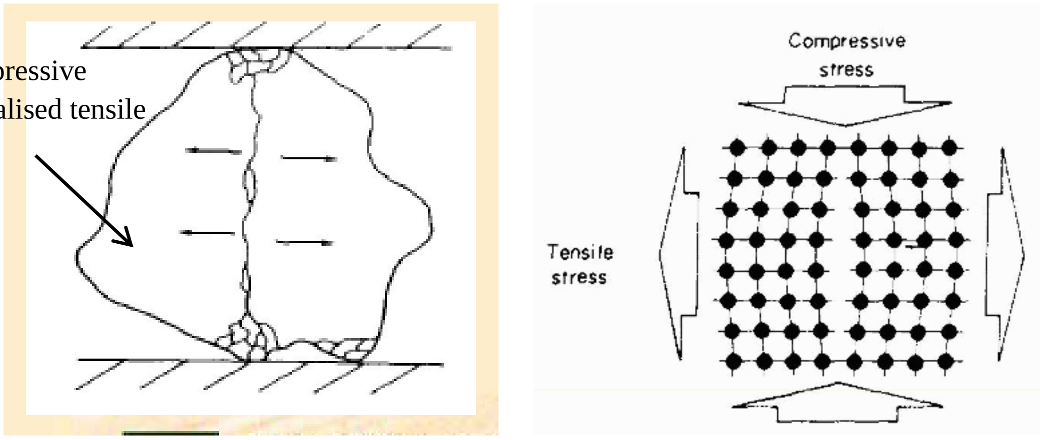


Figure 8: Compressive stresses

Compressive Stress: Is the stress leading to shortening in one dimension of the elastic body due to opposite directed collinear forces tending to crush it.

Tensile Stress: Is the stress leading to expansion

As particle size decreases, the energy required to further reduce size increases sharply.

$$dE = K\frac{dX}{X^n}$$

K is not a constant it is a function of particle size; it is a non-linear relationship.

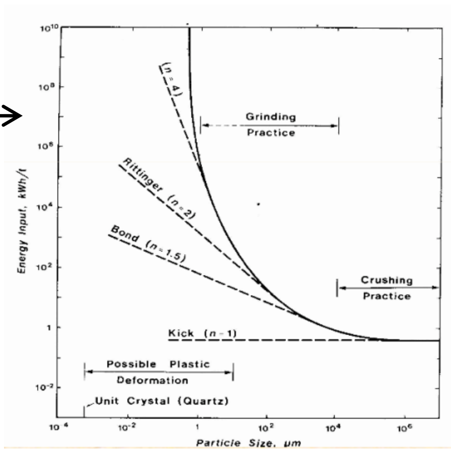


Figure 9: Energy input vs. particle size

There are three accepted laws of multiple particle breaking. These include: Rittinger, Bond and Kick.

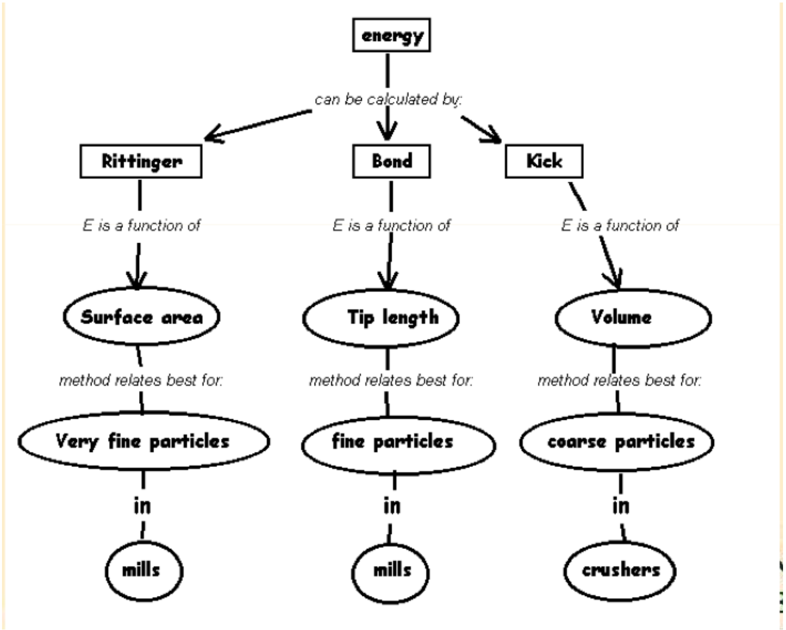


Figure 10: Three accepted laws of multiple particle breaking

Comminution: Is a process in which solid materials are reduced in size by blasting, crushing and grinding.

Blasting: The use of controlled explosives to excavate, break down or remove minerals from an ore body.

Blasting typically reduces particle size to 0.3 m. It can have many ‘unseen’ and ‘seen’ benefits. The seen benefit of blasting is the fragmentation. Poor fragmentation reduces productivity. Coarsely fragmented ores reduce primary crusher throughput as it leads to more downtime for clearing crusher bridging and plugging. It also increases the load to the secondary and tertiary crushers as there will be less undersize that can be spit off to the bypass stream. The unseen benefit of blasting is the crack generation that occurs within fragments, which serve to ‘soften’ the fragments up to make them easier to break.

Figure 11: Good and Bad Blasts

Crushing: Crushing involves the application of compression to the feed rock to reduce particle size.

Crushing typically reduces particle size to 0.005 to 0.02 m. The main benefit is liberation and separation as a result of reducing particle size. It is usually less energy intensive then grinding. Four things determine the efficiency of a crusher:

- The ability to move a rock to a place where it can be broken
- The ability to apply a force large enough to break it
- The ability to transport the particles away
- The ability to perform the above three things at a high rate

Some main types of crushers are listed and described briefly below:

Gyratory Crusher

Gyratory crushers work on a principle similar to that of the jaw crusher in that the particles are fractured under slow compressive stresses but in this case also with some shear stresses. The feed moves into the crusher under the influence of gravity; in this process, however, the crusher plate in the form of a spindle moves in ta gyrating eccentric path within a conical shell. This action has the effect of crushing particles against one part of the shell whilst on the opposite side of the spindle the feed is moving down into the crusher. Therefore whatever the position of the spindle, crushing is taking plate and because of this high throughputs of materials are possible.

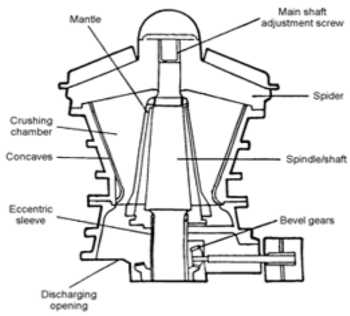


Figure 12: Gyratory Crusher

Jaw Crusher

The jaw crusher applies compression to the feed particles, which descend under gravity into a tapered cavity bounded by a fixed and hinged crushing plate. The hinged plate moves in and out in a cyclic manner. As the plate movies out of the gap between the plates, the feed drops into the cavity. As the plate moves in, the particles between the plates are subjected to slow compression, either by direct contact with the plates or through particle/particle contact and are broken into smaller sizes. Although useful for crushing very large particles, it does suffer from the disadvantage that it is carrying out useful work for only half the operating time because of its cyclic action. Despite this, they are cheap and therefore are often implemented.

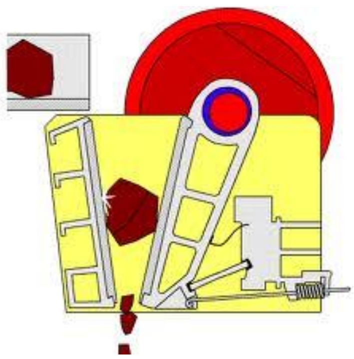


Figure 13: Jaw Crusher

Cone Crusher

Cone crushers can be regarded as modified gyratory crushers. The essential difference is that the moving crushing face is, in this case, supported from underneath rather than being suspended as in a gyratory. Since the throat of the crusher does not now have to accommodate the large central suspended bearing the crushing shell may be made to flare outwards thus allowing for the swelling of broken ore by providing increasing cross sectional area towards the discharge end. The flare of the bowel allows a much greater heard angle than in gyratory crushers while retaining the same angle between the crushing members. This gives the cone crusher a high capacity, which is roughly proportional to the diameter of the head.

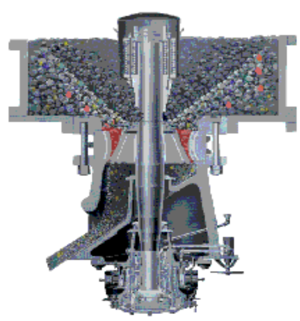


Figure 14: Cone Crusher

Roll Crusher

Roll crushers operate by the rotation of spring loaded horizontal rolls, which revolve towards each other drawing the feed material into the rolls. The rolls may have smooth surfaces or may have sluggers or protruding teeth. The smooth rolls rely on the friction between the feed material and the roll to draw the material through the crusher, and this factor determines the maximum reduction ratio, which may be achieved by the slow application of pressure. The presence of sluggers on the rolls effectively increases the friction between the material and the rolls and, as a result, higher reduction rations can be achieved. This process is mainly used for weak, ductile materials.

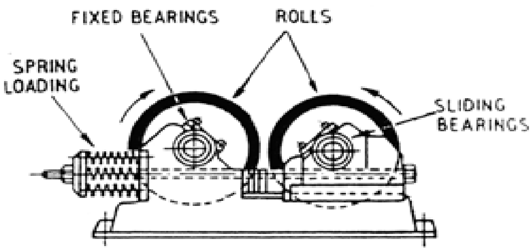


Figure 15: Roll Crusher

Vertical Shaft Impact (VSI) Crusher

VSI crushers use a different approach involving a high speed rotor with wear resistant tips and a crushing chamber designed to 'throw' the rock against. The VSI crushers utilize velocity rather than surface force as the predominant force to break rock. In its natural state, rock has a jagged and uneven surface. Applying surface force (pressure) results in unpredictable and typically non-cubical resulting particles. Utilizing velocity rather than surface force allows the breaking force to be applied evenly both across the surface of the rock as well as through the mass of the rock. Rock, regardless of size, has natural fissures (faults) throughout its structure. As rock is 'thrown' by a VSI Rotor against a solid anvil, it fractures and breaks along these fissures

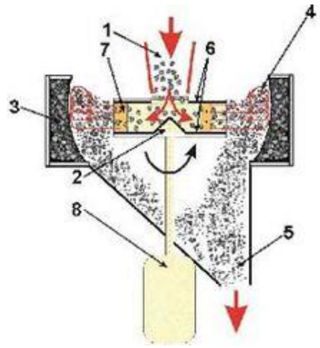


Figure 16: VSI Crusher

F80: 80% passing feed size

P80: 80% passing product size

Grinding typically reduces particle size to 0.00001 to 0.0002m. As crushing can only reduce particle size to approximately 0.005 m, grinding must be used to further reduce particle size to promote liberation and separation.

Some common types of grinders are listed and described below.

Rod Mill

The grinding medium in *rod mills* consists of rods of assorted diameters whose major axes are parallel to the axis of the rotation of the mill. The rods are usually made of high carbon steel. This material is hard and brittle giving rods good wear and resistance and, as the rods are worn down, they tend to break rather than bend and thus avoid being tangled in the mill. The rods in the mil tumble over each other in parallel alignment and the ore particles are trapped between the rods. This type of mill has breakage characteristics, which make it useful for coarse particles

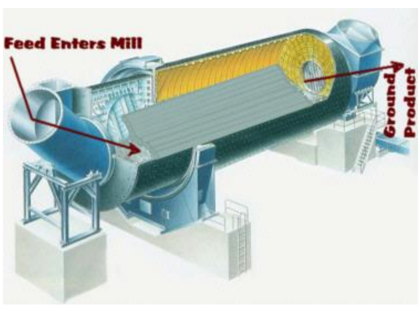


Figure 17: Rod Mill

Ball Mill

Figure 3: Ball Mill

As then name implies the grinding media used in ball mills are hard steel or ceramic balls. The ball size should be small enough to maximize the surface area of the balls/unit mass, but of sufficient size to break the largest particles in the feed material.

Vibrating Mill

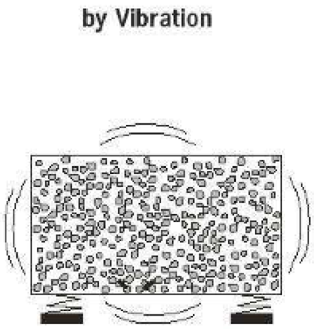


Figure 4: Vibrating Mill

The entire filling of the grinding cylinders, which comprises the grinding bodies (steel balls or Rod mills) and the material intended for grinding, constantly receives impulses from the circular vibrations in the body of the mill. The grinding action itself is produced by the rotation of the grinding bodies in opposite direction towards the driving rotation and by continuous head-on collisions of the grinding bodies. The residence time of the material being inside the grinding cylinders is determined by the quantity of the flowing material. They are advantageous as they have: lower installation and operation costs, can operate on wet and dry mixes and higher efficiencies; however they are disadvantageous as they have lower throughputs.

Autogenous Mill: In *Autogenous Mills* large particles of the ore itself are used as the grinding medium.

Semi-Autogenous Mill: In semi-autogenous grinding the particles are broken by utilises the ore itself and with the help of foreign objects.

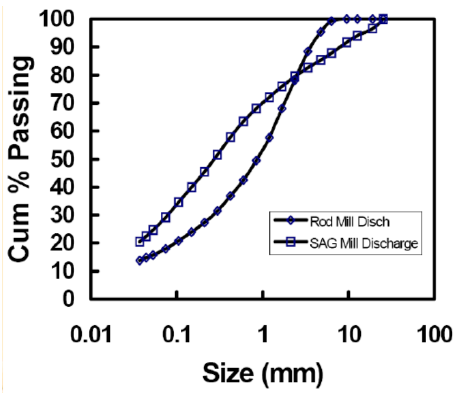


Figure 20: Size Distributions of Grinding

The Rod Mill produces a narrower particle size distribution.

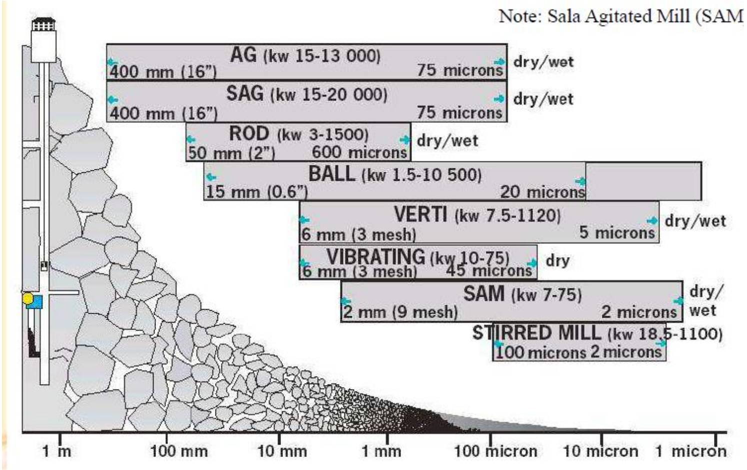


Figure 21: Reduction Ratios of Grinding Units

Open Circuit Grinding: If the material is only passed once through the grinding or crushing machine. It is an open circuit system.

Closed Circuit Grinding: If the partially ground material from the machine is sent to a size separation unit, from where the undersize is withdrawn as the final product and the oversize material is returned to the machine for regrinding, the process is known as closed circuit.

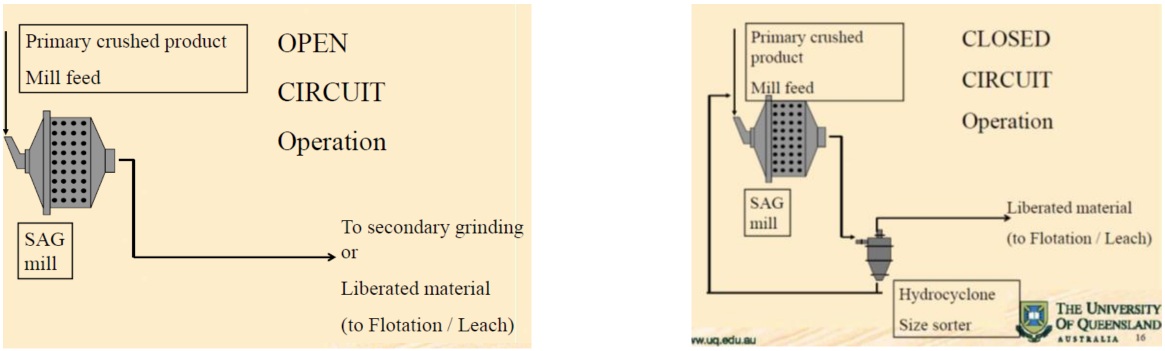
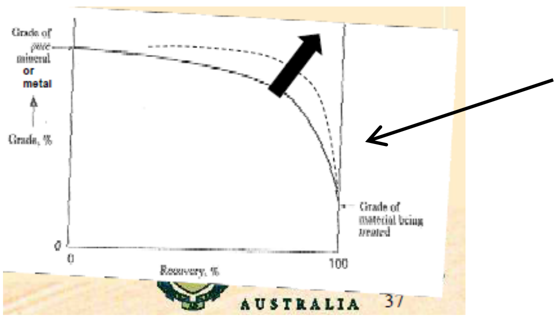


Figure 22: Closed and Open Circuit Grinding

Benefits of Closed Circuit Grinding

- Grinding capacity increases;
- Grain size distribution of refined powder becomes sharp;
- Refined powder temperature is reduced;
- Power consumption rate decreases;
- The abrasion of liners and balls is suppressed;
- Grain size distribution of products can be adjusted by changing the circulation ratio and the classifier's run status.



By increasing the level of liberation the recovery curve is shifted upwards

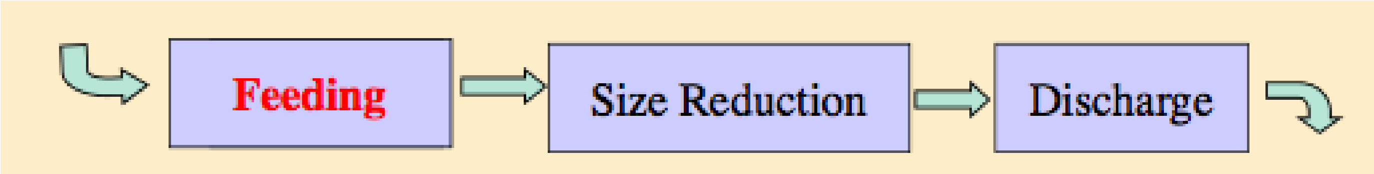


Figure 23: Three effective steps to grinding

There are three steps to effective grinding. These steps are listed and discussed below:

Feeding

To optimize grinding, an adequate diameter to avoid blocking, lining for feed properties, head/input/angle for continuous flow must be maintained. Blocking or build up should also be avoided.

Size Reduction

To effectively grind minerals the appropriate mill should be chosen as well as choosing a mill of the correct size.

Discharge

To cope with industry demands, the correct mill should also be chosen based on the desired feed rate.

Work Index: The work index is a measure of the energy expended in breaking the material but also includes the mechanical efficiency of the machine.

$$W = 10\ WI \left(\frac{1}{\sqrt{P_{80}}} - \frac{1}{\sqrt{F_{80}}} \right)$$

$$P = T * W$$

where

W = work input (kWh/t)

WI = Work Index - ore specific constant (kWh/t)

P_{80} = product 80% passing size (μ m)

F_{80} = feed 80% passing size (μ m)

T = throughp ut of new feed (t/h)

P = power draw required (kW)

Figure 5: Power Requirements for Grinding

Screening: Screens involve using geometric patterns to control particle size.

Screening processes essentially involve the movement of particles over perforated surfaces. Particles, which are smaller than the size of the perforations, tend to fall through the apertures and those that are larger than the perforations continue to move across the surface.

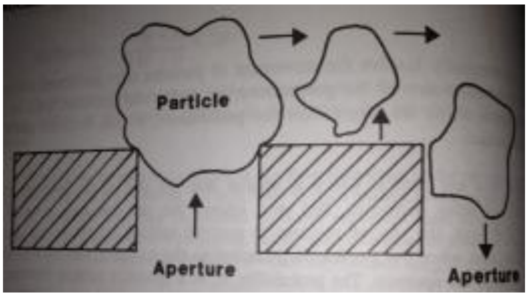


Figure 6: Screening

Although it might be assumed that any particle, which is smaller than the size of the aperture, would pass through the screen without delay. However, this view ignores the fact that only some of the screen is composed of the apertures, the rest of the area is material making up the screen. In this scenario there is a probability that when the particle is presented to the screen it will hit the screen matrix rather than passing through the aperture. The probability can be modelled by the equation below:

$$Probability = \left(\frac{(D_A - D_O)}{(D_A - D_W)}\right)^2$$

where D_a is the length of the aperture, D_o is the size of the particle and D_w is the width of the wire surrounding the aperture.

On top of this there are a number of key screen variables. These include:

- Length of Aperture
- Width of Aperture
- Proportion of Open Area – increases the probability of particles passing through the screen
- Vibration – can greatly enhance screening efficiency
- Surface Material

The panel thickness and aperture design is also key in designing screens. The effects are illustrated in the diagrams below.

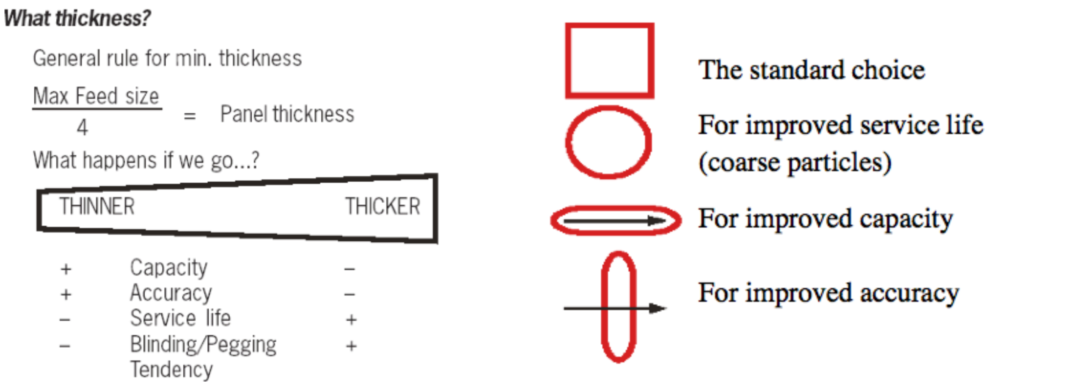


Figure 7: Panel Thickness and Aperture Design

Lastly, the wetness of particles entering the screen also greatly affects screen efficiency. Moist particles tend to cling to screen wires and aggregate together in large clumps of particles. This significantly reduces their probability of falling through the mesh.

Some common types of screens are discussed in the table below:

	Distinguishing Characteristics	Classifications	Description	Motion	Speed, Amplitude	Applications	Advantages and Disadvantages
STATIONARY GRIZZLY	Heavy duty surface of fixed bars.	Conventional	Heavy bars running in flow direction, sloped to allow gravity transport. Bars may spread along length to minimise blinding.	Stationary surface (Vibrating grizzlies also available, bar vibrating screens)		Scalping before crushers	Simple, robust. Probability form blinding resistant.
		Probability	Bars divergent in vertical plane.				
ROLL GRIZZLY	Surface of rotating rolls.		Essentially a stationary screen surface, but non-uniform shape of rolls conveys material.			Coarse separations before crushing. Primarily a conveyor.	Conveying action allows near horizontal operation in low head room situations.
SIEVE BENDS	Slurry feed, fixed bar surface.	Straight or curved surface	Stationary, parallel bars at right angles to slurry flow. Surface may be straight (with steep incline) or curved to 300°.	Stationary		Separations in range 2 mm to 45 μm, or those too coarse for hydrocyclone, or where density effects make classifier unsuitable. Dewatering.	Relatively high efficiency and capacity. Sharpness of cut less than true screen. Separation slightly affected by mineral density. Excessive dewatering can be a problem.
REVOLVING SCREENS	Screen surface rotating around cylinder axis.	Trommel	Slightly inclined cylindrical screen. May have concentric surfaces.	Below critical speed (c.f., ball mill).	15-20 r.p.m.	Wet or dry separations 60 to 10 mm if dry, smaller if wet.	Simple, useful for scrubbing or rough size separations. High wear, low surface utilisation.
		Centrifugal	Vertically mounted cylindrical screen; centrifuges particles through screen.	Operates above critical speed. Also has vertical action of 800-1000 cycles/min.	60-80 r.p.m.	Wet or dry separations 12 mm to 400 μm. Dewatering.	High wear.
		Probability	Particles drop through "surface" formed by bars radiating out like spokes on a wheel.	Radiating bars rotate about vertical axis. Speed of rotation determines cut size.		Developed for separating coal <6 mm.	Relatively high capacity with fine separations. Cut size easily changed and controlled by varying speed.
VIBRATING SCREENS	High speed motion, designed primarily to lift particles off surface.	Inclined	Inclined rectangular screening surface which allows material to flow with aid of vibrations.	Mechanical vibrations give circular motion at center; elsewhere it depends on vibrator. Electro-magnetic vibrators may give linear vibration at center.	600-7000 r.p.m. Low <25 mm	Wide applications, generally down to 200 μm in mineral industry, but down to 38 μm in chemical industry, using the high speeds.	Relatively high efficiency and capacity, but capacity generally inadequate below 200 μm
		Horizontal	Horizontal rectangular screening surface. Linear vibration must have horizontal component to convey material along screen.	Linear motion, with vertical component to provide lift, and horizontal component for conveying.	600-3000 r.p.m. Low <25 mm	Similar to inclined screens.	Similar to other vibrating screens, but can also be used where head room is restricted
		Probability	Series of relatively small inclined screen surfaces; separates by statistics rather than physical constraint.			Similar to inclined screens	Generally superior to conventional vibrating screen. High capacity and efficiency for given space, low noise, low power. Low efficiency at low loading
SHAKING SCREENS	Slow linear motion essentially in plane of screen.		Usually slightly inclined. May have several surfaces in series with different apertures.	Linear motion, essentially in plane of screen, particles tend to remain in contact with screen surface.	30-800 r.p.m. 25-1000 mm	Down to 12 mm for coal preparation and non-metallic minerals. Higher speeds may size down to 250 μm.	Low headroom and power requirements. May be used for conveying and sizing. Accurate for large sizes. High maintenance cost, low capacity
ROTARY SIFTERS	Circular motion applied to screen surface.	Reciprocating	Rectangular screen surface with slight (~5°) incline.	Circular motion is applied at feed end, and produces reciprocating motion at discharge end.	500-600 r.p.m. Low <25 mm	Generally used for finer separations (12 mm to 45 μm, wet or dry) in non-metallurgical industries.	Suitable for finer separations, but with low capacity.
		Gyrating	Circular screen surface	Circular motion over most of the screen surface.			
		Gyrating	Circular screen surface	Screen moves with circular motion, but also has oscillating vertical component.			

Figure 8: Screening

$$\text{Efficiency}\left(\sqrt{d_1 * d_2}\right) = \frac{\text{flow of size fraction } (-d_1 + d_2) \text{ to oversize}}{\text{flow of size fraction } (-d_1 + d_2) \text{ in feed}}$$

Figure 9: Efficiency of a screen

Sieving: Sieving is a batch screening process and is used mostly in laboratories

Classification: Classification involves using particle motion in a fluid medium to control size

Classification relies on the fact that coarser particles and more dense particles move faster than finer and less dense particles in fluid media. It is generally used when particles are smaller than 1mm.

Wet Classification: The term 'wet' classification denotes a particular case of phase separation in a liquid-solid suspension.

Dry Classification: The term 'dry' classification denotes a particular case of phase separation in a gas-solid suspension. It is often preferred, as the discharge does not need drying or slurry treatment.

Two common types of classifiers include: Sedimentation classifiers and hydro cyclones. These are briefly discussed below:

Hydrocyclones

In a hydrocyclone the injection of the slurry tangentially into the classifier results in high centrifugal forces on the particles and therefore accelerates the settling or separation of the particles. The oversize particles (underflow) are thrown to the wall of the cyclone and segregate to the bottom of the container. The undersize particles report to the overflow through a central pipe located at the top of the cyclone, called the vortex finder. The path of the slurry as it first enters the cyclone is in a downward spiral, the larger particles continue on this path remaining close to the lining until discharge. Most of the volume of liquid, however, leaves the cyclone through the top of the cyclone and this fluid movement tends to drag the smaller particles towards the center of the cyclone and then upwards towards the underflow exit.

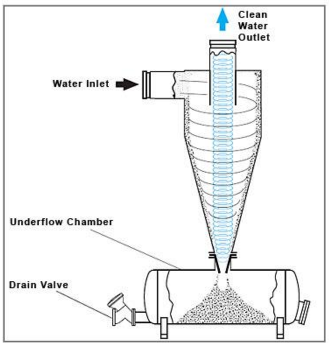


Figure 10: Hydrocyclone

Sedimentation Classifiers

A sedimentation classifier consists of a large pool or tank into which the slurry, the solid/liquid mixture, is fed. The smaller particles, having the lower settling velocity, remain in suspension and are removed in the liquid overflow. The larger particles, with the higher settling velocity, are deposited on the floor of the tank and are removed by mechanical means. In practice perfect separation is not achieved between the undersize and oversize particles because of the turbulence induced by fluid flow, slurry density differences and movement of the mechanical device used to remove oversize material.

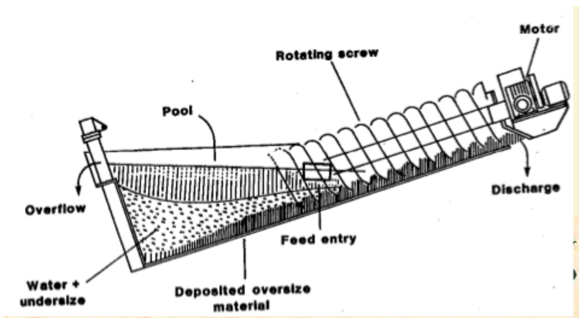


Figure 30: Sedimentation Classifier

D50: The critically sized particle, d_{50}, is one that stands equal chance of reporting to the undersize or oversize and is dependent on the detailed geometry of the cyclone. It is an extremely important parameter in selecting the correct cyclone for a process.

Gravity Separation: Gravity separation utilizes the density differences of different materials to separate impurities.

Gravity separation is often the first consideration in flow sheet development as it is efficient and low cost; however it is often inaccurate owing to the large effects of size and shape. Effective gravity separation relies on the different densities and sizes of particles as well as the works of gravity and drag forces resisting movement. There are a number of ways to achieve gravity separation. The most common include: static separation, centrifugation and jigging. These are briefly described below.

The **static method** relies solely on gravity to separate particles. The suspension is agitated and the left completely undisturbed. As the mixture settles, the larger and denser particles will come to rest first and settle on the bottom of the container. The smaller and less dense particles will settle on the top, forming a distinct layer. A correlation between the density difference and the ease of separation has been found. If the ratio below is greater than 2.5, the medium is easily separated. If the ratio is less than 2.5 it is hard to separate.

$$Ratio = \frac{\rho_{High} - \rho_{Fluid}}{\rho_{Low} - \rho_{Fluid}}$$

The **centrifugal method** uses a spinning motion to push particles down the fluid until they collect into a compact mass at the bottom of the tube. It relies on the concept that smaller particles require a larger force to accelerate the particle sufficiently to produce separation. By using centrifugal motion, particles as low as 10 to 50 µm can be separated, where as conventional gravity separation cannot separate particles less than 80 µm.

The **Jigging method** utilizes an upward water thrusting motion to separate particles. As the water is pushed upwards, lighter particles tend to lift more and denser particles tend to be hindered.

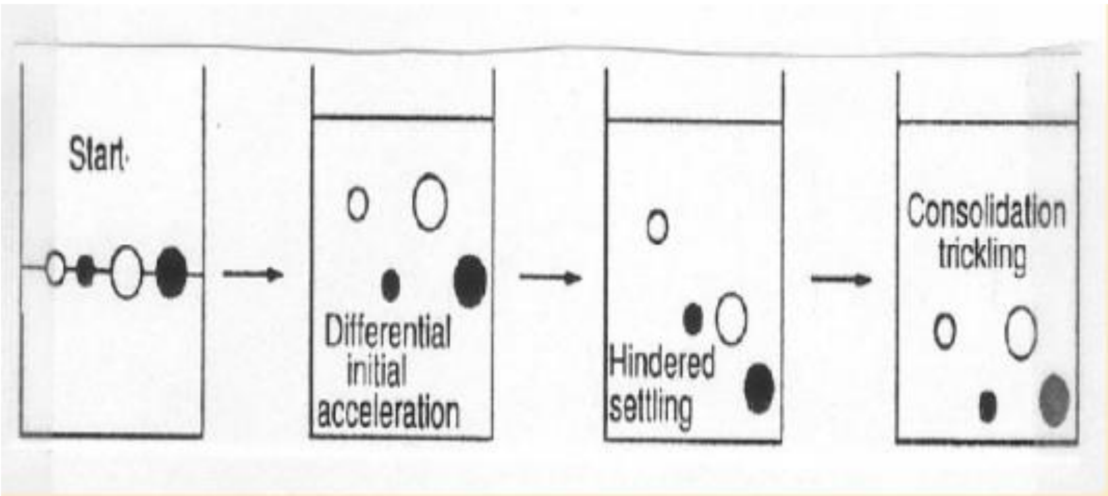


Figure 31: Jigging Mechanisms

Relative Gravity Separation: All particles move in the same direction.

On top of the effects of density, size also is an important parameter. The larger the particles, the easier they are to separate based on density.

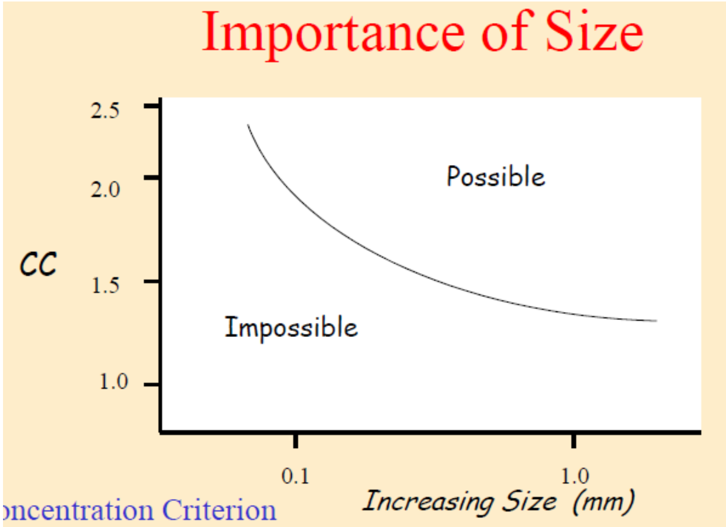
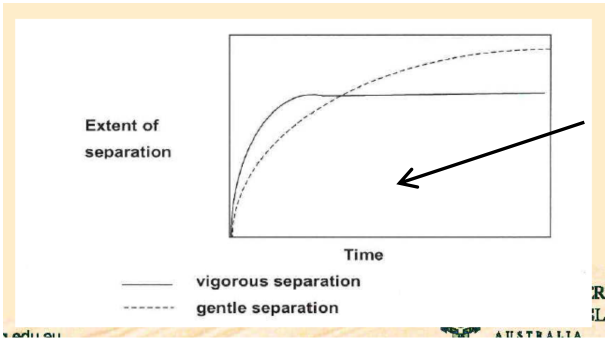


Figure 32: Importance of Size

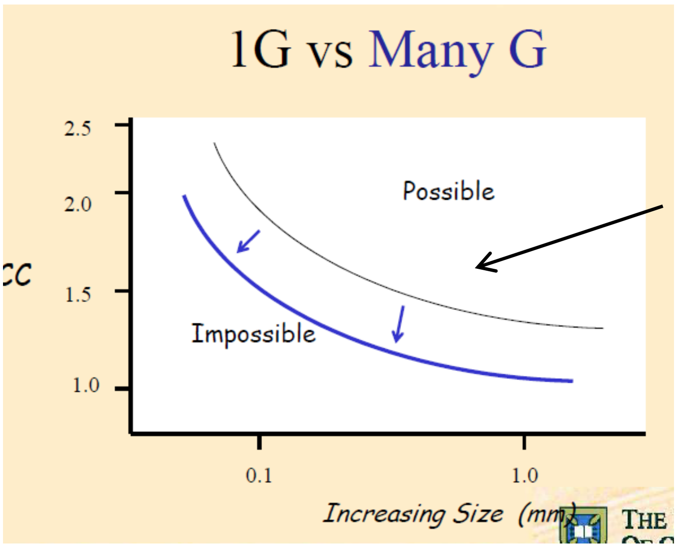
Lastly, separation kinetics is largely affected by the rate of mixing.



Higher rate of beginning but never reaches 100% separation because of remixing.

Figure 33: Separation Kinetics

The effect of many Gs is shown in the figure below.



The region is expanded

Figure 34: Effect of Enhanced Gravity Separation

Falcon Concentrator

The Falcon unit, which is essentially a centrifugal sluice, consists of a smooth-surface truncated cone which rotates at a very high speed. Feed slurry is injected near the bottom of the cone and is accelerated up the cone wall by the centrifugal field (up to 300 g's). The slurry forms a thin flowing film in which particles become stratified based on differences in density. Light particles atop the stratified layer are discharged over the top of the cone lip, while heavy particles sliding along the inner surface of the cone are discharged through the cone wall via small reject ports.

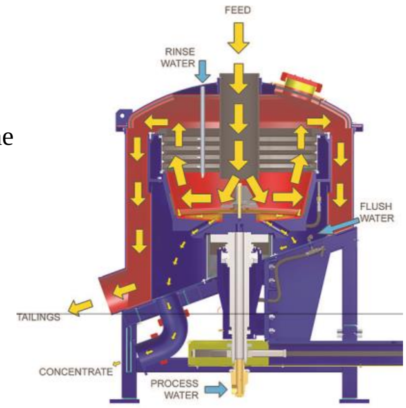


Figure 35: Falcon Concentrator

Kelsey Jig

The Kelsey jig consists of a series of hutches which are rotated about a central feed pipe. The unit is capable of generating centrifugal fields up to 100 g's. A cylindrical screen is mounted across the top of each hutch to retain ragging material. Feed slurry enters the unit through the central feed pipe and flows outward across the bed of ragging. Mechanical pulsators located within each hutch create oscillations in the bed that differentially accelerate particles based on differences in density. Low-density particles flow across the ragging material and overflow the top of the unit, while high-density particles pass downward through the ragging/screen and are discharged through actuated valves. In most cases, the unit forms its own ragging material form coarser and heavier feed particles.

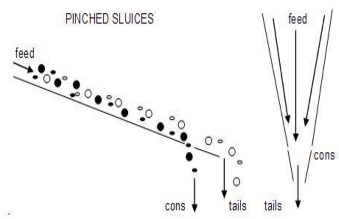


Figure 36: Kelsey Jig

Knelson Concentrator

The Knelson separator consists of a rotating truncated cone which is stair-stepped by several ring-type partitions. Feed slurry is injected through a central feed pipe and is allowed to flow counter current fashion from partition to partition until it overflows the top of the rotating bowl. Rinse water forced through perforations in the rotating bowl creates a fluidized bed of particles between each partition. Particles which have a density higher than that of the fluidized bed are collected behind the partitions, while lighter particles are flushed out over the partitions.

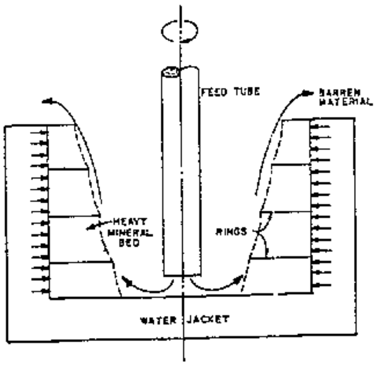


Figure 37: Knelson Concentrator

Mozley Multi-Gravity Separator

The operating principle of the MGS is similar to that of a conventional shaking table, except that centrifugal forces are used to enhance the separation of fine particles (Figure 2d). In this system, feed slurry is distributed along the inner surface of a slightly tapered rotating drum. Light particles are carried by the flowing film to the far end of the drum, while heavy particles pinned against the wall by the centrifugal field are carried by rotating scrapers to the opposite end of the drum. A small amount of wash water is added to the heavies discharge end of the drum to wash out entrained low-density particles.

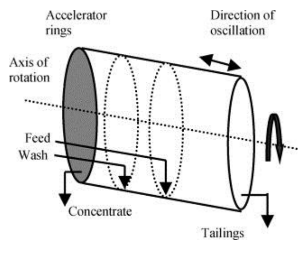


Figure 38: Shake table

Shake Table

Feed slurry is distributed at the head of the table via a launder, together with wash water, and spreads out across the inclined surface on the basis of particle SG, with high SG grains moving along the top of the flowing film to discharge off the far end as concentrate, while low SG grains move down the inclined slope of the table with the majority of the water to discharge at the bottom as tailings. The particle separation is assisted by the backwards and forwards motion (stroke) of the table, the tilt (both longitudinally and laterally), wash water applied along the length of the table, and riffles.

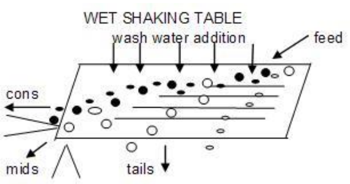


Figure 39: Shake table

Dense Medium Separation: DMS involves the use of a more dense liquid to separate particles.

Rather than rely on the hindered-settling phenomenon and the hindered settling ratio, a plant engineer might choose to use a liquid of density intermediate between those of the minerals to be separated. The particles that are more dense than the medium will sink and the particles less dense than the medium will float. Since most liquids that are more dense than water are expensive and frequently toxic, very fine insoluble particles are suspended in water thereby increasing the apparent density (i.e. as long as the particles are in suspension the density of the fluid is that of the mixture and not of the phases which make up the mixture).

Gravity Separation vs. Dense Medium Separation

Gravity separation relies on the settling rates of particles in water. This is varied with particle size, shape and density.	DMS relies solely on materials being less dense and denser than the medium and is only dependent on density.

Absolute Separation: When particles are separated in opposite directions. Although more accurate it is more expensive and used less in industry.

Applications of DMS:

- Coal Washing
- Diamond and other gemstones
- Metallic ores of copper, lead and zinc
- Gold and Platinum Group Metal minerals
- Non-metallic and industrial minerals e.g. barite, fluorite and chromite etc

Ecart Probable, E_P: The Ecart probable, or probable error, is defined as one half of the specific gravity interval corresponding to recovery values of 25 and 75%.

$$E_P = \frac{D_{75} - D_{25}}{2}$$

Imperfection, I

$$I = \frac{E_P}{D_{50} - 1}$$

How to calculate the specific gravity of a mixture:

$$\boxed{SG(slurry) = \frac{m_1 + m_2 + m_3 + \ldots}{\frac{m_1}{SG_1} + \frac{m_2}{SG_2} + \frac{m_3}{SG_3} + \ldots}}$$

where $m_1, m_2, m_3, \ldots$ = weight of each component (kg)
$SG_1, SG_2, SG_3, \ldots$ = specific gravity of each component

Figure 40: Specific Gravity of A Mixture

Drewboy Bath

The raw material is fed into the separator at one end, and the floats are discharged from the opposite end by a star-wheel with suspended rubber, or chain straps, while the sinks are lifted out from the bottom of the bath by a radial-vaned wheel mounted on an inclined shaft. The medium is generally fed into the bath at two points – a the bottom of the vessel and with the raw material.

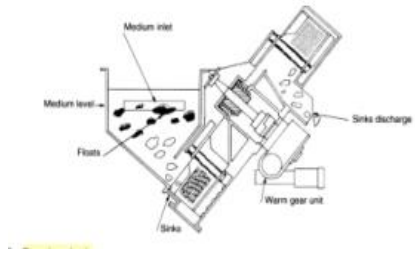


Figure 41: Drewboy Bath

Magnetic Separation: Magnetic Separation is a process in which magnetically susceptible materials are extracted from a mixture using a magnetic force.

All materials are affected in some way by the presence of a magnetic field. These properties can be harnessed to separate particles. It is generally used to separate already liberated granular mixtures that require sorting and **can be wet or dry.**

Magnetic Susceptibility: Is a dimensionless proportionality constant that indicates the degree of magnetization of a material in response to an applied magnetic field.

$$K = \frac{J}{H}$$

Where H is the magnetic field strength and J is the intensity of magnetization.

Diamagnetic: Materials that are repelled by a magnetic field and move to positions of low field intensity (small negative magnetic susceptibility, K).

Paramagnetic: Materials that are attracted to a magnetic field and which move to positions of high field intensity (e.g. small positive magnetic susceptibility, K).

Ferromagnetism: A special case of paramagnetism that is highly susceptible to a magnetic field and involves a larger magnitude of forces (e.g. large positive magnetic susceptibility, K)

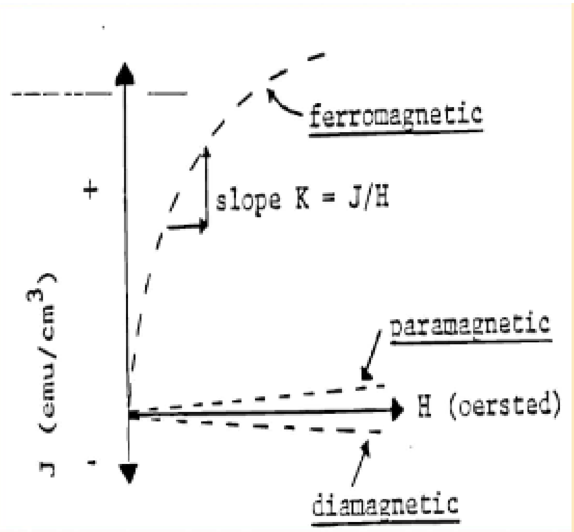


Figure 42: Magnetic Susceptibility

The magnetic force is given by the relationship below:

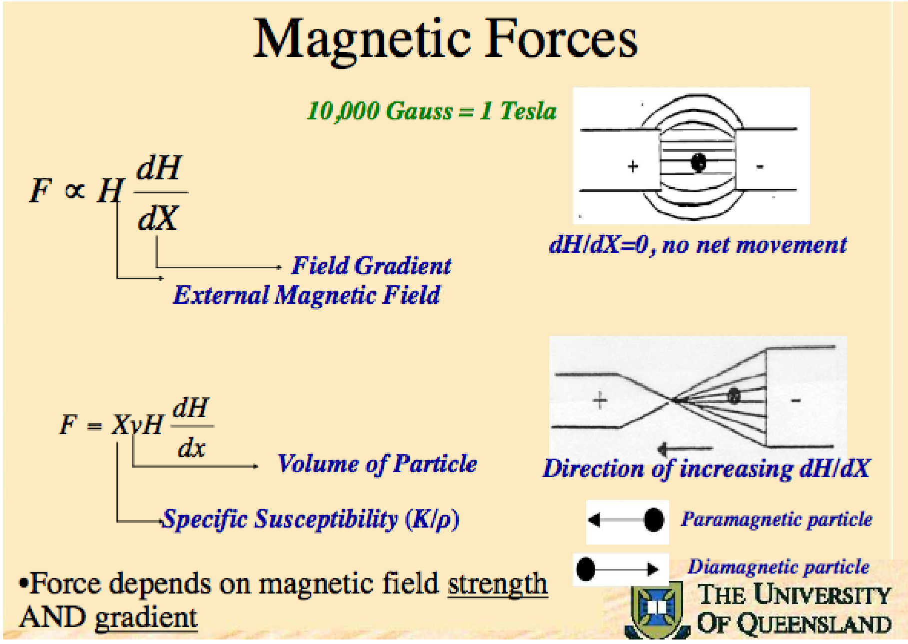


Figure 43: Magnetic Force

To maximize the magnetic force, the field strength or field gradient can be increased.

Low Intensity Processes

Dry

Low intensity magnetic separators are used to recover ferromagnetic particles. Drum separators are an example of low intensity separators. Drum separators commonly carry out particle selection using low intensity magnetic fields. Either permanent or electromagnets may be used. As the particles approach the drum, those having positive susceptibilities are attracted by the magnetic field but are prevented from reaching the magnetic by the drum surface. Dry magnetic drum separators utilize the competing magnetic and gravitational forces to achieve separation. The motion of the non-magnetic drum past stationary alternating poles of the magnets within the drum produces a tumbling motion in the particles which aids the separation of physically trapped, unwanted non-magnetic particles. With these devices it is possible to recover a middlings fraction. The middlings particles are less strongly attracted by the magnetic force than the concentrate particles and hence may be made to fall into the product streams between those of the concentrate and the tailings stream. These middlings are generally composed of incompletely liberated particles contain both magnetic and non-magnetic components. Since grinding of ores is expensive, it is often economically attractive to treat all the ore initially with a dry drum separator and regrind the middlings fraction before retreating it magnetically.

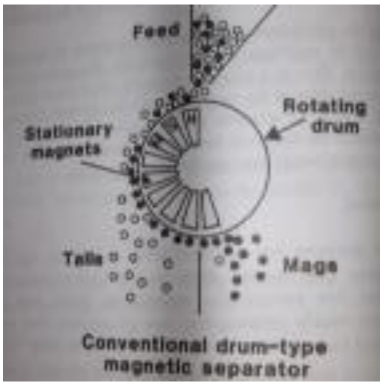


Figure 44: Low Intensity Magnetic Separator

Wet

There are three types of wet drum separators: co-current, counter-rotating and counter-current.

Co-Current

In the co-current drum separator the slurry feed is passed through a trough in the same direction as the rotation of the drum. Magnetic particles are attracted to the drum surface by the stationary magnets within it. Whilst the non-magnetic particles sink to the lowest point in the trough, the magnetic fraction is carried on the drum surface to appoint where it is taken off into a separate process stream. This type of separator produces a high grade of concentrate but at the same time the tailings also contain significant amounts of magnetic material The tailings are then often retreated in a counter-rotating drum separator.

Counter-rotating

In the counter rotating separator, the feed is passed through the trough in a direction opposite to the direction of the drum. This device produces a high recovery but generally a concentrate of low grade since most of the magnetic particles are trapped on the drum surface and there is little opportunity for the release of the non-magnetic particles

Counter-current

The counter-current separator is often used as a finishing separator because it produces an extremely clean concentrate with good recovery.

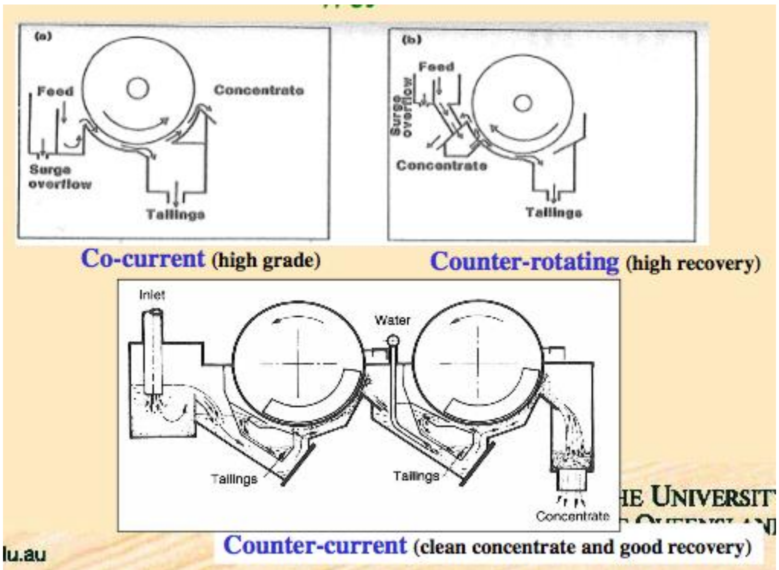


Figure 45: Wet Low Intensity Magnetic Separator

High-Intensity Magnetic Separators

Weakly paramagnetic materials may only be separated effectively from particle streams using high intensity magnetic processes. The magnetism of paramagnetic materials only approach saturation under the influence of very high fields. Since a high induced magnetism is necessary for the particles to be retained at the magnet surface as the material flows through the process high field strengths are required. These conditions can be achieved by the combination of a high applied field and the use of ferromagnetic materials of suitable geometries to locally concentrate the magnetic lines of force.

Jones

In the Jones carousel type separator, feed boxes made of ferromagnetic material are arranged on a circular frame. These boxes consist of vertical grooved plates which are spaced so as to allow the particulate feed material to pass through the holes. Situated at each side of the circle are two strong electromagnetics which magnetize the material in the boxes adjacent to them. By rotating the frame each of the boxes is both magnetized and demagnetized as it moves about the circle. A slurry containing the feed particles is fed into the boxes s they enter the field of the electromagnet. The high intensity field induced in the grooved ferromagnetic plate material magnetizes the weakly paramagnetic particles, which then remain attached to the plates by the magnetic attraction. The unmagnetized material flows through the boxes and is collected as tailings. As the boxes leave the region of influence the electromagnets the field in the boxes decreases and the magnetized particles may be flushed out with jets of water. This material then forms the selected product of the process.

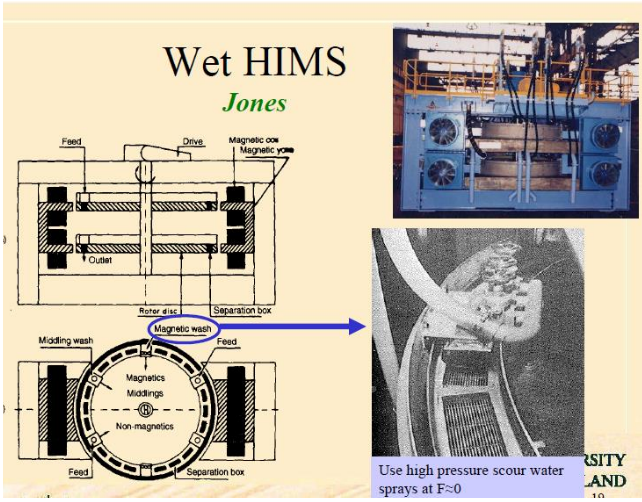


Figure 46: Jones High Intensity Magnetic Separator

Electrical Separation

The selection of solid particles from a mixture may be carried out by utilizes the forces acting on charged or polarized particles in an electric field. Since each material has its own electrical characteristics this results in differential movement of the particles in the field and their subsequent selection into different process streams. It is generally used to separate small grains from 75 to 250μm.

There are three important mechanisms by which particles may acquire a surface charge. These a listed and described below.

Contact Electrification

It has been observed that when two dissimilar materials in contact with each other are moved apart an exchange of charge takes place, probably by the transfer of electrons. Repeated contact of particles, which are poor electrical conductors results in a build-up of static charge. Although commonly observed, contact electrification is difficult to control in practical situations because of the variability of material properties.

Conductive induction

If a solid particle is placed on a grounded rotor in the presence of an electric field, the particle will develop a surface charge by induction. Conductive particles will, in a very short time, assume the ground potential of the rotor, which is opposite to that of the non-discharging electrode. The electrostatic forces on these conducting particles will attract tem towards the electrode away from the grounded surface and the particulate flow. Non-Conducting particles which hare unable to pick up charge from the rotor remain polarized and are attracted to the rotor or pass through the field relatively unaffected. A suitably placed splitter enables the two process streams to be separated.

Ion Bombardment

By applying a very high voltage difference between the electrode and the ground, charged atoms or molecules may be generated in the gas. The feed particles pass through this stream of ions as they move between the electrodes and the charges are attached to the surfaces of these particles. Particles having low conductivity will remain in a charged state for a longer period of time then particles made up of materials, which are good electrical conductors. The attractive force between the charged particle and the rotor results in these particles remaining with the rotor.

High Tension

High tension separators have been used to successfully treat particles between 50 and 500 µm in diameter. Since gravitational and centrifugal forces increase relative to the electrostatic forces as the particle size increase, the coarse particles are more likely to be thrown from the roll surface (i.e. **difference between the two opposing forces increases**). As a result of this effect, although there is an effective separation of the coarse conducting fraction from the fine non-conductors, the conducting fraction often contains a proportion of coarse non-conducting particles. Conversely the finer particles are more influenced by surface charge effects and the non-conducting fraction often contains some fine conducting particles.

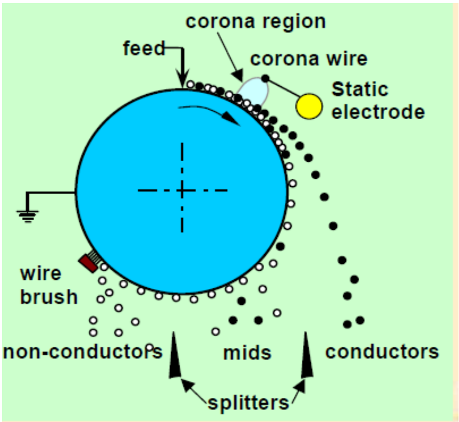


Figure 47: High Tension Electrostatic Separator

Electrostatic Separators

If there is a significant effect of particle size on separation efficiency it may be necessary to further process the non-conducting stream using electrostatic separators. In this type of equipment design the feed material falls under gravity down a sloping, grounded plate into an electrostatic field induced by a large oval, high voltage electrode. In this arrangement the fine conductors are preferentially lifted towards the electrode, away from the plate whereas the coarse non-conductors flow over the plate.

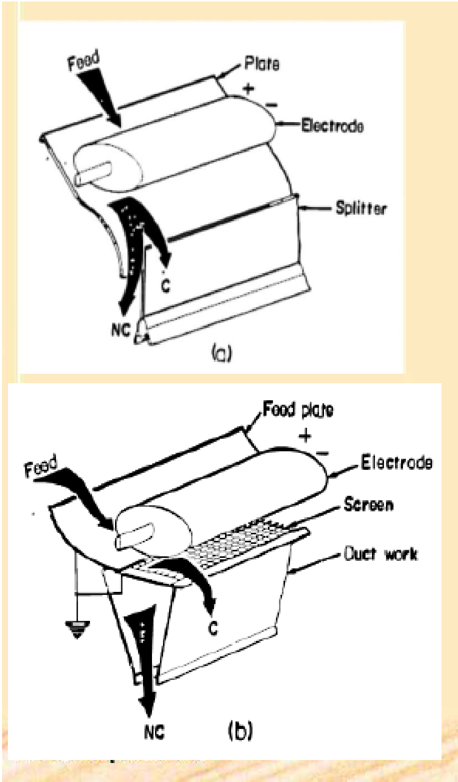


Figure 48: Electrostatic Separator

There are a number of parameters that have an effect on the effectiveness of electric separation. These include:

- Particle size e.g. fine particles are difficult to separate (i.e. feed should have narrow size distribution)
- Particle shape e.g. the force is affected by the effective surface contact area
- Dryness of the atmosphere e.g. water makes non-conductors more conductive and the method becomes less effective.

Froth Flotation

It has been found experimentally that when air bubbles are passed through slurry containing fine mineral particles, certain minerals can become attached to the bubbles. The particles move with the gas bubbles to the surface of the liquid forming froth. The froth and liquid suspended particles are separated from the slurry by skimming the froth from the surface of the liquid. The mineral particles which do not become attached remain in the slurry and are removed in a separate process stream.

The main driving force for the attachment of the particles to the gas bubbles is the reduction of the surface energy of the system. Present in the system are three phases: gas, liquid and solid. Present also are three interfaces, solid/gas. Solid/liquid and liquid/gas. Each of these interfaces possesses an interfacial energy equivalent to the work which has to be carried out on the system to create them. When a particle is in contact with a gas bubble a new gas/solid interface is created. The basic condition for the stable attachment of the particle is that of the total energy lowered by the attachment.

Materials that do not fulfil this condition with aqueous solutions are referred to as hydrophilic I.e. they have an affinity for water. Not all hydrophobic materials will become attracted to gas bubbles rising through a solid/liquid mixture.

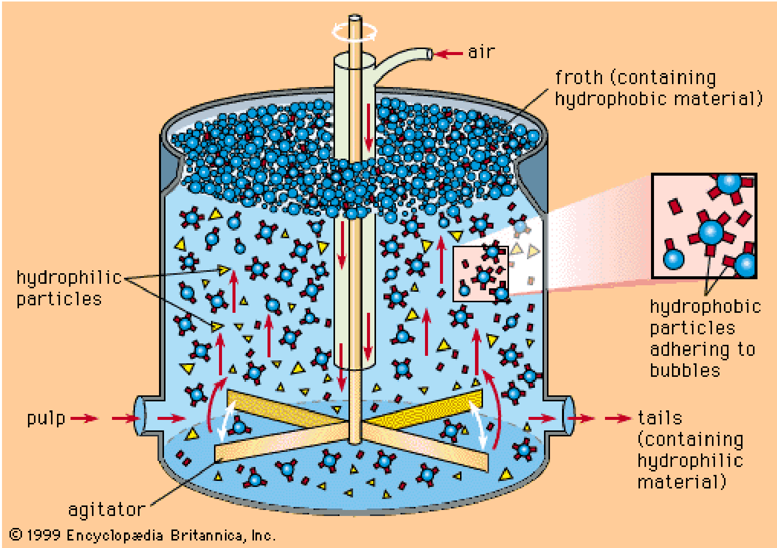


Figure 49: Froth Flotation

Collectors

A collector is a chemical that attaches to the mineral surface and produces a hydrophobic (water-fearing) surface. While certain minerals are naturally hydrophobic and do not require a collector, recovery is often improved when a collector is used (e.g. in these circumstances hydrocarbons are used to enhance hydrophobicity). This water-repellent film facilitates the attachment of the mineral particle to the air bubble.

Frothers

For successful flotation it is necessary not only for the gas bubbles to carry the mineral to the surface of the treatment cell but also for the bubbles to remain stable i.e. not burst. If a stable froth cannot be maintained the particles will, when the bubble breaks, be simply released into the slurry. On the other hand if the bubbles are too stable they can cause problems in handling of the separated froth. The addition of frothers is made to control the stability of the bubbles at the cell surface. These frothing reagents must not only be soluble in water but also be capable of lowering the interfacial energy between gas and water. This combination of effects is produced by using heteropolar molecules in which the polar group provides the water solubility and the organic group the preferential adsorption at the gas/liquid interface.

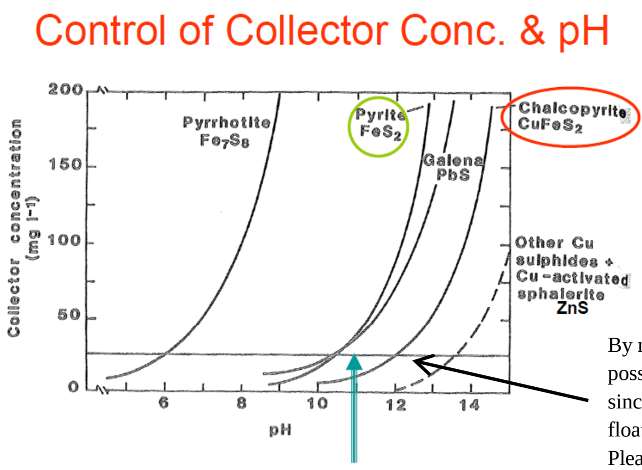
Modifiers

Some minerals do not adsorb sufficient collecter to enable froth flotation to be carried out. To overcome this problem the mineral surface may be activated by the addition of reagents. Sphalerite, for example, does not respond strongly to treatment with xanthate collectors. The addition of $CuSO_4$ to the solution, results in the replacement of Zn^{2+} ions in the surface layers of the mineral by Cu^{2+} ions. Since xanthates are strongly absorbed by Cu^{2+} ions the sphalerite mineral may now be floated. In addition to this, specific minerals can similarly be suppressed by adding depressants. For example, to separate galena, pyrite and chalcocite it is convenient to add sodium cyanide to the slurry. Stable iron and copper cyanide complexes form on the mineral surfaces but the lead cyanide complex is unstable. The addition of the xanthate results in their adsorption on the surface of the galena but not on the depressed surfaces of the iron and copper containing minerals and as a result of these reactions the galena is separated by froth flotation while the pyrite and chalcocite remain behind.

pH

It cannot be assumed that because a reagent is adsorbed at the interface that it alone constitutes all the adsorbed species. The equilibrium concentration of collector atoms at the mineral surfaces is determined by the balance of a number of species which compete for adsorption. Therefore, whilst, for example, xanthate collectors may be adsorbed strongly at sulphide surfaces their concentrations at the interface depend on the other anions present in the solution and their concentrations. In this way by increasing the pH of the solutions at any collector concentration in the mixture there will be a critical pH above which the surface will appear insufficiently hydrophobic and the material will not float. Below this pH the collector species is predominant at the interface and froth flotation is possible.

Thus the control of the pH of the slurry is important in determining not only the efficiency at which particular minerals may be floated but also in discriminating between minerals having similar surface characteristics.



By maintaining a pH between 10.5 and 11.8 it is possible to separate galena from chalcopyrite, since under those conditions chalcopyrite will float whereas galena will not.
Please note area to left is below critical pH and surfactant concentration (e.g. at the same pH galena requires a higher collector concentration to be below critical).

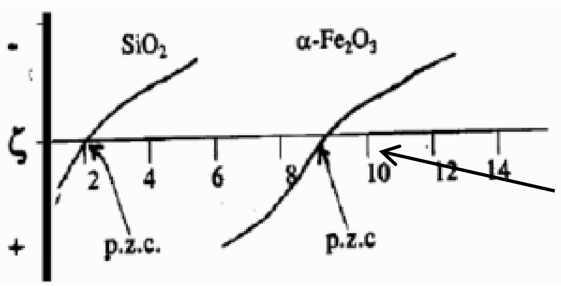
Figure 50: Effect of pH

The main pH control agents are lime CaO and soda ash Na_2CO_3.

The pH control agents have significant functions:

- Precipitate heavy metal ions which might otherwise cause accidental activation or depression or reaction with the collector.
- To prevent hydrolysis of the collector at low pHs and
- To reduce corrosion by acid mine waters

Point of Zero Charge: pH that a mineral has no net surface charge



The pH can also determine which surfactant to use. By choosing a pH of 6, a anionic surfactant can be used as it will only float iron oxide as silica is negative.

Figure 51: Choosing a surfactant

Solid/Liquid Separation (dewatering): The removal of water from solid material

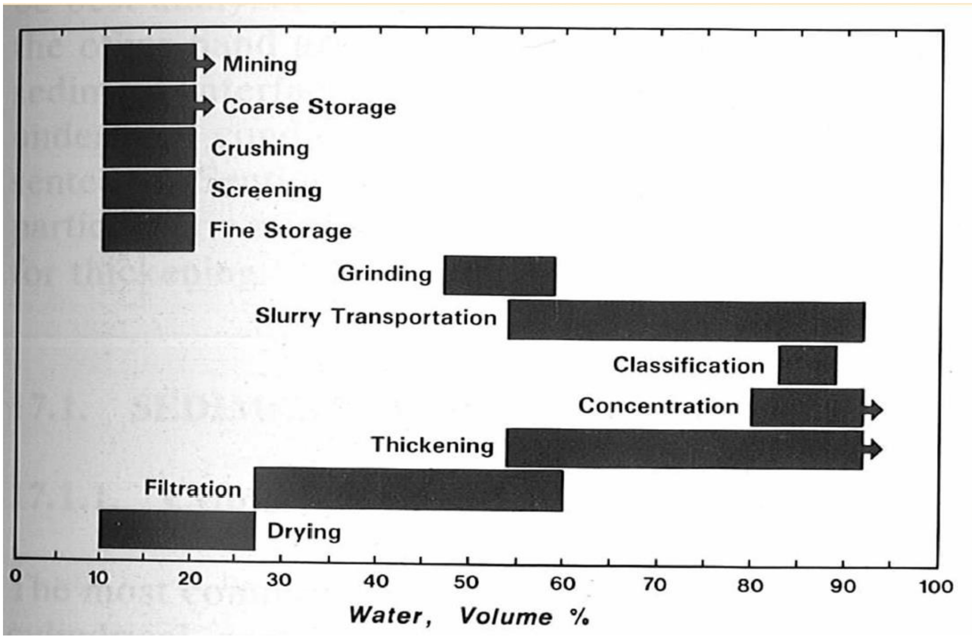


Figure 52: Water Volume during Processing

Most mineral separation processes involve the use of slurry products; however, at some stage it is necessary to remove and recover the water. There are two main reasons why this type of operation may be necessary:

a) To adjust the characteristics of process streams so they are suitable for subsequent treatment
b) To recover and recycle the water within the plant reducing water consumption and preventing contamination of fresh water cycles

Dewatering also has the added benefit of reducing transportation costs and reducing the volume of fines for tailings disposal.

Sedimentation: Is the process of settling particles in a liquid due to differences in relative densities of the two phases.

Clarification: Is the process for removal of solids from a dilute solid/liquid separation

Thickening: Is the process for concentrating particles in a suspension

Coagulation: Coagulation is the process by which colloidal particles and very fine solid suspensions initially present in wastewater are combined into larger agglomerates that can be separated by sedimentation.

The first step destabilizes the particles charge. Coagulants, which have opposite charges to the solid particles, are added to the suspension to neutralise the charges on dispersed non-settable solids. After the charge is neutralized, the surface potential is reduced and the small suspended particles are capable of sticking together.

Agglomerate: A coarse accumulation of particles.

Flocculation: Refers to the process by which destabilized particles actually conglomerate.

Dewatering Screen

The wet slurry is fed to one end of the screen. The solid material is retained on the screen while the water drains from the bed and flows through the screen. The vibration induces the bed of solids to move along the screen at a velocity that is a complex function of the mechanical action and of the properties of the bed itself. The vibration of the bed also induces an oscillating acceleration on the bed and the water it contains. This assists in overcoming the capillary retention forces in the pores and assists the dewatering process.

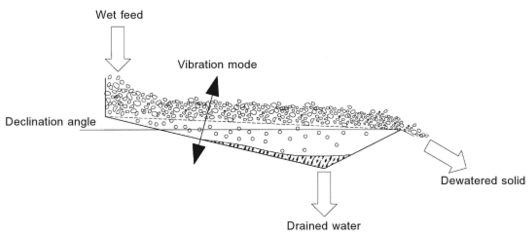


Figure 53: Dewatering Screen

Filtration Is the process of separating solids from liquids by means of a physical barrier which retains the solids but allows the liquid to pass.

As the liquid is extracted from the slurry, a filter cake composed of the solids builds up on the barrier, resulting in a progressive increase in the resistance to fluid flow through the cake. It must be noted that water can only be removed when the pressure drop applied across the filter cake exceeds the pressure of the water present inside the capillaries.

The capillary pressure can be modeled by the Laplace equation:

$$\Delta p = \frac{2\gamma_{23}\cos\theta}{r} \ ,$$

Where r is the capillary radius, γ is the surface tension, θ is the contact angle and P is the pressure drop. Therefore filtration can be made easier by decreasing the capillary pressure. The capillary pressure can be reduced by decreasing surface tension, increases the contact angle or by increasing the capillary radius.

Rotary Drum Filter

The drum is mounted horizontally and partially submerged in the slurry mixture to be treated. The filter medium, which is supported on a porous framework, is rotated at between 0.1 to3 rpm depending on the filtration characteristics of the materials suspended in the slurry. The inside of the drum is divided into umber of separate compartments. As the drum rotates each compartment goes through a cycle of operations which involve filter cake formation, cake washing and drying and cake discharge.

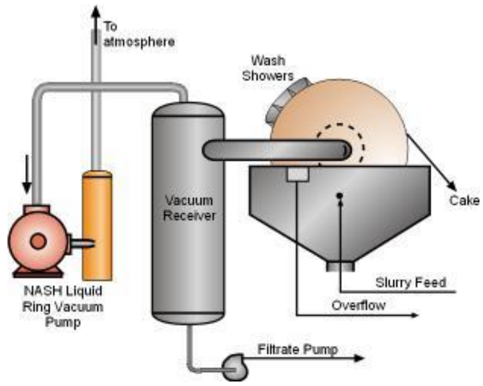


Figure 54: Rotary Drum Filter

Thermal Drying: Application of heat to remove water by vaporization.

Leaching: Any chemical process whereby minerals are dissolved into a solution that is usually aqueous.

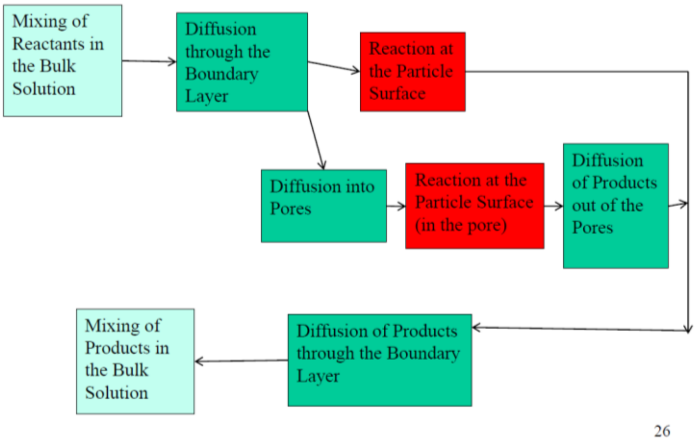


Figure 55: Leaching Reaction Steps

Reactants diffuse through the diffusion layer and are adsorbed onto solid surfaces where they react. This step is slower than diffusion and the surface area is reduced with time; therefore, this step is the rate-limiting step which controls the leaching operation. The next step is desorption where the products are desorbed from the solid after reaction and diffuse through diffusion layer into the leaching solution.

For a successful leaching system there are a number of essential aspects of processing which must be fulfilled and there are a number of features which are desirable if costs are kept to a minimum:

Essential:

- The valuable metal must be soluble in an economically useable solvent
- The metal must be economically recoverable from solution
- Any impurity elements which are co-extracted during leaching must be capable of further separation from the solution

Desired:

- The gangue minerals should not consume excessive amounts of solvent
- The solvent should be recoverable (or capable of regeneration) for recycle,
- The feed material should be free of clay materials, as these make separation of leach liquor from the treated solutions difficult,
- The feed material should be porous to the solution allowing direct contact between the solvent and the phase to be dissolved and providing a high solid/liquid area for reaction for a given amass of material and
- The solvent should preferably be non-corrosive to materials used in plant equipment to minimize capital and maintenance costs, and should be non-toxic to minimize dangers to plant personnel.

In situ Leaching

In situ leaching refers to the leaching of the ore left in a mine after it has been worked out or the application of leach solutions directly to the ore body in the ground. The leach solutions are introduced above the level of the ore body and are allowed to percolate by gravity through the ore and are collected at lower levels by a network of sumps. The pregnant leach liquor is then pumped directly the surface. This technique relies on the permeability of the ore body. If the natural porosity of the rock is low then it may be necessary to induce fractures and shatter the rock by the use of explosives. One of the difficulties with 'in situ' leaching is that extreme care has to be taken to avoid loss of the leach liquor to the natural ground water.

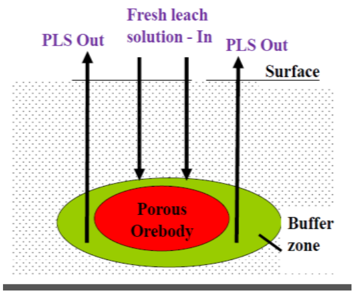


Figure 56: In situ Leaching

Disadvantages: Potential for environmental contamination, low extraction rates and loss of liquor solution to ground water.

Dump and Heap Leaching

Dump and heap leaching refers to the leaching of mined material which has received little or no size reduction following removal from the ore body. The ore, which may have maximized size of between 1.0 and 0.1 m diameter, is piled in dumps or heaps on a pre-prepared impervious base. The heap is then irrigated with leach solution and the pregnant liquor solution is then collected in a drainage system embedded immediately above the impervious base.

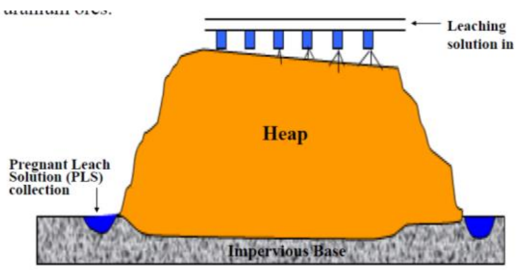


Figure 57: Heap and Dump Leaching

Disadvantages: Low extraction efficiencies, but extremely cheap.

Pressure Leaching

Pressure leaching is the chemical dissolution of soluble minerals within a solid ore or concentrate carried out at elevated pressures and giving rise to a solution containing metals to be recovered. The process is carried out in closed autoclaves which permit higher temperatures (>220°C) and pressures (>20 atm) than are possible with open tanks. The increased pressure improves the solubility rate of solids and increases the speed of dissolution into the leach solution.

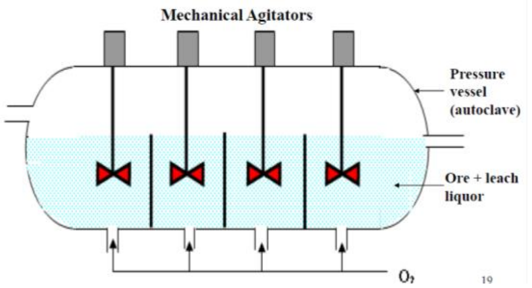


Figure 58: Pressure Leaching

|**Pregnant Liquor Solution:** The solution containing the dissolved minerals after leaching.

Leaching reactions are commonly controlled by varying three things:

- Acidity or basicity of the solution (pH)
- The electrochemical oxidizing or reducing potential
- The presence of complexing agents

Example of an E-PH diagram

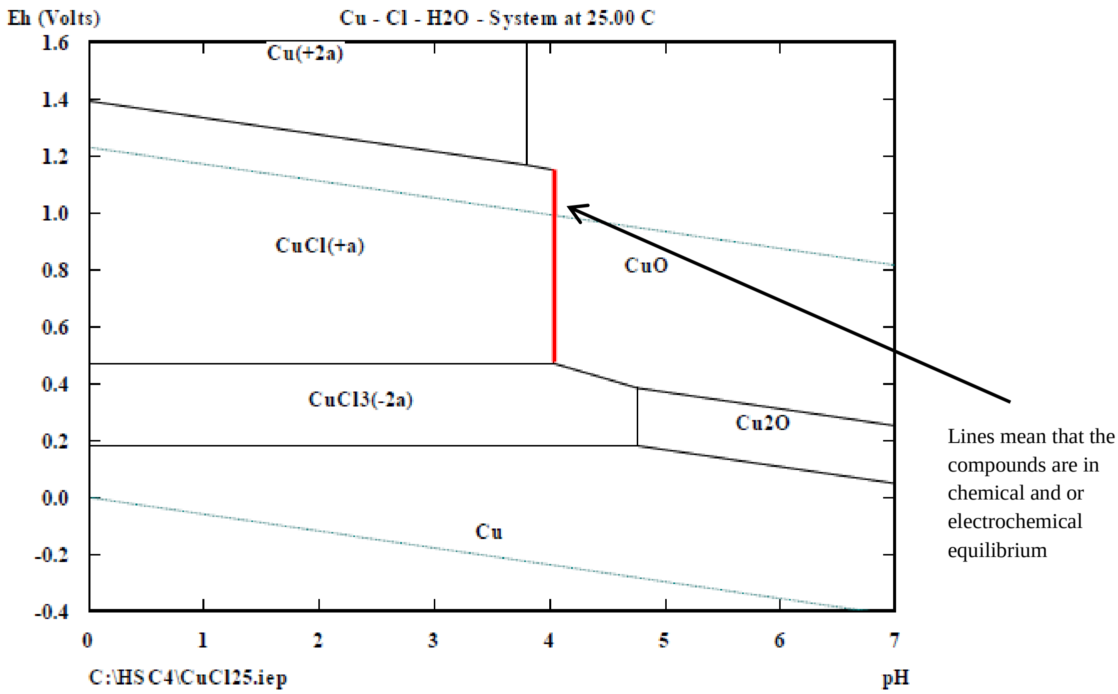


Figure 59: E-pH diagram

Following the leaching of the ore the physical separation of the pregnant liquor from the unreacted minerals is usually carried out. In the case of large ore particles, it is obvious that this can be readily archived; however very fine ore particles can be difficult to separate because they can be help in suspension in the liquid. Solid/liquid separation procedures must be employed to obtain clear liquor free from suspended matter.

Precipitation: The rapid formation of a new phase (e.g. small solid particles). It usually begins at high super-saturation ratios where rapid nucleation and growth of solid phases occur.

Saturated: The solution is considered to be saturated when the new phase and the solution are in equilibrium.

Super-Saturation: The term describes a scenario where there is more dissolved material than could be dissolved by the solvent under normal circumstances.

Saturation Ratio

$$Saturation\ Ratio, S = \frac{Activity\ of\ Solute}{Activty\ of\ Solute\ at\ Saturation}$$

If S>1 the solution is supersaturated.

The process of precipitation is outlined below:

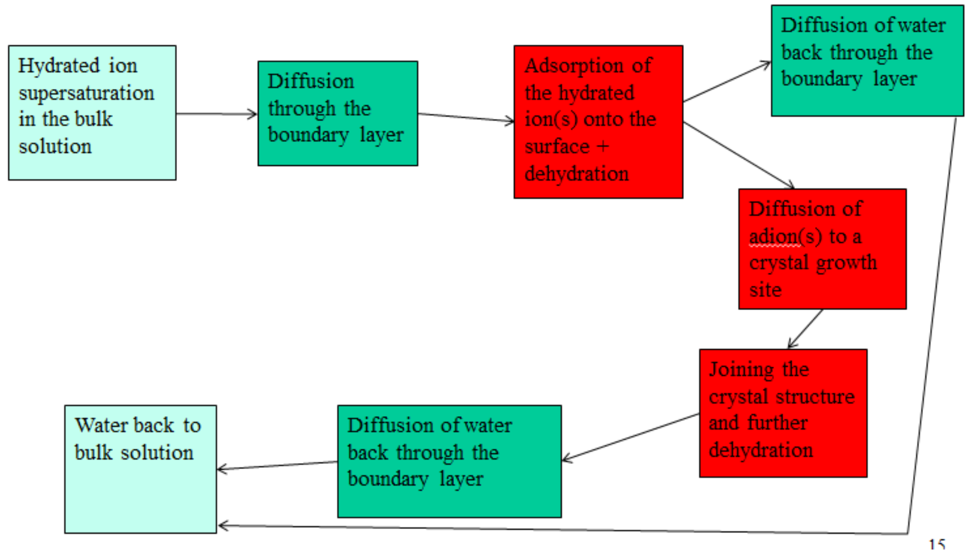


Figure 60: Process of Precipitation

Thermal Precipitation: The use of temperature to precipitate minerals from a solution.

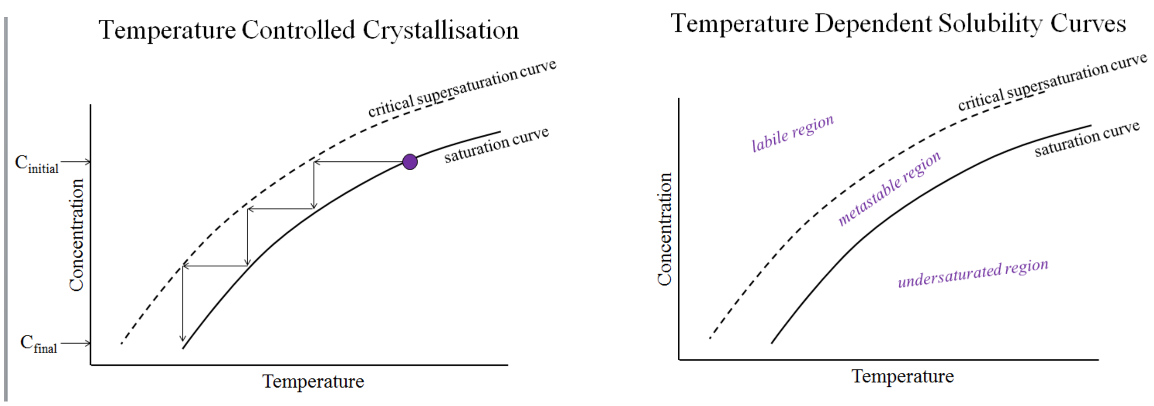


Figure 61: Temperature Controlled Crystallization

Undersaturated: In this circumstance, any crystals present will re-dissolve.

Metastable Region: The metastable region is where spontaneous nucleation does not occur; however crystals may grow.

Labile Region: In the supersaturated or labile zone, where the concentration of the solution is above the solubility curve, spontaneous nucleation followed by rapid crystal growth occurs.

It is advantageous to stay in the metastable region as crystal growth is preferred to nucleation of new crystals. This is because finer crystals are harder to filter, commonly clog filter pores and are often contaminated because of their large relative surface area and crystal imperfections.

This can be achieved by decreasing temperature and removing precipitate to stay within the metastable region.

Selective Precipitation: The process where metal ions are separated by creating precipitates.

The most widely used method of removing impurities is controlled changes in pH.

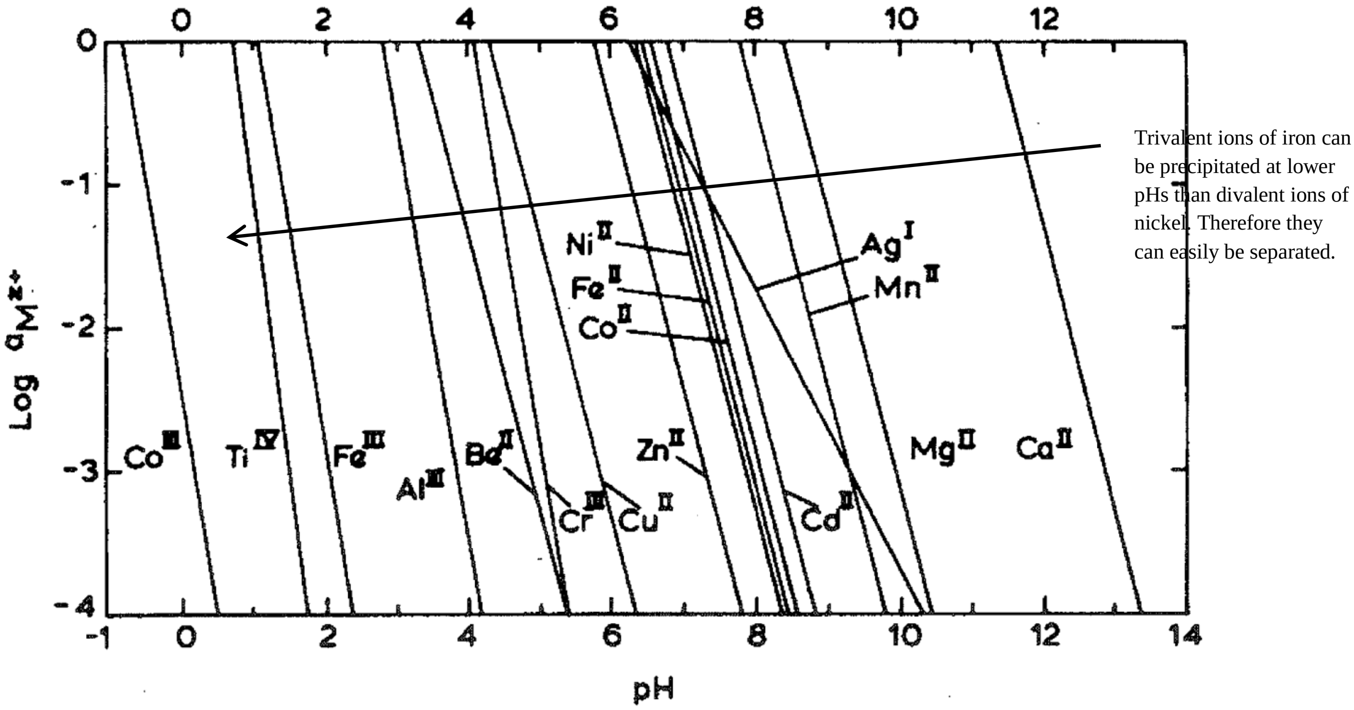


Figure 62: Selective Precipitation using pH

Sometimes reduction or oxidation can be used to allow ions to be more easily separated by altering pH. For example, divalent ions of iron can be oxidized to trivalent ions to allow them to easily be separated from divalent nickel ions as all trivalent iron ions will have precipitated before nickel begins to precipitate.

Ion Exchange: The process where metal ions in solution can be exchanged with specific ions contained in a solid or second liquid phase. It is becoming frequently more popular. It is very similar to solvent extraction.

Ion Exchange Resins: Anion exchange resin consists of a rigid or semi-rigid three dimensional framework of atoms or molecules, which must be chemically stable in solutions to be treated. Functional groups, groups of atoms which supply the exchangeable ions, are chemically bound to this framework. The form of the network determines the physical properties of the resin and the functional groups largely control the selectivity of the exchange reactions.

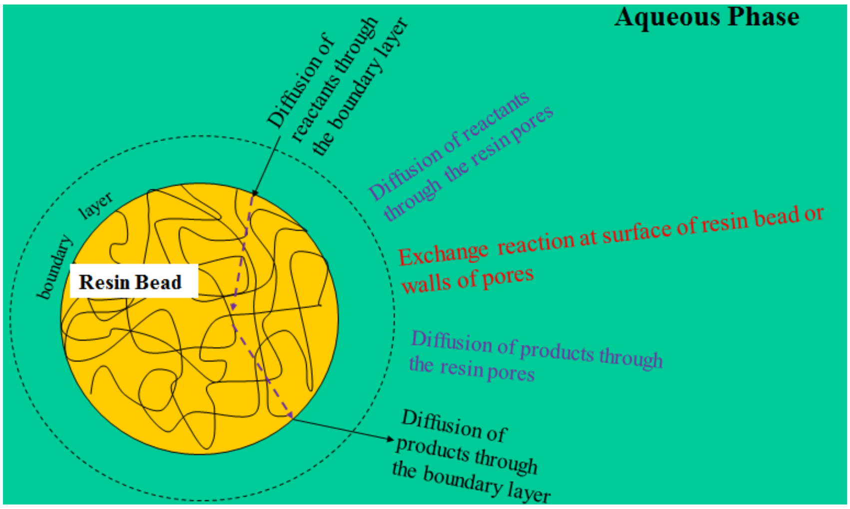


Figure 63: Process of Ion Exchange

The ions are selectively diffused through the boundary layer by exchanging ions at the interface and then the resin is stripped to recollect the extracted ions.

Please note that the rate of pore diffusion is enhanced with macropores.

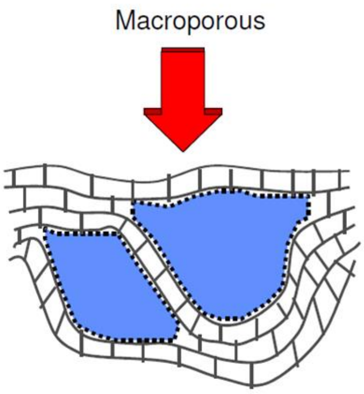


Figure 64: Macropores

Solvent Extraction: is a method to separate compounds based on their relative solubility in two different immiscible liquids.

Loading: The process of

Stripping: Stripping or elution is commonly referred to a process of extracting a material (e.g. ions or compound) from a solution into another by washing with a solvent.

Raffinate: The solution left over after loading.

Eluent: The solution used to strip the organic phase or resin.

Eluate: The solution after stripping**.**

Extractant: Is the functional group that exchanges with the cation or anion.

Dilutant: Is the organic solvent that dissolves the extractant, modifier and accelerator but is immiscible in the aqueous phase.

Modifier: Increases the solubility and stability of the metal extractant complex and enhances phase separation while inhibiting crud formation.

Accelerator: Increases the phase transfer rate.

The process of solvent extraction is shown and described below:

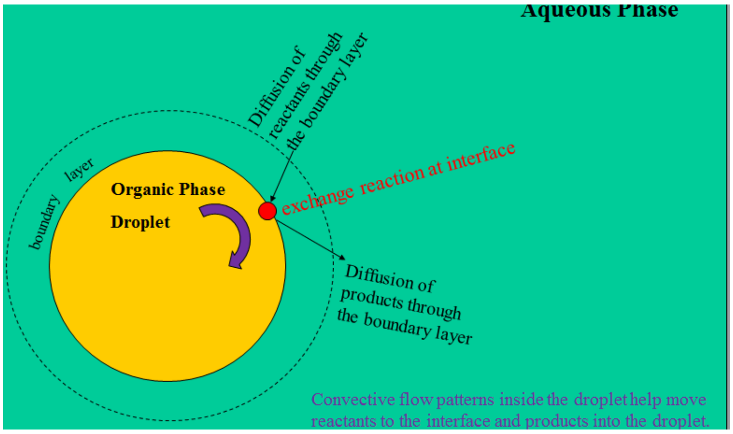


Figure 65: Solvent Extraction

Initially the aqueous phase is loaded with an organic phase that capable of extracting the metal complex. The metal complexes that is miscible in the organic phase cross the boundary layer, leaving an impurity laden solution or raffinate. An eluent is then used to strip the organic phase and collect the metal complex leaving the organic phase or eluate behind.

Crud: Is an immiscible third phase that hinders the separation of the aqueous and organic phases.

Crud is often defined as the material resulting from the agitation of an organic phase, an aqueous phase, and fine solid particles that form from a stable mixture. Crud can constitute a major solvent loss to a circuit and thereby adversely affect the operating costs; it can decrease settler capacity; and transfer impurities throughout the process. However, a small amount of crud can enhance phase separation.

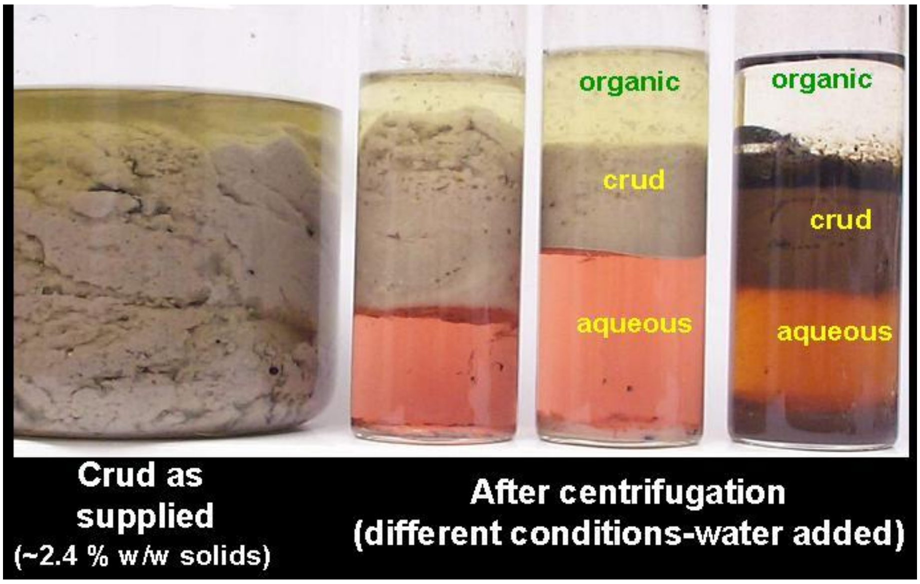


Figure 66: Crud