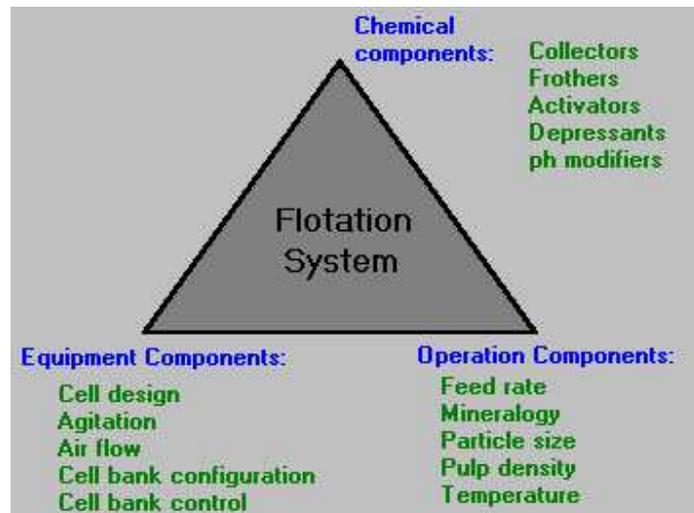


Froth Flotation

Froth flotation is one of the most versatile and flexible of all mineral separation processes. Reasonable results are fairly easy to obtain but outstanding performance from a circuit requires constant attention and good understanding of the process and ore. Some of the variables that affect the operation and control of a flotation process are classified as follows:



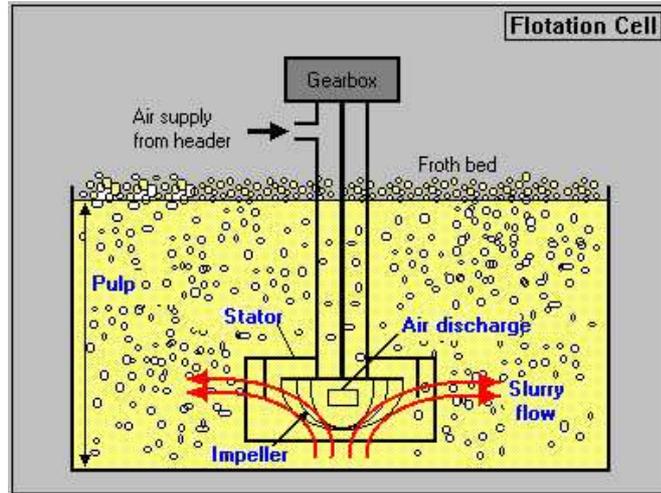
The tendency of the ore to have variable physical, metallurgical, and surface properties produces significant changes in a flotation circuit. The particle size range of the flotation feed can be substantial because of ore hardness changes and changes in the operation of the grinding circuit. This can cause extreme variation in the performance of flotation even under constant operating conditions.

Flotation operators must react and make changes without always understanding the primary cause for the observed decline in metallurgical performance. Thus flotation is often viewed as an Art rather than as a Science.

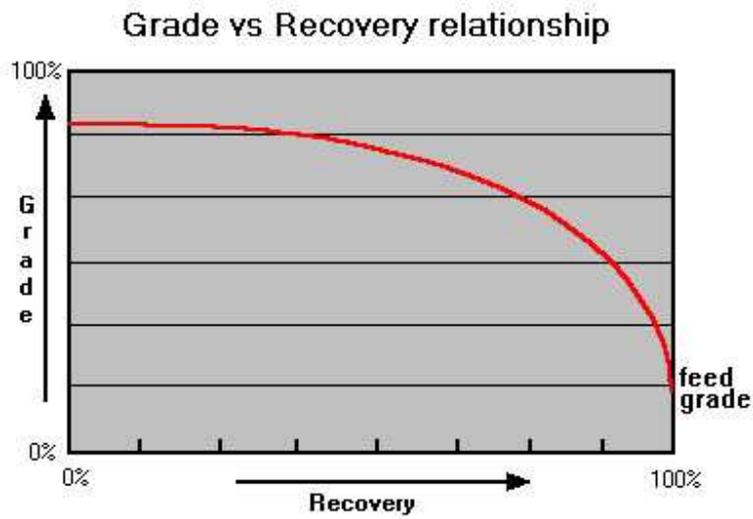
Steps Involved

1. Grinding the ore fine enough so valuable mineral particles become liberated from the waste rock and to a size range suitable to be floated (10 - 200 microns).
2. Creating a rising current of air bubbles in the pulp.
3. Making conditions favourable for the desired mineral particles to adhere to air bubbles.
4. Forming a mineralized froth on the surface of the ore pulp.
5. Removing the froth from the flotation cell or vessel.

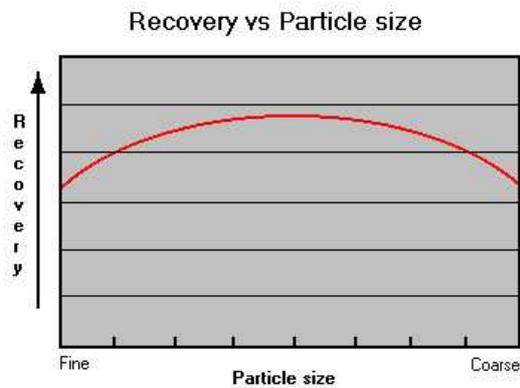
Flotation Machine



Typical Grade-Recovery Relationship



Recovery versus Particle Size



Flotation Mechanisms

Grinding an ore has an important influence on flotation. For optimum results, valuable minerals should be separated completely from the waste and from each other. This is often impractical and can complicate matters by creating particles that are so fine they are difficult to recover by flotation.

The ratio of water to solids is very important. It is usually measured in % solids by weight. If the pulp density is too low, minerals are washed out of the cell before they have a chance to float. If the density is too high, the agitators will be unable to disperse enough air into the cell and the slurry will be difficult to keep in suspension.

Flotation agitators have three basic functions: to keep sand in suspension, to disperse air as discrete bubbles and to pump pulp into the next vessel or agitation zone.

To get the desired minerals to 'stick' to air bubbles, collectors such as xanthates, are stage-added to the pulp. The collector should coat only valuable mineral particles so that water is repelled and bubbles can become attached upon collision.

Air bubbles act like 'hot-air balloons' providing the necessary buoyancy to carry selected minerals to the pulp surface. Collector addition also affects froth formation. Too much can inhibit froth stability and 'flatten the circuit', too little and not all mineral surfaces will be coated. Either way, recovery goes down. Lime is often used in flotation to increase the alkalinity of the pulp. An alkaline pH increases the volume of the froth (possibly increasing the rate at which mineral is recovered), and depresses pyrite.

Frothers such as pine oil and Dowfroth 250 are used to create a froth capable of carrying or holding the mineral-laden bubbles. Frothers impart a temporary toughness to bubbles prolonging life until they can be removed from the cell.

There are three ways that a particle can move or be transported from the pulp phase into the froth phase:

1. Bubble Attachment
2. Mechanical Entrainment
3. Carrier or "piggy-back" flotation

The first mechanism is the one that is desired and conditions with the pulp and surface chemistry must be established such that the desired minerals attach to bubbles while the undesired ones remain hydrophilic. The second mechanism is important in dealing with fine particles that become trapped in the films that exist between coalescing bubbles. It can contribute between 5 and 20% to the total recovery of particles and is a non-selective process. The third mechanism is not well recognized or understood – essentially fine particles that have weak coatings of collector are able to adhere to coarser floatable particles and are carried into the froth phase as these coarse particles attach to a bubble. The mechanism can be selective but generally wears off as flotation and/or conditioning time increases.

Once withdrawn, a froth should break down rapidly, so excess froth in the downstream processes does not occur. The type of frother is also important to bubble formation - both number and size. As the concentration of frother increases, bubble size decreases, thereby improving air dispersion in a flotation cell. Frothers, such as pine oil, do not mix well with water, so addition is often made to the grinding

circuit so agitation can promote dispersion into the pulp. Water-soluble frothers, (Dowfroth 250 and Cyanamid AF65) are often stage-added along a flotation bank to maintain a stable froth phase and reduce consumption.

Flotation operators must pay close attention to froth characteristics as changes in the appearance are indicative of ore or circuit changes. There are many different types of froth that can be seen in a flotation circuit which are unique to each ore.

Reagents

- Frothers
- Collectors
- Depressants
- Activators

General frother information

When mineral-bubble agglomerates reach the surface of a flotation cell, the bubbles can break and the collected mineral fall back into the slurry. To prevent this loss, a frother is added to produce a froth phase stable enough to hold the floated particles until they can be removed from the cell.

Frothers are generally slightly soluble polar compounds which adsorb preferentially at the air-water interface. Their function arises from their ability to reduce the surface tension of the L/G interface when present at low concentrations. Generally, long- chained, complex alcohols are effective frothers in amounts ranging from 15 to 50 g per tonne of ore. The frother molecules orient themselves at the interface with the hydrocarbon end in the air phase and the hydroxyl end in water.

When too much froth is added to the pulp, the froth will collapse when using frothers that are immiscible. This has important implications in dealing with run-away problems in a flotation plant.

Pine oil

Pine oil and its relative reagent - eucalyptus oil (used in Australia), are mixtures of terpene alcohols such as Terpeneol, Borneol, and Frencheol together with various aromatic compounds such as ketones, ethers, and other terpene hydrocarbons.

It is a widely used household cleaning agent (check out PineSol and/or Mr. Clean) and so, is not particularly dangerous to the environment especially at the levels used in flotation (5 - 25 g/t). Its fumes are toxic however, so care must be taken in handling and preparing the chemical.

Pine oil is derived from the pyrolysis (destructive distillation) of pine trees or as a by-product from oil refineries. The alcohol content of commercial agents varies from 60 to 90 percent and is priced accordingly. It is one of the most widely-used frothers, with MIBC being its major rival. Excellent for recovery, up to 85 percent of most base metal sulphide minerals in an ore can be recovered without collector addition. Grade of concentrate however can be a problem and so, often secondary frother additions can be beneficial.

MIBC

Methyl isobutyl carbinol and its related alcohol-type frothers are derived as by-products from oil refining. The reagent is cost competitive with pine oil and so enjoys wide-spread use together with the

isoamyl and isopropyl. MIBC is superior to pine oil at achieving high grade concentrate - froths recover more water and provide better drainage of mechanically-entrained particles.

MIBC lacks staying power, so often stage-addition is needed to maintain froth on the scavenger cells. Froth height can also be a problem with heavily-mineralized froths but the use of wash water addition as is done in Column Flotation can overcome this problem.

Poly-glycols

The poly-glycol ethers are very strong frothers completely miscible in water and capable of providing tough, compact, long-lasting froths. On their own they are effective collectors and are usually added at addition rates considerably less than pine oil and MIBC.

These frothers produce such tough froths that upon removal from the cell, it can be difficult to break them down. This can lead to serious problems with pumping and de-watering.

They are not corrosive and don't attack rubber as do pine oil and MIBC. Their lower addition rate is facilitated by the fact that they are completely miscible in water and can be added as a dilute solution.

Unlike immiscible frothers, the polyglycols do not destabilize the froth upon over-addition - this can lead to significant run-away trouble when processing sump floor material.

Run Away

A run-away problem can occur when excess frother concentration occurs during flotation. This can result from the natural increase in concentration when slurry is processed in a rougher/cleaner circuit or when sump floor material is returned to the process.

A run-away is a frightening experience for a novice flotation operator. Froth begins to flow from the surface of the cells at such a rate that launder water sprays cannot break down the froth and it then begins to overflow the launder depositing on the sump floor.

Even by dropping the cell level, the froth continues to flow and cannot be stopped. The solution with most immiscible frothers is to shut off the metering system and then pour a large bucket of frother into the feed sump. This extreme addition will cause the froth to collapse as the second layer of liquid frother on the bubble surfaces cannot be stabilized. With miscible frothers - such as the poly-glycols - this method does not work.

TEB

Triethoxybutane or TEB frother is used extensively in African operations as a supplement with Pine oil. It is a fast-acting frother with significant effervescence at low concentrations. Pine oil is generally needed as the primary frother to ensure sufficient froth volume is maintained on the scavenger cells.

Cresylic acid

Cresylic acid is a name given to very impure bottom-products produced from the refining of petroleum. Creosotes and cresylic acid predominate in these materials; the exact composition dependent on source. As a result the quality of this frother varies considerably and its use is restricted to cases that can tolerate extreme changes in frothing properties. It is a cheap reagent as one might suspect, but its use is dwindling as more modern approaches to flotation have evolved. Some coal operations still use cresylic acid.

Frother Comparison

TYPE	ADDITION RATE (g/t)	FROTH CHARACTERISTICS	IMPORTANT USES
Pine oil	5 - 25	stable, close-knit bubbles	Recovery problems with sulphides
MIBC (alcohols)	5 - 25	uncompact froth, large bubbles	Grade problems with sulphides
Poly-glycols	1 - 10	compact, long-lasting froth	Selective Sulphide Flotation
TEB	5 - 25	fast-acting, effervescent	Secondary frother good for grade
Cresylic Acid	25 - 50	large bubbles, non-selective froth	Some coal and iron ore use - cheap

Collector reagents

Xanthates

Dithiophosphates

Fatty Acids

Amines

Anionic collectors

Anionic collectors are those class of organic reagents that produce negatively charged ions that contain a hydrocarbon chain upon dissolution in water.

Anionic reagents can adsorb physically onto mineral surfaces that possess active sites having strong positive charge. The sign and magnitude of the surface charge is a function of pulp chemistry conditions such as pH and the concentration of ion species derived from the mineral's crystal lattice as well as from other minerals that are present in the ore.

Of these conditions, pH is perhaps, the most important because of its ease of control with sulphuric acid and/or lime, caustic soda or soda ash. There will be a unique pH value below which a mineral surface is positively charged and above which a negative charge is present. This pH is called the Zero Point of Charge since the surface charge is neutral.

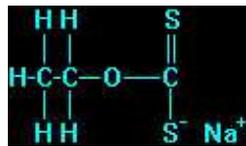
Xanthates

The most widely-used collectors in sulphide mineral flotation are the xanthates or thiocarbonates. These reagents were developed in the 1920's and played a major role in the spread of flotation throughout the world. Hydrocarbon chain length is from: ethyl C2, propyl C3, butyl C4, amyl C5 to hexyl C6. They are classified as Anionic reagents.

Xanthates are supplied as either a potassium or sodium salt in the form of solid pellets which are soluble in water. Normal feeding procedure is to use a solution concentration of 10 to 30 %. All xanthates decompose in acid pulps so their use is restricted to alkali circuits.

Ethyl Xanthate

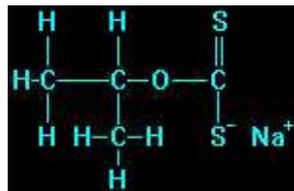
The xanthate hydrocarbon chain C2 is straight chained as follows:



Sodium ethyl xanthate is used most frequently for complex sulphides due to its low collecting power and maximum selectivity. For this reason the use of SEX as an auxiliary collector with one of the more powerful xanthates, is standard practice to increase grade and recover fines. It is the most important collector used to recover galena from Pb/Zn ores.

Propyl Xanthate

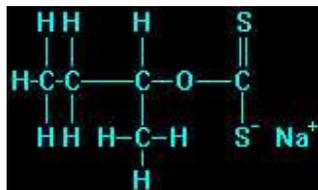
The hydrocarbon chain C3 is generally branch chained as follows:



As a branch chained collector, sodium isopropyl xanthate can be competitive with PAX. It is the most widely used of the xanthates for sulphides due to its lower cost (about 75 percent of the cost of PAX). It provides good compromise between selectivity and power.

Butyl Xanthate

The hydrocarbon chain C4 is generally branch chained as follows:



Sodium isobutyl xanthate is a low cost, powerful collector and has a tendency to float iron sulphides, unless depressants such as lime are used. It can be competitive with PAX, but generally requires higher addition rates.

Amyl Xanthate

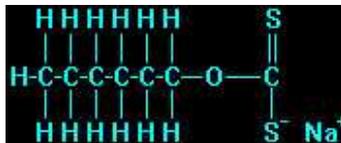
The hydrocarbon chain C5 is generally straight chained as follows:



Potassium amyl xanthate is the most powerful and least selective collector. Improved selectivity however can often result from its use since lower quantities are generally required than the shorter chained xanthates. It is the most widely used collector for chalcopyrite however, and is often used in combination with dithiophosphates. Sodium Amyl Xanthate is often substituted for PAX due its lower molecular weight which transforms into more collector per unit weight of reagent.

Hexyl Xanthate

The hydrocarbon chain C6 is generally straight chained as follows:



Hexyl xanthate is rarely used as its solubility is appreciably less than that of the other xanthates. Because of its lower solubility, it does not always show a reduction in unit additions over shorter chained reagents.

Dithiophosphate

Aerofloat 3477 and 3501 promoters are dithiophosphates manufactured by Cyanamid. These soluble, straight-chained collectors have the following chemical composition:



Although anionic as well, thiophosphates are weaker than xanthates with the same chain length, but are often used as auxiliary collectors due to their higher selectivity.

Aero 3501 is especially effective in the flotation of coarse middlings and in the separation of copper and cobalt minerals. Aero 3477 and 3501 are marketed as soluble salts and can be dissolved readily in water unlike their related chemical group - the Aerofloats. These latter reagents are mixtures of acid thiophosphates and must be metered "neat" into the pulp. The usual dose is 5-25 g/tonne.

Fatty acids

Fatty acid or carboxylate-type collectors have longer hydrocarbon chains than do xanthates and dithiophosphates. Linoleic and Oleic acid are the most well-known types, both having a C17 hydrocarbon chain attached to the carboxyl group. Linoleic is an isomer possessing two double carbon bonds as opposed to the one in oleic acid.

As acids, these reagents are not soluble in water and are often added as emulsions with fuel oil. They function best at pH 5-6 especially when used to float iron oxides which are positively charged in this pH

range. Addition rates are higher at 100-500 g/t in comparison with other anionic collectors, but unit cost is appreciably lower (5-10 times). Sodium salts are sometimes used to reduce addition rate due to the solubility of the salt. However, the benefit of lower hydrocarbon is usually compensated by the increased weight of sodium over hydrogen and selectivity generally is poorer than the equivalent acid.

These reagents are biomass by-products and are not a particularly hazardous environmental concern.

Cationic collectors

Cationic collectors are a class of organic reagents that produce positively charged ions that contain a hydrocarbon chain upon dissolution in water. Cationic reagents can adsorb physically onto mineral surfaces that possess active sites having strong negative charge. The sign and magnitude of the surface charge is a function of pulp chemistry conditions such as pH and the concentration of ion species derived from the mineral's crystal lattice as well as from other minerals that are present in the ore.

Of these conditions, perhaps pH is the most important because of the ease of control with sulphuric acid and/or lime, caustic soda or soda ash.

There will be a unique pH value below which a mineral surface is positively charged and above which a negative charge is present. This pH is called the Zero Point of Charge since the surface charge is neutral at this pH value.

Amines

Amines are cationic collectors manufactured as primary, secondary, tertiary or quaternary ammonium acids or salts (chloride, acetate). They are the most-widely used collector in the treatment of iron ores by flotation. In these applications, they are used to recover silica or quartz to the froth phase with the iron minerals being depressed to the process tailing pulp. As acids they must be added neat but as salts, they are soluble in water. Hydrocarbon chain lengths vary between C18 to C24 with the longer chain lengths being used to float potash ores at very coarse size ranges.

To float quartz from iron ore, pulp pH is held at 10 to 11 with caustic soda (lime would activate hematite) with starch or dextrin addition being used to depress the iron minerals by selective aggregation. Often to upgrade the flotation feed and minimize interference from slimes, the pulp is subjected to selective flocculation ahead of flotation to reject fine quartz.

Collector Comparison

TYPE	STRUCTURE	MINERALS FLOATED	ADDITION RATE [g/t]
Xanthates	$\begin{array}{c} \text{R-O-C=S} \\ \\ \text{S}^- \end{array}$	Sulphides	5 - 75
Dithiophosphates	$\begin{array}{c} \text{R-O} \\ \\ \text{R-O} \end{array} \text{P=S} \\ \\ \text{S}^-$	Sulphides	5 - 100
Fatty Acids	$\begin{array}{c} \text{R}^+-\text{C=O} \\ \\ \text{O}^- \end{array}$	Oxides	100 - 500
Amines	$\begin{array}{c} \text{H} \\ \\ \text{R}^+-\text{N}-\text{H} \\ \\ \text{H}^+ \end{array}$	Oxides	100 - 1000

Depressants

- pH modifiers
- Sodium Cyanide
- Sodium Sulphide
- Sodium Silicate
- Starch/Dextrin
- Sulphur dioxide

pH modifiers - Depression or Activation ?

Depression can be achieved using alkaline pH modifiers as depressants.

There is a critical pH value above which a mineral cannot be floated with a specific collector at a specific concentration. The critical pH values for most sulphide minerals have been measured using Contact Angle data for different collectors. By adjusting pH, the separation of multiple sulphide minerals is possible. The alkali pH modifiers are lime, caustic soda and soda ash. Ammonia is also used in some cases to act as a chelating agent for Cu^{++} ions.

Acid modification can also be used to affect depression. Sulphuric acid is the most typical reagent used together with sulphur dioxide.

Pulp pH modifiers can also be activators for certain minerals. Acid pH conditions can promote collector adsorption on a mineral surface and produce flotation conditions following an initial period of depression.

Critical pH

Critical pH defines the pH value above which a specific mineral cannot be floated with a specific collector at a specific concentration.

For example, critical pH values for the following sulphide minerals in a KEX solution at a concentration of 25 mg/L (25 °C) are:

ZnS	6.0
FeS ₂	6.4
PbS	10.4
CuFeS ₂	10.5
Cu ₄ FeS ₅	13.0
Cu ₂ S	14.0

Separation of galena (PbS) and chalcopyrite (CuFeS₂) from pyrite (FeS₂) can be achieved with this collector at pH values between 6.4 and 10.4. One would probably use a pH value of about 9.5 to 10.0.

Lime

Lime or calcium hydroxide in slurry form is used to adjust the pH of a pulp to an alkaline level between pH 10 to 12. Lime is the cheapest of all alkali chemicals but cannot always be used due to the potential activation of gangue minerals by the bivalent calcium ion.

In some cases however, particularly with the mineral pyrite, it is claimed that calcium has a depressing action over and above that of pH.

Caustic soda

Caustic soda or NaOH (KOH as well) is used to adjust the pulp pH to an alkaline level above 10. Its use is demanded for high pH levels (above 11.5) or when the presence of calcium ions is deleterious.

Soda ash

Soda ash or sodium carbonate (or bicarbonate) is used to adjust pulp pH into an alkaline condition upto pH 10. The reagent begins to buffer at about pH 9.5 and it can affect bubble stability such that some operations do not use a frother. This is not recommended as control of the froth phase is no longer independent of pulp chemistry conditions.

The carbonate ion is also claimed to have a depressing action over and above that of pH. Soda ash is almost exclusively used to adjust the pulp pH of a copper flotation circuit ahead of zinc flotation for nearly all of the milling plants of the Noranda Group. It is claimed that lime depresses chalcopyrite. Caustic soda is too expensive for these applications.

Sulphuric acid

To adjust the pH of a pulp into the acid region, sulphuric acid (H_2SO_4) is almost exclusively used. When bivalent ions (SO_4^{2-}) are a problem, HCl can be substituted but unit cost is much higher and the chemical is slightly more dangerous (Cl_2 gas evolution). Most acid circuits are operated at pH 4 or higher because of the extreme corrosion problems in handling such material.

In some cases, liquid SO_2 under pressure, can be bubbled into the pulp to adjust pH to 4-5 to depress galena from chalcopyrite or to depress sphalerite from pyrrhotite. Sulphur dioxide dissolves to produce sulphurous acid (H_2SO_3) which has a depressing action over and above that due to pH.

Sulphide dioxide

Liquid SO_2 can be used as to separate sphalerite mineral from gangue minerals like pyrrhotite and/or pyrite. The SO_3^{2-} ion is apparently responsible for the depression of sphalerite at pH 4-5 allowing the iron minerals to be floated.

Galena separation from chalcopyrite can also be achieved using SO_2 treatment.

Sodium cyanide

Sodium cyanide is the most widely used depressant chemical to separate multiple sulphide ores. There is a critical cyanide ion concentration above which mineral surfaces cannot be hydrophobic - dependent on mineral and collector type and concentration of collector.

Its use is generally required when pH modifiers are ineffective, particularly with ore containing appreciable pyrite. It can also depress chalcopyrite from galena or molybdenite but strangely, it is also used at similar addition rates to depress pentlandite from chalcopyrite.

If significant precious metal content is in the mineralization, cyanide use should be avoided because of the potential for gold and silver dissolution. Pulp pH when using cyanide should NEVER be less than 10.0 in order to prevent HCN gas evolution.

Sodium sulphide

Sodium sulphide use is sometimes preferred to sodium cyanide because of toxicity problems. Cyanide dissolves heavy metals which can create serious environmental concern.

The reagent acts to strip collector from a mineral surface rendering the mineral hydrophilic. The reagent is widely used in Copper/Molybdenum separations where the chalcopyrite is depressed from a bulk concentrate in a bulk-selective circuit. Galena can also be de-activated using this reagent.

Its depressing action however is only temporary, since the ion species are rapidly oxidized when air bubbles are introduced into the pulp. As the concentration of the specie drops, the depressed minerals can re-adsorb collector and become active once more. Stage addition and a powerful adsorbent like activated carbon can help in this case.

Sodium Silicate

Sodium silicate or "water glass" is a depressant used when excessive gangue "slimes" are interfering with successful flotation. Such material readily forms flocs during flotation causing difficulties with flotation of another mineral - both recovery and concentrate grade problems arise. The reagent acts to disperse such flocs and keep the slimes from interfering with the flotation of the valuable mineral.

Starch/Dextrin

Starch derived from biomass (corn, wheat, rye, etc.) can be used to prevent collector adsorption on specific minerals. The molecular structure of these derivatives is quite complex with very long-chained hydrocarbons having a number of polar groups along the chain. Molecular weights are measured in hundreds of thousands.

The exact mechanism is not fully understood but flotation of quartz from iron ores containing hematite relies on this reagent to keep the iron minerals depressed since at pH 10-11, both hematite and quartz are negatively-charged and will both adsorb collector. Starch coats the hematite surface selectively preventing amine adsorption. It can also act to flocculate fine hematite material allowing upgrading prior to flotation by selective flocculation.

Starch and dextrin are also used in some bulk-selective circuits to separate galena from chalcopyrite, to separate nickel from copper and to depress calcite or dolomite gangue in some copper ores.

Depressant Comparison

TYPE	DEPRESSING ION	ADDITION RATE (g/t)	IMPORTANT USES
pH modifiers	OH^-	50 - 2000	all multiple sulphide ores
Sodium Cyanide	CN^-	5 - 250	sulphides ores with pyrite
Sodium Sulphide	HS^-	25 - 4000	Cu/Mo and Cu/Pb ores
Sodium Silicate	SiO_3^-	50 - 250	gangue dispersant
Starch/Dextrin	-	50 - 250	depression of Fe_2O_3 from SiO_2
Sulphur Dioxide	SO_3^-	100 - 250	ZnS/FeS_2 or ZnS/FeS ores

Activators

pH modifiers

Na Hydrosulphide

Copper Sulphate

Multivalent ions

Sodium hydrosulphide

Sodium sulphide or more frequently sodium hydrosulphide (NaHS) in addition to being effective depressants for sulphide minerals can be used to promote collector adsorption on certain "oxide"-type minerals of copper and lead.

Malachite and azurite - two forms of copper carbonate minerals do not adsorb collector well. Addition of NaHS causes a sulphide film to form on the surface of the mineral particles allowing adsorption of collectors such as amyl xanthate. The crystalline form of cuprite also responds well to this treatment as does the lead carbonate mineral - cerussite.

The film of sulphide is only tenuously bonded to the surface and can be easily washed off by attrition. Too much NaHS can also result in total depression as with sulphides. For mixed sulphide/oxide ores, the usual practice is to first float the sulphides normally, then treat the tailing product with NaHS and PAX to recover the oxide component.

Copper sulphate

There are a number of metal ions which can be used to activate sphalerite - a zinc mineral that does not respond well to xanthate collectors. Zinc xanthate is readily soluble so by replacing zinc in the crystal lattice at the mineral surface with a metal ion that can form stable xanthate salts, adsorption of collector is possible. The reaction is as follows:



Copper sulphate is readily soluble but is a very expensive reagent. No other controllable, cheap reagent has yet been found.

Pyrrhotite activation (monoclinic and hexagonal) is often necessary to increase flotation rate and recovery in copper-nickel ore treatment.

Multivalent ions

In some cases, spectator ions derived from the dissolution of certain ore constituents can lead to inadvertent activation of a mineral. This can be a major problem when grinding copper/zinc ores as the copper minerals release small amounts of copper ion into the solution which can then activate the zinc mineralization during the copper flotation stage.

Other multivalent ions that can lead to difficulties include Ca^{++} , Al^{+++} , Fe^{++} or Fe^{+++} , Ba^{++} and Mg^{++} . These ions can influence the flotation of gangue minerals by acting as bridges between the negatively-charged gangue mineral surface and anionic collectors.

The technique has been exploited in the People's Republic of China where Ca^{++} activated quartz flotation with anionic collector (fatty acids) has been used to treat certain types of fine-grained iron ores at pH 11.

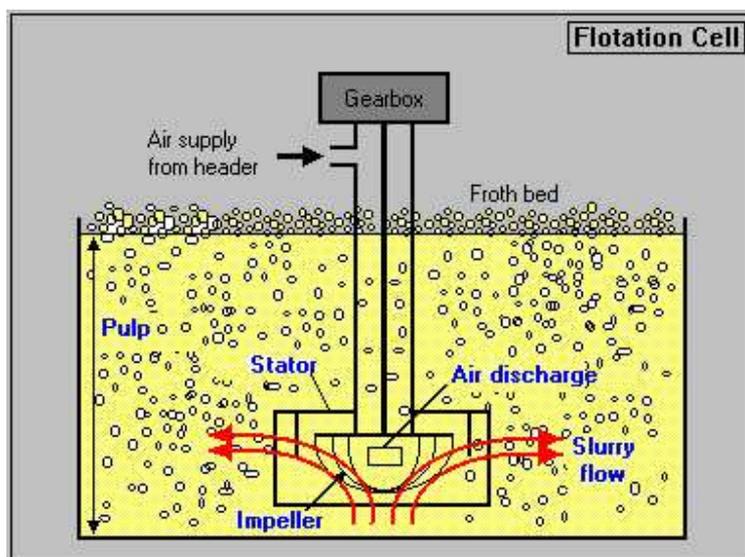
Activator Comparison

TYPE	ACTIVATING ION	ADDITION RATE (g/t)	IMPORTANT USES
pH modifiers	H_3O^+ (H^+)	50 - 2000	all multiple sulphide ores
Na HydroSulphide	S^-	25 - 500	oxide copper and lead ores
Copper Sulphate	Cu^{++}	50 - 500	sphalerite and pyrrhotite
Multivalent ions	-	-	a problem in some ores

Flotation cells

The most popular flotation cells (diagram below) in use today are:

- Denver machines
- Agitair machines
- Wemco-Fagergren machines
- Outokumpu Oy's OK machines
- Dorr-Oliver machines



Each have their own unique characteristic: Denver uses an inverted cone called a DR mechanism to force pulp to flow in a vertical direction; Agitairs have the rotor baffles installed as part of the cell rather than

part of the impeller; Wemco-Fagergrens are squat-type cells with a star-shaped impeller tied into a false bottom system to cause vertical motion in the pulp; the OK and DO units have a parabolic-shaped impeller that equalizes the pressure on all points on the impeller surface so that air blown in through the impeller is distributed to all parts of the cell uniformly.

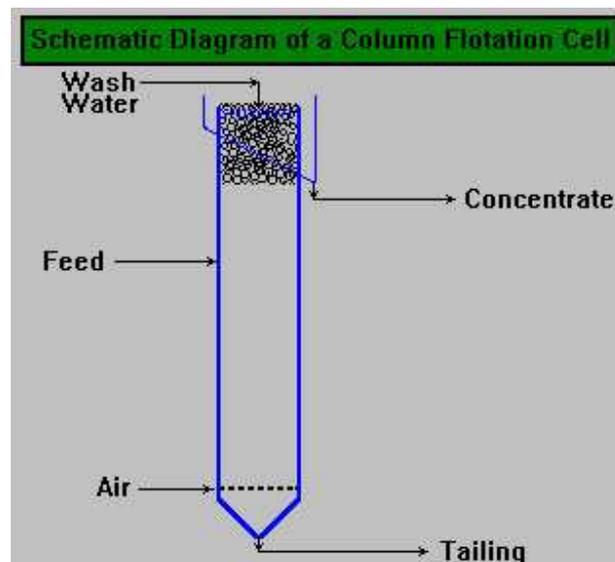
Regardless of the type of cell used, all of the mechanical varieties are installed in banks of 4 to 6 cells in series. Pulp flows between each vessel because of the agitation of the impellers. Tailing leaves the last cell in a bank through a vertical underflow pipe with an automatic control valve tied in to the pulp level in the cell. The concentrate flows off the surface of the vessel into launders hung on each side of the bank. Wash water causes the froth to flow down to a pumpbox for transfer to another stage of the process.

Complete flotation circuits consist of several of these banks in series and perhaps several of these multi-bank stages in parallel. The unit size of flotation cells have been steadily increasing since flotation was first introduced. Early cells were 10 to 20 ft³ while today 300 to 2000 ft³ units are typical. The largest unit is 2000 ft³.

Column flotation is now being used to reduce the floor space and power requirements of the mechanical cells.

Column flotation

In recent years, an increasing number of mills are installing column flotation cells to supplement or replace conventional flotation machines. Column cells (pictured below) consist of a cylindrical or square vessel from 150 mm to 3.6 m across and up to 10 m high. Pulp is introduced about half way down the vessel and tailing pulp is extracted out the bottom through a valve that controls pulp level. The pulp is kept above the point of feed entry and a very high froth column (up to 1.2 m) exists above the pulp. To stabilize this froth and provide a washing action within the froth, water is gently rained down from above the froth.

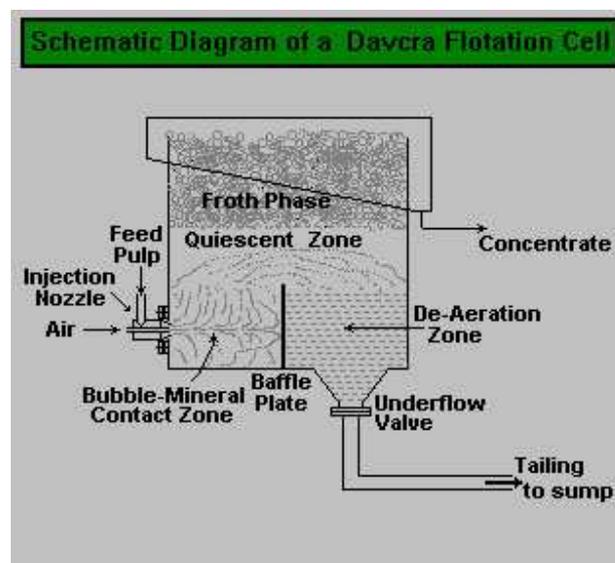


The wash water prevents bubbles from coalescing and increases the drainage rate of mechanically-entrained particles. Air is introduced through a piece of holed rubber or filter cloth or via a sparging unit located at the vessel bottom. Because of this, these units are often said to be counter-current since air

bubbles move in a direction counter to pulp flow. Fluid flow measurements however, indicate that the pulp is close to being fully mixed so the counter-current benefits are not really being exploited.

Column flotation was developed by Boutin and Wheeler in Labrador in 1964 and took about 15 to 20 years to become an important part of the flotation field. Its application virtually exploded following expiration of the patents. Several other flotation cells of a similar principle should also be mentioned here.

Also in 1964, Davis of Consolidated RioTinto of Australia invented the DAVCRA flotation cell (pictured below) in which pulp is introduced into a vessel similar to a Column cell through a bi-phase nozzle. The pulp swirls around an inner core of air ripping bubbles from the air jet surface and enters the cell as a turbulent mass of interacting air, water and solids. Residence times in these units are of the order of 45 seconds compared with 15-45 min. for Column cells and 10 - 20 min. for conventional flotation cells. The unit is particularly good at coarse particle recovery in a grinding circuit. It has been tested in Canada at Hudson's Bay Mining in Flin Flon but has not received widespread use.

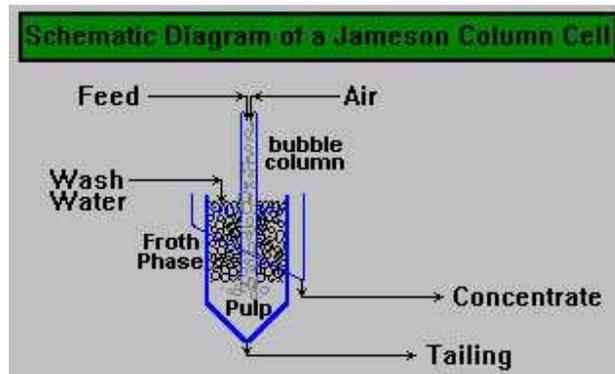


The second unit of importance is Outokumpu Oy's Flash Flotation cell developed specifically as a unit cell to be used within a grinding circuit treating cyclone underflow material. Pulp is fed into this unit underneath the froth phase. An impellor similar in design to the OK machines is used to introduce air. Tailing exits through the bottom of the vessel to be returned to the grinding mill.

Recoveries in these last two types of applications have been reported at 30 to 75 percent - a remarkable level considering that the separation process of a conventional flotation circuit still remains to be used to treat the grinding circuit product.

More recently, the Column cell has evolved into the Jameson "short column" cell. Also an Australian invention, the Jameson cell (pictured below) introduces air into a downcomer pipe installed in the centre of the vessel into which the feed pulp is flowing. The mixture of air and pulp at voidage fractions of 0.5 to 0.6 produces a bubbly-flow down into the pulp phase in the cell where the bubbles with attached particles rise to form a stable froth phase and the hydrophillic tailing particles are discharged from the bottom of the cell. A Jameson short column cell occupies the same floor space as a

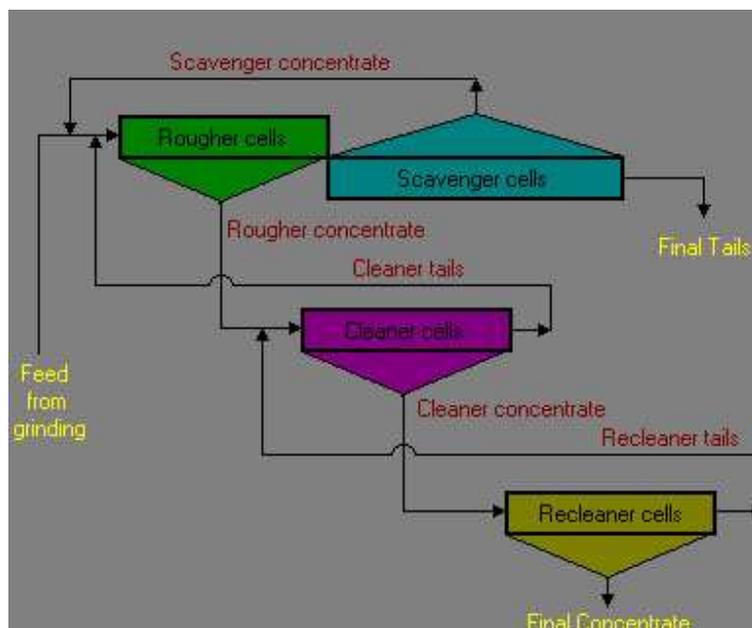
conventional column but does not have the associated height or weight. Capital costs are lower, an air compressor is not required as the pulp entrains the air as bubbles directly. With no sparger, maintenance costs are reduced and operation is easier to control.



Overall cell residence time is about 2 minutes but residence time does not have the same meaning as in a conventional column or mechanical cell. Scale-up is based on cross-sectional area. A better grade/recovery relationship is claimed for the Jameson over conventional column flotation.

Flotation Circuits

Generally, all circuits produce a froth (concentrate) that overflows from the lip of each flotation cell and a slurry (tailing) that flows out of the end of the bank of cells. The amount of copper (expressed as a weight%) in the feed is called the 'Head' Grade. The amount in the froth is called the Concentrate Grade while the amount left in the slurry is called the Tailing Grade. A flowsheet is made up of three circuit stages. A flotation circuit diagram is pictured below.



The first set of cells or bank is called the 'Roughers'. This stage receives flotation feed from the grinding circuit, middling return products (such as scavenger concentrate and cleaner tailing) and material from the floor sumps (mainly clean-up water and discharged sand from pump-boxes). The roughers produce a rougher concentrate which feeds the cleaner circuit and a rougher tailing which flows to the scavenger stage. The froth is normally removed at a maximum rate limited by the available cleaner capacity.

The primary function of the rougher cells is to make a tail as low grade as possible with a concentrate grade that is acceptable to the cleaner circuit.

TARGET: Trade-off between Recovery and Concentrate Grade

The next stage of cells is called the 'Scavengers'. This circuit produces a scavenger concentrate that is too low grade to be sent to the cleaners so it is recirculated back to the roughers. This circuit is the last chance to recover values before the pulp leaves the concentrator. It is therefore highly reagentized and so concentrate is pulled off much faster than in the roughers.

The primary function of the scavenger cells is to make a final tail as low grade as possible.

TARGET: Maximize Recovery

Waste material is pulled off the roughers together with valuable mineral. Some of these waste minerals are free and some are still attached or locked to valuable mineral. In the 'Cleaner' circuit, the rougher concentrate may be reground and then refloatated until the grade is high enough to be sent for dewatering. The recycle of material sets up a trade-off between high concentrate grade and high recovery. The optimum point in most mills is determined by economics.

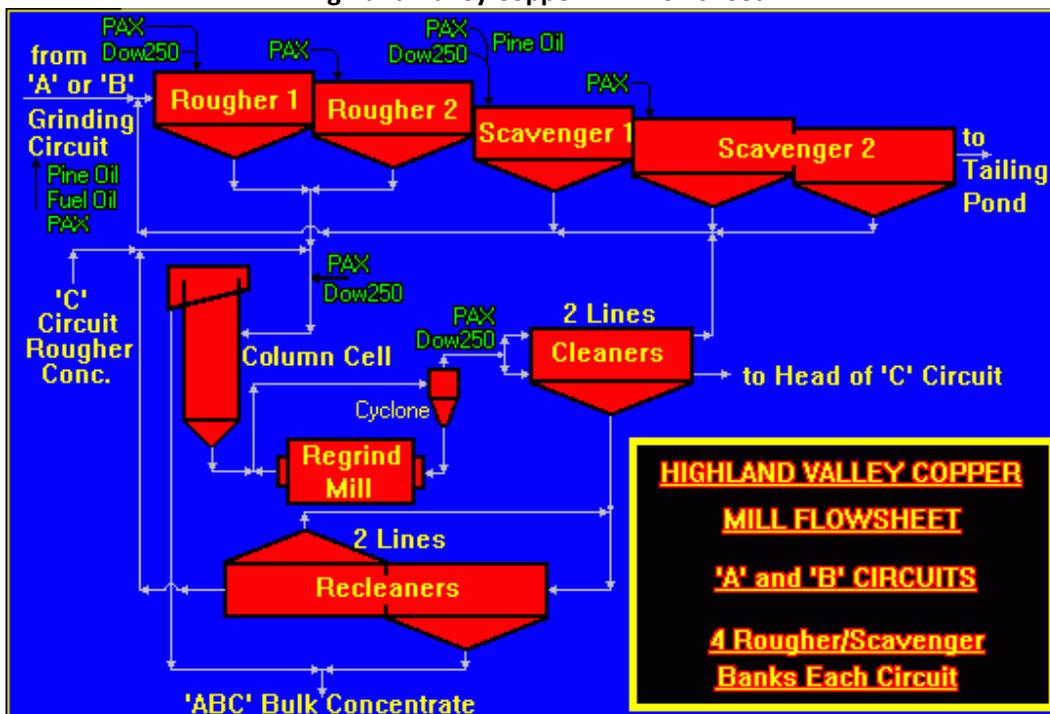
The primary function of the cleaner cells is to make final concentrate grade and to make a cleaner tail as low grade as possible.

TARGET: Final Grade Concentrate

It is important to keep circulating loads as low as possible. Collected minerals should be removed from the roughers as fast as the froth will move - often with the aid of paddles which rotate through the froth zone pulling concentrate into the discharge launder. If too much mineral drifts into the scavengers or is returned to the roughers from the cleaners, it is quite likely that the scavenger tailing assay will increase especially if the circuit becomes unstable due to a temporary shutdown in the grinding circuit or in another part of the flotation plant. The cleaner circuit must be pulled hard enough to remove concentrate from the circuit yet still maintain satisfactory concentrate grade.

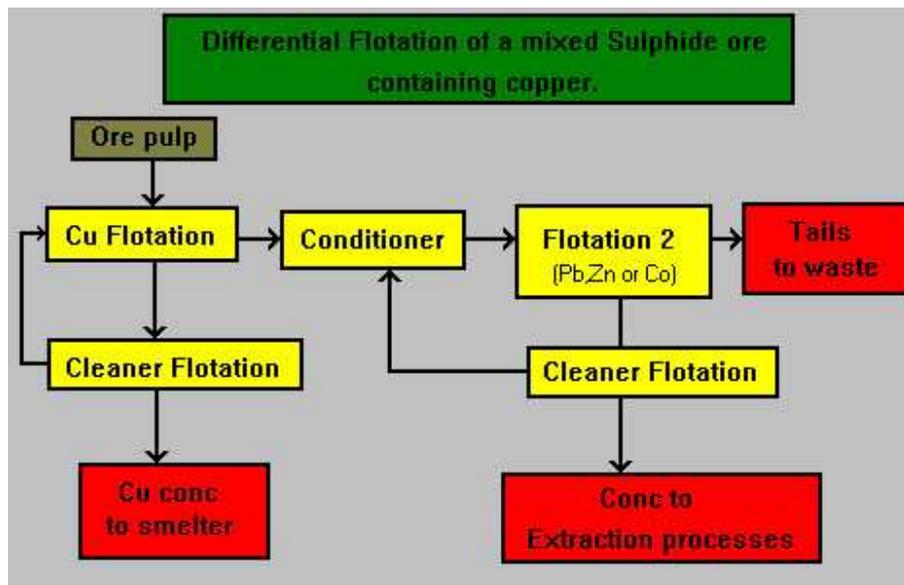
In certain cases, a circuit may be operated as an "open" circuit. In this case, cleaner or recleaner tailing are combined with final tailing and removed from the circuit. Care must be exercised with these circuits to ensure high losses do not occur in the cleaner tailing products.

Highland Valley Copper Mill Flowsheet



Differential flotation

With multiple sulphide ores it is often necessary for the mill to produce separate concentrate products of two or more valuable components. Ores may contain Copper, Lead or Zinc; Copper and Molybdenum; Copper and Nickel; or Copper and Cobalt. The type of circuit used to achieve satisfactory treatment of these ores may be Differential Flotation.



In this circuit, the ore is first prepared to allow one species to be floated while the other(s) remain hydrophillic with the gangue components. Depressants are added to aid in separation with the amounts of collector and frother being carefully managed to provide conditions just sufficient to recover the desired mineral(s). Circuit tailing is then conditioned with activators to promote flotation of the remaining values from the gangue in a second flotation circuit.

In this way, the valuable minerals are recovered "differentially" from the ore one at a time. This type of circuit is expensive in both capital and operating cost requirements, but will consistently outperform a bulk-selective circuit metallurgically.

Bulk-Selective Flotation

If the second valuable component in an ore is of minor abundance, the use of a differential flotation circuit cannot always be justified. A bulk-selective circuit can be used to reduce significantly capital and operating costs. With this circuit, the two components are initially recovered together to produce a high grade bulk concentrate. The concentrate is then treated with depressants to de-activate the more abundant mineral and float off the minor species.

This process is never as efficient as the straight-depression process used by the differential approach. Competition with stripped collector is usually severe and eventually the mineral's hydrophobic nature is restored.

Most copper-molybdenum (Figure 1) and copper-nickel (Figure 2) ores are treated by bulk-selective flotation. Copper-zinc (Figure 3) ores on the other hand, are extremely difficult to process using this technique - a differential circuit is virtually always demanded.

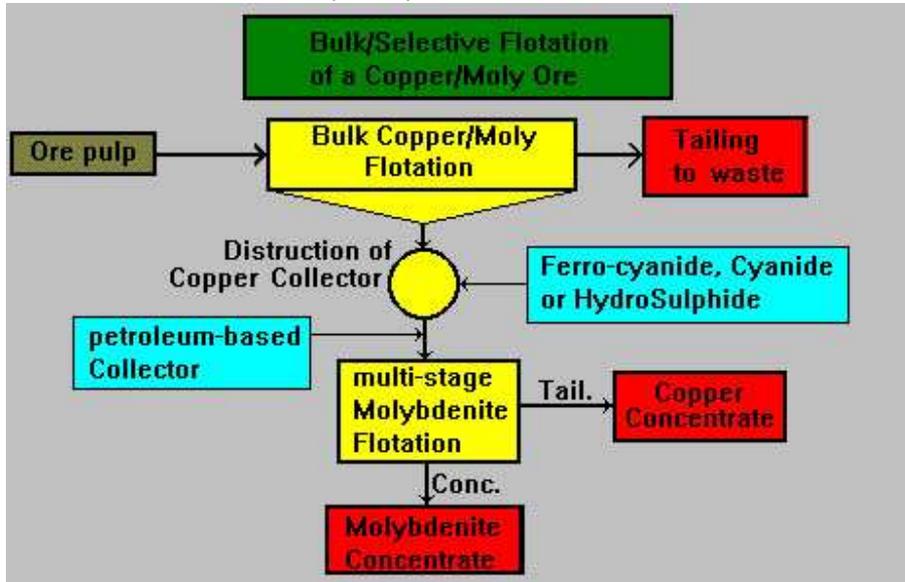


Figure 1. Bulk/Selective Copper/Molybdenum Flotation Circuit.

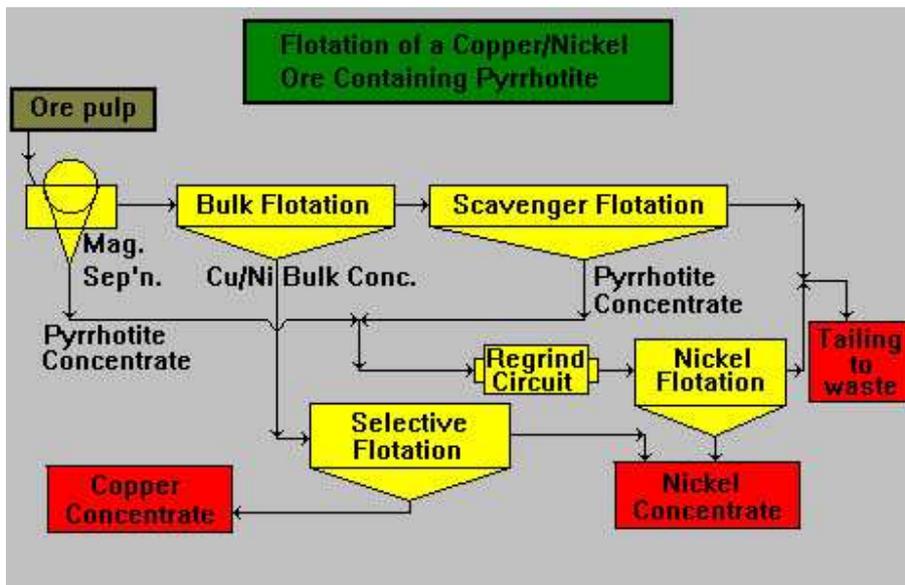


Figure 2. Copper/Nickel Bulk-Selective Flotation with Differential for Pyrrhotite.

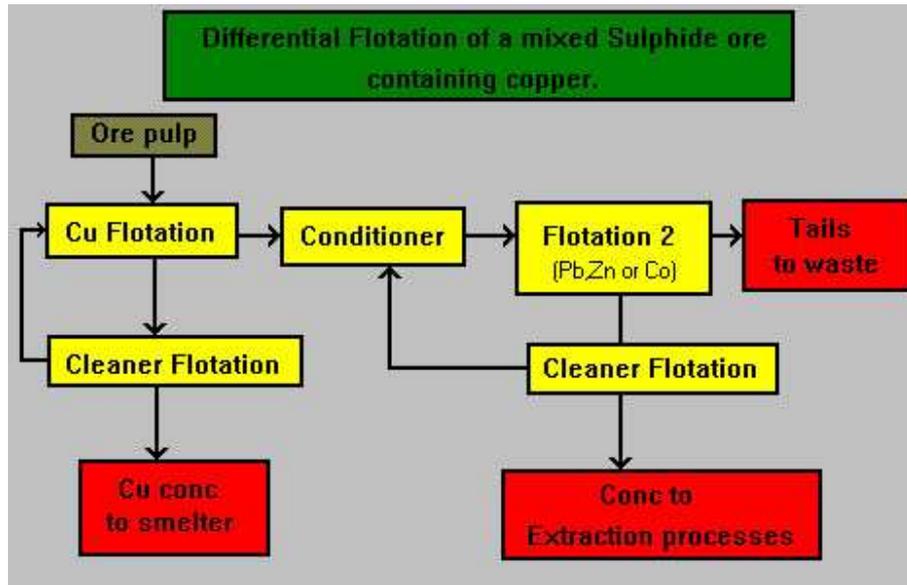


Figure 3. Copper-Zinc/Lead/ or Cobalt Differential Flotation Circuit.