

09 April 2021

D. T1.3.3 Benchmark report on mineral processing for potential resources extraction for reuse on a PMSD

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Version 5



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1 EXECUTIVE SUMMARY

In the Interreg NWE-REGENERATIS project dedicated to the extraction and re-use of raw materials from PMSDs, a research study has been carried out to define the different mineral processing techniques most commonly used in order to prepare, release and concentrate the metal fractions for recovery.

This report is divided into two parts. The first part is a bibliographical study of the mineral processing techniques that may be used in the recycling of metalliferous materials, allowing a better understanding of the parameters involved in the various fragmentation and separation processes. The second part focuses on examples of practices commonly implemented on PMSDs.

2 INTRODUCTION

Recycling and recovery operations involve 4 families of processes, used individually or in combination.

Physical and physico-chemical processes: differences in parameters such as size, density, shape, magnetic, electrical or optical properties are exploited either intrinsically or differentially.

Chemical processes: a particular reactivity is used such as solubility in acidic or basic medium, modification of an oxidation state, etc., usually with a step of selective solution (leaching) of the constituents to be recycled, followed by a step of precipitation of these constituents and a solid/liquid separation. It should be noted that physical processes often come before chemical processes through preliminary stages of mechanical preparation, separation or concentration of the elements to be extracted.

Biological processes: based on the use of enzymatic or bacterial activity for the selective extraction of compounds (metals, for example), regardless of their use in decontamination (foundry sands with phenolic resin, for example).

Thermal processes: a controlled rise in temperature and control of the redox character of the reaction medium enables the recovery or generation of reusable compounds. This is the case of thermolysis processes which differ from incineration by the fact that there is no combustion, the reactions involved being often endothermic (energy consuming).

The main techniques (see Table 1) used in the recovery of raw materials can also be used for recycling and/or recovery, with some modifications, sometimes significant, imposed by the characteristics of the materials to be treated. These differ from natural raw materials by:

- The heterogeneity in terms of granulometry, which ranges from a few micrometres (sludge) to a few centimetres (automobile or metallurgical debris, etc.);
- The diversity of particle shapes, which are much more differentiated than those of the natural mineral constituents: flat particles (plastics), elongated particles (wires, bars),

hollow particles (cans, bottles) with the consequences for the efficiency of conventional screening and classification systems;

- The diversity of concentration of the elements present (recoverable or contaminants), ranging from a few ppm (e.g. Hg or Cd) to a few ten percent :
- The diversity of the chemical compounds present, where organic and mineral compounds, natural or artificial, can coexist in all proportions.

Table 1 : Single operations

Process	Equipment	Objective
Fragmentation	Crusher Grinder Shredder Scissors	Size reduction, release of constituents
Washing	High pressure spraying Rotary sludge remover Paddle sludge remover Attrition machine	Slurrying in wet processes, dispersion and surface cleaning of particles, solubilisation of salts
Sieving	Static grid Vibrating screen Rotary screen	Separation of particles according to their effective size
Classification	Air classifier Cyclone and hydrocyclone Rake or screw classifier	Separation of particles according to their equivalent size
Separation based on:	Density (dense medium, jig, spiral, table) Physical recognition (optical sorting) Magnetic properties (magnetic separator)	Selective concentration based on the distinct physical properties of the constituent elements of the material
Leaching	Pachuca Open stirred tank Closed low pressure tank Autoclave	Chemical or biological modification of the specific properties of some constituent elements of the material
Deshydration	Decanter - Thickener Vacuum filter Pressure filter	Solid/liquid separation

As recycled fractions are often used in a manufacturing process based on the use of primary raw materials, the physical (particle size, moisture, etc.) and chemical (purity, absence of elements foreign to the process) criteria, as well as the consistency of these parameters over time, are particularly important.

On the other hand, a fluctuation in these characteristics, for whatever reason, both qualitatively and quantitatively, can compromise the cost-effectiveness and success of the operation. This is why, when designing a recycling and/or recovery project, it is really essential to find answers as detailed as possible to the following questions: what exactly are the materials to be recovered? Where are they located? Are they released or releasable? What are the application requirements for the final product in its planned reuse chain? What is the technical level of the processes to be implemented to meet these requirements?

3 PHYSICAL AND PHYSICO-CHEMICAL PROCESSES

In many cases, the waste is not at the required particle size for recycling or recovery. Moreover, as the waste is made up of several materials, it is clearly essential to release them before trying to separate them.

3.1 FRAGMENTATION

3.1.1 Introduction

The aim of these techniques is the fragmentation of the raw materials to be recovered to the required size for the treatment to be applied or for the liberation of the constituents, followed by the possible separation of the product obtained into several granulometric sections that are useful or to be eliminated. Generally, fragmentation techniques must be considered as a preparatory stage for subsequent sorting or concentration operations, whose methods of application determine the particle size to be achieved. Nevertheless, they sometimes allow a first classification to be made according to the selective behaviour of the materials to fragmentation. This behaviour results in different particle sizes, according to the nature of the material, which can be used in the particle size separation that usually follows the fragmentation stage.

The materials to be recycled differ from mineral materials by a wide variety of shapes and mechanical behaviour, which can cause problems during processing, but can also generate positive effects when the processing is well adapted. Two examples can illustrate this:

- Impact fragmentation of a mixture of mineral (stone, brick, glass) and metallic particles will result in a significant reduction in the size of the mineral components, as the more ductile metallic elements are not affected and can be separated by sieving to an appropriate size;
- a general reduction in the size of the constituents of a mixture containing elements of low density (e.g. friable plastics mixed with mineral materials) will result in the release of fine, light fragments which can be recovered by vacuum, pneumatic classification or sieving.

3.1.2 Fragmentation techniques

3.1.2.1 Dry process equipments

3.1.2.1.1 Crushers

Jaw crusher consists of two jaws placed face to face in a V-shape, one of which being fixed and the other driven in an alternating movement. The amplitude of the jaw movement and the discharge opening depend on the material to be processed. The application area is the primary fragmentation of large blocks of "rock" type material. This type of machine is therefore well suited for crushing concrete blocks in the recycling of building inerts. Their design makes them relatively unaffected by the presence of steel reinforcement.

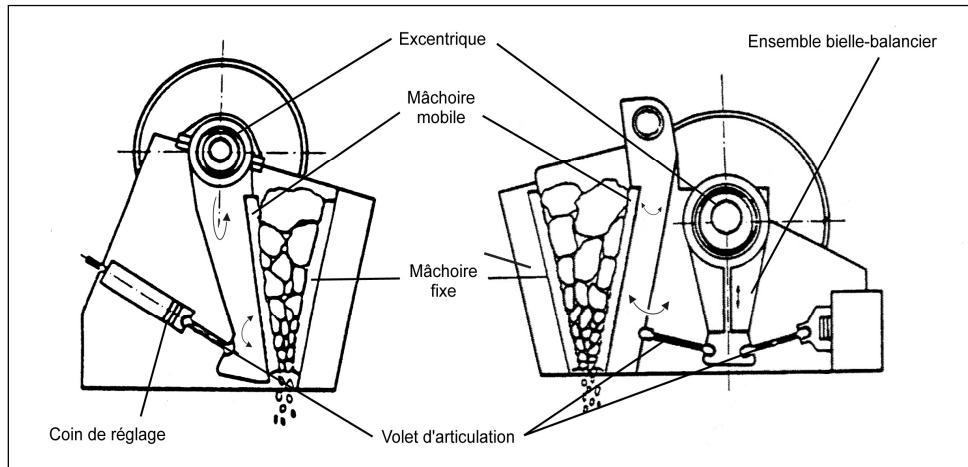


Figure 1 : Single and double-acting jaw crushers

Gyratory crusher: the raw materials are fragmented by crushing between a fixed circular wall and a conical body ("nut") set on a vertical shaft moved at its base by an eccentric (Figure 2). The movement caused by the shaft results in a cone with a compression zone and a diametrically opposed opening zone. The space between fixed and moving parts is adjusted according to the desired fineness. The fields of application are the same as those of jaw crushers but can be extended to finer crushing. Limitations are the moisture content of the material and the presence of relatively fine and/or sticky particles, which can cause clogging. These machines are quite sensitive to the presence of large metal components.

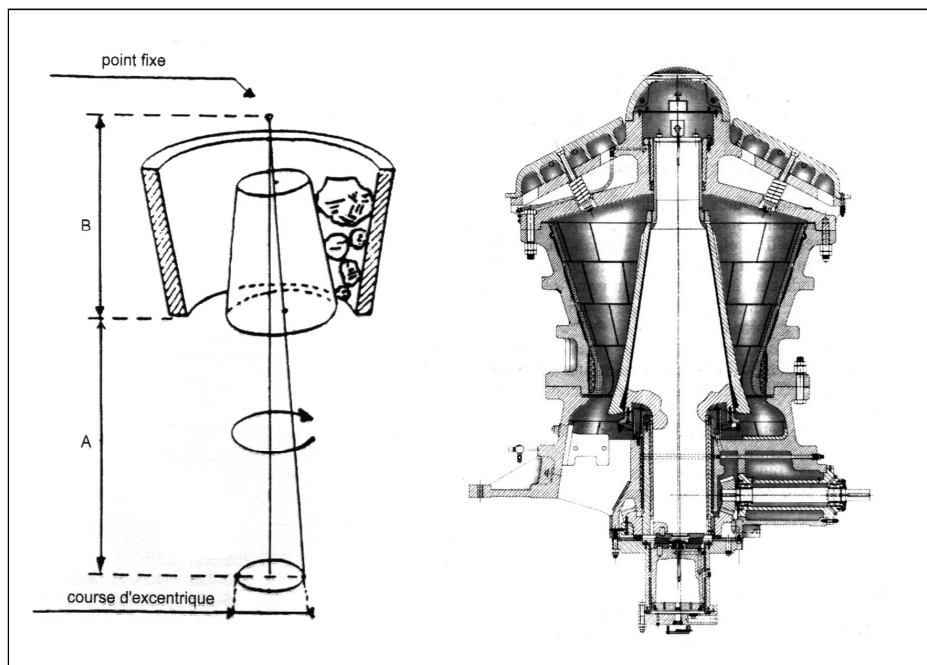


Figure 2 : Gyratory crusher

The **Roller mill** (Figure 3) differs from other crushers in that crushing is carried out continuously as the material passes between two counter-rotating rollers or between a roller and a fixed wear plate. The type of roller can be adapted according to the material to be processed:

- smooth rollers for the processing of soft materials;
- saw-toothed rollers for the processing of materials requiring an additional shearing or splitting component (plastic or adhesive materials);
- ribbed rollers with longitudinal thickened sections acting as bursting rollers.

The gap between the rollers (or the distance between the roller and the fixed wall) determines the output grain size. One of the main characteristics of this type of crusher is a high selectivity in crushing. Each material reacts according to its own characteristics and the springs of the crusher absorb the force differentially. Moreover, the production of fines (<100 µm) is reduced, which is a favourable element in processes where the phenomenon of over-crushing must be avoided. Roller mills are used in both fine and coarse crushing operations, with inlet grain sizes from 5 to 25 mm and outlet grain sizes of around 1 mm. Their selectivity can be used for the selective comminution of mixtures of mineral and metallic elements. They are suitable for wet, but not sticky materials and are not sensitive to the presence of foreign bodies, as long as they have the same grain size as the rest of the material to be treated.

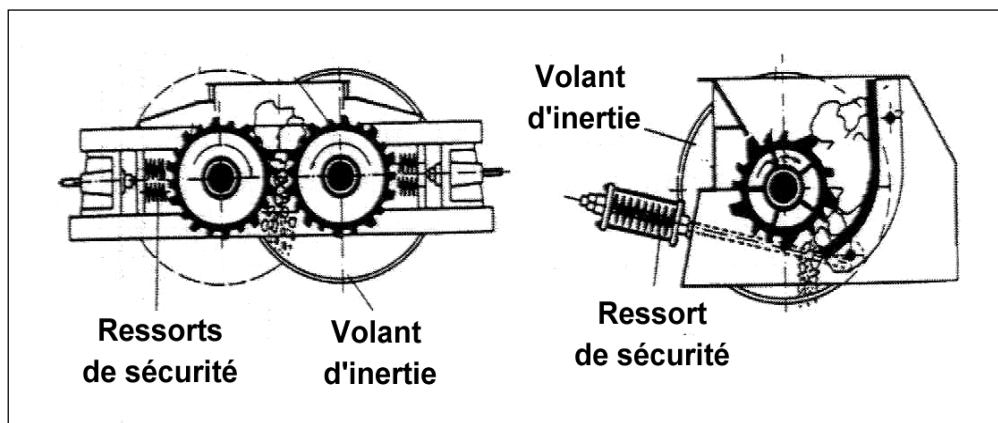


Figure 3 : Roller mills

3.1.2.1.2 Impact crushers

A rotor rotating at high speed and carrying a number of fixed beaters or articulated hammers or flails throws the materials onto fixed impact plates attached to the machine frame. A discharge grid can complete the equipment in order to impose granulometric limits on the treated product. The peripheral speed of the impact pieces is very high (several tens of m/sec). Fragmentation results from the combination of "rotor-particle", "impact plate particle" and "particle-particle" impacts. Overall, this type of fragmentation is suitable for mineral-type materials, of medium hardness, carefully cleaned of foreign bodies (metals and elastic materials, in particular). The articulated hammer system is usually equipped with a discharge grid located at the outlet, which regulates the granulometric characteristics of the product (an

advantage over the impact crusher, which works in free discharge) while making it more sensitive to clogging and unshreddable foreign bodies. It is characterised by:

- a high reduction coefficient (up to 100 / 1)
- a low energy consumption
- a control of the output particle size when using a discharge grid
- the production of a high proportion of fines in the treated product
- high sensitivity to abrasion and product moisture
- the possibility of carrying out a more or less selective fragmentation

3.1.2.1.3 Equipment operating by crushing, impact and friction

This category of fragmentation equipment includes bar and ball mills that can work in both dry and wet processes. These units operate in a mixed mode combining crushing, friction and impact and are used when it is necessary to achieve a fine grain size (entirely below 0.1-4.0mm), which can be the case in the treatment of aggregate products that need to be released (foundry sands) or in the mechanical preparation for thermal (glass) or physico-chemical (flotation) processes. The mill shells are covered with abrasion-resistant linings made of metal, rubber or a mixture of these two components. The grinding bodies can be manufactured non-metallic bodies (alumina balls), natural bodies (pebbles) or metal bodies (balls or steel bars). Grinding can be carried out in dry conditions, generally in an open circuit for bar mills and in a closed circuit for ball mills.

Bar mills

In this type of mill, friction forces predominate over crushing and impact forces. Fragmentation takes place gradually with a low production of fines. Inside the mill there is a natural classification system that holds the coarser particles trapped in the bars (and subjected to their action) until they reach a sufficiently fine size to escape and move towards the discharge of the mill. These mills, which are very common in the mineral industry, consist of a cylindrical drum lined with wear plates (steel or rubber lining) and partially filled with cylindrical steel bars acting as grinding bodies (Figure 4).

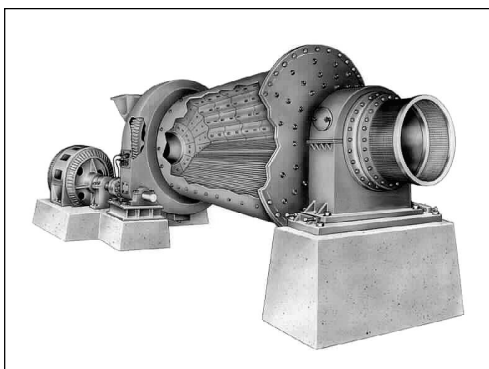


Figure 4 : Bar mills [Hardinge].

The diameter of the bars and their total mass depend on the fineness of milling to be achieved. The percentage of filling by the bars is usually 35-40% of the internal volume of the mill. The speed of rotation is adjusted to give the bars a relative falling speed over the feed that is maximum. This speed depends on the diameter of the mill but should never exceed a critical value beyond which a centrifugal effect of the feed occurs. The usual outlet grain size is of the order of 1 to 4 mm for an inlet grain size of 20 to 30 mm, which can make the bar mill a possible alternative to very fine crushing (quaternary crushing).

Ball mills

These mills, which are widely used in the mineral industry, consist of a cylindrical or conical-cylindrical drum lined internally with wear plates (steel or rubber armouring) and partially filled with steel balls acting as grinding bodies (Figure 5 and Figure 6).

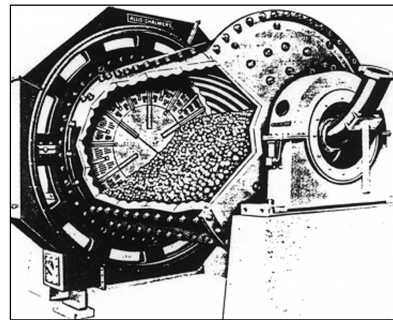
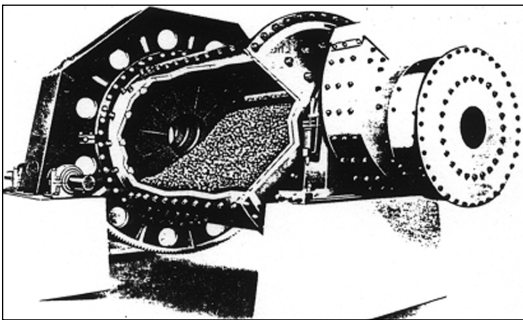


Figure 5 : Ball mills

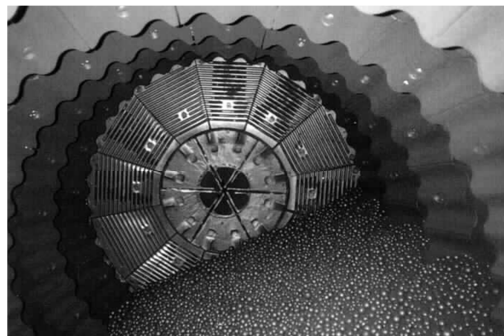


Figure 6 : Inside of a ball mill

The balls are usually made of forged or cast steel. They should be strong, abrasion and corrosion resistant and of uniform hardness. The filling volume of the balls is between 40 and 45% of the internal volume of the mill. Table 2 summarises the main characteristics of the fragmentation equipment that have been mentioned.

Table 2 : Equipment that can be used for dry fragmentation

Equipment	Fragmentation mode	Material	Reduction coefficient	Sensitivity
Jaw crusher	Crush	Hard to medium hard	6 : 1 à 10 : 1	Elastic materials
Giratory crusher	Crush	Hard	12 : 1 à 20 : 1	Moisture, fine or sticky particles
Roller mill	Crush		3 : 1 à 4 : 1	Big stray, clogging
smooth		Hard to mid hard		
Saw-toothed		Mid hard to brittle		
ribbed				
Impact crusher	Impact	Mid hard	15 : 1 à 50 : 1	Moisture
Hammer crusher	Impact	Mid hard	20 : 1 à 30 : 1	Quartz

3.2 SEPARATIONS

The different dry and wet separation techniques are based on the difference in specific properties of the constituents such as size, density, magnetic susceptibility, electrical conductivity and hydrophobicity.

3.2.1 Separations based on the particle size

3.2.1.1 Introduction

After the fragmentation stage, it may be interesting to sort the product obtained for different reasons:

- to complete the fragmentation process by returning to the head of the circuit those elements that are insufficiently fragmented and require further processing ;
- to extract the elements that are detrimental to the proper functioning of the equipment (metals, foreign bodies) as well as very fine elements (dust, light elements) that no longer require further fragmentation and/or must be directed to another appropriate treatment ;
- individualise well-calibrated granulometric slices, for optimum operation of the equipment that follows;
- selectively recover certain elements according to their nature, size or density.

This sorting stage can be carried out according to two criteria:

- The physical dimension of the elements: these are screening or sieving operations, also called direct grading ;
- The equivalent dimension of the elements, which can be deduced from the mass of the elements under the operating conditions of the treatment (effect due to acceleration): these are indirect classification or grading operations, to which cyclones, pneumatic separators and classifiers belong.

In direct grading, a surface with holes of a given size and shape, which can be periodically moved (rotated, vibrated) to increase the capacity of the machine, allows particles smaller than the size of the holes to pass through. The treated material breaks down into two flows: a throughput and a rejection at the cut-off size (or mesh) of the screen, which industrially extends between 100 cm and 200...500 μm in the dry process and a few microns in the wet process.

In indirect grading, the differential sedimentation of the particles takes place within a fluid (gas or liquid) driven by a predominantly rectilinear (pneumatic or hydraulic classifier) or vortex (cyclone or hydrocyclone) movement, adapted to the mass of the particles to be classified. The treated material is also divided into two flows, which may have different names depending on the equipment used: underflow for particles of larger size (or mass), overflow for those of smaller size (or mass).

3.2.1.2 Dry process equipments

3.2.1.2.1 Direct grading

This process involves fixed, vibrating or rotating screens and sieves, used in a wide range of industries:

- **The fixed screens** used for very coarse screening (removal of very large elements), consist of regularly spaced bars mounted on a rigid frame or sometimes sealed in masonry ;
- **Rotary or trommel screens** whose screening surface (often made of rubber or polyurethane) is a cylinder rotating on itself around a horizontal axis at a speed of 10 to 30 rpm (Figure 7) and suitable mainly for coarse mesh screening.



Figure 7 : Trommel screens

- **The vibrating screens (Figure 8)** whose screening panels, consisting of perforated panels of woven steel mesh or grids (steel, polyurethane or rubber), are fixed to a mobile frame, suspended or mounted on shock absorbers which carries the mechanism. Both are mounted in a fixed frame ensuring the feeding and discharging of the fractions.

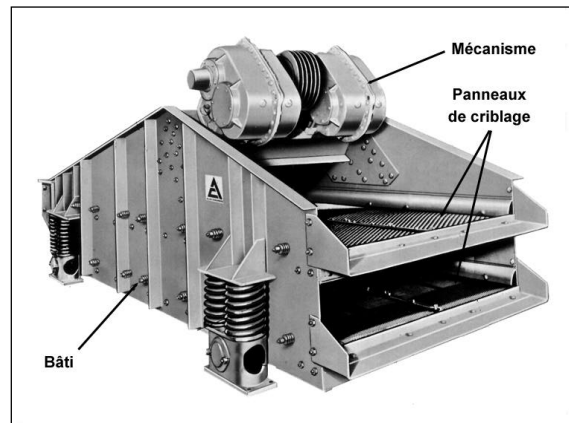


Figure 8 : Vibrating screens [Allis-Chalmers].

The nature and characteristics of the screening panels are important in the treatment of the materials to be processed. Elongated shapes particles behave differently than cubic or spherical particles during screening. Abrasiveness can also be important (for metallurgical slag for example).

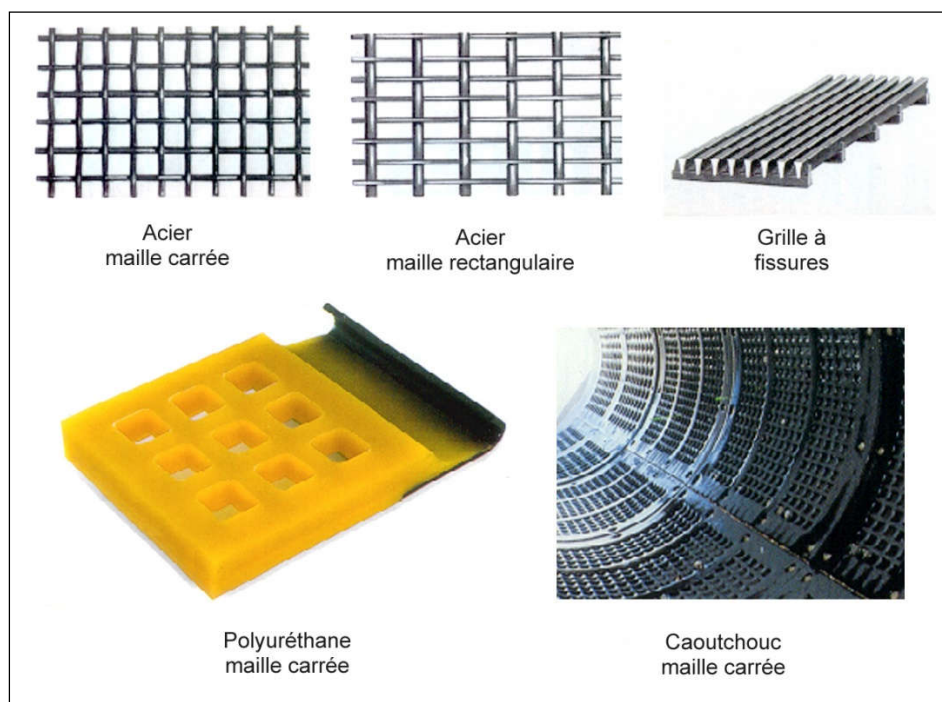
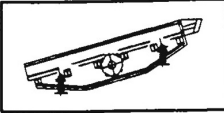
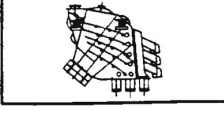
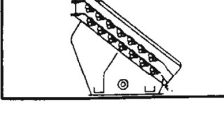
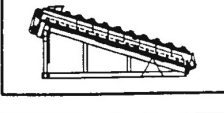
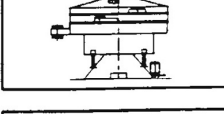
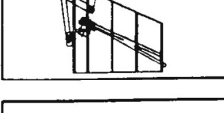
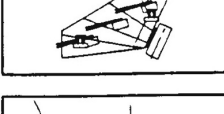
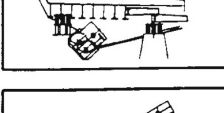
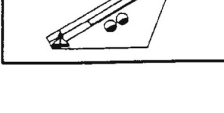


Figure 9 : Appearance of the main types of screening panels

As a general rule, square or rectangular meshes offer the maximum open area and are therefore best suited for screens with a high proportion of passers-by. The recovery of small proportions of fine, elongated material with good efficiency is facilitated by the use of slotted screens. These are very sensitive to the presence of elongated particles. Figure 9 shows an overview of features presented by the main types of screening panels commonly used.

A guide for selecting the type of screen according to the characteristics of the material to be treated and some constraints of use is presented in Table 3.

Table 3 : General criteria for screen selection [Mogensen].

Maille de séparation	0.1 - 1.0 mm	—  3  4  5  6	1  Cribles à mouvement circulaire
	1.0 - 3.0 mm	—  1  2  3  4  5  6	
	3.0 - 10.0 mm	—  1  2  3  4  5  6	
	10 - 30 mm	—  1  2  3  5  7  9	
	30 - 80 mm	—  1  2  7  9  10  11	
	80 - 150 mm	—  7  8  9  10  11	
	> 150 mm	—  8  10  11	
Propriétés du matériau	Collant (cohésion)	—  1  3  4  5  9	2  Cribles à mouvement linéaire
	T > 200 °C	—  2	
	Corrosif	—  1  2  3  4  6	
	Abrusif	—  2  3  8  9  10	
	Rugueux	—  8  9  10  11	
	Fines < 10 %	—  3  4  6	
Caractéristiques machine	Résistance aux poussières	—  1  3  4  6  9	3  Cribles multi-étages (type Mogensen)
	Compacité	—  3  6  8  11	
	Conso énergie minimale	—  3  4  6  8  9	
	Maintenance minimale	—  1  3  6  8  9	
	Plus de 3 fractions	—  3  4  6	
	Non colmatable	—  3  4  5  8  9	
	Toile chauffante	—  3	
	Faible masse	—  1  3  6	
	Adapté à l'égouttage	—  2  6  7	
	Grand débit	—  3  4  8  9	
			4  Cribles à résonance <i>Stimulated deck screens</i>
			5  Cribles anti-colmatage <i>Flip-Flop sizers</i>
			6  Cribles plans <i>Tumbling screens</i>
			7  Cribles rotatifs <i>Revolving screens</i>
			8  Cribles à barreaux <i>Barsizer</i>
			9  Cribles à barreaux vibrants
			10  Crible-alimentateur <i>"Grizzly"</i>
			11  Grille mobile <i>Shaking grids</i>

 = Recommandé
  = Possible
  = Mal adapté

3.2.1.2.2 Indirect grading

This process exploits the different behaviour of particles depending on their particle size and mass, when they are in a stream of air (or any gas) delivered by a fan. Two main families of separators can be defined: gravity separators and centrifugal separators.

For gravity separators, separation between fine and coarse particles takes place in an ascending air stream. Particles whose sedimentation speed is higher than the speed of the air stream fall. The rest are carried upwards and collected in a separator. One of the most common types is derived from the Zick-Zack (or Zig-Zag) classifier, which is well suited to the processing of low density material (Figure 10).

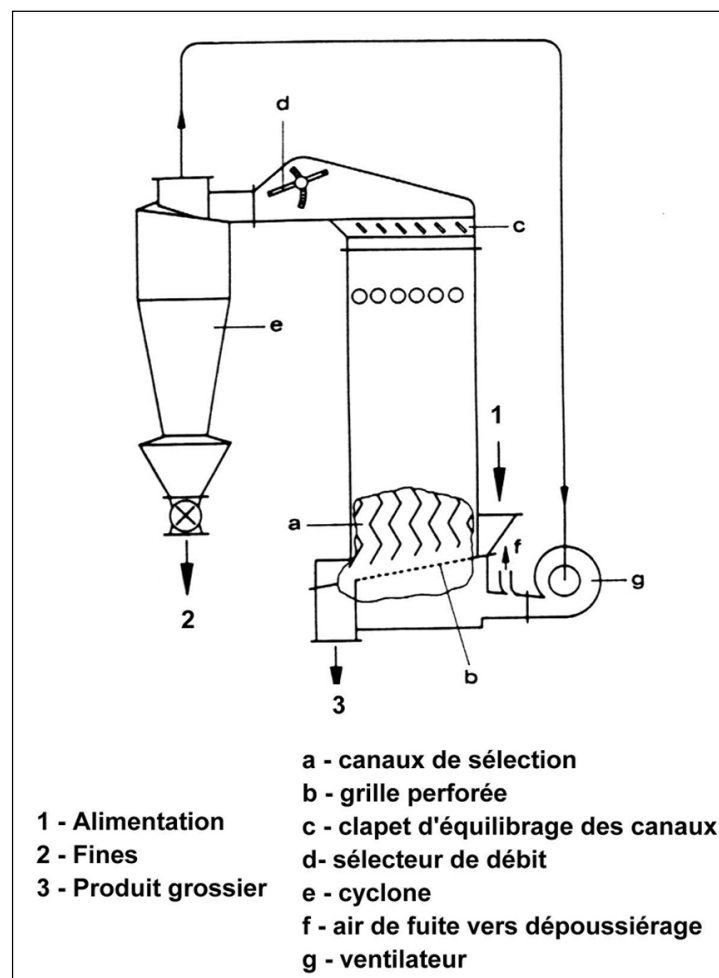


Figure 10 : Zick-Zack classifier

For centrifugal separators, separation takes place in a spiral air stream. The centrifugal force acts preferentially on coarse or heavy particles. Fine or light particles are mechanically carried by the rising air stream flowing through the machine. This separation technique can be used for finer mixtures (size < 150 μm). The most common type of device is the dust cyclone, which consists of a tangentially fed cylindrical-conical body (Figure 11). The air exits with the fine particles at the upper part while the coarse particles fall at the lower part. This device is used in a wide range of applications where the recovery of particles from 5 to 50 μm in a large flow of gas (hot or not) is required.

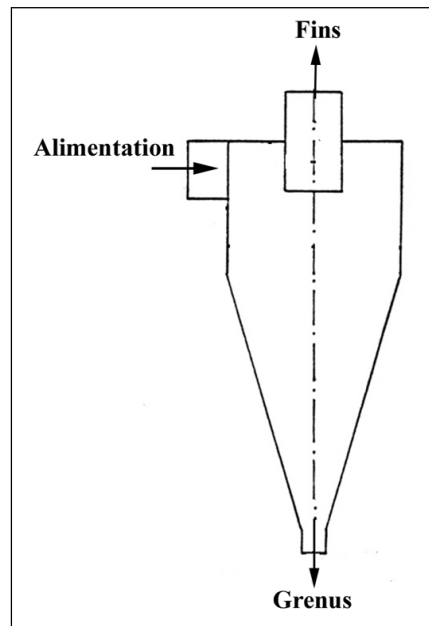


Figure 11 : Cyclone section

3.2.1.3 Performance and limits of use

Table 4 summarizes the various screening and classification equipment and their limitations of use.

Tableau 4 : Main characteristics of screening and classification equipment

Equipment	Range (µm)	Notices
Trommel	1.000 to 250.000	Good accuracy, high flow rate
Unbalance screen	1.000 to 300.000	High flow rate
Elliptical screen	250 to 5.000	Low flow rate
Gravity separator (Zick-Zack)	80 to 300	Good accuracy, high flow rate
Cyclone	5 to 50	Low accuracy, high flow rate

3.2.1.4 Wet process equipments

3.2.1.4.1 Direct grading

The screens do not differ from those in the dry process. The use of water provides a cleaning effect and a better mechanical evacuation through the screening panels, increases the unit treatment capacity, provides a more precise separation, limits the clogging phenomena of the panels and allows the screening mesh to be lowered down to 250 µm on some equipment working by elliptical motion. The curved screens should be added to the range of screens already mentioned. These are fixed (static) screen panels with a curved profile, mounted on a frame with a feed box and a discharge device for the passing and refusals (Figure 12).

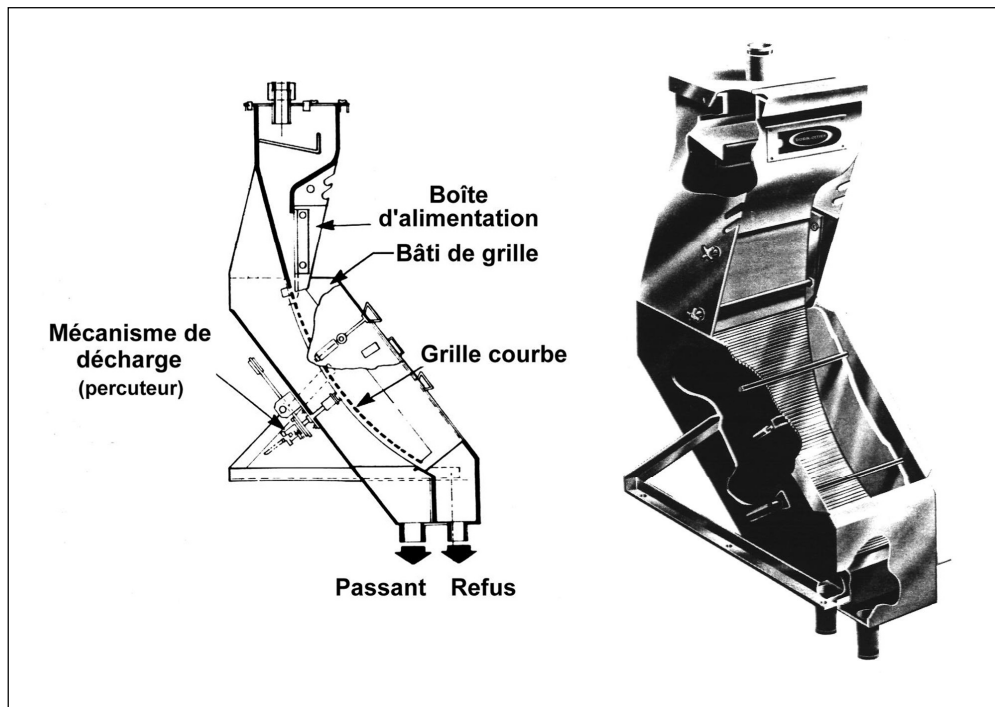


Figure 12 : Curved screen [Dorr-Oliver].

The distribution unit simultaneously ensures that the slurry is homogeneously distributed over the entire width of the screen and gets enough speed for screening. The screening process involves the combination of gravity and centrifugal forces created by the flow of pulp over a curved surface. This type of screen gives good results with a very constant characteristic feed, both qualitatively and quantitatively. It is a complementary process to conventional screens in the following areas:

- Fine screening (dimension $< 300 \mu\text{m}$) ;
- Dewatering of solids;
- The inexpensive removal of small, coarse particles in a very diluted pulp;
- The removal of particles with elongated shapes (e.g. wood fibres or organic matter in a mineral fraction).

3.2.1.4.2 Indirect grading

Like their pneumatic counterparts, hydraulic classifiers can operate by sedimentation.

In **screw or rake type classifiers**, the greasiest and heaviest solids sediment in a rectangular trough-shaped tank at the bottom of which an endless screw rotates and lifts them up to the top of the equipment (a rake, driven in a rectilinear motion, can replace the screw). The low part is a discharge point from which the light particles escape. In high-capacity machines, the screws may be doubled.

Hydrocyclones are not fundamentally different from cyclones. However, as the viscosity of the water minimises turbulence, it is possible to better control the separation parameters in a hydrocyclone.

The function of a hydrocyclone is to classify at dimensions between 2 and 200 μm within moderately diluted slurries (between 10 and 30% solids by mass). To be meaningful, this classification should ideally be carried out on populations of particles of the same density. The higher the density of the solid, the finer the cyclone cuts. Another application is the thickening of a pulp with water removal at the overflow and recovery of the majority of the solids at the underflow. This type of use is quite frequently encountered in the feeding of filters (elimination of excess water and improvement of the filter's operating conditions). Hydrocyclones consist of 3 parts (Figure 13):

- a cylindrical upper part acting as a discharge box for the fine and diluted overflow ;
- a middle, cylindrical part in which the pulp is injected tangentially at a pressure that can vary (from 0.4 bar to 3.0 bars). This middle part is provided, in its upper part, with a cover fitted with a diaphragm ;
- a conical lower part, of well defined angle, provided at its tip with a discharge nozzle (apex) through which the coarse and thickened underflow passes.

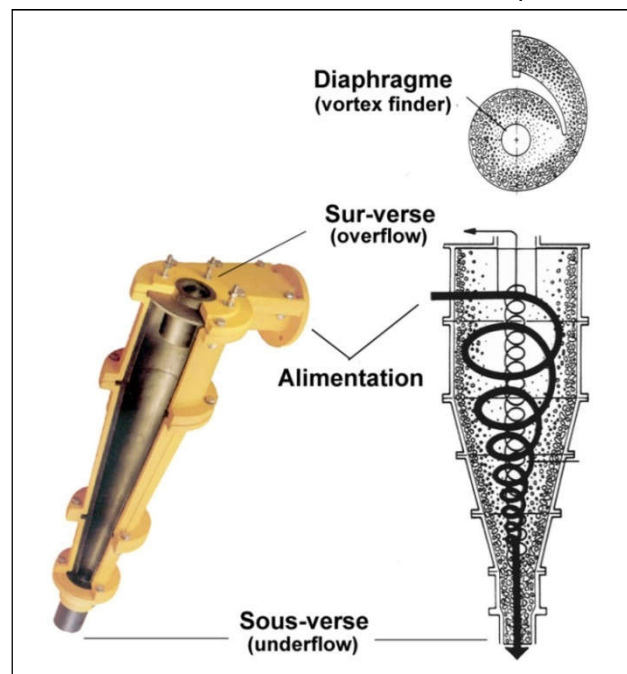


Figure 13 : Hydrocyclone.

Under the centrifugal force created by the tangential feed mode, the greasiest or heaviest particles move towards the walls and slowly fall towards the discharge nozzle. The finer or lighter particles are carried along by the upward flow of water created between the middle and upper parts of the cyclone and are discharged with a large volume of water. It should be noted that some of the finer particles ($< 2\text{-}3\ \mu\text{m}$) present in the feed are found in the underflow. This phenomenon is explained by the fact that water and suspended particles behave homogeneously under the conditions achieved. These particles are therefore an intrinsic part of the dilution water in the underflow.

3.2.2 Separation based on constituent density

3.2.2.1 Introduction

The processes that can be used to separate the constituents of a mixture of particles according to their density are called densimetric and gravimetric processes. They use the combined effect of the mass, volume and shape of the particles to get different paths in a static or moving (liquid or possibly gaseous) medium. Separation may be considered in different contexts:

- the elimination of a population of particles with a given density range within a mixture, as for example, for the extraction of light constituents (wood, plastics, hydrocarbon particles) from a predominantly mineral mixture (construction debris, contaminated soil);
- the separation, according to density, of populations of particles with defined characteristics, for example in plastics sorting operations ;
- the enrichment (concentration) of the densest particles within a mixture,.

According to their nature, the main constituents found in recycling and recovery operations are characterised by clearly differentiated density ranges. Looking at Figure 14 allows assessing which separations can be made relatively easily and which are more difficult or impossible. The criteria used here are (in decreasing order of importance):

- the difference in density between the constituents to be separated
- the similarity in particle size
- the release efficiency of the constituents

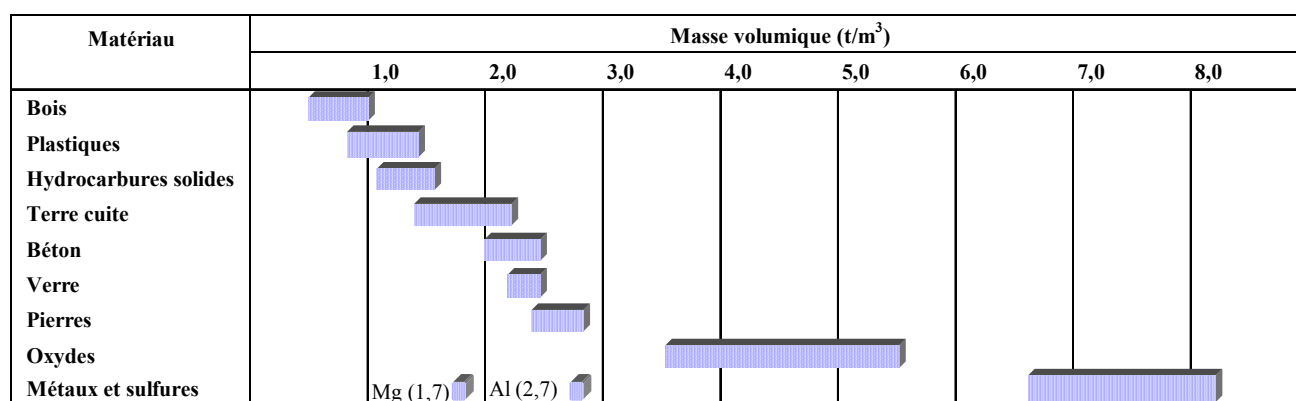


Figure 14 : Density of various common materials

Three methods can be used to achieve a separation of the constituents: dense media, differential acceleration and flow film.

In the dense media method, the material to be treated is immersed in a true solution (dissolved soluble salt) or in a liquid medium (medium) consisting of a suspension of fine solid particles and water, behaving as a pseudo-solution. The lightest particles (density < density of the fluid) float to the surface and the heaviest particles (density > density of the fluid) fall to the bottom. The recovery of the two fractions, respectively called floating and sinking fractions, is carried out mechanically or hydraulically.

In the method by differential acceleration, the particles are subjected to a periodic oscillation applied to the liquid which generates a differential sedimentation between the heavy and light particles. A classification occurs within the solids layer, the heaviest particles being grouped together at the low point of the layers. This phenomenon is exploited in the numerous jig models. The shape, amplitude and frequency of the oscillation transmitted to the solid-water mixture, as well as the way in which it is applied to the material to be treated, determine the efficiency of the separation.

The flowing film concentration method: the solid-water mixture to be treated is distributed in the form of a thin layer of liquid (a few mm to a few cm) flowing over an inclined surface. The particles separate into several densimetric categories according to their falling speed and resistance to movement. This method can be used in various ways in the separation equipment that make up the spirals (where the movement is only due to the gravity action) and also in the shaking tables (where the movement combines the action of gravity and a mechanical acceleration communicated). More and more often, densimetric tables are used to separate constituents of different densities by the dry process, especially when the rest of the processing scheme is dry.

3.2.2.2 Wet process equipments

3.2.2.2.1 Dense media separation equipment

In this type of equipment, the particles separate into two fractions with a density respectively lower and higher than the density of the liquid medium in which they are immersed. The medium (Table 5) may consist of an aqueous suspension of fine solid particles of perfectly defined size and shape, the whole behaving as a homogeneous pseudo-solution. The density of the solid phase added to the medium determines its density. Other applications use true solutions (calcium chloride, zinc chloride) or simply water, for the separation of fractions with a density of less than 1 t/m³ (light hydrocarbon substances, certain plastics). The dense medium must obviously be chosen according to the types of material to be separated.

Tableau 5 : Density of some common dense media

Solids nature	Medium density
Water	1,0
Zinc chloride	1,0...1,3
Calcium Nitrate or chloride	1,0...1,3
Clay	1,3...1,6
Barite	1,8...2,5
Magnetite	2,2...2,4
Ferro-silicon	3,1...3,3

Dense media extraction techniques have some technical constraints:

- the material to be treated must be free of very fine particles, which modify the viscosity of the medium and interfere with the sedimentation of the sinking parts and the cut-off density ;
- the recovery of solid particles from the medium requires washing and draining of the sinking and floating parts, in order to minimise losses and deliver clean products. The use of magnetite or ferro-silicon allows them to be easily extracted by magnetic separation from the washing effluent and reintroduced into the circuit ;
- the homogeneous behaviour of the medium must be constantly monitored since sedimentation phenomena tend to disturb the stability of the pseudo-solution ;
- Solids in the medium must have enough resistance so as not to fragment during its use.

3.2.2.2.2 Differential acceleration gravimetric separation equipment

The jigs jointly apply the effects of the differential acceleration acquired by particles of different mass and the phenomena of disturbed sedimentation within a solid-liquid medium submitted to a pulsation communicated to the liquid. This jiggling mechanism, common to all machines, can be divided into a series of cyclic operations applied to a material layer sitting on a grid (Figure 15).

The pulsation of the water within the material layer to be treated results in the expansion of the substrate, the separation of the particles and an upward movement, which is all the more important when the mass of the particle is low (dominant drive speed). The higher the particle mass, the faster the water is drawn into the layer and the faster the sedimentation occurs (dominant differential acceleration). The repeated cycle leads to a classification of the particles within the layer according to their respective mass and indirectly to their density, if the particle size range treated is not too wide. By giving the material layer a certain inclination, the particles progress and can be separated, at its discharge, into several distinct fractions:

- a light fraction, composed of water and the less dense constituents of the mixture
- a heavy fraction, classified according to the gradient created by the pulsation-suction cycle applied to the material layer by the machine's mechanism and separated mechanically
- a fine fraction consisting of the particles passing through the grid supporting the material layer (depending on the type of jig)

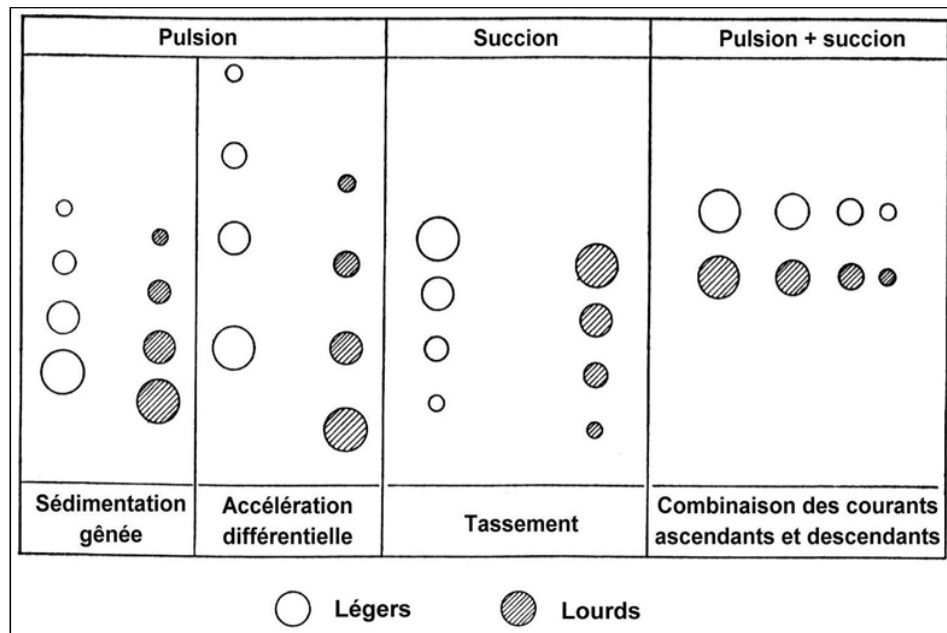


Figure 15 : Principle of separation by differential acceleration

In practice, the quality of the separation is determined by the difference in density between the heavy and light components of the mixture and can be expressed empirically using Taggart's criterion, which is written as follows:

$$C = \frac{\partial_L - \partial_F}{\partial_l - \partial_F}$$

with C: Taggart's criterion

∂_L : density of the heavy mineral (t/m³)

∂_l : density of the light mineral (t/m³)

∂_F : density of the fluid (t/m³).

Depending on the value of this ratio, the conclusions in Table 6 can be drawn. When the criterion is too small to consider a gravimetric separation, water ($\partial_F = 1$) must be replaced by a dense medium. Conversely, it is also immediately apparent that the Taggart criterion is weaker in the case of separation in air than in water.

Table 6 : Taggart's criterion

Taggart criterion	Separation efficiency
$C \geq 2,50$	Easy below 74 μm
$1,75 \leq C < 2,50$	Possible below 212 μm
$1,50 \leq C < 1,75$	Possible below 1,7 mm
$1,25 \leq C < 1,50$	Possible for "gravel" only
$C < 1,25$	Generally not profitable or impossible

Regardless of its design, a jig usually consists of the following elements:

- a frame with an opening grid related to the material to be treated and the feeding and discharge devices for the different products treated
- a container, also called a hutch, designed to collect the particles passing through the grid
- a mechanism for applying oscillations to the water to carry out the classification

The correct operation of a jig for a given material requires a rather rigorous adaptation to the characteristics of the feed:

- the particle sizes of the material to be treated must be as narrow as possible, and for greater selectivity, several fractions can usefully be individualised within the acceptable range of the jigs, which extends from 0.1 to 35 mm. The presence of large quantities of fine sands and clays will affect the efficiency of separation. The mesh size and shape of the screens must be adapted to the percentage of material passing through the selected size and the nature of the product collected
- Depending on the type of drive mechanism, the shape of the pulsation communicated to the material differs. Older models generate sinusoidal pulsations, while newer applications produce saw-tooth, steep-fronted and slowly decreasing pulsations that favour the sedimentation phase by lengthening their duration during a cycle. This has a favourable effect on selectivity but not on the recovery of the fine fractions that have time to be carried along by the current
- the frequency of the pulsation (between 60 and 300 pulses per minute) and the flow rate of the water to be added must be very precisely adjusted according to the characteristics of the material
- The amplitude of the pulsation must be adapted to the grain size and density of the components to be separated in order to allow a good individualisation of the different phases (reduced as the grain size is low and the difference of density is high)
- the positive (pulse) and negative (suction) components play a key role in the treatment
- the frequency of the pulsations conditions the treatable flow rate and is a function of the density of the constituents to be separated. Waiting for the end of sedimentation before starting a new cycle, the finer the products, the faster the cycle will be
- the addition of water makes it possible to limit the settling phenomena within the layer and improves the treatment of coarse materials at the expense of the finest fractions.

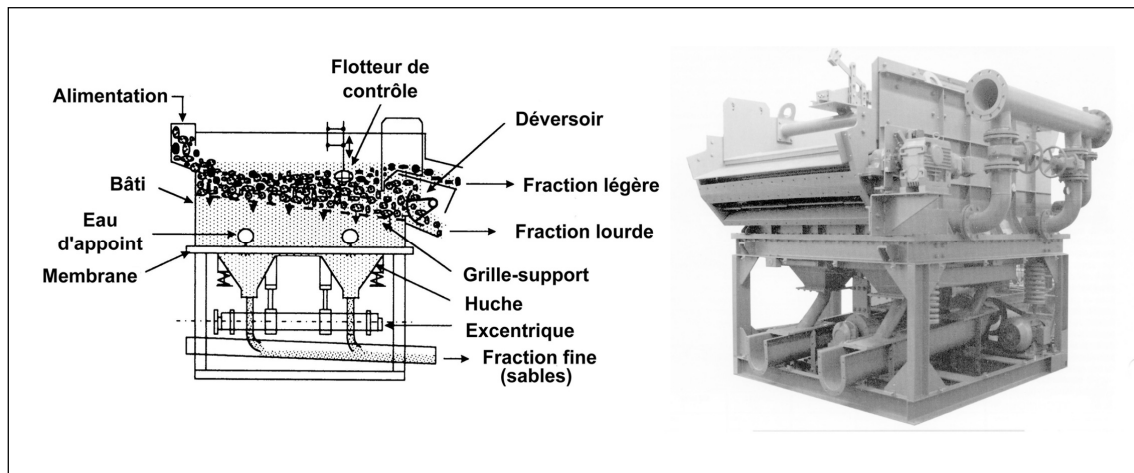


Figure 16 : Jig with mobile hutch – Siebtechnik

3.2.2.2.3 Wet flow film separation equipment

This type of separation is based on the length of the path a particle takes on an inclined surface travelled by a gravity-flowing water wave (Figure 17). For a surface with a given slope and roughness and a given velocity, the resulting displacement is a function of the size, density and shape of the particle.

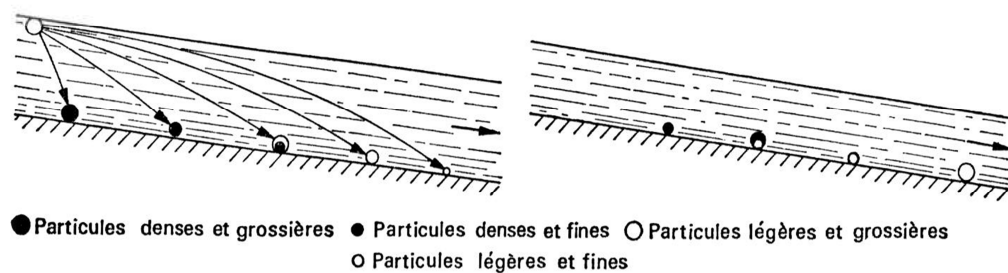


Figure 17 : Principle of the wet flow film separation

Separation is caused by the combination of two successive factors:

- the time it takes for the particle to reach the inclined surface, which is a function of the size, density and shape of each particle
- the resistance offered by each particle to the displacement imposed by the movement of the water wave

The result is a segregation of the components of the material according to their density in the form of accumulations of particles with similar characteristics moving along the same trajectory, at different speeds and in different positions from other groups of particles with different characteristics. These phenomena are implemented through numerous processes, mainly used in the mineral industry (sluices, spirals, shaking tables, Reichert cone, etc.). These include spirals and shaking tables.

A **spiral** consists of an elliptical cross-section element wound in a spiral. Any particle, released without initial velocity at the upper point of the equipment, describes a trajectory whose projection, on the plane perpendicular to the axis, is a straight line. Due to the transverse profile of the element, any particle tends to be located as close as possible to the centre of the device. The spiral is run through by a stream of water, the movement of which inside the element differs according to its position on the radius of the element.

In the vicinity of the axis, the regime is laminar and tends to carry the lightest particles of the mixture towards the periphery. At the periphery, the centrifugal force maintains a turbulent regime, where the lighter particles are stirred and kept at a distance. The heavy particles close to the centre are removed. The result is a spreading of the material with a decreasing density gradient from the centre to the periphery of the element, with the individualisation of a heavy element zone, an intermediate density element zone and a light element zone where the process water is concentrated.

This individualisation becomes increasingly clearer as the mixture describes the path imposed by the spiral. The heavy elements can be recovered during the progression through the spiral through orifices. At the low point of the spiral, orifices or a series of dampers allow the selective recovery of each fraction (Figure 18).

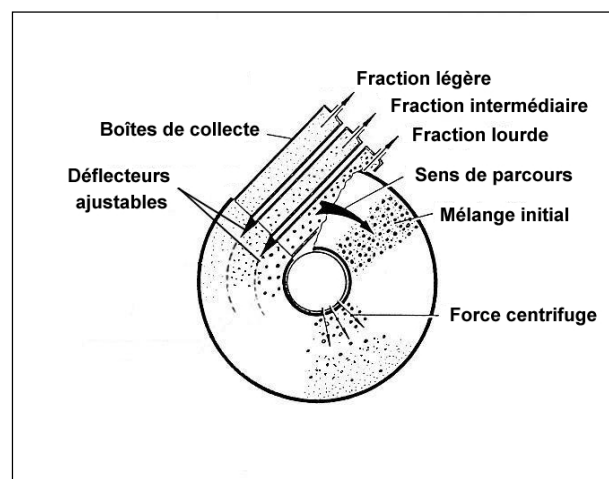


Figure 18 : Separation of the different fractions at the output of a spiral

The spiral components are most often made of glass-fibre reinforced epoxy resin and each unit can be made up of one to three superimposed elementary spirals (single, double or triple pitch) in order to increase the treatment capacity without significantly increasing the height of the unit (Figure 19), which obviously reduces the floor space required. Each spiral, which has 5 to 8 turns, is equipped with a feed box and a box for filling the treated products. In some models, there are additional devices that allow:

- the withdrawal of a part of the already differentiated fractions in the middle of the process which releases the surface, improves the efficiency of the separation and increases the treatable flow rate ;
- additional watering of the dense fraction along its movement close to the spiral axis to remove the last light particles still trapped.

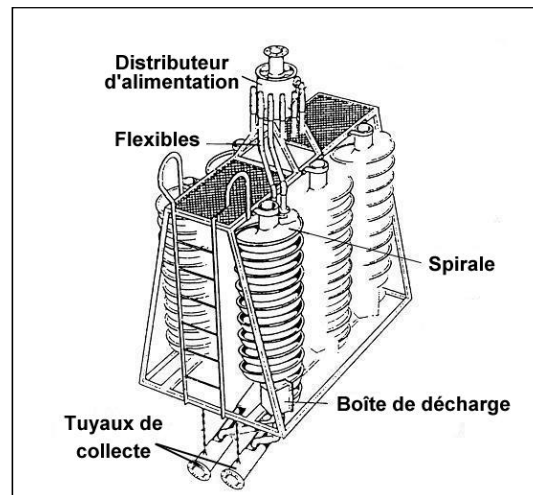


Figure 19 : Arrangement of a bench of spirals

The density of the separated particles is determined by the transverse profile of the element, which has a more or less flared shape (Figure 20):

- the most open profile (left in the figure), which allows a cut-off at a density of around 1.3, was initially developed for the treatment of coals and is perfectly suitable for the recovery of other low-density compounds (vegetable and carbonaceous particles, plastic debris, various solid hydrocarbon compounds, etc.). Because of this low density, separation takes place very quickly and "coal" type spirals are often short (3 to 5 turns)
- the most closed profile (on the right in the figure) allowing a cut-off at densities around 3.5, are used to separate oxides and metals from particles of lower density (foundry sand, shot-blasting sand, etc.)
- there are various intermediate profiles, suitable for the recovery of minerals of medium density (iron oxides, for example) or for the reprocessing of pre-concentrated light fractions with the aim of purifying them

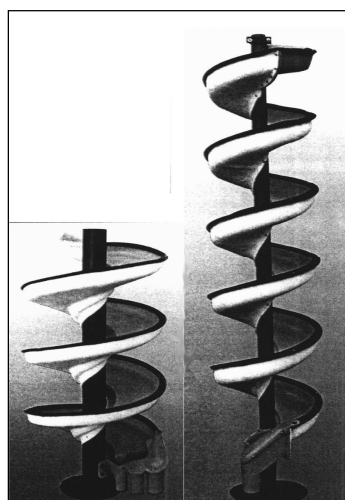


Figure 20 : Spirals for the extraction of light or heavy fractions

The grain size fractions that can be processed by means of spirals range from 80 μm to 2 mm (3 mm for "coal" type spirals). Apart from the pulp feeding device, the energy consumption is zero.

The **shaking tables** consist of a flat surface, slightly inclined to the horizontal and provided with sliders. A mechanism provides the table with asymmetrical (saw-tooth) longitudinal shaking. The surface of the table is covered with a layer of washing water, which is distributed via a distribution channel. The water is fed in at the top (Fig. 21).

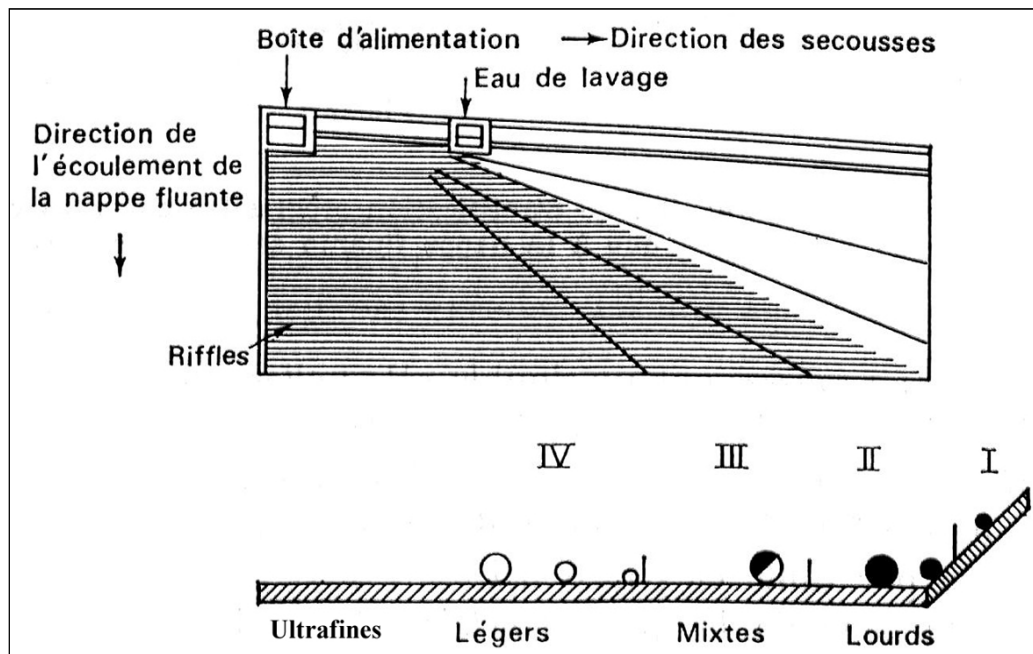


Figure 21 : Operating principle of a shaking table

The heavier particles of the fed material will tend to settle between the riffles, which act as a dam in the progression of the material along the line of greatest slope. The shakes imposed on the table have a double function (Figure 22):

- they ensure a progressive stratification of the heaviest particles at the bottom of the space between each riffle, resulting in the rejection of the lighter particles towards the upper part where they are carried away by the wash water flow ;
- they ensure the progression of the heavy particles along the riffles to the product collection area, located on the opposite side to the feed.

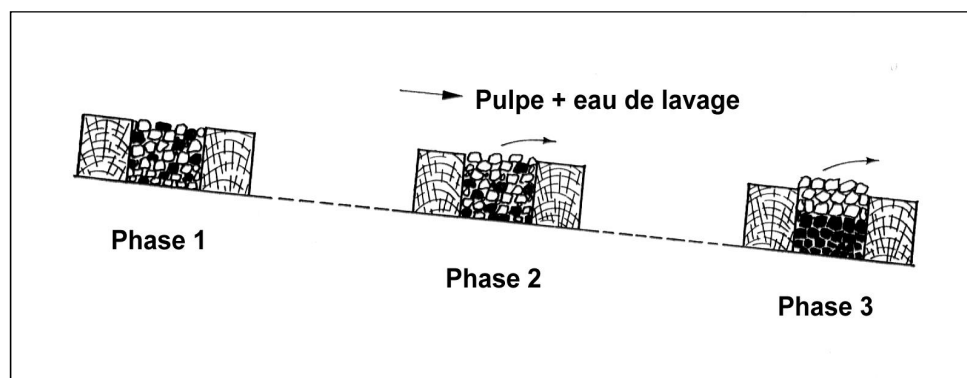


Figure 22 : Particle classification method on a shaking table

The result is a spreading on the table of the different fractions according to density and particle size, which are collected in peripheral chutes. The particle size range of the feed should be as small as possible, between 80 μm and 2 mm. The presence of clays is harmful. Various settings are available:

- the inclination of the table in relation to the horizontal which influences the capacity and selectivity of the treatment
- the amplitude and frequency of the pulsation which influences the capacity and must be adapted to the particle sizes treated
- the design of the table riffles. Several types have been developed according to the type of application (coarse separation, purification, etc.)

Originally developed for mineral processing, shaking tables have not yet found many applications in recycling techniques, probably because of their rather small processing capacity, their rather delicate adjustment and their large footprint compared to spirals, for example. However, they offer much greater flexibility of adaptation than the latter and allow precise densimetric separations, particularly for low densities (removal of organic fractions in washing water) and high densities (separation of oxide-metal mixtures).

The endless belt separator, known as the Hydrobelt or Aquamator (Figure 23), is often included in particle size separation equipment but, in the context of recycling and recovery, is more logical to be classified as a gravimetric separator. It consists of an endless belt with a rough surface on which the fed material is deconsolidated and washed by means of several spray ramps operating in counter-current. The heavier and coarser particles are carried along with the belt movement, while the lighter and finer particles are carried along by the washing water in the direction of flow. The speed of the belt travel, the pressure and flow rate of the washing water and, to a lesser extent, the roughness of the belt surface allow the cut-off density to be adjusted fairly roughly. In any case, the cut-off density is quite low and this type of equipment is intended for the disposal of low-density fractions (e.g. construction waste treatment).

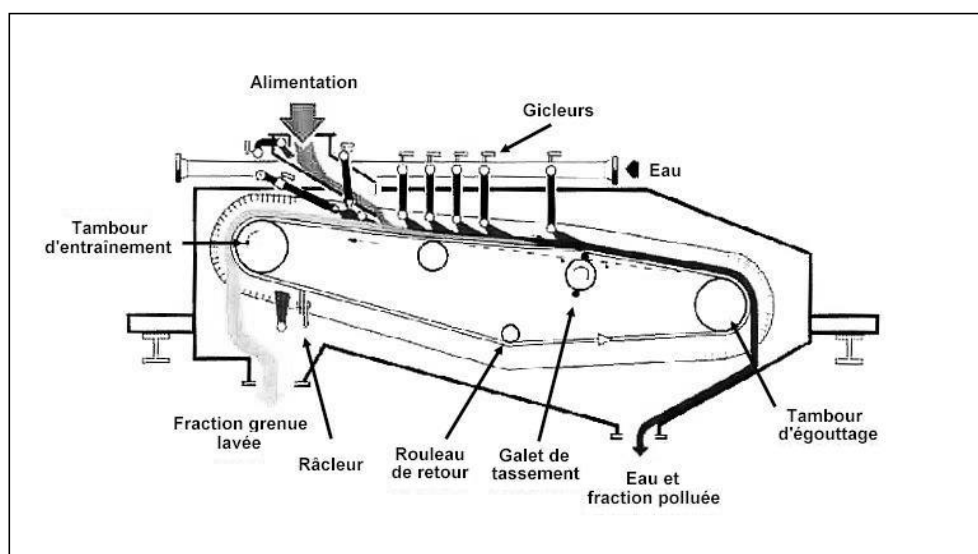


Figure 23 : Endless belt separator - type Aquamator [GKA]

3.2.2.3 Dry process equipments

The pneumatic table, also known as a density table, is sometimes referred to as a Birtley table (Figure 24). It combines the action of dedusting and classifying the coarse constituents based on their density. This type of equipment consists of a tray made up of a porous metal base with an embossed surface, under which a fan blows air that the surface embossing helps to distribute at various angles. This bottom usually has a series of oblique rifles with longitudinal and transverse slopes that can be adjusted by pivoting the tray frame. The platen frame is driven by an eccentric unbalanced drive system, which causes it to shake.

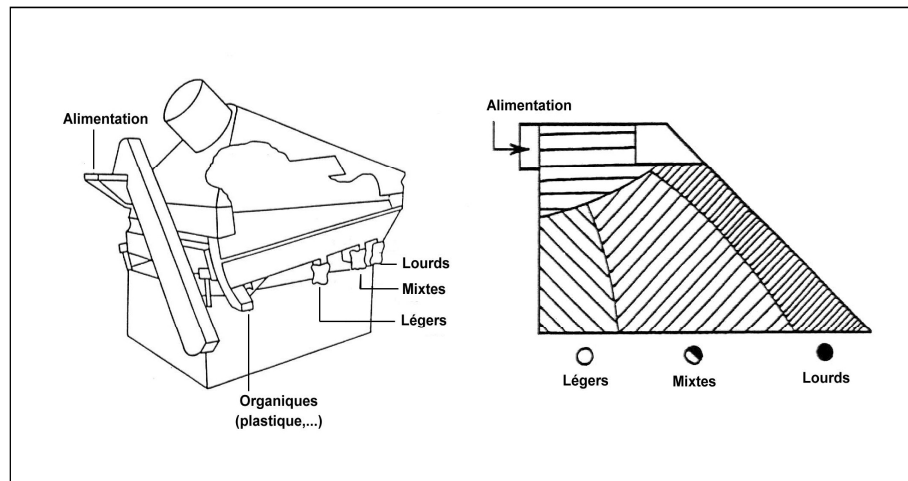


Figure 24 : Birtley table

The fed material spreads out on the table. The heaviest particles are guided by the rifles to the upper part. The lighter particles are fluidised by the air flow and flow down the transverse slope to the lower point of the table. This equipment finds many applications in the treatment of predominantly organic waste (extraction of plastic or textile fragments from mineral components and small metal objects). Separation is best as the particle size range is low.

3.2.2.4 Fields of application

This equipment finds an application in the following operations:

- the elimination of organic fractions present in construction waste (wood, plastic, roofing fragments) in order to recover the "mineral" fraction (bricks, stones, concrete, ...). Jigs are well suited to this type of treatment for fractions < 30 mm and are used industrially with success in this type of operation
- the elimination of organic (wood, plastics, paints) and metallic fractions present in a whole range of sandy and stony materials, soil decontamination, regeneration of foundry and shot-blasting sands. Depending on the particle size of the product to be treated, jigs and spirals (coal and ore) are perfectly adapted
- the separation of light fractions (plastics, paper, rubber, carbon electrode elements) in the treatment of used batteries prior to the recovery of denser metal components (Al, Cu, Zn, Fe); the separation of copper wires from their plastic insulation elements is another area of use for this type of process.

Table 7 shows the main characteristics and limits of use of the different equipment for wet gravimetric and densimetric separation in the wet process.

Tableau 7 : Main characteristics of wet separation equipment

Equipment	Density	Particle size (mm)	Capacity (t/h)	Constraints
Dense media	1.3-3.3 (media) 1.0-1.4 (solute)	3-800	≈ 100	Clay & Fines Medium loss Medium properties (reconditioning)
Jig	Variable (according to conditions)	0.1-30	≈ 30	Clays Mechanical settings Low particle size range
Spiral				Low particle size range
coal	≈ 1.3	0.08-3,0	≈ 4	
ore	≈ 3.5	0.08-2,0	(per spiral)	
Shaking table	Variable	0.05-2,0	≈ 1,5	Limited capacity Low particle size range
Hydrobelt	≈ 1,5	0.1-80	≈ 60	Consumption

3.2.3 Separations based on the magnetic susceptibility of the constituents

3.2.3.1 Introduction

Magnetic separations are based on the differences in magnetic susceptibility of the different constituents and can be carried out either dry or wet. The combination of data collected in mineral chemistry and by crystallographic analyses of various substances has led to a first magnetic classification of solids based on the value of their magnetic susceptibility.

Four main families of compounds are distinguished:

- **non-magnetic**
- **diamagnetics**: low magnetic susceptibility (10^{-9} m³/kg), with a negative value and independent of field strength and temperature. In this case, the force is negative, the particles being repelled by the field
- **paramagnetics**: higher magnetic susceptibility (0.5×10^{-6} - 10^{-7} m³/kg), of positive value, independent of the field intensity and temperature. In this case, the force is positive and the particles are attracted by the field to which they are subjected

- **ferromagnetics** is a sub-family of paramagnetic compounds which is characterised by a high magnetic susceptibility ($10^{-2} \dots 10^{-4} \text{ m}^3/\text{kg}$), of positive value, dependent both on the field intensity, on the temperature and, in some cases, on the mechanical history of the particle (in terms of its crystallographic structure)

Magnetic separators modify the characteristics of the magnetic field in the treatment space, generating a geometry that allows selective action on the particles with the greatest magnetising ability. The heart of the separator is the source of the field that generates the force. The force of attraction created is combined with the gravity and the mechanical and driving forces of the medium, generated by the machine that gives a particular trajectory to the magnetic and non-magnetic particles. This trajectory is used in the various types of devices.

3.2.3.2 Dry process equipments

3.2.3.2.1 Low-intensity magnetic separators

This equipment is more specifically designed to recover ferromagnetic constituents present in a mixture, either by extraction from the mixture (de-ironing) or by separation within the mixture.

Ferrous scrapers are commonly used to extract the ferromagnetic elements contained in a material, often moving on a conveyor, for the purpose of purification or mechanical protection of downstream equipment. Due to the need to extract at a distance, the field created must be deep in order to attract or hold relatively large parts.

The most classic iron remover is of the suspended (overband) type. It is placed above a conveyor belt or often at the conveyor's jetty. If the quantity of parts to be extracted is not important, a simple magnet is sufficient. Otherwise, a small slatted belt ensures the lateral evacuation of the collected elements (Figure 25).

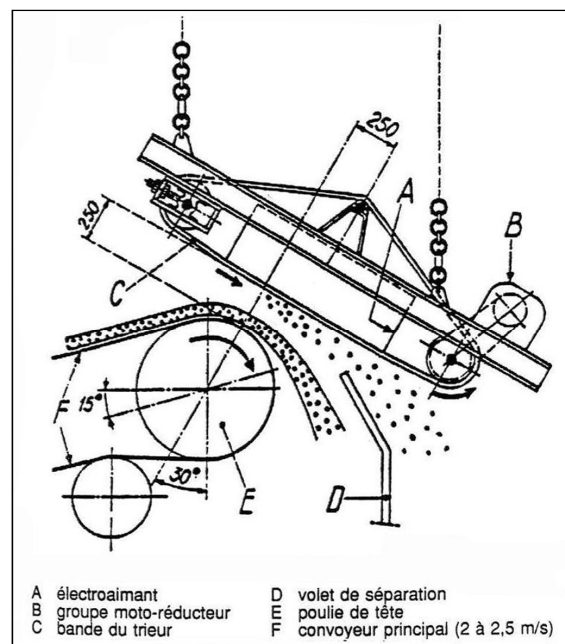


Figure 25 : Suspended magnetic separator

Drum and centrifugal separators consist of a drum rotating around a horizontal axis. This replaces the head drum of a conveyor, holding the magnetic elements, isolating them from the rest of the material discharged by the conveyor, for a short period of time as it passes. It can also be a stand-alone unit. Typical peripheral speed is 1 to 2 m/sec. Inside of the drum is a ring of radially arranged permanent magnets of reversed polarity (Figure 26). As the drum rotates, the magnetic particles move into a zone of lower field at the back of the ring, where they are released. This technique is suitable for processing coarse materials (up to 200 mm).

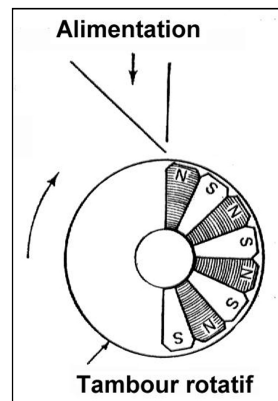


Figure 26 : Arrangement of the magnets of a scraper drum

3.2.3.2.2 High intensity electromagnetic separators

High-intensity equipment generates much stronger magnetic fields and should be used for the extraction of particles with low magnetic susceptibility (certain oxides, special alloys, etc.). An industrial application of this process has been carried out by Carpcu (Outokumpu) for the treatment of coarser feeds (up to 75 mm) of iron alloy slag and automobile shredder residues.

3.2.3.2.3 Magnetic separators with ceramic permanent magnets

These separators use ceramic Co rare earth alloys (Ce, Sm, Nd) or B-Fe-Nd which can develop very high fields of up to 1.5 T.

3.2.3.2.4 Summary of the characteristics of dry magnetic separators

Table 8 summarizes the main characteristics of the different facilities.

Table 8 : Main characteristics of dry magnetic separators

Type	Low intensity			High intensity		
	Permanent magnet	Overband	Drum	Cross bands	Induced rotor	Permroll
Compound	Ferromagnetic			Paramagnetic		
Source	Aimant permanent			Électro-aimant		Céramique
Density (N/m ³)	2.10 ⁴ ...2.10 ⁶			2.10 ⁷ ...4.10 ⁹		10 ⁷ ...10 ⁹
Induction (T)	0,2...1,5			2,0		1,5
Particle size (mm)	0,5...20	> 5...10	> 5...10	< 10	< 15	< 25
Capacity (t/h)	20...300	60	300	3	2...6	10...40
Energy consumption	Low			High		Low
Equipment weight	Low			Very high	High	Low
Space requirement	Low			Very high	High	Low
Investment	Low			High		Medium

* Units : 1 T = 800 kA/m, 10 000 Gauss = 1 T, 1 Oersted = 80 A/m

3.2.3.3 Wet process equipments

There are low and high intensity equipment.

3.2.3.3.1 Low-intensity magnetic separators

The principle is similar to that of dry magnetic drums.

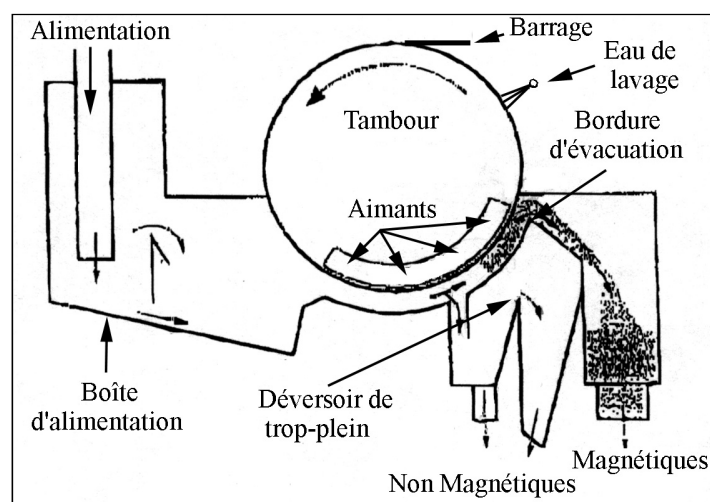


Figure 27 : Low-intensity magnetic drum separator

3.2.3.3.2 High-intensity magnetic separators

At the industrial scale, the traditional Jones type magnetic separator consists of a carousel, containing a metal matrix, rotating between the poles of an electromagnet. Particles that are not retained by the magnetic field pass through the cell while the others remain in the matrix and, after washing, are recovered as soon as they leave the magnetic field.

3.2.4 Separations based on the electrical conductivity of the components

3.2.4.1 Eddy current separation

3.2.4.1.1 Operating system

In this type of separation, the particles to be sorted are subjected to an alternating magnetic field produced when they pass along a row of permanent magnets of alternating polarity or by the rotation of a pole wheel inside a conveyor drum.

The varying magnetic field generated by the pole device induces an alternating electric current within the conductive particles. This current, in turn, develops an induced magnetic field of opposite sign to that of the inducing magnetic field. The combination of these two fields causes the appearance of repulsive forces which, combined with the other forces used (driving forces linked to the geometry of the device, force of attraction of gravity), will give these particles a particular trajectory, different from that of the constituents of the mixture which are insensitive to this phenomenon (Figure 28).

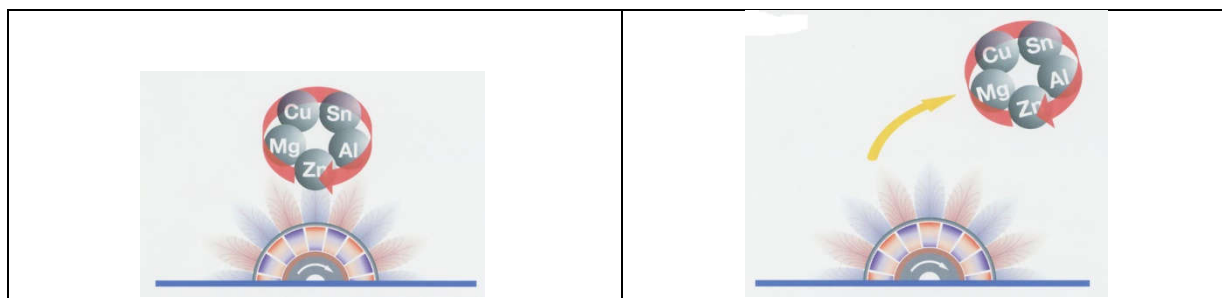


Figure 28 : Principle of induction by high-frequency magnetic flux

It is the ratio between the electrical conductivity and the density of the particle that will condition the behaviour of the particle submitted to the field. The greater the value of this quotient and the greater the mass of the particle, the greater the repulsive force will be. Table 9 gives the values of this ratio for different materials. This table immediately shows the fields of application of eddy currents, classically developed for the extraction of light metals (Al and Mg) and non-ferrous metals (Cu, Zn and alloys of these metals, etc.).

Table 9 : Ratio "electrical conductivity / density"

Material	Electrical conductivity ($\sigma \times 10^6 / \Omega \text{ m}$)	Density ($\rho \times 10^3 \text{ kg/m}^3$)	Ratio (σ/ρ) ($\times 10^3 \text{ m}^2/\Omega \text{ kg}$)
Mg	23,0	1,74	13,2
Al	35,0	2,70	13,0
Cu	59,0	8,93	6,6
Ag	68,0	10,49	6,5
Zn	17,4	6,92	2,5
Au	41,0	19,32	2,1
Brass	1,0...26,0	$\approx 8,40$	1,8...3,1
Ni	12,5	8,90	1,4
Sn	8,8	7,29	1,2
Pb	5,0	11,34	0,4
Stainless steel	0,7	7,70	0,1
Glass	-	2,3...2,6	-
Plastic	-	1,0...2,0	-
Rubber	-	1,0...1,0	-

3.2.4.1.2 Equipments

The current generation of separator uses ceramic-type high-field magnets and the increase in repulsion force due to the rotation of the pole pieces. The equipment can be classified into two distinct types: the belt and pole wheel separator and the single pole wheel separator.

Belt and pole wheel separators consist (Figure 29) of a section of conveyor belt (usually made of synthetic material) in the head drum of which the pole wheel is located, driven by an electric motor separate from that of the belt. The feed is provided by a dosing unit which distributes the material to be treated in a single layer.

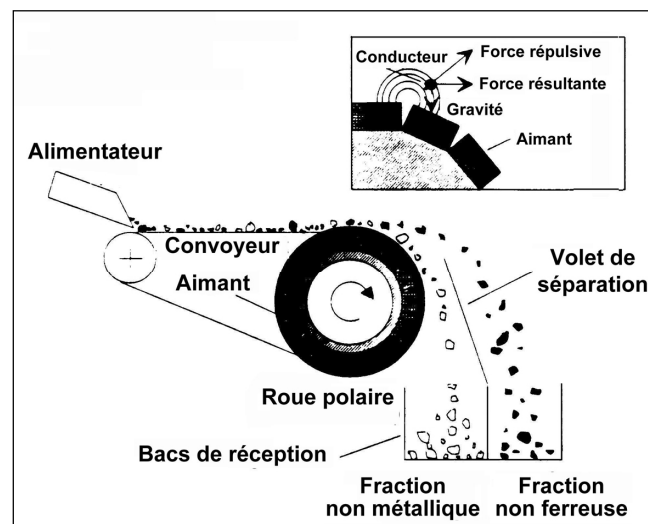


Figure 29 : Eddy current separator with belt and polar wheel

Under the eddy current effect, the parabolic trajectory of the particles, having reacted, is inflected at the belt's jetty, these particles falling further than the others. A separation damper enables the two fractions produced (non-ferrous and non-metallic) to be well isolated.

In the majority of current separators, a rotor is fitted with permanent magnets with high field strength (neodymium - iron - boron) and alternating poles at the periphery. Each magnet thus develops its own magnetic field. The pole wheel is positioned inside the head drum of a flat belt conveyor (Figure 30). This drum is made of a magnetically inert, composite ferrule with high mechanical and chemical resistance. The speed of rotation of the pole wheel is independent of the speed of the drum. Non-ferrous metals are ejected along a trajectory depending on their nature, shape and size. Non-metals, on the other hand, fall by gravity.

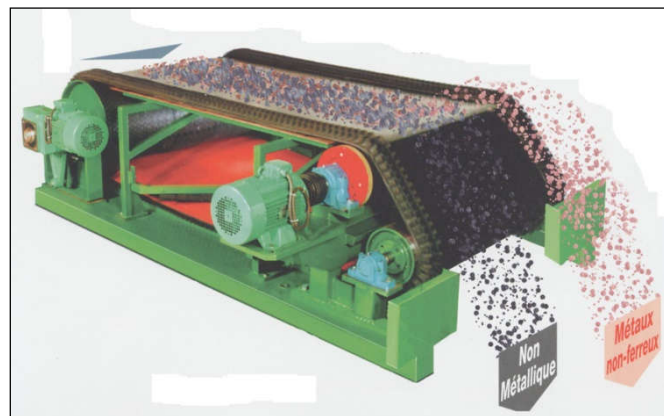


Figure 30 : Diagram of an Andrin SMAR type eddy current separator

One of the limitations of eddy currents is the particle size of the material being treated, the intensity of the force being proportional to the mass of the particles. In practice, the extraction efficiency of belt and pole wheel separators falls below 5 mm and the device becomes inoperative for particle sizes below 2 mm. In order to overcome this limitation, **the single fleece wheel separator** has been developed (Figure 31). In this separator, the vibrating feeder feeds directly at the top a stainless steel ring (rubber coated) inside which the eccentric pole wheel rotates in the opposite direction. The non-ferrous particles will briefly follow a trajectory imposed by the direction of rotation of the pole wheel before being rejected. The non-metallic particles, on the other hand, are mechanically driven by the ferrule and are discharged on the other side. Due to the geometry of the device, no separating damper or pre-adjustment is necessary. As the field is locally very strong at the point of discharge of the fed material, finer grain sizes (between 2 and 5 mm) can be processed with improved selectivity and extraction efficiency.

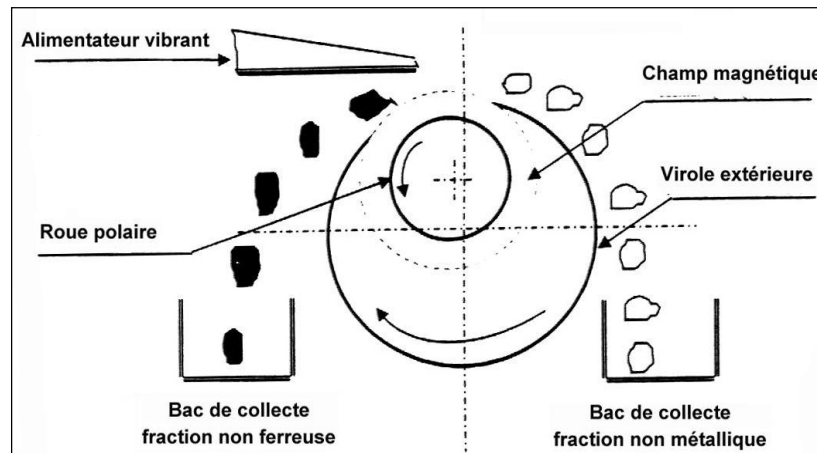


Figure 31 : Eddy current separator with single pole wheel

3.2.4.1.3 Limitations

Several limitations remain at present:

- strong ferromagnetic and paramagnetic constituents must first be extracted using a de-ironer or a magnetic separator with a higher intensity. In belt and drum separators, the presence of more than a few percent of ferromagnetic components is detrimental to the life of the belt, due to the heating that these particles undergo when subjected to eddy currents
- the minimum feed particle size is currently limited to 5-6 mm on most industrial separators
- the moisture of the product can act unfavourably by causing sticking and mechanical entrainment with the non-ferrous fraction
- some metals are refractory to this type of separation (Pb, Sn, stainless steels), others respond only moderately, with limited selectivity and/or extraction yields (Zn)

3.2.4.2 Electrostatic separations

3.2.4.2.1 Implemented mechanisms and equipment

Electrostatic separators exploit the acquisition, by induction, of a surface charge by particles travelling in an intense electric field (potential difference of several tens of kV) with sometimes a preliminary stage of charge development by friction (particle-particle contact with charge transfer, known as triboelectricity).

Classically, (Figure 32) the electrostatic separator consists of a flat surface or a grounded rotor and an electrode (wire or plate) developing the field. Under the action of this field, each particle becomes polarised and acquires its own surface charge. Conductive particles lose this charge by contact with the rotor and are then subjected to the centrifugal force which evacuates them. Non-conductive particles retain their surface charge and remain stuck to the rotor, from which they eventually detach or are recovered by brushing.

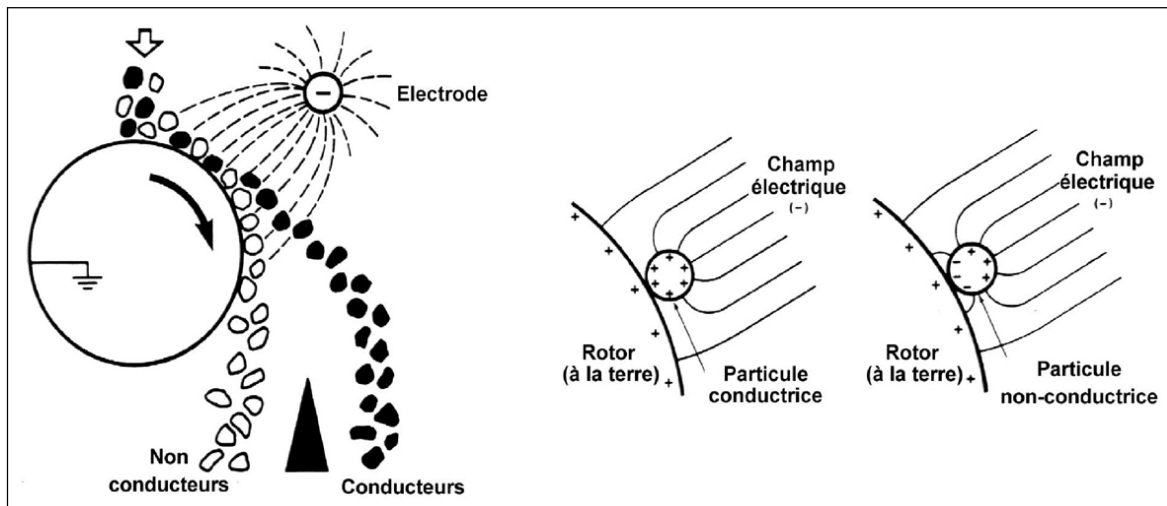


Figure 32 : Electrostatic separators

3.2.4.2.2 Fields of application

In the recovery of non-ferrous metals, electrostatic separators can complement eddy current separators for the separation of finer grain size mixtures (typically in the range 0.1-1.0mm) for which they are inoperative. Under certain conditions (particle size, in particular), they could also be used for the extraction of metals with a low response.

Classification into fairly narrow particle size ranges improves separation efficiency. The finer particles tend to be blocked in their path of ejection from the rotor by larger non-conductive particles surrounding them, resulting in small conductive stray particles in the non-conductive fraction.

3.2.5 Separations based on the hydrophobicity of constituents

3.2.5.1 Implemented mechanisms

Flotation consists mainly of two steps:

- the selective reaction of a family of particles with specifically chosen reagents, leading to making these particles hydrophobic, i.e. not wettable by water like a drop of oil
- the collection of the particles thus rendered hydrophobic in the form of a foam sufficiently stable to be evacuated mechanically

Most solids exhibit hydrophilic behaviour, which means that their natural hydrophobicity is not very great and must be accentuated by the use of specific reagents whose identification is the main difficulty in establishing the process.

The collector is the substance that must be selectively adsorbed on the surface of the particles to be recovered, making them hydrophobic and allowing them to adhere to the air bubbles of the foam. Many collectors are heteropolar organic compounds having two functional parts, one ionic and capable of adsorbing on the surface of the particle to be collected, the other consisting of an organic chain or radical responsible for the

hydrophobicity of the particle thus conditioned. Depending on the charge carried by the ionic part (zeta potential), the collectors can be:

- anionic, used for compounds with metallic properties
- cationic, traditionally used for the flotation of saline and oxidised compounds in an acid medium

The length and nature of the organic radicals (R, R') largely determine the hydrophobicity conferred and play an important role in the selectivity of the product. The collector can act alone or in a mixture with other collectors in lesser proportions, one being likely to reinforce the effects of the other.

In combination with the collector, **the foaming agent** has the function of forming stable foam that collects the collected particles. These are usually partially water-soluble compounds that selectively adsorb at the air-liquid interface around the air bubbles created by the mechanism of the flotation machine. These substances must not develop collecting properties by themselves so as not to interfere with the collector used. They should form foam that is firm enough to retain the particles and prevent their return to the cell, but not too persistent to remain pumpable once evacuated.

A whole series of adjuvants, intended to regulate the action of the main reagents in different areas, can be grouped in this family:

- pH regulation, which is critical in certain applications, with sulphuric acid, milk of lime and sodium carbonate being frequently used
- reinforcement of the collector effect by specific adsorption or by surface reaction with the particles to be recovered. The substances that can fulfil this function are called activators
- inhibition of the effect of the collector by inverse effect to that of the activators, for example to introduce a selectivity effect in the flotation of particles belonging to the same family and which, without the action of a specific depressant, would react in a similar way with the collector
- dispersion of clay and ultra-fine particles (large collector consumers) by adding dispersants

It is possible to operate in two modes, depending on the product extracted in the foams:

- direct flotation where the useful component is floated. This is the most common case as the component is generally less abundant in mass than the reject and therefore requires less reagents
- reverse flotation where the undesirable components (the treatment rejects) are floated. This may be the only solution if no collector has been found for the useful component or if maximum purity of the extracted product is desired.

3.2.5.2 Equipments

There is a very large number of flotation equipment developed since the beginning of the 20th century, initially for mineral processing but also for specific applications such as the recycling of printed paper (from the 1950s onwards).

All of them have the following properties in common:

- The maintenance of all particles in suspension by imposing on them a rate of ascent greater than their own sedimentation rate
- The design ensures that all particles can be subjected to the action of the collector by avoiding any undesirable turbulence that would generate a short circuit and by limiting as far as possible the areas where the material could sediment
- The homogeneous dispersion of fine air bubbles throughout the volume of the cell
- The hydrodynamic regime favouring collisions between particles and air bubbles in order to allow the rapid formation of charged foams
- The existence of a relatively calm pulp zone just below the foam layer so as not to risk breaking it and avoid mechanically incorporating pulp
- The formation of sufficiently thick foam to facilitate the removal, by gravity drainage, of particles accidentally entrained in the foam

Flotation cells belong to two distinct types:

- mechanical cells, which are the initial development of this type of machine
- pneumatic cells (including flotation columns) of more recent appearance

Depending on their unit volume and their application, these cells can be single cells or grouped in benches which the material to be treated then passes through successively.

3.2.5.3 Fields of application

3.2.5.3.1 Mineral constituents

It is in this domain that there are the most proven "gateways" and "formulations":

- Metallic constituents (metals, sulphides) are generally recoverable by the action of an anionic collector of the xanthate or dithiophosphate type used in mineral processing
- the oxidised phases of heavy metals, frequently found in contaminated soils, can also be recovered with the help of xanthates, after a preliminary sulphurisation stage during which the material is placed in presence of sodium sulphide. This reagent acts on the surface of the particles by forming a thin layer of sulphide of the heavy metal concerned (Pb, Cu, Zn), sufficient to allow the action of the collector
- the constituents formed of base metal oxides (Fe, Mn, Cr) are separable by the action of fatty acids or monophosphoric esters used for the purification of glassmaking sands or feldspars intended for the ceramic industry.

3.2.5.3.2 Carbonaceous constituents

Carbonaceous type particles often behave as coal fines and can be collected using a long-chain alcohol. The more or less heavy hydrocarbons, often associated with organic

matter, are extracted industrially using dissolved air cells after the action of an emulsifier which promotes the desorption of these hydrocarbons from the mineral particles they trap and the formation of an oily layer that can be recovered mechanically. A preliminary attrition stage may be useful.

3.2.5.4 Synthesis

More than in other waste separation techniques, the adoption of a flotation process requires knowledge of a number of preliminary data:

- the chemical and mineralogical composition of the material to be treated, which makes it possible to direct the search for the collector(s) likely to be suitable and provides additional data on the buoyancy of the other phases present under the treatment conditions envisaged (negative effect on selectivity)
- the particle size of the phase to be floated, which determines the type of cell to be used
- the objective to be achieved in terms of the quality of the floated product or the degree of elimination of this product from the initial material, which can influence the type of flotation to be considered (direct or inverse) and the additional treatment or purification (rewashing) stages to be foreseen

3.3 CONCLUSIONS

The different physical processes available for the recovery of recyclable solid materials were discussed in an effort to show the many similarities between these processes and those used for decades in the recovery of natural mineral materials. Many "bridges" exist between these two fields and there is a considerable amount of data and application cases in the mineral industry, which are detailed in the following chapter.

4 CASE STUDY

4.1 BENEFICIATION OF IRON ORES

4.1.1 Physical beneficiation method

Two principal physical separation methods exist. These refer to beneficiation methods of iron ore applied in practice. These include magnetic separation and gravity concentration.

4.1.1.1 Magnetic separation

This method is applied on the ores that contain primarily magnetite. The concentrate grade using magnetic separation ranges from 60% to 68% Fe and 5-9% SiO₂. In some cases, using this method, concentrate contains appreciable amounts of P₂O₅ and CaO, which is an unwanted impurity. These can be removed by flotation. A typical flow-sheet involves grinding, desliming, and primary and secondary magnetic separation. Concentrates are reground and recleaned using a magnetic separator provided that the concentrate contains middlings.

4.1.1.2 Gravity separation

This is applied on nonmagnetic iron. Typically, spirals are used to produce concentrate assaying 60-62% Fe and 7-9% SiO₂. In practice, a combination of gravity concentration and flotation is used.

4.1.2 Flotation beneficiation method

The operations of very large deposits that contain finely disseminated ore and considerable amounts of non magnetic iron, makes flotation more and more attractive as a method of concentrating iron ores. Even the magnetite concentrate derived by magnetic separation sometimes contains high silica and other impurities (i.e. CaO, P₂O₅) that need to be removed using the flotation method. There are two principal methods used in iron ore beneficiation using the flotation method. These are silica flotation & iron depression and nonmagnetic iron flotation & depression of silicate.

4.1.2.1 Selective flotation of silicates from iron ore

For the flotation of silicates from iron minerals, a number of methods have been proposed: hydrated lime method, caustic-metaphosphate method and caustic lignin method. For these methods, anionic collectors were used. The iron ore depressants during cationic flotation of silicates include starches, dextrans, lignins, and phosphates. The pH control during silica flotation is done by NaOH. The flotation pH range is between 8.0 and 10.1. This method is used when the ore contains calcite and phosphate. In this case, both calcite and phosphate can be recovered using fatty acid. Normally when using a fatty acid collector, a silica activator is used due to the fact that flottability of silica without the presence of an activator is relatively poor. Calcium chloride and related compounds were effective silica activators using fatty acid as a silica collector.

4.1.2.2 Selective flotation of nonmagnetic iron from iron containing ore

Extensive research work was conducted on nonmagnetic iron flotation from siliceous gangue minerals. In the studies, fatty acid collector with low resin content in conjunction with No. 2 fuel oil was used. The amount of fuel oil used was 3-4 times the fatty acid content. Sodium silicate was used as a silica depressant.

4.1.3 Examples of iron ore beneficiation

4.1.3.1 Swedish method

The iron ore treated in Sweden is a mixture of hematite and apatite. During extensive development testwork, a flow sheet (see Figure 33) consisting of sequential apatite and hematite flotation has been developed. Initially, apatite is floated using a sarcosine collector type followed by hematite flotation using an emulsion consisting of tall oil:fuel in a ratio of 1:2. In the hematite circuit, sodium silicate was used as a silica depressant.

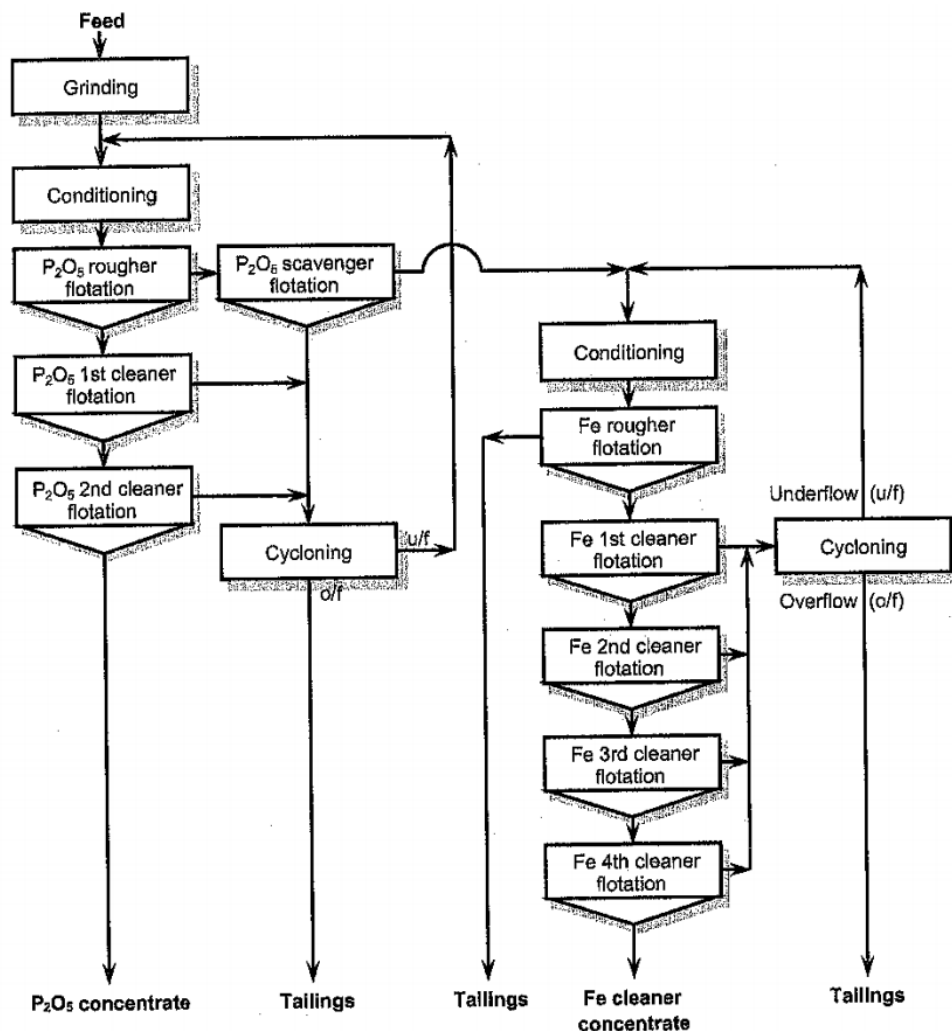


Figure 33: Flow sheet used in sequential apatite hematite flotation

4.1.3.2 U.S. Steel Corporation

U.S. Steel operates the **Minntac** and Keetac mines on the Mesabi iron range in northern Minnesota. Minntac processes magnetite ore concentrate pellets in grate-kiln-cooler induration (see Figure 34).

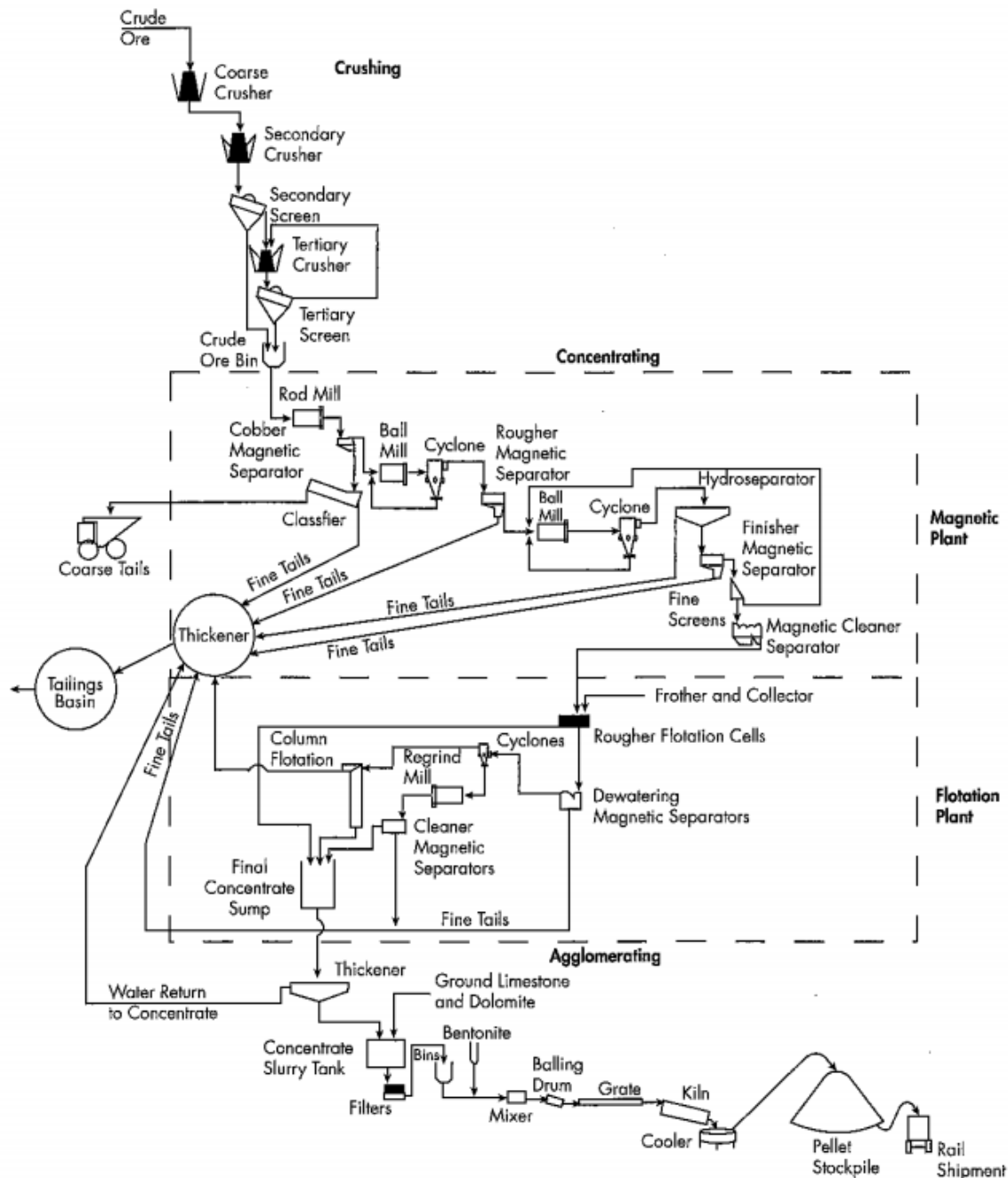


Figure 34: Minntac flow sheet

In addition to Essar Steel Minnesota, another example of modern flow sheet that is also successfully proven to operate is **Keetac**. The flow sheet has been optimized through pilot-scale testing and computer simulation studies. Energy consumption was reduced and grinding capacity increased by replacing the original hydrocyclone classification with fine screens. The combination of cyclones and fine screens is almost universal in magnetite-taconite plants, and some plants are operating circuits in which the cyclone is essentially eliminated and fine screens are used alone.

Tilden mine, located in Ishpeming, Michigan, is a unique mine in that it processes a low-grade ore (30-34% Fe) containing fine, disseminated hematite. Run-of-mine (ROM) ore is crushed to 225mm and the ground in primary fully autogenous mills along with caustic soda to increase pH throughout the beneficiation plant. The primary mill discharge is screened to remove -2mm particles, which are reground to 80% -74 μ m in fully autogenous pebble mills. Part of the primary mill screen oversize is used as grinding media in the pebble mill, and the remainder returns to the primary mill. The 75mm by 32mm fraction of the screen oversize is crushed using secondary cone crushers before it is returned to the grinding mill to avoid accumulation of this critical size material in the primary mill circuit. The pebble mills are closed with cyclones with an overflow size fraction at 80-90% passing at 25 μ m. This fine-size fraction is required to achieve the product silica set point and poses many challenges in the beneficiation processes. A dispersant is added to the pebble mill feed to aid in mill efficiency and in the downstream mineral separation process.

A cooked modified cornstarch is added to the cyclone overflow immediately prior entering the deslime thickeners. The cornstarch is added to selectively flocculate the liberated hematite. The deslime thickeners allow selectively flocculated iron-bearing minerals as well as coarse particulates to settle into the underflow while dispersed siliceous gangue minerals are rejected through the overflow. This process is required to economically produce high grade iron oxide pellet from this ore. The deslime thickeners upgrade the ore from ROM to 45-50% Fe prior to flotation. The deslime underflow is further concentrated by flotation to at least 65% Fe using a rougher-scavenger circuit. Starch is again added to this process to depress iron oxide surfaces while ether amine is added as a flotation collector for the reverse flotation of siliceous material not removed by the deslime thickeners. The final concentration is the thickened, mixed with limestone flux, and filtered using disk filters. Filter cake is pelletized using a bentonite binder, balling drums and a grate-kiln sintering furnace. A process flow diagram is showed in Figure 35.

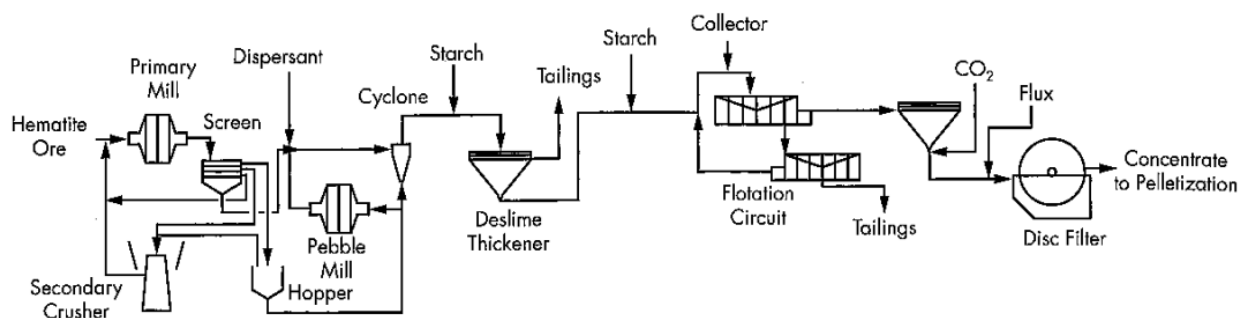


Figure 35: Tilden flow sheet

Because of the surface-chemistry-intensive nature of this process, the water chemistry is as important as the reagents used to facilitate beneficiation. The pH must be held between 10.5 and 11 throughout the process, partly because of the dispersive nature of alkaline environments with oxidized ores and partly because of the increased starch selectivity in this pH range. Of particular importance is the water hardness within the process, as free water hardness-contributing ions, particularly calcium and magnesium, within the process water act to nonselectively flocculate iron oxides and the associated gangue minerals during desliming.

Water hardness contribution ions also reduce the selectivity of starch to hematite surfaces. Levels of water hardness in excess of 20 ppm can cause a substantial loss in deslime thickener underflow grade associated with an increase in deslime iron recovery. This loss in deslime grade must be accounted for during the flotation process, which can handle excursions but results in significant loss in flotation iron recovery. This is a significant balancing act understood by the Tilden process engineers as an optimal pH, and water hardness must be maintained to maximize overall plant iron recovery.

4.1.3.3 Brazil

Brazil is a major producer of iron ore and pellets by Vale and Samarco. Vale's various pellet feeds and sinter fines are described in Table 10.

Table 10 : Vale iron ore process

Process	Natural Moisture Beneficiation Process	Utilization of Flotation Process for Fines of Low-Grade Itabirite	Beneficiation Process of Hard and Low-Fe-Grade Itabirites	Application of High-Intensity Magnetic Separators as Scavengers on the Reverse Flotation of Quartz Aiming Reducing %Fe on the Tailings, <8% Fe	Application of High-Intensity Magnetic Separators for the Concentration of Coarse Particles, -1 +0, 15 mm (10/16 in.)
Years of operation	From 2008	From 1974	From 1974	From 2014	From 1974
Product type†	Natural fines, -16 mm (10/16 in.)	Pellet feed	Pellet feed	Pellet feed	Sinter feed
Ore type	Hematite	Low-grade itabirites	Low-grade itabirites	Low-grade itabirites	Low-grade itabirites
Tons, Mt/yr (million tpy)	90 (88.6)	100 (98.4)	50 (49.2)	5 (4.9)	10 (9.8)
Name	Carajás mine	Iron Quadrangle	Iron Quadrangle	Iron Quadrangle	Iron Quadrangle
Crushing and screening steps	1° jaw crusher, 2° and 3° conic crushers; 1°, 2°, and 3° screening	NA‡	1° jaw or gyratory crusher, 2°, 3°, and 4° conic crushers; 1°, 2°, and 3° screening	NA	NA
Grinding	NA	NA	Ball mill in closed circuit with cyclones	NA	NA
Beneficiation steps	NA	Mechanical and column flotation cells on the reverse flotation of quartz with amine and cornstarch	Mechanical flotation rougher, cleaner, scavenger, recleaner, reverse flotation of silica with amine; vacuum disk filtration	Mechanical flotation rougher, cleaner, scavenger, recleaner, reverse flotation of silica with amine; vacuum disk filtration	One step of magnetic separation
Weight recovery, %	100	50–70	50–60	30–40	55–60
Fe recovery, %	100	70–80	75–85	70–80	60–65
Lines per plant	2	10	4	1	3
Total grade, %Fe	65	>65	>65	>65	>62
Contaminants, %	2.5 SiO ₂ , 1.0 Al ₂ O ₃ , 0.100 P	1.5 SiO ₂ , 0.5 Al ₂ O ₃ , 0.060 P	1.5 SiO ₂ , 0.5 Al ₂ O ₃ , 0.060 P	1.5 SiO ₂ , 0.5 Al ₂ O ₃ , 0.060 P	4.5 SiO ₂ , 0.5 Al ₂ O ₃ , 0.060 P

Courtesy of Vale

* Information obtained by the chapter authors' survey.

† The pellet feeds and sinter fines each have a 10% filter cake moisture.

‡ NA = not applicable.

Current flotation practices in Brazil are explained by Silva et al. (2011) as follows: in the past, iron ore producers would only use either mechanical or column cells, but not combine them. The latest trend has been to combine tank and column cells. Some producers place mechanical cells first in the configuration (which is preferred), and others place their column cells first. A potential alternative to tank cells or column may be the staged flotation reactor (Swedburg et al. 2016).

4.1.3.4 China

Hematite is the main source of iron ore in China and is difficult to beneficiate; Low-grade hematite ores containing 18-26% Fe are typically processed by gravity concentration, low-intensity magnetic separation, high-intensity magnetic separation, and reverse froth flotation. Zou (2007) and Dahe (2009) provide details for two Chinese iron ore mineral processing plants and credit two factors for their improved beneficiation: the SLon high-intensity magnetic separator (Outotec 2013) and anionic collectors for reverse silica froth flotation (Figure 36).

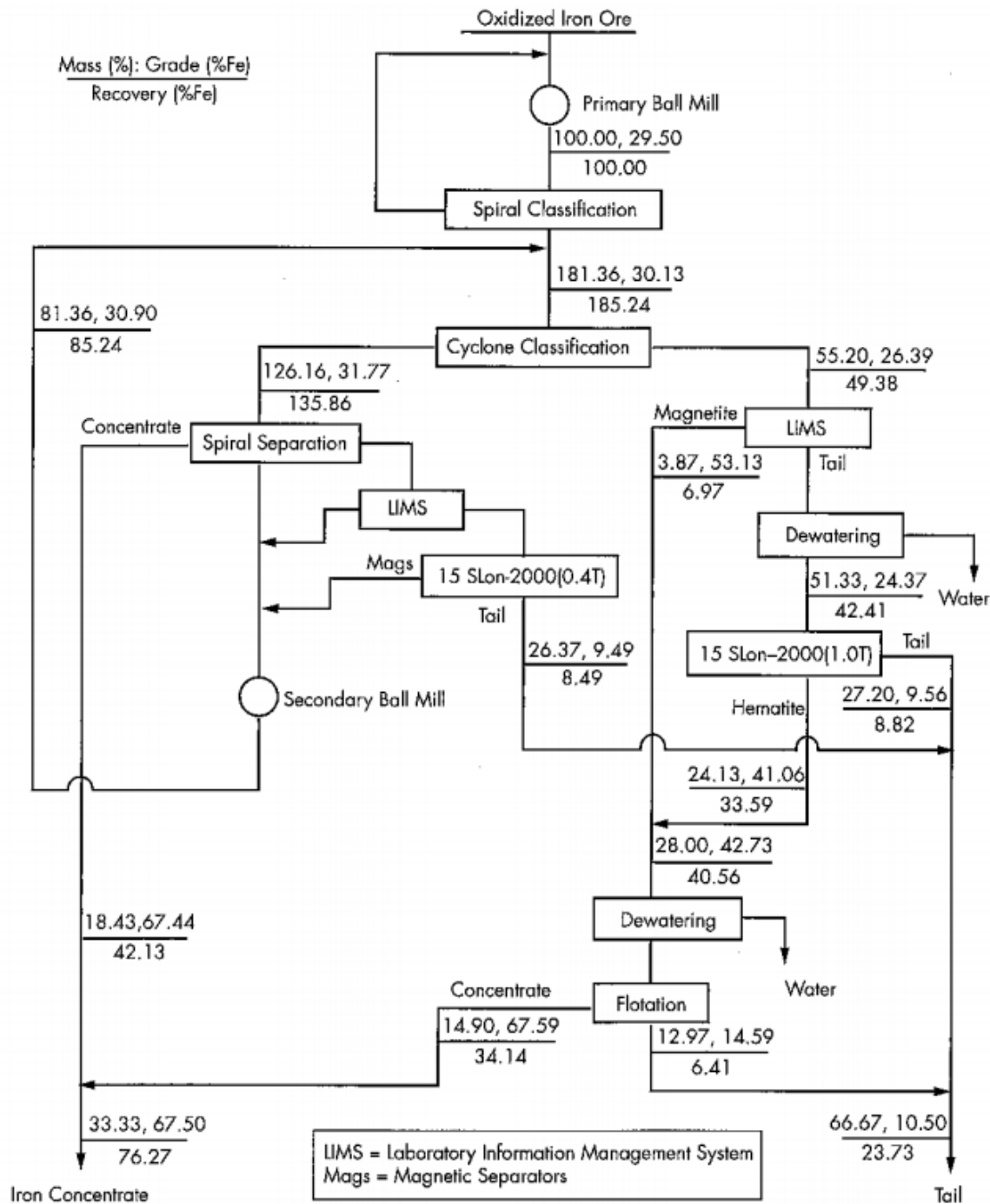


Figure 36: Latest flow sheet for the Diao Jun Tai iron ore processing plant

4.2 MINERAL PROCESSING METHODS ON LEAD ORES

Lead ores are commonly accompanied by zinc ores, with sphalerite (ZnS) predominating, but they are all gradations in relative proportions. Commonly associated sulfides in lead-zinc deposits are pyrite (FeS_2), marcasite and chalcopyrite (CuFeS_2). Copper is often a minor constituent in lead-zinc ores. In some instances, lead ores contain antimony, bismuth, arsenic and selenium in recoverable concentrations. The common gangue minerals include several carbonates, such as calcite (CaCO_3), dolomite (CaMgCO_3), ankerite ($\text{Ca(Fe,Mg,Mn)(CO}_3)_2$) and siderite (FeCO_3). Quartz and jasperoid (SiO_2), fluorite (CaF_2) and barite (BaSO_4) are also common. Many other minerals, both sulphides and gangues, are of local occurrence in lead-zinc deposits but may be prominent in certain ore bodies. The mineral proportions and associations depend on the type of ore deposit that is formed under the varying geologic conditions imposed by the nature of the country rock, its structure, its temperature and pressure at the time of mineral deposition, and the source and composition of the ore-depositing solutions.

Although there have been many recent developments aimed at improving the efficiency of the production and tackling ore-body problems, basic lead mining methods have been essentially unchanged. All ores require some sort of treatment. This process involves concentrating the ore by eliminating the gangue and waste material and, where required, the separation of valuable components in the mineral ore. The ore concentration makes use of the differences in physical properties between the various parts of the ore and typically consists of crushing, a pre-concentration at coarse size if possible, grinding and classification, and concentration.

4.2.1 Crushing

The ore is usually crushed and physically broken down into small particles in stages. Some crushing, particularly the first stage, is often done at the mine, the remainder in the concentrator. The sizing of ROM ore depends on ore type and mining procedures, and crushing practice is correspondingly affected.

4.2.2 Pre-concentration at coarse sizes

Most lead ore concentration is accomplished by flotation after fine grinding to achieve liberation. However, in some cases, an applied sink-float process rejects a discardable light fraction on crushed but unground ore, resulting in savings in subsequent processing.

Ferrosilicon medium is used in the majority of plants, with galena medium in some. Ferrosilicon is generally considered to be a superior medium, but galena offers a cost advantage when indigenous. Fines must be separated from the ore by screening and washing before sink-float. The normal range of treated ores for sink-float feeds is of the general order of 50 to 6 mm but in one application goes down to 0.5mm. Jigs are sometimes used on fines to complement heavy media separation. Sink-float is not widely used. Even when a low-grade float can be produced, some of the values may be recoverable by fine grinding and flotation. The economics vary with each situation.

4.2.3 Grinding and classification

Crushed ore, after pre-concentration at coarse size if practiced, becomes the feed for grinding. If the ore is easy flowing, it may be crushed with cone crushers down to about 3 mm, which will be the feed to ball milling. Otherwise, the crushed ore is further reduced in rod mills or rolls. Flotation feed is ground in ball mills often in one stage, sometimes in two or three stages, and sometimes with more complicated flow sheets for separate treatment of different ores or lead flotation ahead of final grinding. For lead ores, a reduction to under 0.15 mm is required. In most of the recent mills, cyclones, occasionally in two stages, are used as classifiers in grinding circuits, and in some older mills, rake and/or spiral classifiers have been replaced by cyclones. In most modern plants, the ore is ground to the coarse size that will permit suitably low rougher tailings losses. Regrind circuits for intermediate products such as the rougher concentrate, cleaner tailings, or a scavenger product must then be employed. This procedure is followed both to minimize grinding costs and to prevent sliming, particularly of galena. Otherwise, middlings are returned to primary grinding. The overflows stay in their respective circuits.

4.2.4 Concentration

Most lead ores are fine grained (<0.15 mm) and are concentrated mainly by froth flotation. Flotation results are affected by degree of oxidation, abundance in nature of iron sulphides, presence of copper minerals, and nature of a non-sulfide gangue. If necessary, separate streams may be provided for different ore types. Makeup water is normally fresh water but seawater can be used.

4.2.5 Sulfide concentration

The lead mineral is galena, PbS, with a specific gravity of 7.5. Coarse-grained ores are sometimes treated by gravity concentration, but a flotation section is usually justified for the treatment of slimes and reground middlings. Straight flotation is the most common practice. The use of jigs in combination with flotation is employed in some plants. Reagents used in lead and copper-lead flotation are shown in Table 11. In addition, various other reagents are sometimes used as a result of local customs or unusual features of the ore. The optimum reagent balance must be found by experiment on each ore.

Table 11 : Reagents commonly used in lead and copper-lead flotation

Collectors	pH Modifiers	Zinc and Iron Depressants	Frothers	Others
Xanthates (ethyl, propyl, isopropyl, butyl amyl), Aerofloat promoters (alkali dialkyl dithio phosphates sometimes with frother), Minerec A	Lime, soda ash, sodium hydroxide, sulfuric acid, crude dry lake products like tequesquite	Sodium or calcium cyanide, zinc sulfate, sulfur dioxide or sodium bisulfite, zinc hydrosulfite	Dowfroth, cresylic acid, pine oil, MIBC (methyl isobutyl carbinol), coal tar, TEB (triethyloxybutane)	Sodium silicate

Source: Bushell and Testut 1985

With lead-zinc ores, lead and copper (if present) are floated before zinc. Lead and copper are usually floated and cleaned together, but sometimes a copper concentrate is floated first. Occasionally a pre-float removes “natural floaters” such as talc or graphite that would otherwise contaminate the lead concentrate. When iron sulfides are present, lime must be used. Cyanide, often with zinc sulfate, is used to depress zinc and sulfites are occasionally added to depress iron. Lead flotation is generally at a pH in the range of 7.5 to 10.

Table 12 : Reagents scheme used in the operating plants using bulk flotation method

Concentrator	Reagent Additions (g/t)		
	Pb-Zn Bulk flot	Pb-Zn separation	Zn upgrading
Porko (Bolivia)	CaO = 10,800 (pH 10) CuSO ₄ = 450 R242 = 5 SIPX = 80	ZnSO ₄ /NaCN = 214 MIBC = 10	–
Bolivar (Bolivia)	CaO = 3,000 AF242 = 70 SIPX = 200 MIBC = 59 CuSO ₄ = 1,250	NaCN = 1,200 ZnSO ₄ = 1,250	CaO = 200 CuSO ₄ = 350 SIPX = 10 DF1012 = 6
El Mochito 11.8	CaO = 1,200 CuSO ₄ = 400 AF3477 = 20 PAX = 30	NaCN = 150 ZnSO ₄ = 280	CaO = pH CuSO ₄ = 200 SIPX = 10 DF250 = 5

MIBC = 10 gr/t

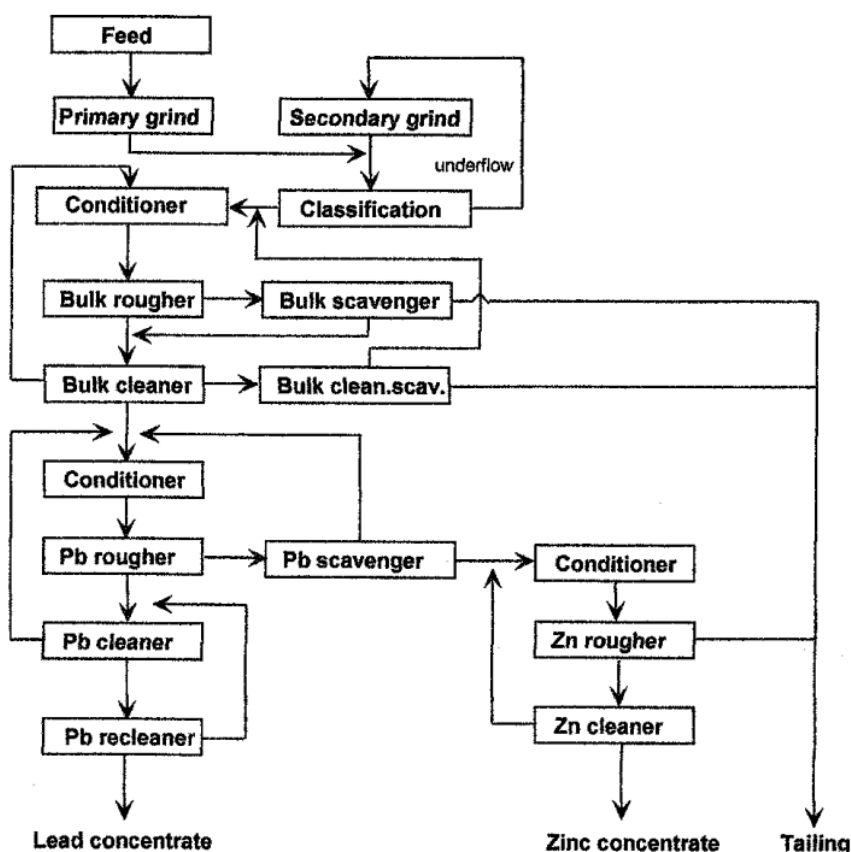


Figure 37: Bulk flotation flow sheet concept used in some operating plants

Table 13: Plant metallurgical results obtained using bulk flotation method

Concentrator	Assays (% , g/t)										
	Feed			Pb conc			Zn conc		Recovery (%)		
	Pb	Zn	Ag	Pb	Zn	Ag	Pb	Zn	Pb	Ag	Zn
Porko	0.82	8.57	95	59.0	9.7	3295	0.71	52.2	70.0	33.6	93.0
Bolivar	0.75	12.7	89	33.3	7.3	6800	2.04	49.1	60.1	61.2	91.5
El Mochito	2.60	11.5	60	63.0	5.4	1500	0.60	55.6	78.0	45.0	90.0

The bulk lead-copper concentrate is cleaned to the optimum grade and then is split into separate lead and copper concentrates. Two orders of lead-copper separation are used. In one, the lead is floated while the copper is depressed (with cyanide), and, in the other, the copper is floated and the lead is depressed (with sodium dichromate, sulfur dioxide or starch).

Sometimes, appreciable zinc reports to the lead concentrate from the final stage of normal cleaning and needs to be removed. "Dezincing" gives two end-products: a final lead concentrate and a zinc concentrate, which is added to the one obtained by normal zinc flotation. The de-leading of zinc concentrate, using lead depression method, was practiced in the Sullivan concentrator (Canada). Initially $\text{Na}_2\text{Cr}_2\text{O}_7$ was used for lead depression (1960-1970) and more recently, dichromate was replaced by pulp thermal treatment. The pulp is heated to 60°C using steam and the zinc is floated away from the lead using frother only.

Table 14: Metallurgical results obtained on the Santa Barbara (Mexico) de-leading circuit

Product	Assays (% , g/t)					
	Pb	Zn	Fe	Ag	Au	Cu
Zn conc (de-leading feed)	5.4	50.2	7.5	294	1.2	1.6
Zn de-leaded conc	1.1	54.5	7.2	171	0.8	1.1
Pb conc (froth product)	42.6	12.9	10.2	1364	4.6	6.0

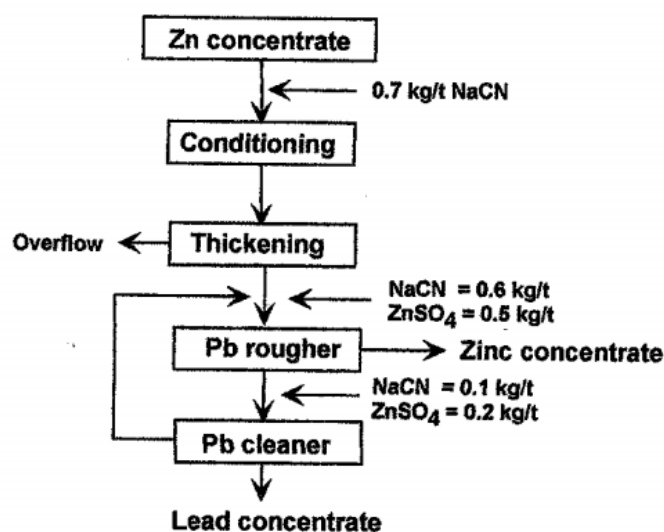


Figure 38: Santa Barbara de-leading of zinc concentrate flow sheet

At other lead-zinc mines, the first-stage flotation concentrate, containing both lead and zinc, is refloatated with activated carbon, caustic soda, maize starch, and sodium dichromate to yield tailings that become part of the final lead concentrate and a float that goes to the low-grade zinc circuit. If the feed is partly oxidized, a bulk float is first made and then separated into lead, zinc and iron concentrates.

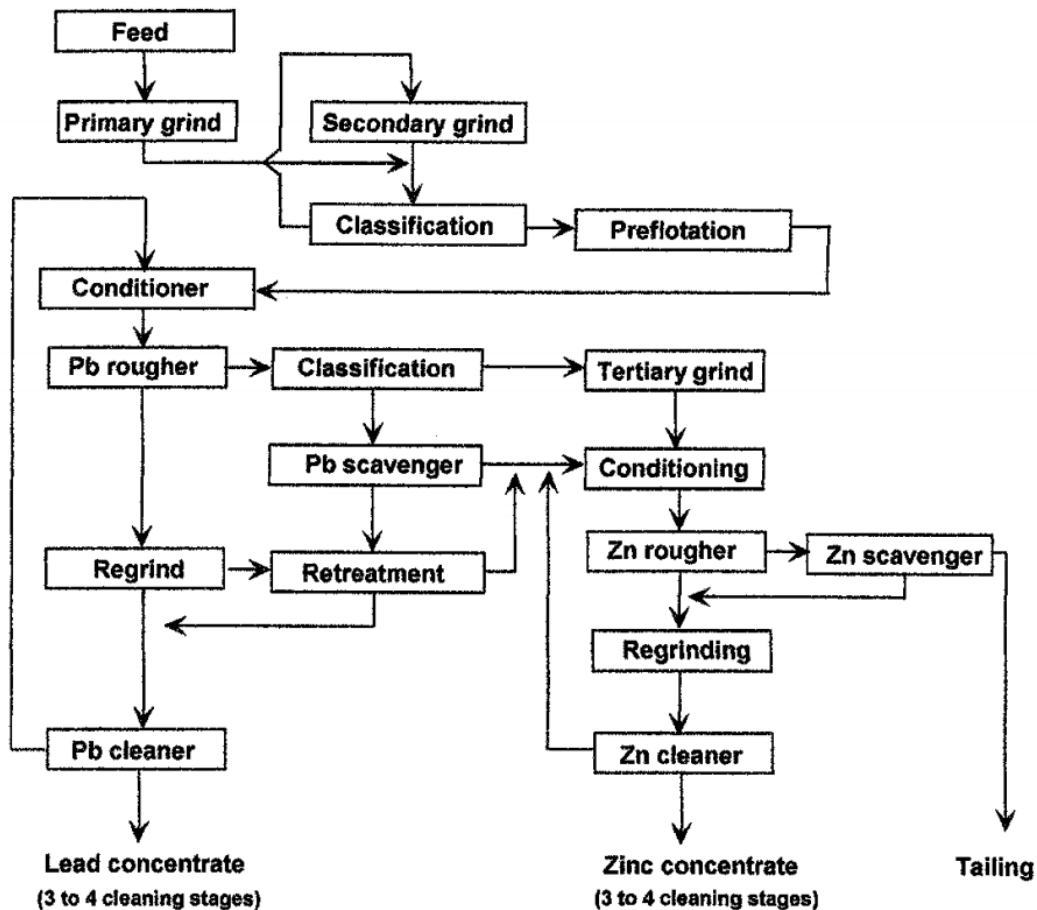


Figure 39: Flow sheet with pyrite or graphite prefloat

4.2.6 Oxidized lead ores

The lead minerals considered first are cerussite (PbCO_3) and anglesite (PbSO_4). Both are soft minerals that usually slime badly during comminution. Cerussite ores are floated with a powerful sulphide collector after the cerussite has been sulfidized. Cerussite usually sulfidizes readily. Sodium sulphide is often used. However, if a large amount of sulfidizing agent is required, a mixture of sodium sulfide and sodium hydrosulfide may be preferred in order not to increase the pH too much (generally close to 8.5). A succession of flotation steps is sometimes used, each step comprising a quick sulfidizing reaction, followed by flotation. A table of widely used reagents are listed in Table 15.

Table 15: Reagents commonly used in oxidized lead flotation

Collectors	pH Modifiers	Zinc Depressants	Sulfidizing Agents	Frothers	Others
Xanthates	Sodium carbonate	Sodium cyanide	Sodium sulfide	Pine oil	Sodium silicate
Amylxanthates	Sodium hydroxide	Zinc sulfate	Sodium sulfhydrate	Cresylic and xyleneic acids	Oil
Thiocarbamates		Sodium sulfide		Dowfroth	Creosotes
Mercaptobenzothiazol				Speld 1333	Coal tar
Long-chain thioalkyl acids				Aerofroth 65	Carboxymethyl cellulose
Aerofloat					Kerosene
Oleic acid					Lignosulfonates
Refined tall oil					
Reagent 404					

Source: Bushell and Testut 1985

Anglesite is more difficult to float by sulfidizing than cerussite, and the permissible pH range is narrower. The sliming tendency of oxidized lead ores is a source of difficulties with long chain collectors. However, where the gangue is acid, fatty acids are sometimes used in the collecting agents. Flotation with fatty acids loses selectivity in the presence of limestone or dolomite.

Pyromorphite $Pb_5(PO_4)_3Cl$ and mimetite $Pb_5(AsO_4)_3Cl$ are generally finely disseminated and associated with cerussite and anglesite. They can be concentrated by flotation. Desliming before fine grinding may be necessary to reject the primary slimes. Two flotation schemes are possible: either a flotation of cerussite and anglesite first, after sulfidizing, followed by pyromorphite and mimetite flotation with fatty acids; or all minerals are floated together with fatty acids.

4.2.7 Lead-zinc ores with both sulfides and oxides

Oxidized ore with insufficient oxidized minerals to justify separate recovery nevertheless poses special problems in flotation. With straight lead-zinc ores, much of the trouble results from activation of zinc and possibly iron sulfides by lead ions coming from oxidized lead minerals. Washing the ore before grinding can be helpful. Cyanide is useless for overcoming lead activation, but addition of soda ash or lime to the grinding circuit can be helpful.

Mixed sulfide-oxide ores with basic gangue can sometimes be treated for recovery of oxidized minerals as well as sulfides. Effective depression of sphalerite, which has been activated by lead ions, is essential. Sodium sulfite and bisulfite, zinc sulfate combined with ammonium sulfate, zinc sulfate and sodium silicate, or reagents that precipitate lead ions like sodium sulfide and zinc powder are used. However, sodium sulfide sometimes depresses sphalerite (ZnS) permanently.

When mixed oxide-sulfide ores contain iron sulfides, flotation is complicated further. The classic flotation sequence is galena (PbS) – sphalerite (ZnS) – pyrite (FeS₂) – cerussite (PbCO₃) – smithsonite (ZnCO₃). If smithsonite is not recovered and pyrite flotation is not justified, a simpler two-circuit scheme (galena + cerussite-sphalerite) is preferred. Pyrite is usually depressed with cyanide and lime.

Ores that have undergone partial or strong oxidation during formation of the orebody usually have an acid character due to the presence of pyrrhotite (Fe_{1-x}S with $0 < x < 0.20$) and marcasite (FeS_2), as well as the presence of acid gangue. The acidic nature of the ore, where the natural pH is between 5.5 and 6.5, restricts the use of conventional depressants such as cyanide, and in some cases, the consumption of alkali is extremely high to obtain an alkaline pH. The use of an excessive amount of alkali may also result in a reduction in the floatability of galena. Typical examples of such ores are the Laurium Mine in Greece and the Carthagena Mine in Spain. The highly acidic ores (natural pH 5.0-5.5) contain a high amount of soluble salts which interfere with flotation. In this case, the pyrite (FeS_2) is extremely active and was difficult to depress. There are several methods by which these ores can be processed to some degree of success.

Table 16: Plant metallurgical results obtained in various plants treating disseminated massive sulfide ores

Concentrator	Assays (% , g/t)								Recovery (%)		
	Feed			Pb conc			Zn conc		Pb conc		Zn conc
	Pb	Zn	Ag	Pb	Zn	Ag	Pb	Zn	Pb	Ag	
Faro I & II	3.3	6.2	66	63.5	6.8	750	1.6	49.2	70.0	46.0	77.0
Faro Grum & Vang	3.7	5.6	75	61.5	7.1	950	2.2	51.0	80.0	58.5	84.4
Cirque	2.8	8.9	40	69.1	4.4	—	1.5	57.0	81.0	—	88.5
Rozberg	6.4	11.2	—	58.9	16.2	—	2.5	56.5	64.3	—	86.4
Mount Isa	7.0	6.5	148	47.6	6.9	1206	2.9	50.0	82.4	80.5	71.8
Elura	4.6	7.5	—	45.5	7.7	—	2.2	51.0	75.5	—	78.2
Lady Loretta	2.7	14.6	—	52.2	6.7	—	3.4	56.0	77.1	—	85.0
Megan	1.3	10.0	15.0	—	—	—	—	—	—	—	—
Tara Mines	3.2	8.0	66.0	58.2	4.4	—	1.6	58.3	78.5	—	86.8
Huallanca	1.5	10.4	180.5	68.3	2.2	2700	0.8	50.0	80.2	66.5	90.0
Kamioka	2.8	6.6	—	56.6	3.4	—	5.4	51.0	70.2	—	75.5
Sullivan	5.8	5.5	59.0	55.0	8.8	—	1.8	52.5	75.0	—	80.1
Red Dog	5.4	17.8	—	51.0	9.1	—	2.2	55.6	35.1	—	75.3
Greens Creek	3.2	9.1	360	55.0	6.8	4800	2.3	55.0	66.0	55.5	64.0

4.2.8 Treatment of lead-zinc-silver ores

Most of lead ores contain some silver or silver and gold, which is recovered in either lead or in both lead and zinc concentrates, in which case the precious metals are considered as a by-product for extra revenue. Emphasis in the treatment of these ores is placed on recovery of lead and zinc and the recovery of precious metals is usually not emphasized for a number of reasons, some of which include:

1. metallurgical problems with lead and zinc need to be solved;
2. lack of research data on the flotation of silver minerals;
3. some silver minerals are capable of releasing cations (Ag^+ , Cu^{2+}) which causes reduced selectivity between lead and zinc. Restoring selectivity between lead and zinc in such cases also reduces recovery of silver.

The lead-zinc ores that contain a silver value or silver and gold value equal or higher than the value of both lead and zinc in the ore are considered as lead-zinc-silver ores. During treatment of these ores, emphasis is placed on maximizing the recovery of silver, preferably in the lead concentrate. So far, more than 200 silver minerals have been discovered in various sulfide ores, including platinum group minerals. Only about 20 of these minerals (see Table 17) are of economic value and are commonly found in lead-zinc-silver ores.

Table 17: Silver carrying minerals in the lead-zinc-silver ores

Mineral	Formula	Ag content (wt %) ^a
Native silver	Ag	100.0
Pyrargirite	Ag ₃ SbS ₃	59.8
Diaphorite	Pb ₂ Ag ₃ Sb ₃ S ₈	23.8
Freibergite	(AgCu,Fe) ₁₂ (SbAs) ₄ S ₁₃	25.0
Argentite (acanthite)	Ag ₂ S	87.1
Proustite	Ag ₂ AsS ₃	65.0
Andorite	PbAgSbS ₆	12.6
Miargirite	AgSbS ₂	36.7
Jalpaite	Ag ₃ CuS ₂	71.6
Stephanite	Ag ₅ SbS ₄	68.3
Pyrostilpnite	Ag ₃ SbS ₃	59.8
Owsheite	Pb ₅ Ag ₂ Sb ₆ S ₁₅	8.8
Tetrahedrite	(Cu,Ag,Fe,Zn) ₁₂ Sb ₃ S ₁₄	1.0–34.0
Ag-bearing galena	PbS	0–0.6
Agularite	Ag ₄ SeS	10–18
Pearcite	Ag ₃ As ₂ S ₂	20–25
Antimonpearcite	(AgCu) ₁₆ (SbAs) ₂ S ₁₁	10–14
Polybasite	(AgCu) ₁₆ Sb ₂ S ₁₁	8–18

^aMay vary from ore to ore

Commonly, the lead-zinc-silver ore contains three or more silver minerals. In some cases, ore contains up to 10 different silver minerals. The presence of multiple silver minerals in the ore, also represent a problem in optimization of silver recovery. Very little is known regarding flotation of different silver minerals. Cyanide has a depressing effect on a number of the silver minerals. Alternative depressants used during the treatment of lead-zinc-ores were Na₂S, Na₂SO₃ or complex cyanide. Typical metallurgical results obtained in lead-zinc-silver ores in different operating plants are summarized in Table 18.

Table 18: Plant metallurgical results obtained on lead-zinc-silver ores

Concentrator	Assays (% , g/t)								Recovery (%)			
	Feed			Pb/Ag conc			Zn conc		Pb conc		Zn conc	
	Pb	Zn	Ag	Pb	Zn	Ag	Zn	Ag	Pb	Ag	Zn	Ag
Krasnorechensky	1.1	3.6	250	47.4	4.5	3980	47.8	250	88.8	79.3	84.1	6.7
Sherlova Gora	1.9	2.6	210	77.9	1.7	5170	41.5	220	80.4	71.9	60.3	5.2
Salmo Mine	1.5	4.4	180	70.8	6.9	1900	58.2	110	85.5	73.1	89.8	2.8
Giant Mascot	4.4	0.3	250	69.9	3.2	2800	50.9	120	94.9	65.5	50.9	3.3
Wilson Silver	4.5	8.6	1364	52.0	12.0	15360	55.0	1023	92.0	87.0	85.0	10.2
United Keno Hill	8.6	8.6	1229	71.3	3.6	9696	56.3	384	93.3	89.0	88.2	6.5
Undaychaqua	1.2	7.1	279	37.0	4.5	8100	56.8	440	89.0	69.5	89.0	4.5
Mahr	0.8	6.3	155	55.5	6.6	6020	58.5	3300	66.5	70.2	85.2	3.6
Uchucchacua	1.1	1.4	450	17.0	3.9	8800	44.0	1100	88.0	71.2	63.0	4.5

4.3 COPPER MINERAL PROCESSING

The mineral processing of copper ores refers to the use of crushing, grinding, and froth flotation to recover copper sulfide minerals from ores to concentrates. Since large semiautogenous grinding (SAG) mills were popularized in copper concentrators in the 1980s and 1990s, and with the treatment of lower grade deposits, SAG mills have prevailed and are included in many of the concentrator flow sheets. In addition, larger giratory crushers, cone crushers, ball mills and circular tank flotation machines have also been included as a feature of these flow sheets, allowing copper concentrators to employ fewer pieces of equipment and at lower overall operating costs.

Emerging comminution technologies such as high-pressure grinding rolls (HPGRs) and new-generation flotation cells are challenging this norm. However, most deviations from this arrangement are usually due to complications in metallurgy related to ore mineralogy, including:

- Oxidation and alterations of the copper or gangue minerals;
- Recovery of credit elements such as gold, zinc or molybdenum;
- Management of penalties species such as arsenic, bismuth, zinc or talc;
- Significantly harder ore requiring different comminution approaches.

Copper ores constitute a large and geologically diverse group of ores. Many are dominated by copper as the primary metal of production, others have co-product or by-product gold or molybdenum, while others are part of polymetallic copper-zinc-lead ores. Common copper ores minerals are listed in Table 19.

Table 19: Common copper ore minerals

Name	Specific Gravity, g/cm ³	Molecular Formula	% Cu	Cu/S Mass Ratio	Hardness
Chalcocite	5.6–5.8	Cu ₂ S	79.9	3.96	2.5–3.0
Covellite	4.6	CuS	66.5	1.98	1.5–2.0
Chalcopyrite	4.1–4.3	CuFeS ₂	34.6	0.99	3.5–4.0
Bornite	4.9–5.1	Cu ₅ FeS ₄	63.3	2.48	3.0–3.3
Digenite	5.6	Cu ₉ S ₅	78.1	3.57	2.5–3.0
Tennantite	4.6–4.7	Cu ₁₂ As ₄ S ₁₃	51.6	1.83	3.5–4.5
Enargite	4.4	Cu ₃ AsS ₄	48.4	1.49	3.0
Tetrahedrite	4.6–5.2	Cu ₁₂ Sb ₄ S ₁₃	45.8	1.83	3.5–4.0
Stannoidite	4.3	Cu ₈ Fe ₂ ZnSn ₂ S ₁₂	38.3	1.32	4.0
Mawsonite	4.7	Cu ₆ Fe ₂ SnS ₈	43.9	1.49	3.5–4.0
Wittichenite	6.3–6.7	Cu ₃ BiS ₃	38.4	1.98	2.0–3.0
Djurleite	4.2	Cu ₃₁ S ₁₆	79.6	3.84	2.3–3.0
Cubanite	4.7	Cu ₂ S·Fe ₄ S ₅	23.4	0.66	3.5–4.0
Luzonite	4.4	Cu ₃ AsS ₄	58.8	1.98	3.5

4.3.1 Process selection

Most copper concentrators use the same arrangement for the process (see Figure 40):

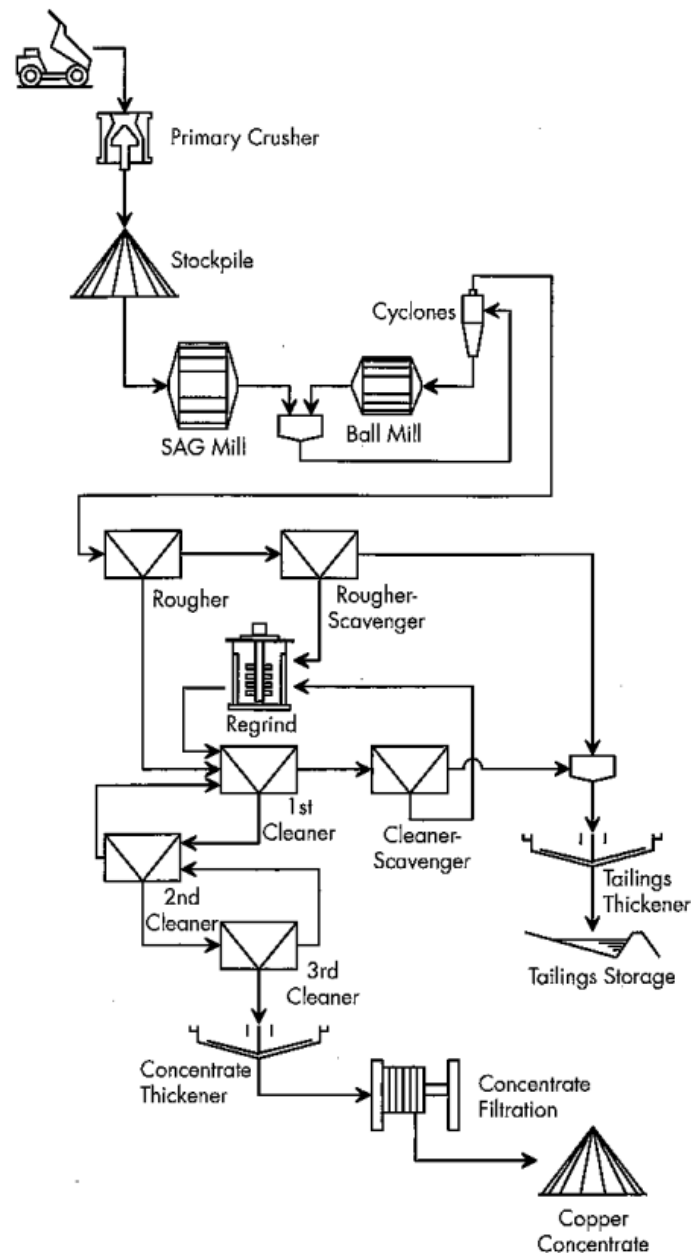


Figure 40: Standard copper concentrator flow sheet

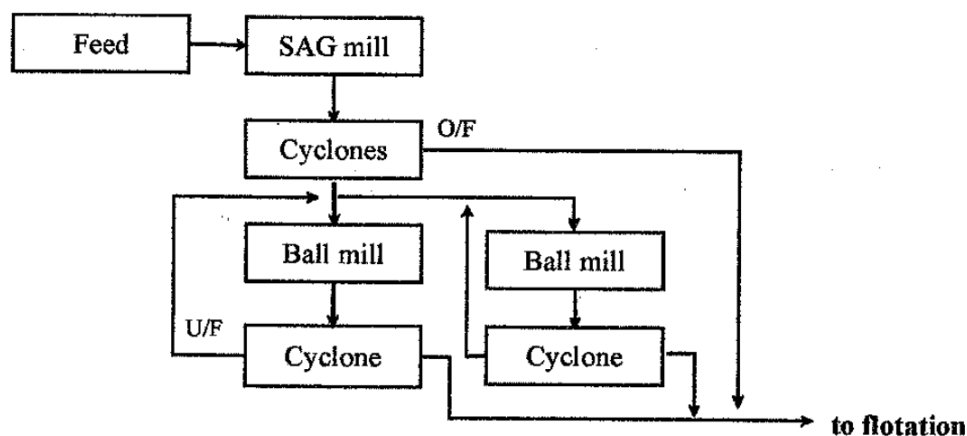
1. Comminution: a combination of crushing, autogenous grinding mills, SAG mills and HPGRs reduce the ore particle size to P_{80} 1-4mm, suitable to be fed to ball mills. The ball mills reduce the particle size further to P_{80} 106-250 μ m.
2. Classification: hydrocyclones are, by far, the most popular equipment for classifying the mill discharge. Fine screen decks have been used in smaller copper concentrators in recent years.
3. Rougher flotation: a high recovery froth flotation stage of 15-40 minutes of residence time produces a rougher concentrate in 5-15% mass pull from the feed. The rougher tailings are usually sent to final tailing storage.

4. Regrind: the regrind circuit can be fed combinations of rougher concentrate, rougher scavenger concentrate or cleaner-scavenger concentrate.
5. Cleaner flotation: 2 or 3 stages of cleaning, 5-15 minutes of residence time each, are used to separate the copper minerals from non-copper sulfides and gangue in the rougher concentrate to produce commercial concentrate quality.
6. Cleaner scavenger flotation of 10-20 minutes of residence time is used to capture slow-floating particles from the first cleaner tailings. The cleaner-scavenger tailings usually report to the final tailings.
7. The copper concentrate is thickened and filtered to produce a cake with 8-10% moisture for shipment to smelters.
8. The combined final tailings are usually thickened to recover water and reagents before being sent to the tailings storage. In some cases, the water is recovered from the tailings storage facility without using a thickener.

4.3.1.1 Comminution

Copper ore particles are reduced in size to liberate the copper minerals from the gangue so that they can be floated selectively. Comminution is expensive because it consumes a lot of energy. Consequently, concentrator designs are configured to preconcentrate the copper at a coarse grind size. The low-grade concentrate is then typically regrind to a finer size to achieve liberation from the gangue.

In the 1980s, semiautogenous (SAG) milling replaced three stages of crushing as the preferred approach to comminution for large grinding circuits. This was due to SAG mills having higher capacities, simpler flow sheets, lower operating costs, higher availabilities, reduced maintenance complexities and the ability to treat wet and sticky ores.



4.3.1.2 Froth flotation

Copper is upgraded from 0.3-2.0% Cu in the ore to 22-45% in a concentrate using the froth flotation process. The flotation circuit design is different in every plant. There is no standard for the flow-sheet arrangement or circuit parameters. There are, however, a few common approaches to pragmatic flow-sheet development.

Since all ores are different, most concentrators also have different reagent regimes for copper flotation. Flotation reagents vary depending on factors that include:

- Copper mineral assemblage and textures;
- Precious metal (gold, silver) and other valuable base metals (lead, zinc, molybdenum, nickel);
- Iron sulfide (pyrite, marcasite, pyrrhotite) abundance, texture and associations;
- Non-sulfide gangue interactions (clays, chlorite, talc, carbonates);
- Penalty element mineralogy (arsenic, bismuth, antimony, cadmium);
- Ore variability.

The objective is to choose a reagent regime that can consistently recover the valuable minerals into a clean concentrate, at a low cost, within the variations of daily mining feed blends to the concentrators.

4.3.1.2.1 Porphyry copper and copper-molybdenum ores

Table 20 shows plant operating conditions for the most important porphyry copper and copper-molybdenum ores. The data for these plants were collected over the past several years (1995-1999). During this period, different types and lower grade ores have been treated and consequently the reagent schemes changed.

Table 20: Copper plant operating data

Plant	Major Cu minerals capacity (tpd)	Head assay %		Concentration assay %		% Recovery		Grind	
		Cu	MoS ₂	Cu	MoS ₂	Cu	MoS ₂	% <200 mesh	K ₈₀ μm
<i>Russia</i>									
Balkhashi	40,000 Cp,Bo	0.40	0.015	24.0	85	85	40	60	143
Bozchshakul	18,000 Cp	0.58	0.020	18.0	75	78	56	50	178
Almalyk	50,000 Cp	0.50	0.01	19	85	77	40	45	190
Kadzharan	20,000 Cp	1.25	0.05	17	79	80	68	61	144
Agarak	12,000 Cp	1.50	0.02	18	81	79	75	70	118
Koundarskoie	30,000 Cp	1.10	0.015	18	83	88	66	66	138
<i>Europe</i>									
Majdanpek, Yug	15,000 Cp	0.77	0.005	26.5	—	85	—	50	169
Krivelj Bor	25,000 Cp	0.35	—	28	—	78	—	40	220
Medez Bulgaria	28,000 Cp	0.35	0.011	15	65	81	30	55	155

Flowsheets used in the flotation of porphyry copper ores are relatively simple (see Figure 42) compared with the flowsheets used in the flotation of massive sulfide ores.

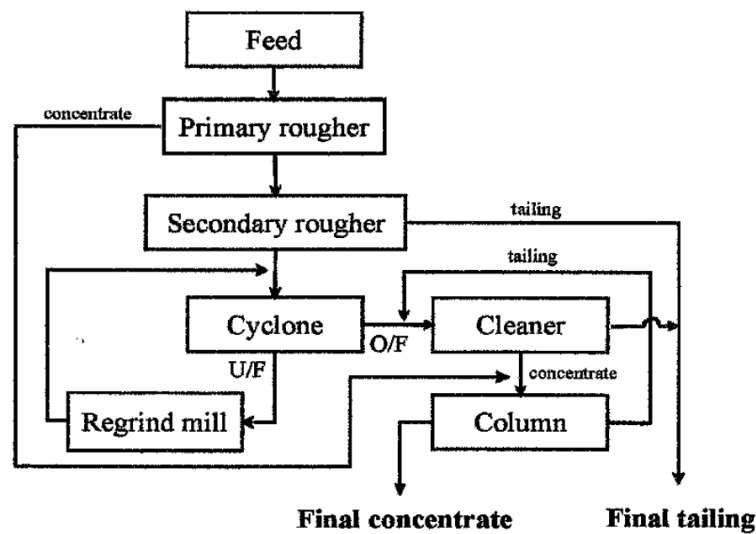


Figure 42: Typical flowsheet used in the flotation of porphyry copper ores

4.3.1.2.2 Massive sulfide copper-zinc ores

This ore is common in many parts of the world, including Europe (i.e. Turkey, Scandinavia, Spain and Portugal). Most of these ores are fine grained and require relatively fine grinding to achieve reasonable liberation. Some deposits contain secondary copper minerals where the separation of copper from zinc becomes very difficult and require the use of a special reagent scheme and flowsheet. The solubility of the ore, in some cases, represents a significant problem in sequential flotation copper-zinc minerals. The ore that contains soluble metals (Cu, Fe, Ag) often require special pre-treatment to restore selectivity between copper and zinc minerals. A typical flowsheet is shown in Figure 43.

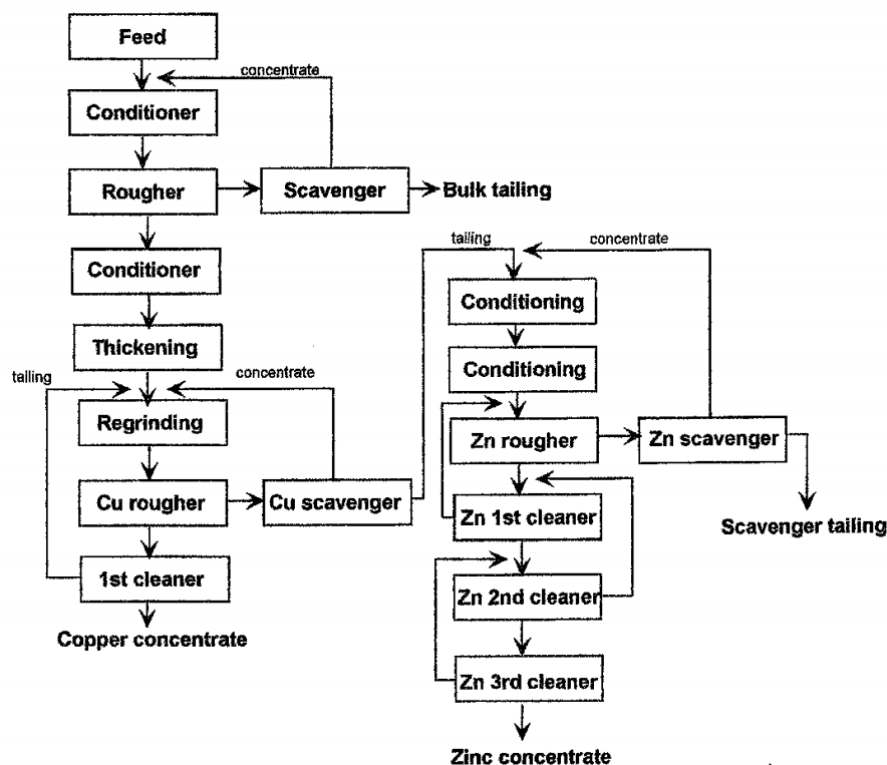


Figure 43: Bulk flotation flowsheet used for the treatment of copper-zinc ores

Table 21 shows metallurgical results obtained in different operating plants that treat massive sulfide copper-zinc ores.

Table 21 : Metallurgical results obtained in operating plants treating massive sulfide copper-zinc ores

Concentrator	Assays (%)						Recovery (%)	
	Feed		Cu conc		Zn conc		Cu conc	Zn conc
	Cu	Zn	Cu	Zn	Cu	Zn		
Flin Flon, Canada	2.5	4.5	25.5	4.3	0.9	52.2	95.5	75.3
Goldstream, Canada	3.1	3.3	27.1	3.8	1.1	47.5	92.4	60.3
Lynn Lake, Canada	1.8	4.6	24.8	4.6	1.2	54.5	89.3	80.5
City Services, USA	1.4	6.0	22.4	3.1	1.1	50.5	85.5	70.2
Priska, South Africa	1.6	1.7	25.5	3.95	2.10	50.1	85.5	70.4
Cayeli Riz, Turkey	3.3	11.5	22.5	8.60	3.10	49.1	80.3	65.6
Bald Mountain ^a , USA	2.1	3.8	27.6	4.4	0.5	54.4	85.4	77.3
Tennessee Copper, USA	1.6	5.7	28.6	3.2	0.6	55.1	88.3	75.4
Lahanos, Turkey	4.2	2.6	22.5	6.1	0.9	50.5	80.1	66.2
Alfredo ^a , Spain	2.1	2.0	25.5	3.1	0.9	52.2	85.5	58.2
Krasnouralskaia, Russia	1.8	2.0	16.6	3.8	0.8	50.0	82.2	68.3
Kirovograd, Russia	1.2	3.3	17.5	2.77	0.42	53.2	89.5	74.5
Sredneuralsk, Russia	1.4	4.0	16.0	8.60	1.80	47.6	75.6	33.2
Karabash, Russia	1.5	2.1	19.1	7.50	0.80	49.5	81.2	55.6
Ioshina, Japan	0.72	2.4	22.8	9.24	1.39	52.4	81.6	83.2
Adjustral ^a , Portugal	1.20	4.40	23.5	5.60	0.89	50.6	75.5	80.2

^aPilot plant data.

4.3.1.2.3 Copper-lead-zinc ores

The copper-lead-zinc ores have an origin similar to copper-zinc ores. Some of these ores contain significant amounts of precious metals and, more rarely, cobalt and nickel. The bulk copper-lead flotation method is the most economic and is used whenever possible. Using such a method, the copper-lead bulk concentrate is floated, followed by Cu-Pb upgrading and separation.

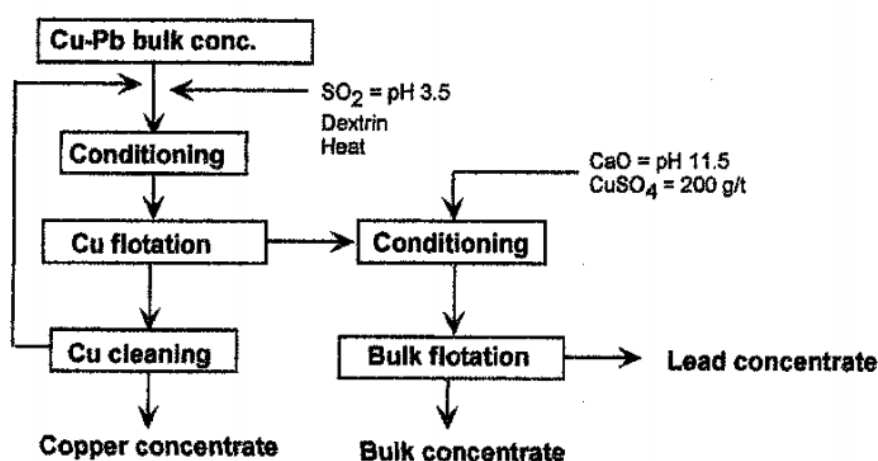


Figure 44: Flowsheet and reagent scheme employed for upgrading of lead concentrate from Cu-Pb separation tailing

Table 22 : Summary of plant metallurgical results

Concentrator	Assays %												% Recovery ^a		
	Head			Cu concentrate			Pb concentrate			Zn concentrate					
	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn	Cu	Pb	Zn
Berozovskia	1.5	4.1	9.2	28.8	2.7	4.5	1.0	53.2	15.2	1.5	0.3	51.0	83.0	82.0	87.1
Mizursk	1.4	2.9	8.8	25.2	4.8	6.8	1.6	73.0	5.0	0.5	1.4	57	75.3	86.1	88.2
Uchinotai	2.5	2.0	4.8	20.0	5.0	5.5	4.2	54.0	9.0	1.2	1.7	54	86	58	78
Doyashiki	1.2	0.3	1.4	16.5	1.4	6.0	6.0	53.0	7.0	2.0	1.0	60	82	63	63
Federal	0.2	1.9	12.1	27.4	2.2	4.1	1.0	68.1	4.2	0.1	0.8	55.5	62.4	94	88.3
Pandora	0.7	2.6	3.5	27.3	2.9	4.5	2.8	67.1	2.9	0.9	0.5	58	78	93	78.1
Viburnum #27	1.1	4.6	1.0	29.2	2.1	1.5	0.2	73.3	0.8	0.1	2.2	55.1	75.0	94.1	66.2
Boliden	1.0	2.0	8.0	19.2	3.3	5.6	2.8	43.3	5.5	0.9	1.2	50	54	66	80.2
Bihonti	0.8	0.5	10.2	25.3	1.7	5.5	1.1	50.9	4.4	0.3	0.1	54.6	80.5	70.3	93.9

^aExclude bulk concentrate

4.4 MINERAL PROCESSING OF NICKEL ORES

There are more than 45 different nickel minerals, but only a few are of economic importance. Table 23 lists some important nickel minerals. Nickel minerals can be divided into 3 major groups, including nickel sulfides, nickel arsenides and nickel antimonides.

Table 23 : List of some important Ni minerals

Mineral	Chemical formula	Content % Ni	Hardness	Specific gravity
Millerite		NiS	3–4	5.2–5.6
Pentlandite	(Fe,Ni) ₉ S ₈	21–30	3–4	4.6–5.0
Gersdorffite	NiAsS	35.4	5.5	5.6–6.2
Rioanlit	NiAs ₂₋₃	14.5–21.2	5.0	6.3–7.0
Nickelin	NiAs	43.9	5.5	7.3–7.7
Annabergite	Ni ₃ (AsO ₄) ₂ ·8H ₂ O	37.5	2.5–3.0	3.0
Garnierite	Ni ₄ (Si ₄ O ₁₀)(OH) ₄ ·4H ₂ O	0–45	–	–
Reevesite	(CO ₃)(OH) ₁₆ ·4H ₂ O	1–15	–	–

4.4.1 Nickel sulfide ores

The most important minerals in these ores are chalcopyrite, pentlandite and pyrrhotite. However, these deposits may contain a fairly large number of other minerals containing silver, gold, cobalt and platinum group metals. The low metal content of sulfide ores renders them unsuitable for either direct smelting or direct hydrometallurgical processing. Beneficiation of nickel sulfide ores is generally by grinding and flotation.

In principle, it is possible to produce separate nickel (pentlandite), copper (chalcopyrite) and iron (pyrrhotite) concentrates. However, a clean separation of pentlandite from pyrrhotite is difficult in practice. Pyrrhotite often contains 0.5%-1.0% Ni that cannot be separated by physical methods. Pyrrhotite can be separated from pentlandite and chalcopyrite either by using its ferromagnetic properties or by flotation. Nickel or Ni-Cu concentrates typically range in grade from 5% to 15% Ni+Cu, depending on the degree of pyrrhotite rejection achieved.

The bulk Ni-Cu concentrate is separated by flotation. Some of the most commonly used Cu-Ni separation methods are listed in Table 24.

Table 24: Commonly used Cu-Ni separation methods

Nickel concentrate quality	Reagent	PH	Pre-treatment
Bulk concentrate with no pyrrhotite present	Lime	11.5	None
	Lime, dextrin	11.0	None
	Lime, oxidized starch	11.0	None
Bulk concentrate with moderate to low amount of pyrrhotite	Lime, cyanide	10.5	none
	NaOCl, lime, cyanide	10.0	Pre-conditioning
	Activated carbon, lime, NaCN	10.5	Pre-conditioning
Bulk concentrate with high pyrrhotite content	Lime, SO ₂ , NaCN	11.0	Aeration
	Lime, NaCN	11.0	Collector desorption
	Lime, dextrin, NaCN	11.0	Aeration
Bulk concentrate where copper is much higher than nickel content	Lime, SO ₂ , starch	5.5	Stage conditioning with lime (pH 10.5) and SO ₂ (pH 5.5)

The flowsheet practiced at the Inco (Sudbury) plant in the copper-nickel separation circuit is illustrated in Figure 45. Using this flowsheet, 2 nickel-type concentrates are produced including low- and high-grade concentrates. Metallurgical results using this method are shown in Table 25. The efficiency of separation was a function of level of cyanide and lime additions.

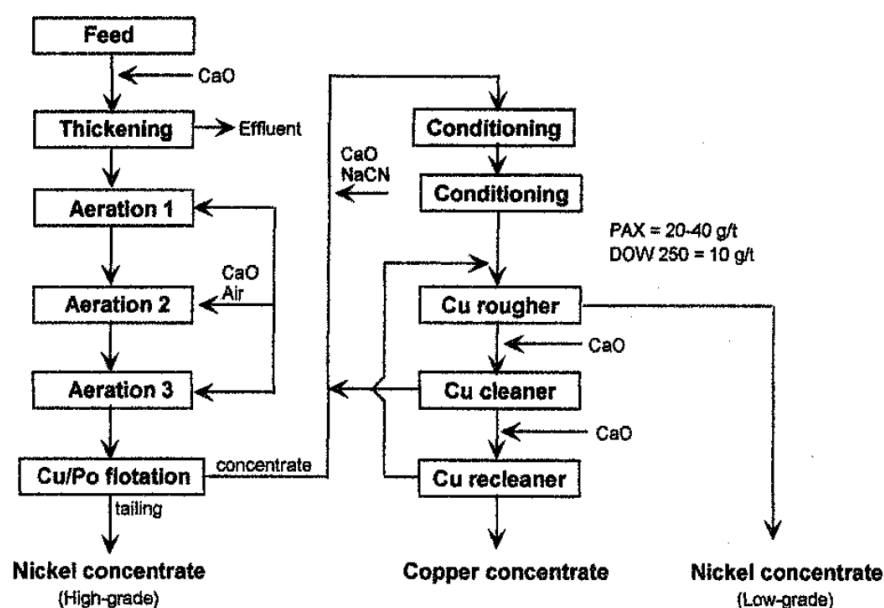


Figure 45: Cu-Ni separation flowsheet used at Inco-Sudbury concentrator

Table 25: Metallurgical results obtained using two-stage separation

Product	Assays %			% Distribution		
	Cu	Ni	Po ^a	Cu	Ni	Po
Copper concentrate	30.4	0.67	3.6	96.2	2.2	5.1
High-grade Ni concentrate	0.09	30.5	4.4	0.2	86.4	5.5
Low-grade Ni concentrate	1.3	4.28	76.4	3.5	11.5	89.5
Feed	11.7	11.4	26.2	100.0	100.0	100.0

^aPo – pyrrhotite.

4.4.2 Copper-Nickel ores

About 85% of the total world nickel production comes from copper-nickel ores. These ores are also important sources of production of cobalt and platinum group minerals. The largest copper-nickel operations are located in Canada and Russia. In other parts of the world, such as Africa, Scandinavian countries and Europe, there are only a few operating plants. The flowsheet used in the treatment of massive sulfide copper-nickel ore is relatively complex and most often involve magnetic separation where the pyrrhotite (Fe) is present in the ore.

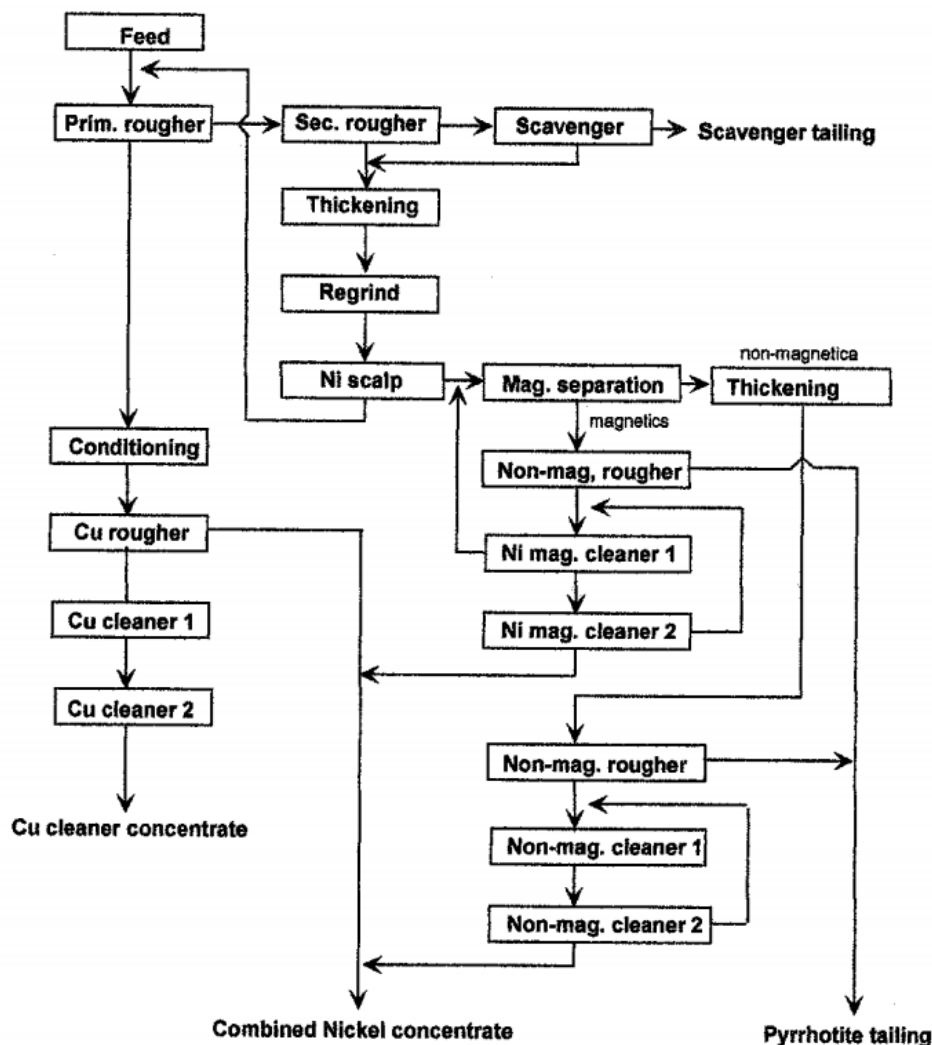


Figure 46: Generalized flowsheet used in the treatment of Cu-Ni massive sulfide ores

A wide variation in the use of various depressants is related to the ore mineralogy. In many operating plants, copper sulfide is also used as activator. Consequently, the reagent schemes used vary considerably from one operation to another. The operation in Finland (Hitura, Kotalahti) use relatively high amounts of sulfuric acid, which is unusual, due to the fact that this ore does not contain clay minerals. The metallurgical results obtained in various plants are shown in Table 26.

Table 26 : Metallurgical results obtained in various plants

Concentrator	Feed		Bulk Cu–Ni concentrate				Cu concentrate	
	Assays %		Assays %		% Distribution		% Distribution	
	Cu	Ni	Cu	Ni	Cu	Ni	Cu	Ni
Pechenganickel	1.22	1.85	4.20	6.65	93.5	86.2	22.5	1.50
Severonickel ^a	0.95	1.35	3.60	5.58	93.3	88.2	–	–
Norilsk	1.2	1.66	4.60	6.60	94.5	79.5	19.7	2.12
Strathcona, Falconbridge	1.32	1.40	6.80	7.10	96.0	83.0	27.5	0.90
Inco Limited	0.92	1.42	13.3	9.20	93.2	80.1	26.5	1.10
Thompson Mill	0.6	1.30	2.2	6.3	92.2	78.0	25.5	1.10
Shebandowan	1.2	1.30	8.8	9.80	92.5	80.1	26.1	0.90
Langmir	0.7	2.1	4.0	14.6	90.2	78.5	–	–
Rankin	0.8	3.3	3.25	13.6	84.1	75.5	–	–
Lynn Lake	0.36	1.15	–	8.3	84.0	88.5	–	–
Iskut River	0.72	0.90	5.58	5.69	83.6	722	20.0	1.81
Union Mine	0.43	0.72	4.2	6.60	93.2	78.5	–	–
Kotalahti	0.31	0.78	3.2	5.80	90.1	93.3	28.6	0.8
Hitura	0.30	0.40	0.10	40.1	81.0	81.2	30.0	–

^aSiberia, Russia.

4.4.3 Nickel Laterite ores

Nickeliferous laterite ores are abundant, with experts estimating that they account for about 70% of known global nickel resources. They are also close to the surface, unlike sulfide deposits, which are mined at much greater depths. This abundance and ease of accessibility makes laterite ores an attractive option to the nickel industry. The down side to laterite ores, and the reason why they haven't been exploited on a widespread scale thus far, is that they require much more energy in processing over sulfide ore types.

While sulfide nickel ores are processed via upgrading to concentrates and then smelting, this approach is not applicable to laterite ores. A variety of approaches are available to process nickel laterite ores. The method(s) chosen is dependent on the composition of the unique ore source. Most laterite ore deposits are made up of both limonite (iron rich) and saprolite layers, with the thickness of each layer varying significantly across different deposits. Limonite, which accounts for nearly double the amount of saprolite available globally, is more amenable to processing via hydrometallurgical techniques, while saprolites are more amenable to processing via pyrometallurgy.

4.4.3.1 Hydrometallurgical approaches

Solvent extraction and electrowinning approach to lateritic ore beneficiation is a hydrometallurgical method that relies on leaching, extractants, and electrowinning to produce nickel from ore.

Leaching typically occurs via either high pressure acid leach (HPAL). An agglomeration step often precedes the leaching step. In the agglomeration stage, ore fines are fed into an agglomerator (ore drum), where they are tumbled with the leachate solution to cause the ore fines to be more uniform in shape and size, allowing the leachate to more effectively

percolate through the heap and jump-start the leaching process. Once agglomerated, ore is piled onto a heap, which is then irrigated with the leachate and allowed to sit for a pre-determined amount of time so the leachate can work its way to the bottom of the heap where it is collected in a pond. An extractant or reagent is then combined with the impregnated solution to extract the target metal, which can then be electrowon.

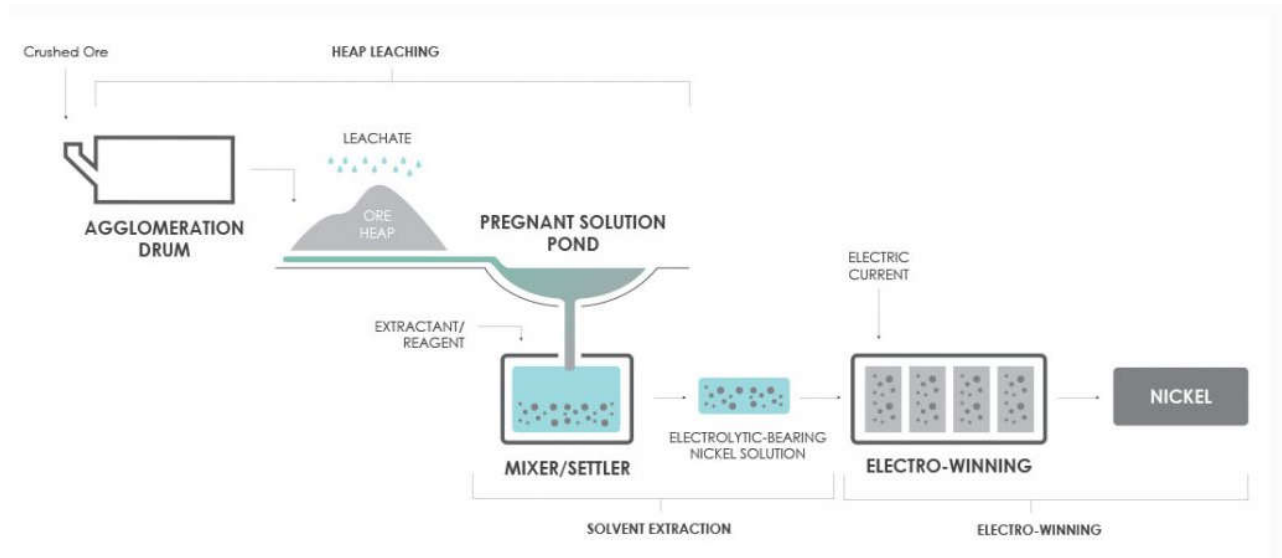


Figure 47: Generalized nickel SX-EW process with heap leaching and agglomeration

4.4.3.2 Pyrometallurgical approaches

4.4.3.2.1 The RKEF Method

The RKEF, or Rotary Kiln Electric Furnace method, is a pyrometallurgical approach to producing ferronickel. As a pyrometallurgical technique, this method is best suited for ores that are predominantly saprolite. The RKEF method involves a variety of steps.

Nickel laterites contain a significant amount of water, making drying an important aspect of processing. A rotary dryer is typically used to remove free moisture from the ore, while bound moisture is removed later via a rotary kiln.

Some novel processes may employ pelletizing at this stage of the process, where drying also facilitates pulverization of the ore in preparation of processing on a disc pelletizer. Pelletizing may also be used as a means of reintroducing recycle to the process.

Once ore has been dried, it is processed in a large-scale rotary kiln to remove chemically bound moisture, as well as the oxide component of the ore. This step is often referred to as pre-reduction.

Nickel is further reduced and smelted in an electric furnace. A cooling step may be implemented after the smelting step, typically through the employment of a rotary cooler.

The RKEF method is criticized for its high energy consumption. As a result, it has been used in settings where the deposit is considered a high grade laterite and can justify the high operating costs.

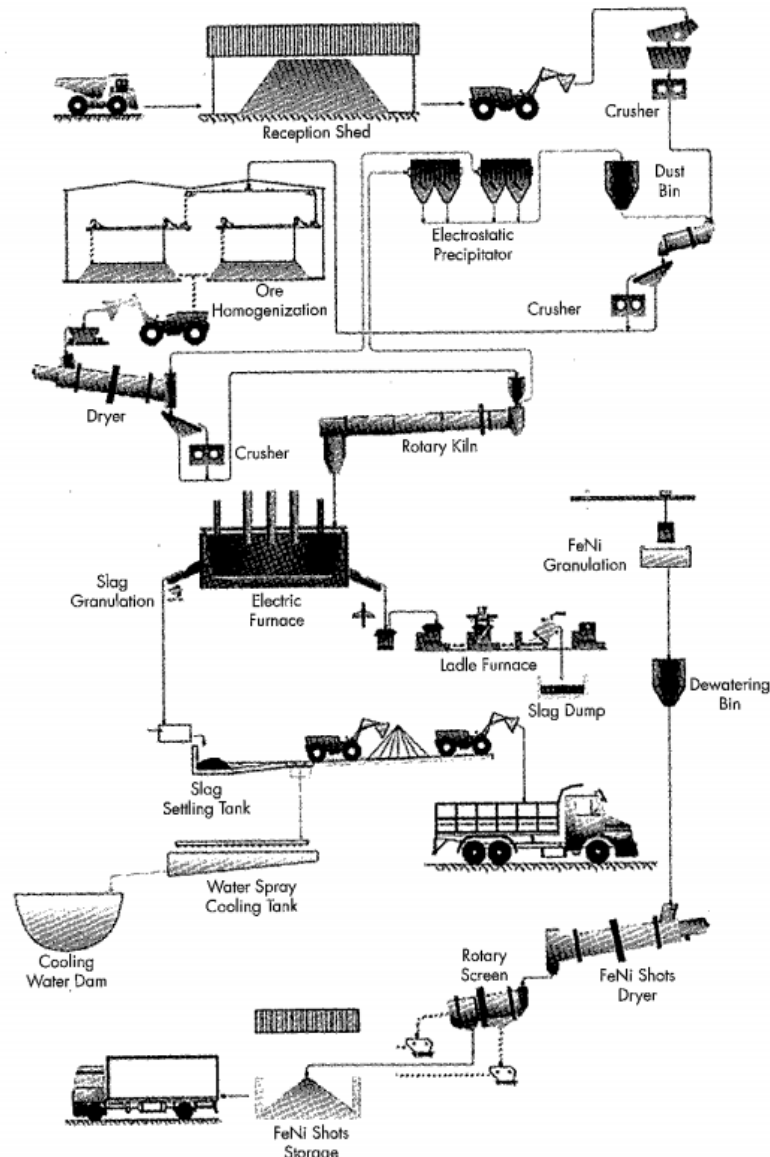


Figure 48: Typical RKEF Process

4.4.3.2.2 The Caron Process

While the Caron process is often categorized as a hydrometallurgical approach, it is actually a combination of both hydrometallurgy and pyrometallurgy. In the Caron process, the ore is first dried and then reduced, similar to the RKEF method. However, once the ore has been reduced, it is then leached via ammonia to extract the metal components (nickel is often accompanied by cobalt and iron). The extracted metals can then be purified/refined.

As a combination of the two approaches, this method is criticized for high operating costs, as a result of the energy intensiveness combined with the need for reagents. It also results in a fairly low recovery.

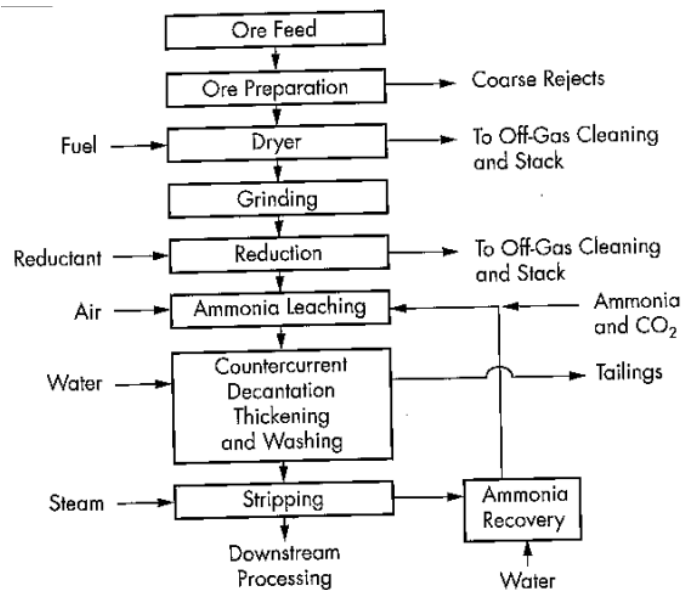


Figure 49: Typical Caron process flow sheet

5 CONCLUSIONS

As can be seen from this report, mineral processing treatments are as many and diverse as the different types of metal-bearing waste encountered. The development of treatment processes is based on a large number of questions:

- What exactly are the constituents to be recovered? If there are several, which ones should be given priority? Are there any undesirable constituents to be eliminated in addition to the recycling operation itself?
- Where are they located? Are they well individualised elements (and therefore potentially extractable) or compounds intimately attached to another phase (adsorption, impregnation, encrustation), whose treatment is more delicate or even impossible?
- If they are well individualised (free) elements, in what form and in what particle size range do they occur? Do they have special properties (density, colour, electrical conductivity, magnetic properties)? Which technology should be chosen, taking into account the properties of the constituents and their particle size? The answers to these questions help to orientate the range of processes, both for screening and classification and for extraction or concentration.
- Is the purity of the recovered fraction compatible with the acceptance criteria in the reuse sector for which is intended?
- Does the equipment offer sufficient operating flexibility to maintain constant production in terms of quality and quantity in the face of a change in the characteristics of the feed and within what limits? To what extent should the technical performance of this equipment be improved?

- Should dry or wet processing be chosen? There are advantages and disadvantages to either process. Overall, the range of processes that can be used with the wet process is greater and allows for significantly finer particle size ranges than with the dry process. These advantages must obviously be weighed against the constraints imposed by the processes in terms of managing the treatment water to recover suspended solids (by decantation and filtration), hydrocarbons and any dissolved salts.

In addition to these purely technical questions, there are also economic questions concerning the treatment of the waste, which could compromise the entire operation, despite the added value provided by the sale of the recovered fraction.

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