ASSESSMENT PROTOCOL OF THE APPLICABILITY OF ORE-PROCESSING TECHNOLOGY TO TREAT CONTAMINATED SOILS, SEDIMENTS AND SLUDGES

Document prepared for:

Eco-Technology Innovation Section
Technology Development and Demonstration Program
Environmental Protection
Environment Canada (Québec Region)

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Sainte-Foy, March 1999

Environment Canada has approved the publication of this document.

Public Works and Government Services Canada 1997
Cat. No.: En 40-542/5-1997E
ISBN: 0-662-82406-7

MANAGEMENT PERSPECTIVE

This final report is published as part of the « Technology Developement and Demonstration Program » of Environment Canada, which promotes private sector initiatives in the development and demonstration of innovative environmental technologies. This program is also associated with Canada Economic Development and is a part of the St. Lawrence Vision 2000 Action Plan from Environment Canada.

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Abstract

Ore-processing technologies have a great deal potential for use in extracting contaminants from contaminated sediments, soils and sludges. Unfortunately, current characterization methods and grain-size and chemical analyses give very little information available on the potential and on the limitations of these technologies with relation to the treatment or the possible reclamation of such contaminated matrices.

The present document is thus designed to describe a protocol for evaluating the treatability of sediments, soils and sludges using ore-processing technologies.

Characterization using an ore-processing approach relies mainly on the knowledge of the grain size of the material, the distribution of contaminants within the various size fractions, and the identification of their mineralogical composition (in the case of inorganic contaminants) and on the liberation degree of the inorganic contaminants present.

The information drawn from characterization includes the liberation degree of contaminants as well as the size, density, surface properties, ferromagnetic properties and electrical conductivity of the particles. Based on this information, the appropriate ore-processing equipment is selected and a preliminary flowsheet can be elaborated. This flowsheet must then be validated and optimized at the semi-industrial scale. The costs related to the decontamination project can be summarily deducted, but a more detailed evaluation of these costs must be based on a detailed study of the tests carried out at pilot-plant scale, then confirmed by a full-scale demonstration project on site.

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Glossary

Attrition: operation designed to detach the fine particles from the large particles and to remove the contaminant layer on the particles by hitting of particles one against the other.

Carrier phase: form under which a metallic element (inorganic contaminant) is present and is identified by its various oxidation stages. The carrier phases are visually identified by their colour, form and texture using an optical or a scanning electron microscope.

Classification: separation of particles with relation to their size, based on the principle of different terminal settling velocities in a fluid.

Concentrate: product obtained at the outlet of an ore-processing technique that includes the enriched fractions (minerals of value or contaminants).

Density: property specific to each substance represented by the ratio of the mass of a body to its volume.

Diffraction: the deviation of the wave (light or X-ray) propagation direction occurring when the waves encounter an obstacle or go through an aperture with dimensions of the same order of magnitude as their wavelengths (X-ray diffraction is used to identify minerals).

Electrical conductivity: property of a material to conduct an electrical current (conducting substance vs. insulating substance).

Electrostatic separation: ore-processing technique that separates materials based on the difference in their electrical conductivity.

Elutriation: particle separation using an ascending fluid flow of adjustable speed (opposite of settling).

Ferromagnetic property: property of certain substances (iron, cobalt, and nickel) to take on a strong magnetization.

Flotation: ore-processing technique which uses the affinity of particle hydrophobic (natural or stimulated) surfaces for air bubbles to carry out the separation.

Fluidization: suspension of solid particles in an ascending flow of fluid.

Gangue: barren substance associated with or enclosing the ore in a deposit. These are thus undesirable minerals of negligible value.

Gravity concentration: ore-processing technique that uses the mass or density difference between materials to carry out a separation.

Heavy liquid separation: separation through settling of a mixture of solid particles of various kinds using a liquid with a density in between that of the minerals to separate.

Hydrometallurgy: a set of extraction processes of metals contained in a raw ore or in a concentrate by dissolution in an aqueous phase.

Hydrophilic property: property of a surface to adsorb water without dissolution.

Hydrophobic property: property of a surface not to adsorb water.

Liberation degree: percent of a given mineral present as free particles in a batch.

Magnetic separation: ore-processing technique that separates materials based on their paramagnetic and ferromagnetic properties (the separation of paramagnetic materials requires a high energy magnetic field while the separation of ferromagnetic materials requires a low energy magnetic field).

Matrix: mineral and/or vegetable solids making up the natural portion of a sample and onto which the contaminating materials can settle.

Mineralogy: branch of geology dealing with minerals, their chemical and physical properties and their identification.

Minerals: homogeneous natural solids, normally formed through inorganic processes, having a definite composition and that present an ordered atomic configuration.

Modal interpretation: conciliation between the mineralogical composition and the chemical composition of a batch in order to establish the probable proportions of each identified mineral.

Ore-processing: series of techniques by which raw ore extracted from a mine is separated to remove the undesirable minerals of negligible values.

Ore: ground element containing useful minerals in sufficient proportion and that require further processing to be used by the industry.

Polarity: specific state of a system where two poles can be distinguished (electrical or magnetic).

Pulp: a solid/liquid mixture. Its main characteristic is the percentage of solids that it contains.

Pyrometallurgy: series of extraction processes of metals contained in a raw ore or in a concentrate through the action of high temperatures.

Screening (or sieving): operation using a screen to separate a batch of particles according to their size.

Sizing: measurement of the dimension of grains in a batch. The result is presented as a statistical distribution.

Tailings: product obtained at the outlet of an ore-processing technique; it includes the depleted portion.

Acknowledgements

The present document was written by Anne Gosselin (INRS-Géoressources) with the cooperation of Denis Blackburn (Centre de recherche minérale, ministère des Ressources naturelles), under the responsibility of Mario Bergeron (INRS-Géoressources).

The authors first wish to thank Jean-René Michaud of the Eco-Innovation Technology Section of Environment Canada who initiated the preparation of this document, supplied many relevant references and acted as the scientific authority for the project.

They also thank the professional and technical personnel of the *Centre de recherche minéral*e who contributed to this document through their appropriate comments. They are Jean-François Wilhelmy, Denis Cotnoir, Gennard Delisle, Arthur Plumpton, and Bertrand Paquet.

Finally, the authors wish to thank the professional and technical personnel of INRS-Géoressources, Marc-Antoine Dion, Jean-Pierre Ricbourg, and André Hébert, who contributed to this document through the relevant information they supplied.

Chapter 1

Introduction

1.1 Context

Mineral processing can be defined as a series of processes by which a raw ore extracted from a mine is separated to remove the undesirable minerals of negligible value. These are commonly referred to as "gangue". The separation can be carried out by gravity concentration, flotation, magnetic separation, or electrostatic separation equipment. The separation concentrates the mineral or minerals of interest in order to reduce the volume of material that will subsequently be treated by hydrometallurgy or by pyrometallurgy.

The mineral processing approach for environmental applications such as sediment, soil, or sludge decontamination has already been used and demonstrated in several countries. In environmental applications, the mineral processing approach consists in considering contaminated matrices as a low grade ore. It is therefore necessary to identify economical and performing technologies.

This is an appropriate approach since mineral processing techniques are based on relatively simple physical separation principals. Generally speaking, the physical methods are among the least expensive to operate compared to the extraction methods or biological, thermal and chemical destruction methods. These technologies are not only simple and have low operating costs, they do not produce by-products that are potentially toxic or dangerous. They thus present a great interest from an environmental stand point.

For environmental applications, mineral processing technologies will be used to extract or concentrate contaminating materials. The products are on one hand the decontaminated matrix and on the other hand one or several concentrated contaminating materials with a much smaller volume than the volume processed. The concentrate or concentrates can be treated, if amenable to beneficiation, in a smelter or in a contract concentrator, if not they can be destroyed by a biological, thermal, or physical/chemical method, or else disposed of in authorized disposal sites. These are thus pre-treatment technologies.

Mineral processing technologies have a remarkable potential to extract contaminants from contaminated soils, sediments, and sludges. Unfortunately, the current methods of characterization and grain-size and chemical analyses yield very little information on the potential and limits of these technologies with relation to processing or to the possible beneficiation of the contaminated matrices.

1.2 Objective of the document

The characterization protocol described in this document is designed to present an protocol to evaluate the treatability of sediments, soils, and sludges by mineral processing technologies that was recently developed by INRS-Géoressources and the Centre de recherche minérale as a technological demonstration project carried out in cooperation with the Eco-Innovation

Technology Section of Environment Canada and Verreault Navigation inc. (Bergeron *et al*., 1997). The objective of the project was to develop a flowsheet for contaminated sediments based on the application of mineral processing techniques.

The writing of this document was financed by INRS-Géoressources, le Centre de recherche minérale and the Eco-Innovation Technology Section of Environment Canada.

The project related to this protocol forms part of the objectives and priorities of the Eco-Innovation Technology Section of Environment Canada that aim at developing environmental technology evaluation guides to assist promoters, consultants, universities, research centres and managers in the planing, design, evaluation and realization of decontamination projects.

Moreover, Environment Canada wishes to demonstrate, through the diffusion of this approach, the expertise, the analytical capabilities and the various equipment available in Quebec universities and research centres to carry out characterization projects and treatability tests on soils, sediments, sludges and other industrial and municipal wastes.

1.3 Summary presentation of the protocol

The proposed protocol for evaluating the treatability of sediments, soils, and sludges by mineral processing technologies is based on the protocol normally used for the characterization and analysis of the treatability of ores. This protocol can help find the contaminants in the various size fractions and identify the mineralogical composition and certain physical properties of the particles (matrix and contaminants). The information gathered through the mineral processing characterization helps determine the applicability of mineral processing technologies. Once confirmed, this information is used to select the appropriate mineral processing equipment and elaborate a preliminary flowsheet. The flowsheet must then be validated and optimized by testing at the laboratory and pilot-plant scale. The diagram in Figure 1.1 shows these steps and the main procedures required to carry them out.

1.4 Content of the document

With the context, the objectives and the approach summarily described in the first chapter, the second chapter will overview the various sampling procedures in relation to the type of material to be collected (contaminated sediments, soils, or sludges). However, these sampling techniques will not be detailed since there is already abundant literature on this subject.

The characterization through the mineral processing approach will be described in a much more detailed fashion and will be the object of chapter three. As this document is intended for a very diversified public, the main mineral processing equipment will then be described and illustrated in the fourth chapter. The principle of operation, operating conditions and the performance of each apparatus will be presented.

The fifth chapter will present the equipment selection strategy based on the information gathered during the characterization. Finally, conclusions and recommendations will complete the document.

In a nutshell, the mineral processing approach presented herein comprises two components: characterization and processing. The contaminated matrix is considered as an ore and the objective is to extract the contaminants as if they were valuable minerals. Consequently, the terms used in this document will come mostly from the field of mineral processing; they are quite different from those used in the field of environment. This is why the glossary should be consulted occasionally in order to avoid any possible confusion.

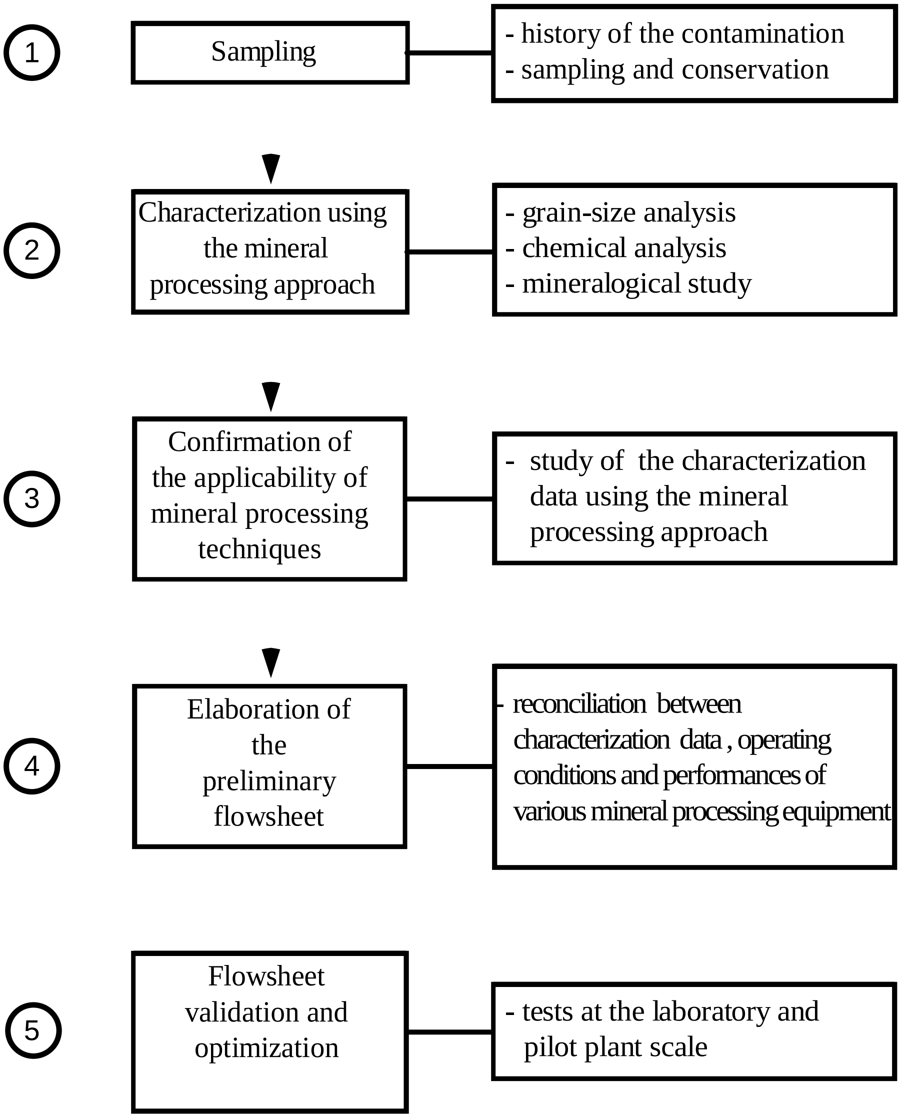


Figure 1.1 - Steps in the assessment protocol of the applicability of ore processing technologies to treat contaminated soils, sediments and sludges

Chapter 2

Sampling Procedures

Sampling is a crucial step in the characterization process of a sediment, a soil or a sludge. The objective is to get a range of representative samples that reflect all physical and chemical characteristics of the entire site under study. At the same time, the number and volume of samples must be restricted to a minimum for economical reasons. It is thus important to get to an acceptable compromise between representativity and the available budget. The main steps in a sampling procedure are: elaborating a sampling strategy, collecting the samples on site, preserving them and preparing them for analysis. The characterization results depend on proper achievement of these steps.

Elaborating a sampling strategy must be the first step in the definition of the objectives. Since each site is unique, it is important to proceed with a specific study with several components, i.e. background of the site, physical characterization of the natural environment and identification of constraints related to the exercise. Planning a sampling campaign for sediments, soils and sludges must be based on a literature search to determine the background of the contamination.

The sampling strategy is based essentially on the volume and number of samples, and on the selection of the sampling stations (total number, location and position). The representativity of samples greatly depends on the choices made.

The choice of the equipment used to gather a sample depends on the nature of the sample (soil, sediment or sludge), the volume required and the location of the site. When collecting the samples, sampling conditions must be written down. The relevant information is presented in Table 2.1.

Table 2.1 - Relevant information to describe the sampling conditions

Type of information	Parameters
Sample identification:	Sample number, location of the sampling, time and date of the sampling, frequency, ...
On-site measurements:	pH, temperature, ...
Climate conditions:	Rain, snow, ...
Sampling method:	Method description, main equipment, containers, preservation agents, ...
Visual description of samples and of the environment sampled:	Colour, odour, turbidity, ...

(Source: ministère de l'Environnement et de la Faune, 1994)

After sampling, there are sample preservation conditions to be respected for transport and storage. These conditions relate mainly to the temperature at which the samples must be maintained and the type of containers in which they must be preserved. It is important to preserve the samples against all forms of possible degradation (biological, chemical, physical, thermal, ultraviolet rays, etc).

The various analyses involved in the characterization often require some kind of sample preparation. The preparation procedure can comprise several operations such as homogenization, sieving, drying, grinding, calcining, dissolution, or extraction. The operations required must be carried out in such a way as to preserve the integrity of the samples (Environment Canada, 1994).

Sampling procedures vary according to the type of material (sediment, soil or sludge). The following sections present some characteristics that must be taken into account during sampling; they are specific to each type of material. However, the sampling procedures are not detailed in this document since they are already the object of abundant literature. Sampling procedure reference documents are proposed for each case.

Finally, it is essential to point out that the significance of the characterization relies entirely on the aforementioned sampling procedures. The characterization results are useless when the representativity of the analyzed samples is poor. However, it is possible that the available budgets are so small that the number of samples must be reduced to a minimum, thus decreasing representativity.

Under such conditions, it might be advantageous to change the orientation of the sampling exercise by taking a small number of samples in the most contaminated zone. Consequently, sampling will not be representative of the entire site but will rather be representative of the worst case that could be encountered. The mineral processing equipment that were deemed applicable for the worst case will thus be applicable for the entire site. This assertion can be qualified as the “worst case scenario”.

2.1 Sediment sampling

2.1.1 Specific characteristics

The sediments cover a large grain size range, including a large fraction located in the very fine sizes that define clays (< 4 µm). The water content of a sediment increases with the fineness of the particles. It is thus important to adjust the volume of samples in relation with this parameter in order to collect enough solids.

With increasing water depth, accessibility to sediments can present a problem. For example, ocean bottoms are normally at much greater depths than lake bottoms. At such depths, visibility can be very poor if not null. Moreover, positioning of sampling stations on the water surfaces is more problematic than on the ground. The seasonal variations of climatic conditions must also be taken into account. The formation of thick layers of ice during winter can also limit accessibility of sediments (Environment Canada, 1994).

2.1.2 Reference documents

There are a few reference documents on sampling sediments. One is entitled “Échantillonnage et conservation des sédiments en vue de la réalisation des projets de draguages”; it was written by R. Rochon et M. Chevalier (1987). Another, written by the Canadian Council of Ministers of the Environment (1993), is entitled “Guidance manual on sampling, analysis and data management for contaminated sites”. This document comes in two volumes, i.e. Volume I constitutes the main report, and Volume II presents the analytical method summaries. The latest reference document on the subject, written by Environment Canada (1994), is entitled “Guidance document on collection and preparation of sediments for physicochemical characterization and biological testing” (report SPE 1/RM/29).

2.2 Soil sampling

2.2.1 Specific characteristics

Soils show great geological variability from one site to the other and also on the same site, giving them a highly heterogeneous nature. This variability is the result of numerous processes and disruptions that lead to the formation of the soils. Soils are composed of several layers, each one with different properties, thus showing vertical variations in composition. Moreover, horizontal variations in composition can depend on the topography of the terrain. The characteristics of the soil can also vary according to the type of vegetation growing on it (Canadian Council of Ministers of the Environment, 1993). The presence of a water course nearby and the elevation of the water table must also be considered.

2.2.2 Reference documents

There are several reference documents on soil sampling. “Guidance manual on sampling, analysis and data management for contaminated sites” was written by the Canadian Council of the Ministers of the Environment (1993) This document is divided into two volumes, Volume I constitutes the main report and Volume II presents the analytical method summaries. Other relevant information is presented in the “Guide standard de characterisation de terrains contaminés” and in the “Conservation et analyse des échantillons d’eau et de sols” which were written by the ministère de l’Environnement et de la Faune (1996).

2.3 Sludge sampling

2.3.1 Specific characteristics

Sludge characteristics vary according to their origin. Municipal sludges are generated mainly from the effluents of waste water treatment plants. They are characterized by a heavy organic load as well as by the presence of colloidal particles. The composition of industrial sludges can vary considerably from one sector of activity to the other. The main characteristics of industrial sludges are their variability and their highly heterogeneous nature. Variations result from the chemical composition, temperature, grain size, and water content. Industrial sludges generally contain much higher contaminant concentrations than municipal sludges.

2.3.2 Reference documents

There are few reference documents on the sampling of sludge lagoons. One of them was written by the United States Environmental Protection Agency (U.S. EPA, 1986). It is entitled “Test Method for Evaluating Solid Waste” (volume IIa, SW846, third edition, Part three, Chapter 9). Another document, “Environmental Sampling and Analysis: a Practical Guide”, was written by Keith (1991).

Finally, the document entitled “Analyse des boues - Tome 1: Généralités et analyses physiques” suggests certain sampling methods for sludges (such as the number of samples in relation to the volume of the sludges). This document was written by the Association française pour l’étude des eaux (1985).

Chapter 3

Characterization by the Ore-Processing Approach

Conventional characterization of sediments, soils and sludges is generally based on the analysis of several chemical and physical parameters. Characterization using the ore-processing approach is mainly based on the distribution of contaminants in the various size fractions, on the identification of their mineralogical composition (inorganic contaminants) and on the evaluation of their degree of liberation (inorganic contaminants). These characterization tools are detailed in this chapter. A special complementary tool for the characterization of the targeted material will be described: it is called model interpretation. There will be a discussion on the laboratory tests designed to get fractions in which the contaminants are concentrated.

Once it is ascertained that the samples collected for the characterization are representative, there are three major steps in the characterization using the ore-processing approach. Figure 3.1 shows these steps, the target objectives and the procedures to carry out. The steps and the procedures are presented in the sequence to be followed. The steps presented in this figure are all detailed in the next sections.

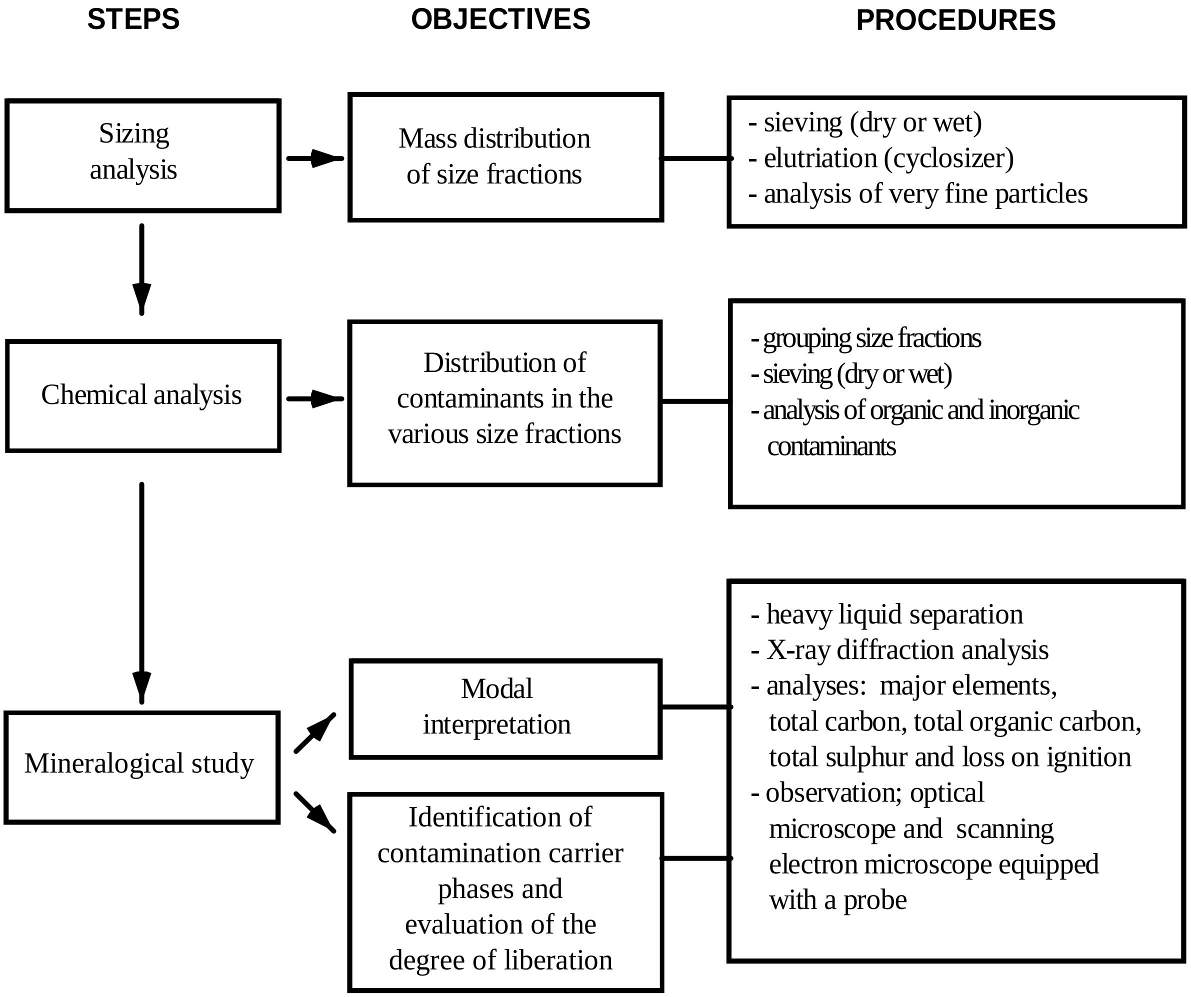


Figure 3.1 - Sequence of the characterization steps using the ore-processing approach

3.1 Sizing analysis

3.1.1 Definition and objective of the sizing analysis

The sizing analysis is defined as the separation of a batch of particles according to their size in order to get smaller sets of particles called size fractions (Figure 3.2). These fractions contain particles, where each size fraction covers a relatively narrow grain size range, and the size decreases from one size fraction to the other.

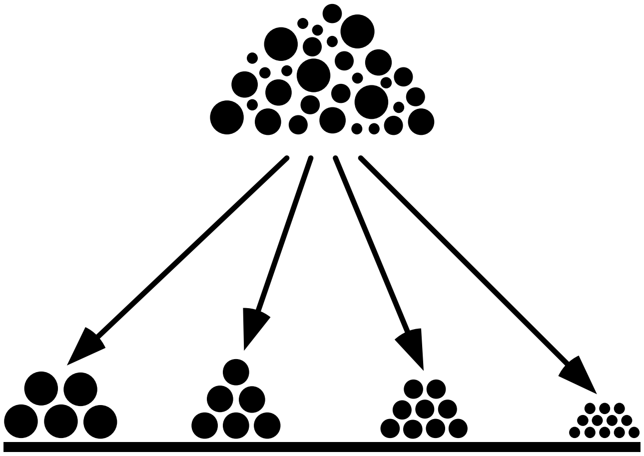


Figure 3.2 - Separation of a batch of particles into several size fractions

This type of analysis is normally designed to evaluate the efficiency of the sieving equipment or the performance of a crushing and/or grinding system. In an environmental context, it is mandatory to use the sizing analysis to locate the substances contaminating the sediments, the soils and the sludges. It is used to determine if the contaminants are located in the fine, medium or coarse fractions. The flowsheet of the ore-processing approach will then be elaborated based on this data.

The size of a spherical particle can be determined using only one dimension, the diameter, and the size of a cubic particle can be determined by the length of a side. However, the particles making up sediments, soils and sludges are generally of irregular shape and their size cannot be determined precisely. This is why the expression «equivalent diameter» is used. This term is defined as the diameter of a sphere that would have the same behavior as an irregular-shaped particle subjected to specific operations such as sieving or centrifugation.

There are several sizing analysis methods. Table 3.1 shows a few according to the particle diameters to which they apply.

Table 3.1 - Some sizing analysis methods

Method	Range of applicability (µm)
Screening	100 000 to 10
Elutriation	40 to 5
Optical microscope	50 to 0.25
Settling (gravity)	40 to 1
Settling (centrifugation)	5 to 0.05
Scanning electron microscope	1 to 0.005

Extract from Wills (1992).

Among these methods, only the sieving and elutriation methods are detailed in this document since they cover almost all ranges of particle sizes. Moreover, they allow the recovery of samples separated into size fractions. To analyze very fine particles, a relatively sophisticated instrument based on the diffraction of light rays going through a suspension of particles will be used. However, it is almost impossible to process particles with a diameter smaller than one micron using the conventional ore-processing methods that will be detailed in the next pages.

3.1.2 Sieves

There are two types of laboratory sieves: those with a grid composed of woven steel wires with square openings, the most frequently used, and those made up of a steel plate drilled with round openings. The sieving surfaces are fastened to a cylindrical support that allows stacking the sieves. The sieves are characterized by the width of the openings.

Among the most used sieve series are the American Tyler series and the ASTM (American Society for Testing and Materials) standard series. These series offer the same geometrical progression, following a ratio of 1.189 (fourth root of 2) from one sieve to the other. However, the ASTM standard series refers to the size of the openings while the American Tyler series refers to the number of square openings per inch. Although often used, this last series has a serious disadvantage since the size of its openings vary with the thickness of the steel wires used in building the sieves.

Table 3.2 presents these two series with relation to the nominal size of openings for the most frequently used series of sieves (refer to appendix A for the entire series).

The sieves used to perform the sizing analysis must be selected according to the material to be analyzed and the availability of the various sieve sizes. Finally, it is important to specify that the maximum capacity of an average sieve is 0.62 g of solid per square centimeter of sieving surface.

3.1.3 Sample preparation

The samples to sieve must be homogeneous and free of agglomerates and large debris. The latter must be removed prior to sieving using a very coarse sieve, for example a sieve number 8 or number 10, since this fraction is generally little

Table 3.2 - Size of frequently used sieves with equivalence of the American Tyler series and the ASTM standard series

Nominal opening (µm)	American Tyler series (mesh)	ASTM standard series
2 360	8	2.36 mm
1 700	10	1.70 mm
1 180	14	1.18 mm
850	20	850 µm
600	28	600 µm
425	35	425 µm
300	48	300 µm
212	65	212 µm
150	100	150 µm
106	150	106 µm
75	200	75 µm
53	270	53 µm
45	325	45 µm
38	400	38 µm

contaminated. Fine particles have a tendency to form undesirable agglomerates; that will classify the fine particles into coarser fractions during sieving. This phenomenon is imputed to a lowered surface tension when the sample is slightly humid. It can also be imputed to electrostatic attraction when a sample is completely dry.

Sediments, soils, and sludges frequently contain a rather large fraction of fine particles. To prevent the formation of agglomerates, it is preferable to proceed with a wet sieving of the material as such on the finest sieve (generally 325 or 400 mesh) using a water jet as described in the following section. It can also be useful to add wetting or dispersing agents depending on the properties of the material (these agents will probably be used in the process). In both cases, make sure to stir the mix properly before sieving. The soil samples must first be added to water before adding these agents, which is not the case for sediments and sludges which have a higher water content.

For samples with a negligible fine particle fraction, the sample is dried in the oven at 60°C until a constant weight is attained before dry sieving. Drying sometimes brings the formation of agglomerates and it can be mandatory to crumble the material before sieving it. The dry material is placed on a 28- or 35-mesh sieve and the agglomerates are broken up using a rubber stopper or spatula. The material is recovered into a pan installed under the sieve.

3.1.4 Sieving methods

During a conventional dry sieving test, the series of sieves selected is piled up vertically with the size of sieve openings decreasing from top to bottom. The coarser sieve is on top of the pile and the finer one is at the bottom of the pile. A dry sample weighing between 200 and 300 g is introduced on the upper sieve and the entire pile is submitted to a horizontal or vertical shaking movement using a sieving apparatus (see appendix B). Figure 3.3 shows a simplified procedure for dry sieving.

During the sieving, the material that is too fine to be retained on a given sieve drops on the following sieve until it is retained by a sieve whose openings are slightly smaller than the size of particles. All the size fractions retained on the various sieves and the one collected at the bottom of the pile must be weighed separately. This is the conventional procedure used in the mining industry.

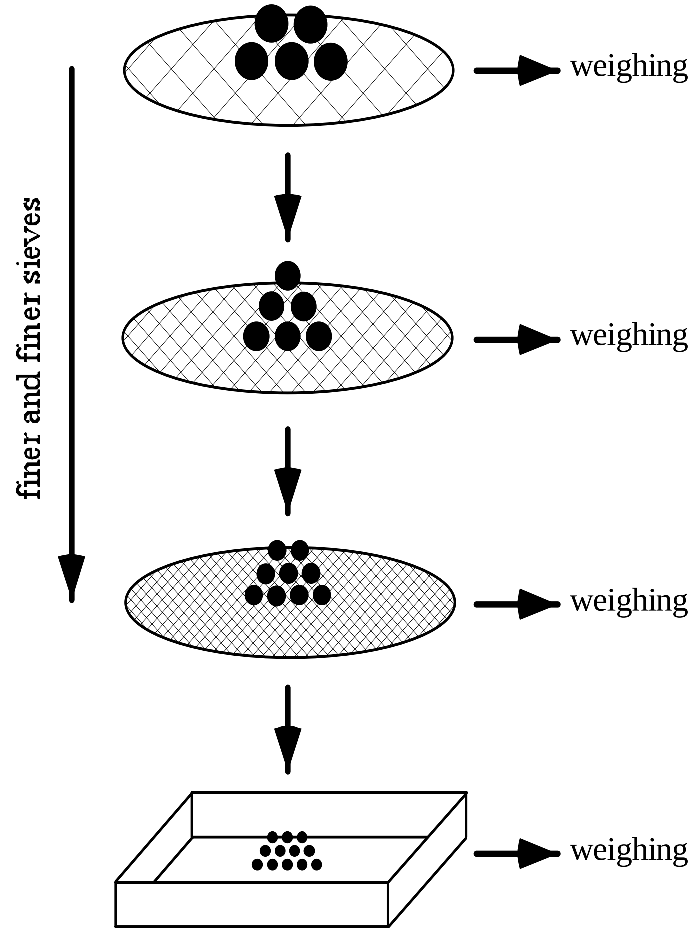


Figure 3.3 - Simplified procedure of dry sieving

As previously mentioned, the material to be analyzed can have an important size fraction of fine particles and it is thus essential to carry out a preliminary step of wet sieving on the finer sieves (generally 325 or 400 mesh). The procedure to follow is illustrated in Figure 3.4.

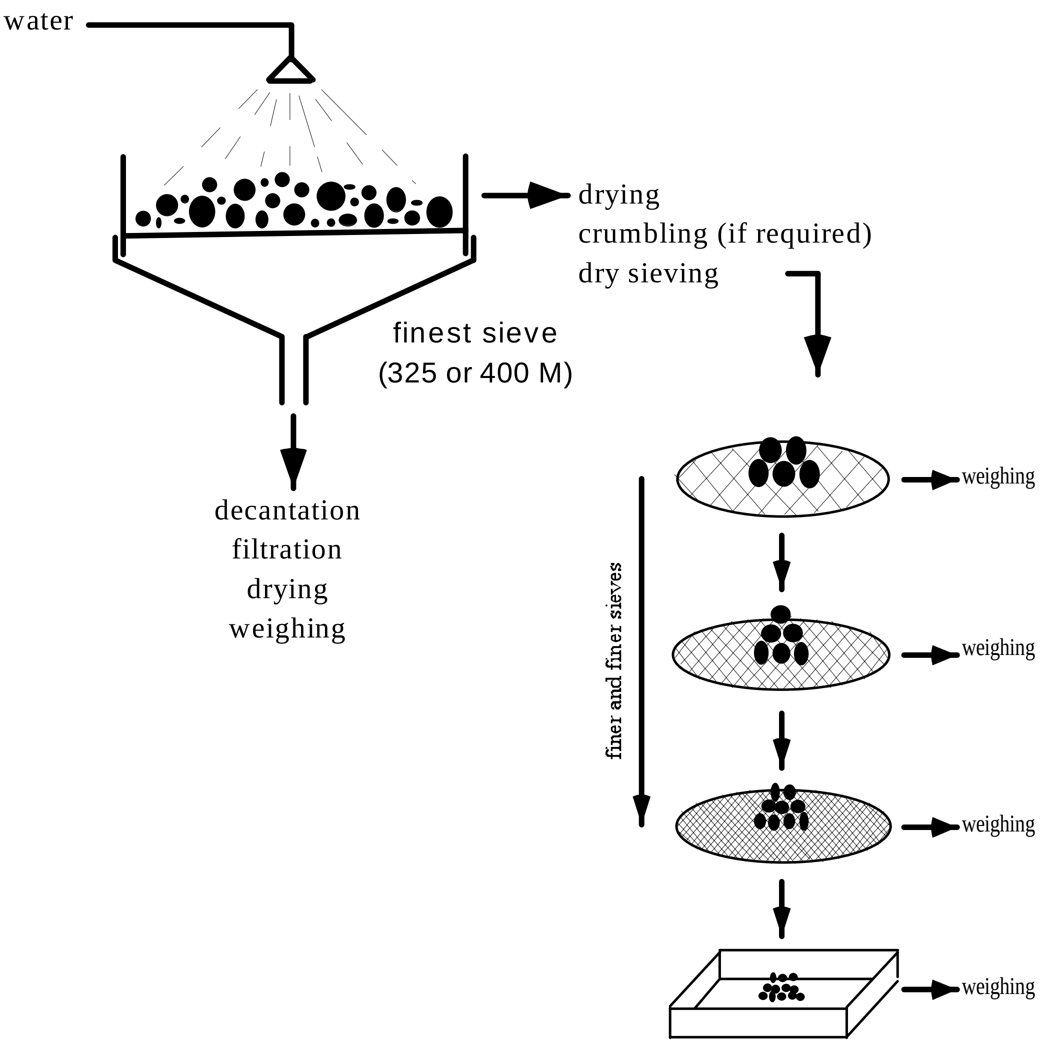


Figure 3.4 - Simplified sieving procedure for a sizeable fraction of fine particles

First, a sample containing between 200 and 300 g of solids is placed on the finest sieve of the series selected for the analysis (generally 325 to 400 mesh). The fine particles that are not retained by the sieve are washed by the water jet and recovered in the recipient under the sieve. This step can be carried out using the set-up on location or using the specially designed equipment (see Appendix C). The fine particle/water mix is left to rest for at least 16 hours, and then excess water is removed by decanting. It may be necessary to add a flocculate when a too large quantity of very fine particles brings about very long and unacceptable settling times. The settled portion is recovered to be analyzed by elutriation (see the following section: cyclosizer) or can be filtered under pressure on the appropriate filter paper. Filter retention (average diameter of openings) must be selected according to the diameter of the smallest particles present. The filtration cake is then dried in the oven at 60°C until a constant weight is attained, then weighed.

The fraction of the sample remaining on the sieve is then dried in an oven at 60°C until a constant weight is attained, then weighed. As previously mentioned, drying often brings about a formation of agglomerates which may have to be broken up before sieving. The dried material is then placed on the 28- or 35- mesh sieve and the agglomerates broken up using a rubber stopper or spatula. The recovered material can then undergo sieving as illustrated in Figure 3.3. The sieve pile used must include a fine sieve at the bottom of the same mesh size as the one used for washing fine particles, i.e. sieve of 325 or 400 mesh. This is standard procedure in the mining industry when there is a large quantity of fine particles.

3.1.5 Treatment of results

Sieving results can be compiled in three different ways: a) by calculating the percentage by mass of each size fraction, b) by calculating the cumulative percentage retained on each sieve, and c) by calculating the passing cumulative percentage of each sieve. A typical example is showed in Table 3.3. It can also be interesting to present the result of a sizing test graphically in order to visualize the most important size fractions. One of these currently used methods is illustrated in Figure 3.5.

Table 3.3 - Example of results for a sizing analysis

Fraction (µm)	Mass (g)	Mass percentage (%)	Cumulative retained (%)	Cumulative passing (%)
+1180	43.1	14.3	14.3	85.7
-1180 +600	9.3	3.1	17.4	82.6
-600 +425	63.8	21.2	38.6	61.4
-425 +300	40.0	13.3	51.9	48.1
-300 +212	25.2	8.4	60.3	39.7
-212 +150	26.9	8.9	69.2	30.8
-150 +106	28.1	9.3	78.5	21.5
-106 +75	14.2	4.7	83.2	16.8
-75 +53	18.0	6.0	89.2	10.8
-53 +45	6.5	2.2	91.4	8.6
-45 +38	5.0	1.7	93.1	6.9
-38	20.8	6.9	100.0	---

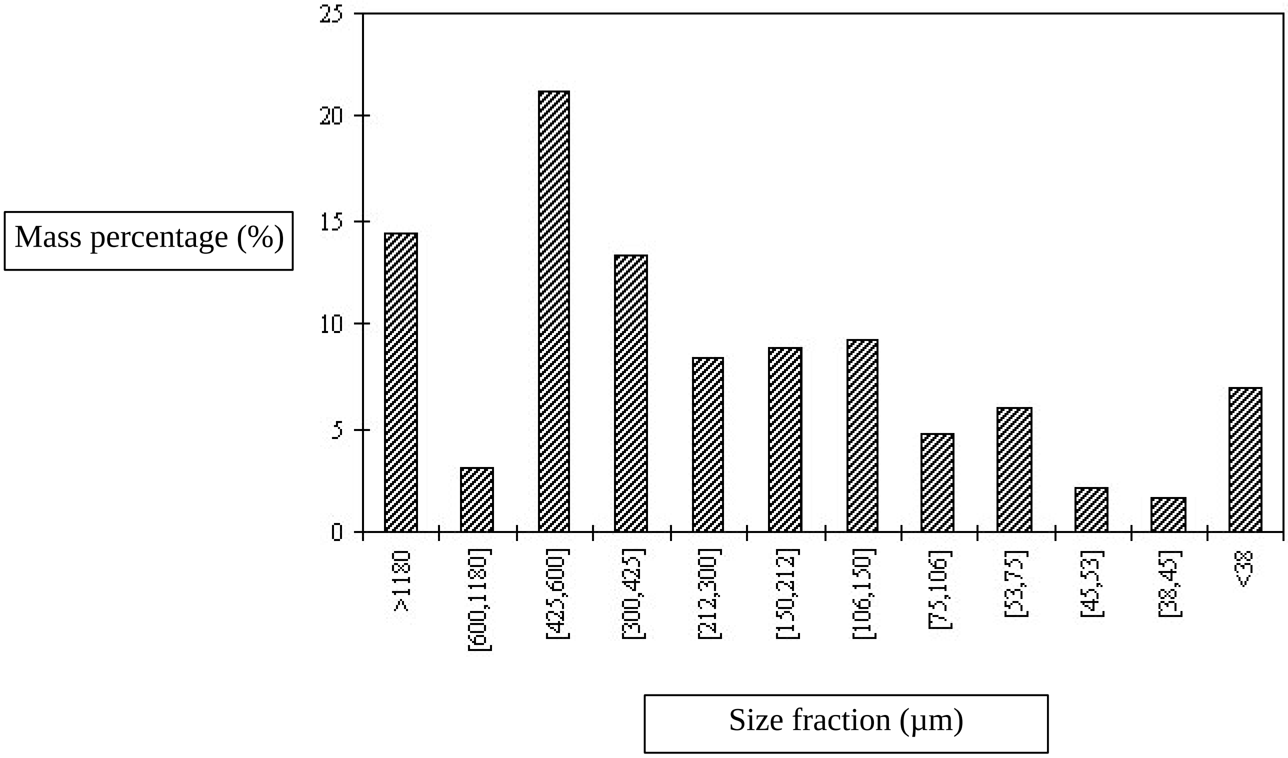


Figure 3.5 - Graphic presentation of results

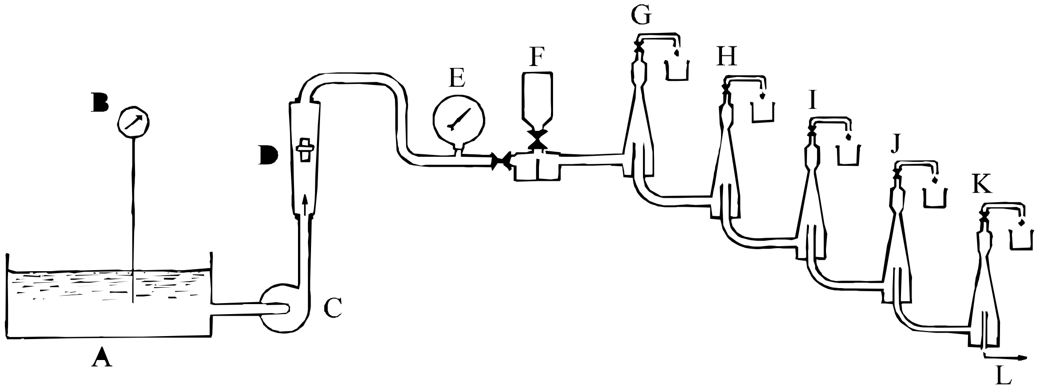
3.1.6 Elutriation

Elutriation is the reverse process of settling. If the water depth is sufficient, a sand grain falling in still water will settle with increasing due to gravity until a constant value, the terminal settling velocity, is attained before reaching the bottom. This is the settling phenomenon. Elutriation is based on the behavior of a particle in an ascending flow of fluid.

The two phenomena depend on the terminal settling velocity specific to each particle in the fluid. It varies according to the diameter of the particle, the viscosity of the fluid and the density of the particle and of the fluid. During the sizing analysis, the viscosity and the density of the liquid are constant. Particle density and diameter influence the terminal settling velocity.

During the elutriation process, particles of different diameters are separated by the following phenomenon: particles having a terminal settling velocity lower than the ascending flow velocity are carried on by the flow, while the particles with terminal settling velocity greater than the flow velocity sink to the bottom. The separation time increases with the decrease in particle diameter. For fine particles, using a centrifugal force greatly decreases the separation time.

The cyclosizer is the most commonly used instrument to separate the size fractions with a diameter smaller than 40 microns. As can be seen in Figure 3.6, it is made up of five hydrocyclones in series (see the following chapter for the complete description of the hydrocyclone). By varying the operating pressure and the diameter of inlets and outlets, it is possible to increase the fluid velocity and the centrifugal force to separate particles of successively smaller and smaller diameters. These diameters are specified by the manufacturer for each hydrocyclone with relation to the density of solids. The density of the various solids present in the heterogeneous samples such as sediments, soils or sludges varies significantly. Consequently, the separation of particles will be carried out based on two compounded parameters: diameter and density of particles. For a mix of quartz and lead particles, the lead particles (density of 11.3 g/cm^3) with a diameter of 50 µm have the same behavior as the quartz particles (density of 2.6 g/cm^3) with a diameter of 81.6 µm since their respective mass is the same, i.e. 7.4×10^{-7} g.



Legend
A: water tank
B: thermometer
C: pump
D: flowmeter
E: pressure gauge
F: feed cylinder
G: hydrocyclone #1
H: hydrocyclone #2
I: hydrocyclone #3
J: hydrocyclone #4
K: hydrocyclone #5
L: tailings

Figure 3.6 - The cyclosizer

This type of equipment is used when the very fine particle size fraction is voluminous. The sample introduced in the feed cylinder is made up of a mix of fine particles and water, which was decanted during the washing of the very fine particles on the smallest sieve (325 or 400 mesh). The elutriation procedure must be carried out following the manufacturer’s instructions. Finally, the fractions collected at each hydrocyclone are dried in the oven at 60°C until a constant weight is attained, then weighed. The results can be presented in a table or in a graph as those obtained by sieving.

3.1.7 Analysis of very fine particles

Lasers can now do sizing analysis of very fine particles. These instruments are designed to use the diffraction of light rays by the particles. Diffraction is defined as being the deviation of the wave propagation direction when these waves hit an obstacle of the same order of magnitude as their wavelength.

The sample to be analyzed consists of a suspension in a liquid (generally water) drawn from a fine particle size fraction obtained by sieving or elutriation and circulated continuously through a glass cell. A low energy parallel laser beam goes through the glass cell and the rays are concentrated towards an electronic sensor by a convergent optical system. The illumination values read by the sensors with and without the sample are processed by an algorithm that presents the result in the form of cumulative percentages of particles smaller than certain predefined parameters. By this method, it is possible to measure particles with a diameter as small as 0.1 µm.

These specially designed instruments are available on the market; they are simple to use and produce reproducible results very rapidly. However, they are very expensive. Among the various models available, we note the Microtrac® (Leeds & Northrup Instruments) and the Analisette 22® (Fritsch GmbH). Typical results of an analysis carried out with the Microtrac are presented in Appendix D.

As a conclusion, it is important to well understand the difference between sieving or elutriation and this analysis method. The sieving and elutriation yield sizing analysis results by separating the sample into various size fractions of known dimensions that can be analyzed in order to determine the contents in organic and inorganic contaminants as well as other characterization properties. The analytical methods using the laser beam instrument produce only sizing analysis results without separating the sample into different size fractions.

3.2 Locating the organic and inorganic contaminants

3.2.1 Sizing analysis and total analysis

The sizing analysis results must be examined carefully to identify the most important fractions. Smaller size fractions can be combined to adjoining size fractions to make up a total of four to six fractions having about the same mass. Choosing the number of fractions to be analyzed is a function of the available budgets, for the costs related to a simple sizing analysis are low while those related to chemical analysis are rather high. Table 3.4 shows an example of grouping into five size fractions by studying the results of a sizing analysis. As the total mass of the sample is 300.9 g, each grouping must have a mass of about 60 g (300.9 g divided by 5). The size fraction between 425 and 600 µm is not combined to another one since its mass is already 63.8 gr. However, adjoining size fractions are added together to obtain the proper mass. The final result of this operation is presented in Table 3.5.

Table 3.4 - Typical example of grouping into five size fractions

Fraction (µm)	Mass (g)	Mass of groupings (g)
+1180	43.1	
-1180 +600	9.3	52.4
-600 +425	63.8	63.8
-425 +300	40.0	
-300 +212	25.2	65.2
-212 +150	26.9	
-150 +106	28.1	
-106 +75	14.2	69.2
-75 +53	18.0	
-53 +45	6.5	
-45 +38	5.0	
-38	20.8	50.3

Table 3.5 - Typical example of the five size fractions that will be analyzed

Fraction (μm)	Mass (g)	Mass percentage (%)
+600	52.4	17.4
-600 +425	63.8	21.2
-425 +212	65.2	21.7
-212 +75	69.2	22.9
-75	50.3	16.8

In order to carry out the analysis on the various organic and inorganic contaminants, it is necessary to separate portions of material by conventional sieving (the two methods described in section 3.1.4) or by elutriation (section 3.1.5) to get the desired size fractions. The analysis of contaminants will be carried out for each selected size fraction and on a sample that underwent no separation. This precaution is to check the mass balance of contaminants in the various size fractions.

A special wet sieving procedure is required when analyzing for the following parameters:

- mercury,
- cyanides,
- all organic parameters.

The compounds mentioned above are volatile and the samples must not undergo any kind of drying. The wet sieving procedure described for this case is illustrated in Figure 3.7. It is important to note that the selected sieves for this procedure are deployed in order of mesh size, starting with the finest sieve and ending with the coarser sieve of the selected series.

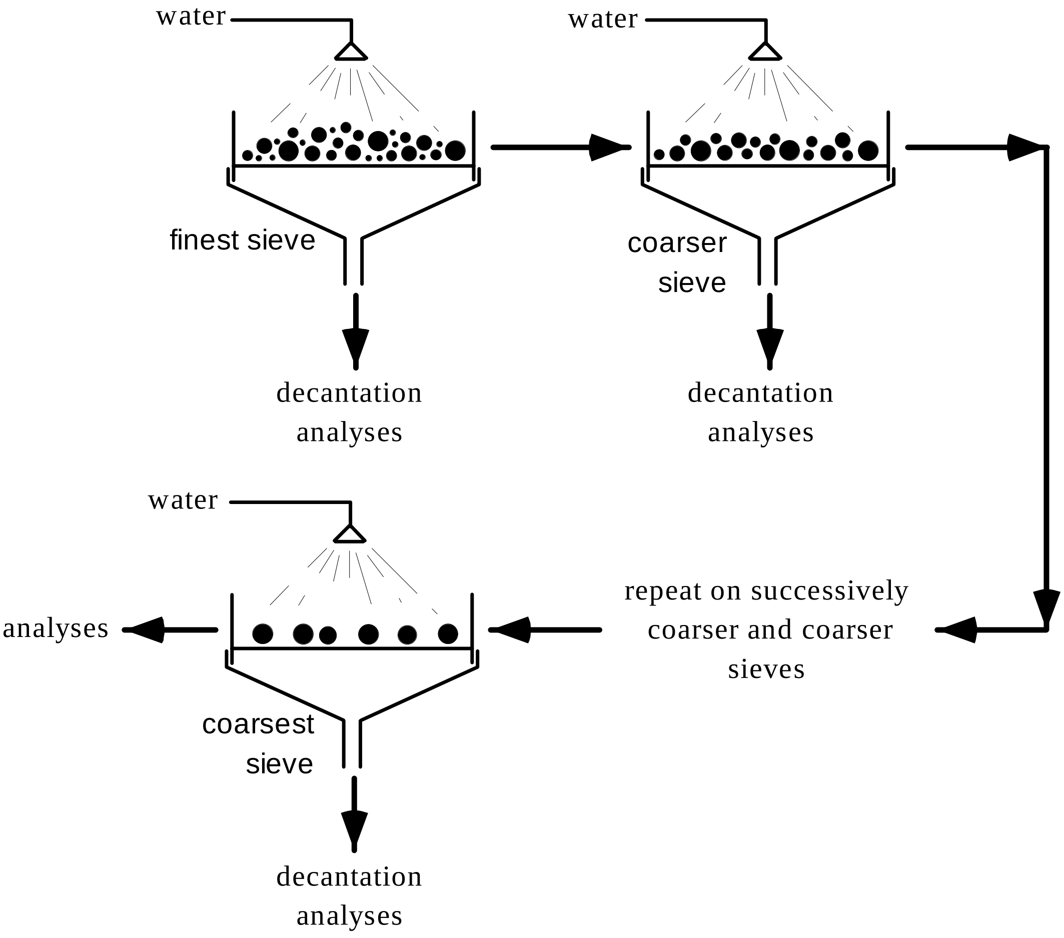


Figure 3.7 - Special wet sieving procedure

The sample is placed on the finest sieve of the series selected for the analysis (generally 325 or 400 mesh). The fine particles that are not retained by the sieve mesh are washed by a water jet and recovered in a container under the sieve. This step can be carried out using the on-location set-up or using a specially designed equipment (see Appendix A). The fine particles/water mix is left to rest for a period of at least 16 hours, then excess water is removed by decanting. It may be necessary to add a flocculate when too large a quantity of very fine particles brings about unacceptably long settling times. Then, the settled portion can by recovered for analysis.

The portion of sample retained on the sieve is recovered to be transferred to a coarser sieve. The particles that are not retained on the sieving surface are washed down to be recovered in a receptacle under the sieve. The content is left to rest for a period of at least 16 hours, then excess water is removed by decanting (adding a flocculate is not necessary in this case). Then, the settled portion is recovered for analysis. This operation must be repeated on coarser and coarser sieves. Finally, the material retained on the coarsest sieve is recovered to be analyzed as is, without any other manipulation.

3.2.2 Analysis of organic and inorganic contaminants

To analyze the various parameters of each size fraction, it is essential to refer to the methods recommended by the ministère de l'Environnement et de la Faune du Québec or by Environment Canada.

The references for sediments were taken from a document written by Environment Canada and the St. Lawrence Centre in cooperation with the Ministère de l'Environnement du Québec (1992) entitled «Guide méthodologique de caractérisation des sédiments». This guide deals mainly with the reception, preservation and preparation of samples and with the analysis methods recommended or required. Moreover, this document deals with quality assurance and control guidelines. Table 3.6 shows the analytical method of assaying for the inorganic and organic contaminants.

Analysis of soil samples must be carried out based on the document entitled «Conservation et analyse des échantillons d'eau et de sol : Guide des méthodes» published by the ministère de l'Environnement et de la Faune du Québec (1996). The chemical analysis procedures applicable to soils are summarily described with regards to the parameters targeted by the Contaminated Sites Rehabilitation Policy. The detailed methods are available for each parameter from the Laboratory service of the Ministère de l'Environnement et de la Faune du Québec. A list of analytical methods of assaying for organic and inorganic contaminants for soil is presented in Table 3.7.

Table 3.6 - List of analytical methods of assaying for inorganic and organic contaminants in sediments

Parameter	Analytical assaying method
Volatile solids	Calcining at 550°C
Total Kjeldahl nitrogen and total phosphorus	Colorimetric method
Total mercury	Atomic absorption spectrophotometer - cold vapor
Arsenic	Atomic absorption spectrophotometer - generation of hydrides
Metals (Cd, Cr, Cu, Ni, Pb, V and Zn)	Flame or furnace atomic absorption spectrophotometer Argon plasma atomic emission spectrophotometer
Total cyanides	Colorimetric method with pyridine and barbituric acid Specific ion electrode method
Total organic carbon	CHN Method Oxidation furnace method
Polychlorinated biphenyls, organochlorine pesticides and hexachlorobenzene	Gas chromatography - electron capture detector
Total and mineral oils and greases	Soxhlet extraction - infrared spectrophotometry
Polycyclic aromatic hydrocarbons	Gas chromatography - mass spectrometry
Chlorinated dioxins and furans	Gas chromatography - mass spectrometry
Phenolic compounds	Gas chromatography - mass spectrometry (with or without preparation of derivative)

Finally, the analysis of sludge samples must be carried out in accordance with the document entitled «Procédures d’évaluation des caractéristiques des déchets solides et des boues pompables» produced by the Ministère de l’Environnement du Québec (1985). This document describes the sampling and analysis methods to evaluate the concentration of some contaminants mentioned in the hazardous waste regulation are described. As for soil analysis, it is possible to get the detailed methods for each parameter from the Laboratory service of the Ministère de l’Environnement et de la Faune du Québec.

Table 3.7 - List of analytical methods of assaying for inorganic and organic contaminants in soils

Parameter	Analytical assaying method
Bromides	Visible spectrophotometry (590-nm wavelength)
Available and total cyanides	Visible spectrophotometry (580-nm wavelength)
Fluorides	Colorimetry (620-nm wavelength)
Metals (Cd, Co, Cr, Cu, Ni, Pb and Zn)	Air-acetylene flame absorption spectrophotometer Plasma atomic emission spectrophotometry
Molybdenum and tin	Flame atomic adsorption spectrophotometer with electrothermic atomization Plasma atomic emission spectrophotometry
Barium	Acetylene nitrous oxide flame atomic adsorption spectrophotometer Plasma atomic emission spectrophotometry
Arsenic and selenium	Atomic adsorption spectrophotometer / generation of hydrides
Silver	Air-acetylene flame absorption spectrophotometer
Mercury	Atomic absorption spectrophotometer after generation of vapor
Total sulphur	Leco-type induction furnace and titration
Polychlorinated biphenyls	Gas chromatography electron capture detector
Chlorobenzene	Gas chromatography / mass spectrometry Gas chromatography / electron capture detector
Volatile monocyclic aromatic compounds	Gas chromatography / mass spectrometry Gas chromatography / ionizing flame or photo-ionization
Phenolic compounds	Gas chromatography / mass spectrometry Gas chromatography / ionizing flame or photo-ionization Colorimetric method
Volatile halogenated compounds	Gas chromatography / mass spectrometry Gas chromatography / electron capture detector or Hall-type detector
Mineral oils and greases (hydrocarbons)	Soxhlet extraction / infrared spectrophotometry
Polycyclic aromatic hydrocarbons	Gas chromatography / mass spectrometry Gas chromatography / ionizing flame detector
Petroleum products (identification)	Gas chromatography / ionizing flame detector

The analysis of petroleum hydrocarbons in soil samples was the object of a specific study by the Ministère de l'Environnement et de la Faune du Québec (1995). The results are presented in the document entitled «Problèmatique des sols et des eaux souterraines contaminés par des produits pétroliers». This document deals with issues related to the analysis of the many different chemical compounds in hydrocarbon mixtures. The application field of the prescribed analysis methods in relation to the nature of hydrocarbons is also described. This is an essential reference document that deals with the numerous analytical problems related to hydrocarbons.

The quantities of material required for each analysis are presented in Table 3.8. They vary according to the type of sample (sediments, soils, or sludges), since the water content is very different from one matrix to the other. Moreover, these are the quantities required for each size fraction analyzed. It is thus necessary to multiply the quantities by the number of size fractions to be analyzed (see section 3.2.1).

Table 3.8 - Quantities required per size fraction to analyze organic and inorganic contaminants

Matrix	Amount required
sediment	3 L (3 to 4 kg)
soil	2 kg
sludge	2 kg (minimum)

3.2.3 Treatment of results

The analysis results for each contaminant are combined to those of the sizing analysis to determine the particle size distribution of the contaminant as developed in Table 3.9.

Table 3.9 - Typical example of particle size distribution of copper over five size fractions

Fraction (µm)	Mass percentage (%)	Cu conc. (ppm)	Weighted mass (mg/100g)	Distribution of Cu (%)
+600	17.4	1405	24.45	30.4
-600 +425	21.2	840	17.81	22.1
-425 +212	21.7	466	10.11	12.6
-212 +75	22.9	695	15.92	19.8
-75	16.8	724	12.16	15.1

The weighted mass represents the copper mass present in each size fraction on a basis of 100 g of sample. This weighted mass is calculated from the content (concentration of copper measured for each size fraction) and from the percentage by mass. The copper distribution for a size fraction is obtained using the corresponding weighted mass and the sum of weighted masses. The results are illustrated on a graph showing the distribution and the grade with relation to the size fractions (see Figure 3.8).

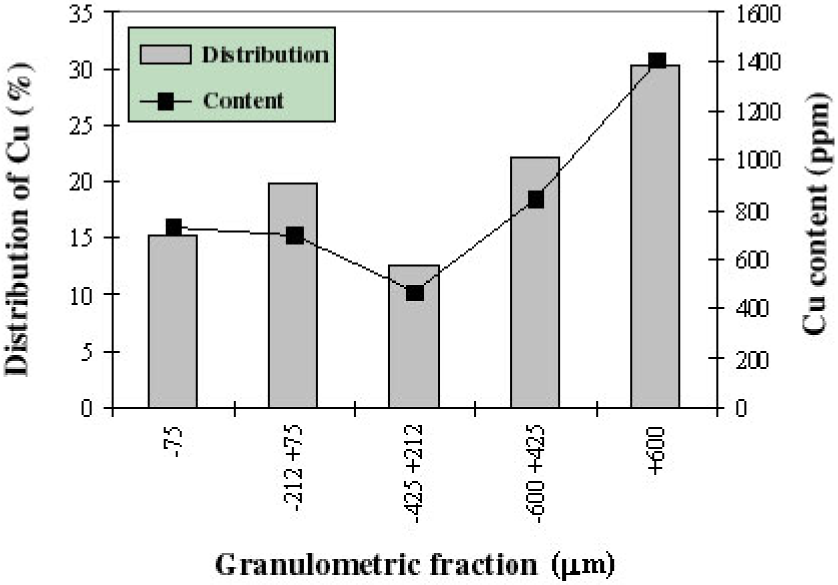


Figure 3.8 - Distribution and content of copper vs. size fractions

For a given size fraction, a high copper content does not necessarily mean a high distribution percentage. The distribution value depends also on the mass percentage of the given size fraction. Size fractions containing particles with a diameter smaller than 75 µm and those with a diameter between 75 to 212 µm are a good example. The copper content of the first size fraction is slightly higher than that of the second, but the value of its mass percentage is clearly smaller. Consequently, the value of the copper distribution is smaller in the first of these two size fractions.

3.3 Mineralogy and analytical tools

3.3.1 Mineralogy

Mineralogy is a branch of geology that deals with minerals, their chemical and physical properties and their formation. The rocks forming mountains, the sand covering the beaches and the fertile ground where wheat grows are examples of the presence of minerals in the environment everywhere we look. A mineral is defined as a homogeneous and naturally occurring solid with a characteristic chemical formula, but generally unfixed, and presenting an ordered atomic arrangement. Moreover, it is normally formed by inorganic processes. The minerals are classified with relation to their chemical formula and their structure (Hurlbut and Klein, 1977). They can be divided into twelve classes:

- native elements,
- sulfides,
- sulfosalts,
- oxides (and hydroxides),
- halides,
- carbonates,
- nitrates,
- borates,
- phosphates,
- sulfates,
- tungstates and
- silicates.

The most important class is silicates since it represents 25% of minerals known to date. Silica is the second most common chemical element encountered in the Earth's crust.

The main property used to identify minerals is related to the crystalline characteristics of each one. These characteristics are a relation of the bond lengths and angles between molecules making up the minerals (Barrow, 1988). Crystals are characterized by a very defined plane structure. The study of diffusion of rays from various sources (X-rays, neutron beams, electron beams) by the crystal lead to the elaboration of experimental mineral identification methods. Among these, the X-ray diffraction method (XRD) is the most frequently used. The data obtained by XRD are combined to obtain the distance between two crystal planes, which is specific to each mineral. The identification of minerals can be carried out by this method since the values of this parameter are known for all known minerals. Generally, XRD analyses give information on the chemical formula of the matrix, i.e. the composition of the sediment or the natural soil.

XRD analyses use two-gram samples from each size fraction selected. Samples are first dried at 110°C then ground using an impact pulverizer to reduce the size of particles (< 75 µm). The analytical procedure varies slightly from one instrument to the other. Refer to the manufacturer's instructions for each instrument. It is possible to identify up to 13 crystalline mineral phases using this method. However, the material in the sample must absolutely be in the crystalline form since the XRD analysis is not designed to identify gels or glasses. Moreover, a high iron content can create interference during analysis.

Mineralogical phases identified by XRD are generally of natural origin and make up the matrix of the analysed sample, i.e. the natural minerals making up sediments, soils or sludges. Only the inorganic contaminants with a content higher than 10 000 ppm can be identified by this method, but contents that high are rarely encountered.

However, the modal interpretation results can be used to determine if an inorganic contaminant that had been detected by chemical analysis (section 3.2.2) is related to a more common mineral, and to confirm if the said contaminant is external to the matrix.

3.3.2 Modal interpretation

Knowing the minerals present in a sample and knowing their chemical composition leads to the modal interpretation, which uses these elements to determine the probable proportions of each mineral identified in the sample. The chemical formula is obtained by the chemical analysis of several parameters: major elements, total carbon, total organic carbon, total sulphur, and loss on ignition.

The major elements normally present in soils and sediments are: Na_2O, MgO, Al_2O_3, SiO_2, P_2O_5, K_2O, CaO, TiO_2, MnO, and Fe_2O_3. In sludges, the elements to analyse depend on the origin of the sludge. There are actually two analytical methods for major elements: X-ray fluorescence and ICP-AES (Inductively Coupled Plasma Atomic Emission Spectroscopy). Two grams of a sample are required for each analysis and the results are presented as oxides. Documents describing these two analytical methods are available from the Centre de recherche minérale (Gagné, 1990 and Boivin, 1989).

The total carbon (TC) and the total organic carbon (TOC) are assayed by heating in a furnace (1200°C) in an oxygen atmosphere. The carbon present in the sample is oxidized into CO_2, which is measured by an infrared detector. The sample is used as is for measurements of total carbon but is acid treated (HCl or HNO_3) to measure the total organic carbon. The inorganic carbon is generally present as carbonates in the mineral. Adding acid decomposes the carbonates into water (H_2O) and carbon dioxide (CO_2). Two grams of the sample are required for each analysis. A document describing these two analytical methods is available from the Centre de recherche minérale (De Blois, 1991.)

The total sulphur (S) is assayed by heating in a furnace (1200°C) in an oxygen atmosphere. The sulphides present in the sample are oxidized into SO_2, which is measured by an infrared detector. The sample is analysed as is, without additional treatment. One gram of the sample is required for this analysis.

The loss on ignition (LOI) is determined by the gravity method. A two-gram sample is calcined in a furnace (1150°C) during two hours. The result is obtained by subtracting the masses before and after calcining. A document describing this method and the method for assaying total sulphur is available from the Centre de recherche minérale (De Blois, 1991).

As stated at the beginning of this section, modal interpretation combines the results of chemical analysis and on the proposed chemical formula from the minerals identified by XRD in order to determine the probable proportions of each mineral. Typical examples of chemical analyses results and modal interpretation are presented in Tables 3.10 and 3.11.

Table 3.10 - Typical example of chemical analyses results

Fraction (µm)	% M (%)	Na_2O (%)	MgO (%)	SiO_2 (%)	P_2O_5 (%)	K_2O (%)	TiO_2 (%)	Fe_2O_3 (%)	LOI (%)	TOC (%)	TC (%)	S (%)	Tot
-45	34.7	2.3	2.9	56.4	0.3	2.6	1.2	7.7	8.3	2.3	5.5	0.5	81.7
-75 +45	12.7	2.9	1.7	63.5	0.3	2.4	1.0	5.7	3.7	1.0	2.2	0.5	81.2
-150 +75	19.4	2.9	1.4	63.8	0.2	2.5	0.9	6.4	3.0	1.0	1.5	0.5	81.1
+150	33.2	2.6	1.0	62.8	0.1	2.4	0.4	4.6	11.3	6.1	4.8	0.4	85.2
Total	100.0	2.6	1.8	60.9	0.2	2.5	0.9	6.2	7.7	3.1	4.1	0.5	82.8

Legend % M: mass percentage
Tot: total amount of analysed compounds (major oxides + LOI)

Table 3.11 - Typical example of a modal interpretation

Fraction (µm)	% M (%)	QTZ (%)	PLA (%)	KFE (%)	DOL (%)	CAL (%)	APA (%)	ILM (%)	MAG (%)	SUL (%)	ORG (%)	ACM (%)	Tot
-45	34.7	27.9	19.2	13.0	1.6	10.7	0.7	2.3	4.5	1.1	2.3	16.6	100.0
-75 +45	12.7	31.4	24.2	12.0	1.0	3.9	0.7	1.9	3.2	1.1	1.0	19.7	100.0
-150 +75	19.4	31.4	24.2	12.5	0.8	2.5	0.5	1.7	3.8	1.1	1.0	20.6	100.0
+150	33.2	32.2	21.7	12.0	0.6	10.3	0.2	0.8	2.9	0.9	6.1	12.4	100.0
Total	100.0	30.5	21.6	12.4	1.0	8.1	0.5	1.6	3.7	1.0	3.1	16.4	100.0

Legend
QTZ: quartz
PLA: plagioclase feldspar
KFE: potassium feldspar
DOL: dolomite
CAL: calcite
APA: apatite
ILM: ilmemite
MAG: magnetite
SUL: sulphurs (mostly pyrite)
ORG: organic compounds
ACM: all amphiboles, chlorites and micas

Only the parameters deemed essential for modal interpretation are presented in Table 3.10. Consequently, the total values in the last columns do not add up to 100 %. Table 3.11 shows the probable proportions of each mineral identified by XRD. These values are calculated by resolving algebraically n equations at n variables. In this example, ilmenite ($FeTiO_3$) is the sole source of titanium previously identified by XRD and its ratio was calculated by stoichiometry by dividing the TiO_2 content by the factor 0.53 (molar mass of TiO_2/molar mass of $FeTiO_3$ = 79.9/151.75). The information collected by modal interpretation is limited to the inorganic and metallic phases present in a given sample. The modal interpretation does not provide any information on contaminating organic phases.

Modal interpretation generally provides information on the chemical composition of the matrix. Metallic phases cannot be integrated to the modal interpretation if they are not detected by XRD (see previous section). However, the information obtained on the matrix is essential to the selection of a separation method. The density and hydrophilic properties of materials are the most useful data. Some mineral processing equipment depend on the difference of densities between minerals and others depend on hydrophobic and hydrophilic properties of the materials. Certain minerals such as graphite, coal or talc are naturally hydrophobic. However, most minerals are hydrophilic at various degrees according to their polarity intensity, i.e. the degree of affinity for water increases with the degree of polarity. The degree of polarity of certain common minerals is presented in Table 3.12.

Table 3.12 - Degree of polarity of certain minerals

Weakly polar	Moderately polar	Strongly polar
Chalcopyrite	Apatite	Feldspar
Galena	Calcite	Quartz
Pyrite	Dolomite	
	Fluorite	

Extract from Wills (1992).

3.3.3 Carrier phases and liberation degree of inorganic contaminants

As modal interpretation rarely provides information on the contaminating metallic phases, the analysis must be pursued in order to identify the carrier phases of the metallic contamination and their liberation degree. The term «carrier phases» refers to the form under which the contaminant is present. Native copper (Cu), chalcopyrite ($CuFeN_2$), covellite (CuS) and cuprite (Cu_2O) are examples of carrier phases for copper at various oxidation states. The liberation degree corresponds to the percentage of a given mineral present under the form of free particles in a mixture (Kelly and Spottiswood, 1982).

The identification of carrier phases is preceded by a concentration of metallic contaminants using the heavy liquid separation method. This method uses a liquid with a density intermediate to that of minerals to separate. Methylene iodide is the heavy liquid most often used since its density is 3.3 g/cm^3. The carrier phases of metals are separated by settling due to their higher density. Minerals in the matrix generally have a lighter density and will tend to float on the surface of the heavy liquid. The density of quartz is 2.65 g/cm^3 and that of plagioclase feldspar is about 2.69 g/cm^3. The amount of material required (per size fraction studied) for this procedure is 50 g when the average diameter of the particles in the sample is higher than 45 µm. When the average diameter of the particles is lower than 45 µm, the amount of material required is 15 g and settling must be accelerated using a centrifuge.

Polished sections of the concentrates thus obtained are prepared for observation under the optical microscope (magnification up to 1000X). The carrier phases are visually identified by their colour, their form and their texture. This is a procedure commonly used in mineralogy. When the grain size is too fine or if there is a doubt, the identification is carried out using a scanning electron microscope equipped with a probe (energy dispersive spectrometer). The grain suspected of carrying a contaminant is analysed using the probe in order to confirm the presence of an inorganic contaminant.

The liberation degree is also estimated by observation using the optical microscope or the scanning electron microscope with the same concentrates but prepared in thin sections. The liberation degree is visually estimated by observing the aspect of the grains. The different states of the carrier phase can be described as follows: free, associated with another mineral, or enclosed in another mineral. These states are illustrated in Figure 3.9.

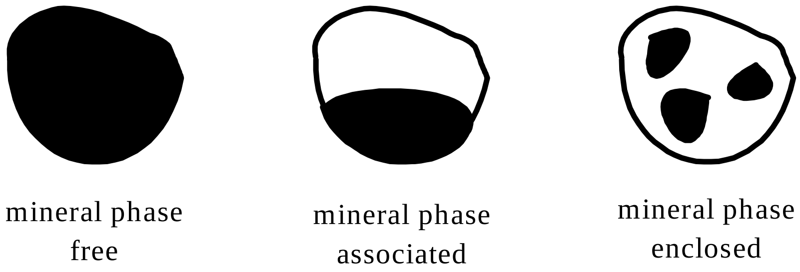


Figure 3.9 - Various states of liberation

The liberation degree of minerals is often a function of the diameter of particles. The increase in the liberation degree is inversely proportional to the diameter of particles.

Moreover, a high liberation degree makes the separation of inorganic contaminants from the matrix easier. When an inorganic contaminant is completly free, the density of particles is identical to that of the contaminant and the surface properties are constant. If the contaminant is associated with another mineral such as silica, the density of the particles varies in relation to the proportions of each mineral present, and the surface properties are not constant. When an inorganic contaminant is enclosed in another mineral, the density of the particles varies once again in relation to the proportions of each mineral present, and the surface properties are constant but not relevant.

3.4 Required amounts of material for analyses, and results

3.4.1 Required amounts of material for analyses

The analyses described in this chapter require different amounts of materials. These amounts are presented in Table 3.13.

Table 3.13 - Amount of material required for the various analyses

Analysis	Amount required
Sizing analysis	200 to 300 g
Analyses of inorganic and organic contaminants	sediment: 3 to 4 kg/fraction* soil: 2 kg/fraction* sludge: >2 kg/fraction*
X-ray diffraction analysis	2 g/fraction*
Major elements	2 g/fraction*
Total carbon	2 g/fraction*
Total organic carbon	2 g/fraction*
Total sulphur	1 g/fraction*
Loss on ignition	2 g/fraction*
Heavy liquid separation	15 to 50 g/fraction*

* Multiply the amount required by the number of size fractions to analyse.

A complete characterization of a sample using the ore-processing approach requires about 11 kg of material on a dry basis, if there are five size fractions. The costs related to such a characterization are about $5000.

3.4.2 Using the results

The sizing analysis results and the grain size distribution of contaminants related to the mineralogical study (liberation degree) indicate the degree of decontaminability and also give an idea as to the equipment that can be used to decontaminate. Figure 3.10 shows the degree of decontaminability with relation to the size of particles in the material to process, if the inorganic contaminants are external to the matrix (high liberation degree).

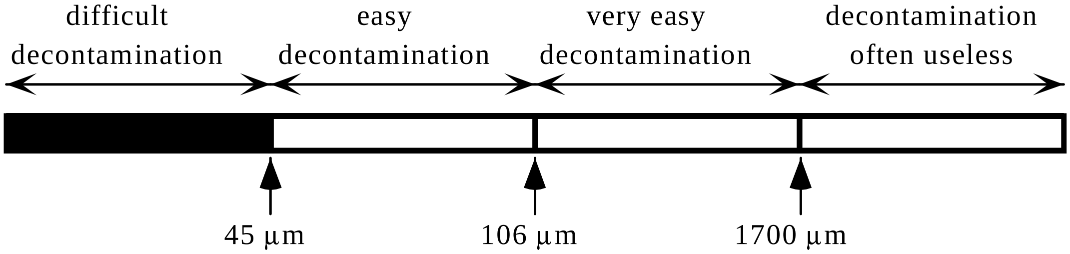


Figure 3.10 - Degree of decontaminability in relation to particle size in matrix free

Generally, it is rather difficult, but not impossible, to decontaminate materials with an average particle size diameter lower than 45 µm. This is an undesirable particle size in conventional ore-processing techniques. The presence of particles of that size decreases the separating efficiency for contaminating phases. This decrease in efficiency is borne by the presence of non-contaminated material in the contaminated phase that has been separated; this results in an unwanted increase in its volume. Recently developed equipment decreases the difficulty. However, processing particles with a diameter varying from 45 to 1700 µm can be easily or very easily carried out using a very wide range of ore-processing equipment.

Scientific literature states the low contamination of mineral particles (soils and sediments) having a diameter larger than 1700 µm. The United States Environmental Protection Agency produced several documents stating that fact (US EPA, 1993 Feb., US EPA, 1993 Aug., US EPA 1992, US EPA 1990). Research work leading to the characterization of sediments in the port of Hamburg demonstrated that the coarse fraction of these sediments was practically contamination free while the fine fraction (clay and silt) contained almost all the contamination (Kröning, 1990). Sediments from a Montreal harbour zone were characterized (St-Laurent *et al*., 1997); the analyses showed that about 70% of the inorganic contaminants were found in the fine portion (< 45 µm).

However, the presence of organic debris such as wood chips shows the inverse phenomenon (US EPA, 1994b). This is attributable to the high affinity of metals and organic substances for organic matter. In all cases, the analysis of the coarse fraction is essential to determine if this size fraction should be decontaminated.

The selection of the appropriate ore-processing equipment is based on the results of the various analyses described. The equipment is classified in four large classes; their operating principles and conditions are summarized in Table 3.14.

Table 3.14 - Operating principles and conditions of ore-processing equipment

Type of equipment	Principle of operation	Operating conditions
Gravity concentration	Difference in density between the minerals	- particle size greater than 1 µm - difference in the density of materials to separate greater than 1 g/cm^3 - high liberation degree of inorganic contaminants
Flotation	Hydrophobic and hydrophilic surface properties of particles	- particle size greater than 5 µm - particle surfaces showing natural or stimulated hydrophobic properties (addition of reagents) - average liberation degree of inorganic contaminants (free of enclosed inorganic phases)
Magnetic separation	Magnetic properties of minerals	- metal contaminants showing ferromagnetic properties (iron, magnetite) - particle size greater than 75 µm - average liberation degree of inorganic contaminants
Electrostatic separation	Difference in electrical conductivity between minerals	- particle size from 60 to 500 µm - materials to separate must be completely dry - high liberation degree of inorganic contaminants

Table 3.14 shows that the minimum particle size required for using gravity concentration equipment is 1 µm. However, the mass of particles having a diameter lower than 45 µm is so small that gravity alone can barely create an efficient separation. It is thus necessary to add centrifugal force.

Flotation requires an average liberation degree of inorganic contaminants. However, enclosed inorganic phases (contaminants) are undesirable since the surface of these particles generally shows the same properties as the matrix particles. Under these circumstances, separation by flotation is impossible. However, among the ore-processing equipment, only flotation equipment can be efficiently used against organic contaminants such as hydrocarbons or polychlorinated biphenyls. Flotation requires the hydrophobicity of the contaminating substance.

Moreover, highly sophisticated magnetic separation equipment can process materials with particle sizes of 1 µm and paramagnetic inorganic contaminants (hematite, ilmenite). As yet, their application is limited to processing certain highly specific minerals (e.g.: kaolinite).

Finally, electrostatic separation can rarely be used for environmental applications. Since it can be applied solely to totally dry materials, the presence of humidity modifies the behaviour of particles. The separation of metallic particles in sand is probably the most advantageous environmental application of electrostatic separation. For other applications (sediments or sludges), the costs related to drying the material are such that they make this alternative less interesting. The costs related to drying a soil are lower, but still non-negligible.

The use of the four types of equipment stated in Table 3.14 is restricted to specific grain size ranges. Consequently, the contaminated material must often be pre-treated by screening or classification to separate the material into different size fractions that are then treated using the most appropriate equipment.

Moreover, the grain size distribution of contaminants shows which size fractions are the least contaminated. Those presenting a very low contamination or no contamination can then be separated by screening or classification, without any further treatment. In some cases, the gravity concentration equipment such as spirals can be used.

The applicability of ore-processing technologies to sediments, soils and sludges can be confirmed by combining the data obtained by characterization using the ore-processing approach and the information contained in Table 3.14. Following such a confirmation, the appropriate ore-processing equipment is selected to design a preliminary flowsheet. The next chapter describes the equipment and the principle of operation.

Chapter 4

Ore-Processing Technologies Applicable to Decontamination

Ore-processing technologies are designed to physically separate ore into an enriched portion containing most targeted minerals (the concentrate) and a lean portion made almost exclusively from waste (the tailings) as illustrated in Figure 4.1.

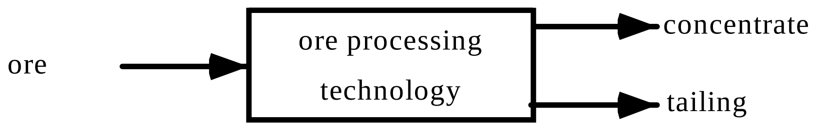


Figure 4.1 - Physical separation carried out by ore-processing technologies

The two parameters used to determine separation efficiency are recovery and concentration (Wills, 1988). Recovery represents the percentage of the total amount of a mineral contained in an ore that is recovered in the concentrate. Concentration means the proportion of the mineral with relation to the gangue and the other minerals. Unfortunately, there is an almost inverse relation between these two parameters. Two very simple cases can illustrate this. Small gold nuggets are dispersed in a pile of sand and must be recovered. In the first case, it is possible to concentrate them manually by picking up a few nuggets. The concentration of the concentrate is thus 100% but recovery is very low since most of the gold nuggets remain in the sand pile. In the other case, no concentration is carried out. Consequently, recovery is 100% but the grade does not increase. Figure 4.2 shows the typical relation curve between these two parameters.

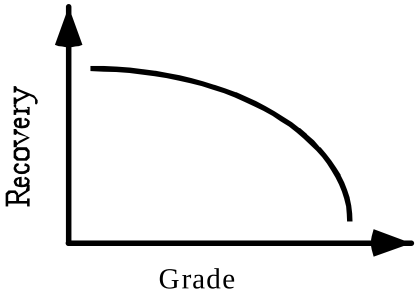


Figure 4.2 - Typical curve of recovery vs. grade

While it is essential to get a high grade, recovery must be sacrificed and vice versa. In fact, each ore concentration case is studied to get an intermediate compromise that will produce an appropriate concentrate at the next processing step, hydrometallurgy or pyrometallurgy.

The decontamination of sediments, soils and sludges can be examined at the same time. The contaminants present must be separated from the matrix (soil or sediment) by concentration as if they were a mineral of value. In this case, the matrix can be compared to the waste. The objective of decontamination is to decrease the concentration of contaminants in the matrix down to the level prescribed by the criteria in effect and to produce the smallest volume of concentrate possible. The decontaminated matrix is the waste while the portion containing the contaminants is the concentrate.

The four concentration principles governing the ore-processing methods are gravity concentration, flotation, magnetic separation, and electrostatic separation. The latter principle will not be detailed since it requires the material to be treated to be completely dry. However, the three other principles will be described, detailing the main equipment and the operating conditions for their application.

The grain size ranges within which the equipment is efficient are relatively narrow. This is why it is almost always essential to classify the material to be processed according to the various grain size ranges. This chapter includes a review of the most frequently used classification methods and a description of their principles of operation.

In most cases, processing techniques must be preceded by a preliminary processing stage through which the material obtains the required processing conditions. Normally, preliminary processing removes the components that could damage the various elements of the processing system. Large debris such as rocks, glass bottles or metal containers are removed by screening. This chapter will begin with the description of the screening equipment.

4.1 Screening

4.1.1 Basics

As seen in the previous chapter, screening is used to classify the material (sediments, soils or sludges) according to particle size. There are three very different types of industrial screens: perforated plates, the metal mesh screens, and the rod-deck screens (Kelly and Spottiswood, 1982). Industrial-scale screening can be carried out dry or wet. The screening equipment can be stationary (static screening surface) or dynamic (revolving, vibrating, or circular vibrating screens).

Like laboratory sieves (see section 3.1.2), the various instruments are always characterized by the size of openings. Their performance is determined by two parameters: capacity and efficiency. Capacity is defined by the material flow range an apparatus can process, and efficiency is the degree of performance of the separation. An efficiency of 100% means that no particles of a size smaller than the screen openings are found in the material retained on that screen. Capacity and efficiency have reverse performance, i.e. high capacity produces low efficiency and vice versa.

Sediments, soils and sludges must generally be screened in order to remove large debris. To prevent blinding, it is often useful to use a series of screens stack in decreasing order of size opening. For example, the size of openings in the first screen can be one inch, that of the second can be ¼ inch and that of the third screen can be 10 mesh (1700 µm). Selection of screen size and the number of screens must be based on the material characterization.

Among the numerous screening equipment, four types of equipment are most commonly used: grizzlys, Trommel screens, vibrating screens, and circular vibrating screens. The description and operating conditions of each one are detailed in the next sections.

4.1.2 Grizzlys

Generally, the material containing a large percentage of coarse particles is separated using a Grizzly. This apparatus is constructed of strong steel bars, evenly spaced and mounted on a frame (see Figure 4.3). There is a modified version of the grizzly in which the bars are replaced by chains. Moreover, this apparatus can be stationary or vibrating. The surface is set at a 20- to 50-degree slope. The capacity of this apparatus increases with the angle but its efficiency decreases with the angle. The material to screen (dry or humid) is introduced at the top of the slope. It slides down in the direction of the parallel bars. This equipment is recommended for separating particles from 20 mm to 300 mm (Wills, 1988). They are characterized by a very high capacity (up to 1000 t/h) and a low efficiency.

4.1.3 Trommel screens

Trommel screens are mainly composed of a cylindrical screen surface with a slightly inclined rotation axis (see Figure 4.4). The material to be screened is fed into the cylinder at the higher end to favour the displacement of material down to the outlet. The retained particles slide on the inside surface of the Trommel screen, following a helicoidal trajectory caused by the rotation of the cylindrical screening surface. The material passing through the screening surface is recovered under the cylinder (Blazy, 1970).

As illustrated in Figure 4.5, the Trommel screens can be disposed in series by decreasing order of screen opening sizes. The particles that are not retained on the screen surface feed the next Trommel screen.

Thanks to a gearing system, the rotation of the Trommel screen series is assured by a single drive mechanism.

Trommel screens are recommended for separating particles from 6 mm to 55 mm, and the screening can be carried out dry or wet (Wills, 1988). This is a low-cost and solid apparatus but its capacity is low: about 0.6 ton (one ton equals 2000 lbs.) per square feet of screening surface per day (a factor should be applied to compensate for the fineness of the material) for dry screening and about 1.04 ton for wet screening (Taggart, 1945). Moreover, they have a tendency to be blinded easily, which explains their average efficiency.

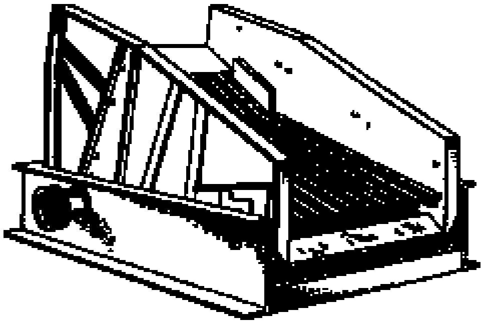


Figure 4.3 - Screening equipment: vibrating Grizzly (source: Taggart, 1951)

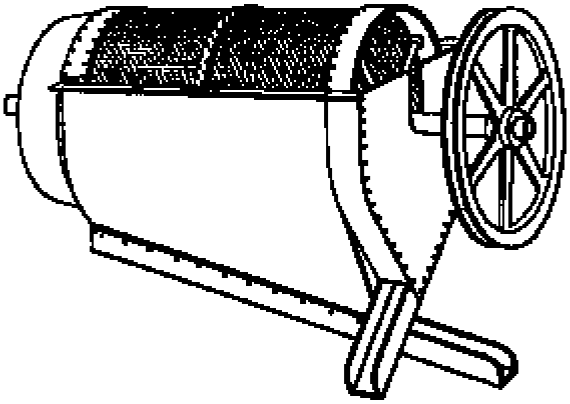


Figure 4.4 - Screening equipment: Trommel (source: Richards and Locke, 1940)

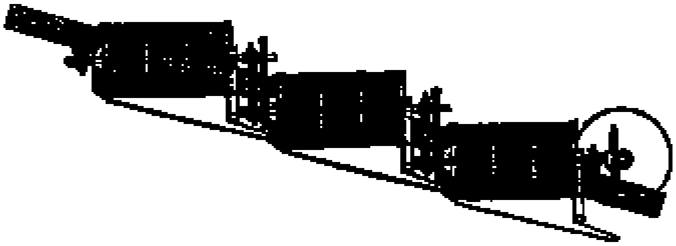


Figure 4.5 - Screening equipment: Trommel screen series
(source: Richards and Locke, 1940)

4.1.4 Vibrating screens

Vibrating screens are the most frequently used screening apparatus. They are made of a flat screening surface inclined at a 35-degree angle. The vibration can be circular, elliptic or by impact (Blazy, 1970). Besides moving the material, vibration is used to prevent blinding the screening surfaces. Whether they are suspended or installed on a spring base, vibrating screens occupy a very small space. Figure 4.6 shows an example of multi-stage vibrating screens. This is a system where the screens (three in this case) are set up by decreasing order of opening size and are activated by the same vibration mechanism. The material to be screened is introduced at the top of the upper screen. The particles retained by this screen are recovered at the toe of the screen slope and the particles passing through the screens fall on the lower screen.

This equipment is used to separate particles from 250 µm to 25 cm, whether wet or dry. Their efficiency and their capacity are high. Capacity is between 10 to 15 tons (one ton = 2000 lbs.) per square foot of screen surface per day (a factor should be applied to compensate for the fineness of the material) (Taggart, 1945). However, the capacity greatly decreases for particle sizes around 250 µm (Kelly and Spottiswood, 1982).

4.1.5 Circular vibrating screens

Circular vibrating screens are made of a circular screening surface that is moved horizontally with a circular motion and vertically by a tapping motion. The complete system is generally made up of three screening surfaces stacked in decreasing order of opening size. The set lies on a spring base and a vibratory movement is transmitted through an eccentric weight on the motor. The rotary screens can be fed with dry material or with a pulp. The material retained on the top screen is removed while the passing material falls on the lower screen. An example of this apparatus is shown in Figure 4.7.

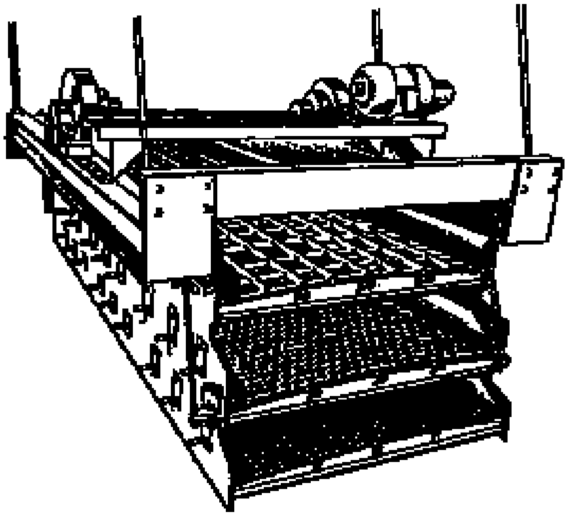


Figure 4.6 - Multi-level vibrating screen (source: Taggart, 1951)

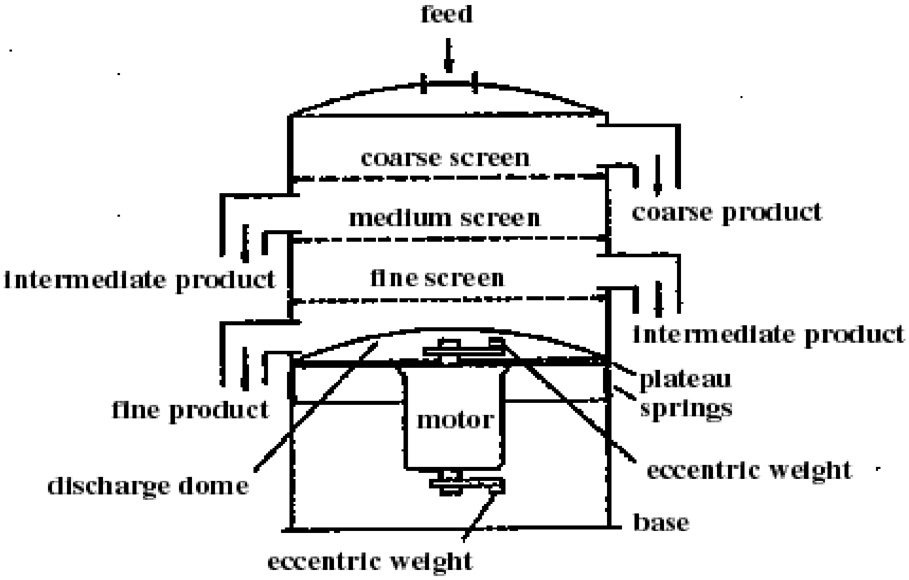


Figure 4.7 - Circular vibrating screen (source: Wills, 1988)

Mostly designed for fine screening, this type of apparatus is designed to separate particles from 40 µm to 12 mm. Its efficiency is very high but its capacity is low, i.e. a maximum of 40 tons per hour for a 60-inch diameter surface (for the Vibro-Energy Separator Scalper Unit apparatus, according to the manufacturer, Sweco Inc.).

4.1.6 Operating conditions

The previous section stated optimal particle sizes with relation to the use of the described apparatus. The next table summarizes these operating conditions by detailing the efficiency and capacity of each apparatus.

Tableau 4.1 - Typical application of screening apparatus

Apparatus	Particle size	Efficiency	Flow	Capacity
Grizzly	20 mm to 300 mm	low	< 1000 t/h	very high
Trommel	6 mm to 55 mm	average	0,6-1,0 t/ft^2.24h.mm	low
Vibrating screens	250 µm to 250 mm	high	10-15 t/ft^2.24h.mm	high
Rotary screens	40 µm to 12 mm	very high	< 40 t/h	low

4.2 Classification

4.2.1 Basics

Classification is defined as the separation of particles according to their size, based on the principle of different terminal settling velocities. This concept was briefly described in the section on elutriation (section 3.1.5) and will be detailed in this section. Figure 4.8 shows a simplified view of the three possible behaviours of a solid particle subject to gravitational force.

When a solid particle is located in an absolute vacuum, its speed increases continually if there is acceleration. However, its speed increases at a lower rate when it is located in a viscous fluid such air or water. Part of the gravitational force is cancelled by the force due to friction caused by the movement of particles in the viscous fluid. Force caused by friction is proportional to the speed of the particle in the fluid. When the force caused by friction reaches a value equal to the force caused by gravity, the speed of the particle reaches a constant value, called terminal settling velocity. This velocity depends on the following parameters:

- size of the solid particle,
- density of the solid particle,
- shape of the solid particle,
- fluid viscosity, and
- fluid density.

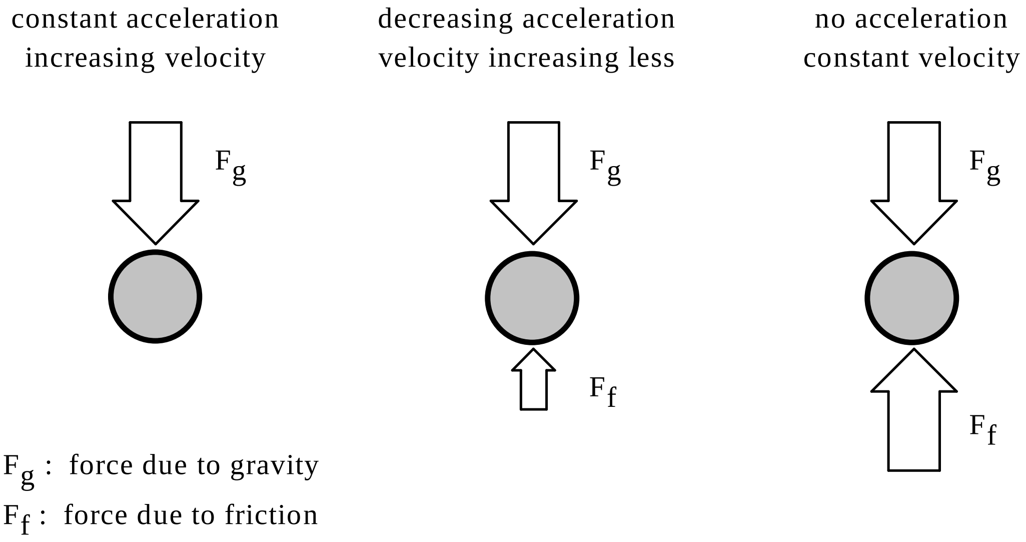


Figure 4.8 - Behaviour of a solid particle in a gravitational force field

The fluid in question is generally water but it can also be air. The pneumatic classification equipment (using air as fluid) requires a perfectly dry material. The costs related to drying the sediments, sludges, and, to a lesser degree, soils make this alternative less attractive. Therefore, only the wet classification equipment (using water as a fluid) will be detailed in this document.

The notions stated above are the basis of the settling phenomenon. There are two types of settling: free settling and hindered settling. Only the amount of solids in suspension can differentiate them. When this amount exceeds a certain threshold, the settling of a particle is hindered by the presence of neighbouring particles that interfere with its downward trajectory. The threshold delimiting the two types of settling corresponds to a 5% solid volume in suspension in the fluid. Free settling occurs with values lower than 5% and hindered settling occurs with values higher than 5%. Whether there is free or hindered settling, the parameters influencing the terminal settling velocity are the same, except for fluid density. The fluid density must be replaced by suspension density (water + solids) when there is hindered settling (Blazy, 1970). In classification, this hindered settling reduces the particle size effect while increasing the density effect. The free settling classifiers are used to perform separations based on size, while hindered settling classifiers are used to perform density separations.

In a still fluid, particles of different sizes and densities settle at a rate that depends on the terminal settling velocity of each particle. However, these particles can be in a moving fluid with an ascending current that cancels gravity. The particles in such an environment will have a behaviour that varies according to their respective terminal settling velocities. The ascending flow brings with it the particles having a terminal settling velocity lower than the flow velocity. Particles that have a terminal settling velocity higher than the flow velocity will settle at the bottom.

The above-mentioned phenomena (section 3.1.5) are the basis of elutriation. Finally, particles with a terminal settling velocity equal to the flow velocity stay in a constant position. This phenomenon is designated by the term fluidization and is the principle of operation of several apparatus used in various fields (ore-processing, chemical engineering, …) including classification. The three phenomena are illustrated in Figure 4.9. To simplify these examples, it was assumed that particles all had the same density and that the separation was carried out uniquely with relation to particle size.

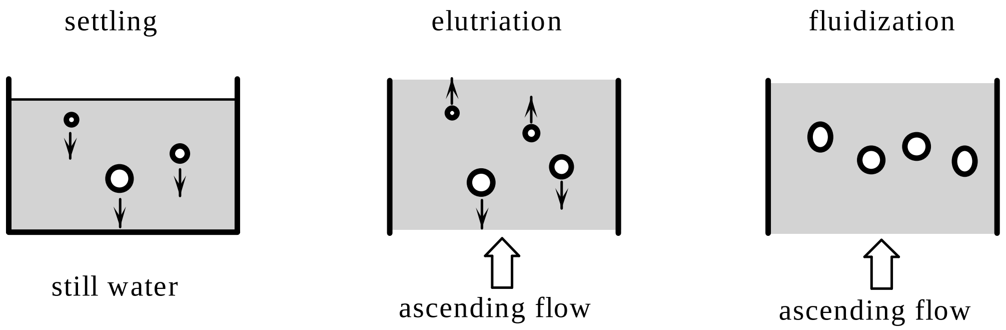


Figure 4.9 - Settling, elutriation and fluidization

Classification applies when it is not economically profitable to use screening. Industrial screening equipment capable of separating particles of about a micron such as rotary screens have a very low capacity (see section 4.1.5). Generally, the classification is designed to limit the feed of a concentration process to the appropriate range of particle sizes (Kelly and Spottiswood, 1982).

The two products obtained after a classification are the overflow and the underflow. The overflow is made up of particles with a low terminal settling velocity while the underflow is composed of particles with a higher terminal settling velocity. It is possible to get intermediate products by varying the operating conditions or by using a series of properly matched apparatus.

There are many types of classification equipment. In mechanical classifiers, separation is carried out by mechanical means while it is carried out by gravitational forces and centrifugal forces in non-mechanical classifiers. Examples of these types of classifiers are presented in the next sections. They are: the screw classifier, the hydrocyclone and the hydraulic classifier (or fluidized bed). There are several other classification equipment (e.g.: cone classifier and centrifuge apparatus) but the previous three apparatus are by far the most frequently used.

4.2.2 The screw classifier

Mechanical screw classifiers use mechanical force to counterbalance the settling of particles with a low terminal settling velocity in order for them to remain suspended while the particles with a high terminal settling velocity settle at the bottom. This equipment is made up of a long worm screw in an inclined auger (see Figure 4.10). The mechanical force rotates the screw to ensure turbulence in the pulp and the transport of settled particles. The particles in suspension are evacuated in the overflow.

Figure 4.11 helps understand the classification principle of this apparatus. The pulp to be processed must not contain more than 30% solids; it is fed at the top of auger. The mechanical screw classifier is divided into three distinct zones. The transport zone, which is located between the feed and the overflow output, is characterized by the free settling of particles. The baffle that divides this zone is designed to adjust its depth and to deviate the course of particles coming from the feed. It also increases the turbulence created by the screw rotation. The classification zone, located under the transport zone, is characterized by the hindered settling of particles. The third zone, settled solids, is located completely at the bottom of the auger. These solids form a heterogeneous layer that is constantly stirred and moved upward by the screw. The solids are brought to a level higher than that of the pulp where they are washed by water jets that return to the settling zone the fine particles accidentally moved upwards with the other particles.

The main parameters to control the operating conditions of these apparatus are the rotational speed of the screw, the slope of the auger and the pulp density. Screw

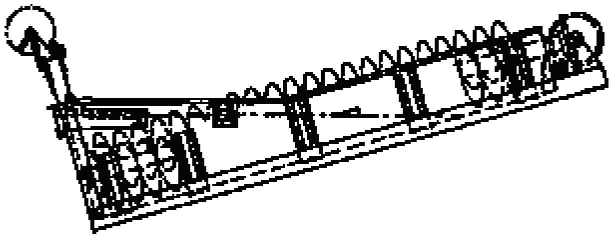


Figure 4.10 - Mechanical coil separator (source: Blazy, 1970)

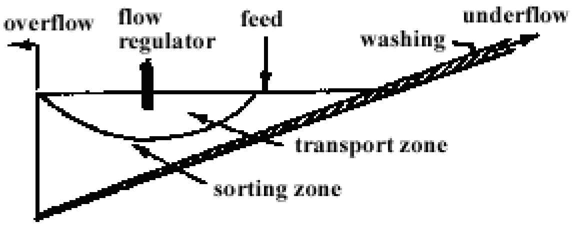


Figure 4.11 - The basis of sorting (source: Blazy, 1970)

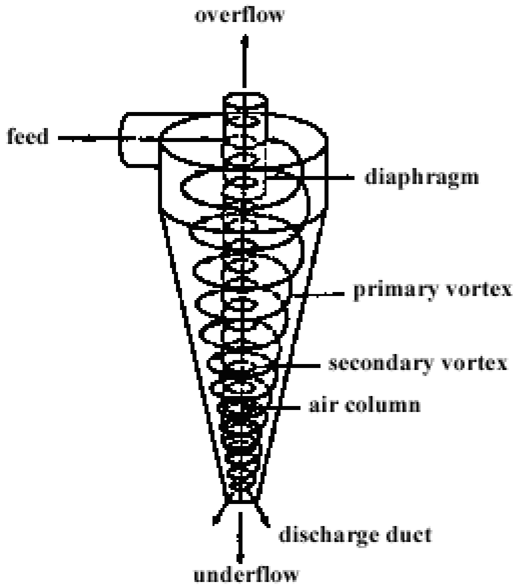


Figure 4.12 - Hydrocyclone (source: Coulson and Richardson, 1991)

classifiers are appropriate to separate particles smaller than 25 mm, they have a cut-off point between 45 µm and 1 mm. They have a good efficiency but a capacity of only 5 to 850 t/h on a dry basis (Kelly and Spottiswood, 1982). The capacity is strongly affected by the size of particles. These values only apply to ore-processing and can vary for environmental applications.

4.2.3 The hydrocyclone

This is without a doubt the simplest piece of equipment since it has no mechanical or mobile parts. This conical equipment uses centrifugal force to separate particles. The combined effects of the specific shape of the apparatus and the pressure at which the pulp is injected create the centrifugal force. This force is much stronger than gravitational force, so the time required to separate the particles is considerably reduced. Figure 4.12 shows a typical cutaway view of a hydrocyclone.

The pulp under pressure is injected tangentially at the top of the hydrocyclone and takes a spiral-shape trajectory inside the equipment. Particles with a high terminal settling velocity are carried towards the walls by the centrifugal force and exit at the bottom of the cone through the apex. Particles with a low terminal settling velocity are gathered at the centre of the equipment. When they reach the bottom of the cone, they are pushed upwards and exit at the overflow of the apparatus. This phenomenon is caused by a constriction at the base of the cone that is designed to push the particle flow back upwards towards the vortex finder.

The three independent parameters used to vary the operating conditions are pulp density, feed flow and pressure, diameter of vortex finder and apex. The cut-off point and the efficiency of separation are controlled by adjusting these parameters. Generally, the hydrocyclones are used to classify particles smaller than 1400 µm in size; they have a cut-off point from 5 µm to 300 µm. These are low cost apparatus that take up very little room. They have a very high capacity (up to 20 m^3 of pulp/min) and a relatively high efficiency (Kelly and Spottiswood, 1982). However, they have a high energy consumption since they must be operated at high pressure. The capacity value applies only to ore-processing and can vary for environmental applications.

4.2.4 The hydraulic classifier (or fluidized bed)

Hydraulic classifiers are generally made of a conical section topped with a cylindrical section. They are characterized by mid-height addition of water that produces an ascending flow against the settling of particles. Their separation principle is based on free settling or on hindered settling. The hindered settling apparatus are the most commonly used. The three phenomena shown in Figure 4.9 (settling, elutriation, and fluidization) are produced simultaneously. Figure 4.13 illustrates the global operating principle of a hydraulic classifier.

The pulp fed to the classifier can contain between 35% and 65% solids on a mass basis and is introduced through a feed well that distributes to prevent perturbing the conditions in the apparatus. Water is introduced by the bottom of the cylindrical portion of the apparatus and creates an ascending flow of controlled velocity. Immediately above it, the fluidized bed of particles is made up of particles with a terminal settling velocity equal to that of the ascending flow. Thanks to the large amount of particles in suspension, the bed forms a controlled density environment with a density higher than that of water. The separation of particles is carried out by elutriation. The ascending flow brings with it particles having a terminal settling velocity lower than the flow velocity. These particles are brought upwards and are evacuated through the overflow. The particles with a terminal settling velocity higher than the flow velocity settle in the lower conical portion of the classifier, where a particle compacting zone is designed to reduce the water content of the underflow. The latter is evacuated by a pneumatically controlled valve.

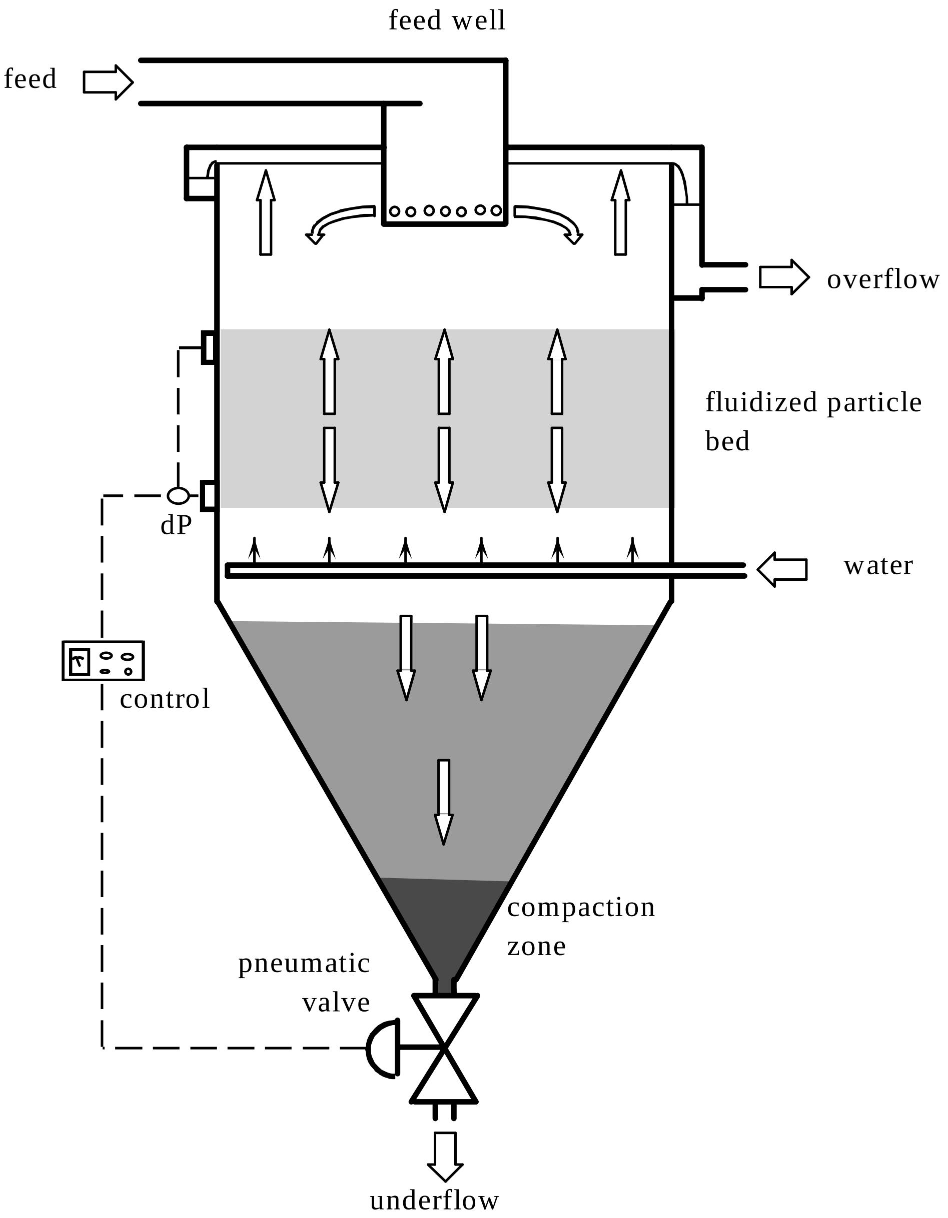


Figure 4.13 - Hydraulic classifier

The density of the fluidized particle bed is adjusted and controlled using two pressure probes. The difference in pressure communicated to a control panel. The real bed density is determined using the pressure difference and the distance between the two probes. The perturbation of conditions inside the apparatus is eliminated by activating the outlet valve of the underflow. These perturbations can be created by variations in feed flow or pulp composition.

The main parameters used to control the operating conditions of these apparatus are the flow rate of added water and the evacuation flow rate of the underflow. Hydraulic classifiers are appropriate to separate particles with a size smaller than 6 mm; they have a cut-off point between 100 µm and 850 µm. These apparatus have a good efficiency but a restricted capacity, between 10 and 120 t/h on a dry basis (Kelly and Spottiswood, 1982). These values apply only to ore-processing and can vary for environmental applications.

4.2.5 Operating conditions

The previous sections stated cut-off points according to apparatus utilization. The next table summarizes the operating conditions by detailing the efficiency and the capacity of each apparatus.

Table 4.2 - Typical application of classification apparatus

Apparatus	Cut-off point	Efficiency	Flow	Capacity
Screw classifier	45 µm to 1 mm	good	5-850 t/h	variable
Hydrocyclone	5 µm to 300 µm	high	< 20 m^3/min	high
Hydraulic classifier	100 µm to 850 µm	good	10-120 t/h	low

4.3 Gravity concentration

4.3.1 Basics

Gravity concentration equipment uses the difference in density between materials to carry out the separation, as the combined action of gravity and various other forces come into play. In fact, as for classification, separation is also affected by the volume and by the shape of particles. The effects of these two factors are canceled by limiting the range of particle sizes in the feed of the equipment using screening or classification.

As for classification, gravity concentration is carried out in water. Air is also used in some cases (air tables) but thanks to its higher density, water is a better fluid to carry out the separation. The phenomena governing gravity concentration separation are the same as those governing classification (settling, elutriation and fluidization). Moreover, it is important to know that, under certain conditions, classification equipment can be used as gravity concentrators and vice versa (Kelly and Spottiswood, 1982).

Under the action of gravity and/or another force, the particles in a fluid (water) start moving to create two distinctive layers: one with the low-density particles and the other with the high-density particles. Gravity concentration equipment is divided into four groups using different separation principles. These principles are illustrated in Figure 4.14.

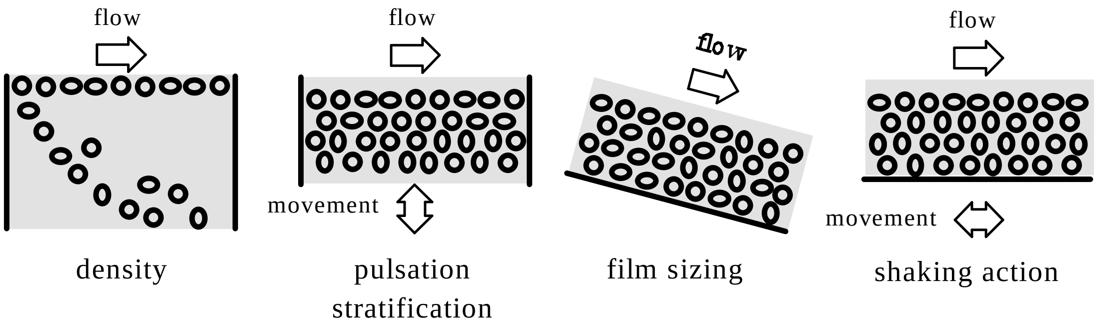


Figure 4.14 - Separation mechanisms

The mechanism involving gravity concentration uses the **density** of a fluid or pulp and the gravitational force to separate the particles into two products, the float and the sink. Adjusting the pulp density by varying the amount of solids present can modify the cut-off point (in terms of density) between the two products. The separation is then carried out by hindered settling (see section 4.2.1). Among the equipment of this type, the heavy media separation equipment is the most commonly used. However, the separation process time is considerably prolonged when the particle size becomes too fine. Under these circumstances, centrifugal force is used to carry out the separation since it can be much stronger than gravitational force The heavy media hydrocyclone and the tubular heavy media separator are also part of this group particles, and stratifies the particles according to their density (Plumpton, 1996). The jigs are the main equipment of this group.

The mechanism using **pulsation and stratification** is based on vertical pulsations in a water flow. This creates an expansion of the bed that facilitates the interaction of
The **film sizing** separators are based on the interstitial percolation action through a particle bed flowing on an inclined surface. The high-density particles tend to form the lower layer of particles that flows slowly along the incline surface. The upper layer is mainly composed of low density particles; it flows more rapidly since these particles are easily carried out by the flow and are not hindered by the friction created by the inclined surface (Wills, 1988). Among the equipment of this group, spirals differ as they add the effect of the centrifugal force generated by their specific configuration.

The horizontal **shaking action** combined to the action of the film sizing also contributes to the desired stratification. Due to the shear force it creates, the shaking action mainly produces the intergranular voids required for the movement of particles. The shaking tables are among the equipment based on such a principle.

There is equipment based on the combined action of several phenomena. Such is the case of the Knelson concentrator and the Mozley MGS separator that will be described after the previously mentioned equipment.

The use of gravity concentration equipment can only be applied to the decontamination of matrices that have solid contaminating substances. Generally speaking, these are inorganic components such a metallic, oxidized or sulphured metals. As the organic contaminating substances are generally liquid, it is impossible to use this type of equipment to concentrate them except if they are associated with a specific solid phase. For example, PCBs have a tendency to adsorb on organic matter such as wood chips.

Generally, gravity concentration equipment efficiently separates particles in a very narrow range of sizes. For this reason, it is necessary to classify the material before carrying out the gravity concentration separation. The classification is designed to remove particles whose size is not adequate for the process. The gravity concentration then separates particles according to density. It is possible to estimate the applicability of such a method using the following formula:

$$\text{Concentration criterion} = (\rho_H - \rho_M) / (\rho_L - \rho_M)$$

where ρ_H represents the density of the heavy solid phase, ρ_L the density of the light solid phase and ρ_M the density of the liquid (Weiss, 1985). Water is normally the liquid used. Table 4.3 presents the value of the concentration criterion indicating the applicability of gravity concentration with relation to the size of particles.

Table 4.3 - Gravity concentration criterion vs. size of particles

Criterion	Applicability
> 2.5	Easy separation for particle size greater than 200 mesh
2.5-1.75	Efficient separation up to 100 mesh
1.75-1.50	Separation possible but difficult up to10 mesh
1.50 to 1.25	Separation possible but difficult up to ¼ inch
< 1.25	Separation almost impossible

Source: Weiss, 1985.

The apparatus mentioned previously are presented in the next sections.

4.3.2 Heavy media separators

Heavy media separation was developed from the heavy liquid separation, detailed in section 3.3.3. However, separation by heavy liquid requires the use of heavy liquids necessitates the use of liquids whose toxicity and costs render them difficult or impossible to use on an industrial scale. The separation media used at such a scale is rather made up of a suspension of fine and heavy particles (high density) in water forming a pulp with an intermediate density to that of particles to be separated (see Figure 4.15).

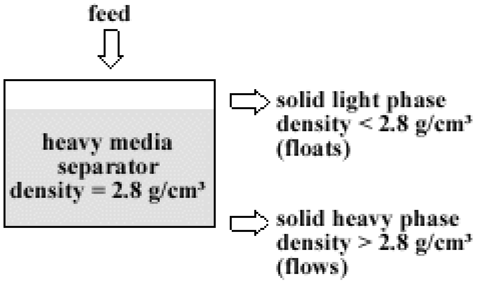


Figure 4.15 - Principle of heavy media separation

Separation is carried out by gravity acting on solids of different densities. The density of the pulp forming the separation media is a function of the size and composition of the particles suspended in the water. Magnetite and ferrosilicon are the most commonly used materials. Magnetite (density = 5.1 g/cm³) is mostly used in coal separation while ferrosilicon (density = 6.8 g/cm³) is used to process various ores. These two products are available in various particle size ranges. With magnetite, it is possible to create separation media with an apparent density of about 2.5 g/cm³. With ferrosilicon, it is possible to create a separation media with an apparent density between 2.5 and 4.0 g/cm³. The two products are easily recovered using magnetic separation; they can thus be reused (Gill, 1991).

The heavy media separation is the gravity concentration process requiring the smallest difference in densities, i.e. as low as 0.1 g/cm³ (Gill, 1991). There are two main types of heavy media separation equipment: cone separators and drum separators. The cone separators (Figure 4.16) are recommended to separate particles smaller than 10 cm; they have a high capacity of about 500 t/h.

The drum separators are recommended for separation of particles smaller than 30 cm; they have a capacity of up to 450 t/h (Wills, 1988). However, the most common application of a heavy media separator is the separation of particles with a size between 2.5 and 5 cm (Gill, 1991). The fines, such as clays, must be previously removed from the feed by screening or classification.

The hydraulic classifier (section 4.2.4) can carry out the same function as a heavy media separator when the range of particle size is very narrow, i.e. between 100 µm and 5 mm (Plumpton, 1996).

4.3.3 The heavy media hydrocyclone and tubular separator

The heavy media hydrocyclone is composed of a conventional hydrocyclone (section 4.2.3); its principle of operation is about the same. However, the material to separate has been previously suspended in an adequate heavy media (magnetite or ferrosilicon) and the hydrocyclone has been set up at an angle varying from 14 degrees to 25 degrees (Weiss, 1985). This apparatus can process particles with a size between 0.5 and 14 mm. Its capacity varies with the diameter of the equipment and can reach 100 t/h for a hydrocyclone of 0.6 metre in diameter (Burt, 1984).

The heavy media tubular separator (Dyna Whirlpool Processor) operates on the same principle as the heavy media hydrocyclone. However, its geometry is different since this apparatus only has a slightly inclined cylindrical section as shown in Figure 4.17.

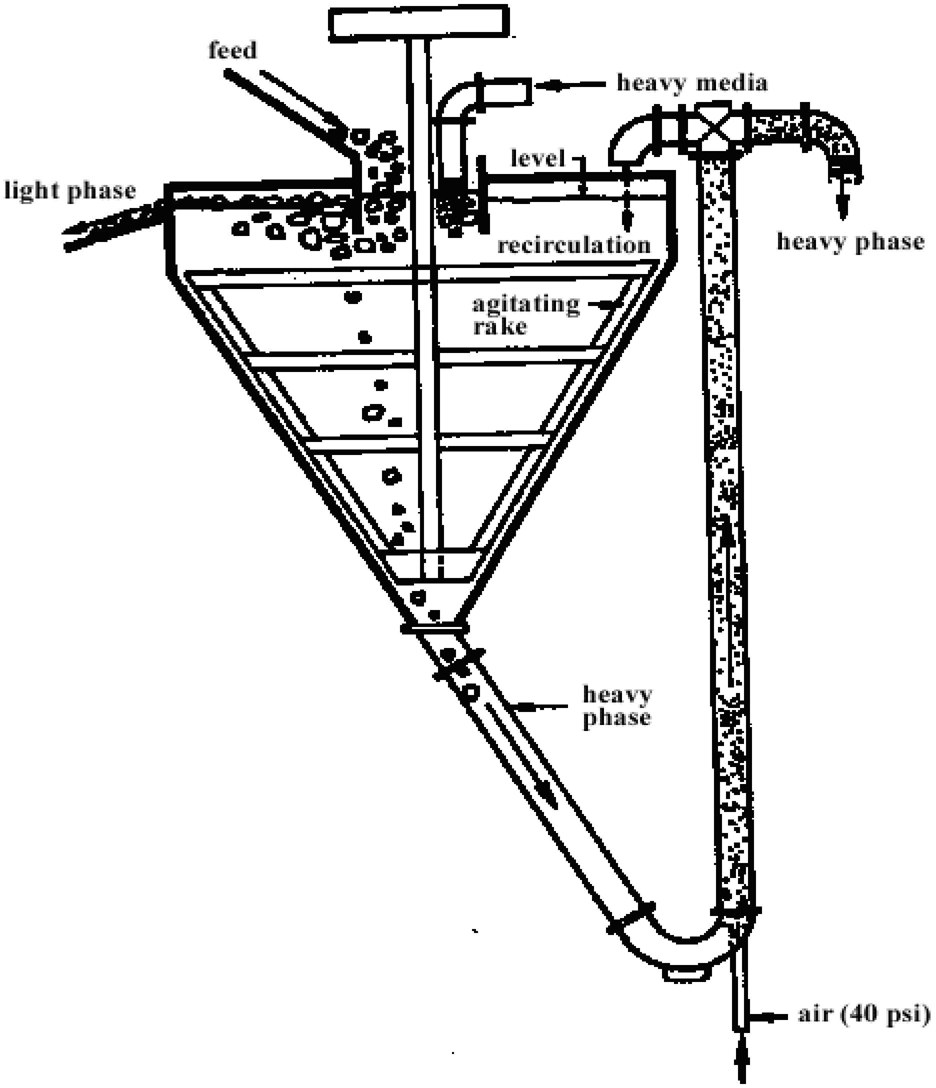


Figure 4.16 - Heavy media conical separator (source: Gill, 1991)

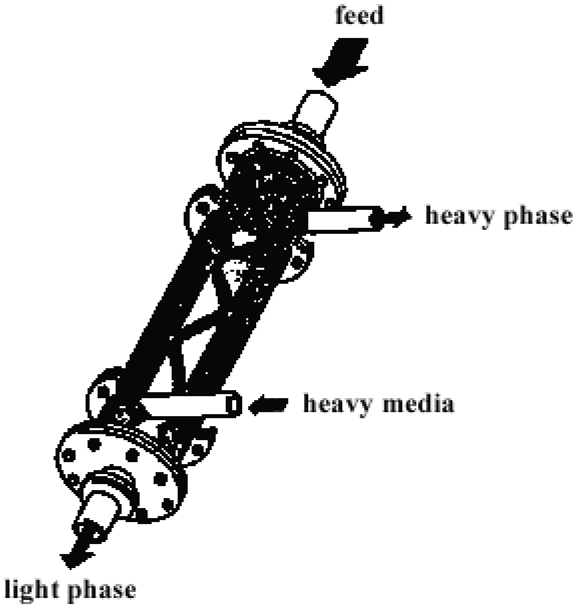


Figure 4.17 - Heavy media tubular separator (source: Wills, 1988)

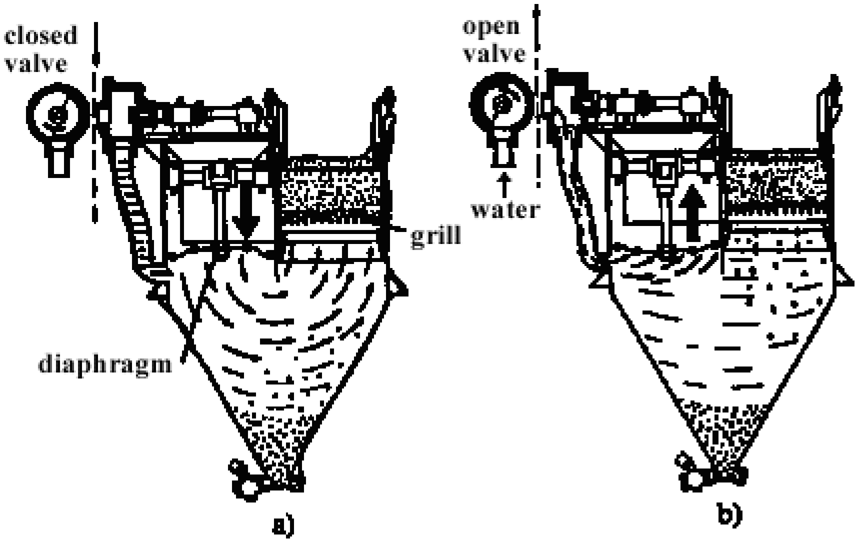


Figure 4.18 - Denver fixed-grill jig (source: Coulson and Richardson, 1991)

a) pulse, b) suction

The heavy media is tangentially introduced under pressure at the bottom of the cylinder while the material to be separated is introduced into the upper section in the same direction as the cylinder axis. Inside the apparatus, the dense media follows an ascending helicoidal trajectory creating a vortex on the entire length. The floats (density lower than that of heavy media) float at the contact of the vortex and are discharged at the bottom of the cylinder. The sinks (density higher than that of heavy media) penetrate through the heavy media to the apparatus wall and are carried out upward by the vortex movement. The mixture of heavy media and sinks is evacuated through a tangential outlet located in the upper portion. As the outlet is located close to the feed, heavy particles are rapidly removed from the apparatus, thus reducing the wear and tear of the apparatus.

The heavy media tubular separator is designed to process particles between 0.5 and 30 mm (Wills, 1988). The cylinder diameter varies between 150 and 470 mm and its length must be at least five times its diameter. The capacity of this apparatus also varies with the diameter and can reach 100 t/h (Burt, 1984).

4.3.4 The jigs

The principle of operation of jigs is based on the action of successively ascending (pulse) and descending (suction) water currents that circulate through a bed of particles. First, the bed of particles on the grid is submitted to an ascending water flow that fluidizes the particle bed and dilates it. Then the descending water flow brings the particles toward the grid and compacts the bed. Stratification of particles starts with large heavy particles at the bottom of the bed; they are then covered by small heavy particles. The dilatation of the bed allows the small heavy particles to move downward with greater ease under the effect of the descending water flow (Wills, 1988). The stratification results in two distinct layers: one of high-density particles (lower layer) and one of low-density particles (upper layer). The main phenomenon of the particle separation is thus hindered settling.

There are two types of industrial equipment: fixed-grid jigs and mobile-grid jigs. A diaphragm or a piston ensures the pulse and suction of liquid in the fixed-grid jig. In the mobile-grid jigs, pulse and suction of the liquid are created by an alternate up and down movement of the grid by a mechanical device (Blazy, 1970). Figure 4.18 shows the operation of a fixed-grid Denver jig during a) the pulse phase, and b) during the suction phase.

Jigs are normally used to process relatively large particles, i.e. between 0.5 and 200 mm (Kelly and Spottiswood, 1982). However, the lower limit can be set as low as 0.1 mm for some specific applications (Burt, 1984) but the capacity is reduced accordingly. The quality of separation is clearly superior when the range of particle size in the feed is narrow and exempt of fines (Wills, 1988). It is thus important to proceed with a pre-classification of the material, each size fraction being eventually treated adequately by adjusting the operating parameters of the jigs. The capacity of jigs can reach 25 t/h (Blaze, 1970).

4.3.5 The spirals

Spirals are simple apparatus to operate since they do not have mechanical parts except for a pump used to feed the pulp. This equipment is made of a helicoidal channel with a semi-circular section (Figure 4.19). Pulp is introduced at the upper spiral and follows a helicoidal trajectory to the bottom; during this time, there is stratification of the pulp. Its separation principle is based on the combined effects of gravity, centrifugal force, friction force and hindered settling through the flowing particle bed (Gills, 1991).

In the spiral, heavy particles concentrate in a strip located close to the inner rim of the spiral while less heavy particles have a wider trajectory resulting from their higher tangential velocity. Figure 4.20 presents a spiral section indicating where the particles concentrate depending on their density.

The wash water fed on top of the spiral brings the lighter particles to the bottom of the spiral where they are collected. The high-density particles are withdrawn in the upper portion of the spiral. These particles accumulate rapidly in the strip located close to the inner rim since their movement is barely influenced by the wash water flow. They are thus withdrawn by collectors located in the upper portion of the spiral. A mixture of mixed particles, including both light particles and heavy particles, is withdrawn by collectors located in the lower portion of the spiral. The mixed particles are normally recirculated in the spiral (Gill, 1991).

Spiral are mostly used for sandy particles with a diameter between 75 µm and 3 mm (Wills, 1988). The separation quality is higher when the range of particle size in the feed is narrow and the difference between densities of materials is equal to or higher than 1 g/cm³. Consequently, it is important to proceed with a pre-classification of the material. The capacity of lightly sloping spirals varies between 1 to 2.9 t/h and that of steeply sloping spirals can reach 2 to 6 t/h (Gill, 1991). Capacity is generally increased by multiplying the number of spirals.

4.3.6 The shaking tables

Shaking tables are made of a slightly inclined table (setting from 0º to 6º) on the shortest dimension and equipped with a mechanism that gives it a longitudinal asymmetric reciprocating motion. The amplitude and speed of this motion are also adjustable (Gill, 1991). The surface of the table is covered with longitudinal parallel

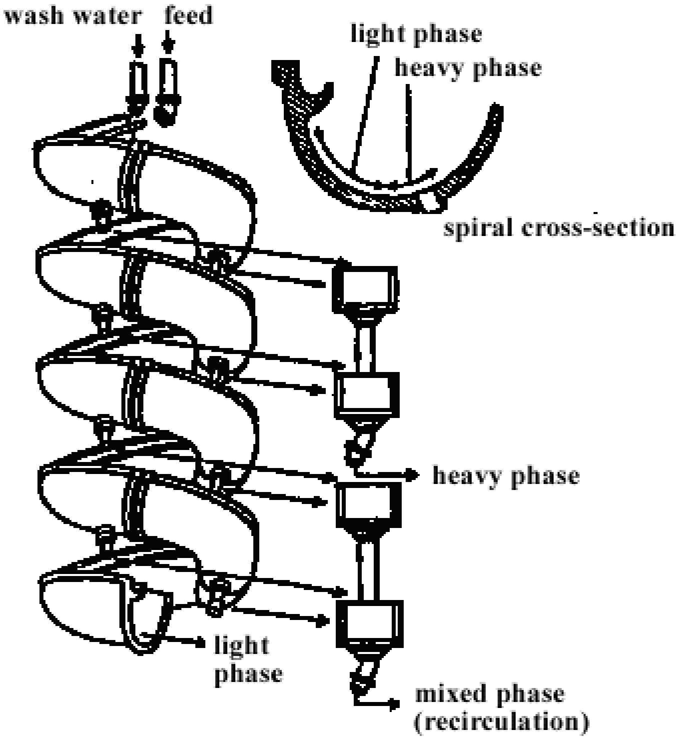


Figure 4.19 - Overview and cross-section of a spiral (source: Gill, 1991)

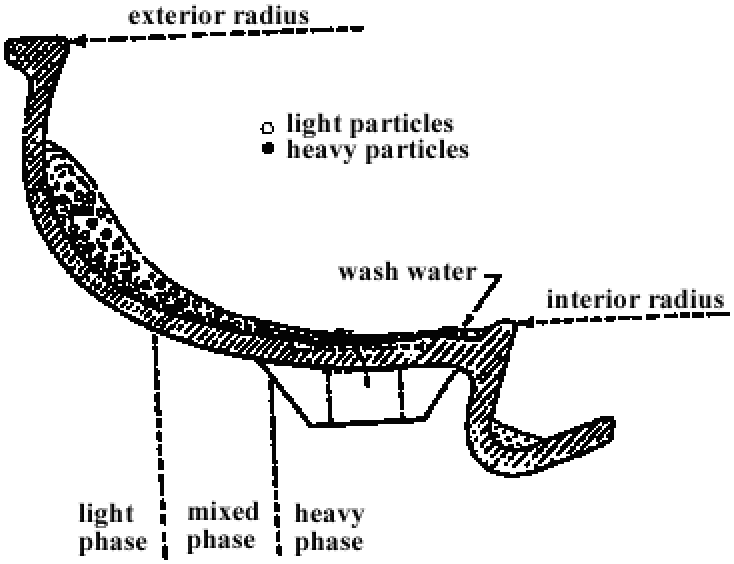


Figure 4.20 - Positioning of particles according to their volumetric mass (source: Gill, 1991)

grooves whose depth decreases progressively from the feed point to the outlet, diagonally opposite the feed point (Figure 4.21). The wash water on the table brings the light particles in the transverse direction (towards the bottom).

Stratification of particles in the grooves is produced by the shaking and by the action of the wash water flow. The shaking dilates the particle beds so the large heavy particles reach the surface of the table. The shaking forms two layers of particles: one of high-density particles (lower layer) and one of low-density particles (upper layer). The stratification is identical to that produced in jigs. The light particles are brought by the wash water to the bottom of the slope where they are collected (Blazy, 1970). The various phases detailing stratification progression are illustrated in Figure 4.22.

The heavy particles are sent longitudinally to the other end of the table due to the direction and asymmetrical nature of the shaking. Figure 4.23 shows a plan view of a shaking table with the distribution of various products recovered with relation to their density.

With adjustable collectors, the longitudinal border can recover two different products: particles with low density, and a mixture of mixed particles with small light particles. It is also possible to recover two different products along the transverse border: a concentrate of fine heavy particles and large heavy particles with mixed particles (Blazy, 1970).

Shaking tables are used to process particles with a diameter between 75 µm and 4,75 mm (Gill, 1991). Their capacity varies mainly according to the size of the particles to separate. For example, the capacity of a Wilfley table is about 4 t/h for grains of 2.5 mm and about 0.4 t/h for grains of 100 to 400 µm (Blazy, 1970). For an efficient separation, the difference between the densities of heavy particles and light particles must be at least 1 g/cm³ (Weiss, 1985).

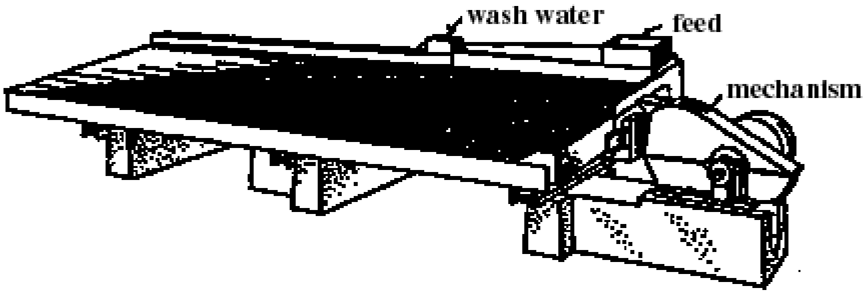


Figure 4.21 - Cross-view of an agitating table (source: Taggart, 1951)

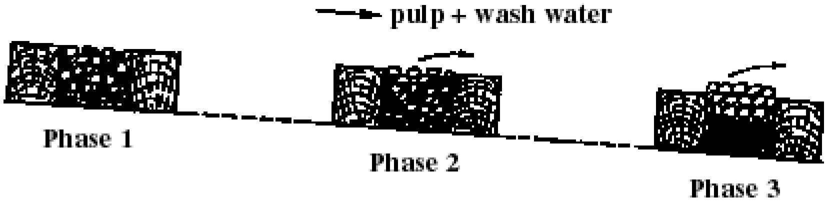


Figure 4.22 - Progression of stratification between grooves (source: Blazy, 1970)

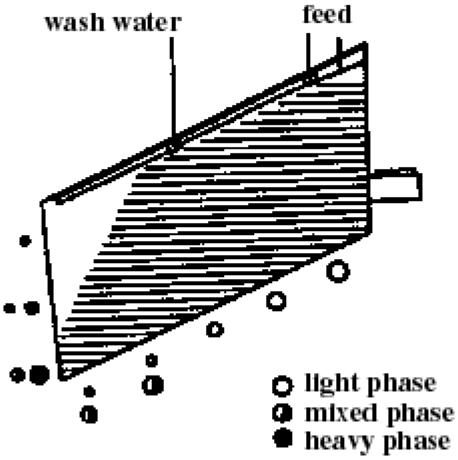


Figure 4.23 - Distribution of the recovered products with relation to their density

4.3.7 The Knelson concentrator

The Knelson concentrator is a compact apparatus using the centrifugal effect and was initially developed to concentrate gold. This apparatus is made of an exterior wall and an interior perforated wall allowing the passage of water jets (Figure 4.24). The rotation axis is hollow in order to bring water to the inside wall. The inside surface of this wall is made up of horizontal strips designed to hold heavy particles. The high rotation speed can develop a centrifugal force up to 50 times the gravitational force. The combined action of the centrifugal force and the water jets creates a fluidized bed which captures the heavy particles (Wills, 1988). The terminal settling velocity being too low, the light particles are not captured by the fluidized bed but are caught by the water flow.

The Knelson concentrator was used up to now for the concentration of ultra fine gold particles, for the concentration of iron and for the preparation of coke (Knelson, 1992) but can easily be used for environmental applications. This type of apparatus is appropriate to process fine particles with a diameter between 10 and 100 µm. However, its capacity is rather low and it cannot process more than 36 t/h (Knelson, 1992). There are two types of apparatus whose principle of operation is similar to the Knelson concentrator: the Superbowl concentrator and the Falcon concentrator. However, their operating conditions and applications vary slightly.

4.3.8 The Mozley MGS separator

The Mozley MGS separator is a recently designed equipment to process fine particles. It can be compared to rolling up the horizontal surface of a conventional shaking table (see section 4.3.6) inside a slightly inclined cylinder and to impart a rotary motion that creates a centrifugal force much higher than the gravitational force. The separation is carried out by the combined action of centrifugal force and

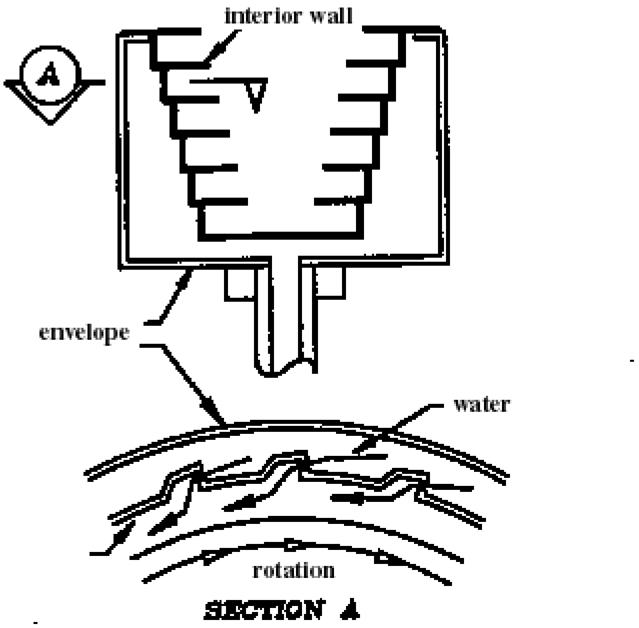


Figure 4.24 - Knelson concentrator (source: Knelson, 1992)

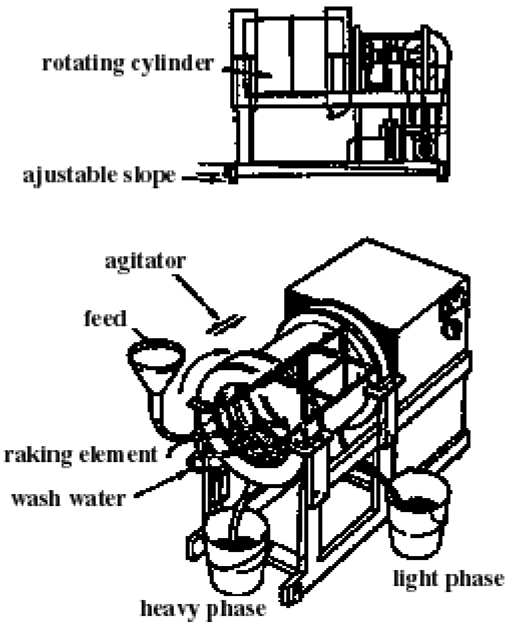


Figure 4.25 - Mozley MGS separator

the various forces produced by a sinusoidal shaking motion of variable amplitude and frequency (Traoré *et al.*, 1993). The rotational velocity of the cylinder can be modified to develop a centrifugal force 5 to 15 times higher than the gravitational force (Wills, 1988). The Mozley MGS separator is shown in Figure 4.25

The pulp is introduced almost at the centre of the cylinder and the wash water is added to the cylinder at the top of the slope. Due to the rotation of the cylinder, the pulp follows a spiral trajectory inside the cylinder. The heavy particles pass the pulp layer and rest against the cylinder wall in reaction to the centrifugal force. A scraper system sends the particles upwards. The light particles are drawn to the bottom by the wash water flow. The shaking motion stratifies the particles, thus liberating the light particles that could be caught in the layer of heavy particles (Traoré *et al.*, 1993).

The Mozley MGS separator is available in the pilot-plant format of a maximum capacity of 200 kg/h and in an industrial format of a maximum capacity of 5 t/h (Traoré *et al.*, 1993). This technology can be applied to particles with a difference in density of at least 1 g/cm^3 and with a diameter between 1 µm and 1.0 mm (according to the manufacturer's specifications).

4.3.9 Operating conditions

The use of the previously described equipment is limited by the specific conditions pertaining to the most efficient grain size for each apparatus. The following table summarizes these operating conditions and presents the maximum capacity of each equipment with a qualitative appreciation. The capacity units are in metric tons of dry solids per hour. Moreover, capacity values apply only to ore-processing and can vary for environmental applications.

Table 4.4 - Application and capacity of gravity concentration apparatus

Apparatus	Size interval	Maximum capacity	Evaluation of the capacity
Heavy media separator	2.5 to 5 cm	500 t/h	high
Heavy media hydrocyclone	0.5 to 40 mm	100 t/h	medium
Tubular separator	0.5 to 30 mm	100 t/h	medium
Knelson concentrator	10 to 100 μm	36 t/h	low
Mozley MGS separator	1 μm to 1 mm	5 t/h	very low
Jig	0.5 to 200 mm	25 t/h	low
Spiral	75 μm to 3 mm	6 t/h	very low
Shaking table	75 μm to 4.75 mm	4 t/h	very low

4.4 Flotation

4.4.1 Basics

Flotation is, without a doubt, the most important process among the various techniques used in ore-processing. This versatile technique can process several complex ores (lead-zinc, copper-zinc, …), sulphides (copper, lead, zinc, …), oxides (hematite, cassiterite, …), oxidized minerals (malachite, cerusite, …) any non-metallic ore (fluorite, phosphates, carbon, …). Thanks to flotation, it is possible to concentrate economically lean ores when concentration by gravity concentration techniques would not be profitable (Wills, 1988).

Environmental applications of flotation are very large. Most of inorganic contaminants of metallic nature (copper, zinc, …) can be concentrated by flotation. Moreover, the hydrophobic organic contaminants such as petroleum hydrocarbides (HC_x), the polycyclic aromatic hydrocarbons (PAH) and the polychlorinated biphenyls (PCB) can be concentrated by flotation. One of the next sections will deal with that application.

Flotation is based on hydrophobic and hydrophilic properties of solid surfaces. These properties can be natural or stimulated using the appropriate reagent added to the water. When air is introduced as small bubbles in such an environment, it produces a selective transportation of hydrophobic particles. Particles with hydrophobic surfaces get attached to the air bubbles when colliding with them (Figure 4.26). This phenomenon is due to the great affinity of hydrophobic surfaces for air, which by nature is non-polar. Air bubbles bring these particles to the surface of the pulp where they form a loaded froth. However, the particles with hydrophilic surfaces do not bond with air bubbles and remain in suspension in the pulp (Blazy, 1970).

Flotation products are the concentrate and the tailings. The froth layer floating on top of the liquid and loaded with contaminating substances is the concentrate. The remaining pulp is the tailing and is composed of the decontaminated matrix.

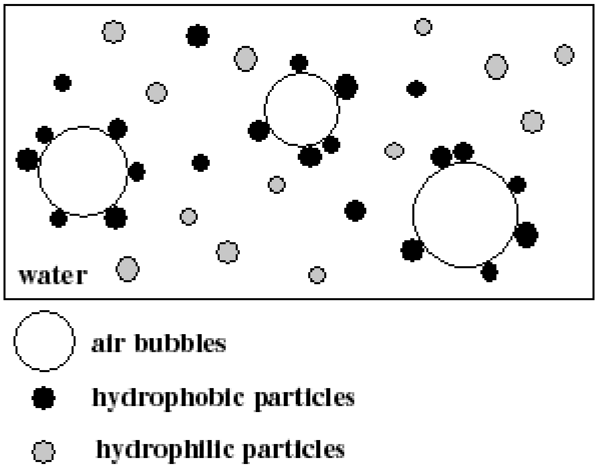


Figure 4.26 - Fixation of particles with hydrophobic surfaces to air bubbles

The pulp must be prepared adequately according to the substances to concentrate. This preparation mainly consists in adding various agents. Frothers, collectors, depressors and activators are flotation reagents. The froth stability is assured by the frothers. The collectors are designed to adhere to surfaces to make them hydrophobic while the depressors make the surfaces hydrophilic. The activators alter the surfaces of particles to make them more susceptible to the action of a collector. The activity of most of these reagents depends on the pH in the environment. It is thus important to correct the pH value with relation to the reagents used.

The main types of flotation equipment are the flotation cell and the flotation column. Flotation circuits also comprise conditioning tanks and attrition cells that prepare the pulp. Of course, pumps are required to transport the pulp from one equipment to the other. The specifications of these types of equipment are detailed in the next sections.

Flotation can be used to process particles with a diameter between 5 and 212 µm. However, for light minerals such as carbon, the upper limit is raised to 1.7 mm (Gill, 1991). The upper limit is dictated by the capacity limit of the bubbles to lift a weight. At equal density, flotation of large particles requires much larger bubbles than the flotation of small particles (Charles and Woodcock, 1984). This limit is also dictated by the detachment of large particles from the bubble to which it was affixed. This detachment is caused by the friction force between water and the solid during the lifting of the bubble/particle complex. Large particles create much more friction than smaller particles since their surface is larger. Bubble diameter is a very important characteristic since it also determines the available surface for the adhesion of hydrophobic particles. The total available surface increases with the reduction in bubble diameter.

Consequently, it is important to classify the pulp before flotation. Moreover, the presence of ultra-fine particles has a negative effect on flotation. Their presence can create two phenomena: an increase in collector consumption and entrainment. Due to their very high specific surface, the small particles have a considerable effect on the consumption of collector. The entrainment can be translated by the presence of undesirable very fine hydrophilic particles in the froth. These particles are accidentally carried up since they are very sensitive to turbulence created by the lifting of air bubbles.

4.4.2 Preparation of the pulp and flotation reagents

The pulp must undergo a certain preparation before flotation. In ore-processing, the crushed ore is normally combined with water to form a pulp containing between 5 and 50% of solids on a mass basis (Gill, 1991). Various flotation agents are previously added to the pulp so that its properties can correspond to the appropriate conditions for efficient flotation.

The pulp must be free of all agglomerates. As flotation is a surface phenomenon, the surfaces must be totally free. The first preparation stage is thus the dispersion of particles using dispersants when necessary. The pulp is introduced in an agitated conditioning tank to ensure material homogeneity. The dispersants are usually added in this tank or injected in the tank feed pipe. Figure 4.27 shows an example of a conditioning tank.

An attrition cell can sometimes replace the conditioning tank when a more violent agitation is required. The attrition detaches the fine particles from the larger ones and cleans the particles of the contaminant layer by friction of the particles. In ore-processing, attrition is carried out to liberate the surface of its oxidation layer. The equipment is composed of a reservoir with two stirring axes on which are fastened two impellers (Figure 4.28). The rotational speed is very high to ensure intense agitation. For the attrition to be effective, pulp density must be relatively high. Several conditioning and attrition apparatus are described by Weiss (1985).

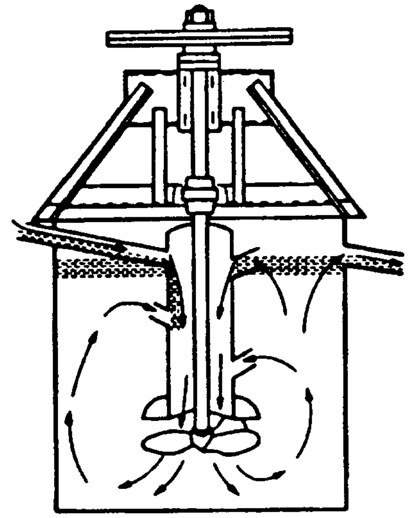


Figure 4.27 - Denver conditioning tank (source: Wills, 1988)

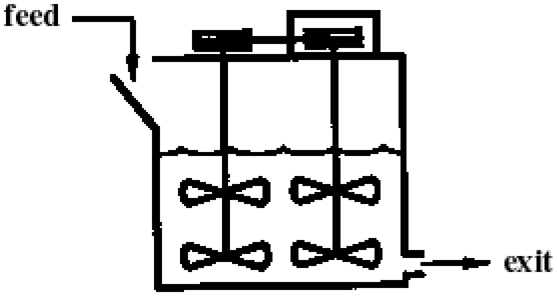


Figure 4.28 - Attrition cell

When the minerals to be concentrated are not naturally hydrophobic, flotation agents called collectors are added. The collectors are organic molecules or ions that are absorbed selectively on certain surfaces to make them hydrophobic. These are thus the most important and the most critical flotation agents. The collectors are generally heteropolar compounds. As can be seen in Figure 4.29, the polar section is absorbed at the surface of the particle while the non-polar section is oriented to the outside in order to expose a hydrophobic surface (Gill, 1991).

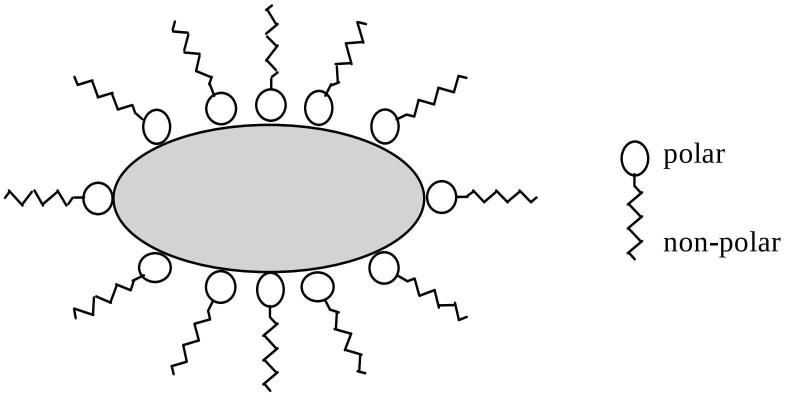


Figure 4.29 - Mode of action of a collector

The activity of collectors varies greatly according to the pH. The pH must be adjusted by adding a base or an acid. The optimal pH value depends on the nature of the mineral (or contaminating substance) that must be concentrated by flotation and on the collector used. The collector manufacturers normally prescribe optimal pH conditions. Such a precaution normally decreases considerably the collector consumption (Kelly and Spottiswood, 1982).

Frothers are organic surfactants that are absorbed at the air/water interfaces (bubbles). The molecules or frothers are made of a polar head oriented toward the water and a non-polar tail oriented toward the air (Gill, 1991). The mode of action of a frother is presented in Figure 4.30.

The two main functions of frothers are to ensure the dispersion of fine bubbles in the pulp and to maintain an adequate stability of the froth on top of the pulp. The froth must be sufficiently stable to prevent the release of the hydrophobic particles into the pulp. However, a froth that is too firm will hinder the subsequent processing of the flotation concentrate (Weiss, 1985).

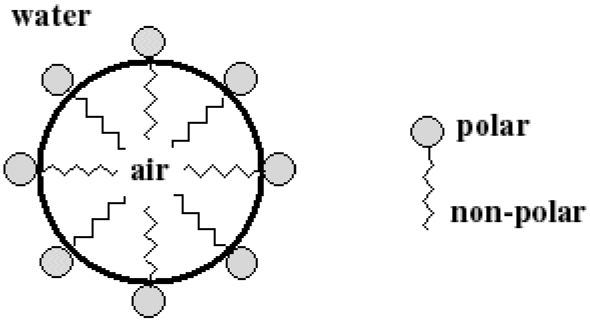


Figure 4.30 - Mode of action of a frother

Depressors are inorganic compounds whose action consists in selectively covering the surfaces to make them hydrophilic and thus decreasing their affinity for collectors. The use of depressors increases the selectivity of flotation by preventing the flotation of undesirable particles. The activity of depressors varies with pulp pH (Wills, 1988).

Activators are generally soluble salts that ionize in water. The ions in solution react with the surfaces to favour the absorption of a collector. Activators are used when collectors and frothers cannot adequately float the concentrate. As with collectors and depressors, the activity of activators varies according to pulp pH (Wills, 1988).

Several manufacturers produce collectors, frothers, depressors and activators. A list of these different products is presented in the «SME Mineral Processing Handbook» (Weiss, 1985). Information available in these tables includes: name of the manufacturer, name of the product, chemical composition of the product, favoured minerals, dosage, and flotation conditions.

The various flotation reagents can be added simultaneously in the conditioning tank. However, flotation efficiency is increased when each reagent is added one at a time (Wills, 1988). The order in which the reagents must be added is presented in Figure 4.31. This order is established with relation to the nature and the function of reagents (Gill, 1991).

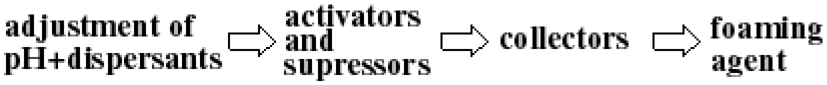


Figure 4.31 - Addition of flotation reagents during pulp preparation

The addition of reagents can be carried out using a peristaltic pump to inject the reagents in various locations of the flotation circuit such as the conditioning tanks or directly into the feed pipes. When adding a collector, a depressor or an activator, the conditioning time must be sufficiently long to allow the various chemical reactions to take place. This is current practice to decrease the flotation time (Wills, 1988).

Each matrix and each contaminating substance is a unique case. The flotation reagents and the adequate conditions must thus be studied in laboratory by testing each situation. However, manufacturers are an indispensable source of information that should be consulted.

4.4.3 Flotation cells

Flotation cells are mechanical flotation apparatus. They are composed of a tank equipped with a turbine, baffles at the periphery ensure homogeneity of the pulp (see Figure 4.32). Air is fed into the system through the turbine axis. Aeration can be carried out autonomously because of the very rapid rotation of the turbine that creates a vacuum and draws in air. Aeration can also be produced using a low-pressure blower. Due to the action of the turbine and the baffles, air introduced into the system is violently dispersed in the pulp as fine bubbles (Gill, 1991).

Fineness of bubbles is an important characteristic since it determines the available surface for the adhesion of hydrophobic particles. The froth concentrate loaded with hydrophobic particles is recovered by overflow in the top of the cell. On paddle can facilitate the recovery of the froth. In continuous operation flotation, the tailings are drawn at the bottom of the tank. Cell flotation can be carried out at a small scale in a laboratory or can be carried out at an industrial scale. At the industrial scale, the cells are placed in series to form cell banks. An example is presented in Figure 4.33.

Pulp is introduced into the first tank where part of the hydrophobic particles are recovered in the froth. Then, the pulp is introduced into the second tank where other hydrophobic particles are recovered. The process is repeated from one cell to the other until the last cell where very few hydrophobic particles are recovered. The tailing exiting the last cell is made of the relatively decontaminated matrix. The pulp level rises from one cell to the other, which simultaneously decreases the thickness of the froth layer. The froth layer in the last cell is the thinnest since it is the one with the least particles (Wills, 1988). Flotation circuits can be composed of several flotation apparatus in series or in parallel. The terms scavenging, roughing and cleaning are used to describe the various functions of the flotation equipment.

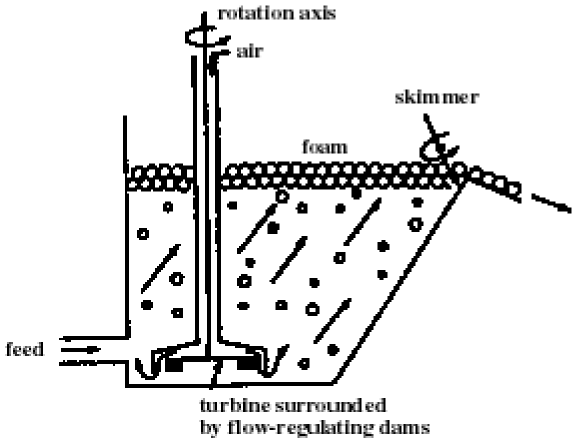


Figure 4.32 - Transverse section of a flotation tank (source: Gill, 1991)

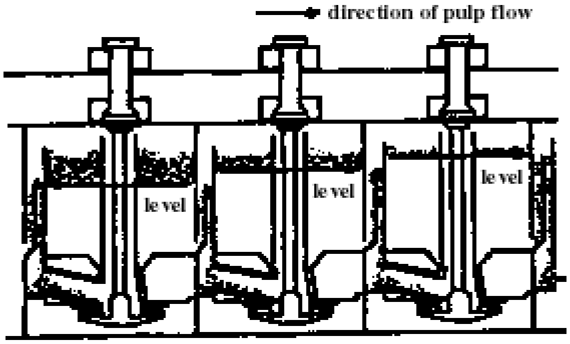


Figure 4.33 - Flotation cell bank

The capacity of flotation cell varies according to the volume of the tank and can be as high as 38 000 m^3/hour for a pulp with 25% solid at a density of 2.7 g/cm^3 (Kelly and Spottiswood, 1982).

4.4.4 Flotation columns

Flotation columns are part of the pneumatic flotation equipment. They were developed recently and are especially efficient in processing fine particles. Their purchasing and operating costs are advantageously low (Wills, 1988).

Flotation columns are mainly composed of a long vertical tube (see Figure 4.34). Air is fed into the system using a diffuser that disperses air under pressure in fine bubbles. The pulp is pumped into the column. The feed point is located one-third from the top of the column and limits the two zones characterizing the operation of the column.

The lower zone is characterized by a countercurrent motion that favours the contact between ascending air bubbles and particles. Hydrophobic particles attach to the air bubbles when they collide. The loaded air bubbles continue to rise up into the upper zone. This is the wash zone. A wash water jet is sprayed on the froth floating on top of the column. Water flowing through the froth brings the undesirable particles back down into the pulp.

The concentrate (froth) is recovered by overflow at the top of the column and the tailings (decontaminated matrix) are removed by pumping at the bottom. The underflow rate of the tailing must be higher than the feed flow rate in order to favour the circulation of the pulp towards the bottom. Such a circulation ensures the countercurrent movement in the lower section of the column.

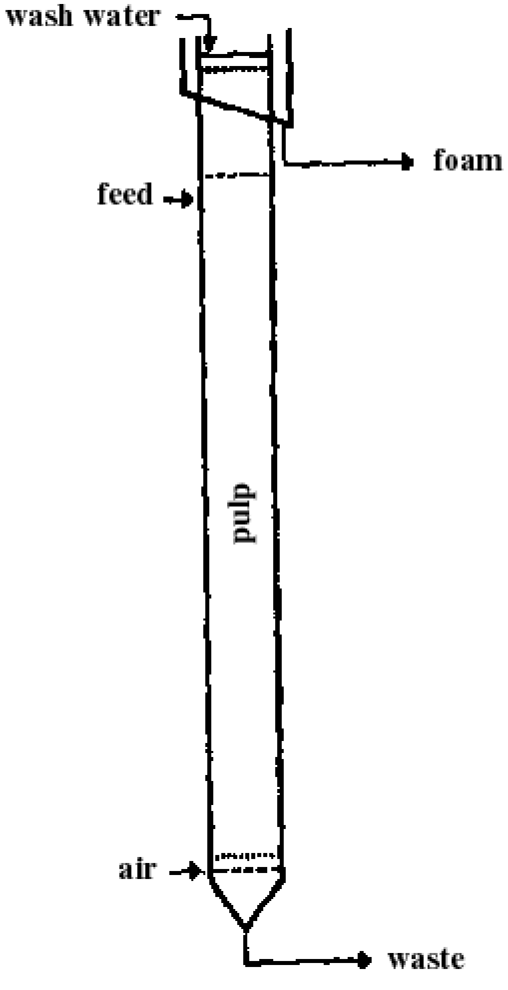


Figure 4.34 - Flotation column (source: Wills, 1988)

The flotation column has two main advantages over the flotation cell. First, entrainment is reduced by the addition of wash water. Second, the chances of collision between air bubbles and particles are increased due to the height of the column, that can rise as high as 15 metres for industrial applications (Gill, 1991). As for cells, flotation column can be carried out at a small scale and at the industrial scale. For laboratory testing, flotation columns can be manufactured at low cost.

The capacity of a flotation column is mainly a function of its volume. It can be up to 230 m^3/hour for a pulp containing 25% solid at a density of 2.75 g/cm^3 (Kelly and Spottiswood, 1982). The capacity of columns is smaller then that of cells but their efficiency is much greater.

4.4.5 Concentration of organic contaminants by flotation

The concentration of organic contaminants by flotation is not within the scope of the ore-processing field. The application of this technique requires an essential condition: the contaminating substances must be hydrophobic. It is thus possible to concentrate by flotation such substances as petroleum hydrocarbides, polycyclic aromatic hydrocarbides (PAH) and polychlorinated biphenyls (PCB). These substances have a strong affinity for air and have a tendency to absorb to the surface of air bubbles during flotation. Observing through an optical microscope, it is possible to see a thin film of contaminating substances covering the air bubbles. Consequently, the froth floating at the surface of the flotation equipment is loaded with organic contaminants. The flotation of organic contaminants can be carried out using cell or column flotation.

However, these contaminating substances are viscous and have a tendency to coat solid particles, which complicates their separation. The flotation separation must thus be preceded by a step that will remove them from the solid particles. Several processes are available to carry out this operation. They use heat, friction, ultrasound or surfactants.

One of the recovery processes of petroleum products in bituminous sands is based on the use of heat. It is called the hot water process. The pulp is heated to a temperature between 80º and 90ºC and its pH is adjusted between 8.0 and 8.5. After conditioning, the pulp is introduced in a separation cell fed with air at the bottom. Froth loaded with petroleum hydrocarbons is recovered on top (Kirk and Othmer, 1983). This technique can probably be used for PCBs.

Rubbing particles one against the other can remove the contaminated substance by friction. The attrition cells (see section 4.4.2) frequently used in ore-processing can be used for that operation. The action of attrition cells is increased because of the heat created by the friction between particles. It is important to remember that the efficiency of this equipment increases with pulp density (percentage of solids).

Ultrasound is waves of the same nature as sound but with a much higher frequency (20 kHz and more). Ultrasound is communicated to the pulp using a specially designed probe. Vibrations transmitted to the pulp create friction between particles while creating heat. The contaminating substances are removed in the same way as in the attrition cells. However, this technique is not conventional.

Surfactants are products that carry out sensibly the same role as detergents (for example washing detergents). They are designed to reduce the hydrophobic characteristic of organic contaminants to such a level that they are removed from the solid particles. The surfactant molecules are heteropolar as the frother molecules (see Figure 4.30). After removing the contaminating substances from the surfaces, the surfactants create agglomerates similar to air bubbles. The agglomerates can then be separated by flotation tanks due to their high affinity for air bubbles. The flotation of contaminants in sediments using surfactants was the object of a large study by the U.S. Environmental Protection Agency (U.S. EPA, 1994b).

4.4.6 Operating conditions

The flotation equipment only performs effectively in a narrow range of grain sizes. The next table summarizes these operating conditions and presents the maximum capacity of the equipment and a qualitative appreciation. The capacity units are in metric tons of dry solids per hour. Moreover, the capacity values apply only to ore-processing and can vary for environmental applications.

Table 4.5 - Application and capacity of flotation apparatus

Apparatus	Size interval	Maximum capacity	Evaluation of the capacity
Flotation cell	5 μm to 212 μm	1130 t/h *	very high
Flotation column	5 μm to 212 μm	70 t/h **	medium

* For a 25% solid pulp (mass basis) with a density of 2.7 g/cm^3, 3800 m^3/h ≅ 1130 t/h

** For a 25% solid pulp (mass basis) with a density of 2.7 g/cm^3, 230 m^3/h ≅ 70 t/h

It is important to underscore that if the grain size range is the same for both equipment, the efficiency of flotation columns is much higher then that of cells in the finer portion of the grain size interval. Moreover, the upper limit of the interval can increase in the case of light materials (low density) such as carbon.

4.5 Magnetic separation

4.5.1 Basics

Magnetic separation uses the magnetic properties of materials to carry out the separation. The magnetic susceptibility is the property of a material that determines its behaviour in a magnetic field. Based on this property, materials can be divided into three classes. The first class comprises ferromagnetic materials whose magnetic susceptibility is very strong. The second class includes paramagnetic materials that have a weak magnetic susceptibility. The third class is made up of diamagnetic materials with no susceptibility (Gill, 1991).

Magnetic separation is carried out by passing susceptible materials through a magnetic field (Figure 4.34). This field can be produced using a permanent magnet or an electromagnet. Using electromagnets has several advantages including the possibility of adjusting the intensity of the magnetic field by varying the intensity of the electrical current. Moreover, the magnetic field produced by the electromagnets can reach a much higher intensity than the field intensity created by permanent magnets (Gill, 1991).

The size and density of particles or blocks that must be separated have an influence on the processing. The separation of large heavy particles requires a much stronger magnetic field than the separation of light small particles (Gill, 1991). It is essential to underscore that the efficiency of the process depends on the liberation degree or on the purity of the materials to separate.

There are two types of magnetic separation equipment: the high intensity separators and the low intensity separators. Each category can be divided in two, i.e. the wet type and the dry type. The low intensity separators are used to separate ferromagnetic

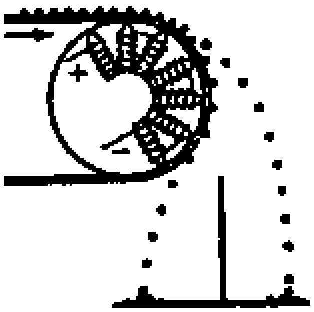


Figure 4.35 - Driving of particles susceptible to magnetic separation (source: Taggart, 1951)

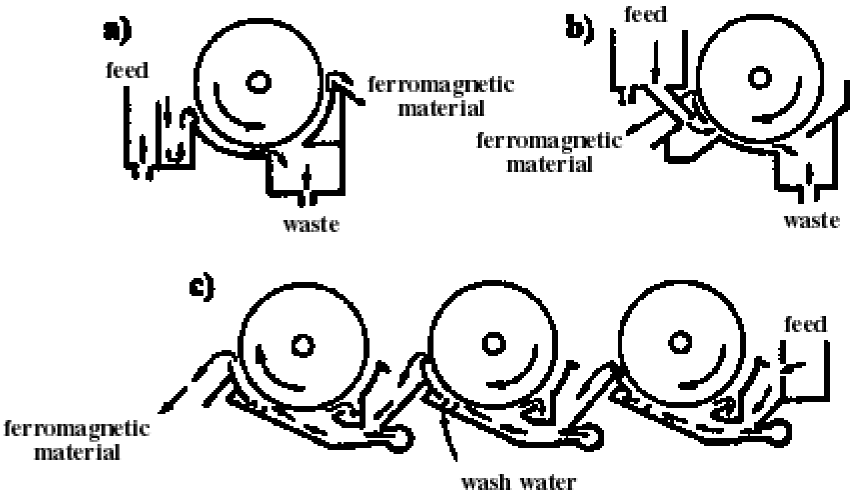


Figure 4.36 - Wet magnetic-drum separator (source: Gill, 1991)
a) concourse separator b) counter-rotation separator
c) counter-courant separator

materials and certain paramagnetic materials that are highly susceptible (Wills, 1988). The high intensity separators have very high purchasing and operating costs. The production of an intense magnetic field requires high electrical consumption. The value of processed minerals by this method justifies such costs. However, the profitability of environmental applications of such a method is doubtful. Consequently, only the low intensity separation equipment will be detailed in this document.

An example of a dry low intensity separator and an example of a wet low intensity separator will be presented in the next sections. Certain ferromagnetic materials that were separated using this equipment must sometimes undergo demagnetization. After going through a magnetic field, they have a tendency to acquire a residual magnetism that provokes agglomerates. Such a phenomenon can hinder the subsequent processing of the concentrate.

4.5.2 The magnetic-head pulley conveyor

The magnetic-head pulley conveyor is the most frequently used dry low-intensity separation equipment. It is composed of a belt conveyor equipped with a stationary magnet inserted inside one of the pulleys operating the belt. The magnetic materials are held on the belt and fall under the pulley when they exit the magnetic field. The non-magnetic materials are not affected and follow a normal trajectory (Gill, 1991). Figure 4.35 (previous section) presents a schematic of this system.

The capacity of this equipment depends on the thickness of material on the conveyor and on the width of the conveyor belt. The maximum of permanent magnet conveyors is 130.5 m/min and that of electromagnet conveyors is 150 m/min (Gill, 1991). The efficiency decreases when the speed increases and when the thickness of material increases. The humidity level of the material to separate must be as low as possible to prevent agglomerates. The use of this equipment applies to processing coarse materials with a size greater than 0.5 cm (Wills, 1988).

4.5.3 The wet drum separator

The wet drum separator is a wet low-intensity magnetic separation equipment. It is composed of a rotating drum with the lower section in the pulp. The cylinder encloses a stationary permanent magnet or electromagnet that does not follow the drum in its rotation. The separation principle in this equipment is the same as the magnetic-head pulley conveyor. There are three different versions of this apparatus: the concurrent separator, the counterrotation separator and the countercurrent separator. There are all illustrated in Figure 4.36.

The use of this equipment is limited by various grain sizes intervals. The concurrent separator is used to process large particles of minus 6.36 mm, the counterrotation separator is used to process particles of minus 1.70 mm and the countercurrent separator to process particles minus 0.21 mm. The maximum capacity of this apparatus is respectively 1875, 1500 and 900 L/min per metre of cylinder width (Gill, 1991).

4.5.4 Operating conditions

Magnetic separation equipment is efficient only in a narrow grain size interval. The next table summarizes the operating conditions and presents the maximum capacity of every equipment. Moreover, capacity values apply only to ore-processing and can vary for environmental applications.

Table 4.6 - Application and capacity of magnetic separation apparatus

Apparatus	Size limit	Maximum capacity
Magnetic head pulley conveyor (permanent magnet)	> 0.5 cm	130.5 m/min *
Magnetic head pulley conveyor (electromagnet)	> 0.5 cm	150 m/min *
Wet drum separator (concurrent)	< 6.36 mm	1875 L/min.m
Wet drum separator (counterrotation)	< 1.70 mm	1500 L/min.m
Wet drum separator (countercurrent)	< 0.21 mm	900 L/min.m

* The true capacity must be based on the thickness of material on the belt and on the width of the belt.

4.6 Electrostatic separation

4.6.1 Basics

Electrostatic separation is based on the difference in electrical conductivity between the materials to separate. This technique applies to a relatively small number of minerals such as rutile, ilmenite, zircon, tin, phosphates and certain salts. It can also apply to the separation of metallic particles in sand (Gill, 1991).

There are two types of electrostatic separators: the electrostatic separators and the electrodynamic separators (also called high-tension separators). Only the electrodynamic separators will be detailed in this document since they are the most commonly used types of equipment. However, the separation principle is relatively the same for both pieces of equipment.

The electrodynamic separator is composed of a positively charged grounded cylinder, a negatively charged ionic electrode and a negative static electrode (Figure 4.37). The particles in the feed fall on the cylinder and go through a mobile ion beam from the ionic electrode. The particles with a low electrical conductivity acquire a strong surface negative charge and remain stuck to the surface of the cylinder. The conductive particles don't acquire the charge and follow a normal trajectory. This trajectory brings them into the attraction field of the second electrode (the static electrode), which is designed to bring the conductive particles away from the cylinder in order to increase the selectivity of the separation. These particles then fall by gravity at a good distance from the cylinder. The non-conductive particles remain stuck to the cylinder during the process. A brush located opposite the electrodes detaches and recovers these particles.

The maximum capacity of this equipment is 1.5 metric tons of dry solids per hour and per metre of cylinder width (Gill, 1991). Thus electrodynamic separators do not have a high capacity. Moreover, this capacity value applies only to ore-processing and can vary for environmental applications.

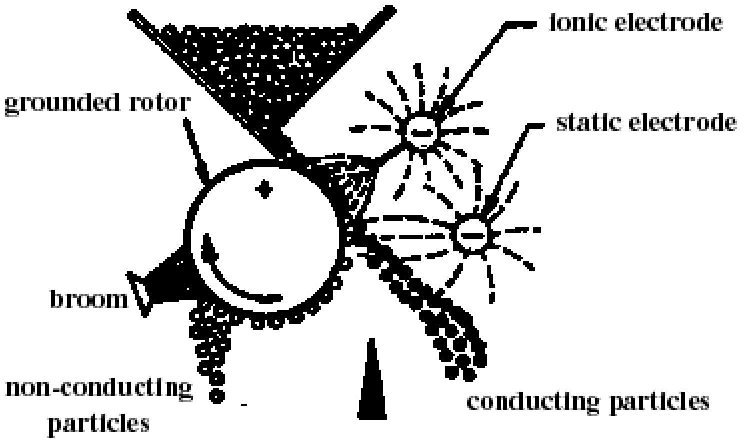


Figure 4.37 - Electrodynamic separator (source: Gill, 1991)

4.6.2 Operating conditions

The use of electrostatic separation equipment is appropriate for particles between 60 and 500 µm. However, the capacity decreases considerably for particles of 75 µm and less (Wills, 1988). An electrostatic separation operates under a mandatory condition: the material to process must be completely dry since the presence of humidity alters the behaviour of particles (Taggart, 1951). The separation of metallic particles in sand is probably the most advantageous environmental application of electrostatic separation.

Chapter 5

Selection of the Appropriate Technology

Characterization using the ore-processing approach gives invaluable information for the selection of equipment and the design of a flow sheet. This information includes size of particles, their density, their surface properties, the liberation degree of the contaminating substances, the ferromagnetic properties and the electrical conductivity of the contaminating substances present. The application of the ore-processing equipment detailed in the previous chapter requires special conditions pertaining to the information obtained through characterization. The specific requirements for the application of the various technologies are detailed.

Moreover, each matrix (sediment, soil, and sludge) has specific characteristics that bring constraints and influence the selection of processing equipment. These constraints also have repercussions on the sampling procedures and will be reviewed in this chapter.

From the information gathered through characterization and the specific requirements of each technology, it is possible to design a strategy to select the appropriate ore-processing equipment.

The pre-treatment stages (screening and classification) and the subsequent stages (dehydration, processing the wastewater and tailings) that are required are then determined according to the selection of the equipment. By combining all these elements, a preliminary flow sheet is obtained. With laboratory testing and pilot plant testing, it is possible to check and optimize the performance of this flow sheet. The information obtained after these two stages can lead to a summary evaluation of the costs related to the decontamination project.

5.1 Specific requirements for each technology

5.1.1 Gravity concentration

Gravity concentration uses gravity to separate particles of different masses. The mass of a spherical particle depends on its diameter and on the density of the material composing the particle. Consequently, the application of gravity concentration is a function of particle size. The size must be between 1 µm and 5 cm. Moreover, the materials to separate must present a difference in density of more than 1 g/cm^3. The species to separate must also be in a free form, i.e. they must not be associated with other species or with the matrix. When a grain is composed of two different species, its density varies with relation to the proportions of each species and corresponds to an intermediate value to that of the distinct species. A high liberation degree facilitates separation by ensuring a clear differentiation between grain densities.

5.1.2 Flotation

Flotation concentration is based on hydrophobic and hydrophilic properties (natural or stimulated) of the contaminant surfaces. These surfaces must thus be totally or partially free. The stability of the particle/air bubble complex depends on the particle size. The large particles (diameter greater than 212 µm) have a tendency to detach from the bubble under the action of friction with water during the lift of the particle/air bubble complex. The very fine particles (diameter smaller than 5 µm) are extremely sensitive to the turbulence created by the lift of the air bubbles. Parasitic flotation is often caused by these fine particles.

5.1.3 Magnetic separation

Low-density magnetic separation requires that the materials to separate have adequate ferromagnetic properties. If this condition is not met, magnetic separation can not take place. Moreover, the liberation degree must also be high. There is no separation when the material to separate is entirely made up of grains that include both ferromagnetic species and non-ferromagnetic species. Moreover, magnetic separation does not apply to fine particles with a diameter smaller than 75 µm. For smaller diameters, the drag force of the pulp exceeds the magnetic field force and the fine particles are dragged by the pulp (Kelly and Spottiswood, 1982).

5.1.4 Electrostatic separation

The application of electrostatic separation depends on the presence of a difference in electrical conductivity between the materials to separate. Moreover, the conductive species must not be enclosed or associated with insulating species (a high liberation degree is required). The appropriate grain size for this type of separation is between 60 and 500 µm. The upper value is limited by the weight of particles. The behaviour of fine and conductive particles (diameter lower than 60 µm) is influenced by the surface charge acquired by the non-conductive particles. This influence leads to conductive non-conductive particles dragging fine particles. Finally, the materials to separate must be completely dry.

5.1.5 Summary of requirements

The application of various ore-processing methods requires certain special conditions; Table 5.1 summarizes these conditions.

Table 5.1 - Summary of specific requirements for the various ore-processing technologies

Property	Gravity concentration	Flotation	Magnetic separation	Electrostatic separation
Particle diameter	1 µm to 5 cm	5 to 212 µm	> 75 µm	60 to 500 µm
Difference in density	> 1	n.a.	n.a.	n.a.
Liberation degree	high	medium	medium	high
Surface properties	n.a.	high	n.a.	n.a.
Ferromagnetic properties	n.a.	n.a.	high	n.a.
Electrical conductivity	n.a.	n.a.	n.a.	high

n.a. not-applicable

5.2 Constraints relative to various matrices

5.2.1 Sediments

Sediments are often characterized by a very fine grain size. Results of grain size analyses must often be considered when selecting the equipment. Moreover, the presence of organic matter in the lake and river sediments can be important if they come from heavy sedimentary zones (very low water flow). Contaminants generally have a great affinity for organic matter and can absorb on it. The organic matter can be easily separated because of the considerable difference between the density of organic matter and that of the sedimentary matrixes.

5.2.2 Soils

Soils are characterized by their heterogeneous chemical nature, mineralogical composition and grain sizes. The distribution of contaminants can thus also be heterogeneous. As for sediments, the presence of organic matter must be taken into account.

5.2.3 Sludges

Sludges are characterized by a great variability in composition according to the type of industrial activity that generates them. The grain size can cover a wide range and the presence of very fine particles and colloidal particles can cause processing difficulties since the equipment previously described does not cover that range of particles (diameter lower than 1 µm).

5.3 Strategy for elaborating a flowsheet

5.3.1 Selection of equipment

The selection of appropriate ore-processing equipment is based on the information gathered from characterization using the ore-processing approach. Figure 5.1 states this information and the importance of representative sampling.

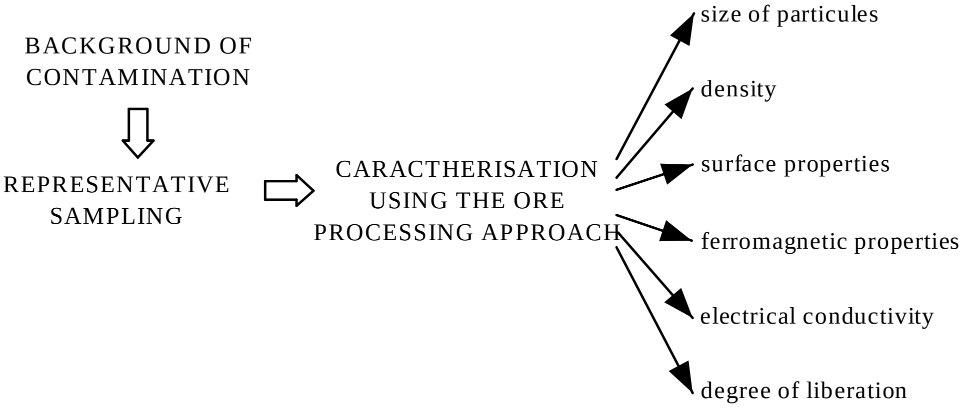


Figure 5.1 - Information obtained through characterization using the ore-processing approach on a representative sample

The information must be analyzed in a specific order. Consequently, Figure 5.2 shows the strategy to follow when selecting the type of ore-processing equipment. The first point to consider in the decisional process is the liberation degree of contaminating inorganic substances. If these substances are not free, the ore-processing equipment can not be used and other techniques must be determined. However, it is possible in some cases to crush and/or grind the material in order to increase the liberation degree. If the substances are free, then the size of particles must be considered. When the material is mainly composed of very fine particles (diameter < 1 µm), using the ore-processing equipment is not appropriate. If that is not the case, the type of equipment to be used can be based on the different grain size fractions that were identified.

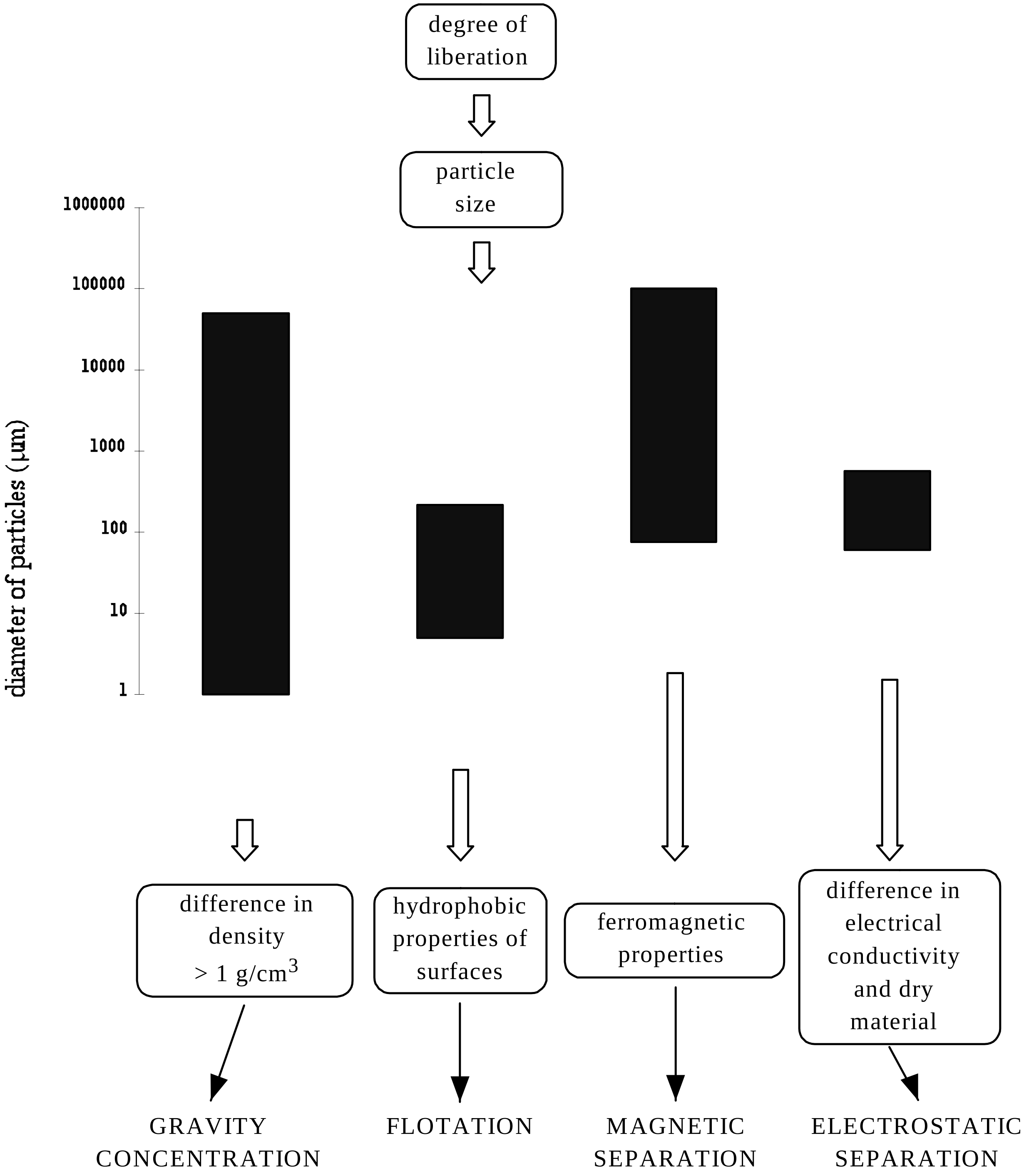


Figure 5.2 - Strategy for selecting ore-processing equipment

The difference in density, the hydrophobic properties of the surfaces, the ferromagnetic properties and the difference in electrical conductivity must be successively considered if several types of equipment can be used.

At the end of this selection process, it is possible that several types of ore-processing equipment can be appropriate to carry out the decontamination. One must then take into account the economical factor in order to select the most appropriate type of equipment.

Generally speaking, gravity concentration equipment is favoured among the other types of equipment due to their low cost (purchasing and operating). Moreover, only flotation can be used for the decontamination of organic substances of hydrophobic nature such as petroleum hydrocarbone and polychlorinated biphenyls (section 4.4.5).

When the material to process has a wide grain size range, it is often useful to proceed with classification of the material. The most important grain size fractions (2 to 4) are first identified by grain size analysis. Then, the types of appropriate ore-processing equipment are selected for each identified size fraction.

Once equipment has been evaluated and identified (gravity concentration, flotation, magnetic separation or electrostatic separation), select the appropriate equipment is selected in relation to grain size, capacity and desired performance are selected (Tables 4.4, 4.5 and 4.6).

5.3.2 Elaboration of the preliminary flowsheet

It is possible that the characterization results using the ore-processing approach show that the coarse fraction of a material is barely or not contaminated. If such is the case, processing must be preceded by a screening to separate this portion of material that must not be processed. The screening equipment is selected in relation to the cut-off point desired and the grain size of material (Table 4.1).

As seen in the previous section, in most cases, the material must be separated by classification into several grain size fractions. As for screening equipment, the classification equipment must be selected with relation to the grain size of the material, the cut-off point, the capacity and the desired performance (Table 4.2).

The products obtained after processing are composed of a tailing comprising the decontaminated matrix and one or several concentrates of contaminating substances. These various products must sometimes by dehydrated for certain specific reasons (transportation, disposal, and reclamation). Thickening in basins, filtration and centrifugation are among the available dehydration techniques. However, the water obtained from dehydration could be contaminated and should, if such is the case, be also treated. The process waters can also be recirculated. Dehydration, processing and recirculation of process waters not detailed in this document since there is already abundant literature on them (Ramalho, 1983, Degremond, 1989, Coulson and Richardson, 1991, Wills, 1992, Centre St-Laurent, 1994 and U.S. EPA, 1994a).

The concentrated contaminants may sometimes be valuable when they contain an appreciable amount of valuable metals (gold, silver, copper, …) or combustible matters (petroleum hydrocarbons). However, each case must be studied to determine if the reclamation is profitable since the concentrate must often undergo cost by processing first. For example, a concentrate of inorganic contaminants containing metals such as gold, silver or copper can be sent to a contract smelter. In return, an appreciable amount of money can be made based on the value of metals. However, this amount may be reduced if impurities (bismuth, cadmium, arsenic, etc …) are present in the concentrate. The benefits of such an alternative are difficult to ponder since they vary considerably according to the composition and quality of the concentrate.

Screening, classification, processing using ore-processing equipment, dehydration, recirculation and treatment of process waters are the components of the flow sheet. Figure 5.3 shows a simplified schematic of the preliminary flow sheet. This schematic shows a theoretical example since the flow sheet must be elaborated specifically for the characterized site (ore-processing approach). The electrostatic separation apparatus are not illustrated since they represents a very specific case. As this type of technology frequently requires a high cost pre-drying, the advantage of such an approach must be carefully studied to evaluate its profitability.

5.3.3 Validation and optimization of the flowsheet

Validation of the preliminary flow sheet must be carried out in laboratory and/or at the pilot plant scale. Small scale tests can be carried out for most equipment described in the previous chapter. After validation, it might be interesting to optimize the flow sheet. The data collected could then be used during the summary evaluation of the processing costs. In Quebec, the Centre de recherche minérale has a pilot plant where qualified personnel can perform the validation and optimization tests.

Laboratory tests require 50 to 100 kg of material on a dry basis and their costs vary between 10 000 and 20 000 $. The pilot-plant scale tests require about 10 tons of material on a dry basis and their costs vary between 100 000 and 200 000 $. These numbers are very approximate since they vary with the type of matrix and the complexity of the contamination (case by case).

As for the summary evaluation of costs to carry out a decontamination project, it must be based on the data obtained during validation and optimization of the preliminary flow sheet. However, a more detailed evaluation of the costs must be based on the data obtained after tests are carried out at the pilot plant scale (scale of about 1/100).

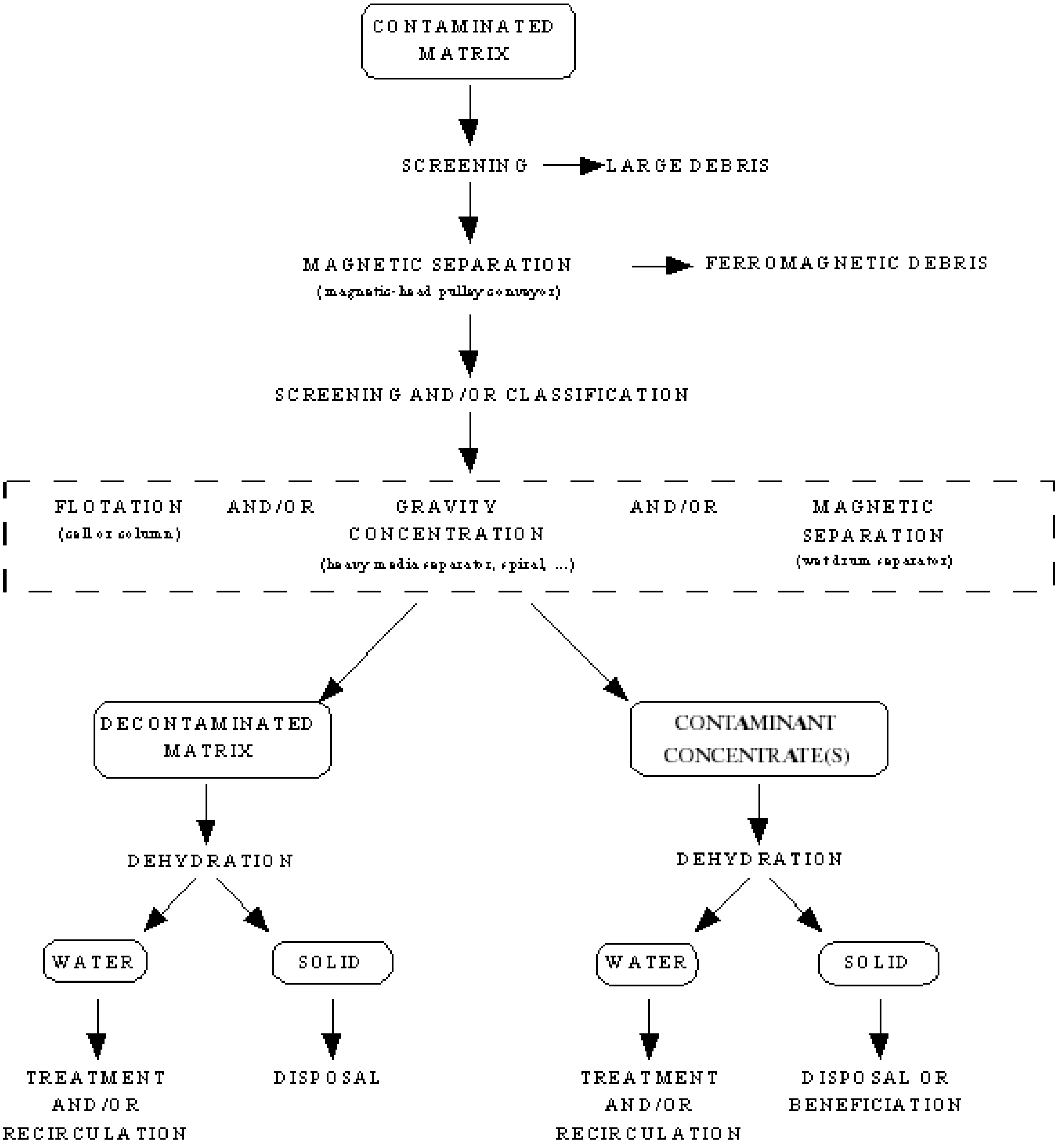


Figure 5.3 - Schematic of the simplified flowsheet

The purchasing cost of the equipment can be evaluated by contacting the suppliers directly. A list of the main ore-processing equipment suppliers is presented each year in the «Mining Annual Review» (published by the Mining Journal, London). There is also a professional listing, a buyers guide and a manufacturers index.

Chapter 6

Conclusions and Recommendations

This document is designed to help varoious decision-makers plan, design, evaluate and carry out treatability tests for ore-processing technologies (gravity concentration, flotation, magnetic separation and electrostatic separation) to extract contaminants from sediments, soils and sludges. Unlike to the usual characterization methods, those used in ore-processing provide sound information on their potential and their limitations in processing or reclamation the contaminated matrices. This information helps locate the contaminants in the various size fractions and identifies the mineralogical composition and certain physical properties of particles that the ore-processing equipment can use to extract the contaminants.

It is also important to remember that the value of characterization results depends mostly on the representativity of the samples analyzed. When the characterization results confirm the applicability of the ore-processing approach, it is then possible to design a preliminary flow sheet that will then have to be validated using laboratory testing or pilot plant testing. The designed flow sheet is only valid for the site that was characterized. Any extrapolation of the applicability to another site must always be confirmed by characterization and validation using small-scale testing.

In addition to the easy and economical decontamination of soils, sediments and sludges, ore-processing techniques can also be applied to the treatment and reclamation of municipal, industrial and mining waste when the contaminants are in a free form and are not agglomerated, melted or chemically bonded to the matrix.

The ore-processing technologies are applicable where:

- the targeted inorganic contaminants are not chemically associated with the matrix;
- the grain size of the material is appropriate for separation;
- the discrepancy between the values of one or many of physical properties of contaminants is large enough to allow separation.

The physical processing technologies described in this document are not applicable when the grain size of material is inferior to 1 µm for gravity concentration, 5 µm for flotation, 75 µm for magnetic separation and 60 µm for electrostatic separation. The hydrometallurgical and pyrometallurgical technologies were not detailed although the characterization methods proposed there in may be used to determine their applicability. These technologies may be applied when the grain size of materials is lower than the previously mentioned limits.

Characterization by the ore-processing approach applies exclusively to the treatability of various matrices using ore-processing techniques. It is not designed to evaluate the environmental risks and other such studies (environmental monitoring).

The following recommendations are based on this document:

- the objectives of the projects must be clear since they have a large influence on the volume of sample to collect. The quality of material required for a characterization is small with relation to the amount required for treatability tests at the laboratory or pilot plant scale;;

- special care must be given to the representativity of samples;

- before proceeding with analyses, the laboratories must know the history and nature of the contamination since these two parameters have a great influence on the selection of the analytical methods;

- it is preferable to consult specialists (mineralogists, metallurgists) to carry out the characterization studies and the various treatability testing. University departments (mines and metallurgy) and the research centres normally employ these kinds of specialists;

- a reasonable evaluation of costs related to a decontamination project (by the ore-processing approach) must be based on the data acquired from tests at the pilot plant scale (about 1/100 of the targeted industrial scale).

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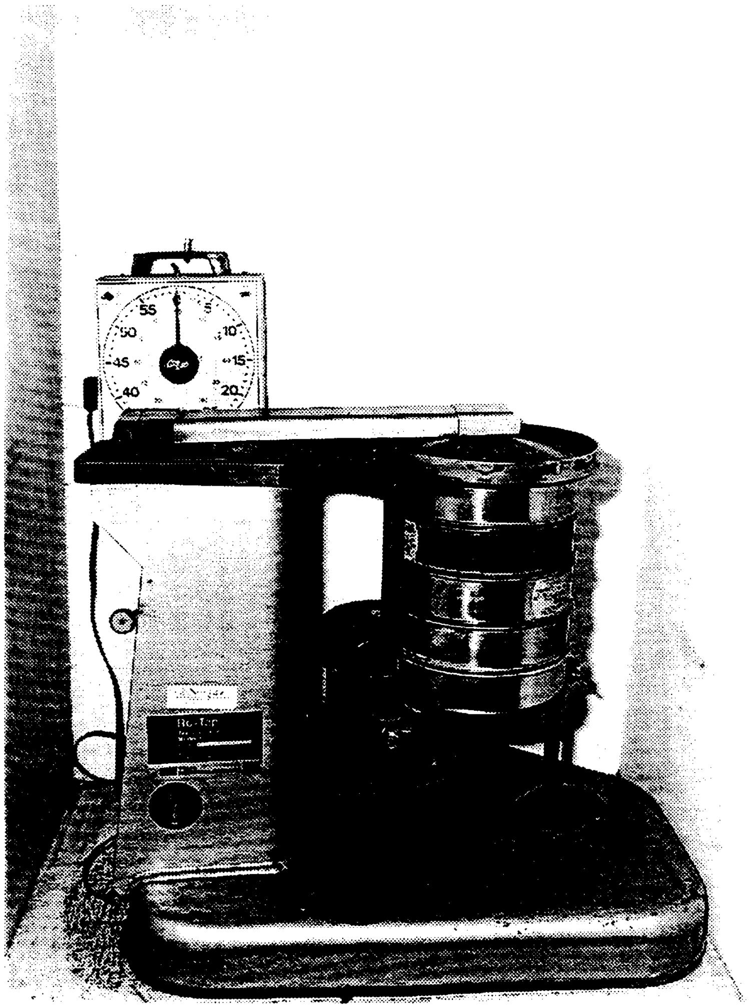
Annexe A

Table of the complete sieve series

ASTM standards series	Tyler American series (mesh)
8,0 mm	2 ½
6,7 mm	3
5,6 mm	3 ½
4,75 mm	4
4,00 mm	5
3,35 mm	6
2,80 mm	7
2,36 mm	8
2,00 mm	9
1,70 mm	10
1,40 mm	12
1,18 mm	14
1,00 mm	16
850 µm	20
710 µm	24
600 µm	28
500 µm	32
425 µm	35
355 µm	42
300 µm	48
250 µm	60
212 µm	65
180 µm	80
150 µm	100
125 µm	115
106 µm	150
90 µm	170
75 µm	200
63 µm	250
53 µm	270
45 µm	325
38 µm	400

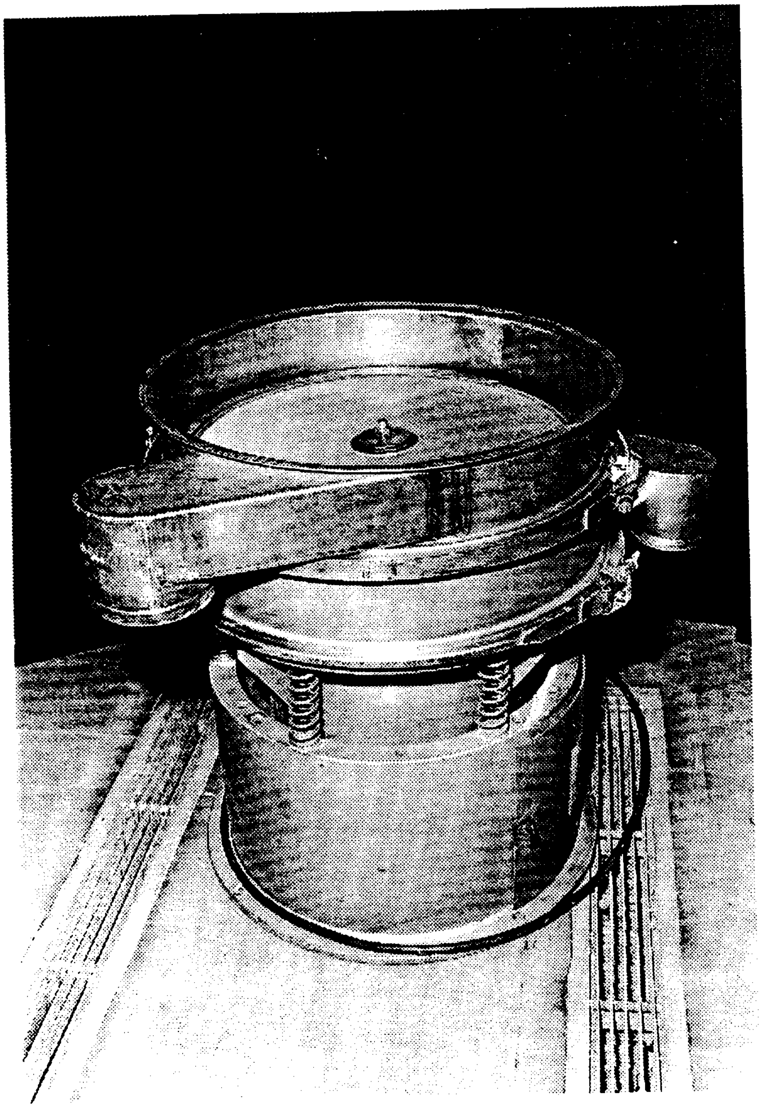
Annexe B

Multi-deck sieve shaker (Ro-Tap)


Ro-Tap

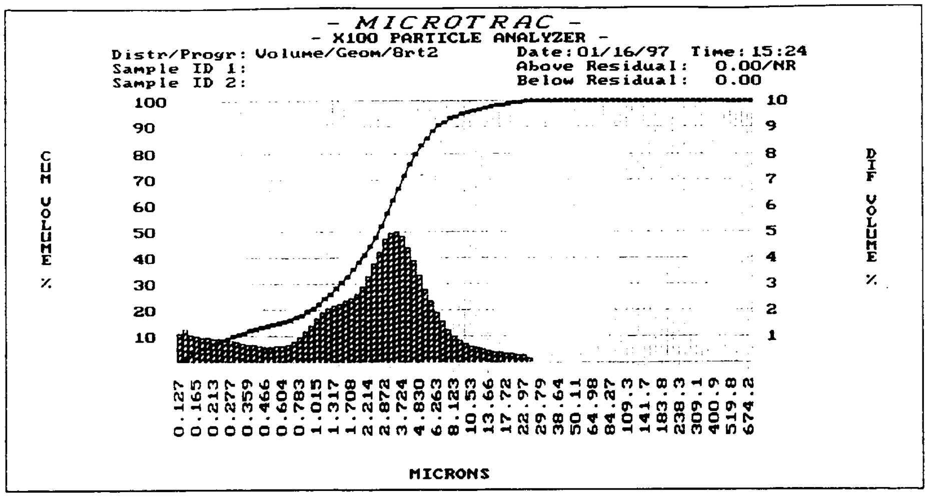
Annexe C

Wet sieve shaker (Sweco)



Annexe D

Typical sizing analysis results with the Microtrac



Distr/Progr: Volume/Geom/8rt2
Sample ID 1:
Sample ID 2:
Date: 01/16/97 Time: 15:24
Above Residual: 0.00/NR
Below Residual: 0.00

- MICROTRAC X100 PARTICLE ANALYZER -
Percent Passing Data
Version 6.01

Centre de Recherches Minerales

ASVR Parameters

Flow Rate: n/a ml/sec
Ultrasonic Power: n/a watts
Ultrasonic Time: n/a seconds

Meas/Pres #: 721 - 1 Param #2: 0.000 Lot code:
Param #1: 0.000 Param #3: 0.000 Account#:

Id #1:
Distrib. Format: Volume
Filter: On
Run Time: 30 seconds
Run Number: 3 of 3 runs
Transmission: 0.87
Laser Int: 1.001/1.001/1.009
Residuals: Disabled
Above Residual: 0.00
Below Residual: 0.00

Summary Data
dv = 0.0567
10% = 0.296
50% = 2.627
90% = 6.426
mv = 3.307
mn = 0.177
ma = 0.948
cs = 6.331
sd = 2.237

Id #2:
Date: 01/16/97 Time: 15:24
Chan. Progression: Geom/8rt2
Upper Channel Edge: 704.0
Lower Channel Edge: 0.122
Number of Channels: 100
Fluid Refractive Index: n/a
Particle Transparency: Absorb
Spherical Particles: n/a
Part. Refractive Index: n/a

ch top	%pass	%-chn	ch top	%pass	%-chn	ch top	%pass	%-chn	ch top	%pass	%-chn
704.0	100.00	0.00	80.70	100.00	0.00	9.250	94.99	0.84	1.060	22.32	1.68
645.6	100.00	0.00	74.00	100.00	0.00	8.482	94.15	1.01	0.972	20.64	1.41
592.0	100.00	0.00	67.86	100.00	0.00	7.778	93.14	1.24	0.892	19.23	1.18
542.9	100.00	0.00	62.23	100.00	0.00	7.133	91.90	1.53	0.818	18.05	0.97
497.8	100.00	0.00	57.06	100.00	0.00	6.541	90.37	1.88	0.750	17.08	0.80
456.5	100.00	0.00	52.33	100.00	0.00	5.998	88.49	2.31	0.688	16.28	0.69
418.6	100.00	0.00	47.98	100.00	0.00	5.500	86.18	2.80	0.630	15.59	0.62
383.9	100.00	0.00	44.00	100.00	0.00	5.044	83.38	3.33	0.578	14.97	0.59
352.0	100.00	0.00	40.35	100.00	0.00	4.625	80.05	3.90	0.530	14.38	0.57
322.8	100.00	0.00	37.00	100.00	0.00	4.241	76.15	4.40	0.486	13.81	0.58
296.0	100.00	0.00	33.93	100.00	0.00	3.889	71.75	4.81	0.446	13.23	0.61
271.4	100.00	0.00	31.11	100.00	0.00	3.566	66.94	4.99	0.409	12.62	0.64
248.9	100.00	0.00	28.53	100.00	0.00	3.270	61.95	4.96	0.375	11.98	0.69
228.2	100.00	0.00	26.16	100.00	0.18	2.999	56.99	4.70	0.344	11.29	0.73
209.3	100.00	0.00	23.99	99.82	0.27	2.750	52.29	4.25	0.315	10.56	0.78
191.9	100.00	0.00	22.00	99.55	0.29	2.522	48.04	3.77	0.289	9.78	0.83
176.0	100.00	0.00	20.17	99.26	0.32	2.312	44.27	3.28	0.265	8.95	0.86
161.4	100.00	0.00	18.50	98.94	0.36	2.121	40.99	2.90	0.243	8.09	0.87
148.0	100.00	0.00	16.96	98.58	0.38	1.945	38.09	2.62	0.223	7.22	0.89
135.7	100.00	0.00	15.56	98.20	0.41	1.783	35.47	2.42	0.204	6.33	0.92
124.5	100.00	0.00	14.27	97.79	0.45	1.635	33.05	2.32	0.187	5.41	0.95
114.1	100.00	0.00	13.08	97.34	0.49	1.499	30.73	2.25	0.172	4.46	0.99
104.7	100.00	0.00	12.00	96.85	0.54	1.375	28.48	2.19	0.158	3.47	1.08
95.96	100.00	0.00	11.00	96.31	0.61	1.261	26.29	2.07	0.145	2.39	1.29
88.00	100.00	0.00	10.09	95.70	0.71	1.156	24.22	1.90	0.133	1.10	1.10