

Mineral resources and geo-engineering

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ABSTRACT

Metals used in everyday life are produced from ores occurring in the Earth's crust. Geological processes are known to concentrate minerals to form ores of economic value. Mineral processing engineers concentrate these ores by mechanical and physico-chemical methods while the extractive metallurgist extracts the metals by chemical means.

Keywords: *Beneficiation, Earth's Crust, Extractive Metallurgy, Industrial Minerals, Lithosphere, Ore Deposits, Relative Abundance.*

1. Introduction

The upper 20 km thick layer of the Earth is called the crust and it is the source of all metals and industrial minerals used by man. It makes up less than 1% of the mass of the Earth and is composed of three parts:

- Lithosphere. This is the solid part accounting for about 95% of the crust.
- Hydrosphere. This is the liquid part which includes the oceans, seas, and lakes, and contributes about 5% of the Earth's mass.
- Atmosphere. This is the gaseous part and it accounts for about 0.02% of the Earth's mass.

The lithosphere is composed of three types of rocks namely:

- Igneous rocks: They result from the cooling and solidification of magma

which originates from deep within the Earth.

- Sedimentary rocks: They are formed as a result of the *accumulation of debris resulting from the erosion and weathering of other rocks.*
- Metamorphic rocks: They are formed when the minerals comprising a rock are subjected to shearing forces and high pressure.

2. Relative abundance of metals

The solid part of the Earth's crust is composed mainly of igneous rocks (Table 1) and its average composition is given in Table 2. The data in this Table are based mainly on the analysis of more than 50,000 samples of rocks (from all over the world), at the US Geological Surveys by Frank W. Clarke and co-workers

in 1904. From this information, it can be concluded that the concentration of other metals in this rock is very small. Their relative abundance in the Earth's crust was thus established (Table 3).

Table 1. Components of the lithosphere

Rock type	Weight, %
Igneous rocks	95.00
Shale	4.00
Sandstone	0.75
Limestone	0.25
	100.00

Table 2. Average composition of the lithosphere

Oxide	%
SiO ₂	59.07
Al ₂ O ₃	15.22
FeO	3.71
Fe ₂ O ₃	3.10
CaO	5.10
Na ₂ O	3.71
MgO	3.45
K ₂ O	3.11
H ₂ O	1.30
TiO ₂	1.03
CO ₂	0.35
P ₂ O ₅	0.30
MnO	0.11
	99.56

Table 3. Relative abundance of metals in the lithosphere in percentage

> 1	Si 27.7	Al 8.1	Fe 5	Ca 3.6	Na 2.8	K 2.6	Mg 2.1
≥ 0.1	Ti 0.44	Mn 0.1					
10 ⁻²	Ba 4.3	Rb 3.1	Zr 2.2	Cr 2	Sr 1.5	V 1.5	
10 ⁻³	Zn 8	Ni 8	Cu 7	Li 635	Sn 4	Nb 2.4	Co 2.3
	La 1.7	Nd 1.7	Pb 1.5	Ga 1.5	Th 1.1	B 1	Y 1
10 ⁻⁴	Ge 7	Be 6	As 5	Gd 5	Pr 5	Sc 5	Hf 4.5
	U 4	Cs 3.5	Sm 3	Ce 2.5	Mo 2.3	Ta 2.1	Dy 2
	Tb 2	Yb 1.5	Er 1.5	Ho 1.2	Sb 1	Eu 1	W 1
10 ⁻⁵	Lu 7.5	Hg 5	Tl 3	Bi 2	Tm 2	Cd 1.5	In 1
10 ⁻⁶	Se 9	Ag 2	Ru 1	Os 1	Pd 1		
10 ⁻⁷	Pt 5	Te 1.8	Au 1	Re 1	Ir 1	Rh 1	
10 ⁻¹⁰	Ra 1.3						
10 ⁻¹¹	Pa 8						
10 ⁻¹⁴	Ac 3	Po 3					

It is thus clear that before any metal can be profitably extracted from the Earth, it must have been highly concentrated by geological processes to form ores of economic importance.

3. Formation of ore deposits

Many physical and chemical processes have been going on for millions of years, and result in the enrichment of the earth's crust with certain minerals. Hence, their exploitation have become of economic importance (Table 4).

Table 4. Geological processes in transforming the Earth's crust

Process	Examples
Crystallization from molten magma	The massive magnetite deposits in Sweden and almost all the massive deposits of chromite and ilmenite.
Precipitation from hot aqueous solution of magmatic origin	Most sulfide and the cassiterite deposits in Cornwall, England.
Weathering in place	Most types of clay are the results of rock weathering, and when they remain in the place they were formed they are referred to as residual clays, e.g., bauxite. In this case, under favourable atmospheric conditions, the silica content of the clay is diminished and there is a concentration of the alumina content.
Weathering, transportation, and settling	When rocks containing heavy and stable minerals such as gold, platinum, cassiterite, magnetite, or monazite are weathered and eroded, the minerals are washed away by running water and then settle when the velocity of the water decreases, thus forming alluvial or placer deposits.
Precipitation from surface waters	Most surface waters carry some iron in solution. Under certain conditions of pH, etc., the iron is precipitated as hydrated iron III oxide (limonite), as carbonate (siderite), or oxide (hematite).
Evaporation of surface waters	During the weathering of rocks, the easily soluble substances are carried by water into lakes, seas, and oceans. Under certain conditions the dissolved substances may become concentrated to form mineral deposits of great commercial importance, e.g., the Dead Sea, the Great Salt Lake in Utah, Stassfurt deposits in Germany, etc.
Concentration by circulating waters	Small amounts of carbonates of calcium, sodium, magnesium, potassium, and iron are dissolved in water during their passage downward through the rocks. The dissolved salts may be deposited in open cavities and along fissures in the rocks. For example, magnesite deposits ($MgCO_3$) may be formed by dissolution of certain magnesium silicate rocks followed by precipitation with CO_2 .

4. Prospecting for ores

Chance has played a dominant role in the discovery of mineral deposits. Prior to the twentieth century, mineral deposits were found by wandering prospectors who were looking for visible evidence of mineralization. Valuable minerals were recognized by their various distinctive physical properties. Gold is a heavy yellow metal; galena is a dark grey, heavy and lustrous substance while magnetite is a black heavy magnetic mineral; etc. This tedious method gave way as science progressed. Once an ore deposit has been located, its size and quality are determined by sample drilling and studying the carrots obtained.

The latest radar Earth-observation satellite, Canada's RADARSAT-1 relays much information about the earth and is used by

exploration geologists. The Earth's linear structures, faults, and topographic features become clearly defined. The satellite emits electromagnetic energy towards the Earth and records the energy returned to the radar. When the radar beam interacts with the surface, it is scattered in all directions. An image is produced when the energy is reflected back to the radar. This process helps to identify hydrothermal alteration zones associated with mineral deposits, areas of sedimentation, flooded areas, old river systems, alluvial fans, rounded intrusions and other information useful for mineral exploration.

5. Mining of ores

The methods by which minerals are mined from the ground depend chiefly on the nature

and form of the deposits, and the position they occupy relative to the surface. Underground mining is mainly used for mining gold, copper, lead, and zinc ores. Open pit mining methods are mainly used for mining ores of iron, aluminium, manganese, and copper. Open pit mining is less costly compared to underground mining. The mining industry is the major consumer of explosives (used for exploration purposes). Dynamite, ammonium nitrate–fuel oil (AN–FO), and trinitrotoluene (TNT) are commonly used. Automation, robotics, tele-operation, auto-loading and guidance systems are now being applied in mining. For example, in tele-operation of trucks, cameras are mounted on the vehicles which are operated by remote control for video monitoring.

5.1. Surface mining

Water washing. The simplest and oldest form of mining is the washing of sands and gravel containing valuable minerals. In almost all such occurrences, the valuable minerals have a higher specific gravity than the bulk of the deposit. In Malaya, for example, the large deposits of cassiterite are mined by directing powerful jets of water against the face of the gravel; the released gravel is then directed through channels where the cassiterite is trapped at the bottom. In placer mining, the gold-bearing sand or gravel is washed in running water which carries away the lighter sands and stones leaving the heavy gold in the basin.

Dredging. The dredger is usually erected on the ground in a natural or an artificial pond and the gravel is excavated by a number of large steel buckets.

5.2. Open-pit mining

Ore-bodies at or near the surface are usually mined by open pit methods. Any overburden or waste rock capping the ore must be removed before mining operation commences. The material is usually removed by mechanical shovels into trucks. If parts of the deposits are too large, they are first drilled and blasted. The ore is then transported from the open pit to the beneficiation plant.

5.3. Underground Mining

One of the first essentials in underground

mining is to enter the ore body. If the topography is suitable, as on a hilly ground, a tunnel may be driven into it through the hillside. Most ore bodies, however, are reached through a vertical shaft, and in fewer cases through an inclined shaft. In underground mining, tunnels, ventilation shafts, narrow gauge tracks, elevators, etc., must be installed. Holes are drilled in the ore body, powder is inserted, fuses are made ready, and at the end of a shift the fuses are lighted and the miners depart. When the charge is fired the whole wall crumbles and falls to the floor below. Then, the next shift of miners proceed to drill further into the ore to make ready for another blast. The ore body is cut and removed as fast as it is broken.

5.4. Mining in place

This method is used to mine water soluble underground ore deposits such as potash, trona, etc. Water is injected into the bed and brine is pumped out through special holes drilled for that purpose. Mining of sulfur requires a unique case of underground mining to be in-place. In this process, hot water is run through pipes to melt the sulfur bed and the molten sulfur rises to the surface as a liquid.

5.5. Quarrying

Quarrying is a special type of mining applied to materials that are used for construction purposes, e.g., granite, marble, quartzite, slate, limestone, etc. In this case the intention is to get large pieces of certain dimensions with the generation of minimum waste without shattering the rock. For this purpose, a series of holes are drilled on the same line that are then charged lightly with a slow-burning black powder and fired simultaneously to break away a block of material. For softer rocks, no explosives are used; instead, flat pieces of steel are introduced into the holes and a wedge-shaped plug is driven down between them to split the blocks.

6. Minerals and ores

Ores are a mixture of minerals. They may be processed to yield an industrial mineral or treated chemically to yield a single or several metals. A deposit is a place where a concentration of minerals is found. If during a certain period it is economical to extract a mineral or a metal from a deposit, then such a

deposit is called an ore deposit, and the calculated quantity of metal supposed to be found in this deposit is known as a reserve. A resource today may be a reserve tomorrow; this transformation depends on two factors (Fig. 1):

- Technology. Improved technology in mining methods, mineral processing, transportation and availability of skilled labour could lead to reduction of production costs, i.e., increased feasibility of economic recovery.
- Certainty of existence. A higher degree of certainty of existence can be achieved through extensive drilling and

analysis of the core samples obtained, after an expensive operation.

6.1. Classification of minerals

Minerals may be classified into two groups: Metallic and non-metallic. Metallic minerals are the chief raw materials for the manufacture of metals. Non metallic minerals which constitute about 75% of all the minerals are so-called because they do not contain metals and lack the characteristic nature of metals such as lustre, malleability, ductility etc. Of these, about 300 are used industrially in the chemical industry, in building materials, in fertilizers, as fuels, etc. They are known as industrial minerals (Tables 5 and 6).

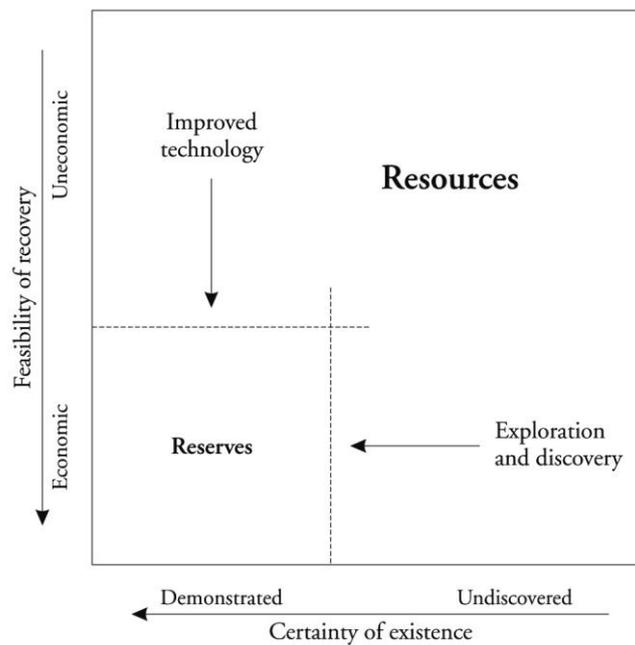


Fig. 1. Relationship between resources and reserves. Tendency increases in the direction of the arrow

Table 5. Metallic minerals for uses other than metal production

Mineral	Metal produced	Non-metallic use
Bauxite	Al	Refractories
Chromite	Cr	refractories, chemicals
Magnetite	Fe	Pigment
Zircon	Zr	Refractories
Beryl	Be	Gemstone

Table 6. Classification of industrial minerals according to their use

Industry	Minerals used	Remarks
Abrasive	Corundum Sandstone Diamonds (industrial)	
Building	Sand, gravel Limestone Gypsum	
Ceramics & glass	Clay Feldspar	
Chemical	Clay Sulfur Salt Trona Gypsum Borax Fluorite Zeolite Diatomite	Cement Sulfuric acid Alkali, chlorine Sodium carbonate Cement Hydrogen fluoride and fluorine Water treatment Adsorbent
Fertilizer	Phosphate rock Potash Nitrates	Chile is the main supplier
Fuels	Coal Lignite Peat Natural gas Petroleum Tar sands	Used to make coke Distilled into many fractions Petroleum
Insulation	Asbestos Mica	
Jewellery	Diamonds (gem) Amethyst Aqua marine	
Metallurgy (flux)	Quartz Limestone	
Pigment	Iron oxides	Yellow, red, black
Pigment filler	Clay Barite	
Refractories	Clay Magnesite Chromite	

- A metallic mineral may be used for the production of a metal, or after a minor treatment for the production of refractories or pigments. For example:
 - Bauxite, the main source of aluminium: 90% is used in the manufacture of the metal and 10% in the manufacture of refractories, abrasives, and other chemicals.
 - Chromite, the main ore for chromium, is used for manufacturing certain refractories as well as chemicals for the tanning industry.
 - Magnetite is used for iron production and as a black pigment.

- Zircon, the main zirconium ore is used for the production of specialized refractories.
- Beryl, the main beryllium ore, when occurring in large transparent crystals, is a gemstone.
- When a mineral is used for more than one purpose, then its grade and the impurities present are the decisive factors of its utilization, for metal production or otherwise. For example:

6.2. Non-metallic and industrial minerals

According to their abundance, industrial minerals can be classified into three main groups:

- Rare. These occur in small quantities, in limited areas, used in small quantities, and command a high market price. For example, diamonds, sheet mica, graphite, corundum, precious stones, and the semi-precious stones.
- Widely available. These occur in large quantities in few geological environments; they are used in appreciable amounts, and command a moderate price. For example asbestos, coal, phosphate, gypsum, kaolin, potash, salt, sulfur, talc, trona, barite, borates, feldspar, fluorite, magnesite, and diatomite.
- Abundant. These are abundant in all geological environments, used in large amounts, and are relatively cheap. For example, clay, limestone, sand, gravel, and stones.

It should be noted that some members of these groups are not minerals but ores having a geological name. For example, phosphate

rock is neither a rock nor a mineral; it is a geological name for a certain type of formation containing phosphates and gangue materials such as calcite, iron oxides, clays, etc. The major phosphate mineral of economic value in this type of deposit is apatite, which is principally calcium phosphate. Similarly, clay is a geological name for a large variety of hydrated aluminium silicate minerals, including kaolinite

6.3. Oceans and natural waters as a source of minerals

The hydrosphere covers 70% of the Earth's surface. Oceans and natural waters contain on the average 3.5% of dissolved salts. At present, sodium and magnesium are recovered from this source on industrial scale. While sodium is recovered as sodium chloride by evaporation, magnesium is usually recovered through precipitation as magnesium hydroxide by lime water. Sodium is present in 1.06% while magnesium is 0.13%.

Bromine is found in a concentration of 65 ppm; it is also recovered on an industrial scale by displacement with chlorine. Sea water also contains 0.05 ppm of iodine, an insufficient quantity to warrant promise for its recovery. However, some sea weeds absorb iodine from seawater and accumulate it in their cell structure. When they are dried and burned properly, the resulting ash contains 1.4 to 1.8% iodine. The major source of iodine, however, is from the nitrate deposits in Atacama Desert in Chile — it contains 0.2%. These nitrate deposits were the main source of nitrogen before the discovery of the ammonia synthesis process. Analysis of salts obtained by the evaporation of sea water is given in Tables 7 and 8.

Table 7. Typical analysis of salt residue obtained by evaporation of sea water

	%
Cl-	55.06
Na+	30.6
SO ₄ ²⁻	8.06
Mg ²⁺	3.7
Ca ²⁺	1.175
K+	1.1
Br-	0.186
All others	1
	100

Table 8. Composition of salts obtained by evaporation of sea water

	%
NaCl	77.83
MgCl ₂	9.44
MgSO ₄	6.57
CaSO ₄	3.44
KCl	2.11
MgBr ₂	0.22
All others	~ 1
	100

6.4. Surface and subsurface waters

Some lakes, wells, and oilfield brine contain appreciable amounts of metals (and iodine) in solution and are important sources of these metals. Examples include the following:

- Searle Lake in California contains sodium carbonate, Na_2CO_3 , and sodium borate, $\text{Na}_2\text{B}_4\text{O}_7$, in solution. The first is recovered by carbonation with CO_2 followed by crystallization of sodium bicarbonate, NaHCO_3 , while the latter is recovered by extraction with organic solvents.
- The Great Salt Lake in Utah contains 0.45% Mg from which magnesium chloride is recovered by evaporation, purified and used to prepare metallic magnesium.
- Salar de Atacama in Antofagasta, Chile, contains 1.4 g/L lithium as well as appreciable amounts of magnesium and potassium, which are recovered on industrial scale. The brine is pumped from underground and left to evaporate in ponds, then transported by railway cisterns to the plant for lithium carbonate recovery.
- The Dead Sea in Jordan contains various salts in large quantities. Sodium chloride, potassium chloride, and carnallite are recovered by solar evaporation.
- Underground waters including those separated from petroleum in oil fields are usually a source of lithium, magnesium, and other metals. For example, lithium is recovered from underground water in Silver Peak, Nevada by evaporation and precipitation.

6.5. Manganese nodules

Oceans also contain manganese, copper, nickel, and cobalt in the form of black nodules (about 10 cm in diameter), deposited on the ocean floor. These nodules are mainly manganese dioxide containing about 1% copper, 1% nickel, and 10 to 15% iron. The nodules are present at a concentration of about 12 kg/m^2 . Studies are under way to exploit this source.

6.6. Tar sands

Tar is a mixture of many organic substances,

which are separated by distillation at different temperatures. The distillation residue is pitch. The tar sands of Alberta constitute one of the largest deposits of liquid hydrocarbons in the world. The tar sands are estimated to contain 126×10^9 tons. A part of the deposit located at Athabasca is amenable to surface mining, while the major part is obtained by *in-situ* techniques. The major components of tar sands are quartz grains of about 0.2–1 mm, wetted by a layer of water which entrains silt and clay. The Bitumen surrounding the wet sand, forms a continuous phase which bonds the particle together. The average content of bitumen in the sand is about 12%; and about 2 tons of tar sand produces 1 barrel of crude oil (1 barrel = 140 kg).

Bitumen is separated from the sand by slurring tar sands with hot water at 80°C . The sand particles remain in the aqueous phase, while at this temperature the viscosity of bitumen is lowered, to dislodge bitumen from sand so that it can float on the surface. To facilitate the separation process, caustic soda is added to raise the pH to 8.5. The raw bitumen obtained is then heated and mixed with naphtha to reduce its viscosity and density, then centrifuged to separate it from the remaining solids. The diluted bitumen obtained contains about 5% H_2O and 1% solids. The solids separated at this stage contain rutile and zircon and it may be possible to recover these minerals economically. It is estimated that 94 million tons of titanium minerals containing 8% Ti and 41 million tons of zirconium minerals containing 4% Zr can be recovered each year from this source.

The bitumen is treated to produce crude oil and coke. The bulk of this coke is burned in boilers to produce steam for power generation. The combustion gases are laden with dust which is collected in boiler hoppers and electrostatic precipitators. This dust is rich in vanadium and nickel. It is estimated that one hundred tons of bitumen containing 0.02% V produces about 0.9 tons of fly ash containing 2.2% V.

6.7. Asphalt lakes

Asphalt occurs naturally in Trinidad as a lake in which pitch is mixed with sand and clay. Artificial asphalt is a solution of pitch in heavy tar oils and is used in making hard

pavements. The asphalt lake in Trinidad has an area of about 40 hectares and is about 60 meters deep. It has been analyzed to contain about 39% bitumen, 30% minerals, 31% seawater, and 6% sulfur. A similar lake occurs in Bermudez, Venezuela, but with about 60% bitumen. Asphalt rock contains less than 10% bitumen and occurs in Texas, California, Oklahoma, and other localities.

6.8. Economic aspects

The distribution of mineral resources throughout the world is irregular. Some countries have abundant minerals of one kind but are deficient in others. As a result, there is an active world trade in minerals. There are certain ores that are always treated at the mine, e.g., gold, uranium, nickel oxide, copper oxide, and sometimes aluminium. All other ores may be shipped as concentrates. Shipping an ore from a country represents a loss to that country because if this ore were processed locally to metal, more jobs would be created and the know-how could be acquired locally. Wars have been waged through out history to acquire and control mineral resources.

7. Treatment of ores

An ore may be treated both physically and chemically (Fig. 2). The components of an ore are the valuable minerals and the waste or gangue minerals. The need to beneficiate ores by mechanical and physical means arises from the following facts:

- Transportation and handling costs can be greatly reduced, if the unwanted gangue minerals were first removed.

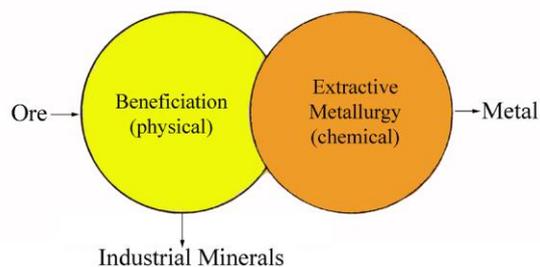


Fig. 2. Treatment of ores

- The size of reactors for treating such concentrates is also greatly decreased, which results in decreased capital cost, if the gangue minerals were removed.
- The ore may contain more than one valuable mineral, or certain undesirable impurity, and it is usually cheaper to separate them by physical rather than by chemical methods.

7.1. Beneficiation

A beneficiation plant is divided into two sections which perform the following:

- Liberation of minerals from rocks, and
- Separation of the liberated minerals.

At present, a beneficiation plant is capable of treating 100,000 tons/day. Handling of such large amounts of material necessitates great efforts from engineers, designers, and automatic control specialists. Figure 3 shows a general flowsheet for a mineral beneficiation plant.

- *Liberation of Minerals.* Liberation of minerals by comminution is an expensive operation. The cost increases proportionally as the particle size of the product decreases. On the other hand, the cost of any subsequent metallurgical operation, e.g., heating, leaching, etc., decreased as the particle size of the treated solid became smaller, as a result of the increased surface area. Therefore, there must be a compromise between the cost of grinding and the ideal particle size required for a particular process. This is represented by the minimum in Figure 4. A relation between particle size and surface area is given in Figure 5. Excessive grinding may also be undesirable, since it may cause problems in a subsequent step, e.g., during filtration if the ore or concentrate is treated by hydrometallurgical methods. The comminution of ores is usually done in three steps:

- Coarse or primary crushing,
- Fine or secondary crushing, and
- Grinding to fine powder

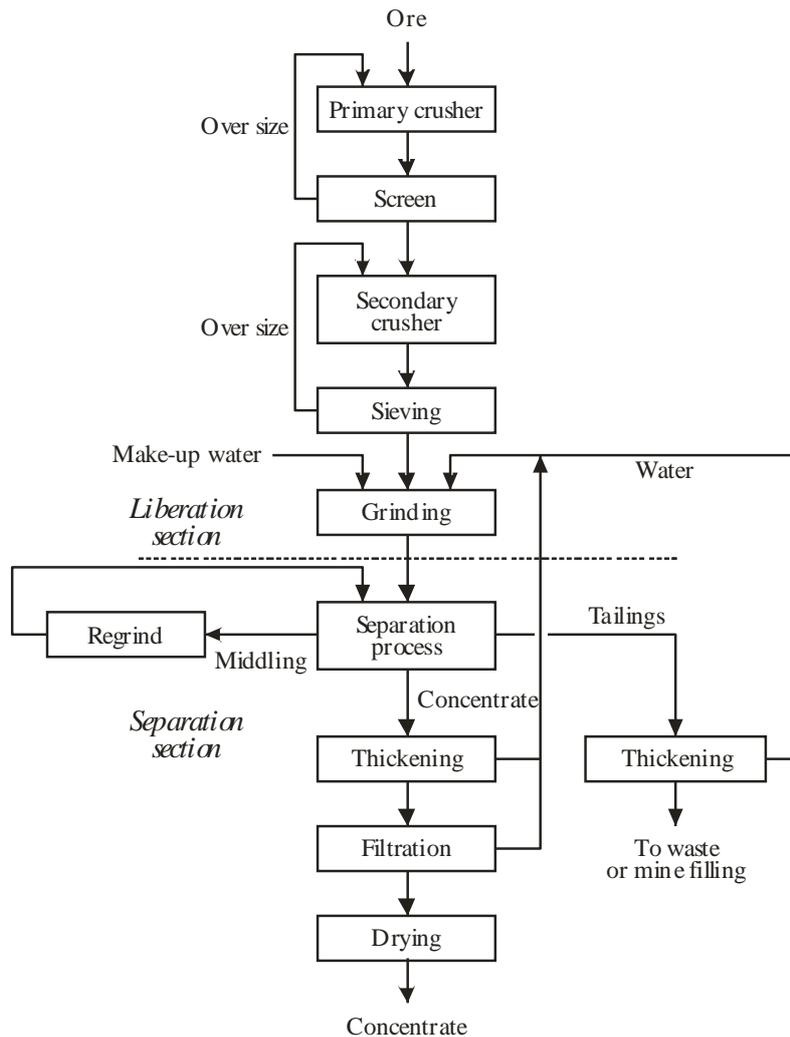


Fig. 3. General scheme of beneficiating an ore

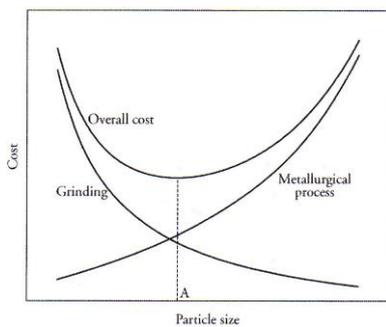


Fig. 4. Relation between cost and particle size. Point A represents the most economic particle size

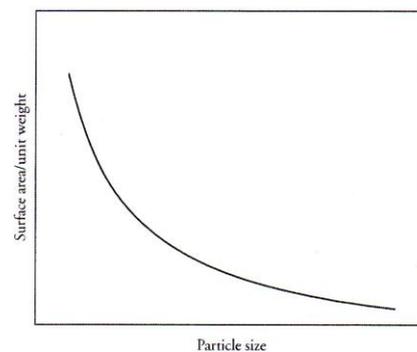


Fig. 5. A relation between particle size and surface area

Separation of Minerals. Separation of minerals is based on differences in their physical or physico-chemical properties. Among the physical properties that are extensively exploited are the specific gravity, magnetic and electrostatic properties, and

radioactivity. Physico-chemical methods are based on the surface properties of the minerals. These methods are not very effective, but they are cheap and rapid.

For each property on which a separation process is based, the feed has an optimum

particle size at which the process functions most effectively. For example, flotation can be most effectively conducted when the mineral particles are 1 to 0.01 mm; particles larger than 1 mm will be too heavy to be lifted by the air bubble and all particles smaller than 0.01 mm will be floated because at this small size loose agglomeration takes place. Usually, more than one process is used to effect a separation.

Two parameters have to be determined in any separation process:

- Recovery. This is the percentage of the metal recovered in the concentrate.
- Grade. This is the metal content of the concentrate expressed in percent.

The relationships between these parameters are as follows (Fig. 6):

- There is an inverse relationship between recovery and grade. To obtain a high grade concentrate, a larger quantity of the metal will be lost in the tailings, hence the recovery will be low. A 100% recovery is only possible when the ore is not concentrated.
- There is a direct relationship between the value of a concentrate and its grade. This is because the cost of extracting metal values from a concentrate is largely determined by the cost of rejecting the valueless material still present. For example, the lower the grade of a copper sulfide concentrate the more energy the concentrate will require when treated by pyrometallurgical methods.

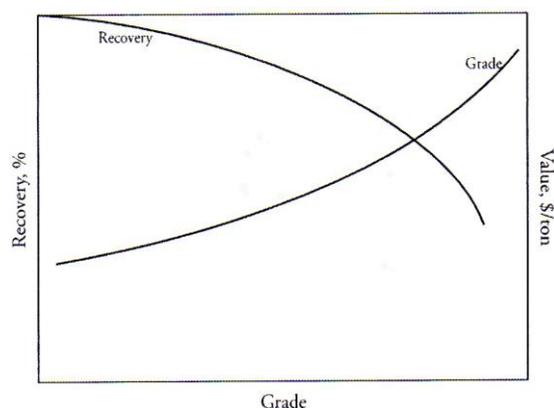


Fig. 6. Relationship between recovery of a certain mineral grade of the concentrate obtained, and its value

Thus, the production of a high-grade concentrate will result in the loss of some values, but the value of the concentrate would

be higher. Therefore, a compromise is generally sought between the metal values lost in the tailings and the ease of subsequent metallurgical treatment of the concentrate. The physical and physico-chemical properties on which separation of minerals is based are the following.

7.2. Chemical treatment of ores

An ore or concentrate is treated by pyro-, hydro-, or electro-metallurgical operation.

- Pyrometallurgy is most successful when high grade massive ores are treated in a blast furnace, because such a furnace has maximum heat economy being itself a heat exchanger: the cold charge descending from the top is preheated by the hot gases ascending in the furnace. Dust problems were also minimized because the ore was in the form of large lumps. With the exhaustion of such raw material, metallurgists turned their attention towards the treatment of low-grade ores. This has necessitated extensive grinding and flotation, which has resulted in the production of finely divided concentrates as raw material. Naturally, these could not be charged to a blast furnace because they are capable of blocking the movement of the ascending gases. This gave birth to the fossil-fired horizontal reverberatory furnace, for melting sulfide concentrates. This results in pollution of the environment, as well as high energy consumption, and excessive dust formation. This was later overcome by the flash smelting technology.
- Pyrometallurgical treatment of sulfide ore is plagued by the problem of sulphur IV oxide (SO_2) generation. If the concentration is high, it must be used for making sulfuric acid for which a nearby market must be found. If the SO_2 concentration is too low for making acid, disposal methods must be employed. Such methods are available but are rather expensive. As a result, in many cases, SO_2 is simply emitted to the atmosphere. On the other hand, sulfides can be treated by hydrometallurgical methods without generating SO_2 , thus eliminating the need to manufacture sulfuric acid.

Sulfur can be recovered in the elemental form which can be easily stock-piled, or transported at low cost.

- In pyrometallurgical processes, the metallurgist is forced to transfer molten slags and matte from one furnace to the other in large, heavy, refractory-lined ladles. Besides the inconvenience and cost of handling these materials, there is also the inevitable emission of gases, because they are usually saturated with SO₂ and during the transfer they cool down a little, resulting in decreased gas solubility and emission, hence the inconvenient working condition. In hydrometallurgical plants, solutions and slurries are transferred by pipelines without any problem.
- As a result of the high temperature involved in pyrometallurgical processes, usually around 1500°C, the reaction rates are high but much fuel is needed. To make a process economical, heat recovery systems are essential. Heat can be readily recovered from hot gases, but rarely from molten material like slag or metal. Thus, a great deal of energy is lost. Furthermore, the equipment needed for heat economy is bulky and expensive. In a reverberatory furnace, heat is mainly transferred from the ceiling of the furnace by radiation and has to penetrate a thick layer of slag which has a low thermal conductivity; for this reason it is regarded as an inefficient method. In hydrometallurgical processes, on the other hand, less fuel is needed because of the low temperature involved (usually below 100°C). Heat economy is usually no problem.
- Combustion of fossil fuels in a reverberatory furnace results in the formation of a large volume of gases which carry large amounts of dust. This must be recovered to abate pollution because the dust itself is also a valuable material. The technology of dust recovery is well established but the equipment is bulky and expensive. In hydrometallurgical processes this is no problem because wet materials are usually handled.

- Treatment of complex ores by pyrometallurgical method is unsuitable because separation is difficult; complex ores can be treated more conveniently by hydrometallurgy.
- Treatment of low-grade ores by pyrometallurgy is unsuitable because of the large amount of energy required to melt the gangue minerals. On the other hand, it is especially suitable to use hydrometallurgy since a selective leaching agent can be used to solubilize the valuable minerals, leaving behind the gangue.
- The economics of a pyrometallurgical process is usually suitable for large scale operations and requires a large capital investment. On the other hand, hydrometallurgical processes are suitable for small scale operations and low capital investments. The hydrometallurgical units can be increased in number when the need arises without any economic disadvantage.
- Many residues of pyrometallurgical processes are coarse and harmless. For example, slags which are a silicate phase can be stored in piles that are exposed to air and rain without the danger of dissolution and stream contamination. They are just unacceptable from the aesthetic point of view. On the other hand, most residues of hydrometallurgical processes are finely divided solids. If dry, they create dust problems when the wind blows and when wet, they gradually release metal ions in solution thereby contaminating the environment. Hence, well prepared storage sites must be created.

7.3. Pyro- versus electrometallurgy

The competition between pyro- and electrometallurgy is mainly between metallothermic reduction processes for producing metals, i.e., displacing a metal from its compounds by heating with a more reactive metal, and the electrolysis of molten (fused) salts. While both processes require the use of pure materials and handling under strict anhydrous conditions, the metallothermic reduction usually involves more handling

steps than the electrolytic method. On the other hand, electrolytic processes require cheap electric power.

The first metallic aluminium produced commercially was prepared through the pyrometallurgical route, specifically, by the reduction of aluminium chloride with metallic sodium. The process, however, gave way when the electrolytic reduction of alumina (Al_2O_3) was invented. While the choice between pyro- and electrometallurgy has been settled a long time ago in the aluminium industry, this is not the case for other metals like beryllium and magnesium. For these two metals, both routes are used. On the other hand, the production of titanium by metallothermic reduction is still unchallenged by the electrometallurgical route.

8. Conclusions

Geological processes are known to concentrate minerals to form ores of economic value. Mineral processing engineers further concentrate these ores by mechanical and physico-chemical methods. The job of the extractive metallurgist then, is to extract metals from these concentrates by chemical means. The thermal processes are known as pyrometallurgy, the aqueous processes are known as hydrometallurgy, while those using electric current are known as electrometallurgy. This classification is only a matter of convenience since all processes are usually involved in extracting a metal.

Suggested readings

- [1] Habashi, F. (2003). *Metals from Ores. An Introduction to Extractive Metallurgy*, Métallurgie Extractive Québec, Québec City, Canada, 472 pages. Distributed by Laval University Bookstore www.zone.ul.ca.
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- [6] Habashi, F. (1999). *A Textbook of Hydrometallurgy*, Métallurgie Extractive Québec, Québec City, Canada, second edition, 750 pages.
- [7] Habashi, F. (2002). *Textbook of Pyrometallurgy*, Métallurgie Extractive Québec, Québec City, Canada, 660 pages.
- [8] Habashi, F. (2000). *Extractive Metallurgy Today. Progress and Problems*, Métallurgie Extractive Québec, Québec City, Canada, 325 pages.