INTRODUCTION

Most metals, both metallic and non-metallic, are found in nature as low-grade, complex ore mixtures, which for the most part require some pretreatment to remove and discard a large part of the associated valueless waste rock, prior to the recovery and separation of the metall values by pyrometallurgical or hydrometallurgical methods.

This separation of values from waste rock is known by a variety of names, **Materials Beneficiation, Mineral Dressing, Mineral Processing, Ore dressing, or Mineral Beneficiation.**

It is usually carried out by relatively simple **physical-mechanical operations** that do not destroy either the physical or chemical identity of the materials being treated.

The physical-mechanical mineral beneficiation which removes a large portion of the waste material is much simpler and less expensive to do than the pyrometallurgical or hydrometallurgical processes.

**Economic Benefits**

Some of the economic benefits of beneficiation preceding a pyrometallurgical treatment would be:

(a) lower transportation and handling costs;
(b) reduction in smelting costs as less tonnage treated less fuel required, fewer fluxes for slage making;
(c) furnace capacity increased, more space available for metal production; and
(d) less slag produced carrying off metal values.
The degree of efficiency and its cost is very important, and it could be that a 90% recovery of the values in a concentrate is quite reasonable and inexpensive, but that a 93% recovery is not. With the collection of the additional 3% (from 90% to 9 being more difficult and costly than recovering the first 90%), and doubling or tripling the cost of the whole operation for a very slight additional improvement in the amount of values collected.

**Conservation**

**Reclamation**

**Recycling**

Reclamation and recycling also enter into conservation by reusing many times essentially indestructible, noncorrosive materials.

All of these separations, recoveries, and cleanings, are done by conventional beneficiation processing methods and equipment, and by the reuse of these materials it is possible to conserve and stretch the amount of new natural raw materials that otherwise would have to be used.

**Air and Water Pollution**

Environmentally, air pollution from beneficiation is quite low or can be easily controlled, while water pollution can be contained by recycling in-plant water to use over and over.

**Stages of Beneficiation**
Beneficiation can be separated into three separate areas which are usually combined into an inclusive series of overall treatments.

**Area I** has to do with crushing to liberate or expose metallic compound values which are scattered through the waste rock, or it may be used only to satisfy a sizing requirement of the product if only simple sizing is sought.

**Area II** is concerned with the separation of the values (concentrate) from the waste material (tailings) after the values have been liberated by crushing. This is done by a variety of methods, often making use of such physical properties as specific gravity differences or differences in magnetic permeability between the values and the waste.

**Area III** is the cleaning and recovery of the various products, and will cover such operations as dewatering, screening, and transportation.

Several beneficiation methods still in common use, which had an ancient counterpart, are the following:

(a) Hand picking  
(b) Washing  
(c) Crushing  
(d) Gravity Concentration  
(e) Jigging

*Minerals* by definition are natural inorganic substances possessing definite chemical compositions and atomic structures. (p.1)
**Isomorphism**

The mineral olivine, for example, has the chemical composition \((\text{Mg, Fe})_2\text{SiO}_4\), but the ratio of Mg atoms to Fe atoms varies in different olivines. The total number of Mg and Fe atoms in all olivines has the same ratio to that of the Si and O atoms. ( p.1 )

**Polymorphism**

Different minerals having the same chemical composition, but markedly different physical properties due to a difference in crystal structure. ( p.1 )

Thus the two minerals **graphite** and **diamond** have exactly the same composition, being composed entirely of carbon atoms, but have widely different properties due to the arrangement of the carbon atoms within the crystal lattice. ( p.2 )

The term "**Mineral**" is often used in a much more extended sense to include **anything of economic value** which is extracted from the earth. Thus coal, chalk, clay, and granite do not come within the definition of a mineral, although details of their production are usually included in national figures for mineral production. ( p.2 )

**Rocks**

**igneous rocks**

**magma**
Coals are not minerals in the geological sense, but a group of bedded rocks formed by the accumulation of vegetable matter. Most coal-seams were formed over 300 million years ago by the decomposition of vegetable matter from the dense tropical forests which covered certain areas of the earth. (p.2)

Metallic Ore Processing

Base metals - copper, lead, zinc and tin (p.3)

Fig. 1.1 Annual mined production of base metals (p.3)
The **price** of most metals is governed by supply and demand, and the prices of many common metals, particularly copper, have not kept pace with inflation. (p.4)

keep pace with（並駕齊驅）

---

**Table 1.1 Abundance of metals in the earth's crust (p.4)**

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance</th>
<th>Amount in 3.5 km of crust (tones)</th>
<th>Element</th>
<th>Abundance</th>
<th>Amount in 3.5 km of crust (tones)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>46.4</td>
<td>--</td>
<td>Vanadium</td>
<td>0.014</td>
<td>10^{14}-10^{15}</td>
</tr>
<tr>
<td>Silicon</td>
<td>28.2</td>
<td>10^{16}-10^{18}</td>
<td>Chromium</td>
<td>0.010</td>
<td>--</td>
</tr>
<tr>
<td>Aluminium</td>
<td>8.2</td>
<td>10^{16}-10^{18}</td>
<td>Nickel</td>
<td>0.0075</td>
<td>10^{13}-10^{14}</td>
</tr>
<tr>
<td>Iron</td>
<td>5.6</td>
<td>10^{16}-10^{18}</td>
<td>Zinc</td>
<td>0.0070</td>
<td>10^{13}-10^{14}</td>
</tr>
<tr>
<td>Calcium</td>
<td>4.1</td>
<td>--</td>
<td>Copper</td>
<td>0.0055</td>
<td>10^{13}-10^{14}</td>
</tr>
<tr>
<td>Sodium</td>
<td>2.4</td>
<td>--</td>
<td>Cobalt</td>
<td>0.0025</td>
<td>10^{13}-10^{14}</td>
</tr>
<tr>
<td>Magnesium</td>
<td>2.3</td>
<td>10^{16}-10^{18}</td>
<td>Lead</td>
<td>0.0013</td>
<td>10^{13}-10^{14}</td>
</tr>
<tr>
<td>Potassium</td>
<td>2.1</td>
<td>--</td>
<td>Uranium</td>
<td>0.00027</td>
<td>10^{11}-10^{13}</td>
</tr>
<tr>
<td>Titanium</td>
<td>0.57</td>
<td>10^{13}-10^{16}</td>
<td>Tin</td>
<td>0.00020</td>
<td>10^{11}-10^{13}</td>
</tr>
<tr>
<td>Manganese</td>
<td>0.095</td>
<td>10^{13}-10^{16}</td>
<td>Tungsten</td>
<td>0.00015</td>
<td>10^{11}-10^{13}</td>
</tr>
<tr>
<td>Barium</td>
<td>0.043</td>
<td>10^{15}-10^{16}</td>
<td>Mercury</td>
<td>8 \times 10^{-6}</td>
<td>10^{11}-10^{13}</td>
</tr>
<tr>
<td>Strontium</td>
<td>0.038</td>
<td>--</td>
<td>Silver</td>
<td>7 \times 10^{-6}</td>
<td>10^{11}-10^{13}</td>
</tr>
<tr>
<td>Rare earths</td>
<td>0.023</td>
<td>--</td>
<td>Gold</td>
<td>&lt; 5 \times 10^{-6}</td>
<td>&lt; 10^{11}</td>
</tr>
<tr>
<td>Zirconium</td>
<td>0.017</td>
<td>10^{14}-10^{16}</td>
<td>Platinum</td>
<td>&lt; 5 \times 10^{-6}</td>
<td>&lt; 10^{11}</td>
</tr>
</tbody>
</table>

The sea-bed may become a heavily exploited source of metals in the future for the so-called "manganese nodules" are rich in a variety of metals in addition to manganese. These nodules are continuously being formed in oxygen-rich waters particularly in the Pacific Ocean. (p.5)
Table 1.2  Abundance of Metal in the Oceans (p.5)

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance in sea-water (tonnes)</th>
<th>Element</th>
<th>Abundance in sea-water (tonnes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesium</td>
<td>$10^{15} - 10^{16}$</td>
<td>Vanadium</td>
<td>$10^9 - 10^{10}$</td>
</tr>
<tr>
<td>Silicon</td>
<td>$10^{12} - 10^{13}$</td>
<td>Titanium</td>
<td></td>
</tr>
<tr>
<td>Aluminium</td>
<td></td>
<td>Cobalt</td>
<td></td>
</tr>
<tr>
<td>Iron</td>
<td>$10^{10} - 10^{11}$</td>
<td>Silver</td>
<td></td>
</tr>
<tr>
<td>Molybdenum</td>
<td></td>
<td>Tungsten</td>
<td>$10^8 - 10^9$</td>
</tr>
<tr>
<td>Zinc</td>
<td></td>
<td>Chromium</td>
<td></td>
</tr>
<tr>
<td>Tin</td>
<td>$10^9 - 10^{10}$</td>
<td>Gold</td>
<td></td>
</tr>
<tr>
<td>Uranium</td>
<td></td>
<td>Zirconium</td>
<td>$&lt; 10^8$</td>
</tr>
<tr>
<td>Copper</td>
<td></td>
<td>Platinum</td>
<td></td>
</tr>
<tr>
<td>Nickel</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Sorensen (1989) has estimated that, at mid-1980s mining production, the lifetime of current base metal reserves is no more than 150 years.

(p.5)

alluvial deposit (p.6)

Most ores are mixtures of extractable minerals and extraneous rocky material described as gangue. (p.6)

Gold may be recovered profitably in ores containing only 5 parts per million (ppm) of the metal, whereas iron ores containing less than about 15% metal are regarded as low grade.

Mining Grades

<table>
<thead>
<tr>
<th>ORE</th>
<th>GRADE</th>
<th>CONCENTRATE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(Minimum is open</td>
<td>Metal Recovery from Ore</td>
</tr>
<tr>
<td></td>
<td>pit grade)</td>
<td>percent</td>
</tr>
<tr>
<td>ANTIMONY (Sk)</td>
<td>4.5 – 15%</td>
<td>80-105</td>
</tr>
<tr>
<td>COPPER</td>
<td>0.5 – 5.0%</td>
<td>60-95</td>
</tr>
<tr>
<td>COPPER + Mo</td>
<td>0.23% Cu+ 0.05% Mo</td>
<td>85-90</td>
</tr>
<tr>
<td>COPPER + Au and Ag</td>
<td>0.4% Au + 0.06% Ag</td>
<td>40-50</td>
</tr>
<tr>
<td>CHROMIUM</td>
<td>35%</td>
<td>70-105</td>
</tr>
<tr>
<td>GOLD</td>
<td>5 – 30 g/t</td>
<td>70-105</td>
</tr>
<tr>
<td>IRON</td>
<td>28 – 65%</td>
<td>70-105</td>
</tr>
<tr>
<td>LEAD</td>
<td>2 – 15%</td>
<td>70-90</td>
</tr>
<tr>
<td>MANGANESE</td>
<td>38 – 53%</td>
<td>70-100</td>
</tr>
<tr>
<td>NICKEL</td>
<td>0.3 – 9%</td>
<td>85-95</td>
</tr>
<tr>
<td>TUNGSTEN (Wolfram &amp; scheelite)</td>
<td>4.0 –11 g/t</td>
<td>30-300 g/t</td>
</tr>
<tr>
<td>SILVER</td>
<td>0.2 – 2.0 kg/m²</td>
<td>70-90</td>
</tr>
<tr>
<td>TIN + COPPER</td>
<td>1.0 - 2.0%</td>
<td>70-90</td>
</tr>
<tr>
<td>TUNGSTEN</td>
<td>0.7% Sn + 0.4% Cu</td>
<td>70-90</td>
</tr>
<tr>
<td>URANIUM</td>
<td>1 – 5 kg/metric ton</td>
<td>70-90</td>
</tr>
<tr>
<td>ZINC</td>
<td>3 – 20%</td>
<td>70-90</td>
</tr>
</tbody>
</table>

* May be sold as ferrocerium, ferromanganese, ferro nickel.
† PGM – Platinum group metals: sold as combined total.

For precious metals g/t = grams per tonne
10 dwt = 1 oz troy = 31.1035 g
1 lb/short ton = 0.5 kg/metric tonne
1 ton/short ton = 1.714 g/t
**Alluvial mining** is the cheapest method and, if on a large scale, can be used to mine ores of very low contained value due to low grade, low metal price, or both. For instance, in Malaysia, tin ores (cassiterite) containing as little as 0.01% Sn are mined by alluvial methods. (p.7)

High-tonnage **open-pit** and underground **block-caving** methods are also used to treat ores of low contained value, such as low-grade copper ores. (p.7)

In order to produce metals, the ore minerals must be broken down by the action of heat (**pyrometallurgy**), solvents (**hydrometallurgy**) or electricity (**electrometallurgy**), either alone or in combination, the most common method being the pyrometallurgical process of smelting. These chemical methods consume vast quantities of energy. Treatment of 1 t of copper ore consumes in the region of 1500-2000 kWh of electrical energy which at a cost of say 3.5p per kWh is around £60/t, well above the contained value of all current copper ores. (p.8)

The cost of **transportation** of mined ore to remote smelters could in many cases be greater than the contained value of the ore. (p.8)

**Mineral processing** is usually carried out at the mine site, the plant being referred to as a **mill** or **concentrator**. The essential purpose is to reduce to bulk of the ore which must be transported to and processed by the smelter, by using relatively cheap, low-energy **physical methods** to separate the valuable minerals from the waste (gangue) minerals. (p.8)
Compared with chemical methods, the physical methods used in mineral processing consume relatively small amounts of energy. For instance, to upgrade a copper ore from 1% to 25% metal would use in the region of 20-50 kWh/t. (p.8)

Mineral processing not only reduces smelter energy costs but also smelter metal losses, due to the production of less metal-bearing slag. (p.8)

Losses to tailings are one of the most important factors in deciding whether a deposit is viable or not.

The introduction of solvent extraction enable Nchanga Consolidated Copper Mines in Zambia to treat 9 million tonnes per year of flotation tailings, to produce 80,000 tonnes of finished copper from what was previously regarded as waste. (p.9)

In many cases not only is it necessary to separate valuable from gangue minerals, but it is also required to separate valuable minerals from each other. For instance, porphyry copper ores are an important source of molybdenum and the minerals of these metals must be separated for separate smelting. (p.9)

Apart from processing costs and losses, other costs which must be taken into account are indirect costs such as ancillary services - power supply, water, roads, tailings disposal - which will depend mush on the size and location of the deposit, as well as taxes, royalty payments, investment requirements, research and development, medical and safety costs, etc. (p.10)

Non-metallic Ores
Diamond ores are the lowest grade of all ores presently mined, the diamond content usually being between 0.03 and 0.15 ppm. (p.11)

**Tailings Retreatment**

There are many plants where minerals are recovered in secondary circuits, treating tailings, where the feed grades are much lower than would be economic on a mined ore.

Tin has been recovered from about 10,000 t/d each of tailings from the lead-zinc, and copper-lead-zinc plants of the Sullivan concentrator in British Columbia and from the Kidd Creek plant of Texasgulf, near Timmins, respectively, the plant feeds being about 0.06 and 0.15% Sn respectively. (p.11)

The working costs for treating old tailings dumps are much lower than conventional mining costs, and operations have been set up in many old mining area. The slimes dams are treated by monitoring, i.e. diverting high-pressure jets of water at the working face. The resultant slurry gravitates to transfer pump stations adjacent to each dam, and is pumped to a central processing plant. The plant treats over 1.5 million tonnes per month of slimes, grading 0.53 ppm gold, 40 ppm U3O8, and 1.04% S. (p.11)
Reprocessing of old tailings on a large is worthy of examination by those with access to sufficient material of this type, and in 1991 there were about 30 discrete tailings retreatment units around the world, two-thirds of these being in South Africa and Australia, mainly treating tailings from old gold and silver mines. (p.12)

**Mineral Processing Methods**

Mineral processing - ore dressing, mineral dressing, milling

Mineral processing follows mining and prepares the ore for extraction of the valuable metal in the case of metallic ores, but produces a commercial end product of non-metallic minerals and coal. (p.12)

It has been predicted that the importance of mineral processing of metallic ores may decline as the physical processes utilised are replaced by the hydro and pyrometallurgical routes used by the extractive metallurgist, because higher recoveries are obtained by some chemical methods. (p.12)

There are two fundamental operations in mineral processing, namely the release, or liberation, of the valuable minerals from their waste gangue minerals, and separation of these values from the gangue, this latter process being known as concentration. (p.13)

Liberation of the valuable minerals from the gangue is accomplished by comminution, which involves crushing, and, if necessary, grinding, to such a particle size that the product is a mixture of relatively clean particles of mineral and gangue. (p.13)
Grinding is often the greatest energy consumer, accounting for up to 50% of concentrator's energy consumption. (p.13)

Fine grinding increases energy costs and can lead to the production of very fine untreatable "slime" particles which may be lost into the tailings.

**Texture** - the texture refers to the aggregation (size), dissemination (distribution) and shape of the minerals within the ore.
The most important physical methods which are used to concentrate ores are:

1. Separation dependent on optical and radioactive properties, etc. This is often called Sorting.

2. Separation dependent on specific gravity differences.

3. Separation utilising the different surface properties of the minerals.
   
   **Froth flotation**

4. Separation dependent on magnetic properties.

5. Separation dependent on electrical conductivity properties.
   
   **High-tension separation**
In many cases, a combination of two or more of the above technique is necessary to concentrate an ore economically. (p.20)

**Gravity separation** is often used to reject a major portion of the gangue, as it is a relatively cheap process. It may not, however, have the selectivity or efficiency to produce the final clean concentrate. **Gravity concentrates therefore often need further upgrading by more expensive techniques**, such as froth flotation.

**Chemical methods**, such as pyrometallurgy or hydrometallurgy, can be used to alter mineralogy, allowing the low cost mineral processing methods to be applied to refractory ores. For instances, non-magnetic iron oxides can be roasted in a weakly reducing atmosphere to produces ferromagnetic magnetite. It has also been suggested that the magnetic response could be increased without chemically altering the minerals, by the adsorption of fine magnetite particles onto the surfaces of non-magnetic minerals in the slurry. (p.21)

Some refractory copper ores, containing sulphide and oxidized minerals, have been pre-treated hydrometallurgically to enchance flotation performance.

**Comminution** deals with all crushing, grinding, and initial rejection. (p.23)

**The Flowsheet**

![Simple block flowsheet](image1)

![Line flowsheet](image2)
Liberation

One of the major objectives of comminution is the liberation, or release, of the valuable minerals from the associated gangue minerals at the coarsest possible particle size. If such an aim is achieved, then not only is energy saved by the reduction of the amount of fines produced, but any subsequent separation stages become easier and cheaper to operate. (p.25)

If high-grade solid products are required, then good liberation is essential; however, for subsequent hydrometallurgical processes, such as leaching, it may only be necessary to expose the required mineral.
Figure 1.5 (p.26) shows a lump of ore which has been reduced to a number of cubes of identical volume and of a size below that of the grains of mineral observed in the original ore sample.

The “degree of liberation” refers to the percentage of the mineral occurring as free particles in the ore in relation to the total content. This can be high if there are weak boundaries between mineral and gangue particles, which is often the case with ores composed mainly of rock-forming minerals, particularly sedimentary minerals. (p.26)

A high degree of liberation may only be possible by intensive fine grinding, which may reduce the particles to such a fine size that separation becomes very inefficient. On the other hand, froth flotation requires as much of the valuable mineral surface as possible to be exposed, whereas in a chemical leaching process, a portion of the surface must be exposed to provide a channel to the bulk of the mineral. (p.27)

In practices, ores are ground to an optimum mesh of grind, determined by laboratory and pilot scale testwork, to produce an economic degree of liberation.

Figure 1.6 is a cross-section through a typical ore particle, and illustrates effectively the liberation dilemma often facing the mineral processor.
Regions A represent valuable mineral, and region AA is rich in valuable mineral, but is highly **intergrown** with the gangue mineral. (p.28)

![Diagram of ore particles](image)

**Particles of type 1** are rich in mineral, and are classed as concentrate as they have an acceptable degree of locking with the gangue, which limits the concentrate grade.

**Particles of type 4** would likewise be classed as tailings, the small amount of mineral present reducing the recovery of mineral into the concentrate.

**Particles of types 2 and 3** would probably be classed as middlings, although the degree of regrinding needed to promote economic liberation of mineral from particle 3 would be greater than in particle 2.
This method discards most of the coarse gangue early in the process, thus considerably reducing grinding costs, as needless comminution of liberated gangue is avoided. (p28, 29)

**Concentration**

The object of mineral processing, regardless of the methods used, is always the same, i.e. to separate the minerals into two or more products with the values in the concentrates, the gangue in the tailings, and the “locked” particles in the middlings. Such separations are never perfect, so that much of the middlings produced are, in fact, misplaced particles, i.e. those particles which ideally should have reported to the concentrate or the tailings. (p.29)
The technology for treating fine-sized minerals is poorly developed, and, in some cases, very large amounts of fines are discarded.

It should be pointed out that the process is also limited by the mineralogical nature of the ore. For example, in an ore containing native copper it is theoretically possible to produce a concentrate containing 100% Cu, but, if the ore mineral was chalcopyrite (CuFeS$_2$), the best concentrate would contain only 34% Cu.

Cu=63.55, Fe=55.85, S=32
CuFeS$_2$=183.4
(63.55÷183.4) ×100%=34.5%

The grade, or assay, usually refers to the content of the marketable end product in the material. Thus in metallic ores, the per cent metal is often quoted, although in the case of very low-grade ores, such as gold, metal content may be expressed as parts per million (ppm), or its equivalent, grams per tonne (gt-1). (p.31)

Some metals are sold in oxide form, and hence the grade may be quoted in terms of the marketable oxide content, e.g. %WO$_3$, %U$_3$O$_8$, etc. (p.31)

In non-metallic operations, grade, usually refers to the mineral content, e.g. %CaF$_2$ in fluorite ores; diamond ores are usually graded in carats per 100 tonnes, where 1 carat is 0.2 g. Coal is graded according to its ash content, i.e. the amount of incombustible mineral present within the coal; most of the coal produced in Britain is consumed in power stations, which require a feed with an ash content of between 15 and 20%.

Recovery
**Enrichment ration** is the ration of the grade of the concentrate to the grade of the feed.

Ratio of concentration and recovery are essentially independent of each other, and in order to evaluate a given operation it is necessary to know both. For example, it is possible to obtain a very high grade of concentrate and ration of concentration by simply picking a few lumps of pure galena from a lead ore, but the recovery would be very low. On the other hand, a concentrating process might show a recovery of 99% of the metal, but it might also put 60% of the gangue minerals in the concentrate. (p.31)

**Metallurgical efficiency**

![Fig. 1.9 Typical recovery-grade curve](image)

Fig. 1.9 is a typical recovery=grade curve showing the characteristic inverse relationship between recovery and concentrate grade.

Schulz (1970) proposed the following definition: (p.33)
Separation efficiency (S.E.) = \( Rm - Rg \)

\( Rm = \% \) recovery of the valuable mineral
\( Rg = \% \) recovery of the gangue into the concentrate

If

then \( Rm = 100 \frac{Cc}{f} \) ....................(1.2)

The gangue content of the concentrate = 100 – ( 100 \( c / m \) ) \%

\( m = \) the percentage metal content of the valuable mineral

(e.g. PbS = 86.6%; SnO\(_2\) = 78.6%; CuFeS\(_2\) = 34.6%)

i.e. gangue content = 100 \( (m - c) / m \)

Therefore \( Rg = C \times \) gangue content of concentrate / gangue content of feed

\( Rg = 100 \ C \ (m - c) / (m - f) \)

Therefore \( Rm - Rg = 100 \ Cc / f - [100 \ C \ (m - c) / (m - f) ] \)
Example: (p.34)

A tin concentrator treats a feed containing 1% tin, and three possible combinations of concentrate grade and recovery are:

- High grade: 63% tin at 62% recovery
- Medium grade: 42% tin at 72% recovery
- Low grade: 21% tin at 78% recovery

Determine which of these combinations of grade and recovery produce the highest separation efficiency?

Solution:
Assuming that the tin is totally contained in the mineral cassiterite (SnO₂), which, when pure, contains 78.6% tin, then since mineral recovery (equation 1.2) is

\[ R_m - R_g = \frac{100 C (c - f)}{(m - f) f} \]  

(1.3)

100 × C × concentrate grade / feed grade, so for the high-grade concentrate:
\[ 62 = C \times 63 \times 100 / 1, \text{ and } C = 9.841 \times 10^{-3} \]

Therefore, S.E. (eq.1.3) = \( 0.984 \times 78.6 \times (63-1) \times (78.6-1) \times 1 = 61.8\% \)

medium-grade concentrate: \( 72 = 100 \times C \times 42 / 1 \)
therefore, \( C = 1.714 \times 10^{-2} \) S.E. = 71.2\% 

low-grade concentrate: \( 78 = 100 \times C \times 21 / 1 \)
therefore, \( C = 3.714 \times 10^{-2} \) S.E. = 75.2\% 

The highest separation efficiency is achieved by the production of a low-grade (21% tin) concentrate at high recovery (78%) 

Ore Handling

Ore handling, which may account for 30-60\% of the total delivered price of raw materials, covers the processes of transportation, storage, feeding, and washing of the ore en route to, or during, its various stages of treatment in the mill. (p.58)
Ore that has been well broken can be transported by trucks, belts, or even by sluicing, but large lumps of hard ore may need individual blasting. Modern developments in microsecond delay fuses and plastic explosive have resulted in more controllable primary breakage and easier demolition of occasional very large lumps. At the same time, crushers have become larger and lumps up to 2 meters in size can now be fed into some primary units.

Open-pit ore tends to be very heterogeneous, the largest lumps often being over 1.5 m in diameter. The broken ore from the pit, after blasting, is loaded directly into trucks, holding up to 200 t of ore in some cases, and is transported directly to the primary crushers.

The Removal of Harmful Materials: (p.59)

Ore entering the mill from the mine normally contains a small proportion of material which is potentially harmful to the mill equipment and processes. For instance, large pieces of iron and steel broken off from mine machinery can jam in the crushers. Wood is a major problem in many mills as this is ground into a fine pulp and causes choking or blocking of screens, etc.

Clays and slimes adhering to the ore are also harmful as they hinder screening, filtration, and thickening, and again consume valuable flotation reagents. All these must be removed as far as possible at an early stage in treatment.

Hand sorting from conveyor belts has declined in importance with the development of mechanized methods of dealing with large tonnages, but it is still used when plentiful cheap labour is available. Crushers can be protected from large pieces of “tramp” iron and steel by electromagnets suspended over conveyor belts.
Large pieces of wood which have been “flattened out” by passage through a primary crusher can be removed by passing the ore feed over a **vibrating scalping screen**. Here the apertures of the screen are slightly larger than the maximum size of particle in the crusher discharge, allowing the ore to fall through the apertures and the flattened wood particles to ride over the screen and be collected separately.

Wood can be further removed from the pulp discharge from the grinding mills by passing the pulp through a fine screen.

**Washing** of run-of-mine ore can be carried out to facilitate sorting by removing obscuring dirt from the surfaces of the ore particles. However, washing to remover very fine material, or **slimes**, of little or no value, is more important.

**Washing is normally performed after primary crushing** as the ore is then of a suitable size to be passed over washing screens.

The fine product from classification, i.e. the “**slimes**”, may be partially **dewatered** in shallow large diameter settling tanks known as **thickeners** and the thickened pulp either pumped to **tailings disposal** or, if containing values, direct to the **concentration** process, thus removing load from the grinding section.
Ore Transportation: (p.63)

The basic philosophy requires maximum use of gravity and continuous movement over the shortest possible distances between processing units.

Dry ore can be moved through chutes, provided they are of sufficient slope to allow easy sliding, and sharp turns are avoided. Clean solids slide easily on a 15-25° steel-faced slope but for most ores, a 45-55° working slope is used.

The belt conveyor is the most widely used method of handling loose bulk materials. Belts are now in use with capacities up to 20,000 t/h and single flight lengths exceeding 5,000 m, with feasible speeds of up to 10 m/s. (p.63)

The standard rubber conveyor belt has a foundation of sufficient strength to withstand the driving tension and loading strains. This foundation, which may be of cotton, nylon, or steel cord, is bound together with a rubber matrix and completely covered with a layer of vulcanised rubber.
Several methods can be sued to minimize loading shock on the belt. A typical arrangement is shown in Fig. 2.6 where the fines are screened on to the belt first and provide a cushion for the larger pieces of rock.

Where space limitation does not permit the installation of a belt conveyor, gravity bucket elevators can be used (Fig. 2.7). These provide only low handling rates with both horizontal conveying and elevating of the material.

Hydraulic transport of the ore stream normally takes over from dry transportation at the grinding stage in most modern mills. Pulp may be made to flow through open launders by gravity in some cases. (p.67)

In plants of any size, the pulp is moved through piping via centrifugal pumps. Pipelines should be as straight as possible to prevent abrasion at bends. The use of oversize pipe is dangerous whenever slow motion might allow the solids to settle and hence choke the pipe.

Centrifugal pumps are cheap in capital cost and maintenance and occupy little space. Single-stage pumps are normally used, lifting up to 30m, and 100m in extreme cases. Their main disadvantage is the high velocity produced within the impeller chamber, which may result in serious wear of the impeller and chamber itself, especially when a coarse sand is being pumped.

Ore Storage: (p.69)

For various reasons, at most mines, ore is hoisted for only a part of each day. On the other hand, grinding and concentration circuits are most efficient when running continuously. Mine operations are more subject to unexpected interruption than mill operations, and coarse-crushing machines are more subject to clogging and breakage than fine crushers, grinding mills, and concentration equipment. Consequently, both the
mine and the coarse-ore plant should have a greater hourly capacity than the fine crushing and grinding plants, and storage reservoirs should be provided between them.

Ordinary mine shut-downs, expected or unexpected will not generally exceed a 24-h duration, and ordinary coarse-crushing plant repairs can be made within an equal period if a good supply of spare parts is kept on hand. Therefore, if a 24-h supply of ore that has passed the coarse crushing plant is kept in reserve ahead of the mill proper, the mill can be kept running independent of shut-downs of less than a 24-h duration is mine and coarse-crushing plant.

Depending on the nature of the material treated, storage is accomplished in stock piles, bins, or tanks.

Feeding: (p.72)

Feeders are necessary whenever it is desired to deliver a uniform stream of dry or moist ore, since such ore will not flow evenly from a storage reservoir of any kind through a gate, except when regulated by some type of mechanism.

A typical feeder consists of a small bin, which may be an integral part of a large bin, with a gate and a suitable conveyor. Feeders of many types have been designed, notably apron, belt, chain, roller, rotary, revolving disc, and vibrating feeders.

grizzly

The elliptical bar feeder consists of elliptical bars of steel which form the bottom of a receiving hopper and are set with the long axes of the ellipses in alternate vertical and horizontal positions. Material is dumped directly onto the bars which rotate in the same direction, all at the same
time, so that the spacing remains constant.

The **apron feeder** is one of the most widely used feeders for handling coarse ore, especially jaw crusher feed.

**Belt feeders** are essentially short belt conveyors, used to control the discharge of material from inclined chutes. They frequently replace apron feeders for fine ore and are increasingly being used to handle coarse, primary crushed ore.
FROTH FLOTATION

Introduction

Flotation is undoubtedly the most important and versatile mineral-processing technique, and both use and application are being expanded to treat greater tonnages and to cover new areas.

Originally patented in 1906, flotation has permitted the mining of low-grade and complex ore bodies which would have otherwise been regarded as uneconomic. In earlier practice the tailings of many gravity plants were of a higher grade than ore treated in many modern flotation plants.

Flotation is a selective process and can be used to achieve specific separations from complex ores such as lead-zinc, copper-zinc, etc. Initially developed to treat the sulphides of copper, lead, and zinc, the field of flotation has now expanded to include oxides, such as hematite and cassiterite, oxidised minerals, such as malachite and cerussite, and non-metallic ores, such as fluorite, phosphates, and fine coal.

Principles of Flotation

The theory of froth flotation is complex and is not completely understood. Froth flotation utilises the differences in physico-chemical surface properties of particles of various minerals. After treatment with reagents, such differences in surface properties between the minerals within the flotation pulp become apparent and, for flotation to take place, an air-bubble must be able to attach itself to a particle, and lift it to the water surface.
The process can only be applied to relatively fine particles, as if they are too large the adhesion between the particle and the bubble will be less than the particle weight and the bubble will therefore drop its load.

In flotation concentration, the mineral is usually transferred to the froth, or float fraction, leaving the gangue in the pulp or tailing. This direct flotation as opposed to reverse flotation, in which the gangue is separated into the float fraction.

The air-bubbles can only stick to the mineral particles if they can displace water from the mineral surface, which can only happen if the mineral is to some extent water repellant or hydrophobic. Having reached the surface, the air bubbles can only continue to support the mineral particles if they can form a stable froth, otherwise they will burst and drop the mineral particles. To achieve these conditions it is necessary to use the numerous chemical compounds known as flotation reagents.

The activity of a mineral surface in relation to flotation reagents in water depends on the forces which operate on that surface. The forces tending to separate a particle and a bubble are shown in following figure. The tensile forces lead to the development of an angle between the mineral surface and the bubble surface. At equilibrium,
\[ \gamma_{s/A} = \gamma_{a/A} + \gamma_{o/A} \]

Where \( \gamma_{s/A} \), \( \gamma_{s/w} \), and \( \gamma_{w/A} \) are the surface energies between solid-air, solid-water and solid-air, respectively, and \( \theta \) is the contact angle between the mineral surface and the bubble.

It can be seen that the greater the contact angle the greater is the work of adhesion between particles and bubble and the more resilient the system is to disruptive forces. The floatability of a mineral therefore increases with the contact angle; minerals with a high contact angle are said to be aerophilic, i.e. they have a higher affinity for air than for water. Most minerals are not water repellant in their natural state and flotation reagents must be added to the pulp.

The most important reagents are the **collectors**, which adsorb on mineral surfaces, rendering them hydrophobic (or aerophilic) and facilitating bubble attachment. The **frothers** help maintain a reasonably stable froth. **Regulators** are used to control the flotation process; these either activate or depress mineral attachment to air-bubbles and are also used to control the pH of the system.

**Collectors**
All minerals are classified into non-polar or polar types according to their surface characteristics. The surfaces of non-polar minerals are characterised by relatively weak molecular bonds. The minerals are composed of covalent molecules held together by van der Waals forces, and the non-polar surfaces do not readily attach to the water dipoles, and in consequence are hydrophobic. Minerals of this type, such as graphite, sulphur, molybdenite, diamond, coal and talc, thus have high natural floatabilities with contact angles between 60 and 90 degrees. Although it is possible to float these minerals without the aid of chemical agents, it is universal to increase their hydriphobicity by the addition of hydrocarbon oils or frothing agents. Creosote, for example, is widely used to increase the floatability of coal.

Use is made of the natural hydrophobicity of diamond in grease tabling, a classical method of diamond recovery which is still used in some plants. The pre-concentrated diamond ore slurry is passed over inclined vibrating tables, which are covered in a thick layer of petroleum grease. The diamonds become embedded in the grease because of their water repellency, while the water-wetted gangue particles are washed off the table. The grease is skimmed of the table either periodically or continuously, and placed in perforated pots, which are immersed in boiling water. The grease melts, and runs out through the perforations, and is collected and re-used, while the pot containing the diamonds is transported to the diamond-sorting section.
Minerals with strong covalent or ionic surface bonding are known as polar types, and exhibit high free energy values at the polar surface. The polar surfaces react strongly with water molecules, and these minerals are naturally hydrophilic.

The polar group of minerals have been subdivided into various classes depending on the magnitude of polarity, which increases from groups 1 to 5. Minerals in group 3(a) can be rendered hydrophobic by sulphidisation of the mineral surface in an alkaline aqueous medium. Apart from the native metals, the minerals in group 1 are all sulphides, which are only weakly polar due to their covalent bonding, which is relatively weak compared to the ionic bonding of the carbonate and sulphate minerals. In general, therefore, the degree of polarity increases from sulphide minerals, through sulphates, to carbonates, halites, phosphates, etc., then oxides-hydroxides, and, finally, silicates and quartz.
Hydrophobicity has to be imparted to most minerals in order to float them. In order to achieve this, surfactants known as collectors are added to the pulp and time is allowed for adsorption during agitation in what is known as the conditioning period. Collectors are organic compounds which render selected minerals water-repellant by adsorption of molecules or ions on to the mineral surface, reducing the stability of the hydrated layer separating the mineral surface from the air-bubble to such a level that attachment of the particle to the bubble can be made on contact.

Collector molecules may be ionising compounds, which dissociate into ions in water, or non-ionising compounds, which are practically insoluble, and render the mineral water-repellant by covering its surface with a thin film.

Because of chemical, electrical, or physical attraction between the polar portions and surface sites, collectors adsorb on the particles with their non-polar ends orientated towards the bulk solution, thereby imparting hydrophobicity to the particles. They are usually used in small amounts, substantially those necessary to form a monomolecular layer on particle surface, as increased concentration, apart from the cost, tends to float other minerals, reducing selectivity. It is always harder to eliminate a collector already adsorbed than to prevent its adsorption.
An excessive concentration of a collector can also have an adverse effect on the recovery of the valuable minerals, possibly due to the development of collector multi-layers on the particles, reducing the proportion of hydrocarbon radicals orientated into the bulk solution. The hydrophobicity of the particles is thus reduced, and hence their floatability.

The flotation limit may be extended without loss of selectivity by using a collector with a longer hydrocarbon chain, thus producing greater water-repulsion, rather than by increasing the concentration of a shorter chain collector. However, chain length is usually limited to two to five carbon atoms, since the solubility of the collector in water rapidly diminishes with increasing chain length and, although there is a corresponding decrease in solubility of the collector products, which therefore adsorb very readily on the mineral surfaces, it is, of course, necessary for the collector to ionise in water for chemisorption to take place on the mineral surfaces. Not only the chain length, but also the chain structure, affects solubility and adsorption; branched chains have higher solubility than straight chains.

It is common to add more than one collector to a flotation system. A selective collector may be used at the head of the circuit, to float the highly hydrophobic minerals, after which a more powerful, but less selective one is added to promote recovery of the slower floating minerals.
Frothers

When mineral surfaces have been rendered hydrophobic by the use of a collector, stability of bubble attachment, especially at the pulp surface, depends to a considerable extent on the efficiency of the frother.

Ideally the frother acts entirely in the liquid phase and does not influence the state of the mineral surface. In practice, however, interaction does occur between the frother, mineral, and other reagents, and the selection of a suitable frother for a given ore can only be made after extensive test work.

In sulphide mineral flotation it is common practice to employ at least two frothers and more than one collector. Specific frothers are chosen to provide adequate physical properties to the froth, while the second frother interacts with the collectors to control the dynamics of the flotation process.

Frothers are in many respects chemically similar to ionic collectors, and, indeed, many of the collectors, such as oleates, are powerful frothers, being in fact too powerful to be used as efficient frothers, since the froths which they produce can be too stable to allow efficient transport to further processing. Froth build-up on the surfaces of thickeners, and excessive frothing of flotation cells, are problems occurring in many mineral processing plants. A good frother should have negligible collecting power, and also produce a froth which is just stable enough to facilitate transfer of floated mineral from the cell surface to the collecting launder.

Frothers are generally heteropolar surface-active organic reagents, capable of being adsorbed on the air-water interface. When surface-active molecules react with water, the water dipoles combine readily with the polar groups and hydrate them, but there is practically no reaction with the non-polar hydrocarbon group, the tendency being to force the latter into the air phase. Thus the heteropolar structure of the frother molecule leads to its adsorption, i.e. the molecules concentrate in the surface layer with the non-polar groups oriented towards the air and the polar groups...
towards the water.

Frothing action is thus due to the ability of the frother to adsorb on the air-water interface because of its surface activity and to reduce the surface tension, thus stabilising the air-bubble.

Frothers must be to some extent soluble in water, otherwise they would be distributed very unevenly in an aqueous solution and their surface-active properties would not be fully effective. The most effective frothers include in their composition one of the following groups:

- **Hydroxyl** $\text{--OH}$
- **Carboxyl** $\text{--C=O}$ $\text{--OH}$
The acids, amines, and alcohols are the most soluble of the frothers. The alcohols (-OH) are the most widely used, since they have practically no collector properties, and in this respect are preferable to other frothers, such as the carboxyls, which are also powerful collectors; the presence of collecting and frothing properties in the same reagent may make selective flotation difficult. Frothers with an amino group, and certain sulpho group frothers, also have weak collector properties.

Pine oil, which contains aromatic alcohols, the most active frothing component being terpineol, $C_{10}H_{17}OH$, has been widely used as a frother. Cresol (cresylic acid), $CH_3C_6H_4OH$, has also had wide use.