CHAPTER 1.1

Mineral Properties and Processing

Avimanyu Das and Courtney A. Young

Critical players employed in the mining industry include scientists and engineers involved in geology, mining, mineral processing, extractive metallurgy, environmental stewardship, and occupational safety and health. All these professionals should have overlapping knowledge about minerals and how their properties are used for both identification and separation purposes. This promotes cross-communication among all participants as required in ore-to-product optimization, a concept that is also termed *mine-to-mill* and *pit-to-plant*. By optimizing all facets of the mining industry, ores will be mapped, mined, and processed to their highest efficiency, ultimately resulting in maximum metallurgical performance and therefore recovery and concentrate grade of the valuable minerals. The more professionals know about minerals and the better they communicate with others, the greater their success will be. This is particularly true for mineral processors and extractive metallurgists.

Mineral processors and extractive metallurgists work with geologists throughout most of the exploration phase to help identify the type and amount of minerals present and how they are associated with one another. Associations can lead to the identification of other minerals, particularly if those minerals are present in amounts that are difficult to detect. To do this, mineral processors and extractive metallurgists will collect and examine hand specimens, chip samples, and drill core and cuttings from all over the mining property. Mineral identification will initially be accomplished through visual examination in the field with the naked eye, magnifying lenses, and portable light microscopes and then progress to the laboratory where high-power, ore microscopy, and various spectroscopic analyses are conducted. Accuracy normally increases with the cost of the identification technique, not only because of the analytical devices being used but also because of the equipment needed to properly prepare the materials for examination.

After the minerals are identified and quantified, mineral processors and extractive metallurgists will catalog their properties and evaluate differences to determine which can be exploited to provide the best separation. They will then study and optimize those separations in the laboratory, gather necessary data for scaling up to pilot plant or industrial-size equipment, estimate capital and operating costs, and ultimately recommend the best, most economical strategy. These studies also require mineral processors and extractive metallurgists to consider ore hardness and liberation patterns to determine the best comminution practices to minimize energy consumption and match the resulting product size to the recommended separation strategy. The recommended strategy might be the reverse of the process that formed the ore in the first place. Therefore, understanding ore genesis can aid process development, and it is another example of why communicating with geologists is critical.

While the mineral and metallurgical testing is being conducted, geologists will be mapping the ore body and working with mining engineers to determine the best way to mine and haul the ore to the process plant. Mining engineers will also be working with the mineral processors and extractive metallurgists to determine the best method for blasting so that the optimal feed size is delivered to the first stage in comminution. Ore-to-product optimization in subsequent stages will lead to appropriate particle sizes being fed to the separation process and therefore obtain maximum metallurgical performance.

Clearly, mineral identification must be established beyond a doubt so that a strategy can be developed for concentrating valuable minerals or extracting valuable metals. However, the final product also must meet the quality specified by the end user. While this implies that the primary goal is to keep waste minerals, referred to as gangue, away from valuable minerals reporting to the concentrate, it is also important to get as much valuable mineral to report to the concentrate as possible. Both actions help maximize concentrate grade and recovery and therefore lead to optimal metallurgical performance, as already mentioned. A good understanding of how differentially the valuable and gangue minerals behave in the separation process is important. However, given the set of machinery in the processing plant, it will be difficult for mineral processors and extractive metallurgists to meet the specifications

Avimanyu Das, Associate Professor, Metallurgical & Materials Engineering, Montana Tech, Butte, Montana, USA
Courtney A. Young, Department Head & Professor, Metallurgical & Materials Engineering, Montana Tech, Butte, Montana, USA

without having a thorough knowledge of minerals and their properties and being able to communicate with one another.

KEY DEFINITIONS

Minerals

Formed through biogeological processes, *minerals* are naturally occurring, predominantly inorganic solids that have specific physical and chemical properties, highly ordered atomic/crystal structures, and characteristic chemical compositions usually of high purity and homogeneity, ranging from simple elements to complex solid solutions. By comparison, *rock* is an aggregate of minerals and may be igneous, sedimentary, metamorphic, or any combination thereof. A *deposit* is an aggregate of rock. An *ore* is a deposit or a system of deposits containing at least one valuable mineral that can be separated from the other minerals and marketed for a profit.

Properties

Polymorphs are minerals that have the same chemical composition but possess different crystal structures. Because structure determines properties, the physical and chemical properties of the polymorphs will vary, albeit usually minimally. Of course, changing the chemical composition will also change the properties, but in this case the changes are likely to be significant. Measuring the various physical and chemical properties of a mineral can lead to its identification. Furthermore, if there are differences in those properties, even if those differences are small, the properties can be exploited to separate the minerals.

Processing

Processing is a series of actions taken to achieve mineral separations. Valuable minerals report to a concentrate, or con, and gangue minerals report to tailings, or tail. To achieve separation, differences among the physical or chemical properties of minerals must be exploited using physical or chemical processes. In general, *mineral processing* is the field of engineering concerned with the separation of valuable minerals from ores into concentrates usually without chemical change, while *extractive metallurgy* is the field of engineering concerned with the extraction of valuable metals from ores or concentrates usually with chemical change.

MINERAL IDENTIFICATION

Although many physical and chemical properties are used to identify minerals, typically several properties are needed to identify them definitively. The properties most commonly used include chemical composition, crystal structure, hardness, tenacity, cleavage, fracture, streak, color, luster, transparency, and refractivity. Except for chemical composition, all are physical properties typically quantified with the naked eye, a magnifying lens, or an ore microscope. Because there are more than 4,000 minerals, all these properties are important for identification purposes, but not in all cases. The properties are briefly described in the following sections. Table 1 includes a quantitative compilation for a few select minerals using information from Hurlbut and Klein (1977), Craig and Vaughan (1981), Bolles and McCullough (1985), and Thomas (2010). Other important properties are also discussed but are not included in the table.

Chemical Composition

All minerals have definite chemical compositions with specific stoichiometric ratios. A few are native elements, such as Fe, Ni, Cu, Ag, Au, S, and C as graphite and diamond; and some are alloys, including electrum (AuAg) and tetrataenite (FeNi). However, most are molecular, ranging from simple compounds to complex solid solutions. Compositions indicate the chemical analyses of the minerals and, thereby, the anions and cations that comprise the minerals. Because an anion is usually significantly larger than a cation, the anion plays a dominant role in crystal structure and which characteristics the minerals are likely to exhibit. Consequently, mineral classification systems such as Dana or Nickel–Strunz are based on crystal structure and type of anion. Because of recent modification by Mills et al. (2009), mineralogists tend to favor the latter.

Crystal Structure

Minerals have a well-defined crystal structure. However, that structure can be modified by a mineral's association with other minerals, impurities, and inclusions. Because it is not always possible to establish a mineral's crystal structure by visual examination alone, techniques such as X-ray diffraction are used. Some minerals may have poorly organized internal arrangement and will thus exhibit near-amorphous behavior rather than crystallinity. There are six major crystal structures: isometric or cubic, tetragonal, orthorhombic, monoclinic, triclinic, and hexagonal. Some classify trigonal as a seventh structure, but it is usually recognized as a division under the hexagonal structure. Depending on how the crystal structure grows, minerals generally take on one of 11 forms (i.e., monohedron, parallelohedron, dihedron, disphenoid, prism, pyramid, dipyramid, trapezohedron, scalenohedron, rhombohedron, and tetrahedron), but numerous subcategories have also been defined.

Mohs Hardness

This property is a measure of resistance to scratching abrasion. Because talc is the softest known mineral, it cannot scratch other minerals. By comparison, diamond is the hardest known mineral and cannot be scratched. Using these as extreme cases, Mohs developed a hardness classification system on a 10-point scale. The higher the number, the harder the mineral:

1	Talc	6	Orthoclase feldspar
2	Gypsum	7	Quartz
3	Calcite	8	Topaz
4	Fluorite	9	Corundum
5	Apatite	10	Diamond

While kits are available that contain these minerals, the following common objects can also be used:

2.5	Thumbnail
3	Copper penny
4.5	Iron nail
5.5	Knife blade and window glass
6.5	Steel file
7	Flint
8.5	Emery wheel/paper
9.5	Carborundum wheel/paper

Tenacity

Tenacity refers to the cohesiveness of a mineral and its resistance to breaking, bending, and deforming. A mineral is sectile if it can be cut with a knife. *Tough* means a mineral resists hammering. *Malleable* indicates it flattens when hammered. *Brittle* or *fragile* means it breaks when hammered. If much smaller forces than hammering are used and the mineral breaks into pieces, it is *friable*; however, if it breaks into powder, it is *pulverulent*. *Flexible* means it can be bent but stays bent. *Elastic* indicates the mineral returns to its original state after being bent. These and other terms are also used to describe metals when they are worked.

Cleavage

Cleavage occurs when minerals break preferentially along crystallographic planes as a result of relatively weak bonds across the planes where particular ions are located. Most classification systems have at least five categories of cleavage quality: perfect, good, poor, indistinct, and nonexistent. *Perfect cleavage* occurs when breakage is with ease; continues to be parallel to crystallographic planes; and reveals smooth, lustrous surfaces. The crystal structures and planes involved define the types of cleavage that occur. Types of crystal structures and planes include basal, cubic, octahedral, pinicoidal, rhombohedral, and prismatic.

Fracture

Fracture refers to a breakage that does not take place along defined crystal planes. There are seven types of fracture:

1. Even results in smooth, straight surfaces.
2. Conchoidal produces smooth, curved surfaces.
3. Subconchoidal yields smooth but irregular curved surfaces.
4. Uneven generates rough, irregular surfaces.
5. Hackly indicates sharp, jagged surfaces.
6. Splintery forms elongated slivers.
7. Earthy makes small pieces, often referred to as crumbles.

Streak

Streak is the color of a powdered mineral. The powder should be as fine as possible. It is made by crushing the mineral with a mortar and pestle or, more commonly, by swiping the mineral across a streak plate usually composed of unglazed porcelain; however, clean whetstone and fine-cut files can also be used. This technique requires the mineral to be softer than the streak plate or mortar and pestle. On the Mohs hardness scale, the streak plate has a hardness of about 6.5.

Color

In some instances, the *color* of the mineral is definite and clearly helps in its identification. Minerals that have a metallic luster are good examples. However, many minerals exist in a variety of colors. Variations can be caused by defects in the lattice or by the presence of impurities, leading to polymorphism and isomorphism. Some minerals possess prismatic effects in light, including play in color, opalescence, asterism, and iridescence. The degree of these effects often depends on the mineral's amount of polish and tarnish. Consequently, the same mineral can possess a range of colors.

Luster

Like color, *luster* is an optical property of a mineral. It describes how a mineral appears to reflect light and how bright the reflection is. If a mineral is transparent, it will change with its refractivity. There are 11 categories of luster: metallic, submetallic, vitreous, adamantine, resinous, silky, pearly, greasy, pitchy, waxy, and dull. Metallic lusters are opaque with high mirror-like reflectivity, whereas submetallic lusters are nearly opaque and slightly translucent. Approximately 70% of minerals have vitreous luster, which makes them look like broken glass. Adamantine minerals may be translucent but normally have a high refractivity. They display a high brilliance and shine similar to that of diamonds. Resinous minerals are also highly refractive but are dull in color, often yellow-to-brown like honey. Silky lusters are usually caused by fibrous minerals. Pearly typically refers to reflections that come from not only the surface but also the layers below. Greasy, pitchy, and waxy lusters have the appearance and often the feel of organic coatings of grease, tar, and wax, respectively. Dull lusters have little reflectivity, which is usually caused by the mineral's rough or porous surfaces.

Diaphaneity

Diaphaneity refers to a mineral's degree of transparency or the percentage of light that is transmitted through it. There are three cases of diaphaneity: transparent, translucent, and opaque. If objects can be clearly seen through a mineral, then it has *transparent diaphaneity. Translucent diaphaneity* occurs when objects cannot be clearly seen through a mineral. *Opaque diaphaneity* means the objects cannot be seen at all.

Refractivity

Refractivity is an optical property of a transparent mineral. It can be quantified by measuring its refractive index (n), which is defined as the ratio of the velocity of light in a vacuum (c) to the velocity of light in the mineral (v). If c is taken as unity, then n is the reciprocal of v. Thus, as n increases, v decreases. In addition, Snell's law states that the refractive index (n) is also equivalent to the ratio of the sine of the angle of incidence (θ) to the sine of the angle of refraction (α).

Other Properties

Many other properties are used to identify minerals. While not included in Table 1 for simplicity reasons, they include a variety of optical and hardness properties other than those already discussed in this chapter.

Optical

Ore microscopy can also be used in reflection mode to observe several optical properties, including but not limited to pleochroism, bireflectance, polarization colors, anisotropy, internal reflection, and, of course, reflectance. These properties are differentiated by rotating a polished mineral in the absence or presence of polarized light with or without crossed polarizers. The techniques are predominantly used on opaque minerals, but they can also be used to examine translucent minerals.

Pleochroism. With pleochroism, a mineral changes colors as it is rotated while being illuminated with plane polarized light. The polarizers are not crossed.

Table 1 Select common minerals and their major properties used for identification

Name/Chemical Composition	Mohs Hardness	Color	Luster	Streak	Crystal Structure	Refractive Index (589 nm)
Apatite $Ca_5(PO_4)_3(F,Cl,OH)$	5.0	Seagreen	Vitreous to resinous	White	Hexagonal dipyramidal	1.634–1.638
Beryl $Be_3Al_2Si_6O_{18}$	7.5–8.0	White, bluish green, greenish yellow, etc.	Vitreous to resinous	White	Hexagonal dihexagonal dipyramidal	1.564–1.602
Borax $Na_2B_4O_7 \cdot 10H_2O$	2.3	Colorless, white, grayish, bluish, greenish	Vitreous to resinous	White	Monoclinic prismatic	1.45
Calcite $CaCO_3$	3.0	White or colorless	Vitreous to pearly	White to grayish	Hexagonal hexagonal-scalenohedral	1.640–1.660, 1.486
Chalcopyrite $CuFeS_2$	3.5–4.0	Brass yellow	Metallic	Greenish black	Tetragonal scalenohedral	—
Copper Cu	2.7	Copper-red, tarnishes to brown, red, black, green	Metallic	Copper-red metallic	Isometric hexoctahedral	—
Dolomite $CaMg(CO_3)_2$	3.5–4.0	Colorless or white gray	Vitreous to pearly	White	Hexagonal rhombohedral	1.679–1.681, 1.500
Galena PbS	2.5	Silvery	Metallic	Lead-gray	Isometric hexoctahedral	—
Gibbsite $Al(OH)_3$	2.5–3.0	White, greenish, blue, gray	Vitreous to dull		Monoclinic prismatic	1.58
Gypsum $CaSO_4 \cdot 2H_2O$	2.0	Colorless to white, gray, yellowish	Vitreous to silky	White	Monoclinic prismatic	1.519–1.530
Ilmenite $FeO \cdot TiO_2$	5.0–6.0	Iron-black, brown	Metallic to submetallic	Black	Hexagonal rhombohedral	—
Limonite $FeO(OH) \cdot nH_2O$	4.0–5.5	Dark brown to yellow	Vitreous to dull	Yellowish brown	Amorphous nature	2.27–2.28
Marcasite FeS_2	6.5	Pale bronze-yellow	Metallic	Grayish to brownish black	Orthorhombic dipyramidal	—
Molybdenite MoS_2	1.0–1.5	Black, silvery gray	Metallic	Greenish/bluish	Hexagonal dihexagonal dipyramidal	—
Niccolite NiAs	5.0–5.5	Pale red, white with yellowish pink	Metallic	Pale brownish	Hexagonal dihexagonal dipyramidal	—
Pyrite FeS_2	6.0–6.5	Brass-yellow	Metallic	Greenish or brownish	Isometric diploidal	—
Rutile TiO_2	6.0–6.5	Red, brown, pale yellow or blue	Metallic to adamantine	Pale brown to yellowish	Tetragonal ditetragonal dipyramidal	2.613, 2.909
Scheelite $CaWO_4$	4.5–5.0	Colorless, white, gray, brown	Vitreous to adamantine	White	Tetragonal dipyramidal	1.918–1.938
Sphalerite ZnS	3.5–4.0	Brown, yellow, red, green, black	Adamantine to resinous	Brownish to light yellow	Isometric hextetrahedral	2.369
Sylvite KCl	2.0	Colorless to white, pale gray or blue, reddish	Vitreous	White	Isometric hexoctahedral	1.4903
Talc $Mg_3Si_4O_{10}(OH)_2$	1.0	Green, brown, white gray	Pearly to greasy	White	Monoclinic triclinic	1.538–1.600
Uraninite UO_2	5.5	Steel black, brownish, pale gray	Submetallic to greasy	Brownish black	Isometric hexoctahedral	—
Wolframite $(Fe,Mn)WO_4$	4.0–4.5	Grayish to brownish black	Submetallic to resinous	Reddish brown	Monoclinic prismatic	—
Zircon $ZrSiO_4$	7.5	Reddish brown, yellow, green	Vitreous to adamantine	Uncolored	Tetragonal ditetragonal dipyramidal	1.925–2.015

Adapted from Bolles and McCullough 1985

Table 1 Select common minerals and their major properties used for identification (continued)

Tenacity	Cleavage	Fracture	Diaphaneity	Occurrence	Common Names	Special Feature
Brittle	Imperfect	Conchoidal/ uneven	Transparent to opaque	Metamorphic crystalline rocks, associated with beds of iron ore	Asparagus stone, cellophane	May be confused with beryl
Brittle	Imperfect	Conchoidal/ uneven	Transparent to subtranslucent	Granite rocks and pegmatites	Aquamarine, emerald, goshenite	May be confused with apatite
Rather brittle	Perfect	Conchoidal	Translucent to opaque	Saline lakes, beds due to evaporation of such lakes	Tincal	Co-complexing with others
Brittle	Highly perfect	Conchoidal	Transparent to opaque	Widespread constituent of sedimentary rocks and minor constituent of igneous rocks	Iceland spar, limestone	Phosphorescent
Brittle	Distinct	Uneven	Opaque	Primary veins or disseminated often with pyrite, quartz	Copper pyrites, cupropyrite	Turns magnetic on heating
Malleable and ductile	None	Hackly	Opaque	Secondary, with copper minerals near igneous rocks	Native copper	—
Brittle	Perfect	Subconchoidal	Transparent to translucent	Vein mineral or altered limestone	Pearl spar, rhomb spar, bitter spar	—
Brittle	Cubic	Even	Opaque	Veins often with pyrite, sphalerite, chalcopyrite, intrusive replacement	Galenite, lead glance, plumbago	Semiconductor
Tough	Eminent	—	Translucent	Usually with bauxite	—	—
Flexible or brittle	Eminent	Conchoidal	Transparent to opaque	Forms extensive sedimentary beds	Satin spar, alabaster, selenite	Retrograde solubility
Brittle	—	Conchoidal	Opaque	Veins near igneous rocks	Titanic iron ore, menaccanite	Paramagnetic
Brittle	None	Uneven	Opaque	Secondary iron mineral	Brown ocher, bog iron ore	Mix of hydrated iron oxides
Brittle	Poor	Uneven	Opaque	Formed near surface with galena, sphalerite, calcite, dolomite	White iron pyrites, cockscomb	Exhibits strong anisotropism
Flexible, sectile	Perfect	—	Opaque	Veins often with quartz and copper sulfides	Moly, molybdena	Feels greasy
Brittle	None	Uneven	Opaque	With sulfides and silver-arsenic minerals	Copper nickel, nickeline	Garlic odor when hot
Brittle	Indistinct	Uneven	Opaque	Primary, veins or disseminated, usually crystalline	Fool's gold, iron pyrites, mundic	Semiconductor
Brittle	Distinct	Uneven	Transparent to opaque	Frequently secondary in micas or igneous rocks; black sands	Edisonite, titanite	Among highest refractive index
Brittle	Distinct	Uneven	Transparent to translucent	Pegmatite veins or in veins associated with granite/gneiss	Tungstein, schellspath	Fluorescent under UV light
Brittle	Perfect	Conchoidal	Translucent	Often in limestone with other sulfides	Zinc blende, ruby zinc, black jack	Fluorescent and triboluminescent
Brittle	Cubic perfect	Uneven	Transparent to translucent	An evaporite	Muriate of potash, hoevelite	Optically isotropic
Sectile	Perfect	—	Subtransparent to translucent	Secondary mineral formed by alteration of nonaluminous magnesium silicates	Steatite, soapstone	Fluorescent under UV light
Brittle	—	Uneven	Opaque	Granitic pegmatites, or with ores of silver, lead, copper	Pitchblende, ulrichite	Radioactive
Brittle	Very perfect	Uneven	Opaque	In granite and pegmatite veins	Wolfram, mock-lead	Strategic mineral
Brittle	Imperfect	Concoidal	Transparent to opaque	Accessory mineral in igneous rocks	Hyacinth, azurite	Fluorescent and radioactive

Bireflectance. Bireflectance is similar to pleochroism. In this case, changes in intensity are observed as the mineral is rotated while being illuminated with plane-polarized light. The polarizers are not crossed.

Polarization colors. With polarization colors, a mineral changes colors as it is rotated while being illuminated with plane-polarized light and observed with crossed polarizers.

Anisotropy. Like bireflectance, anisotropy occurs when changes in intensity are observed as the mineral is rotated while being illuminated with plane-polarized light and observed with crossed polarizers.

Internal reflection. Internal reflections are observed when translucent minerals allow light to penetrate below the surface and reflect to the observer from cracks, crystal boundaries, cleavages, and other flaws within the crystal. The internal reflections are usually visible with plane-polarized light but are best observed with crossed polarizers.

Reflectance. Reflectance is the ratio of reflected light intensity to incident light intensity as measured with a photometer. Because some portions of the light are absorbed or transmitted, reflectance is never 100% but approaches this value with opaque minerals that have metallic lusters. Silver has the highest reflectance, near 95%. A common reference is pyrite, which has a reflectance of 55%. Reflectance can also be expressed by measuring the reflectance of a mineral, dividing by the value measured for pyrite under the same conditions, and then multiplying by 55%. If quartz (5%), magnetite (20%), galena (43%), or other common minerals with known reflectances are also present, reflectances can be simply estimated by visual inspection and comparison.

Hardness

In ore microscopy, there are three types of hardness: scratch, polishing, and micro-indentation. While they are not equivalent because they are responses to different types of forces, they are used for mineral identification.

Scratch hardness. This is Mohs hardness; however, scratches made intentionally or left behind from polishing during the sample preparation process might be observed in some minerals and not others.

Polishing hardness. During polishing, soft minerals are abraded away faster than hard minerals, producing a relief in which the harder minerals lie above the softer minerals. The Kalb-line test can be used to determine which mineral is softer if the relief is appreciable.

Micro-indentation hardness. Micro-indentation is favored over the other two methods for measuring hardness because it is more quantitative and yields linear responses to Mohs hardness in a log-log plot. Although the Vickers and Knoop techniques yield similar results, Vickers has been used more widely. When micro-indentation hardness and reflectance at a defined wavelength are plotted against one another, an identification map results. Although the map is crowded at moderately low hardness and reflectance, it is a useful tool in the identification process despite the ranges that some minerals have for both properties.

MINERAL PROCESSING

Properties that are relevant for mineral identification might not be very useful to a process engineer when the main goal is to separate the valuable mineral from the gangue. In fact, only a handful of properties can be exploited to accomplish separation on a commercial scale: specific gravity, magnetic susceptibility, electrical conductivity, and hydrophobicity. These properties are briefly described in the following sections and are compiled in Table 2 for 150 of the more common minerals using information from Carpco (2000). These properties are also used for identification purposes but were excluded from the previous discussion in this chapter because of their criticality here. However, they are discussed in detail later throughout Volume 1 of this handbook.

Specific Gravity

Density is the weight per unit volume of a substance. Specific gravity is the density ratio of the substance to water. A specific gravity of 7.5 implies that the substance is 7.5 times heavier than water of the same volume. The pycnometer is the tool most commonly used for measuring specific gravity. Its accuracy is dependent on weighing precisely and removing air, usually in the form of bubbles but sometimes in pores. The easiest way to remove air is by pulling a weak vacuum over the system. Most minerals have a definite specific gravity, but many have a range because of substitutions, impurities, and inclusions. Gravity separations are very common in mineral processing and are used to separate denser minerals from less dense minerals.

Magnetic Susceptibility

Depending on how minerals are affected by an applied magnetic field, they are generally classified as diamagnetic, paramagnetic, or ferromagnetic. When the field repels a mineral, it has a negative magnetic susceptibility and is therefore classified as diamagnetic. However, the repulsion is negligible and unlikely to be noticed. Paramagnetic minerals behave oppositely; they have positive susceptibility and thus are attracted to the magnetic field. If a paramagnetic mineral retains magnetic properties after the applied field is turned off, it is called ferromagnetic. All minerals have a magnetic susceptibility, but the applied field must be strong enough to invoke a response. Minerals that do not respond traditionally have been called nonmagnetic, although this is a misnomer. This has been corrected in Table 2 as best as possible; however, some minerals might not be diamagnetic because of substitutions, impurities, and inclusions that slightly change their composition or crystal structure. Such minerals would be very weakly paramagnetic and, similar to diamagnetic minerals, unlikely to respond to an applied field. Many minerals are paramagnetic and are normally classified as weak to strong, but only a few are ferromagnetic (e.g., magnetite and pyrrhotite).

Magnetic separations are becoming more popular in mineral processing because of the somewhat recent advent of rare earth magnets and supercooled electromagnets. Prior to approximately 1990, magnetic separations were primarily conducted with permanent magnets and electromagnets. In typical separations, the paramagnetic minerals are separated into the “mag” fraction away from the diamagnetic minerals that then report to the “nonmag” fraction. There are two other classifications of magnetic minerals: ferrimagnetic and antiferromagnetic; however, as always, they separate with the paramagnetic minerals into the mag fraction. To avoid confusion, Table 2 was not corrected in this regard.

Electrical Conductivity

Minerals are either conductors or insulators depending on their ability to transport electrical charge. When minerals are placed on a metal surface and charged, usually by passing

Table 2 Common minerals and their major properties used for identification and separation

Mineral Name	Chemical Composition	Specific Gravity	Magnetic Property*	Electrostatic Property†	Naturally Hydrophobic
Actinolite	$Ca_2(Mg,Fe)_5(Si_4O_{11})_2(OH)_2$	3.0–3.2	Paramagnetic	Insulator	No
Albite	$Na(AlSi_3O_8)$	2.6	Diamagnetic	Insulator	No
Almandine	$Fe_3Al_2(SiO_4)_3$	4.3	Paramagnetic	Insulator	No
Amphibole	$(Ca,Mg,Fe)_x(SiO_3)$	2.9–3.5	Paramagnetic	Insulator	No
Anatase	TiO_2	3.9	Diamagnetic	Conductor	No
Andalusite	Al_2SiO_5	3.2	Diamagnetic	Insulator	No
Andradite	$3CaO \cdot Fe_2O_3 \cdot 3SiO_3$	3.8	Paramagnetic	Insulator[4]	No
Anhydrite	$CaSO_4$	3.0	Diamagnetic	Insulator	No
Ankerite	$Ca(Mg,Fe)(CO_3)_2$	2.9–3.1	Paramagnetic	Insulator	No
Apatite	$Ca_5(PO_4)_3(F,Cl,OH)$	3.2	Diamagnetic	Insulator	No
Aragonite	$CaCO_3$	3.0	Diamagnetic	Insulator	No
Arsenopyrite	$FeAsS$	5.9–6.2	Paramagnetic[1]	Conductor	Weak
Asbestos	$Mg_3(Si_2O_5)(OH)_4$	2.4–2.5	Diamagnetic	Insulator	No
Augite	$Ca(Mg,Fe,Al)[(Si,Al)_2O_6]$	3.2–3.5	Paramagnetic	Conductor[5]	No
Azurite	$Cu_3(CO_3)_2(OH)_2$	3.8	Diamagnetic	Insulator	No
Baddeleyite	ZrO_2	5.6	Diamagnetic	Insulator	No
Barite	$BaSO_4$	4.5	Diamagnetic	Insulator	No
Bastnaesite	$(Ce,La,F)CO_3$	5.0	Paramagnetic	Insulator	No
Bauxite	$Al_2O_3 \cdot 2H_2O$	2.6	Diamagnetic	Insulator	No
Beryl	$Be_3Al_2(Si_6O_{18})$	2.7–2.8	Diamagnetic	Insulator	No
Biotite	$K(Mg,Fe)_3(Si_3AlO_{10})(OH,F)_2$	3.0–3.1	Paramagnetic	Insulator	No
Bismuth	Bi	9.8	Diamagnetic	Conductor	No
Borax	$Na_2B_4O_7 \cdot 10H_2O$	1.7	Diamagnetic	Insulator	No
Bornite	Cu_5FeS_4	4.9–5.0	Diamagnetic[2]	Conductor	Weak
Brannerite	$(UO,TiO,UO_2)(TiO_3)$	4.5-5.4	Paramagnetic	Conductor	No
Brookite	TiO_2	4.1	Diamagnetic	Conductor	No
Calcite	$CaCO_3$	2.7	Diamagnetic	Insulator	No
Carnotite	$K_2(UO_2)_2(V_2O_8) \cdot 2H_2O$	5.0	Diamagnetic	Insulator[4]	No
Cassiterite	SnO_2	7.0	Diamagnetic	Conductor	No
Celestite	$SrSO_4$	4.0	Diamagnetic	Insulator	No
Cerussite	$PbCO_3$	6.6	Diamagnetic	Insulator[4]	No
Chalcocite	Cu_2S	5.5–5.8	Diamagnetic	Conductor	Weak
Chalcopyrite	$CuFeS_2$	4.1–4.3	Diamagnetic[2]	Conductor	Weak
Chlorite	$(Mg,Al,Fe)_{12}[(Si,Al)_8O_{20}](OH)_{16}$	2.6–3.2	Paramagnetic	Insulator	No
Chromite	$(Mg,Fe)(Cr,Al)_2O_4$	4.6	Paramagnetic	Conductor	No
Chrysocolla	$CuSiO_3 \cdot nH_2O$	2.0–2.3	Diamagnetic	Insulator	No
Cinnabar	HgS	8.1	Diamagnetic	Insulator	Yes
Cobaltite	$(Co,Fe)AsS$	6.0–6.3	Paramagnetic	Conductor	Weak
Colemanite	$Ca_2B_6O_{11} \cdot 5H_2O$	2.4	Diamagnetic	Insulator	No
Collophanite	$Ca_3P_2O_8 \cdot H_2O$	2.6–2.9	Diamagnetic	Insulator	No
Columbite	$(Mn,Fe)(Ta,Nb)_2O_6$	5.2–8.2	Paramagnetic	Conductor	No
Copper	Cu	8.9	Diamagnetic	Conductor	No
Corundum	Al_2O_3	3.9–4.1	Diamagnetic	Insulator	No
Covellite	CuS	4.7	Diamagnetic	Conductor	Weak
Cryolite	Na_3AlF_6	3.0	Diamagnetic	Insulator[4]	No
Cuprite	Cu_2O	5.8–6.2	Diamagnetic	Insulator	No
Diamond (nat)	C	3.5	Diamagnetic	Insulator	Yes
Diamond (syn)	C	3.5	Paramagnetic	Insulator	No
Diopside	$CaMg(Si_2O_6)$	3.3–3.4	Paramagnetic[1]	Insulator	No
Dolomite	$CaMg(CO_3)_2$	1.8–2.9	Diamagnetic	Insulator	No
Epidote	$Ca_2(Al,Fe)_3(Si_3O_{12})(OH)$	3.4	Paramagnetic	Insulator	No
Euxenite	$(Y,Er,Ce,La,U)(Nb,Ti,Ta)_2(O,OH)_6U_3O_8$	4.7–5.2	Paramagnetic	Conductor	No

(continues)

Table 2 Common minerals and their major properties used for identification and separation (continued)

Mineral Name	Chemical Composition	Specific Gravity	Magnetic Property[*]	Electrostatic Property[†]	Naturally Hydrophobic
Feldspar	$(K,Na,Ca\ldots)_x(AlSi)_3O_8$	2.6–2.8	Diamagnetic	Insulator	No
Ferberite	$FeWO_4$	7.5	Paramagnetic[3]	Conductor	No
Flint	SiO_2	2.6	Diamagnetic	Insulator	No
Fluorite	CaF_2	3.2	Diamagnetic	Insulator	No
Franklinite	$(Zn,Mn)Fe_2O_4$	5.1–5.2	Ferromagnetic	Conductor	No
Gahnite	$ZnAl_2O_4$	4.6	Diamagnetic	Insulator	No
Galena	PbS	7.5	Diamagnetic	Conductor	Weak
Garnet	Complex Ca,Mg,Fe,Mn silicates	3.4–4.3	Paramagnetic[1]	Insulator[4]	No
Gibbsite	$Al(OH)_3$	2.4	Diamagnetic	Insulator	No
Goethite	$HFeO_2$	4.3	Paramagnetic	Insulator[4]	No
Gold	Au	15.6–19.3	Diamagnetic	Conductor	No
Graphite	C	2.1–2.2	Diamagnetic	Conductor	Yes
Grossularite	$Ca_3Al_2(SiO_4)_3$	3.5	Diamagnetic	Insulator[4]	No
Gypsum	$CaSO_4 \cdot 2H_2O$	2.3	Diamagnetic	Insulator	No
Halite	$NaCl$	2.5	Diamagnetic	Insulator[4]	No
Hematite	Fe_2O_3	5.2	Paramagnetic	Conductor	No
Hornblende	$Ca_2Na(Mg,Fe^{2+})_4(Al,Fe^{3+})[(Si,Al)_4O_{11}](OH)_2$	3.1–3.3	Paramagnetic	Insulator[4]	No
Hubnerite	$MnWO_4$	6.7–7.5	Paramagnetic[1]	Conductor	No
Hypersthene	$(Mg,Fe)SiO_3$	3.4	Paramagnetic	Insulator	No
Ilmenite	$FeTiO_3$	4.7	Paramagnetic	Conductor	No
Ilmenorutile	$(Nb_2O_5,Ta_2O_5)_xTiO_2$	5.1	Paramagnetic	Conductor	No
Ilvaite	$CaFe_2(FeOH)(SiO_4)_2$	4.0	Paramagnetic	Conductor[5]	No
Kaolinite	$Al_2Si_2O_5(OH)_4$	2.6	Diamagnetic	Insulator	No
Kyanite	$Al_2O(SiO_4)$	3.6–3.7	Diamagnetic	Insulator	No
Lepidolite	$KLiAl_2(Si_3O_{10})(OH,F)_2$	2.8–2.9	Diamagnetic	Insulator	No
Leucoxene	$FeTiO_3 \rightarrow TiO_2$ (Alteration product)	3.6–4.3	Paramagnetic[1]	Conductor	No
Limonite	$HFeO_2 \cdot nH_2O$	2.2–2.4	Paramagnetic[1]	Insulator[4]	No
Magnesite	$MgCO_3$	3.0	Diamagnetic	Insulator	No
Magnetite	Fe_3O_4	5.2	Ferromagnetic	Conductor	No
Malachite	$Cu_2CO_3(OH)_2$	4.0	Diamagnetic	Insulator	No
Manganite	$MnO(OH)$	4.3	Paramagnetic[1]	Conductor	No
Marcasite	FeS_2	4.6–4.9	Diamagnetic	Conductor	Weak
Martite	Fe_2O_3	5.2	Paramagnetic	Conductor	No
Microcline	$KAlSi_3O_8$	2.6	Diamagnetic	Insulator	No
Microlite	$Ca_2Ta_2O_7$ (Pyrochlore group)	5.5	Diamagnetic	Insulator	No
Millerite	NiS	5.2–5.6	Paramagnetic	Conductor	Weak
Molybdenite	MoS_2	4.7–5.0	Diamagnetic	Conductor	Yes
Monazite	$(Ce,La,Y,Th)PO_4$	4.9–5.5	Paramagnetic	Insulator	No
Mullite	$Al_6Si_2O_{13}$	3.2	Diamagnetic	Insulator	No
Muscovite	$KAl_2(AlSi_3O_{10})(F,OH)_2$	2.8–3.0	Diamagnetic	Insulator	No
Nahcolite	$NaHCO_3$	2.2	Diamagnetic	Insulator	No
Nepheline Syenite	$(Na,K)(Al,Si)_2O_4$	2.6	Diamagnetic	Insulator	No
Niccolite	$NiAs$	7.6–7.8	Paramagnetic	Conductor	No
Olivine	$(Mg,Fe)_2(SiO_4)$	3.3–3.5	Paramagnetic	Insulator	No
Orpiment	As_2S_3	3.4–3.5	Diamagnetic	Conductor	Weak
Orthoclase	$K(Al,Si_3O_8)$	2.5–2.6	Diamagnetic	Insulator	No
Periclase	MgO	3.6	Diamagnetic	Insulator	No
Perovskite	$CaTiO_3$	4.0	Diamagnetic	Insulator	No
Petalite	$LiAl(Si_2O_5)_2$	2.4	Diamagnetic	Insulator	No
Phosphate (pebble)	$Ca_3P_2O_8 \cdot H_2O$	2.6–2.9	Diamagnetic	Insulator	No
Platinum	Pt	14.0–21.5	Diamagnetic[2]	Conductor	No
Pyrite	FeS_2	5.0	Diamagnetic[2]	Conductor	Weak

(continues)

Table 2 Common minerals and their major properties used for identification and separation (continued)

Mineral Name	Chemical Composition	Specific Gravity	Magnetic Property*	Electrostatic Property†	Naturally Hydrophobic
Pyrochlore	$(Na,Ca...)_2(Nb,Ta...)_2O_6(F,OH)$	4.2–4.4	Diamagnetic	Conductor	No
Pyrolusite	MnO_2	4.7–5.0	Diamagnetic[2]	Insulator	No
Pyrope	$Mg_3Al_2(SiO_4)_3$	3.5	Diamagnetic	Insulator[4]	No
Pyroxene	$(Ca,Mg,Fe,Al)_2Si_2O_6$	3.1–3.6	Paramagnetic[1]	Insulator[4]	No
Pyrrhotite	$Fe_{x-1}S_x$	4.6–4.7	Ferromagnetic	Conductor	Weak
Quartz	SiO_2	2.7	Diamagnetic	Insulator	No
Realgar	AsS	3.6	Diamagnetic	Conductor	Weak
Rhodochrosite	$MnCO_3$	3.7	Diamagnetic	Insulator[4]	No
Rhodonite	$MnSiO_3$	3.6–3.7	Diamagnetic	Insulator[4]	No
Rutile	TiO_2	4.2–4.3	Diamagnetic	Conductor	No
Samarskite	$(Y,Er...)_4[(Nb,Ta)_2O_7]_3$	5.6–5.8	Paramagnetic[3]	Conductor	No
Scheelite	$CaWO_4$	6.1	Diamagnetic	Insulator	No
Serpentine	$Mg_6(Si_4O_{10})(OH)_8$	2.5–2.7	Paramagnetic	Insulator	No
Siderite	$FeCO_3$	3.9	Paramagnetic	Insulator[4]	No
Sillimanite	$Al_2O(SiO_4)$	3.2	Diamagnetic	Insulator	No
Silver	Ag	10.1–11.1	Diamagnetic	Conductor	No
Smithsonite	$ZnCO_3$	4.1–4.5	Diamagnetic	Insulator	No
Sodalite	$Na_8(Al_6Si_6O_{24})Cl_2$	2.1–2.3	Diamagnetic	Insulator	No
Spessartine	$Mn_3Al_2(SiO_4)_3$	4.2	Diamagnetic	Insulator	No
Sphalerite	ZnS	3.9–4.0	Paramagnetic[1]	Conductor[5]	Weak
Sphene	$CaTi(SiO_4)(F,OH)$	3.3–3.6	Diamagnetic	Insulator[4]	No
Spinel	$MgAl_2O_4$	3.6	Diamagnetic[2]	Conductor	No
Spodumene	$LiAl(SiO_3)_2$	3.1–3.2	Diamagnetic	Insulator	No
Stannite	Cu_2FeSnS_4	4.3–4.5	Diamagnetic	Conductor	No
Staurolite	$Fe^{2+}Al_4(Si_4O_{11})_2O_2(OH)_2$	3.6–3.8	Paramagnetic	Insulator[4]	No
Stibnite	Sb_2S_3	4.6	Diamagnetic	Conductor	Weak
Struverite	$(Ta_2O_5,Nb_2O_5)_xTiO_2$	5.1	Paramagnetic	Conductor	No
Sulphur	S	2.1	Diamagnetic	Insulator	Yes
Sylvite	KCl	2.0	Diamagnetic	Insulator	No
Talc	$Mg_3(Si_4O_{10})(OH)_2$	2.7–2.8	Diamagnetic	Insulator	Yes
Tantalite	$(Fe,Mn)(Ta,Nb)_2O_6$	5.2–8.2	Paramagnetic	Conductor	No
Tapiolite	$Fe(Ta,Nb)_2O_6$	7.3–7.8	Paramagnetic	Conductor	No
Tetrahedrite	$(Cu,Fe)_{12}Sb_4S_{13}$	5.0	Paramagnetic	Conductor	No
Thorianite	ThO_2	9.7	Diamagnetic	Insulator	No
Thorite	$ThSiO_4$	4.5–5.4	Diamagnetic	Insulator	No
Topaz	$Al_2SiO_4(F,OH)_2$	3.5–3.6	Diamagnetic	Insulator	No
Tourmaline	$(Na,Ca)(Mg,Fe^{2+},Fe^{3+},Al,Li)_3Al_6(BO_3)_3Si_6O_{18}(OH)_2$	2.9–3.2	Paramagnetic[1]	Insulator[4,6]	No
Uraninite	UO_2	11.0	Paramagnetic	Insulator	No
Vermiculite	$Mg_3(AlSi_3O_{10})(OH)_2.nH_2O$	2.4–2.7	Diamagnetic	Insulator	No
Wolframite	$(Fe,Mn)WO_4$	6.7–7.5	Paramagnetic	Conductor	No
Wollastonite	$CaSiO_3$	2.8–2.9	Diamagnetic	Insulator	No
Wulfenite	$PbMoO_4$	6.7–7.0	Diamagnetic	Conductor	No
Xenotime	YPO_4	4.4-5.1	Paramagnetic	Insulator	No
Zeolite	Hydrated alumino-silicate of Ca and Na	2.0–2.5	Diamagnetic	Insulator	No
Zincite	ZnO	5.7	Diamagnetic	Insulator	No
Zircon	$ZrSiO_4$	4.7	Diamagnetic	Insulator	No

Adapted from Carpco Inc. 2000

* Magnetic property will change subject to exact composition of the mineral from various locations. The most common state is shown in the table. 1: Magnetic property may change from paramagnetic to diamagnetic. 2: Magnetic property may change from diamagnetic to paramagnetic. 3: Magnetic property may change from paramagnetic to ferromagnetic.

† Electrical conductivity will change subject to exact composition and treatment of temperature on the mineral from various locations. The most common state is shown in the table. 4: Transformation may occur from insulator to conductor due to temperature. 5: Transformation may occur from conductor to insulator due to composition. 6: Transformation may occur from insulator to conductor due to composition.

through an electrical field or corona, they become pinned to the metal surface. However, conductors dissipate that charge quickly and no longer remain pinned, whereas insulators retain their charge and remain pinned. Other forces, such as momentum or gravity, are then used to separate the minerals. Such practices are rare in mineral processing with the exception of beach sands, where differences among insulating minerals are significant compared to differences among conducting minerals.

Hydrophobicity

Hydrophobicity is the property exploited in froth flotation separations. If a water droplet spreads across the surface completely, the surface is wetted and referred to as hydrophilic. If the droplet stays beaded up, even partially, it is hydrophobic. Bubbles generated in a slurry of mineral particles will attach to the hydrophobic particles and float them to the top where a froth forms and is scraped off. Because hydrophilic particles stay in the slurry, a separation is made. Coal, diamond, talc, and sulfur are known to possess strong natural hydrophobicity. Several sulfide minerals do as well, but most are naturally weak. However, in many instances, the sulfide can be made more hydrophobic by slight oxidation of its surface forming metal-deficient surfaces, sulfide-rich surfaces, and even elemental sulfur. Most minerals are not naturally hydrophobic and have to be treated with surface-active reagents called collectors to make them hydrophobic. Many other reagents are used to enhance the process, including frothers to stabilize the froth, activators to promote collector adsorption and help make particles hydrophobic, depressants to prevent collector adsorption and help keep other particles hydrophilic, and modifiers to act as depressants for one mineral and activators for another. Most modifiers are used to adjust the pH.

From the perspective of flotation reagents, minerals/ores are classified into two distinct groups: (1) sulfide minerals/ores and (2) nonsulfide minerals/ores. The rationale for this classification is that separation schemes and reagent selection and usage for nonsulfide minerals are distinctly different from those for base metal sulfide minerals. Tables 3 and 4 list the reagents used for common sulfide and nonsulfide minerals, respectively, using information from two major flotation reagent manufacturers: Cytec and Clariant (Thomas 2010; Clariant Mining 2013).

Natural resources are nonrenewable. It is indisputable that richer ores are becoming less abundant and poor-quality resources are being processed. Not only are the valuable contents in these ores decreasing, but the association of the gangue is also becoming increasingly intricate with the valuables. This calls for very fine grinding to achieve an adequate degree of liberation. Most unit operations in mineral processing fail to produce good separation in such fine ranges. Therefore, froth flotation is increasingly used in ore beneficiation. Experts estimate that more than 50% of the world's natural resources are now processed by flotation.

EXTRACTIVE METALLURGY

In extractive metallurgy, hydrometallurgical and pyrometallurgical processes are used in the presence and absence of liquid water, respectively. The processes involve extracting the valuable metal content in concentrates and ores through chemical change and then recovering the metal value. To do both, chemical properties are primarily exploited and are greatly dependent on the final metal product being made. However, only a few of these chemical properties are used to identify minerals (e.g., if dilute acid is added to the mineral and it effervesces, it is likely calcite; if a slag cools at 800°C as opposed to 1,000°C, it may be because of the presence of Na-rich plagioclase). The primary property being exploited in hydrometallurgy is solubility that, in turn, is affected by system factors such as temperature, pressure, and chemistry (e.g., pH, lixiviant, concentration, aqueous/gaseous oxidant, presence of contaminants). Likewise, for pyrometallurgy, the property being exploited is phase change (e.g., melting or sublimation points) as determined by the same system factors although the chemistry is slightly different (e.g., partial pressures, reactants, solid/gaseous oxidant, and presence of contaminants). These system factors can be thermodynamically modeled to explain how a process works or to determine whether a proposed process is feasible. The details are discussed in Part 12 of this handbook.

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Table 3 Reagent selection guidelines for the flotation of common base metal sulfide minerals*

Valuable	Major Minerals	Common Ore Concentration	Ore Types	Collector†	Modifier‡	Depressant or Dispersant‡§	Activator‡	pH Range
Ag (silver)	Argentite Ag_2S Pyrargyrite Ag_3SbS_3 Proustite Ag_3AsS_3 Acanthite Ag_2S Freibergite $(Ag,Cu,Fe)_{12}(Sb,As)_4S_{13}$	0.1–100 ppm	Ag values found in polymetallic ores (e.g., Pb-Zn, Cu-Pb-Zn, and Cu-Zn)	Dithiophosphinates, xanthate, alkyl/aryl dithiophosphates, mercaptobenzothioazoles, dithiocarbamates	Na_2CO_3, lime, H_2SO_4	$ZnSO_4$, dextrin, nigrosine, NaCN, $Zn(CN)_2$, tannin, sodium silicate, sulfoxy compounds	—	5–10.5
	Native silver Ag-Au alloys (electrum)		Ag values in primary Au ores	Xanthate, dithiocarbamates, mercaptobenzothioazoles, dithiophosphinates, monothiophosphates	H_2SO_4, lime	—	$CuSO_4$, $Pb(NO_3)_2$	5–9.5
Au (gold)	Native gold Au-Ag alloys (electrum) Au-Cu alloys	0.05–10 ppm	Bulk flotation of tellurides and alloys	Xanthates, dithiophosphinates, mercaptobenzothioazoles, dithiocarbamates, alkyl/aryl mono/dithiophosphates	H_2SO_4, lime	Na_2CO_3, sodium silicate, polyphosphates, synthetic polymeric modifiers	—	5–10
	Krennerite $(Au,Ag)Te_2$ Calaverite $AuTe_2$ Petzite Ag_3AuTe_2 Sylvanite $(AuAg)_2Te_4$							
	Pyrite FeS_2 Marcasite FeS_2 Arsenopyrite FeAsS, Enargite Cu_3AsS_4, Tennantite $Cu_{12}As_4S_{13}$ Tetrahedrite $Cu_{12}Sb_4S_{13}$ Chalcopyrite $CuFeS_2$, Pyrrhotite $Fe_{(1-x)}S_x$	0.05–10 ppm	Flotation of Au/Ag values associated and disseminated in these minerals	Xanthates, dithiocarbamates, mercaptobenzothiazoles, alkyl/aryl mono/dithiophosphates	H_2SO_4, lime	Na_2CO_3, sodium silicate, polyphosphates, synthetic polymeric modifiers	$CuSO_4$, $Pb(NO_3)_2$	5–9
Co (cobalt)	Cobaltite CoAsS Heterogenite CoO(OH) Safflorite $(CoAs_2)$ Glaucodot (Co,Fe)AsS Skutterudite $(Co,Ni,Fe)As_3$	0.2%–1%	Cu-Co ores (Zambian Cu belt)	Dithiophosphates, xanthates, xanthate ester thionocarbamates	Na_2CO_3	Na_2CO_3	Na_2S NaSH	8–10
Cu (copper)	Azurite $Cu_3(CO_3)_2(OH)_2$ Chrysocolla $Cu[SiO_3]$ ÈnH_2O Malachite $Cu_2CO_3(OH)_2$ Cuprite Cu_2O	0.2%–4%	Selective flotation of oxide and sulfide Cu minerals	Xanthates, alkyl hydroxamates, fatty acids, fuel oil†	Na_2CO_3, lime	Na_2SiO_3 Na_2S Polyphosphates Na_2CO_3	Na_2S NaSH	6–9.5
	Bornite Cu_5FeS_4 Chalcopyrite $CuFeS_2$ Chalcocite Cu_2S Covellite CuS	0.2%–1.5%	Selective flotation of Cu sulfide minerals	Aliphatic and aromatic dithiophosphates, thionocarbamates, xanthate esters, alkyl sulfides, dithiophosphinates, hydrocarbon oil†	lime	Na_2SiO_3, synthetic polymeric modifiers, sulfoxy compounds	—	8–12
	Enargite Cu_3AsS_4 Tennantite $Cu_{12}As_4S_{13}$ Tetrahedrite $Cu_{12}Sb_4S_{13}$							
Mo (molybdenum)	Molybdenite MoS_2	0.005%–0.1%	Primary Mo	Xanthate esters, hydrocarbon oil†	—	Sodium silicate	—	7–9
		0.1%–0.4%	Cu-Mo ores	See Cu section	—	—	—	—

(continues)

Table 3 Reagent selection guidelines for the flotation of common base metal sulfide minerals* (continued)

Valuable	Major Minerals	Common Ore Concentration	Ore Types	Collector†	Modifier‡	Depressant or Dispersant‡§	Activator‡	pH Range
Ni (nickel)	Millerite NiS Niccolite NiAs Pentlandite $(Fe,Ni)_9S_8$, Mackinawite $(Fe,Ni)_{1+x}S$ Violarite $Fe^{2+}Ni_2^{3+}S_4$	0.2%–2%	Ni, Ni-Cu Massive sulfide ores	Xanthates, alkyl dithiophosphates, dithiocarbamates, dithiophosphinates	H_2SO_4, lime	Na_2SiO_3, NaCN, synthetic polymeric modifiers, DETA	$CuSO_4$	5–10
			Serpentine-hosted Ni ores		H_2SO_4, Na_2CO_3	CMC, dextrin guar gum	$CuSO_4$	
Pb (lead)	Cerussite $PbCO_3$ Anglesite $PbSO_4$ Plumbojarosite $Pb_{0.5}Fe^{3+}_3(SO_4)_2(OH)_6$	0.5%–2%	Sulfidization-flotation or direct flotation	Condensate amines, xanthates, mercaptobenzothiazoles	Na_2CO_3	—	Na_2S	7–9
	Galena PbS	0.2%–3%	Selective flotation from Cu/Pb or bulk	Dithiophosphinates, xanthates, aryl dithiophosphates	Lime, Na_2CO_3	NaCN, $Zn(CN)_2$, $ZnSO_4$, MBS, SO_2, dextrin, nigrosine	NaCN	6–9.5
Pt/Pd/Rd (platinum group metals, or PGMs)	Braggite (Pt,Pd,Ni)S Sperrylite $PtAs_2$ Cooperite PtS Metallics/alloys such as: Platiniridium (PtIr) Ferroplatinum (FePt)	0.5–5 ppm	Selective flotation of PGM mineral values disseminated in Ni and Cu minerals	Xanthates, mercaptobenzothiazoles, dithiocarbamates, thionocarbamates, dithiophosphates	—	CMC, dextrin, guar gum, synthetic polymers	$CuSO_4$	7–9
Zn (zinc)	Hemimorphite $Zn_4Si_2O_7(OH)_2{*}H_2O$ Hydrozincite $Zn_5(CO_3)_2(OH)_6$ Smithsonite $ZnCO_3$ Willemite $ZnSiO_4$	0.2%–5%	Bulk flotation of oxide and sulfide zinc minerals	Condensate amines, ether amines, alkyl hydroxamates, xanthates, hydrocarbon oil†	NaOH	Na_2SiO_3	Na_2S NaSH	7–9
	Sphalerite ZnS Marmatite (Zn,Fe)S	1%–15%	Activation and flotation of Zn in polymetallic ores	Xanthates, dithiophosphates, dithiophosphinates, thionocarbamates	Lime	—	$CuSO_4$	9–12
Others (e.g., Bi, Sb, and Hg)	Bismuthinite Bi_2S_3 Aikinite PbCuBiS3	0.2%–0.5%	Selective flotation in polymetallic ores	Xanthates, mercaptobenzothiazoles, alkyl dithiophosphates	Lime	Na_2CO_3 NaCN Activated carbon	$Pb(NO_3)_2$	8–12
	Stibnite Sb_2S_3	0.5%–1%	—	Xanthates, hydrocarbon oil†	Na_2CO_3	Excess NaCN, Na_2SiO_3	$Pb(NO_3)_2$ $CuSO_4$	6.5–8
	Cinnabar HgS	0.2%–5%	—	Xanthates, alkyl and aryl dithiophosphates	—	Na_2SiO_3	—	7–10

*Notes:

- This table is based on industry-wide averages and is therefore meant to be a starting-point recommendation and not an end-means conclusion. A reagent scheme cannot be determined for a given ore type without proper laboratory and plant testing.
- Frothers are also subject to these parameters but are not listed here because all essentially work. Short-chain aliphatic alcohols include methyl isobutyl carbinol (MIBC) as the most widely used frother for sulfide flotation; others are cresylic acid and alkoxy-substituted paraffins (e.g., triethoxybutane); hydrocarbons may be needed to stabilize the froth, but caution is needed because they could act as a nonselective collector. Long-chain polyglycols include both unsubstituted and alkyl monoethers.

†Collectors of hydrocarbon and related oils can be used and may be specified above as fuel oil, kerosene, and so forth.

‡pH modifiers, depressants/dispersants, and activators (type and dosage) depend on value and gangue mineralogy, ore type, flow-sheet and operating philosophy, equipment, particle size, and process water chemistry.

§CMC = carboxymethyl cellulose; DETA = diethylene triamine; MBS = sodium metabisulfite.

Table 4 Reagent selection guidelines for flotation of common nonsulfide minerals*

Valuable	Minerals	Weight % in Ore	Processing Strategy	Collector†	Frother‡	Extender	Modifier	Depressant§	Activator	pH Range
Aluminum	Bauxite Al_2O_3ÈH_2O Gibbsite [Al(OH)$_3$], Diaspore [α-AlO(OH)] Boehmite [γ-AlO(OH)]	30–70	Direct selective flotation of bauxite from silica (current practice); reverse flotation of gangue (silica, etc.) is an option	Fatty acid (primarily), primary amine for reverse flotation	Alcohol and/ or glycol as needed	Hydrocarbon oil	Na_2CO_3	Na_2SiO_3, Na_2CO_3	—	8–9
Barite	Barite $BaSO_4$	0.2%–0.5% Ba	Flotation of barite from calcite, fluorite, and other silicates	DASS, alkyl sulfate, PS, fatty acid	Alcohol and/ or glycol as needed	—	NaOH, Na_2CO_3, Na_2SiO_3, citric acid	$AlCl_3$, $FeCl_3$, F, $K_2Cr_2O_7$, quebracho	$BaCl_2$ Pb salts	8–10
Coal	Coal	15%–40%	Flotation of coal from ash	Hydrocarbon oil and frothers (mixture of aliphatic alcohol, ethers, and esters)	See Collector column	—	—	—	—	Natural
Feldspar	Feldspar [Na,K] (Al Si_3O_8), $CaAl_2Si_2O_8$	7%–8% Na_2O or K_2O	Removal of mica, silica, and Fe oxides from feldspar	Alkyl diamine, alkyl ether diamine for mica removal, fatty acid for Fe removal, amine again for feldspar removal	Alcohol and glycol as needed	Hydrocarbon oil	—	Na_2SiF_6, Na_2SiO_3, H_2SO_4, Al_2 $(SO_4)_3$	HF	1.5–3
Fluorspar	Fluorite CaF_2	2%–10% CaF_2	Flotation of fluorite from silica	Fatty acids, PS	Alcohol and glycol as needed	PAE, modified sodium carboxylate, hydrocarbon oil	Na_2CO_3, Na_2SiO_3, quebracho starch	$K_2Cr_2O_7$, $BaCl_2$, Na_2SiF_6, citric acid, Al^{3+} salts, Na_2SiO_3	Hot pulp	7–9
Garnet	Garnet minerals (Mg,Fe,Mn,Ca)$_3$ (Al,Fe,Cr)$_2$ [SiO$_4$]$_3$	Variable	Flotation of garnet from silicates	AEM, alkyl amine, fatty acids, sulfonated fatty acids, PS	—	Hydrocarbon oil	H_2SO_4	Excess acid	—	3–4
Glass and foundry sands	Quartz SiO_2	1%–3%	Removal of Fe and Ti impurities from sand	AEM, alkyl ether diamine, quaternary alkyl amine, fatty acid, PS, DASS	Alcohol and glycol as needed	Hydrocarbon oil	NaOH	H_2SO_4, HF, NaF Na_2SiO_3	$CaCl_2$	8.5–9.5
Heavy mineral sands (Ti, Zr)	Anatase TiO_2 Brookite TiO_2 Ilmenite $FeTiO_3$ Rutile TiO_2 Titanite $CaTiSiO_5$ Zircon $ZrSiO_4$	2%–5% THM (total heavy minerals)	Flotation of heavy minerals from silica, optional feldspar removal	PAE, fatty acids, AS, fatty amine to remove feldspar	Alcohol and glycol as needed	Hydrocarbon oil	H_2SO_4, Na_2SiO_3, Na_2Co_3	Caustic starch, dextrin, synthetic polymeric modifiers	$CuSO_4$	8–9
Iron	Hematite Fe_2O_3 Magnetite Fe_3O_4	32%–50% Fe	Reverse flotation of silica from hematite	Fatty and etheramines, fatty acids, PS	Alcohol or glycol as needed	Hydrocarbon oil	H_2SO_4	Caustic starch, tannic acid	Desliming (optional)	3–6

(continues)

Table 4 Reagent selection guidelines for flotation of common nonsulfide minerals* (continued)

Valuable	Minerals	Weight % in Ore	Processing Strategy	Collector†	Frother‡	Extender	Modifier	Depressant§	Activator	pH Range
Kaolin	Kaolinite $Al_4Si_4O_{10}(OH)_8$	2%–3% TiO_2	Flotation of TiO_2 and Fe_2O_3 from kaolin	Alkyl hydroxamates	—	—	—	—	—	2–2.5
Kyanite	Kyanite Al_2SiO_5	Variable	Flotation of sulfide impurities followed by flotation of kyanite	Sulfides removed using dithiocarbamate, fatty acids, and PS; DASS for floating kyanite	Alcohol or glycol as required	—	H_2SO_4	—	—	8 then 2.5–3
Limestone	Calcite Aragonite $CaCO_3$ Dolomite $CaMg[CO_3]_2$	1%–9% Silica	Flotation of limestone from silica	Fatty acid or amine, PAE	Alcohol and/ or glycol as needed	—	Na_2CO_3,	Excess Na_2SiO_3, caustic starch, NPPE, quebracho $K_2Cr_2O_7$	—	Natural
Lithium	Lepidolite $KLi_2Al(Al,Si)_3O_{10}(F,OH)_2$	Li_2O_5- 5%–8%	Flotation of Li minerals from other silicates	Fatty acids, alkyl amines	Alcohol or glycol as needed	Hydrocarbon oil	H_2SO_4	Lactic acid HF, starch, dextrine, Na_2SiO_3	—	7–11
	Spodumene $LiAl[Si_2O_6]$								$Pb(NO_3)_2$	
Manganese	Pyrolusite MnO_2	8%–15% Mn	Flotation of Mn minerals away from silicates	Fatty acid, PS, DASS	Alcohol or glycol as needed	Hydrocarbon oil	Na_2CO_3, NaOH, Na_2SiO_3	Phosphates quebracho, excess Na_2SiO_3	Mn^{2+}can be used	4–5 and 8–10
	Rhodochrosite $MnCO_3$									8–10
Mica	Muscovite $KAl_2(AlSi_3O_{10})(OH,F)_2$	5%–15%	Flotation of mica away from silicates	PAE, fatty acids, AS, fatty amines	Alcohol as needed	Hydrocarbon oil	H_2SO_4 polyphosphates	HF, starch, Na_2SiO_3	—	2.5–4
Niobium	Columbite $FeNb_2O_6$	0.5%–7%	Reverse flotation of carbonate/silicates followed by direct flotation of Nb	Fatty acids for gangue, alkyl amines, imidazoline for Nb	Alcohol or glycol as needed	—	Na_2SiO_3	Caustic starch	H_2SiF_6, oxalic acid	8 for reverse, 3–5 for Nb
	Pyrochlore $(Na, Ca)_2(Nb, Ti, Ta)_2O_6(OH,F,O)$									
Phosphate	Apatite $Ca_5(PO_4)_3(F,OH)$ Collophanite $Ca_5(PO_4, CO_3)_3F$ Phosphorite $Ca_5(PO_4)_3(F,OH,CO_3)$	5%–23% P_2O_5	Double flotation of phosphate then purification by silica removal	Fatty acids, PS, DASS, PAE modified sodium carboxylate, alkyl ether diamine	Glycols	Hydrocarbon oil	NaOH, Na_2CO_3, NH_3, caustic starch, synthetic polymeric modifiers	NaF, H_2SiF_6, H_3PO_4, Na_2SiO_3, excess NaOH	Pb salts	9.0–10.0 then 6–7

(continues)

Table 4 Reagent selection guidelines for flotation of common nonsulfide minerals[*] (continued)

Valuable	Minerals	Weight % in Ore	Processing Strategy	Collector[†]	Frother[‡]	Extender	Modifier	Depressant[§]	Activator	pH Range
Potash	Sylvite KCl	25% K_2O, 40% KCl	Flotation of sylvite from halite (NaCl)	Alkyl amines	Alkyl polyglycols as needed	Hydrocarbon oil	—	Dextrin, guar, starch, CMC, synthetic polymeric modifiers	—	Natural
Rare earth elements (REE)	Bastnaesite [REE(CO_3)]F Monazite (REE)PO_4 Xenotime (REE)PO_4	1%–5% REE	Flotation of rare earths from silicates	Fatty acids, alkyl hydroxamates	Alcohol and glycol as needed	—	Na_2S Na_2CO_3, Na_2SiO_3	Strong acids	Hot pulp	5–8, 9.5–10 with hydroxamates
Talc	Talc $Mg_3Si_4O_{10}(OH)_2$	40%–55%	—	—	Alcohol as needed	—	—	—	—	7–9
Tantalum	Tantalite $MnTa_2O_6$	0.5%–1%	Removal of sulfides then flotation of Ta and Sn	Xanthate to float sulfides, DASS, PAE, AS for Ta	Alcohol and glycols as needed	Hydrocarbon oil	—	Caustic starch Na_2SiO_3	H_2SiF_6	5
Ti, Zr (heavy mineral sands)	Anatase TiO_2 Brookite TiO_2 Ilmenite $FeTiO_3$ Rutile TiO_2 Titanite $CaTiSiO_5$ Zircon $ZrSiO_4$	2%–5% THM (total heavy minerals)	Flotation of heavy minerals from silica, optional feldspar removal	PAE, fatty acids, AS, fatty amine to remove feldspar	Alcohol and glycol as needed	Hydrocarbon oil	H_2SO_4, Na_2SiO_3, Na_2Co_3	Caustic starch, dextrin, synthetic polymeric modifiers	$CuSO_4$	8–9
Tin	Cassiterite SnO_2	0.5%–1%	Removal of sulfides then flotation of Sn	Xanthate to float sulfides, PS, DASS styrene phosphonic acid to float Sn	Alcohol and glycols as needed	Hydrocarbon oil	H_2SO_4	NaF, $BaCl_2$, lime, tannic acid, Na_2SiO_3	Desliming	3–5
Tungsten	Huebnerite $MnWO_4$ Scheelite $CaWO_4$ Wolframite (Fe,Mn)WO_4	0.1%–5%	Flotation of W away from gangue silicates	Fatty acids, modified sodium carboxylate	Alcohol or glycol as needed	—	Na_2SiO_3, Na_2CO_3, NaOH	Quebracho, citric acid	—	9–10.5
Uranium	Uraninite U_3O_8 Carnotite $K_2(UO_2)_2(VO_4)_2 3H_2O$	0.1%–1%	Flotation of U minerals from silicates	Fatty acid	Alcohol and glycol as needed	—	Na_2CO_3	Na_2SiO_3	Pb salts	8–9
Vanadium	Vanadinite $Pb_5(VO_4)_3Cl$	0.5%–2%	Flotation of calcite then silica	Fatty acid	Alcohol or glycol as needed	—	Na_2CO_3	—	Na_2S, $CuSO_4$, Pb salts	8–9
Wollastonite	Wollastonite $Ca_3[Si_3O_9]$	20%–50%	Flotation of impurities away from wollastonite	Alkyl amines, AS	Alcohol or glycol as needed	—	H_2SO_4	Tannic acid	Pb salts to activate pyroxene	9 then 3–5

[*] This table is based on industry-wide averages and is therefore meant to be a starting-point recommendation and not an end-means conclusion. A reagent scheme cannot be determined for a given ore type without proper laboratory and plant testing, as detailed in Chapter 7.5, "Flotation Chemicals and Chemistry."

[†] AEM = alkyl ether amine; AS = alkyl sulfate; DASS = dialkyl sulfosuccinamate; PAE = phosphoric acid esters; PS = petroleum sulfonate

[‡] Frothers: Although specified in this table, the footnote regarding frothers in Table 3 generally applies here too.

[§] CMC = carboxymethyl cellulose; NPPE = nitrophenyl pentyl ether