INFLUENCE OF THE MINERALOGY AND THE EXTRACTION PROCESS ON THE TAILINGS MANAGEMENT

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In the design of the most cost-effective metallurgical process for treating ores and concentrates, the importance of good mineralogy has become of increasing importance. Increased metal recoveries, reduction in process chemicals, and the possibility for recovery of valuable by-products have led to incentives for improved mineralogy.

The past few years has shown that mineralogy is every bit as important in optimizing tailings management in order to reduce the environmental impact as well as to minimize the high costs tailings management.

The paper briefly describes the aspects of the milling process and the important facets of tailings management where mineralogy is of extreme importance.

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INTRODUCTION

If the total plant is designed concurrent with the tailings, taking into consideration the various chemical, physical (and possibly biological) interactions due to the influence of the mining and the processing, then the tailings management problems and costs can be reduced. Once a plant is in operation there may be further opportunities to alter the process flowsheet slightly to reduce problems in the tailings impoundment. This paper is based on certain sections of a textbook on tailings management by the author (1).

Possible sources of environmental migration from the mine/mill complex include:

- waste rock
- mine water
- mill tailing slurry
- flotation tailings
- iron-aluminum hydroxide sludges
- gypsum sludges
- effluents from purification and product recovery

An appreciation of the "upstream and downstream" of the total process is necessary if any one or more of the unit processes is to be a viable component of the integrated plant. Some of the questions to ask before a choice of the process route is made include the following:

- what is the nature of the ore (mineralogy, values, gangue)?
- will beneficiation be viable?
- based on mineralogy, what are the possible lixivants?
- what impurities would be expected in the leach solution?
- what metal or metals are to be recovered?
- what type of purification process is possible?
- are by-products possible?
- what are the environmental constraints?
- what are the energy requirements?
- what are the corrosion problems?
- what are the overall costs?

The choice, design and optimization of the process involve economics, energy and environment.

MINING

Following a successful exploration and drilling program the mining operation, whether open pit or underground, commences. Mining involves the drilling, blasting and moving the broken ore to the mill by conveyors and trucks. The operation involves contamination to the site due to the oils, chemicals and blasting
contaminants are transported by the considerable volumes of water necessary to the mining activity. This mine water is occasionally treated to recover any values before discharging to the tailings impoundment, or used in one of the subsequent unit processes. However, in most mines this mine water is discharged to the tailings area.

In addition to the liquid effluents arising from the mining operations there is waste rock. Because this rock contains mineralization of little or no value, this waste rock was, in the past, and is still in many operations, deposited in various areas throughout the mining property. Often it is used for fill for roads construction, or left in various heaps. However, waste rock really becomes the major area of concern in many mining operations due to the sulphide mineralization present. With weathering and oxidation due to air, sunlight and bacteria the sulphides are oxidized with the eventual formation of sulphuric acid together with other constituents dissolved from the rock. This acid mine drainage (AMD) thus freely enters the receiving environment. The subject of AMD is covered later. Of course if the waste rock is deposited in the general tailings impoundment area then the seepage can be contained and treated so that the final effluents discharged will meet the particular environmental regulations or guidelines.

CRUSHING, GRINDING, BENEFICIATION AND MINERALOGY

The grind of the ore must be optimised with respect to the leach, roast-leach, or possible beneficiation circuits such as tabling, flotation, high intensity magnetic separation, heavy media, etc. Liberation of the mineral by the process is governed by the grain size and the complexity of the mineralization (e.g., complex fine grained sulphides). Also the gangue material is important as it may provide a clue to possible excessive reagent consumption during the leaching process. It is therefore essential to have a good and thorough mineralogical examination performed to determine not only the minerals of economic interest but also the possible reagent consumers. Such an examination may strongly influence the type of process that is used to recover the values as well as the tailings impoundment design. Once a process has been selected, the mineralogy of the ore before and after treatment must be considered, as well as the mineralogy of the solids going to tailings impoundment. Beneficiation processes such as flotation, although successful in producing desirable separations and concentrates, nevertheless results in possible toxic chemicals being discharged to the tailings.

The most effective way to prevent acid conditions in the tailings due to sulphide oxidation is to provide for a separation process in the mill before discharge to the tailings. The separation of sulphide components from the non-sulphide components (silicates, oxides, carbonates, etc.) of the gangue resulting from the milling process could be, (and is practised in some mills) achieved relatively easily. Flotation of the
sulphide can be achieved so that a sulphide concentrate is produced that can be separately stored, perhaps underground. Depending upon the type of ore, the mineralogy and the extraction process being used, each circuit will vary as to the stage in which the gangue sulphides are segregated. Such an approach has been successful with uranium ores containing sulphides (2).

With improved instrumentation coupled with computer control, significant improvements have already resulted in the last several years in the area of applied mineralogy which is a necessary tool for the successful metallurgical plant operation. Image analysis is one prominent example and this coupled with other sophisticated analytical and surface chemistry techniques will undoubtedly assist in improving the process and provide an understanding of tailings weathering as well as decreasing the overall costs.

Some operations, because of the mineralogical nature of the ore, or the particular process design, employ a roasting of the ore/concentrate at elevated temperatures prior to the next stage which is possibly the leaching stage. The roasting or calcining step used to make a particular conversion to a reduced or oxidized state to provide for enhanced metal recovery, can evolve toxic volatile materials. Thus, depending upon the ore and its mineralogy and process used (oxidizing, reducing, sulphating, chloridizing) various volatile materials can be produced which must be isolated in a specially designed system.

LEACHING

The material fed to the leaching stage may be a low grade ore, concentrate or a complex ore. In recent years there has been a renewed interest in the reprocessing of very low grade tailings for metal recovery, such as for copper, uranium, silver or gold. Leaching takes place under many situations. The common methods employing vat leaching, stirred tanks or pachucas are still common. With the decrease in higher grade ores, and the viability of reprocessing tailings, we now have heap leaching, in-situ leaching and in-place leaching of broken rock underground. While atmospheric leaching was for many years the normal method, pressure leaching at elevated temperatures has proven extremely useful for some ores and concentrates, particularly those that are refractory or those which, because of their mineralogy, are high acid consumers at normal temperatures and pressures. The use of bacterial leaching to oxidize the iron sulphides, with conversion to acid and ferric sulphate, has been shown to be effective for the dissolution of uranium ores containing pitchblende (3), uraninite and brannerite, copper ores (4) as well as some refractory gold ores containing arsenopyrite (5). Because of the varied mineralogy, economics, energy requirements and environmental problems that might be associated with any particular lixiviant, we have seen plants using H_2SO_4, HNO_3, HCl, HF, thiourea (6), or mixtures of some of these such as H_2SO_4 + HF (7), H_2SO_4 + HNO_3 (8), H_2SO_4 + H_2O_2 (Caro's acid
H_2SO_3 (9). Alkaline circuits have included Na_2CO_3 or (NH_4)_2CO_3 and alkaline cyanide.

As an alternative to conventional processing of base metals, chloride metallurgy has made considerable progress in the laboratory and pilot plant, and even a few commercial plants are now using some aspect of chloride technology (10). Although most of the effort has been devoted to treating complex base metal sulphide bulk flotation concentrates (10,11), other ores have included uranium, gold and precious metals (12,13,14). Chloride leaching can be an aggressive lixiviant to most complex mineralized ores and concentrates, and enables increased metal and by-product recoveries, as well as decreasing the tailings management problems.

Arsenic minerals constitute another potential problem in the metallurgical process as well as in the tailings and in the receiving environment. Because arsenic chemistry is quite complex, due to its several oxidation states, then its treatment for safe disposal is also complex. During the extraction process, arsenic will generally be partially solubilized, in a hydrometallurgical process, with the remainder reporting in the tails. Thus the arsenic may be discharged to the tailings in at least two forms. It would therefore be advantageous to control the process conditions, e.g. controlled emf leaching, to ensure either complete dissolution or no attack on the arsenic bearing materials. If the arsenic is completely solubilized it can be recovered from the solution in the mill process, as a by-product or for separate safe disposal. Arsenic is present in many ores, such as gold milling, uranium, and cobalt-nickel operations. Roasting techniques can be a means of arsenic removal and recovery and in some cases may be the only way to liberate the values, such as gold or cobalt for their subsequent recovery.

With the developments and improvements in leaching, together with the aid of improved mineralogy, the leaching recovery efficiency has increased. Also by-product recovery is now easier to achieve and improvements in the character of the tailings may improve with the adoption of some of the newer technologies.

LIQUID-SOLIDS SEPARATION

The liquid-solids separation is the single most expensive unit operation in the mill, accounting for about 50% of the capital and operating costs in most circuits (15). It is also a very important step in order to minimize the loss of soluble metal values to the tailings. Good washing, settling and clarification are necessary before purification. Filters such as vacuum, pressure, leaf, drum and disk were used for many years. More efficient belt filters have been in recent use in many mills and have resulted in decreased soluble losses because of increased washing efficiency. Liquid-solids separation has been achieved by cyclones and thickeners. Thickener separation using a continuous countercurrent decantation system has been improved.
by high capacity thickeners resulting in improved economics to
the plant. To improve the separation, various additives such as
polyacrylamides are used which will eventually appear in the
effluents sent to tailings. It is essential to attain good
washing at this stage in the process to prevent not only loss of
values, but also discharge of contaminants to the tailings area.

This expensive operation requires the most attention if we
are to reduce the total capital and operating costs of the
circuit and to reduce the present metal soluble losses going to
tailings, and which provide increased contaminant load in the
impoundment area. Incorporation of solvent-in-pulp or resin-in-
pulp would be major factors in achieving a significant cost
reduction, and could, with optimization, provide for decreased
environmental impact.

However, for such processes to succeed, the particular ore
type and its mineralogical composition must be compatible with
the solvent or the resin process selected.

TAILINGS SYSTEM

The tailings system is comprised of many components which
include: tailings treatment in the mill; slurry thickening;
slurry transport; tailings impoundment; water recycle; tailings
treatment and disposal site; effluent treatment; and site
restoration. This is indicated schematically in Fig. 1.

TAILINGS CHARACTERIZATION

The properties of tailings range widely, and even tailings
of the same type may possess different mineralogy and therefore
different physical-chemical characteristics. There are, however,
some characteristics which are quite similar. These include
percent clay material, water retention, bulk density, pH, content
of organic matter and total nitrogen.

Associated minerals may include sulphides and various
quantities of base metals, rare metals, rare earths, etc. Other
minerals which are often present include siliceous quartz,
carbonates, feldspar and micas. In addition, lime may have been
added in the mill to neutralize the effluents before discharge;
therefore gypsum and metal hydroxide precipitates will also be
present in the tailings discharge, as well as SO4^{2-}, NO3^{-}, NH3
and dissolved metals.

Sulphides present in the tailings constitute the greatest
single problem in tailings management. Sulphides are usually
oxidized in the weathering process, by oxygen in the air or
water, and also by iron-oxidizing bacteria. The oxidation product
is sulphuric acid, which then becomes a leaching medium in the
tailings and results in considerable chemical processes occurring
in the tailings with increased weathering time. The migration of
the solubilized contaminants is thus seriously affected by the
initial presence of the sulphides and the subsequent conversion to sulphuric acid.

Conversely, if there are no sulphide minerals present, or a minimum as compared to calcareous minerals, then acid generation will not occur, and therefore tailings management is considerable reduced.

Physically, the tailings have a specific gravity of about 2.5 and are a mixture of coarse and very fine sand (plus chemical precipitates). Depending upon the original ore mineralogy, and the process, precipitates, clays and fines, the porosity and permeability will also vary. The tailings are discharged into the tailings basin at a slurry density of 25-45% solids. Thickened discharge, at about 70%, has also been successful. While the mill is in operation the tailings are ion a wet condition and the tailings settle-out in the disposal pond into coarse and fine fractions. The fine fractions can account for about one-third to one-half of the total solids discharged, and are of 75 um size or less.

Fine tailings, on drying-out in the tailings area will shrink and crack. This fraction is often less susceptible to wind erosion than coarse tailings because of their water sorption characteristics. Fine tailings are often difficult to dewater. Often the coarse tailings are used as mine backfill. Tailings with a sulphide content may eventually have a pH of 1.5-3.5, and
such acidity will seriously impede, if not destroy, any attempts by vegetation to grow. During periods of hot weather and drying conditions upward capillary action in the tailings results in efflorescence salts on the surface and just below the surface.

Because the weathering process is a continuing phenomenon, changes in chemistry and mineralogy with time will affect the rate and composition of the migrating solution.

**TAILINGS DEPOSITION**

With the mineralogical complexity of the solids and the chemical speciation and composition of the liquid effluents discharged into the tailings impoundment, it is important that the disposal method be carefully considered. For, as noted above, the mineralogical composition due to clays and fines can affect the drainage and dewatering of the tailings. Previously segregated sands, from a sands-slime separation, may have to be added in order to improve dewatering. The slurry density for discharge will be determined by the settling tendency and therefore the type of discharge method selected. The method of discharge may range from subaqueous to subaereal to thickened discharge or to the discharge of a dry residue. The mineralogical composition, as well as the grind affecting porosity and permeability, must therefore be considered in the choice of deposition method. Naturally, the nature of chemical precipitates also discharged, together with the effluent composition will also have to be considered, as well as the climatic conditions, runoff vs seepage from the impoundment, and possible dusting problems if the tailings become very dry.

**HYDROLOGY AND GEOLOGY INFLUENCE**

Due to the variety of hydrogeological and climatic factors existing in an area, each tailings site and the selection of the optimum disposal option must be independently evaluated. To a limited extent, geological, hydrological and geochemical variables can be selected and modified, either by process selection or in the tailings management. For example, the amount of water remaining with the tailings can affect the quality of the seepage from the tailings into local groundwater. Therefore, by utilizing dewatering techniques in the mill and discharging tailings containing less water, or by recycling and treating tailings decant water, the environmental impact from subsequent weathering will be minimized.

The physical nature of the tailings, with respect to porosity and permeability and size, are significant factors in affecting migration rates. The subsoil characteristics, as well as the presence of clays in the tailings, are important as regards permeability and sorption characteristics. A high water table in the tailings impoundment will mean a longer retention time for the weathering-leaching process to proceed. Therefore, the seepage quality can be worse, particularly if sulphides are
present. The interaction of surface water with the tailings also involves geochemical factors as weathering proceeds, resulting in subsequent sorption on clays and sediments, precipitation and redissolution as migration proceeds downward through the tailings.

Research on uranium tailings in Canada (16) showed that the pore water just below the water table had a low pH, as well as low sulphate and iron concentrations. The low pH pore water was indicative of the shallow tailings losing their capability (loss of calcite) to neutralize acid resulting from pyrite oxidation. Also, the decrease in sulphate and iron concentrations was considered to be due to the decreased pyrite oxidation resulting from the coating of the pyrite grains with iron hydroxide. As the acid, from the pyrite oxidation in the uppermost layers, moves downward and across the bed, the acid is consumed by calcite present in the tailings. Investigations of the plume from the tailings showed that the $SO_4^{2-}$ had moved more than 300 m, while the low pH water with $^{226}$Ra had travelled only 5 m.

The geochemical processes within the tailings are complex and an understanding of the mechanism is essential if the minimum costs to provide minimum environmental impact due to weathering over time are to be realised. The geochemical processes are dynamic and, while some contaminants are being solubilized, others are being removed by precipitation or sorption on the solid surfaces. As noted, the presence of calcite can impede or retard the movement of the acid front, as well as precipitate iron or other metals present. The geochemical precipitation is reversible, and changes in pH will solubilize the precipitates (17). In Fig. 1 are shown typical precipitation data as a function of pH changes in the pore water. Decrease in pH will be accomplished by sulphide oxidation or by hydrolysis of metals from solution, such as the oxidation of ferrous to ferric iron and the resultant precipitation of ferric hydroxide. A similar effect occurs when aluminum and silica combine to form aluminosilicate precipitates, and the liberation of hydrogen ion. Depending upon the Eh-pH relationships, metal sulphides are precipitated from solution, particularly in the vicinity of the water table.

The presence of calcite will result in an increase in pH and, if sulphate is present, the precipitation of gypsum, as well as co-precipitation of metals, as indicated in Fig. 2. The reaction of calcite with ferrous iron precipitates siderite, which may then react with ferrous iron to consume acid. This results in the dissolution of ferrous iron and the subsequent raising of the pH.

WEATHERING

There are many reactions that will take place during the weathering process, based on the mineralogy of the tailings solids, the composition of the liquid effluents, and the
constituents of the chemical precipitates. The results are complex biogeochemical interactions. Once oxidation of the sulphide minerals begins, exothermic reactions provide heat for the catalization of the oxidation reaction and cause formation of products that may be environmentally deleterious. These products can include hydrogen sulphide, partially oxidized oxyanions such as thiosulphate and polythionates, iron sulphate in solution, elemental sulphur, various jarosite compounds, sulphuric acid, and heavy metals associated with the original ore mineralization.

There are four methods by which sulphides may be oxidized: a) chemical; b) electrochemical; c) bacterial; and d) a combination of all three. Sulphides differ in their mineralogical composition and considerable variation can be expected in different ore bodies and in different zones in the same ore body. Thus, the reactivity, or tendency, of a sulphide mineral to oxidize is a complex function of mineral composition. These variables may include, among others, the:

a) type of sulphide mineral present;

b) number of sulphide minerals present;

c) concentration of sulphides;

d) type of non-sulphide minerals present; and
e) immediate, environment (wet, dry, bacteria, etc.).

The reactivity of sulphide minerals is shown, in decreasing order, in Table I (18). The presence of two or more sulphides in an ore can also significantly increase the rate of reactivity. Each mineral sulphide has a different redox potential, and therefore the response to weathering differs.

The nature of the gangue material present in the tailings will have an effect on the reactivity of the sulphides. The presence of magnesium and calcium containing minerals tend to enhance the formation of ferrous and ferric sulphate, which will also increase the rate of oxidation (19).

The oxidation process is usually accelerated by the alternative wetting and drying of sulphides in the tailings. The oxidation products are dissolved by the wetting, thus exposing a fresh surface for further oxidation to take place. To assist the oxidation of the sulphides, there are certain physical factors which must be present:

1) Sulphide grain size and surface area,
2) Porosity and permeability of the tailings.

The oxidation of pyrite can be described by the following reactions (20):

\[
\begin{align*}
\text{FeS}_2 + \frac{7}{2} \text{O}_2 + \text{H}_2\text{O} & = 2\text{SO}_4^{2-} + \text{Fe}^{2+} + \text{2H}^+ \\
2\text{Fe}^{2+} + \frac{1}{2}\text{O}_2 + \text{2H}^+ & = 2\text{Fe}^{3+} + \text{H}_2\text{O} \\
2\text{Fe}^{3+} + \text{3H}_2\text{O} & = \text{Fe(OH)}_3 + \text{3H}^+
\end{align*}
\]

Secondary reactions will then take place between ferrous sulphate, sulphuric acid, clays, shales, sandstone, and the minerals such as limestone.

The oxidation of sulphides in the tailings and the conversion to sulphuric acid is enhanced in the presence of certain bacteria, such as Thiobacillus ferrooxidans and Thiobacillus thiooxidans. All reduced sulphur compounds are oxidized virtually to completion if present. Iron precipitates are deposited on particles within the tailings bed as hydrates of FeSO₄, usually as FeSO₄·7H₂O. As dilution by water proceeds, the Fe⁺⁺ salts are converted to Fe(NH)₃·(H₂O)₅x, which are deposited within the tailings or in receiving stream beds external to the tailings impoundment area.

Sulphate reducing bacteria, such as Desulfovibrio, can also be present and their reaction on sulphates produces H₂S. With the release of sulphide into the tailings, any base metals or other metals that have been previously solubilized, may precipitate as the metal sulphides. This reaction occurs in the anaerobic zone.
Table I Reactivity of Sulphide Minerals

<table>
<thead>
<tr>
<th>Pyrrhotite</th>
<th>Pyrrhotite-pyrite</th>
<th>Pyrrhotite-arsenopyrite</th>
<th>Arsenopyrite</th>
<th>Pyrite</th>
<th>Chalcopyrite</th>
<th>Sphalerite</th>
<th>Galena</th>
<th>Chalcocite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactivity</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tbody>
</table>

and will thus form concentrated bands of mineralization.

The chemical processes important in the weathering of minerals and those which determine the character of the solution generated and its composition (Brownlow 1979) include: (a) hydrolysis; (b) ion exchange; (c) oxidation-reduction; and (d) organic reactions. The process of dissolution of minerals is governed by the pore water composition and the mineral type.

The products of the weathering process can be considered in the following four categories (21): (1) soluble constituents removed from the weathering site; (2) residual primary minerals that were not affected by the weathering reactions; (3) new stable minerals; and (4) organic compounds resulting from organic decay. Table II indicates some of the common products of weathering (21, 22).

**SOIL DEVELOPMENT AND PROFILE**

As weathering advances, soils are formed and layers are formed at depth. These layers are quite different in content and mineralogy as well as colour, pH, organic matter, clay content and amount of Fe-Al-Mn oxides. These soil horizons, together comprising the soil profile, may range from a few centimetres to more than a meter in thickness depending upon the total environment. Most developed profiles can be divided into four principal horizons (Rose, Bridges). The upper A and B horizons may constitute the actual soil or solum; C is the partly-weathered material, and D the underlying bedrock. Organic matter may be present above the A horizon due to vegetation decomposition. The schematic of such a soil profile is shown in Fig. 3 (23).
Table II Common Products of Biogeochemical Weathering Processes

<table>
<thead>
<tr>
<th>Soluble constituents</th>
<th>Na⁺ Ca²⁺ K⁺ Mg²⁺ H₄SiO₄ SO₄²⁻ Cl⁻</th>
</tr>
</thead>
<tbody>
<tr>
<td>Residual primary minerals</td>
<td>Quartz, zircon, magnetite, ilmenite, rutile, garnet, sphene, tourmaline, monazite</td>
</tr>
<tr>
<td>New minerals</td>
<td>Kaolinite, montmorillonite, illite, chlorite, hematite, goethite, gibbsite, boehmite, diaspore, amorphous silica, pyrolusite</td>
</tr>
<tr>
<td>Organic compounds</td>
<td>Organic acids, humic substances,</td>
</tr>
</tbody>
</table>

Fig. 3 Soil Profile Showing the Principal Horizons

Weathering and the effects on oxidation on minerals are profound. The various minerals that may be present are altered and their structure often obliterated. Metallics are leached or converted to new compounds so that the texture and type of material are changed and obscured. A deposit thus becomes oxidized and generally leaching of many of its constituents occurs down to the groundwater table, or to a depth where
oxidation cannot take place. The oxidized area is called the oxidation zone. As the solutions gradually move downward and through the water table into the transition zone, some of the dissolved constituents may be lost, by precipitation or adsorption, in the form of secondary minerals or altered products. This zone is also known as the enrichment zone. The lower unaffected part of the deposit is called the primary or hypogene zone or the reduction zone. Such a zone arrangement is common with many mineral deposits that have undergone weathering. One could also anticipate such a zonal arrangement to occur in weathered tailings.

The weathering of soils thus results in the establishment of different zones of mineralization. An impervious zone, hardpan, may develop in some tailings in the transitional zone due to the formation of alteration minerals. A mineralogical examination of weathered tailings in Canada was performed at CANMET on the high pyrite-pyrrhotite tailings of Waite-Amulet (24,25) to determine the changes that had occurred since deposition prior to 1962. Although the tailings had been vegetated, nevertheless acid seepage was found at the base of the tailings area. The investigation showed that there was a progressive change in mineral composition from the surface to the base of the tailings pile, and that there were distinct mineralogical zones near the surface zone and in the unsaturated zone below the water table. Alteration proceeded from pyrrhotite to an iron sulphate, which broke down to sulphur-rich goethite, and by breakdown of pyrite to a low-sulphur goethite (24). Oxidation of the pyrite and pyrrhotite and formation of ferrous sulphate and sulphuric acid would provide mobility for iron and sulphate, gradually washed through the tailings. Examination of the same samples (25) showed bassanite (CaSO₄·H₂O) throughout the core, probably due to the large quantities of limestone applied to neutralize the surface of the tailings prior to vegetation. This calcium source would be available to react with acidic sulphate solutions resulting from the oxidation-decomposition of sulphides. The principal alteration minerals identified were goethite, sulphur, ferrous sulphate, jarosite, lepidocrocite and marcasite. The mineralogy showed that: (a) the pyrite and pyrrhotite were essentially absent in the near surface zone, (b) about 10-30% of the original pyrite and pyrrhotite were still present in the unsaturated zone, and (c) about 50% of the pyrite and 25% of the pyrrhotite were still present below the water table.

In the development of hardpan, in which there is a depletion of minerals in the upper zone as weathering progresses, the difference in rate of oxidation by the different minerals will determine the rate of accumulation of oxidation products to form the hardpan zone. Since pyrrhotite (FeS) oxidizes faster than pyrite (FeS₂) we can expect the former to be depleted at a faster rate. Thus tailings may be deposited with a FeS/FeS₂ ratio of 1, and as weathering and oxidation proceeds, the ratio will soon be 0.5. Little information or data are available on the depletion of the oxidation zone and the development of the hardpan as the
mineralization changes, but because of the Eh-pH relationships in the tailings can expect the FeS/FeS$_2$ ratio to decrease due to oxidation above the water table, and to remain relatively constant below the water table.

**MIGRATION**

As noted throughout, the tailings area is chemically very complex and heterogeneous. Such a system is dominated by the following factors (26,26):

(a) high ionic strength and interstitial pore water;
(b) soluble salts of calcium and magnesium sulphates and sodium chloride;
(c) electroactive species, such as uranium, iron, magnesium and vanadium; and
(d) low pH values.

Water and water chemistry affects both the transport as well as the rate of migration, and the control is by both physical and chemical factors. In the aquatic environment, changes in the Eh-pH, dissolved gases (O$_2$, CO$_2$, H$_2$S), temperature, ionic strength, mineralogy of solids, and presence of fines or clays may be interrelated to affect mobility. Solubilized metals and radionuclides may form colloids, be incorporated by adsorption into sediments, organic or inorganic material, or be taken up by organisms.

Examples of the relative mobilities of various elements in the secondary environment are given in Table III (28).

Chemical and geochemical reactions result in the formation of bands of precipitated iron and manganese together with gypsum and other salts. Precipitation results in the reduction of the affective pore space and can have an effect on hydrodynamic correlations. The precipitation of iron hydroxide on a silicate surface may potentially change the adsorption characteristics of the solid matrix (26,27). Precipitates of silica, alumina and aluminosilicate are possible scavengers for the adsorption of trace metals from the migrating solute.

The Eh-pH can vary within the tailings, and the reactions will continue until the Eh-pH of the pore water are in equilibrium with the solid phases and the environment. With a chemically-dynamic system in the tailings, the time required to attain equilibrium may take many centuries. The pH controlling reactions are the silicate minerals and the interactions between carbonate ions from the atmosphere and those transported by water. The acidity, as noted earlier, is due to the oxidation of sulphides and the hydrolysis of metals precipitating.
<table>
<thead>
<tr>
<th>RELATIVE MOBILITIES</th>
<th>OXIDIZING</th>
<th>ENVIRONMENTAL CONDITIONS</th>
<th>NEUT-ALK</th>
<th>REDUCING</th>
</tr>
</thead>
<tbody>
<tr>
<td>VERY HIGH</td>
<td>Cl, I, Br</td>
<td>Cl, I, Br</td>
<td>Cl, I, Br</td>
<td>Cl, I, Br</td>
</tr>
<tr>
<td></td>
<td>S, B</td>
<td>S, B</td>
<td>S, B, Mo, V</td>
<td>S, B, Mo, V</td>
</tr>
<tr>
<td>HIGH</td>
<td>Mo, V, U, Se</td>
<td>Mo, V, U, Se</td>
<td>Ca, Na, Mg</td>
<td>Ca, Na, Mg</td>
</tr>
<tr>
<td></td>
<td>Re, Ca, Na, Mg</td>
<td>Re, Ca, Na, Mg</td>
<td>F, Sr, Ra</td>
<td>F, Sr, Ra</td>
</tr>
<tr>
<td></td>
<td>F, Sr, Ra, Zn</td>
<td>F, Sr, Ra, Zn</td>
<td>Cu, Co, Ni, Hg, Ag, Au</td>
<td>Cu, Co, Ni, Hg, Ag, Au</td>
</tr>
<tr>
<td>MEDIUM</td>
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<td>As, Cd</td>
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<td>Ag, Au, As, Cd</td>
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<tr>
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<td>Li, Rb, Ba, Be</td>
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<tr>
<td></td>
<td>Li, Rb, Ba, Be</td>
<td>Bi, Sb, Ge, Cs</td>
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<tr>
<td></td>
<td>Cs, Tl</td>
<td>Tl, Fe, Mn</td>
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<tr>
<td>VERY LOW TO IMMOBILE</td>
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<tr>
<td></td>
<td>Fe, Mn, Al, Ti</td>
<td>Wa, Nb, Ta, Pt</td>
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<tr>
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<tr>
<td></td>
<td>Ta, Pt, Cr, Zr</td>
<td>Cr, Zr, Th</td>
<td>Cr, Zr, Th</td>
<td>Cr, Zr, Th</td>
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<td></td>
<td>Th, Rare Earths</td>
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<td>Rare Earths</td>
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<tr>
<td></td>
<td>Zn, Cu, Co, Ni</td>
<td>Hg, Ag, Au</td>
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Table III Relative Mobilities
Water acts as the transport mechanism for cationic and anionic constituents, as well as influencing the solubility and the migration of salts. Salt migration towards the surface of the tailings is affected by the distance of the water from the surface. Salts are dissolved and move by capillary action to the surface, where they precipitate. This occurs particularly well with a shallow water table and evaporation. Depending upon the nature of the original mill process and the nature and mineralogy of the particular tailings, various salts are present which may appear on the surface throughout the tailings bed. Such precipitates have included: various metal arsenates, jarosites, ferric hydroxide, alunite, lead salts, gypsum, magnesium sulphate, and alum. Co-precipitation of other migrating salts will also occur, such as Cd, Se, U, $^{226}$Ra, Ag, Cu, Mo, Mn. The rate of upward migration will depend on the amount of moisture present and the pH.

In tailings where numerous salts are being formed by precipitation from solutions, and where salts are being dissolved, there will be a concentration gradient through the tailings. This difference in salinity causes increased pore pressures or osmotic pressure from below. The tailings provide an ideal situation for osmotic pressures to develop. Osmosis results in a volume increase in the highly concentrated side, resulting in a separation of particles due to the hydrostatic pressure. The result of osmotic pressures in the tailings have been observed (26, 27) as follows:

- the surface material becoming loose, resulting in erosion;
- tailings material migrating through dykes;
- water transport from the subsurface into the tailings;
- transport of contaminants by the available water;
- water available for chemical reactions within the tailings (to react with the minerals and bacteria); and
- generation of long-lasting forces.

The disruptive forces owing to osmotic pressures must then be considered in the design of the containment area and in its maintenance.

DECOMMISSIONING AND RECLAMATION

When the mine ceases operation, or when the impoundment area has been filled, there is the requirement for rehabilitation and revegetation. Obviously, in highly mineralized tailings, and in the absence of soils, nutrients, and fertilizers, vegetation will be difficult. Also, if the tailings are highly porous, moisture
instability, and salts moving upwards can kill any possible root development. In the case of sulphidic tailings, these will still be oxidizing and therefore generating acid. Large amounts of limestone application are required for neutralization in order to sustain growth. By contrast, highly alkaline asbestos tailings also will not support growth, and they must be treated with sulphur and sulphide tailings.

Before any attempts are made to establish vegetation, certain information is required, including the mineralogy and size analysis, pH, chemical composition of effluents and solids (particularly those that would be harmful to plants), physical characteristics, climatic conditions, topography and problems of erosion and dust.

CONCLUSIONS

It is very obvious that the mineralogy of the ore will have major impacts on not only the process—which was always considered the only significant area— but also on all aspects of tailings management. Thus a good appreciation of the mineralogy early in the development of the mining project will provide for process optimization, selection of disposal option and impoundment design, rehabilitation, reduced environmental impact, and therefore a significant reduction in overall costs.

Much of the prediction and optimization required in tailings management can be achieved by use of controlled weathering tests using lysimeters, as described by Ritcey (1), and such research is recommended.

REFERENCES


