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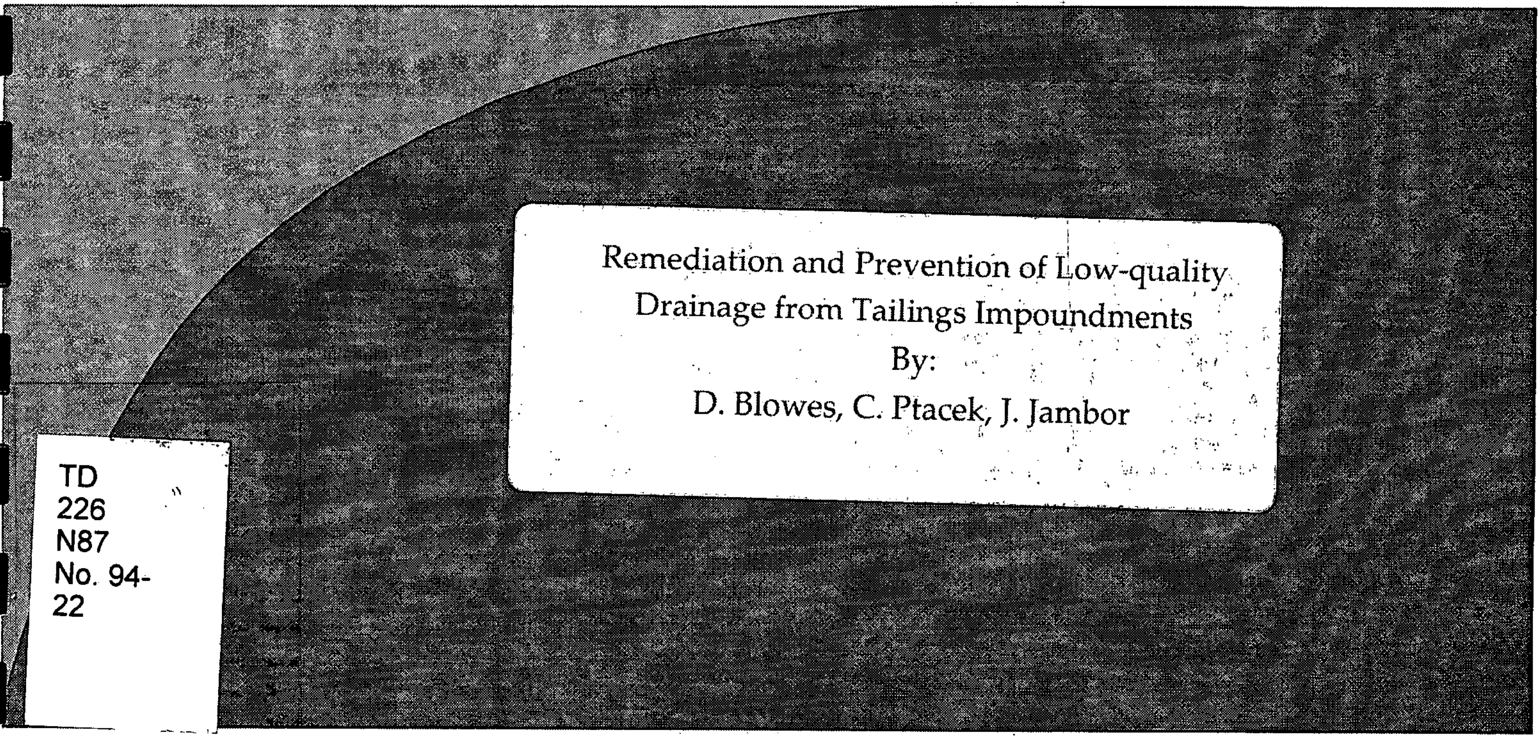

# Remediation and Prevention of Low-quality Drainage from Tailings Impoundments

By:

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## Management Perspective

Mill tailings are the finely ground residue formed as a byproduct of ore processing. These tailings often contain high concentrations of sulfide minerals that are not economical to extract. It is conventional practice to dispose of sulfide-rich tailings in piles or impoundments in the open environment, where they are allowed to gravity drain and become exposed to atmospheric oxygen. Oxidation of the sulfide minerals contained in the tailings releases elevated concentrations of dissolved $H^+$, $SO_4$, Fe and other metals to the tailings pore water. This pore water is displaced downward and laterally through underlying tailings and nearby aquifers, and eventually is discharged to the surface water flow system. Case studies describing the application of various remediation techniques, both *in situ* and above ground, for treating low-quality drainage are presented in this handbook chapter. Alternative disposal techniques designed to prevent the formation of low-quality drainage are also summarized.

pore water discharges to the peripheral, flat-lying area of tailings. Characterization of the flow regime within the tailings should help in future planning for decommissioning.

## 12.6. ACKNOWLEDGEMENTS

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# Chapter 13

# Remediation and Prevention of Low-quality Drainage from Tailings Impoundments

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## 13.1. INTRODUCTION

Since recognition of the problems of acidic and low-quality drainage associated with tailings impoundments, the mining industry has attempted to develop reliable techniques for the prediction, remediation, and prevention of these problems. The development of these techniques requires an understanding of the complex interactions among the hydrogeological, geochemical, mineralogical, and microbiological characteristics of tailings impoundments, as have been described in the preceding chapters of this Volume. Understanding these interactions has led to the development and testing of innovative approaches for the disposal and treatment of mine tailings. As our understanding improves, additional techniques undoubtedly will be put forward.

Robertson (1987) reviewed the abatement techniques that had been developed to date, and prepared a cost-benefit comparison for the various approaches, which were grouped into three broad categories: (a) collection and treatment of tailings-derived discharge, (b) infiltration controls, and (c) sulfide-oxidation controls. An alternative abatement approach not included in the above is to promote the reduction of sulfate and the subsequent precipitation of low-solubility sulfide minerals at a depth within the tailings under conditions at which these minerals will remain stable. The effluent from many tailings impoundments in North America is collected and treated prior to discharge from the minesite. Acceptable effluent quality is achieved, but the capital and consumable costs associated with perpetual maintenance of treatment facilities are sufficiently large that the development of alternative prevention and abatement techniques is highly desirable.

## 13.2. REMEDIATION OF EXISTING SOURCES OF ACIDIC DRAINAGE

At many locations mining has been active for several decades. Although mine wastes at these locations were deposited according to the best practices available at the time of disposal, many of these wastes are now the source of low-quality drainage waters. At many of these sites the period of most intense sulfide oxidation and associated release of dissolved metals has passed, but transport of sulfide-oxidation products through the tailings or underlying aquifers will continue for several decades (*e.g.*, Coggans *et al.*, 1994). Remedial programs for these sites focus on the collection and treatment of tailings-derived discharge or on reducing the infiltration and movement of recharge water through the tailings. At tailings impoundments in which sulfide oxidation is in its early stages, it is beneficial to inhibit these reactions through the use of sulfide-oxidation controls, such as saturated soil covers or organic-carbon covers, to inhibit oxygen ingress. For older tailings areas in which the peak period of sulfide oxidation has passed, a potential alternative remediation approach is to install sulfate-reducing porous reactive walls in the path of plumes of tailings-derived water.

### *13.2.1. Collection and Treatment*

Collection and treatment facilities are in place at many tailings sites throughout North America. Conventional water-treatment plants vary from relatively simple, to automated, computer-controlled facilities. Even relatively primitive facilities in some instances can provide an effective control on the release of acidic drainage and dissolved metals. The cost of maintenance of these facilities, however, is large and there is a strong desire to develop and implement alternative treatment systems. A relevant example of the costs associated with conventional treatment systems is that the annual expenditure for lime for the Noranda-group companies alone is on the order of $5 million (Kuyucak *et al.*, 1991). Moreover, the disposal of low-density sludge residues has become an environmental concern, both in terms of disposal and in the potential release of dissolved metals through subsequent leaching.

Alternative passive-treatment systems which have been proposed include downstream polishing or metal scavenging by using wetlands, woodwaste, or peat. These passive-treatment systems may be enhanced through the use of anoxic limestone drains to precondition water prior to discharge to the wetland systems (Hedin and Watzlaf, 1994). Other proposals focus on concentrating the beneficial biological activity observed in a wetland within a constructed facility. For many years wetlands and peat bogs have been recognized as areas of metal accumulation (Kalin and van Everdingen, 1987; Ritcey, 1989; Brown, 1991; Machemer and Wildeman, 1992). Passive treatment of acidic coal-mine drainage by constructed wetlands has been demonstrated to be efficient and effective. In the Appalachian region of the United States more than 400 wetland systems were treating low-quality drainage waters derived from coal minesites (Kleinmann *et al.*, 1991). In addition, the use of constructed wetlands for treatment of drainage from base- and precious-metal mine-tailings impoundments has been proposed (Kleinmann *et al.*, 1991; Gould *et al.*, this Volume). Passive polishing by downstream wetland requires the establishment and maintenance of wetlands that not only will remain stable over long periods, but will also survive the metal loadings associated with base- and precious-metal tailings. As metal loadings from many tailings impoundments are expected to increase over future decades (Blowes and Jambor, 1990; Blowes *et al.*, 1994; Coggans *et al.*, 1994), the wetland must withstand both current and future loadings to be suitable as a long-term treatment system. One of the major concerns with this concept is the gradual infilling of the wetland basin and the potential for the remobilization of contaminants associated with the tailings impoundment.

The mechanisms resulting in the immobilization of dissolved metals in wetlands have been the focus of much research in recent years. Kleinmann *et al.* (1991) noted that a significant attenuation of dissolved metals results from the bacterially catalyzed reduction of sulfate to sulfide and the accompanying reprecipitation of metal sulfides through reactions of the form:

$$CH_2O + SO_4^{2-} \Rightarrow HS^- + HCO^-_3 + H^+ \qquad (1)$$

$$Me^{2+} + HS^- \Rightarrow MeS_{(s)} + H^+ \qquad (2)$$

where $CH_2O$ represents a labile source of organic carbon, and *MeS* represents an amorphous or poorly crystalline sulfide precipitate. These reactions increase the pH and alkalinity of the tailings discharge-water, and decrease the concentrations of dissolved metals. In wetlands, organic carbon is supplied and replenished through the annual growth of wetland plants and their degradation in the wetland. Sulfate, Fe(II), and other dissolved metals are supplied by the captured acid mine drainage-water.

Isolation of the controlling reactions in wetland systems has resulted in the proposal and development of treatment systems in which mine drainage-water is directed through continuous-flow reactors. Dvorak *et al.* (1991) proposed that mine drainage-water be directed through continuous-flow reactors containing solid-phase organic carbon to induce sulfate reduction and precipitation of metal sulfides. The results of pilot-scale experiments demonstrated significant decreases in the concentrations of $SO_4$ and the dissolved metals Fe, Zn, Mn, Ni, and Cd; these decreases were accompanied by increases in effluent pH and alkalinity. Dvorak *et al.* indicated that scaling up of the reactors to treat acidic drainage from minesites is economically feasible. A further variation of this continuous-flow system is the use of a sulfate-reduction treatment zone, followed by treatment using an anoxic limestone layer (Kepler and McCleary, 1994).

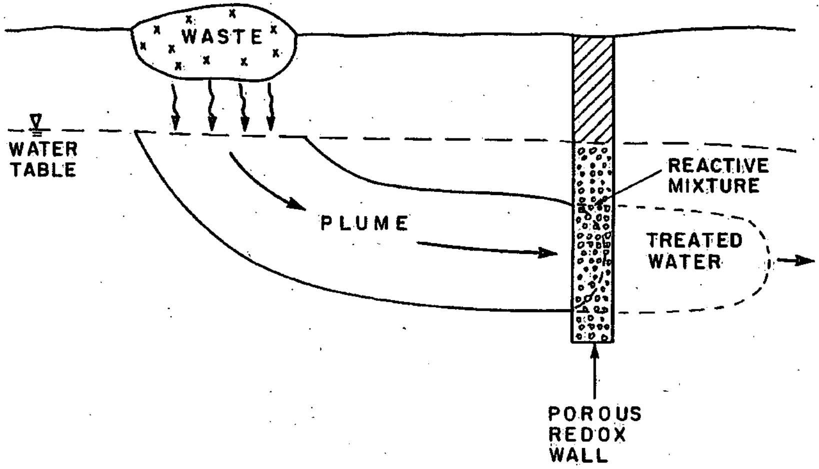

Figure 13.1. Schematic diagram of a porous reactive wall for *in-situ* treatment of contaminated groundwater.

Plumes of tailings-derived water moving in aquifers affected by mine-tailings impoundments are anaerobic, the pH is near neutral, and the temperature is relatively constant throughout the year (Morin, 1983; Bain, 1994). These conditions are well-suited for the *in-situ* treatment of mine drainage-water. Blowes and Ptacek (1992a, 1994) proposed intercepting Fe(II)- and $SO_4$-laden groundwater prior to discharge to the surface-water flow system through the use of porous reactive walls containing labile organic carbon (Figures 13.1, 13.2). Treatment using these porous walls requires that the contaminant be sufficiently reactive for the reaction to proceed as the plume of contaminated water passes through the wall. The wall material also must be sufficiently reactive during the limited residence time of the contaminant plume, and the wall material must be sufficiently stable so its lifespan is economically competitive with other treatment systems. Preliminary experiments, conducted using potential wall components, suggest that the sulfate-reduction and metal-sulfide precipitation reactions proceed rapidly enough that treatment of tailings-derived water by sulfate-reducing reactive walls is feasible (Figure 13.3). To examine the potential for treatment of tailings-derived waters using reactive walls under field conditions, a test cell has been installed in the path of a plume of tailings-derived water at the Nickel Rim minesite near Sudbury, Ontario.

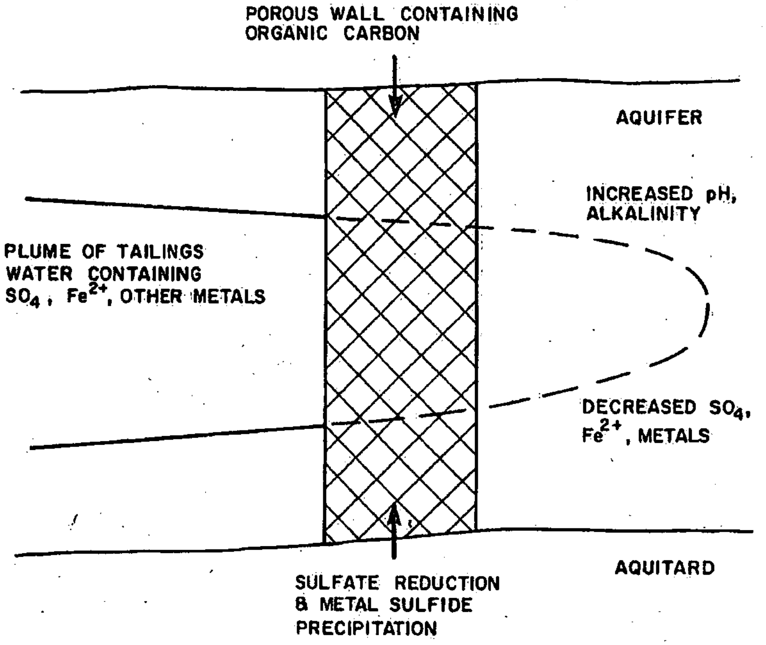

Figure 13.2. Schematic diagram showing relevant reactions for treatment of tailings water containing $SO_4$, Fe(II), and other metals.

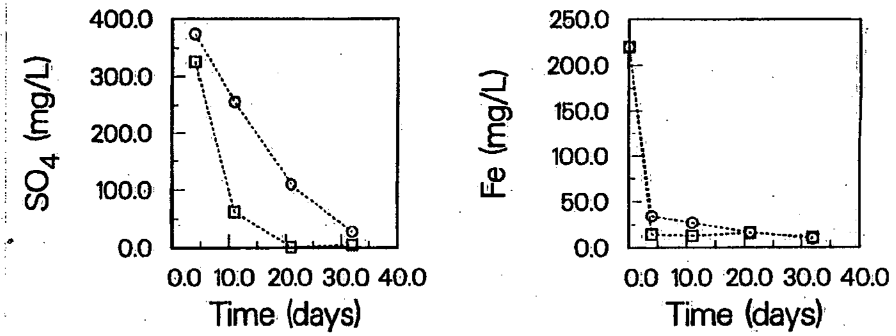

Figure 13.3. Removal of $SO_4$ and iron using mixtures of organic-carbon sources as a function of time. Circles represent results for mixtures with low concentrations of added calcite and squares represent results for mixtures with high concentrations of added calcite.

### 13.2.2. *Infiltration Controls*

Although numerous design strategies to restrict the movement of tailings pore-water from the impoundment to adjacent groundwater and surface-water flow systems have been proposed, the most effective strategy to control the movement of tailings pore-water from the impoundment is to restrict the entry of meteoric waters, surface water, and groundwater into the impoundment. This in turn will reduce the quantity of tailings-derived seepage leaving the impoundment (Robertson, 1987).

Entry of groundwater and surface water into the tailings can be avoided by appropriate site selection. Where suitable impoundment locations are not available, or where tailings are already placed in an undesirable location, the use of synthetic liners, cutoff walls, and diversion trenching may be considered. Infiltration of meteoric water can also be restricted by surface contouring and by emplacement of low-permeability covers, either of natural geologic or synthetic materials, over the tailings. Optimal cover design would provide a barrier both to infiltration of meteoric water and to atmospheric $O_2$.

Although it is desirable to limit the entry of meteoric water, groundwater, and surface water into tailings areas, this may not be economically feasible given the large areas (> 200 ha) of many tailings impoundments. In these cases it may still be desirable to restrict the movement of tailings water into underlying aquifers to prevent degradation of aquifer-water quality and to direct tailings-derived water to collection points prior to treatment. Cutoff walls, diversion trenching, and impermeable barriers can be used to direct flowing groundwater toward *in-situ* treatment zones (Figure 13.4; Starr and Cherry, 1994) or toward surface treatment systems.

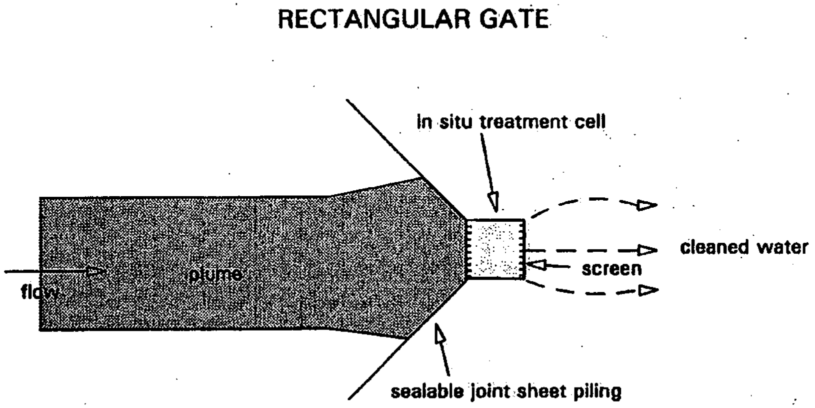

Figure 13.4. Schematic diagram showing funnel-and-gate design for *in-situ* treatment of mine-tailings water, as described by Starr and Cherry (1994).

### 13.2.3. *Sulfide-oxidation Controls*

Abatement techniques that limit sulfide oxidation are bactericidal controls, precipitates that coat sulfide surfaces, and $O_2$-diffusion barriers. The first involves attempts to inhibit the naturally occurring sulfide-oxidizing bacteria through the use of bactericides applied either directly to the tailings surface or as an intimate mixture with the tailings in the impoundment (Erickson and Ladwig, 1985). In the absence of these bacteria the rate of sulfide-mineral oxidation decreases as the pH decreases, and the concentrations of dissolved metals remain low. Preliminary results using this approach have been encouraging, but the bactericides currently available require continual reapplication (Sobek, 1987). The requirement for continual reapplication suggests that bactericides may be better suited to short-term disposal sites, such as locations where tailings are temporarily exposed during impoundment construction.

The second type of oxidation control armors the sulfide mineral surface with a coating of an insoluble, non-reactive precipitate, thereby isolating the sulfide mineral from oxidants (*e.g.*, $O_2$ and $Fe^{3+}$). Among the various armoring phases that have been proposed are ferric phosphate (Huang and Evangelou, 1994), and ferric oxyhydroxides (Ahmed, 1991). Huang and Evangelou (1994) observed decreased rates of sulfide oxidation in samples amended with $PO_4^{3-}$ compared to control samples. In field settings ferric oxyhydroxide rims are observed on altered sulfide minerals (Blowes and Jambor, 1990; Jambor and Blowes, 1991). Studies which model sulfide oxidation in mine wastes using "shrinking core" models (Davis and Ritchie, 1986; Davis *et al.*, 1986) assume that similar coatings affect the rate of sulfide oxidation. These field and modelling studies suggest that the observed oxidation rates in the presence of these altered rims remain sufficiently high to represent an environmental concern. To be an effective remedial system the armoring coating must maintain rates below those observed for naturally occurring alteration.

The third type of sulfide-oxidation control restricts the entrance of gas-phase $O_2$ into the impoundment by placing a diffusion barrier between the atmosphere and the reactive sulfide tailings. Several approaches to the barrier technique have been proposed, including dry covers composed of fine-grained materials, which may be layered to maintain high water contents and low $O_2$-diffusion coefficients (Collin and Rasmuson, 1986; Sodermark and Lundgren, 1988; Rasmuson and Collin, 1988; Nicholson *et al.*, 1989; Yanful and St. Arnaud, 1991); covers composed of synthetic low $O_2$-diffusivity materials (Sodermark and Lundgren, 1988; Malhotra, 1991); or covers containing $O_2$-consuming materials (Reardon and Poscente, 1984; Reardon and Moddle, 1985; Broman *et al.*, 1991; Tassé *et al.*, 1994).

Covers constructed of fine-grained material rely on the moisture-retaining characteristics of these materials to maintain high moisture contents several meters above the water table (Collin and Rasmuson, 1986; Nicholson *et al.*, 1989, 1991;

Yanful *et al.*, 1994). Because of the moisture-retaining capabilities of fine-grained materials, it is possible to layer these materials (silt- and clay-size sediments) over coarser grained tailings and maintain a saturated or near-saturated condition several meters above the water table (Figure 13.5).

Covers which include synthetic layers have also been proposed (Sodermark and Lundgren 1988). A cover incorporating a synthetic layer constructed of 25 cm of Cefill flyash-stabilized concrete was installed over a waste-rock pile at the Bersbo site in Sweden (Figure 13.6; Lundgren and Lindahl, 1991). Such covers are expensive to construct (Sodermark and Lundgren, 1988) and may be susceptible to cracking after installation due to desiccation or to subsidence (Collin, 1987). Collin (1987) conduced a sensitivity analysis which indicated that cracks in soil covers would lead to the oxidation of the underlying sulfide minerals. Based on this analysis, it was recommended that soil covers be protected from root penetration, frost action, and desiccation. The effectiveness of covers for tailings areas relies on their long-term integrity. Because covers are located on the tailings surface, they are at the location most susceptible to erosion.

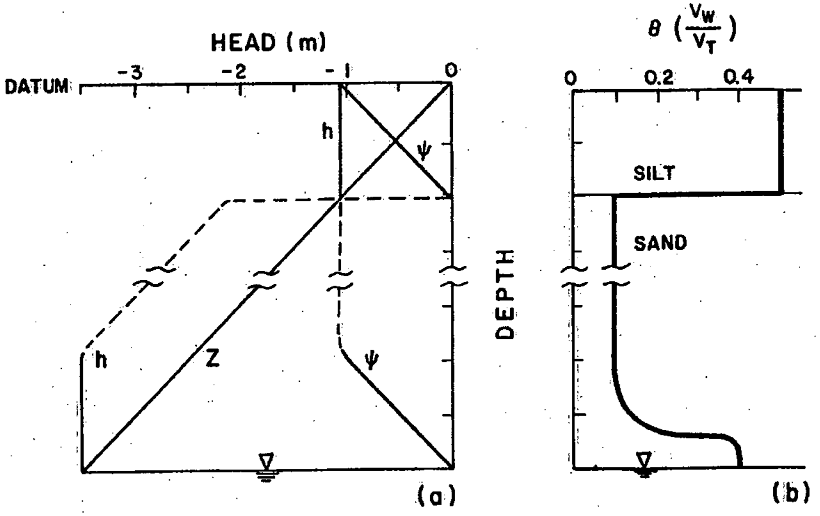

Figure 13.5. Hypothetical head distribution and expected moisture contents through a silt and an underlying coarse sand layer (Nicholson, 1984).

In addition to covers with low $O_2$-diffusion characteristics, several authors have proposed covers which consume $O_2$ (Reardon and Poscente, 1984; Blenkinsopp, 1991; Broman *et al.* 1991; Tassé *et al.*, 1994). Covers rich in organic carbon in the form of woodwaste, sewage sludge, and industrial byproducts have been proposed. The intent is to consume $O_2$ by reaction with organic carbon, preventing $O_2$ contact with the underlying sulfide minerals (Figure 13.7). Several studies (*e.g.*, Tassé *et al.*, 1994) have demonstrated that these covers are able to consume $O_2$, illustrating their potential effectiveness. Reardon and Poscente (1984) calculated the mass of organic carbon required for covers composed of wood waste to serve as long-term prevention of acidic drainage. They concluded that the mass of organic carbon required was prohibitive, and alternative techniques were suggested. Pierce *et al.* (1994) proposed the use of composted sewage sludge as a potential tailings cover. Advantages of its use include its fine-grained nature, high organic-carbon content, and high-pH condition.

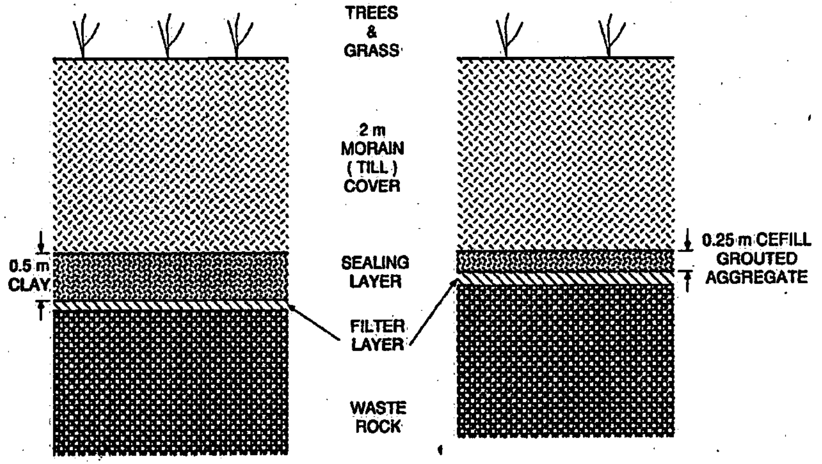

Figure 13.6. Composition of cover materials placed over the Bersbo waste-rock pile. (a) shows the addition of a clay sealing layer, and (b) shows the addition of a Cefill sealing layer to limit sulfide oxidation.

As with all tailings covers, organic-carbon covers must be applied shortly after tailings deposition has ended. Unlike other dry covers, however, organic-carbon covers have the potential to release high concentrations of organic acids to the tailings surface. Interaction between these organic acids and ferric oxyhydroxide minerals precipitated during previous periods of oxidation has the potential to result in reductive dissolution of the ferric oxyhydroxides through reactions of the form

$$4Fe(OH)_3 + CH_2O + 7H^+ \Rightarrow 4Fe^{2+} + HCO^-_3 + 10H_2O \qquad (3)$$

These reactions will also release trace and heavy metals adsorbed on, or coprecipitated with these ferric oxyhydroxides. Ribet *et al.* (1994) conducted reductive leaching experiments that demonstrated that significant masses of metals were present in the shallow, altered zone of the Nickel Rim tailings impoundment in a form that was susceptible to attack by reductive dissolution (Figure 13.7).

An alternative to the use of dry covers is the use of wet covers. This is achieved by disposal of tailings into deep lakes (*e.g.*, Pedersen *et al.*, 1993), or by the

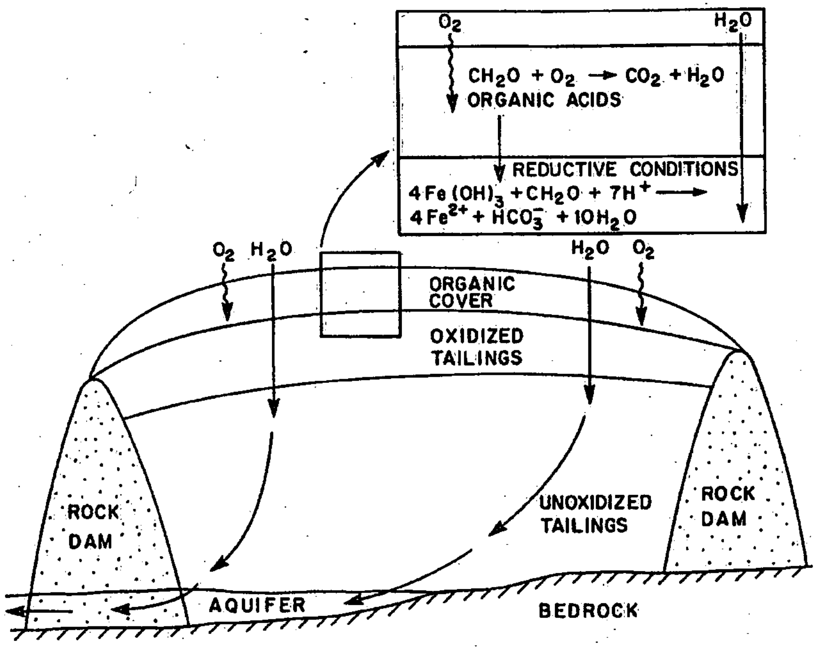

Figure 13.7. Schematic diagram of a tailings impoundment covered with organic matter.

construction of wet covers on existing tailings impoundments (*e.g.*, Robertson, 1992). Wet covers can be established either as ponded water maintained behind a water-retention dam, or as a bog on the tailings surface (Kalin and van Everdingen, 1987). In all of these cases, $O_2$ ingress into the tailings is limited by the slow diffusion of $O_2$ through the cover. The establishment of a bog on the tailings surface may also lead to the development of reducing conditions in the cover overlying the tailings, similar to the conditions encountered in natural bogs, which would further lessen the movement of $O_2$ into the tailings. An attempt to establish bog deposits on an existing tailings surface required that water continually be added to the tailings surface to maintain water-saturated conditions. Without the addition of water the tailings drained due to their coarse-grained nature and the high permeability of the sediments underlying the tailings (Michelutti, 1988). In this case the presence of the bog cover decreased the aqueous concentrations of dissolved metals, but increased the total metal loadings because of the large volume of water that was added to the test plot. In other hydrogeologic settings establishment of bogs on tailings surfaces may be more effective. In all cases, the emplacement of a wet cover on the tailings surface will increase the hydraulic gradient across the dam. Many tailings dams were designed to be permeable in order to allow the tailings to drain and consolidate, and thereby enhance the structural stability of the impoundment. The maintenance of saturated conditions in such impoundments may reduce the stability of the dam and increase the potential of catastrophic dam failure. In addition to the potential for diminished dam stability, the imposition of a large hydraulic gradient through a tailings impoundment would increase the flow of water through the tailings and into the adjacent groundwater or surface aquatic environments.

To be most effective, $O_2$-diffusion barriers should be put in place shortly after tailings deposition has ended. The rate of sulfide oxidation is greatest in the early stages of tailings weathering because at this time the sulfide-mineral surfaces are pristine and the $O_2$-diffusion path length is short. As oxidation proceeds the sulfide minerals are armored by the precipitation of alteration products, and the length of the diffusion path increases. Simulations conducted by Johnson (1993) for the Nickel Rim tailings using the model of Davis and Ritchie (1986), showed that the peak period of oxidation occurs shortly after tailings deposition ends. The rate then declines quickly to a relatively low value, but continues to decline for several years. The depletion of sulfides in the shallow tailings has the effect of developing an expanding silt-size cover on the surface of the tailings. Field determination of Fe and $SO_4$ concentrations from the Nickel Rim site show maximum Fe and $SO_4$ concentrations occur 5 m to 8 m below the tailings surface. These higher concentrations represent Fe and $SO_4$, derived from oxidation shortly after tailings disposal has ended, that has been displaced into the deeper tailings by infiltrating rain and snowmelt. Concentrations of Fe and $SO_4$ from the vicinity of the tailings surface are lower, indicating that the rate of oxidation has declined.

### 13.2.4. *Prevention of Sulfide Oxidation*

The recognition that existing tailings-management programs have the potential to generate low-quality drainage for long periods has lead to alternative proposals for tailings management. These proposals include, but are not limited to, disposal of tailings in deep lakes, separation of sulfide minerals for separate disposal, disposal of tailings as a thickened slurry with improved moisture-retaining capabilities, and enhanced sulfate-reduction within tailings impoundments through the addition of solid-phase organic carbon.

Deep-water disposal of tailings has several advantages. The tailings are located at the base of the flow system and are thereby isolated from the effects of erosion and catastrophic dam failure. The sulfide content is isolated from atmospheric $O_2$ by a thick water cover, limiting oxidation to the mass of $O_2$ dissolved in the overlying water cover (approximately 9 mg/L at 25 °C and atmospheric $O_2$ concentrations and pressures). Studies of tailings deposited in lakes in northern Canada suggest that sulfide minerals are stable in deep lake environments, and that the concentrations of dissolved metals associated with these wastes are low (Pedersen *et al.*, 1993, 1994).

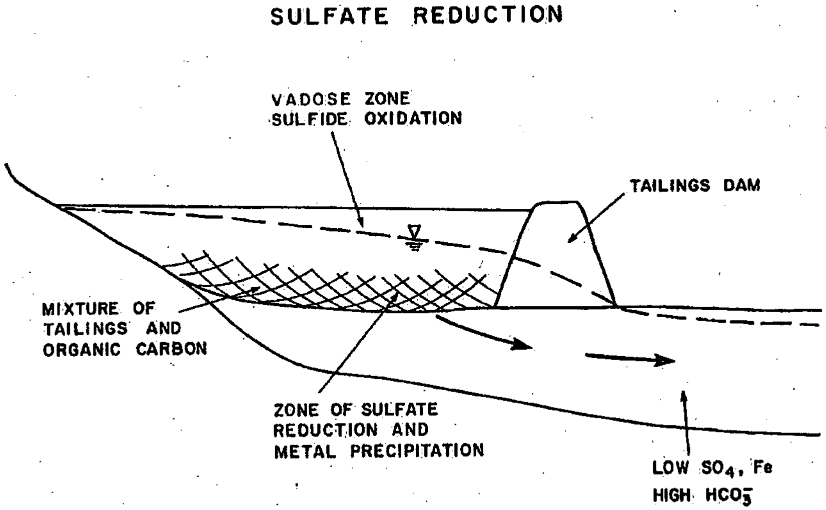

Figure 13.8. Addition of organic carbon dispersed throughout the tailings to enhance sulfate reduction and precipitation of sulfide minerals.

Concentration of sulfide minerals can be achieved by more completely extracting the sulfide minerals in the final stage of flotation in a mill. The separation process would result in two tailings streams, a large-volume low-sulfur tailings product and a smaller volume sulfide-rich portion of the tailings. The sulfur-rich portion of the tailings must be handled in a manner that will prevent contact with atmospheric $O_2$. The larger volume of low-sulfur tailings may be disposed of by conventional techniques, or may be used for backfill, dam construction, or other surface construction applications.

Separation of the sulfide portion of the tailings represents "geochemically engineering" the tailings properties to beneficial conditions for long-term disposal. Amendments made to the tailings represent an alternative form of geochemical engineering. Addition of organic carbon to tailings as they are deposited in the impoundment was proposed by Blowes (1990) and Blowes and Ptacek (1992b). The addition of organic carbon enhances sulfate-reduction reactions and reprecipitation of metal sulfides. If the organic-carbon-rich zone is located below the equilibrium water-table position (Figure 13.8), the reprecipitated sulfide minerals will be isolated from atmospheric $O_2$ by the overlying tailings solids and water column.

Mass-balance calculations conducted by Blowes (1990) suggest that it is feasible to add sufficient organic carbon to stabilize much of the Fe and $SO_4$ contained in a tailings impoundment which has low to moderately high sulfide contents (5—20 wt % S). The volume of organic carbon required for higher sulfide contents, however, is prohibitive. As a result, this approach is not well-suited to the sulfide-rich tailings derived from some base-metal mining operations.

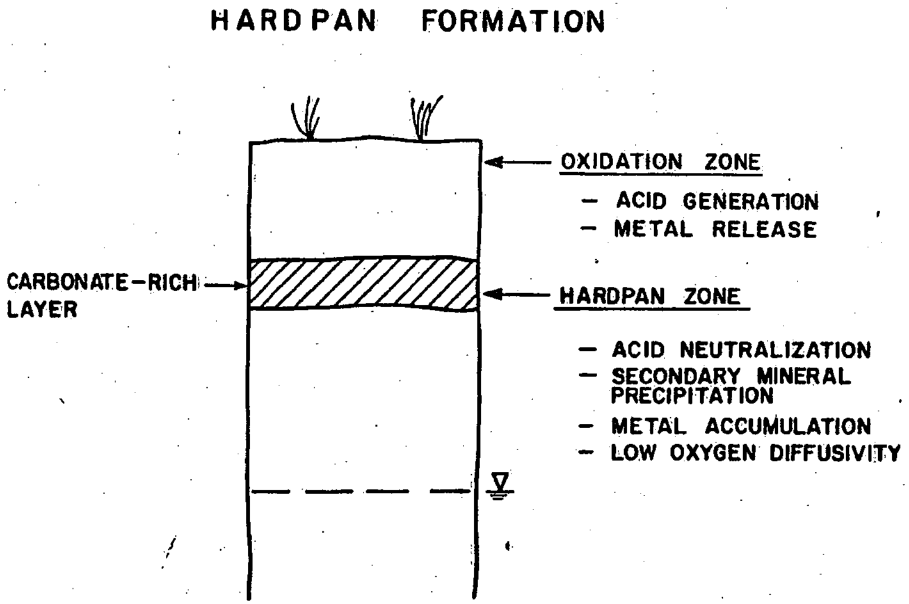

Figure 13.9. Geochemical blending of tailings to promote chemical precipitation of a low-$O_2$-diffusivity barrier within an impoundment.

In contrast to geochemically engineering a tailings-management system, it has been proposed that the physical hydrogeological characteristics of the tailings be modified as they are deposited in the impoundment. Two of the proposed alternatives are thickened tailings deposition (Robinsky, 1975, 1978; Robinsky *et al.*, 1991), and the intentional formation of cemented "hardpan" layers (Blowes *et al.*, 1991; Ahmed, 1994). Deposition of thickened tailings prevents the segregation of grain sizes that is observed in conventional tailings areas (Robinsky *et al.*, 1991; Robertson, this Volume); thus, the tailings are poorly sorted and have unique moisture-retaining characteristics that result in an extensive tension-saturated zone above the water table. Tension-saturated zones measured at Kidd Creek tailings, at which the thickened-tailings disposal technique is employed, extend > 4 m above the water table.

The oxygen diffusion coefficient of unconsolidated materials is dependent on the moisture content. Empirical equations have been developed to describe the relationship between gas diffusion coefficients and the gas-filled porosity of unconsolidated sediments. Reardon and Moddle (1985) developed the equation

$$D(O_2) = 3.98 \cdot 10^{-5}[(\varepsilon - 0.05)/0.95]^{1.7}\, T^{3/2} \qquad (4)$$

where $D(O_2)$ is the diffusion coefficient for $O_2$ gas, $\varepsilon$ is the air-filled porosity, and $T$ is the temperature in Kelvin. This relationship indicates that the rate of the diffusion of gas-phase $O_2$ through saturated tailings is much less than through unsaturated tailings. The large tension-saturated zone observed in thickened tailings deposits (Woyshner and St. Arnaud, 1994; Al *et al.*, 1994a) limits the zone of rapid oxidation to near the tailings surface.

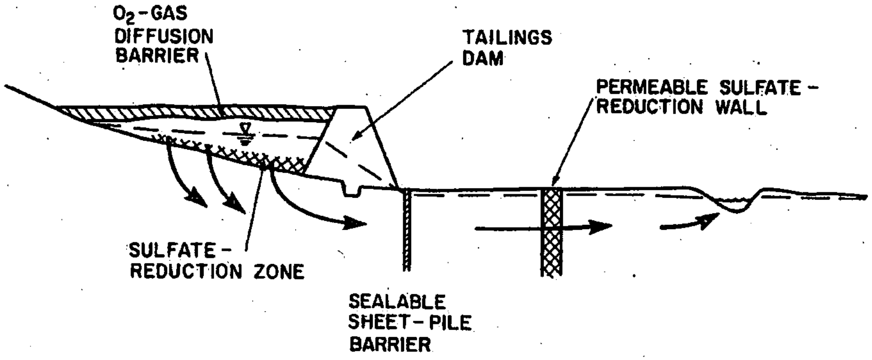

Figure 13.10. Schematic diagram showing the use of a combination of treatment techniques including a low-$O_2$-gas diffusion barrier, a sulfate-reduction treatment zone in the tailings, an impermeable-sheet-pile barrier, and a permeable sulfate-reduction wall installed along the groundwater flowpath.

The occurrence of cemented or "hardpan" layers has been documented at many mine-waste sites (Boorman and Watson, 1976; McSweeny and Madison, 1988; Blowes *et al.*, 1991). The formation of those layers inhibits the diffusion of pore gases into and out of tailings impoundments. Blowes *et al.* (1991) proposed enhancing the formation of these layers through the selective layering of tailings during the late stages of deposition (Figure 13.9). Ahmed (1994) proposed the addition of $FeSO_4$ solutions to enhance the formation of cemented layers. Although the formation of cemented layers has been proposed by several authors, it has yet to be demonstrated on a field scale.

For sites where extremely low release rates are required, a combination of prevention and treatment techniques can be used (Figure 13.10). For example, geochemical blending of the tailings with organic carbon to promote sulfate reduction below the water table can be used in conjunction with a $O_2$-gas diffusion barrier. Other techniques, such as the use of a sealable sheet-pile barrier or a permeable reaction wall installed in the path of the plume can be used in the event one of the previous techniques should fail.

## 13.3. CONCLUSIONS

Conventional approaches to tailings deposition ensure the structural stability of inactive tailings impoundments. Although revegetation programs stabilize the tailings with respect to aeolian and water erosion, these programs do little to prevent sulfide-mineral oxidation or the transport of dissolved constituents through inactive tailings. Programs intended to remediate the environmental effects of existing tailings areas include collection and treatment of drainage waters using conventional water-treatment facilities, and passive downstream treatment using constructed wetlands or porous reactive walls. To date, of these options, only conventional treatment systems have been demonstrated to be effective for metal-mine wastes at the field scale.

Sulfide-oxidation controls include the use of bactericides, surface armoring processes, and $O_2$-diffusion barriers. Bactericides have been demonstrated to be useful over short time periods, but their ability to prevent sulfide oxidation over long periods has yet to be demonstrated. Surface-armor systems result in the precipitation of inert coatings on sulfide minerals. The stability of these coatings over the long term, and their effectiveness relative to natural surface coatings, are not yet known.

Oxygen-diffusion barriers, including water covers, layered soil covers, and synthetic covers have been demonstrated to limit $O_2$ gas diffusion over short time periods (months to years) in field settings. The ability of these barriers to prevent sulfide oxidation over the longer term (decades to centuries) remains unknown. Further testing is required.

Among the various techniques to prevent the oxidation of sulfide minerals under current study, deep-water disposal seems to be most thoroughly evaluated. Separation of sulfide-rich and sulfide-poor tailings is technically feasible, but the environmental benefits of this process have yet to be evaluated. The benefits of thickened-tailings disposal and the addition of organic carbon during tailings deposition are currently being examined at the field and laboratory scale.

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