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DRY COVER SYSTEMS

FOR MINE WASTE MITIGATION

Status Report
June 30, 1999

Minnesota Department of Natural Resources
Division of Minerals
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1. INTRODUCTION

1.1. Mining in Minnesota

Minnesota has an extensive mining industry and potential for mineral expansion and diversification. Iron mining began in Minnesota over a century ago and led to the taconite mining industry which, in 1996, shipped 45 million long tons of iron ore valued at 2.4 billion dollars (Minnesota Department of Revenue, 1997). Nonferrous mining development shows promise for the future. The state is presently the subject of extensive mineral exploration, with 59 leases covering over 26,000 acres of state land (MN DNR, 1998).

Considerable mineral potential for base and precious metals is associated with Minnesota's Precambrian rocks, specifically its Archean metavolcanics, metasedimentary formations and the Duluth Complex. The Archean metavolcanics and metasedimentary formations, or greenstone belts, of Minnesota extend north into Canada, where they have yielded substantial mineral production. These formations are potential hosts for gold, zinc-copper massive sulfides with various by-products, and magmatic sulfide deposits containing copper, nickel and platinum group elements. Recent exploration of greenstone belt metasedimentary formations has focused on gold, base metals, and silver-cobalt-copper deposits. The Duluth Complex contains an estimated copper-nickel resource of 4.4 billion tons (Minnesota Environmental Quality Board, 1979), as well as significant titanium resources. Drill core analyses have also revealed the presence of chromium, vanadium, cobalt, and platinum group elements.

If mineral development occurs, tailings and waste rock, as well as the mine itself will be wastes remaining after the operation is abandoned. The potential for generation of acidic mine waste drainage is the primary water quality concern, and this potential is largely determined by the mine waste composition. Mine wastes capable of producing problematic drainage must be managed such that the quality of waters of the state is not adversely impacted. Mine waste management strategies directed at this objective include prevention, control, and treatment of problematic drainage.

1.2. Objectives and Scope

Our goal is to identify and evaluate current methods of mine waste mitigation in terms of potential use within the state of Minnesota. A literature search of the Reclamation Unit's literature database for the keyword "mitigation" yielded approximately 533 titles (MN DNR, Saint Paul, MN). An additional 305 titles were found in proceedings of mine waste management conferences that took place between 1994 and 1998 and other, miscellaneous sources that have not yet been entered into the database. A total of 838 titles were arranged in an outline format, grouped according to the mitigation strategy addressed (Appendix 1). It is important to note that the list of titles in Appendix 1 is largely comprised of references that were on hand in the MN DNR office in Saint Paul, MN. It does not represent an exhaustive literature review of mine waste mitigation strategies.

Due to the large number of titles found during the initial literature search, each mitigation strategy will be addressed separately. This document will review the much of the current state-of-technology of preventative dry cover systems for reactive mine wastes. Approximately 112 of the 838 titles identified dealt with the topic of dry cover systems. Thirty six of these titles were selected for review in this document because they were considered current and potentially relevant to mining activity in Minnesota.

The selected literature will be reviewed in terms of 1) laboratory and modeling studies on the performance and effectiveness of specific types of dry cover systems; 2) case studies on the development of appropriate cover systems for specific sites; and 3) when available, the implementation and results of the cover system at these sites. The review presented here does not represent an comprehensive literature review on the subject of dry cover systems for the prevention of acid mine drainage, nor does it address the entire range of possible preventative technologies (e.g. encapsulation, subaqueous disposal, wetlands etc.) currently in use. The cover systems that are addressed utilize natural and synthetic dry cover materials either as a single layer cover or as part of a multi-layered design.

2. BACKGROUND: Mine Waste Dissolution and Acid Mine Drainage

Sulfide minerals are commonly occurring constituents in mining wastes. When metal sulfide minerals are exposed to the oxidizing conditions present in waste rock stockpiles, mine walls, and tailings basins, sulfide is oxidized and the associated metals are released (Nelson, 1978; Garrels and Christ, 1965; Sato, 1960a, 1960b). Acid is produced as a result of the oxidation of iron sulfide minerals present in mine waste as indicated by reactions 1 (Nelson, 1978) and reaction 2 (Stumm and Morgan, 1981). Two moles of acid are produced for each mole of sulfur oxidized.

$$FeS + (9/4)O_2 + (3/2)H_2O = FeOOH + SO_4^{2-} + 2H^+ \qquad (1)$$

$$FeS_2 + (15/2)O_2 + (5/4)H_2O = FeOOH + 2SO_4^{2-} + 4H^+ \qquad (2)$$

The rate of oxidation is proportional to the available sulfide surface area (Nelson, 1978; Sato and Mooney, 1960; Sato, 1960a, 1960b), and the concentration of dissolved oxygen (Nelson, 1978; Dobrokhotov and Maiorova, 1962; McKay and Halpern, 1958), with only a slight dependence on pH (Nelson, 1978; Majima and Peters, 1966). When the pH of reacting water decreases below 4.0, the rate of oxidation can be accelerated by the activity of iron oxidizing bacteria (*Thiobacillus ferrooxidans*) which rapidly oxidize sulfide minerals when adequate oxygen is present.

The oxidation of trace metal sulfide minerals releases trace metals and sulfate but does not necessarily produce acid.

$$CuS + 2O_2 \rightarrow Cu^{2+} + SO_4^{2-} \qquad (3)$$

Reactions subsequent to the sulfide dissolution affect the net trace metal release to the environment. The transport of a given component in the environment is the net result of release to solution by dissolution and removal from solution by precipitation, coprecipitation, exchange reactions, and adsorption. The degree of trace metal transport is dependent upon drainage composition (in particular pH), the chemistry of the released component, and the chemical character and surface area of solid surfaces present. Concentrations of trace metals tend to increase exponentially as solution pH decreases, therefore acidic drainage often contain elevated trace metal concentrations. However, circumneutral drainage can contain elevated concentrations of trace metals such as nickel (Eger and Lapakko, 1985) and molybdenum (Brown, 1989) which, compared to other trace metals are relatively soluble in this pH range.

Chemical release is affected by the amount of water percolating through the mine waste, which is dependent on the input volume and subsequent flow routing. Precipitation is an ever-present input, but surface water and ground water can also contribute under certain conditions. The water input will be incorporated as storage or discharged as evapotranspiration, surface runoff, subsurface flow (or interflow) and baseflow (Hewett, 1980).

3. DRY COVER SYSTEMS

3.1. Objectives of a Dry Cover System

The amount of acidity and associated trace metals released due to oxidative sulfide dissolution is a function of the amount of water and oxygen present in reactive mine wastes. Furthermore, water is necessary to transport these reaction products from the mine wastes to the environment. The rate of sulfide oxidation can be minimized, by limiting exposure of mine waste materials to water and oxygen (equations 1, 2, and 3). Dry cover systems are designed to achieve one or more of the following objectives: 1) minimize water infiltration into underlying mine wastes, 2) inhibit oxygen diffusion into reactive mine wastes, and 3) consume oxygen within a cover layer over reactive mine wastes. Each cover system will have an effect, to some degree, toward these objectives depending on the physical properties (permeability, grain and pore size, etc.) of the cover materials used.

3.2. Categories of Dry Cover Systems

In reality, there are as many dry cover system designs as there are dry cover systems. However, dry cover system designs generally fall into one of six categories: soil covers, compacted clay covers, anisotropic barriers, capillary barriers, oxygen consuming barriers, and synthetic covers. Three main design components can be used to describe a dry cover system (Figure 1). Frequently, a distinct, support layer is incorporate into a dry cover system design. A barrier layer is then laid out over the support layer. Physical properties of barrier layer materials are utilized to inhibit water infiltration and/or oxygen diffusion. Certain materials (e.g. organic matter) may be used to consume oxygen within the barrier layer. Usually a protection layer is laid out over the barrier layer. Protection layers increase lateral drainage of surface runoff, minimize erosion, protect against damage caused by freeze-thaw cycles, and prevent biointrusion of the barrier layer. Frequently, an additional layer of topsoil is added as a support for vegetation, which increases evapotranspiration further reducing water infiltration into the underlying mine wastes. Each of the six dry cover system designs will be described in terms of the support layer, active barrier layer, and any protection layers incorporated into the design.

3.2.1. Conventional Soil Covers

The simplest and least expensive dry cover system to install is a basic soil cover (Figure 2). This cover design does not necessarily involve a support layer. Instead, a barrier layer of soil is deposited directly over the mine waste. The thickness of the soil layer depends upon the type of mine waste and site-specific requirements. While this design will reduce infiltration to the underlying mine waste, it will not eliminate it unless used in an arid climate. However, compaction of the soil barrier layer will further reduce infiltration. A protective layer of loose topsoil is often used with conventional soil covers. This layer supports vegetation as well as protects against erosion.

3.2.2. Compacted Clay Covers

Compacted clay cover designs are similar to conventional soil covers. The main difference is that clay (e.g. bentonite) is mixed into the soil used for the barrier layer (Figure 2). The addition of clay to the barrier layer increases the cost and the complexity of this cover design. However, the higher clay content and compaction serve to minimize the hydraulic conductivity of the barrier layer, and consequently, limit downward movement of water to the underlying mine waste. Occasionally, a drainage layer of a relatively coarse grained material (e.g. sand) will be installed directly over the barrier layer. The drainage layer helps minimize infiltration into the barrier layer by enhancing lateral drainage away from the mine waste. Finally, a protection layer of loose soil is used to support vegetation and to prevent damage to the barrier layer caused by erosion or freeze-thaw cycles.

3.2.3. Anisotropic Barriers

Anisotropic barriers utilize layers of capillary breaks to minimize vertical movement of water while maximizing horizontal drainage. Different physical properties and compaction techniques are used to maximize lateral drainage away from underlying mine wastes. One example of an anisotropic barrier consisted of four layers (Figure 2). A coarse-grained support layer of gravel is used to create a capillary break beneath an interface of fine sand. The fine sand interface increases lateral drainage of any water that percolated through the barrier layer. Native soils are typically used for the barrier layer which is designed to store water for subsequent evapotranspiration. The barrier layer is overlain by a soil and gravel protection layer which encourages evapotranspiration as well as protecting underlying layers and allowing vegetation growth.

3.2.4. Capillary Barriers

Capillary barrier designs contrast hydraulic properties of cover materials to minimize downward migration of water by creating a capillary break between layers. The capillary break is achieved by placing a fine-grained (i.e. barrier) layer between two coarse-grained layers (i.e. support and protection layers; Figure 2). The capillary barrier itself consists of the support layer and the barrier layer. Coarse sand or gravel is typically used for the support layer. The support layer also has the added benefit of enhancing lateral drainage of any water that infiltrates the barrier layer. Fine sand, soil, clay, and inert tailings have been used as barrier layers in capillary barrier covers. The lower hydraulic conductivity of these materials relative to that of the support layer enhances moisture retention and inhibits oxygen diffusion across the capillary break. A protection layer of sand or gravel overlies the capillary barrier to encourage lateral drainage. Once again, topsoil is usually used as the surface layer to support vegetation and minimize damage to the underlying active layers.

3.2.5. Oxygen Consuming Barriers

Oxygen consuming barriers utilize organic material as a barrier to oxygen diffusion into underlying mine wastes. If adequate organic material is present, the rate of oxygen consumption will exceed the rate of oxygen diffusion through the barrier layer, preventing oxygen from reacting with the underlying reactive wastes. The relatively low hydraulic conductivity of most organic materials coupled with increased compaction of the barrier layer as organic materials oxidize often results in the additional benefit of reduced infiltration of water to underlying wastes. Organic barrier layers are often applied as a single layer, simplifying the construction of the design (Figure 2). Furthermore, organic materials are usually locally available, reducing the cost of this cover design.

3.2.6. Synthetic Covers

Impermeable cover systems can also be constructed of synthetic materials such as plastic liners. Oftentimes, synthetic cover materials provide a simple alternative to natural soil materials. Synthetic cover materials have also been incorporated into other cover system designs to maximize their effectiveness. A number of plastic (geosynthetic) liners are commercially available, most of which consist of flexible polymeric membranes (e.g. PVC or HDPE) that act as a barrier to water infiltration. Another option is a geosynthetic clay liners (GCLs), where sodium bentonite clay is encapsulated between two layers of geotextiles (Stewart and von Maubeuge, 1997; Miller and Hornaday, 1998).

Geosynthetic membranes can be installed year round and is very simple. Installation merely involves unrolling the geosynthetic membrane out over the mine waste. Since they are relatively light weight, thin, and do not require compaction, geosynthetic membranes are relatively inexpensive to install. Geosynthetic membranes are extremely durable and resistant to leaching, however, they are also thin and susceptible to damage (i.e. tears, leaks along seams, photodegradation), particularly during installation. Geosynthetic membranes and GCLs perform well under extreme conditions such as freeze-thaw cycles and dessication, but because they tend to deteriorate when exposed to sunlight, they are commonly covered with one or more protective layers of soil. A common configuration involves a geosynthetic membrane overlain by a drainage layer (e.g. sand) and a topsoil protective layer, although geosynthetic membranes have been used in combination with numerous natural cover materials (Figure 2).

4. GENERALIZED APPROACH TO DRY COVER SYSTEM DESIGN

4.1. Variables Affecting the Type of Cover System Implemented

The primary issue concerns the type of materials to be used in the dry cover system. Cover requirements are almost always site-specific, depending on variables such as the physical, chemical and mineralogical properties of the wastes, climatic conditions, local regulations, and availability of cover materials. Consequently, a cover system implemented at one mine site may not meet the objectives intended for similar reactive wastes at another site. The choice of cover materials is often based upon numerous variables including costs, constructability, and overall effectiveness. In general, the expense associated with each type of cover system increases as the cover system becomes more complex (Table 1). If cover materials require compaction or other special treatment, construction costs increase. However, using locally available cover materials such as glacial till or non-reactive mine wastes can substantially decrease costs.

4.2. Predictive Modeling of Proposed Cover System Design

How well a proposed cover system will perform is usually tested using predictive modeling, and occasionally, laboratory column studies. Predictive models are frequently used to predict the long-term effectiveness of a cover system, since long-term performance of a specific cover system cannot be determined prior to installation. Predictive models are typically used to meet one of the following objectives: determine ground water flow through a mine waste mass as well as over or around it, estimate surface water and precipitation infiltration through the cover system, and predict the water quality of drainage from the covered mine wastes. The use of models in this way is an inexpensive method to evaluate multiple cover systems and their long-term impacts on local surface and ground water quality in a very short amount of time.

4.3. Materials Testing

Laboratory tests are typically used to determine the hydraulic and geotechnical properties of particular cover materials under consideration as well as how layers of multiple cover materials may interact to reduce infiltration and oxygen diffusion to the underlying waste.

Hydraulic conductivity and porosity are the most frequently determined properties. However, D_{10}, specific gravity, plasticity index, and numerous other parameters have been determined as well. Occasionally, the same parameters will be determined for the mine waste, particularly if the mine waste is tailings rather than waste rock. The most thorough studies also determined the physical, chemical, and mineralogical properties of potential cover materials and/or the mine waste.

4.4. Effectiveness of a Cover System Design

The effectiveness of a cover system is typically measured in terms of oxygen concentrations and water content profiles throughout and beneath the cover. Column experiments are designed with instrumentation to measure temperature and pressure changes, water content and oxygen concentrations at regular intervals in the column. Since sulfide oxidation is an exothermic reaction, temperature measurements provide a qualitative indication of the extent to which oxidation had occurred in the mine waste. Pressure changes were measured using tensiometers connected to pressure transducers, while moisture content was measured by Time Domain Reflectometry (TDR) electrodes. Oxygen sensors placed at regular intervals down the length of the column measured oxygen concentrations at various depths. These were used to construct oxygen profiles and gradients ($\delta C/\delta z$), which in conjunction with the effective diffusion coefficient (D_e), were used to determine the oxygen flux for the cover system.

5. LITERATURE REVIEW

For the purposes of this document, dry cover system designs will be discussed according to the type of materials used in construction (i.e. natural or synthetic). The first five categories (see section 3.2) of cover system designs use natural materials. No distinction will be made between the first three design types because they are similar and conceptually simple to understand. Natural materials are also used for capillary, however, they are more complex and will be discussed separately. Similarly, cover systems that utilize organic materials to consume oxygen rather than inhibit diffusion will be discussed in a separate section. Finally, the use of synthetic cover materials will be discussed.

5.1. Natural Cover Materials

5.1.1. Native Soils

A number of preventative technologies have been developed to reduce the ingress of water and oxygen into reactive mine wastes. The most commonly implemented technologies involve covering mine wastes with dry, relatively impermeable, natural materials to prevent water and/or oxygen from reacting with sulfide minerals beneath the cover system. The simplest method is to cover a reactive mine waste with several feet of soil, particularly soils with high clay contents (soil cover). This type of cover design is particularly useful as a store-and-release mechanism for water, whereby water is trapped within the pore spaces of the cover and slowly evaporates over time. In addition to preventing downward migration of water to the underlying mine waste, the water filled pore spaces inhibit diffusion of oxygen through the cover. These properties can be enhanced by compacting the soil, reducing the permeability of the cover (compacted clay cover). Oftentimes, a compacted soil layer will be covered with several inches of topsoil and revegetated. Evaporation and lateral drainage is often enhanced by incorporating multiple layers of different grain sizes and hydraulic properties (anisotropic barrier).

One major advantage of a soil cover system is that the soils are locally available which reduces transportation and material costs of construction. Also, soils provide nutrients and a physical support for vegetation, although biointrusion (e.g. plant roots) may compromise the integrity of the cover. Another drawback to soil covers is that they are susceptible to erosion and cracking caused by freeze-thaw cycles and dessication, especially when clayey materials are used in the cover. Thus, additional measures may be required at sites with extreme environmental conditions such as arid climates or cold temperatures.

5.1.1. Case Studies

Case studies of selection, design, and/or implementation of **composite soil cover systems** have been reported at numerous minesites world-wide (Eger and Lapakko, 1985; O'Kane et al., 1995; Aziz and Ferguson, 1997; Lindvall et al., 1997; Wilson et al., 1997; Kowalewski et al., 1998; Udoh, 1993). Six test stockpiles containing 820 to 1300 metric tons of sulfidic mine waste material were constructed in 1977 at the Dunka Mine near Babbitt, Minnesota (Eger and Lapakko, 1985). Three of the stockpiles remained exposed to the atmosphere as controls, and the other three were covered with 18-29 cm of soil obtained from a nearby borrow pit in 1978. Stockpile 2 was covered with topsoil, while piles 3 and 5 were covered with a coarse, sandy soil. However, 30 cm of sandy till was added to the coarse sand on pile 5 in 1980. Revegetation efforts began immediately in 1978 and continued for approximately three growing seasons. For the six year period of record, runoff coefficients for the control piles ranged from 0.44 to 0.58, as compared to 0.41 for natural watersheds in the area. There was no flow reduction by the vegetated coarse sand cover (pile 3). The vegetated covers of topsoil (pile 2) and combined sandy till over coarse sand (pile 5) both produced runoff coefficients of 0.30, a value which was 30 to 50% less than the control values.

Three different soil cover systems were evaluated for their effectiveness at stemming infiltration into sulfidic mine wastes at LTV's Dunka Mine near Babbitt, Minnesota (Udoh, 1993). The cover materials under consideration were glacial tills screened to minus 2.5 inches and 0.5 inches, and glacial till screened to -2.5 inches mixed with 5% bentonite. Laboratory tests indicated that the permeability of these materials ranged from 1.55 x 10^{-6} cm/s (49 cm/yr) for the glacial till down to 4.12 x 10^{-9} cm/s (0.13 cm/yr) for glacial till mixed with 5% bentonite, meeting the set standard of 2 x 10^{-6} cm/s (63 cm/yr). These results were similar to Hydrologic Evaluation of Landfill Performance (HELP) model simulations that predicted permeabilities ranging from 2.1 x 10^{-6} cm/s (66 cm/yr) for -2.5inches of glacial till down to 5.2 x 10^{-10} cm/s (0.02 cm/yr) for glacial till mixed with 5% bentonite. The model simulations also indicated that the major water loss would be to evapotranspiration. Infiltration was predicted to be reduced by 34% for glacial till cover, and could be decreased by up to 80% if the cover materials were compacted. Actual field test results showed that infiltration was reduced by 60%, 88%, and 89% for -2.5 inches of till, -0.5 inches of till and -2.5 inches of till mixed with 5% bentonite, respectively.

At the Kennecott Ridgeway Mine near Ridgeway, South Carolina, predictive models (SEEP/W and SoilCover) were used to evaluate composite cover options for a 300 acre gold tailings impoundment (Kowalewski et al., 1998). Three cover systems (two soil covers and one anisotropic barrier) and two construction options were evaluated for limiting percolation while maintaining a saturated tailings mass. Based on the modeling results as well as cost and construction considerations, a soil cover system comprised of 36 inches of saprolite and 7 inches of topsoil was chosen as the preferred reclamation option.

The Saxberget Mine, Sweden was decommissioned in 1988 after a century of mining (Lindvall et al., 1997). Closure plans included a soil cover system to be placed over a mill tailings area. The cover system had to comply with the Swedish EPA's program objectives of long-term, low maintenance remediation techniques. A composite cover consisting of a low permeability barrier layer overlain by a protective layer was determined to meet these objectives. Compacted municipal sewage sludge and Cefyll (a concrete-fly ash product) were considered for barrier layer materials. However, local glacial till with a high clay content was found to have adequate hydraulic properties and the lowest cost. Therefore, 30 cm compacted glacial till was selected for the barrier layer. One and a half meters of unclassified glacial till was used as the protection layer. Reported results after approximately two years indicate that the infiltration rates were close to or less than 5 x 10^{-9} m/s (approximately 16 cm/yr) and that oxygen concentrations below the cover system have dropped below 0.5%.

At Equity Silver Mines Ltd. near Houston, British Columbia, a soil cover system was investigated for long-term performance at reducing the transport of oxygen and minimize water infiltration to underlying sulfidic mine wastes (O'Kane et al., 1995; Aziz and Ferguson, 1997; Wilson et al, 1997). The investigation program included predictive modeling, laboratory characterization of materials, and field monitoring. The cover system placed on top of the waste rock dump consisted of approximately 50 cm compacted till (barrier layer) overlain by 30 cm uncompacted till (protective layer). For the slopes of the waste dump, 50 cm of compacted clay was substituted for compacted till as the barrier layer (Aziz and Ferguson, 1997). Although evaporation occurred in the uncompacted protective layer, the compacted sealing layer maintained at a degree of saturation of 85% or higher over a two year period (O'Kane et al., 1995). After five years, water infiltration to the waste rock has been reduced to 4% of the total annual precipitation (Wilson et al., 1997). The 50 cm of compacted till sealing layer has maintained a high level of saturation, minimizing oxygen flux through the cover. After approximately six years of monitoring, average infiltration consistently remains below 5% and oxygen concentrations beneath the cover have decreased to a few percent (Aziz and Ferguson, 1997). Production of acidic drainage is expected to cease in approximately 15 years.

Arid climates pose a challenge when designing a cover system to minimize water and oxygen infiltration. Heavy, seasonal rainfalls result in high velocity surface runoff and probable erosion of the cover surface. Therefore, lateral drainage layers may actually serve to diminish the integrity of the cover. The infrequency of rainfall results in eventual drying of the cover, rendering it useless as an oxygen barrier. The ideal cover system in an arid climate balances rainfall with water storage, evaporation, and transpiration. This type of soil cover system was installed on a 23 ha waste rock dump at Kidston Gold Mines, North Queensland, Austrailia (Williams et al., 1997). The waste rock was sloped at about 3% to assist drainage and compacted to about 1 m. Above this surface, a layer of compacted, nearly saturated, clay was placed. This layer is then covered with a layer of "rocky soil mulch," piled loosely in mounds and vegetated. No results were reported, however, this cover system has been proposed at other dry climate mine sites in Austrailia.

A soil cover system for waste rock material generated by BHP Iron Ore's Mt. Whaleback operation in western Austrailia was designed to prevent water infiltration to underlying waste material (O'Kane et al., 1998). The cover system was designed to minimize infiltration by storing as much precipitation as possible within the cover. This moisture can then evaporate without significant reaction. Design phases included physical characterization of the waste rock and cover materials as well as one dimensional soil-atmosphere modeling (SoilCover). It was determined that a key design feature was the use of pit run waste as the cover material. Two field test plots with cover layers of 2 m and 4 m were installed in early 1997. Monitoring of the test plots was scheduled for at least two annual wet/dry cycles.

One alternative to soils in dry cover systems is the use of **non-reactive mine wastes** (Elliott et al., 1997a, 1997b; Woyshner and Swarbrick, 1997; Muller et al., 1998). The use of a non-reactive mine waste as a cover material is an attractive alternative because the waste materials are located on-site which reduces transportation costs appreciably. Desulfurized tailings, among other options, were tested for their effectiveness as a barrier layer material during a one year long, pilot scale study (Elliott et al., 1997a, 1997b). Earlier phases of this study included characterization of the reactive tailings and cover materials and a salt migration column bench scale test. Only the pilot-scale field tests will be discussed here. PVC pilot cells measuring 2.5 m long, 1.5 m high, and 0.6 m wide were filled with 0.65 cm of reactive tailings and covered with a 75 cm layer of desulfurized tailings. The high degree of saturation (>90%) of the desulfurized tailings cover was consistent with decreasing oxygen levels within the cover. Oxygen concentrations beneath the cover were approximately zero. However, generation of sulfate and dissolved iron indicated that oxygen still diffuses to the underlying tailings. This was said to be due to the formation of cracks at the surface which extended to considerable depths in the cover.

Non-reactive mine wastes were evaluated as barrier layer materials in test plots at the Kidd Creek tailings impoundment, Timmins, ON (Woyshner and Swarbrick, 1997). Three cover systems were constructed: 1) 60 cm non-reactive beach tailings, 2) 45 cm non-reactive beach tailings underlain by 15 cm slag, and 3) 60 cm clay, and monitored for one year. Lysimeters installed in the tailings remained dry during the monitoring period indicating that rainfall did not infiltrate the covers as saturated flow. The covers were not effective as oxygen barriers, however, oxygen flux calculations indicated that sulfide oxidation was reduced from 729 mol $O_2/m^2/yr$ for uncovered tailings to 36.1, 73.7, and 13.1 mol $O_2/m^2/yr$ for covers 1, 2, and 3, respectively. Further evidence for decreased sulfide oxidation could be found in the decreased sulfate production from 40 $kg/m^2/yr$ to 2, 4, and 1 $kg/m^2/yr$, respectively. These covers are expected to eliminate the high rates of sulfide oxidation that typically occurs during the first twenty years of exposure.

A tailings management plan was proposed for controlling pyrite oxidation at a mining property in central Idaho (Muller et al., 1998). Modifying operations with an additional pyrite flotation circuit will produce two tailings products. Pyrite concentrates will be disposed of underwater in the tailings pond, while the low sulfur inert tailings will be deposited in areas susceptible to oxidation, effectively capping the pyrite concentrates. The degree of tailings saturation was evaluated using the hydrologic model, HELP. Maximum sulfide oxidation rates were calculated based on kinetic control in the upper 0.5 m of the tailings and oxygen diffusion control beneath 0.5 m. A 2 m cover of inert tailings was predicted to reduce the pyrite oxidation rate from 13,750 g pyrite/m^2/yr to 2,500 g pyrite/m^2/yr (18%). Ultimately, the pyrite concentrates are expected to be covered by 42 m of inert tailings which was predicted to reduce pyrite oxidation rates by 90%.

5.1.2. Capillary Barriers

By combining multiple cover materials with different physical properties in layers over a mine waste, the effectiveness of the cover can be maximized. The basic capillary barrier cover system consists of a layer of fine grained material sandwiched between two coarser materials. The base of the cover consists of a coarse grained material to act as a support for the remaining layers. A barrier layer of fine grained material that retains moisture and inhibits oxygen diffusion overlies the support layer. Usually, the final layer is of a coarse material designed to protect the moisture retaining layer by enhancing surface runoff. Additional protective layers may be added at the surface of the cover system as a support for vegetation and/or to prevent biointrusion.

5.1.2.1. Principles of Capillary Barriers

When water infiltrates soil, it immediately fills the largest pore spaces. Water flow tends to be dominated by capillary forces, which may pull some water into smaller pores. Capillary forces can act in any direction, depending on the concavity of liquid-air interfaces within the pore spaces. However, gravity tends to pull water downward until the absorptive capacity of the soil or a water table is reached. Water will continue to infiltrate the soil column until the downward force is balanced by the upward pull from liquid-air interfaces near the soil surface (e.g. evaporation).

The texture of soils exerts a strong influence on the efficiency of capillary flow. Capillary forces are typically largest in fine grained materials. Thus, clay particles tend to have a higher water content than gravel under the same conditions. More specifically, the water content (θ) of a particular medium is related to the pressure head (ψ). In geotechnical terms, pressure head is analogous to the height of capillary rise for a given material, becoming more negative with elevation above the water table. As the pressure head becomes more negative, the water content of the medium generally decreases (figure). The pressure at which capillary forces are overcome and the water content of the medium rapidly decreases to a residual value (Θ_r) is known as the Air Entry Value (AEV). Finer grained materials tend to have higher AEV than coarser materials under identical conditions. In simpler terms, a fine-grained material will remain saturated at a higher elevation above the water table than a coarse-grained material.

As water infiltrates the surface, dissolved oxygen, which may react with unoxidized minerals, is carried through the mine waste. However, the principle mode of atmospheric oxygen transport in a mine waste stockpile is by diffusion through gas filled pore spaces. The effective diffusion coefficient for oxygen moving through pore spaces depends upon the proportion of gas filled pores. As water content of the pore spaces increases, the effective diffusion coefficient decreases. The magnitude of this decrease can approach several orders of magnitude as saturated conditions are approached.

5.1.2.2. Laboratory Tests of Capillary Barrier Systems

The use of capillary barriers in cover systems has been investigated for approximately a decade. Many of the earlier studies involved a series of laboratory tests, and occasionally, predictive modeling efforts to evaluate the performance of specific materials as capillary barriers. Laboratory test and modeling methods were similar to those used to evaluate the simpler cover systems described in section 4. However, column experiments were typically used to evaluate the performance of capillary barrier materials. The type of materials selected for use in a capillary barrier cover system varied between laboratory experiments. While medium to coarse grained sand was typically used for the coarse grained layers in these experiments, several different materials have been investigated for use as the fine grained, or moisture retaining, layer. Fine sand (Nicholson et al., 1991), till (Yanful, 1991), clay (Yanful, 1993; Yanful et al., 1994) and desulfurized or low sulfur tailings (Aachib et al., 1994; Bussiere et al., 1997; Benzaazoua et al., 1998) have been tested for their effectiveness as a capillary barrier.

Earlier laboratory experiments generally tested the moisture retention characteristics of a fine grained material overlying a coarser material (Nicholson et al., 1991; Yanful, 1991, 1993). Columns were packed with a layer of medium to coarse sand overlain by a layer of fine sand (Nicholson et al., 1991) or glacial till (Yanful, 1991, 1993). Selected materials were chosen and matched such that the material properties would enhance capillarity in the fine grained material. Nicholson et al. (1991) used 20 cm of a fine sand with an AEV of 37 cm overlying 80 cm of a coarser sand with an AEV of 8 cm. Tensiometers with pressure transducers and

TDR electrodes were placed at 10 cm intervals within the columns. The columns were initially saturated and then drained. The coarse sand layer drained to the residual water content in approximately five hours. After fourteen days, the fine sand layer had retained 75% of the initial, saturated water content.

In two separate column experiments, Yanful (1991) tested a 20 cm layer of glacial till as moisture retaining layer. In each experiment, the till was underlain by 80 cm of a medium sand with an AEV of 10 cm. The glacial tills were characterized as a sandy silt with 8% in the clay fraction (Heath Steel till) and a silty sand with 10.5% in the clay fraction (Yukon/Faro mine site till). Tensiometers with pressure transducers and TDR electrodes were placed at 10 cm intervals within the columns. The columns were initially saturated and then drained. In both experiments, the coarse layer drained to the residual water content relatively quickly (approximately seven days). Both glacial till layers were reported to have maintained saturated conditions during the course of the fourteen day experiment.

Laboratory column experiments on the Heath Steel till were continued in order to determine oxygen diffusion coefficient with respect to water saturation (Yanful, 1993; Yanful et al., 1994). Laboratory column experiments were designed to compare moisture content and oxygen concentration profiles in covered and uncovered sulfidic tailings. Square columns were constructed of Plexiglas measuring 105 cm in length and 28 cm per side. Two test columns were packed with 45 cm of unoxidized tailings beneath layers of 15 cm coarse sand, 30 cm compacted clay, and 15 cm fine sand. Two additional control columns contained 90 cm of unoxidized tailings with no cover materials. Each column was equipped with oxygen ports at 10 cm intervals, temperature probes at 15 cm intervals, and at least one TDR probe within each layer. Precipitation was simulated by periodic water additions, and the effluent from the control columns were analyzed for metals, major cations and sulfate. The clay layer prevented infiltration into the test columns, therefore, no effluent was available for analysis. Consequently, the tailings beneath the cover were flushed with water on four occasions over 760 days. Over the course of 200 days, the clay layer remained at or near saturation ($\geq$95 %). The water content in the tailings remained at 30 to 35% until the column was flushed with water, after which the tailings were saturated. Chemical analyses indicated that the capillary barrier cover system reduced acid production in the tailings by 95.4%

The effective oxygen diffusion coefficient of the clay layer was on the order of 3.9×10^{-9} m^2/s. After 65 days, oxygen concentration profiles revealed that oxygen concentrations decreased from ambient levels (21%) at the fine sand-clay interface to less than 1% in at the clay-coarse sand interface. These low oxygen concentrations were maintained through the tailings to the base of the column, demonstrating the effectiveness of this capillary barrier cover system to inhibit oxygen diffusion into sulfidic tailings.

Based on the laboratory and modeling results, a capillary barrier system consisting of a 60 cm thick compacted fine-grained layer sandwiched between two 30 cm thick sand layers was tested in the field at the Waite Amulet site. Early results showed that the oxygen concentration at the base of the capillary barrier was approximately 4%. Simulations using

POLLUTE indicated that the effective diffusion coefficient of the capillary barrier was about 9.9×10^{-9} m/s (31 cm/yr), an order of magnitude lower than for uncovered tailings. Oxygen flux into the tailings was reduced by 99% by the capillary barrier.

Desulfurized or low sulfur content tailings have also been investigated as potential moisture retaining layers for capillary barrier cover systems (Aachib et al., 1994; Bussiere et al., 1997; Benzaazoua et al., 1998). Desulfurized tailings are often available on site, or at least nearby, making their use both economical and practical. Aachib et al. (1994) used laboratory column experiments to evaluate the performance of a capillary barrier cover system using non-reactive tailings. Test columns were constructed of Plexiglas 1.7 m in length, while two smaller columns were used as controls. Each column test was done in duplicate, where one column contained instrumentation and the duplicate remained intact. The cover layers consisted of a 20% iron sulfide tailings layer at the base followed by 30 cm sand, 50 cm non-reactive tailings and 20 cm sand. Three different desulfurized tailings and one low sulfur tailings material were tested for their effectiveness as moisture retaining layers. Precipitation was simulated by percolating water from the top of the column and collecting it at the base. The tailings properties included low hydraulic conductivity and high water retention characteristics resulting in reduced diffusion of oxygen through the moisture retaining layer. Preliminary calculations showed that a degree of 90% saturation in a porous material produces a layer with an effective diffusion coefficient that approximates the effective diffusion coefficient in water.

Bussiere et al. (1997) and Benzaazoua et al. (1998) conducted laboratory column experiments to determine the effectiveness of a capillary barrier cover system using desulfurized tailings. Plexiglas columns measuring 0.106 m inner diameter were mounted 2 m above the floor, where an artificial water table was fixed. The columns were flushed with water every three to four weeks, and the effluent was analyzed for pH, Eh, sulfate, calcium and soluble metals. Oxygen consumption was also measured on a weekly basis (Benzaazoua et al., 1998) or biweekly (Bussiere et al., 1997). Methods for the oxygen consumption tests were described previously (Elberling et al., 1994). Columns were designed such that 0.3 m of tailings containing 27.5% S (primarily pyrite) were overlain by 0.4 m sand, 0.6 m desulfurized tailings, and 0.3 m sand. The amount of residual sulfur in the tailings varied for three of the experiments (0.14% S, 0.41% S, and 1.00% S). The fourth column contained only sulfidic tailings. The effluent from the capillary barrier cover columns maintained a near neutral pH and relatively low metal and sulfate concentrations during the year long test. Sulfide oxidation rates in the capillary barrier cover column tests were reduced by a factor of approximately seven to twenty two, depending on the degree of desulfurization in the cover material. The cover with the lowest sulfide content was the most efficient at inhibiting sulfide oxidation.

Numerous studies have demonstrated the behavior of capillary barriers over mine wastes. However, these studies either dealt with saturation in horizontal layers or water diversion capabilities of a capillary cover system. Aubertin et al. (1997a) addressed the issue of the effectiveness of a capillary barrier in an inclined cover system. A two dimensional numerical investigation (SEEP/W) showed that it was more difficult to maintain high saturation levels near the top of an inclined cover system. If the elevation difference between the upper and lower part of a continuous system approaches the AEV, then the top portion may become unsaturated. The larger the elevation difference, the more difficult it will be to keep this layer close to saturation. Modeling results indicated that even a relatively low slope (2 - 4%) may not maintain adequate saturation.

5.1.2.3. Field-Scale Experiments

Field scale experiments have also been used to evaluate the effectiveness of capillary barrier cover systems over sulfidic mine wastes, particularly in Canada (Yanful and St-Arnaud, 1991; Aubertin et al., 1997b; Gardiner et al., 1997). Field experiments often utilize cells shaped like an inverted truncated pyramid. A combination of support layers, liners and water collection systems are placed in the base of the cell. Water collection systems are designed such that water flows easily from the base of the cell without allowing air to enter. Reactive tailings or waste rock can be placed within the cell and overlain with the cover system to be tested.

Four 20 m x 20 m test plots were designed to determine the effectiveness of a capillary barrier cover system for the Waite Amulet tailings site, near Rouyan-Noranda, Quebec (Yanful and St-Arnaud, 1991). Two of the test plots were covered with a 60 cm compacted varved clay layer sandwiched between upper and lower sand layers (30 cm). The test plots were designed with 3:1 end slopes that were lined with 40 mil HDPE. A third test plot was covered with a 80 mil HDPE geomembrane sandwiched to upper and lower layers of sand. The final test plot was the uncovered control. Results for the first two months of monitoring one of the clay-capillary barrier cover tests was presented. Oxygen concentrations in the clay capillary barrier had decreased to 10% and had an associated volumetric water content of 40%. Water quality of the drainage indicated that some acidity had been released from the tailings. Lysimeters beneath the tailings remained dry, except for the uncovered control plot, indicating that infiltration had been eliminated.

Six experimental cells were constructed on ITEC Mineral Inc.'s Norebec-Manitou site near Val d'Or, Quebec (Aubertin et al., 1997b). Approximately 1.5 m of reactive tailings were covered with a base layer of 0.4 m coarse sand, a capillary barrier of 0.3 - 0.9 m clean tailings or silt, and a final layer of 0.3 m sand. Five capillary barriers were tested: 1) 0.6 m clean tailings, 2) 0.6 m silt, 3) 0.3 m tailings, 4) 0.15 m clean tailings overlain by 0.15 m tailings mixed with bentonite, and 5) 0.9 m tailings. The sixth cell had no cover layers as a control. Each cell was instrumented to monitor volumetric water content, matric suction, and subsurface temperature in each of the cover layers as well as climatic conditions and leachate quality. Preliminary results from the first year of monitoring show that the capillary barrier has maintained approximately 85% saturation and was considered to be an effective barrier to oxygen diffusion. The pH of drainage collected from the test cells has remained at about 6, while the pH of drainage from the control cell has dropped to about 3.

The Sullivan Mine, BC is planning for closure in 2001. Reclamation of the tailings pond will include a capillary barrier cover system constructed of local materials and is intended to limit infiltration and support vegetation (Gardiner et al., 1997). Predictive modeling using SoilCover and field test plot were used to evaluate the performance of several cover material options such as float rock, both compacted and non-compacted glacial till and phosphogypsum. The field investigation was initiated in 1993 to compare various capillary barrier designs using float rock and glacial till. The till capillary layers did not maintain saturation continually, resulting in high oxygen concentrations beneath the cover. However, the compacted till capillary layer was able to reduce precipitation infiltration to 2 - 6%. The non-compacted till capillary layer did not perform as well, with precipitation entry in the range of 8 - 28%.

5.1.2.4. Case Studies

In some instances, capillary barrier cover systems have been installed over existing waste rock piles and tailings basins (Yanful et al., 1993a, 1993b; Bell et al., 1994; Ricard et al., 1997; Woyshner et al., 1997). Adoption of a capillary barrier cover system usually involves physical characterization of the mine waste as well as potential cover materials and occasionally predictive modeling of the proposed system. Design and construction of a capillary barrier cover system for a waste rock pile at Heath Steele mine site near Newcastle, New Brunswick was completed as part of the Heath Steele Waste Rock Project under Canada's Mine Environment Neutral Drainage Program (MEND) in 1989 (Yanful et al., 1993a, 1993b; Bell et al., 1994). A three layer system with 60 cm of till sandwiched between 30 cm layers of sand was proposed based on moisture drainage characteristics of the till measured in the laboratory (Yanful et al., 1993a). Hydrologic modeling of this system indicated that the till layer would remain fully saturated for a 60 day period without precipitation. Oxygen flux through this cover system was predicted to be minimal, with oxygen concentrations reaching zero at a depth of 70 cm below the surface.

The cover system actually constructed over the waste rock pile at Heath Steele also included a final drainage layer of 10 cm gravel to prevent erosion of the cover (Yanful et al., 1993b; Bell et al., 1994). The waste pile was relocated onto an impermeable membrane that would permit collection of drainage, and contoured to a maximum slope of 3:1. Surface runoff was collected in a perimeter ditch. A local glacial till was used as the capillary barrier. The till layer was installed in three lifts, each compacted to a final thickness of 20 cm. Appropriate instruments were installed to monitor oxygen concentrations in the pile and cover, temperature in the pile, hydraulic properties in the cover, and the quality of drainage from the pile. Oxygen concentrations in the pile had decreased to less than 3% and temperatures appeared to by decreasing two years after cover installation. The volumetric moisture content in the capillary layer was approximately 30%, corresponding to 2-2.5% of precipitation infiltrating the cover. Drainage quality from the pile had not changed significantly, implying that two years had not been long enough to flush residual acidity out of the tailings. Because of the low hydraulic conductivity of the cover, a transition period of several years was anticipated.

Technical aspects of cover material selection and construction of a capillary barrier cover system for the Les Terrains Auriferes tailings area near Val d'Or, Quebec were discussed by Ricard et al. (1997). Based on physical and chemical characterization of the tailings as well as geochemical AMD modeling results, a capillary barrier design was adopted. The cover was composed of 0.5 m sand at the base, a barrier layer of 0.8 m layer of non-reactive tailings, and a drainage layer of 0.3 m sand and gravel. Site water budget and various drainage and seepage components were evaluated with hydrologic models (HELP and SEEP/W). These results predicted that the AEV of the non-reactive tailings was 2.0 to 2.5 m, and that they must be saturated at 85% in order to minimize oxygen diffusion through the cover. The capillary barrier system was installed in two phases. Phase one focused on the installation of the base layer over the tailings and on the completion of field-scale tests. Construction of the cover system was completed during phase two. After six months of monitoring, saturation levels averaged about 86% and 84% for the top and slopes of the stack, respectively. Furthermore, oxygen flux through the surface of the cover have been reduced by an average factor of 75, with a maximum factor of 1000.

The Millenbach tailings site near Rouyn-Noranda, Quebec, was decommissioned in 1990 and 1991. Pyritic waste rock and tailings were relocated and covered with a capillary barrier cover system. The cover system was designed to limit oxygen diffusion into the waste using four cover layers: a base layer of 30 cm coarse sand, a capillary barrier of 50 cm compacted clay, a drainage layer of 30 cm fine sand, and vegetation support layer of 10 - 15 cm top soil (Woyshner et al., 1997). Water quality of drainage from the site reflected high concentrations of sulfide oxidation products (e.g. acidity, iron, and sulfate) for two years after the waste had been covered. By extrapolating piezometer monitoring data, the length of time required for the water quality of drainage to stabilize was 20 to 30 years. After this "flushing period," oxidation should be curtailed and drainage quality should reflect natural levels.

5.1.3. Organic Matter

Another type of dry cover system utilizes organic matter as an oxygen consuming layer within the cover system by the reaction:

$$CH_2O + O_2 \rightarrow CO_2 + H_2O \qquad (4)$$

where CH_2O represents an organic material. As long as adequate quantities of organics are present, the rate of oxygen consumption will be greater than the rate of oxygen diffusion through the pore spaces of the cover material. Consequently, oxygen will be consumed within the cover rather than reacting with the underlying mine wastes. The oxygen consuming organic layer ultimately results in an anoxic environment beneath the cover. Anoxic environments promote the activity of sulfate-reducing bacteria, which may actually reverse acid production and remove trace metals (Kleinmann et al., 1991).

$$CH_2O + 1/2SO_4^{-2} \rightarrow HCO_3^- + 1/2HS^- + 1/2H^+ \qquad (5)$$

$$Cu^{2+} + HS^{-} \rightarrow CuS + H^{+} \quad (6)$$

The relative abundances of trace gases, such as methane, within interstitial pore spaces provide further evidence that reducing conditions have been achieved. Methane is produced through the biogenic fermentation of organic matter, particularly acetate, in a process known as methanogenesis (Manahan, 1991).

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (7)$$

Organic cover layers may also reduce water infiltration, because most organic materials have naturally low hydraulic conductivities. The hydraulic conductivity of an organic layer may be further reduced due to the compaction that occurs as the organic material decomposes.

A one year, pilot-scale study of three different organic cover materials (peat, lime stabilized sewage sludge, and municipal solid waste) were evaluated for their effectiveness at reducing acid generation (Elliott et al., 1997a, 1997b). PVC pilot cells measuring 2.5 m long, 1.5 m high, and 0.6 m wide were filled with 0.65 cm of reactive tailings and covered with a 75 cm organic cover layer. Of the three organic materials tested, lime stabilized sewage sludge was the most effective at increasing pH and reducing sulfate, iron and nickel concentrations in the drainage. The high degree of saturation maintained in the lime stabilized sewage sludge cover (>90%) appeared to limit oxygen diffusion, resulting in oxygen concentrations near zero in the tailings beneath the cover. Peat and municipal solid waste were not effective at preventing sulfide oxidation in the underlying tailings. Quantification of chemical and mineralogical changes in the tailings and cover as well as hydraulic conductivity tests were in the progress, but not yet reported.

At Quebec's East Sullivan Mine tailings impoundment, forestry wastes have been laid down over reactive mine wastes continually since 1984 (Tasse et al., 1997). Acidity and trace metal concentrations in drainage from the tailings pile has been monitoring since 1992. In general, the drainage pH from the covered test plots has increased above 6.0, implying that sulfide oxidation has been reversed. Furthermore, analysis of the interstitial gases in the organic cover indicate that oxygen concentrations decreased to 3-5% at a depth of 60 cm, while secondary gases (CO_2 and CH_4) increased. These results are consistent with oxidation of organic matter (reaction 4) and methanogenesis (reaction 7) within the cover layer.

5.2. Synthetic Cover Materials

Impermeable cover systems can also be constructed of synthetic materials such as plastic liners. A number of plastic (geosynthetic) liners are commercially available, most of which consist of flexible polymeric membranes (e.g. PVC or HDPE) that act as a barrier to water infiltration. Another option is a geosynthetic clay liners (GCLs), where sodium bentonite clay is encapsulated between two layers of geotextiles (Stewart and von Maubeuge, 1997; Miller and Hornaday, 1998).

A 20 mil PVC membrane was used to cover a waste rock stockpile at the Dunka Mine, MN (Udoh, 1993). The membrane was sandwiched between one foot of compacted sand beneath and six inches of sand above. The entire surface was then revegetated with native grasses and minor amounts of legumes. The PVC membrane cover reduced the amount of contaminated bottom flow by 97% within two years of installation.

Several closure options for the tailings management area at the Crandon Project, WI, were evaluated using a one dimensional dilution model and a water balance model (Sevick et al., 1998). The preliminary assessment of options concluded that a lined facility with leachate collection and a dry cap with a composite hydraulic barrier would be required. The hydraulic barrier consisted of one foot of fine soil, GCL, and 60 mil HDPE, covered with a drainage layer and vegetation. Based on the modeling analysis, the cover would limit water infiltration to such an extent that sulfide oxidation within the tailings will be minimized.

6. FUTURE WORK

This document reviewed selected literature on the development, implementation, performance, and effectiveness of specific types of dry cover systems for reactive mine waste materials. However, two important subjects related to dry cover systems were not fully addressed. First, although case studies were cited, these studies were relatively short in duration (i.e. no more than a few years). In general, predictive modeling suggests that these designs should remain effective for decades, however, the long-term performance of these cover designs must be proven in the field. Therefore, one area in which future efforts should be focused is in collecting updated information on the long-term performance of the cover systems implemented at specific sites.

A second area that was not adequately addressed in this document was the application of hydrologic and predictive models to dry cover systems. Four models (HELP, SEEP/W, SoilCover, and POLLUTE) were referred to in the literature review. While these four appear to be the most commonly used models in the field of mine waste management at this time, there may be other models available or in development that could be applied to dry cover systems. Furthermore, the advantages and limitations of each of these models were not determined here. A full understanding of the capabilities of these models is necessary in order to apply them appropriately to dry cover systems or any other reactive mine waste disposal setting.

Finally, it is important to remember that this document is the first on the topic of mitigative strategies for reactive mine waste materials. Future work in this area should also include reviews on a wider range of possible preventative technologies (e.g. encapsulation, subaqueous disposal, wetlands etc.) currently in use.

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DRY COVER SYSTEMS

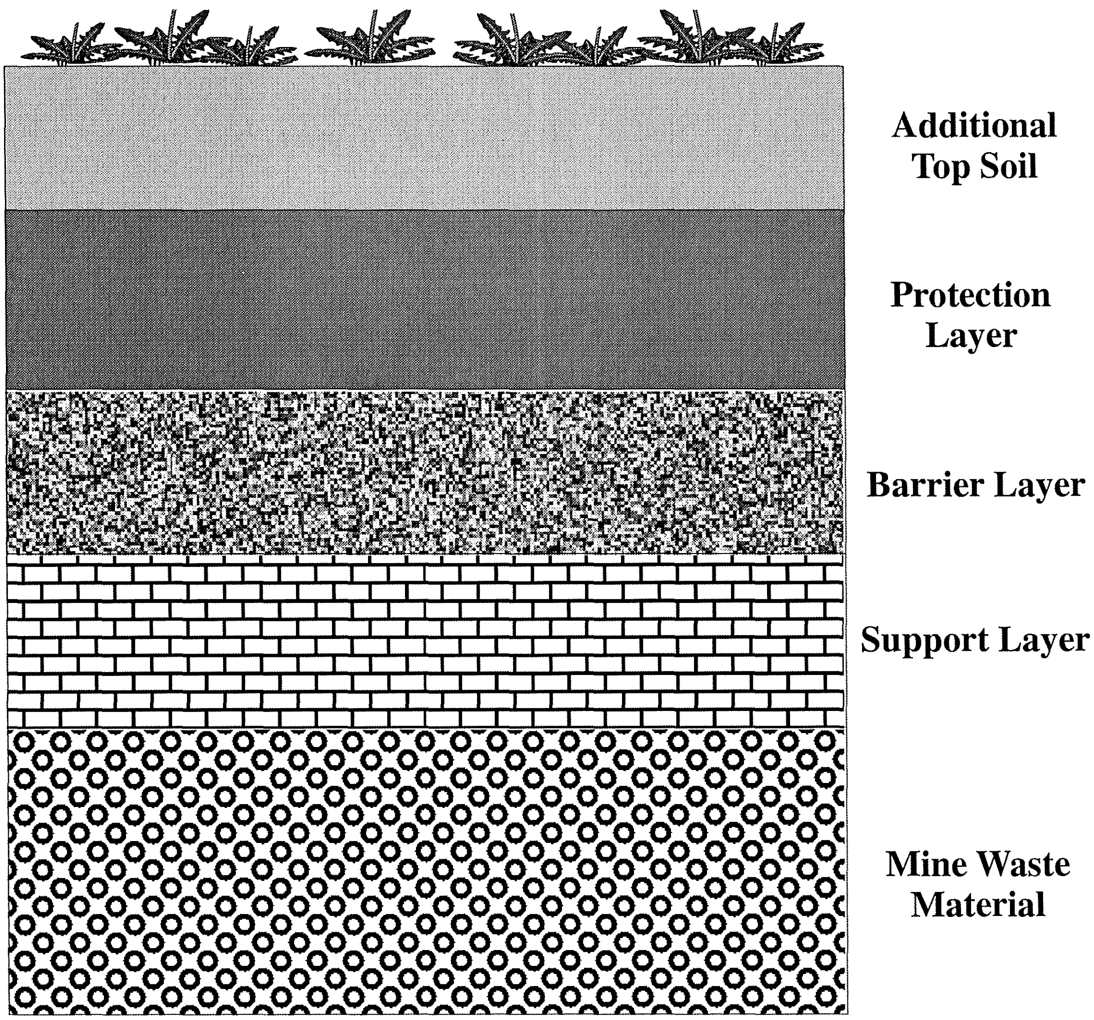

Figure 1. Schematic of a generalized dry cover system design for acid producing mine waste material.

DRY COVER SYSTEM DESIGNS

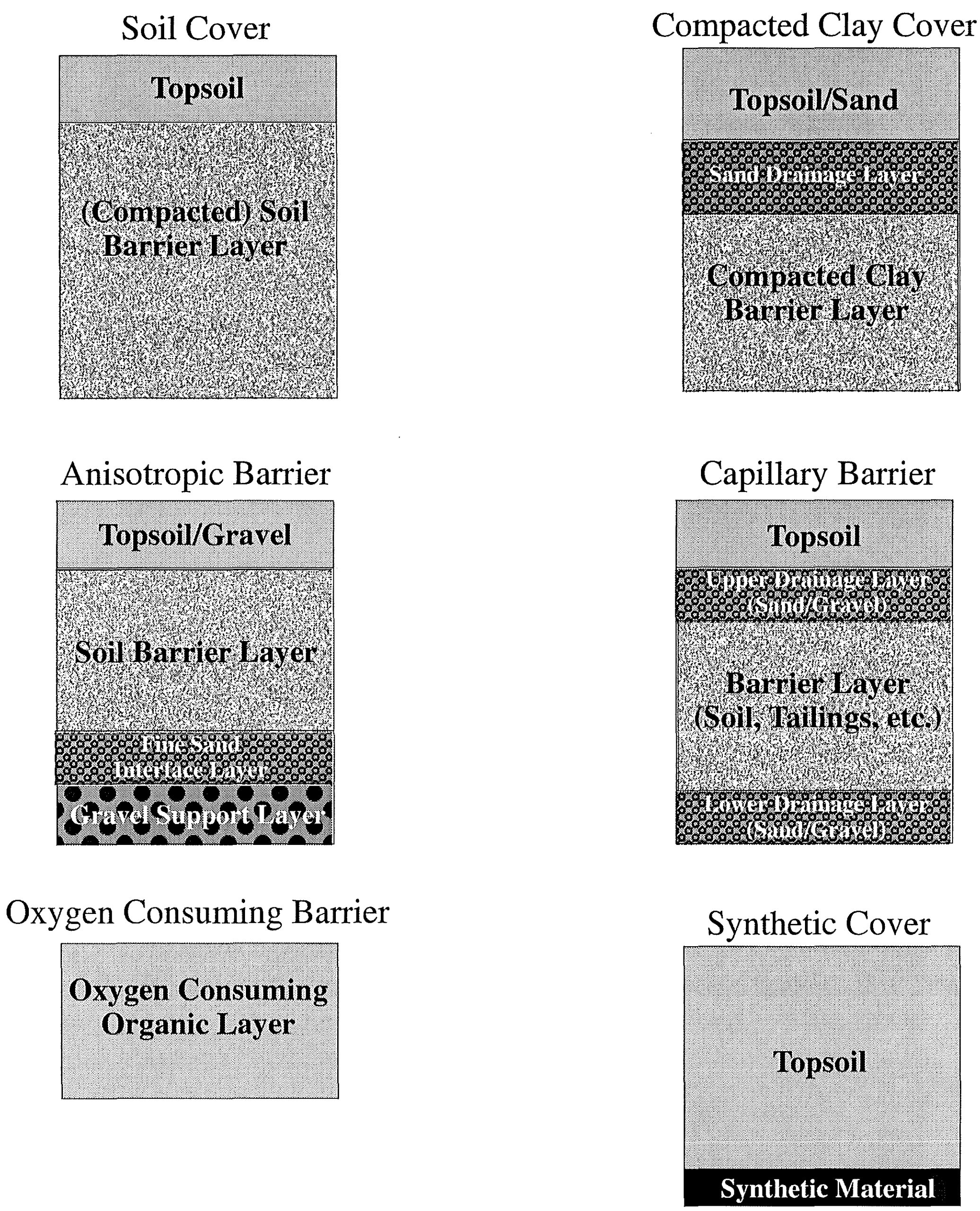

Figure 2. Dry cover designs generally fall into one of six categories, each of which is designed to minimize water infiltration and/or oxygen diffusion into the mine waste.

Table 1. Summary of cover construction costs by type of cover. The estimated price range generally increases as the complexity of the cover system increases.

Type of Cover System	Estimated Price Range (US$/hectare[1])
Single layer of clay or clayey till	$9 - 62 k[2]
GCL	$17 k
Single layer of soil	$ 15 - 25 k[2]
PVC	$36 - 60 k[3]
Capillary barrier (non-reactive mine wastes)	$59-70 k
Capillary barrier (general)	$50 - 300 k

[1]No attempt was made to adjust for inflation or fluctuating exchange rates.
[2]The higher end of this range includes compaction costs.
[3]Range varies depending on the required thickness.

Table 2. Physical properties of cover materials

Cover Material	Hydraulic conductivity (cm/s)	Permeability (cm^2)	Porosity (%)
Geosynthetic Liner	10^{-12} - 10^{-9}	nd	nd
Clay	10^{-11} - 10^{-7}	10^{-15} - 10^{-12}	40-70
Glacial Till	10^{-11} - 10^{-4}	10^{-15} - 10^{-9}	nd
Tailings	10^{-6} - 10^{-4}	nd	41-46
Organic Matter	nd	nd	nd
Fine Sand	10^{-5} - 10^{-1}	10^{-11} - 10^{-6}	25-50
Coarse Sand	10^{-4} - 1	10^{-9} - 10^{-5}	25-50

nd = no data available at the time this document was produced.

APPENDIX 1

Outline of Additional References

MITIGATION METHODS
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0. Intentional oxidation

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Summary: This paper highlights some of the research reslts from the Tech. U of Nova Scotia. During the research commenced several years ago, an innovative technology has been developed in order to achieve the goal of preventing contamination from mine wastes, reusing them and enabling land reclamation. A special cementing composite material, HiFa-Bond, has been used as a solidifying agent. Tailings produced by both metal mines from hard rocks and oil companies from soft clay-oil sands have been tested. The tailings containing up to 85% water were turned into a solid stone in a few minutes. At a tailings to HiFa-Bond ration of 1.95:1 by weight, compressive strength of 8.8 MPa has been achieved in three days. At a high ration of 5.84:1, the strength maintained at around 1MPa. The solidified tailings has high early stregth and can develop over 85% of the long term strength. The oil-sands fine tailings, which contained bitumen and suspoended fine clays, were turned into a solid with similar strength. This technology is believed to be a potential practical and sustainable solution to the treatment of mine tailings and other industrial wastes in any form of liquids, pastes and solids.

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