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EVALUATION OF ALTERNATE DRY COVERS FOR THE INHIBITION OF ACID MINE DRAINAGE FROM TAILINGS

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FINAL REPORT

EVALUATION OF ALTERNATE DRY COVERS FOR THE INHIBITION OF ACID MINE DRAINAGE FROM TAILINGS

Prepared for

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ABSTRACT

A basic understanding of the theoretical concepts which can be applied to prevent or at least reduce acid mine drainage from tailings through the use of dry covers has been obtained. Recent research has focussed on evaluating potential barrier materials. This has produced a multitude of suggestions with regards to alternate barrier materials and the direction of future dry covers research. This study reviews dry covers theory and current research; evaluates potential materials including several which have not yet been evaluated for use in covers; and after evaluation, provides recommendations regarding further dry covers research.

The theoretical concept of dry covers is reviewed and the barriers are classified as oxygen barriers (moisture retaining), oxygen consuming, or reaction inhibiting. Potential barrier materials are identified through a technical literature search; a literature review focussed on forest product industry wastes; and a search for potential materials that may be obtained from municipal and industrial waste streams. A short list of potential materials is developed applying a two stage screening process which takes technical aspects, cost, and practical application into consideration. Potential barrier materials considered to provide broadly based (country wide) benefit and a good likelihood for success are listed. Recommendations are made regarding the future direction of dry barrier research and specific research work currently underway.

Potential materials given a high priority for future research include natural soils, modified soils, desulphurized tailings, tailings slimes, wood waste, and paper mill sludge. Materials given a lower priority for future research include peat, waxes, ashes, and the PHITO layer. Available barrier materials not requiring additional research are limestone (mixed into the tailings mass), and synthetic liners.

TABLE OF CONTENTS

			Page #
ABSTRACT			
1.0	INTRODUCTION		1-1
	1.1	Requirements for Study	1-1
	1.2	Study Methodology	1-3
		1.2.1 Phase 1: Identification and Evaluation of Alternate Materials	1-3
		1.2.2 Phase 2: Recommended Research	1-4
	1.3	Report Structure	1-4
2.0	DRY COVER INHIBITION OF ACID MINE DRAINAGE		2-1
	2.1	Overview of Current State of Knowledge	2-1
	2.2	Oxygen Transport Barriers	2-5
	2.3	Oxygen Consumption Barriers	2-7
	2.4	Reaction Inhibiting Barriers	2-9
3.0	ALTERNATE DRY COVER MATERIALS		3-1
	3.1	Identification of Materials	3-1
	3.2	Dry Cover Materials	3-2
	3.3	Natural Soils (Moisture Retaining)	3-3
		3.3.1 Natural Clays and Tills	3-4
		3.3.2 Lake Bottom Sediments	3-5
		3.3.3 Loess	3-5
	3.4	Processed Soils	3-5
		3.4.1 Clay Modified Soil	3-5
		3.4.2 Polymer Modified Clays	3-6
		3.4.3 Waste Modified Soils	3-6
	3.5	Oxygen Consuming Materials	3-7
		3.5.1 Crumb Rubber	3-7
		3.5.2 Wood Waste	3-8
		3.5.3 Peat	3-9
		3.5.4 Sewage Sludge	3-12
		3.5.5 N-Viro Soil	3-12
		3.5.6 Other Industrial Sludges	3-13
		3.5.7 Shredder Fluff	3-14
		3.5.8 Compost	3-14
		3.5.9 Municipal Refuse	3-15
		3.5.10 Manure	3-15
		3.5.11 Hay/Straw/Silage	3-16
		3.5.12 Paper Mill Sludges	3-16
	3.6	Moisture/Infiltration Barriers	3-19
		3.6.1 Synthetic Liners	3-19
		3.6.2 Asphaltic Liners	3-20

3.6.3 Concrete Liners 3-21
3.6.4 Waxes 3-21
3.6.5 Biopolymers 3-22
3.6.6 Desulphurized Tailings 3-22
3.6.7 Tailings Slimes 3-23
3.7 Chemical Agents/Inhibitors 3-23
3.7.1 Ashes 3-23
3.7.2 N-Viro Soil 3-24
3.7.3 Limestone 3-24
3.7.4 Phosphate Rock/Slag 3-24
3.7.5 Alkaline Sludges/Solutions 3-25
3.7.6 Inhibitors 3-25
3.8 Special Application 3-26
3.8.1 PHITO Layer 3-26

4.0 SCREENING CRITERIA FOR PROPOSED DRY COVER ALTERNATIVES 4-1
4.1 General 4-1
4.2 Screening Criteria 4-1
4.2.1 Preliminary Screening 4-1

5.0 SCREENING ANALYSIS - ALTERNATIVE DRY COVER MATERIALS 5-1
5.1 Preliminary Screening 5-1
5.2 Natural Soils 5-1
5.3 Processed Soils 5-2
5.3.1 Clay Modified Soils 5-2
5.3.2 Waste Modified Soils 5-2
5.4 Oxygen Consumers 5-3
5.4.1 Crumb Rubber 5-3
5.4.2 Wood Waste 5-3
5.4.3 Peat 5-3
5.4.4 Sewage Sludge 5-3
5.4.5 N-Viro Soil 5-4
5.4.6 Other Industrial Sludges/Wastes 5-4
5.4.7 Shredder Fluff 5-4
5.4.8 Compost 5-4
5.4.9 Municipal Refuse 5-5
5.4.10 Manure 5-5
5.4.11 Hay/Straw/Silage 5-5
5.4.12 Paper Sludge 5-5
5.5 Moisture/Infiltration Barriers 5-6
5.5.1 Synthetic Liners 5-6
5.5.2 Asphaltic Liners 5-6
5.5.3 Concrete Liners 5-6
5.5.4 Waxes 5-7
5.5.5 Biopolymers 5-7

5.5.6 Desulphurized Tailings 5-7
5.5.7 Tailings Slimes 5-7
5.6 Chemical Agents/Inhibitors 5-8
5.6.1 Ashes 5-8
5.6.2 N-Viro Soil 5-8
5.6.3 Limestone 5-8
5.6.4 Phosphate Rock 5-9
5.6.5 Alkaline Sludges/Solutions 5-9
5.6.6 Inhibitors 5-9
5.7 Special Application 5-10
5.7.1 PHITO Layer 5-10
5.8 Summary 5-10

6.0 CRITICAL REVIEW - HIGH PRIORITY DRY BARRIER MATERIALS 6-1
6.1 Overview 6-1
6.2 Oxygen Transport Barriers 6-2
6.2.1 Natural Soils and Synthetic Liners 6-2
6.2.2 Modified Soils 6-2
6.2.3 Tailings as Dry Barriers 6-2
6.3 Oxygen Consuming Barriers 6-3
6.3.1 Wood Waste 6-3
6.3.2 Paper Mill Sludges 6-5
6.4 Reaction Inhibiting Barriers 6-5
6.4.1 Limestone 6-5
6.5 Research Needs 6-7
6.5.1 General 6-7
6.5.2 High Priority Items 6-8
6.5.3 Lower Priority Items 6-9
6.5.4 Other Dry Barriers 6-10

REFERENCES

Table of Contents, cont'd.

APPENDIX A: TASK 2 REPORT, LITERATURE REVIEW
DRY COVERS FOR SULPHIDE TAILINGS - REVIEW OF CONCEPTS AND CURRENT PRACTICE
APPENDIX B: TASK 3 SUMMARY
WASTES PRODUCED BY THE FOREST PRODUCTS INDUSTRY
APPENDIX C: TASK 4 SUMMARY
POTENTIAL DRY COVER MATERIALS FROM MUNICIPAL AND INDUSTRIAL WASTE STREAMS

1.0 INTRODUCTION

The need to develop practical and acceptable methods of inhibiting acid mine drainage from reactive tailings has been long recognized by the mining industry, governments, and other stakeholders. Special industry-government task forces such as the Mine Environment Neutral Drainage (MEND) program were established to address acid mine drainage and its control. This study on the Evaluation of Alternate Dry Covers for the Inhibition of Acid Mine Drainage from Tailings represents part of the ongoing acid mine drainage (AMD) research effort.

In this study, the direction of further dry covers research was addressed. The theoretical basis of the concept of dry covers was reviewed. Potential dry cover materials currently being laboratory or field tested, along with alternate materials from various sources were identified, classified, and evaluated. The study concluded by providing a ranking of identified potential materials, and recommendations regarding further research into dry covers.

1.1 REQUIREMENTS FOR STUDY

Dry covers continue to hold promise as a means of inhibiting AMD from tailings in situations where acid generation cannot be effectively controlled by other means such as subaqueous tailings disposal.

A limited, however, useful understanding has been achieved through research regarding the basic physicochemical processes by which dry covers may inhibit AMD from tailings. Research involving low permeability, oxygen consuming, and other types of dry covers has demonstrated that the basic requirements to limit the molecular diffusion of atmospheric oxygen through interstitial pores in a cover can be accomplished, albeit on a small scale. This research has also brought to light several as yet unresolved concerns such as: the long term effectiveness of dry covers as oxygen barriers; the net impact on the rate of oxidation of reactive tailings; poor availability of dry cover material in some locations; prohibitive cover construction costs; and effluent quantity and quality and its impact on the receiving environment. Dry cover research continues to address these and other concerns through modelling, bench tests, and field studies; which have increasingly involved the use of cover materials other than natural soils.

A wide range of alternate dry cover materials from municipal compost to engineered composite covers have been considered to date. Research has been proposed for several alternate materials.

It has become apparent that further research into dry covers should continue to be carefully directed in order to: narrow and maintain the focus of dry covers research; and, if possible, develop appropriate dry covers methodologies. However, new ideas should continue to be sought and assessed. It is truly incredible to see the plethora of dry cover concepts Canadian researchers have proposed as potential solutions for AMD control.

The broad variety of concepts for dry cover research has clouded the current picture regarding the direction that future research should follow. In this regard the MEND Dry Barriers Sub-Committee is providing the direction for future dry covers research in accordance with the MEND objective of developing appropriate technologies for the closure of AMD sites, in this case reactive tailings areas, in a manner that is predictable, timely, affordable, and environmentally acceptable.

In response to the need to address the future of dry covers research MEND issued an open Request for Proposals, the terms of reference of which are summarized below:

> The technical and economic potential of alternate materials likely to inhibit acid mine drainage from tailings is to be researched. The study team's knowledge of key covers and alternate materials is to be supplemented through: literature reviews (primarily to identify alternate materials); discussions with researchers about the direction of current and envisaged dry covers research; and discussions/contacts with various industry specialists. This information is to be evaluated taking into account technical and economic considerations. The objective is to identify alternate materials that warrant further research.

Findings are to be summarized in a report that includes a listing of potential cover materials along with a ranking of their likelihood of technical and economic success.

The study was subsequently awarded to SENES Consultants Limited. The findings of the study are presented in this report.

1.2 STUDY METHODOLOGY

The study was carried out in two distinct phases as follows:

Phase 1: Identification and Evaluation of Alternate Materials

Phase 2: Recommendations for Research

1.2.1 Phase 1: Identification and Evaluation of Alternate Materials

Two literature reviews were carried out during this phase. The first literature review focussed on technical literature regarding covers for AMD sites in order to identify potential alternate materials and relevant technical information. The second literature review focussed on raw materials and wastes produced by the wood, and pulp and paper industries that could be made available for use as dry covers.

A technical search was carried out to identify potential cover materials from other sources including municipal and industrial waste streams. The search also addressed the perceived benefits, and problems of importing waste materials to tailings sites and the use of these waste materials in dry covers.

The findings of the two literature reviews and the materials search were documented in separate letter form reports (Appendix A, B, C). Information regarding the cover materials was later summarized in matrix form.

Screening criteria based on technical, cost, material availability, and other issues were developed and applied to the dry cover materials matrix. The resultant shorter list of alternate materials was further considered in Phase 2.

1.2.2 Phase 2: Recommended Research

Potential materials were ranked according to their judged likelihood for success based on technical, economic, environmental, and practical implementation considerations.

Recommendations regarding the selection of materials to be further researched, as well as the future direction of dry covers research were also developed.

1.3 REPORT STRUCTURE

This report is organized into three main sections to provide:

- an overview of the current state of understanding of processes by which AMD may be inhibited by dry covers;

- a discussion of findings from Phase 1 Identification and Evaluation of Alternate Materials; and

- Phase 2 recommendations regarding alternate cover materials that warrant further research, and the future direction of dry covers research.

2.0 DRY COVER INHIBITION OF ACID MINE DRAINAGE

2.1 OVERVIEW OF CURRENT STATE OF KNOWLEDGE

Research into the oxidation processes, both chemical and biochemical, of sulphide minerals has led to a limited; however, useful understanding of the basic physicochemical reactions involved. As a consequence, several means of inhibiting AMD have been identified in concept. One such concept is the use of a dry cover applied over and/or mixed into the surface layer of tailings.

In tailings and waste rock, the iron sulphides, pyrite and pyrrhotite, are regarded as the dominant sulphide minerals. The oxidation of these sulphides and their reaction products can be expressed by the following stoichiometric equations (Lowson 1982; Nordstrom 1982):

Pyrite Oxidation:

$$FeS_2 + \frac{7}{2} O_2 + H_2O \rightarrow Fe^{2+} + 2\,SO_4^{2-} + 2\,H^+ \qquad (2.1)$$

Pyrrhotite Oxidation:

$$Fe_7S_8 + 3\frac{1}{2} O_2 + H_2O \rightarrow 7\,Fe^{2+} + 8\,SO_4^{2-} + 2\,H^+ \qquad (2.2)$$

Iron Oxidation:

$$2\,Fe^{2+} + \frac{1}{2} O_2 + 2\,H^+ \rightarrow 2\,Fe^{3+} + H_2O \qquad (2.3)$$

Iron Precipitation:

$$Fe^{3+} + 3\,H_2O \rightarrow Fe(OH\,)_3(s) + 3\,H^+ \qquad (2.4)$$

Anoxic Oxidation:

$$14\,Fe^{3+} + FeS_2 + 8\,H_2O \rightarrow 15\,Fe^{2+} + 2\,SO_4^{2-} + 16\,H^+ \qquad (2.5)$$

Equations (2.1) and (2.2) represent the overall stoichiometry of pyrite and pyrrhotite oxidation, respectively. Pyrrhotite is considered more reactive than pyrite (Pearse 1980), and according to theoretical iron-sulphur stability diagrams may be unstable at pH values below 2. Both pyrite and pyrrhotite oxidation may be catalysed by bacteria, the most important species being *Thiobacillus ferrooxidans* (Brierley 1978; Lundgren and Silver 1980; Torma and Banhegy 1984; Ahonen *et al.* 1986; Ahonen and Tuovinen 1991). Bacterial oxidation becomes significant at pH values below 4.1. At pH 2.5 to 3.0, the bacterial oxidation rate is approximately 16 to 35 fold greater than the chemical rate. The oxidation of ferrous iron (see Equation (2.3)) is pH dependent, but can be also catalysed by bacteria. In acidic solutions, the rapid bacterial oxidation of iron results in indirect leaching mechanisms that implicate ferric iron as the principal oxidant. Ferric iron does not remain in solution much above pH 3 when it is hydrolyzed to $Fe(OH)_3$ as shown in Equation (2.4). The oxidation of pyrrhotite by ferric iron is particularly fast and can result in the accumulation of significant quantities of intermediate oxidation products, particularly elemental sulphur. Equation (2.5) is abiotic, but is believed to be the most important acid forming reaction under anoxic conditions.

Considering the stoichiometry, it is evident that the oxidation of sulphide minerals and the production of AMD requires two key constituents; water and oxygen. If either constituent is not present, oxidation cannot proceed. The control of either constituent may effect the rate of AMD production if oxygen is limiting or inadequate water is present to support optimal rates of oxidation.

In tailings, the inherent oxidation is coupled with mass transport processes. The transport of oxygen through the pore space is widely regarded as the AMD rate controlling process (Cathles and Schlitt 1980; Nicholson 1984; Davis and Ritchie 1986; Jaynes 1991). The principal mode of oxygen transport above the water table is molecular diffusion, while advective flow by barometric pumping has a less important, but measurable effect. The advective transport of oxygen in the percolating pore water is considered to be less significant in the hydraulically unsaturated zone, but becomes important in the fully saturated layer at or below the water table. The differential equation describing the transport process is the following:

$$\frac{\delta C}{\delta t} - D_e \frac{\delta^2 C}{\delta z^2} - \frac{v}{K_H} \frac{\delta C}{\delta z} = \gamma R_s \qquad (2.6)$$

where:

C	=	concentration of oxygen in the pore space (mol.m^{-3})
D_e	=	effective diffusion coefficient of oxygen through the tailings (m^2.s^{-1})
z	=	depth into the tailings (m)
t	=	time (s)
v	=	water infiltration rate (m.s^{-1})
K_H	=	modified Henry's law constant (mol.m^{-3} oxygen in liquid per mol.m^{-3} oxygen in the gas phase)
γ	=	stoichiometric constant relating oxygen uptake to sulphate production
R_s	=	sulphide oxidation rate (mol kg^{-1} s^{-1})

It can be shown (Scharer et al. 1991) that the oxidation of sulphides rapidly approaches a steady state provided that the temperature and the pH remain constant. In relatively fresh tailings and at low infiltration rates, the steady state sulphate flux can be derived from the oxygen concentration gradient in the following manner:

$$J = \left[\left(\frac{v K_{HC_o}}{\gamma} \right)^2 + \frac{\sigma D_e R_s C_o}{\gamma} \right]^{\frac{1}{2}} \qquad (2.7)$$

where:

J = sulphate generation flux ($mol.m^{-2}\ s^{-1}$)

C_o = oxygen concentration at the top most interface where sulphide exists ($mol.m^{-3}$)

σ = tailings bulk density ($kg\ m^{-3}$)

Equation (2.7) has been employed to predict AMD assuming cyclic stationary state (monthly average temperature, precipitation, etc.) conditions (Scharer et al. 1991; Elberling et al. 1993a). The significance of Equation (2.7) is that the inherent sulphide reactivity (R_s), the effective diffusion (D_e), and the oxygen concentration at the tailings interphase (C_o) carry approximately equal weight in determining the AMD flux. It is self-evident that an effective cover design should be based on mitigating any one or more of these parameters. Equation (2.7) also illustrates the non-linear nature of the mitigating measures. Nicholson et al. (1989) have defined a cover effectiveness factor, which included similar diffusional and reactivity dependence. For example, 10-fold reduction of either the reaction rate (R_s) or the diffusion rate (D_e) is expected to produce approximately one third reduction in the AMD flux.

The control of water infiltrating into a waste dump or tailings basin (see Equation 2.7) can be readily achieved; however, unless truly impervious materials are available, (e.g. synthetic liners) some residual water will typically infiltrate through the cover. A barrier which effectively reduces infiltration is likely to have a high degree of saturation which also limits oxygen diffusion into the pile. As a general rule, it is much easier to control oxygen flux through a dry cover than to control infiltration (synthetic liners excluded). Thus, an important function of a dry cover is to provide a barrier to the transport of atmospheric oxygen to the surface of sulphide minerals in tailings. Dry covers may also serve to reduce the infiltration of water into the tailings mass thereby reducing the quantity of contaminated effluent.

In accordance with the above considerations, dry cover materials may be classified as follows:

Dry Cover Material Classification	Primary Role of Cover in Inhibition of AMD
Oxygen Transport Barriers	Act to retain moisture and hence provide a low diffusion barrier to atmospheric oxygen.
Oxygen Consuming Barriers	Act as an oxygen consuming sink to provide low oxygen concentration at the interphase.
Reaction Inhibiting Barriers	Act to inhibit reactions, neutralize pH.

2.2 OXYGEN TRANSPORT BARRIERS

The primary mode of atmospheric oxygen transport to the surfaces of sulphide minerals in tailings is by molecular diffusion through interstitial pore spaces. The diffusion of oxygen through the tailings pore space is a strong function of the moisture content. From experimental data in tailings, which can be generalized to other porous media, a useful expression for the effective diffusion coefficient (D_e) as the function of the degree of saturation is as follows (Elberling et al. 1993b):

$$D_e = D_a \tau (1 - S)^{\alpha} + \frac{D_w \tau s}{H} \qquad (2.8)$$

where:

D_e = effective diffusion coefficient in cover material ($m^2 s^{-1}$)

D_a = diffusion coefficient of oxygen in air ($m^2 s^{-1}$)

D_w = diffusion coefficient of oxygen in water ($m^2 s^{-1}$)

τ = experimental parameter (tortuosity factor)

S = degree of saturation (volume of water/volume of pore space)

H	=	modified Henry's constant
α	=	experimental parameter

Chao et al. (1991) devised a mass spectrometer - based method for the rapid measurement of the effective diffusion coefficient in till covers. For compacted till covers, the fitted parameter values were $\tau = 0.032$ and $\alpha = 3.92$. The effective diffusion coefficient with field samples varied from $5.64 \times 10^{-7}\ m^2\ s^{-1}$ to $1.66 \times 10^{-8}\ m^2\ s^{-1}$, depending on the degree of saturation (0.20 - 0.86).

The dependence of the effective diffusion coefficient (D_e) on the degree of saturation indicates that the diffusion coefficient can vary over five orders of magnitude. However, significant attenuations in D_e occur at saturation values above 0.6. This means, that the effective covers must remain nearly saturated to provide orders of magnitude decrease in diffusive oxygen transport. The maintenance of high moisture content depends, in turn, on both the hydraulic properties of the cover material and the hydrology of the tailings sites.

The physics of moisture retention in porous materials have been summarized by Nicholson et al. 1991. In general, moisture retention is enhanced by fine grained materials (10 percentile particle size) and decreases rapidly with increasing particle size. In addition, the suction or negative pressure imposed on materials by gravitational forces contributes to drainage, hence, a reduction in the degree of saturation. Fine grained material, however, may remain saturated under greater suction values.

Even fine silty materials will not remain saturated near the tailings surface if the water table is deeper than a few metres below ground surface. However, as demonstrated by Nicholson et al. (1991), placement of a cover as a fine layer over the coarser-grained material provides a "capillary barrier" that will help to maintain high moisture content in the fine-grained cover. It is conceivable under these conditions that a cover could maintain near saturated conditions indefinitely if it is protected by a coarser cover layer.

A capillary barrier concept was used in field testing of a clay-till cover at the Waite Amulet site (St.

Arnaud et al. 1993). In this case, a capillary barrier is not as critical because the clay-till can retain higher degrees of moisture than silt (non-cohesive) and at greater depths to the water table.

2.3 OXYGEN CONSUMPTION BARRIERS

The primary function of these cover materials is the reduction of the ambient oxygen concentration at the tailings/cover interphase by consumption of oxygen. Almost invariably, the covers contain organic matter, primarily lignocellulosics such as wood chips, wood wastes, peat, sewage sludge, hay, straw, silage, and paper mill sludge. The reduction of oxygen is achieved by microbial degradation of the carbohydrate (empirical formula: CH_2O) fraction, primarily celluloses (glucose polymer) hemicelluloses (xylose/glucose/xylulose copolymer). The aerobic oxidation of organic matter proceeds according to the following stoichiometry (Germain et al. 1991):

$$(CH_2O)_{106}(NH_3)_{16}(H_3PO_4) + 138\,O_2 \rightarrow 106\,CO_2 + 16\,HNO_3 + H_3PO_4 + 122\,H_2O \qquad (2.9)$$

The oxidation expressed by Equation (2.9) is carried out by a consortium of microbial flora. Generally, two biochemical phenomena are recognized. The first step is the enzymatic hydrolysis of lignocelluloses to dissolved constituents. This is followed by the uptake and metabolism of the dissolved mono- and diso-charides.

In a high sulphate environment, such as tailings, a significant fraction of the organic matter may be consumed by redox processes involving the sulphate ion:

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 + 53\,SO_4^{2-} \rightarrow 53\,S^{2-} + 106\,CO_2 + 16\,NH_3 + H_3PO_4 + 106\,H_2O \qquad (2.10)$$

Biochemical sulphate reduction is significant at near neutral to alkaline pH values. The reaction proceeds by the cooperative (mutualistic) interaction of anaerobic hydrolytic bacteria and

Desulphovibrio sp.

Organic matter can also be degraded by the fermentative (glycolytic) pathway:

$$(CH_2O)_{106}(NH_3)_{16}H_3PO_4 \rightarrow$$
$$53\,CO_2 + 53\,CH_4 + 16\,NH_3 + H_3PO_4 \qquad (2.11)$$

This heterotrophic fermentation (Equation (2.11)) requires the interaction of three bacterial populations; hydrolytic, acetogenic, and methanogenic bacteria. Usually, methanogenesis is the rate limiting step. Evidence for fermentative biodegradation of lignocellulosics is provided by the accumulation of organic acids (acetic, propionic, and butyric acids) in the pore water and significant levels of methane (CH_4) in the gas phase.

The efficiency of a lignocellulosic cover depends on its oxygen demand. From the data of Reardon and Poscente (1984) and Germain et al. (1992), the annual average oxygen consumption flux of wood waste covers (1 m thickness) is 1-2 x 10^{-5} mol O_2 m^{-2} s^{-1}, with seasonal maximum value of 10^{-4} mol O_2 m^{-2} s^{-1}. These consumption rates agree with field observations that oxygen concentrations in the pore space reach near zero values at a depth of 60 cm from the wood cover surface. Using an average consumption rate of 2 x 10^{-5} mol O_2 m^{-2} s^{-1}, the average life span of a 1 m cover is estimated to be 10.7 years if anaerobic degradation is neglected. Organic acids produced by anaerobic fermentation can account to 2% or more of the degraded wastes (Reardon and Poscente 1984). These organic acids, however, may be detrimental since they mobilize zinc and copper as carboxylic complexes and provide energy for heterotrophic iron oxidation (Yanful and Payant 1992).

Peat is one of the most abundant natural organic matter to serve as a potential cover. However, the intrinsic oxygen demand of peat may be too low to serve as an effective oxygen interceptor. Reardon and Moddle (1984) have shown that peat cover on top of tailings did not result in any appreciable decline in AMD generation. The concentrations of the sulphide oxidation products did not decrease even if the peat was covered with sand to retain sufficient moisture in the peat layer.

The incorporation of organic matter into the reactive tailings mass makes use of sulphate reduction by Equation (2.10). It has been shown by Blowes et al. (1988) that sulphate reduction will occur under anoxic and near neutral pH conditions. Although this approach does not limit acid generation in the oxic zone, it causes the precipitation of metal ions as sulphides as the pore water migrates through the organic-rich zone.

2.4 REACTION INHIBITING BARRIERS

The function of these covers is to provide an environment, which results in a significant reduction of the intrinsic sulphide oxidation rates. The bacterial oxidation rate and, to a lesser extent, the chemical oxidation rate are dependent on the environmental conditions.

The rate of bacterially-assisted pyrite oxidation, R_B, is a function of several biological and environmental parameters (Hoffmann et al. 1981; Halbert et al. 1983; Jaynes et al. 1984; SENES 1984). It may be stated by the following expression:

$$R_B = f\,(X_p, Y_{x/s}, pH, T, P_{O2}, P_{CO2}, S, [N], [P], E_a, A, [I]) \qquad (2.12)$$

where:

R_B = rate of microbial oxidation

X_p = bacterial population density

$Y_{x/s}$ = growth yield coefficient

pH = measure of hydronium ion concentration

T = soil temperature

P_{O2} = oxygen partial pressure

P_{CO2} = carbon dioxide partial pressure

S = degree of saturation

[N] = nitrate or ammonia concentration

[P] = phosphorus concentration

E_a = biological energy of activation

A = surface area of pyrite

[I] = inhibitor concentration

One of the controllable parameters in the field is the pore water pH. The optimal pH for the bacterial oxidation of pyrite, for example, is pH = 3.0 (Arkesteyn 1980), while the pH optimum for pyrrhotite is near 2.0 (Scharer et al. 1993). At pH values of 4.5 and above, the biological activity is negligible. Since bacterial reaction rates are an order of magnitude higher than abiological rates, it is not surprising that most research effort has been directed towards inhibiting bacterial action.

Fyson and Kalin (1993) and Hart et al. (1991) proposed the employment of ground phosphate rock or phosphate refuse to be applied as a simultaneous reaction inhibitor and transport barrier. The phosphate would neutralize the acidity and provide pH conditions, which are unfavourable for chemolithotrophic, sulphide oxidizing bacteria. The phosphate would act as a fertilizer resulting in heterotrophic (organic-rich) environment, which is inhibitory to *Thiobacillus* and related obligate autotrophs. In addition, phosphate may form a hardpan by cementation as hydroxyapatite at the tailings interphase and thereby preventing the migration of pore water into the underlying sulphidic zone.

The applications of fly ash (Balsamo 1986) coal ash (Grace Dearborn Environmental 1993) lime kiln dust, and scrubber ash (have been either proposed or carried out) for providing alkalinity. High alkalinity results in the precipitation of ferric ion which reduces the chemical oxidation of sulphides as well.

These highly alkaline materials (paste pH = 10 - 13) have not been applied directly, rather they are mixed with normal soil covers. Fly ash has considerable neutralizing capacity (6 - 35% $CaCO_3$ equivalent). The ash material should be mixed to a minimum of 15 cm of cover material. The application rate depends on local pH conditions, usually varies between 50 - 150 tons per acre (Balsamo 1986). A 100 ton per acre fly ash application rate is equivalent to a 3 cm thick fly ash layer mixed into 25 to 50 cm cover material.

The application of a salt (NaCl) supplemented clay cover as a seal cover over pyritic slate was employed to limit bacterial activity at the Halifax International Airport (White 1990). The chloride ion is known to inhibit bacterial activity (SENES 1984). Furthermore, the addition of salt resulted in an impermeable seal, which essentially eliminated the downward migration of water. The addition of salt to clay to improve hydraulic properties, however, is not consistent and depends upon the nature of the clay. Often times, ion substitution can increase permeability.

A number of organic and inorganic compounds are known to inhibit *Thiobacillus ferrooxidans* activity (SENES 1984). A partial listing of compounds which have been employed in one or more oxidation studies include:

N-ethylmaleimide (NEM) has been employed to prevent oxidation of the sulphur moiety; a concentration of 1 mmol L^{-1} has been found to be effective.

Sodium azide (NaN_3) has been used to inhibit oxidation of the ferrous iron component; a concentration of 10^{-2} mmol L^{-1} was found to be inhibitory (Beck and Brown 1968, Arkesteyn 1980).

2,4 dinitrophenol (DNP) to prevent the oxidation of both the ferrous iron and sulphur components was reportedly only partially successful at a concentration of 10^{-1} mmol L^{-1}. Carbon dioxide fixation was prevented at a concentration of 10^{-2} mmol L^{-1}.

Panacide, a biocide, was found to be quite effective as a bacterial inhibitor.

Sodium lauryl sulphate (SLS), an anionic detergent, has been found to be effective in blocking bacterial activity.

Acriflavine, an antiseptic, has been employed to inhibit the activity of sulphur oxidizing bacteria.

Calcium formate was used to inhibit bacterial activity.

Dodecylbenzenesulfonate (DBS) a detergent, has proven to be particularly inhibitory to ferrous iron oxidizing bacteria.

Fructose, lactose, meat extract, yeast extract, peptone and tryptone completely inhibited bacterial activity at a concentration of 0.5 percent (w/v basis).

Chloride and nitrate inhibited bacterial activity when present in high concentrations.

A number of these substances are either uneconomical to employ or biodegrade rapidly in a tailings environment.

Certain of these compounds, notably the detergent based compounds DBS and SLS, have been tested in the laboratory and the field as agents for inhibiting acid production from pyritic material. The degree of success reported in the literature varies considerably.

In field plots established in three strip-mined areas, DBS detergent sprayed on tailings was effective in reducing the number of iron-oxidizing bacteria except in very acidic soils. Sulphur-oxidizing bacteria were not affected; consequently the use of detergent had minimal impact. Even the iron-oxidizing bacteria were seen to recover within only a few weeks. More significantly, none of the inhibitory treatments had any measurable effect on either pH or total acidity in the drainage water from the plots.

In conclusion, several organic and inorganic compounds are know to inhibit the growth and metabolism of oxidizing bacteria including *Thiobacillus ferrooxidans* - the prominent iron and sulphur oxidizer found in low pH (acidic) environments. Research into the use of such compounds (e.g. surfactants) to inhibit acid generation from pyritic material has provided mixed results. At best, such bacterial inhibitors provide a short term solution (SENES 1984).

3.0 ALTERNATE DRY COVER MATERIALS

This section describes dry cover materials that are currently being evaluated in research projects, as well as alternate materials identified during the course of this study. To facilitate the review of this information the section is structured as follows:

- subsection 3.1 addresses the process used in this study to identify materials;
- subsections 3.2 to 3.8 provide descriptions of alternate cover materials and related laboratory or field testing experience;
- information for each potential material is summarized in matrix form in Table 3.1.

3.1 IDENTIFICATION OF MATERIALS

An alternate dry cover material is considered to be a material that is likely to provide the necessary low permeability, oxygen consuming, or reaction inhibiting properties outlined in Section 2.0. Ideally, an alternate material should also provide a solution to some of the problems associated with dry cover material identified in recent research. These problems include, but are not limited to, the poor availability of suitable quantities of materials in some regions, and the projected high cost of dry cover construction.

Potential cover materials were identified through the use of two technical literature reviews, and a desktop search supplemented by input from dry cover researchers and other industry specialists.

Summary reports of the technical literature review; the literature review of wastes produced by the forest products industry; and the search for potential dry cover materials from municipal and industrial waste streams are provided in Appendices A, B and C respectively.

3.2 DRY COVER MATERIALS

Potential dry cover materials are:

1. Natural Soils (Moisture Retaining)
   a) clays and tills, lake bottom sediments, loess
2. Processed Soils
   a) clay modified soils
   b) waste modified soils
   c) ash modified soils
3. Oxygen Consuming Materials
   a) crumb rubber
   b) wood waste
   c) peat
   d) sewage sludge
   e) N-Viro Soil
   f) other industrial sludges
   g) shredder fluff
   h) compost
   i) municipal refuse
   j) manure
   k) hay, straw and silage
   l) paper mill sludge
4. Moisture/Infiltration Barriers
   a) synthetic liners
   b) asphaltic liners
   c) concrete liners
   d) waxes
   e) biopolymers
   f) desulphurized tailings

g) tailings slimes

5. Chemical Agents/Inhibitors
   a) ashes
   b) N-Viro Soil
   c) limestone
   d) phosphate rock
   e) alkaline sludges/solutions
   f) inhibitors
6. Specific Application
   a) PHITO layer

3.3 NATURAL SOILS (MOISTURE RETAINING)

Considerable research has been undertaken regarding the evaluation of natural soils for use as dry covers. Research has focussed on natural fine grained soils such as clays and tills that are known to be capable of providing low permeability and/or high moisture retention capability in a constructed layer having a high level of saturation.

Research has involved the theoretical assessment of natural soils as dry covers, as well as, laboratory and field testing. The fundamental hydraulic principles and physics of moisture retention in porous materials such as natural soils have been addressed by Nicholson et al. (1991). In brief, moisture retention is enhanced by fine grain size. As the elevation of a layer of fine grained, porous material increases above the water table so does the degree of interstitial suction which in turn decreases the moisture retention capability of the layer and increases the proportion of air filled interstitial pore spaces. As the primary route of atmospheric oxygen through a fine grained, porous layer is diffusion through air filled pore spaces, a significant decrease in pore water content is undesirable. Fortunately, research has demonstrated that a "capillary break" can be established by placing a fine grained, porous material over a coarser layer. Using this approach a fine grained layer could be maintained in a near saturated state indefinitely provided it is protected from moisture loss due to evapotranspiration.

Materials that could be used alone, or as part of a composite dry cover, and that are classified as natural soils include:

clays and tills,
lake bottom sediments,
loess, and
silty sands.

3.3.1 Natural Clays and Tills

The effectiveness of dense clay covers in laboratory experiments was demonstrated by Yanful and Payant (1992). Results indicated that acid release rates were up to three orders of magnitude less for covered tailings as opposed to uncovered tailings. Tests at Waite Amulet involving a clay cover indicated that oxygen diffusion was substantially reduced. Previous acid generation at this site, however, complicated the interpretation of "true" acid generation rates.

The long term effectiveness of clay covers has been questioned due to cracking and other deterioration caused by natural forces such as freeze/thaw, desiccation, burrowing, root penetration and erosion. Research to significantly reduce the deterioration of clays due to repeated freeze/thaw cycles through the additional of ameliorative materials has been proposed.

Till consisting of nonsorted, unstratified glacial deposits is more plentiful than clay in many mining districts and may be useful as a clay substitute. Laboratory tests involving till have indicated that the material provides high moisture retention and exhibits a low diffusion coefficient for oxygen when saturated.

Field test plots at Faro, including the use of a till cover, remain inconclusive even after five years of monitoring. A lack of water level control in test pits and the colder climate may have slowed the oxidation process.

A 1 to 2 m thick natural soil, or composite, cover constructed using material obtained at a unit cost of \$10 to \$20/m^3 would cost in the order of \$10 to \$40/m^2.

3.3.2 Lake Bottom Sediments

Lake bottom sediments have been suggested for use as dry covers. These sediments are expected to have low permeability and/or high moisture retention, and be available in significant quantities. In concept, the cost of removing the lake bottom sediments and constructing a dry cover could be reduced by pumping the material and depositing it in slurry form. Lake bottom sediments could also provide additional benefit due to the high oxygen demand of its organic components.

The uniformity and availability of lake bottom sediments is unknown. Regulatory approval to remove these sediments may be difficult to obtain if a threat to fisheries or wildlife is perceived.

3.3.3 Loess

Loess is a natural deposit of windblown, glacial origin sediments consisting of a uniformly sorted mix of silt, fine sand and clay minerals. The material has a density of approximately 1.36 t/m^3, and a porosity of approximately 50%. The *in situ* permeability of loess is often greater in the vertical direction due to the presence of vertical tubes (probably casts of plant roots).

This material has been suggested as a potential dry cover material due to its uniform, fine grain size distribution. The quantity and availability of loess in mining areas is uncertain.

3.4 PROCESSED SOILS

Research has also considered the use of additives to modify and improve the moisture retaining characteristics of natural soils, or make them less susceptible to damage from freeze/thaw cycles.

3.4.1 Clay Modified Soil

A sand-bentonite mixture was evaluated in the laboratory along with other soils including a clay, tills, and sands by Shikatani and Yanful (1993). Results are summarized below:

	Sand-Bentonite Mix	Heath Steele Till	Waite Amulet Till	Faro Till
Clay (%)	8	8	52	10.5
Silt (%)	-	37	44	51
Sand (%)	92	55	4	38.5
Optimum moisture content (weight %)	10.8	9.5	23.5	16.6
Hydraulic conductivity (m/sec)	1.7×10^{-11}	2.0×10^{-10}	1.5×10^{-10}	2.0×10^{-9}

This approach may allow best use to be made of local natural materials at perhaps an incremental cost increase of $5/m^2 of cover.

3.4.2 Polymer Modified Clays

A study into the polymer modification of clays to produce a material that will swell to create a gel while absorbing up to 1,000 times its weight in water thereby inhibiting the penetration of additional water is nearing completion by the Alberta Research Council.

Polymers have been used to enhance the characteristics of drilling muds. If polymer chains can be set to block interstitial pore spaces they may provide a stable moisture retaining zone. This is a potential area in which dry covers research is essentially just underway.

The report from the Alberta Research Council is expected to be issued soon.

3.4.3 Waste Modified Soils

The addition of wood ash to local clays in order to develop a suitable low permeability dry cover (not susceptible to freeze/thaw deterioration) using local materials has been proposed. Wood ash is expected to provide:

- additional silt size materials;
- a source of alkalinity; and
- serve as a natural fertilizer.

Basic research has yet to be undertaken to determine:

- geotechnical parameters such as Atterburg Limits, and permeabilities of clay/ash mixtures; and
- influence of freeze/thaw and evaporation on various clay/ash mixtures.

Concerns with the use of such admixtures include:

- the sensitivity of the cover properties due to variances in clay/ash content;
- quality of cover leachate and runoff; and
- the long term performance of both the wood ash component and the cover.

3.5 OXYGEN CONSUMING MATERIALS

3.5.1 Crumb Rubber

Crumb rubber is produced by the grinding of passenger vehicle and truck tires to small size particles (currently down to 60 mesh).

Disposal of used tires remains a problem and the rubber industry is looking for alternate disposal/recycle options.

The quantity of used tires is small in comparison with the demand for dry cover material. It is expected that crumb rubber would offer limited benefits as a component of a dry cover for reasons including concerns about biotoxicity (W. Baker 1993), autocombustion, and expected high rates of diffusion of oxygen.

3.5.2 Wood Waste

Wood waste consists of sawdust, bark, and other wood scraps generated by the lumber and pulp and paper industries.

A study of sawmill wastes by Reardon and Poscente (1984) investigated the rate of oxygen consumption within a wood waste pile and oxygen diffusion through the waste itself. The results indicated that oxygen was consumed rapidly in fine wood waste but may not have been very effective at removing oxygen in very coarse materials. The pore gas concentration of oxygen in the fine wood waste decreased from atmospheric values to near zero values in the top 60 cm of the waste pile. Calculations showed that the wood material was being consumed at a rapid rate due to the oxidation process. It was estimated that the rate of degradation of this fine-grained waste was on the order of about 10 cm of waste per year caused by the high diffusion coefficients within the wood material itself. This led the authors to conclude that wood waste would be effective only for relatively short periods, perhaps tens of years, and to be an effective oxygen barrier would require an overlying material to reduce the flux of oxygen into the subsurface. It was also noted that about 2% of the degraded waste mass was transferred into dissolved organic carbon (DOC) concentrations in the water that infiltrated to depth. The implications of this are uncertain, however, with high concentrations of DOC, mobility of some metals may be increased.

A study of wood bark and other potential cover materials was carried out by Yanful and Payant (1992). Bench scale testing involved outdoor lysimeter and indoor laboratory column experiments.

Test results for a 150 mm thick wood bark cover demonstrated a significant increase in the rate of acid production (in the crushed reactive waste rock) over a time span of about 60 weeks.

The rate of acid generation was quantified (in terms of acidity as mg Ca CO_3/day/kg rock) and found to be higher in the indoor laboratory experiments - probably due to favourable temperatures. The wood bark was found to accelerate acid production by about 60% in the laboratory and 500% outdoors.

At present, it is thought that perhaps autotrophic bacteria had become more active by using CO_2 produced by the fungal decomposition of wood bark. It is believed, therefore, that wood bark accelerated the biological oxidation process.

Work is underway to measure the CO_2 profile through the wood bark layer. Results to date indicate that a relatively thin wood bark cover is not a good technique for reducing acid generation in reactive waste rock (St. Arnaud 1994).

A field study of wood chips as a cover on mine tailings was reported by Germain et al. (1992). This field study at the East Sullivan Mine focused on the gas concentrations in the wood wastes above the tailings. The results agree with those of Reardon and Poscente (1984) and suggest that oxygen is consumed rapidly in the subsurface with oxygen concentrations approaching near zero values at a depth of about 60 cm from the wood waste surface. The authors concluded that the wood waste layer prevented oxygen from entering the tailings and, therefore, represented an effective oxygen barrier on the tailings surface. Unfortunately, there is no direct evidence to show a reduction in the acid generation rates below the wood cover. This is not necessarily a shortcoming of that particular study, however, as noted previously, the evaluation of oxidation rates by examining water chemistry from the tailings is not trivial. Unfortunately, no estimates in the reduction of oxidation rates were given.

Although wood waste is not an ideal cover material it does offer potential cost savings due to the proximity of forest products industry operations to some mine sites.

3.5.3 Peat

Peat is a general term that is applied to surficial organic, vegetative, deposits.

The use of peat as a dry cover to provide a self-sustaining oxygen barrier has been suggested by several researchers.

One type of organic deposit available in large quantities and often in the vicinity of mine sites is a peat bog. It is typically composed of sphagnum moss and may also contain trees and shrubs. Peat bogs are formed under anaerobic, waterlogged, conditions where the growth rate of sphagnum moss at the surface exceeds the rate of decomposition within the bog. Over time continued growth may raise the perched water table of the bog above the local ground surface to produce a raised bog. Water is inhibited from flowing through the bog by the presence of carbon dioxide and methane produced by the microbial degradation of organics. As precipitation becomes the sole source of nutrients, conditions become ombrotrophic.

Organic material is classified in the Organic Soil Order in Canada (Histosol Order in the USA) on the basis of the type of organic deposit (i.e. parent material - bog, fen, swamp, folic), the degree of decomposition of the material, the arrangement of the soil layers (soil horizons) and their thickness, and the depth of the deposits. If permafrost is present within 1 m of the surface, the organic soils are classified in the Cryosolic Soil Order - the presence of permafrost takes precedence over degree of decomposition, horizon arrangement, etc., although these are of importance at lower levels in the classification system (Goodwin 1993).

The upper layer of bogs are often fibric having an acidic pH (less than 4.5); a typical bulk density of less than 0.075 g/cm^3; a total porosity in excess of 90% by volume; a water content of less than 48%; and a hydraulic conductivity in excess of 6 cm/hr (Luttmerding 1993). The fibre content is very high and in excess of 85%. The permeability of bog is in the range of 10^{-5} to 10^{-6} ms^{-1} versus 10^{-7} to 10^{-9} ms^{-1} for compacted till. In concept, the use of bog as a dry cover material would provide a moisture retaining layer with an anoxic environment. It has been suggested that peat could be slurried from bogs to tailings areas. Peat was moved in a similar manner to cover coal heaps in British Columbia in the 1960's (Goodwin 1993). The direct cost to pump peat is estimated to be in the order of \$3 to \$5/m^3.

Reardon and Moddle (1984) investigated the use of peat as an oxygen interceptor. The results of the study showed that peat used as a surface layer on pyritic tailings did not result in an appreciative decrease in oxidation rates. Even when the peat was covered by a sand layer, the concentrations of oxidation products did not decrease significantly compared to uncovered columns. Some of these experiments were conducted over a period of one year or more and so the results represent a significant amount of data collection. However, it should be noted that the experiments did not consider the degree of moisture content or the oxygen concentration levels into the peat towards the tailings surface. The experiments were conducted to simulate six years of infiltration over a 100 day period. This means that excess water was being added to the columns and could have caused near-saturated conditions to exist through the tailings. Although differences among the columns were examined, it is possible that the overly wet conditions prevented the uncovered columns from oxidizing as they would under well-drained conditions representative of the field. So although the results indicate very little difference in the concentrations of oxidation products released from each of the columns, the test results may not have been representative of peat covers compared to well-drained tailings. The results are, therefore, somewhat questionable in comparing peat layers and composite sand over peat layers compared to no cover.

Concerns about the use of bog in this application include:

- destroying the overall structure and effectiveness of the bog by disturbing it;
- uncertainty regarding the ability to maintain a perched water table in the transported bog (if necessary);
- low biological oxygen demand;
- and uncertainties regarding its long term performance; and
- reclamation of peat borrow areas.

Peat was used as the source of indigenous anaerobic microflora in laboratory studies by Shelp et al. (in press) in which the peat was subjected to extremely acidic conditions (pH 3). The systems showed evidence of recovery within two weeks, and the formation of relatively insoluble black iron precipitates indicated a viable sulphate reducing bacteria (SRB) population.

In a subsequent unpublished study, Shelp showed that the indigenous bacteria can respond immediately to AMD pulses without earlier acclimation. The ability of an organic system composed of a consortium of indigenous bacteria to survive AMD application may be enhanced by the capacity of peat to uptake metals, and the ability of peat to provide elements required for bacterial survival.

A series of batch column experiments using peat/wood chip admixtures has been initiated to examine the characteristics of the admixtures which make them an excellent source of indigenous celluloytic and sulphate reducing bacteria and efficient scavengers of heavy metals. An anaerobic environment has been maintained in the columns. Research to date has focussed on microbiological aspects - specifically on the ability of natural celluloytic organisms to break down wood chips and provide a soluble carbon source required by the natural SRB population. The ability of all natural bacterial populations to survive pulses of extreme acidification is also being addressed (Shelp et al. in press).

3.5.4 Sewage Sludge

Dewatered sewage sludges are available in significant quantities in large urban centres, but in small quantities in most mining districts.

These sludges may be useful as an oxygen consuming material. Concerns with the use of this material include:

- cost of transportation;

quality of cover leachate; and

long term performance.

3.5.5 N-Viro Soil

N-Viro Soil is a trade name used to describe *"engineered soil"* produced by mixing dewatered sewage sludge with an admixture such as cement kiln dust, fly ash, or wood ash to produce a granular material with desirable soil properties. The product may, in theory, be useful as a component in a composite dry cover as it may increase the water retention capability and provide a short term supply of nutrients to heterotrophic bacteria and has substantial alkalinity to buffer acid production.

N-Viro Soil is essentially a process developed to provide an alternate disposal technique for sewage sludge. The process is claimed to destroy pathogens.

N-Viro Soil as a processed waste may be economically attractive as an alternative to conventional soil conditioners. However, large scale use for dry covers will be substantially limited by transportation costs from the major production centres and available quantities. A typical large city with 1 million people might produce on the order of 40,000 t/yr of dried sewage sludge. From this about 60,000 t/yr of dry N-Viro Soil could be produced or 100,000 t/yr of N-Viro Soil at 60% solids. Total quantities are therefore insufficient to supply large demands for cover application.

It has been estimated that in the Province of Ontario, over 2 million tonnes of biosolids are produced annually. Fourty percent of this is incinerated and could produce in excess of 1.1 million tonnes/yr of N-Viro Soil. The proposed Toronto Leslie Street Sewage Treatment Plant at full capacity could produce over 120,000 t/yr of N-Viro Soil - sufficient to cover about a 14 ha tailings basin to a depth of one metre. Falconbridge Limited is considering the reclamation of at least one tailings area using N-Viro Soil (Wiseman 1993).

While this material is not likely to become available in sufficient quantities, for widescale use, the material may be of interest to dry cover researchers.

3.5.6 Other Industrial Sludges

These industrial sludges are residues of industrial processes or clean-up operations. Quantities are typically small and have varying characteristics. Many of these materials are currently disposed of using waste disposal/recycling services.

3.5.7 Shredder Fluff

Shredder fluff is a byproduct of the mechanical shredding of automobiles, appliances and loose metal to recover ferrous materials. Shredder fluff is a mixture of materials primarily composed or organic polymers (plastics, rubber, fibres). It also contains lesser amounts of other nonferrous materials (i.e. glass, sand, cloth, copper) (Boeger and Braton 1985).

Shredder plants are located outside population centres and near steel making facilities.

At present, there are no established markets for shredder fluff. It is landfilled or used as a cover material at landfills (CH2M Hill 1990).

Quantities of this material are modest at 140,000 t/yr (440,000 m^3 at 0.32 t/m^3). Its potential application as a dry cover component is limited due to:

- small quantities;
- concerns with concentrations of contaminants (i.e. metals, PCB's);
- undesirable properties (i.e. autocombustion); and
- expected high rates of diffusion of oxygen through voids in this material.

Note that the characteristics of shredder fluff are dependent upon the ever changing characteristics of the feedstock - primarily automobiles. As a consequence, shredder fluff characteristics may change over time.

Although shredder fluff is unlikely to have use as a dry cover, the material has potential as a general cover material for use in surface stabilization and reclamation.

3.5.8 Compost

Compost produced by the decomposition of food and yard wastes from municipal waste streams was found to be an inappropriate material. It poses several concerns including:

- possible contamination of heavy metals, toxic compounds and pathogens;
- uncertainties regarding its long term performance; and
- prohibitive cost.

The material does, however, provide an oxygen consuming biomass that could be useful as a component in a composite cover. Concerns about contamination may be addressed by using another source of organic matter. The high cost of producing compost is expected to remain a concern.

Although organic wastes from municipal waste streams may be obtained at no cost (in the vicinity of municipalities) the cost of producing the compost is high. One study has estimated the cost of producing 75,000 t of compost in the Toronto region to be in the range of $100 to $126/t (Molot 1992). Even before transportation costs this cost is prohibitive.

3.5.9 Municipal Refuse

Municipal refuse is available in large quantities and has been suggested for use as a dry cover. In concept, current high disposal charges for this refuse at landfills could be applied to cover the transportation and placement of the refuse at an AMD site. While this may provide a dry cover, it would likely introduce new liabilities to the long term management of an AMD site such as the collection and treatment of the tailings area/landfill leachate.

It is expected that current and proposed legislation would make the planning and operation of such a tailings area landfill quite complex.

3.5.10 Manure

Manure is a bulky organic material derived from plants or animals that decomposes to form humus. Animal manure is a valuable source of nitrogen, phosphorus, and potassium the proportion of which vary according to the type of animals, feed, etc. Fresh animal manures have a high ammonia content and need to be rotted prior to being applied for agricultural use.

While the quantities of manure may be significant on a national basis they are generally inadequate on a regional basis. This material may, however, be useful as a component of a dry cover.

3.5.11 Hay/Straw/Silage

These materials are available in large quantities and in the proximity of several mining districts.

These materials would need to be purchased and transported to the site. It is expected that these materials could be put in place for less than $25 to $50/t. If in excess of 0.5 t/m^2 of these materials were required in a dry cover, they would become cost prohibitive.

Aside from cost considerations, these materials are quite porous, poorly compressible, and present spontaneous combustion concerns.

3.5.12 Paper Mill Sludges

Paper mill sludges are the products of primary and secondary treatment of paper making waste waters. It has been estimated that 1.1 x 10^6 t/yr of paper mill sludges are produced each year on a national basis.

During the paper making process, a paper web is formed by filtering pulp fibres and fillers suspended in water. Fibres and fillers that pass through the filter fabric along with particulate wastes from wood handling and pulping operations are settled during primary wastewater treatment in sedimentation ponds or clarifiers. These sedimented materials are known as primary sludges.

Primary sludge composition is typically:

50 to 60% cellulose fibre
10 to 25% fine fillers (i.e. clay)
10 to 25% lime $CaCO_3$

Most of the inorganic components, and about two thirds of the organic component (fibres) are minus 150 mesh in size. Primary sludges are moderately permeable to water.

The biodegradability of the organic fibre content is dependent upon the pulp process used - either chemical or mechanical pulping. Chemical pulping is based on removing the lignin that glues wood fibres together. Most chemical pulp is made using the kraft process. Chemical pulp products include fine papers, and wrapping and sack papers. The fibre content of chemical pulps is biodegradable.

Low cost papers such as newsprint are made from mechanical pulps which retain the lignin present in wood. The fibre content of mechanical pulps is biodegradable under aerobic conditions, but not under anaerobic conditions due to its lignin content.

Lignin is a complex natural polymer that provides support and protects plant cells in woody plants. Dry wood consists of up to 30% lignin. Lignin is also a byproduct of the pulp and paper industry. It is used in drilling muds and as an extender in plastics, but much of it becomes waste as it is chemically difficult to breakdown.

Secondary waste water treatment in aerated lagoons or activated sludge reactors, involves the use of microorganisms to remove dissolved organic compounds and reduce the biological oxygen demand (BOD) of effluent. The sludge produced by these treatment operations is referred to as secondary sludge. Typical composition from an activated sludge reactor is:

70 to 75% microbial biomass
25 to 30% inorganic fines (i.e. lime, clay)

Secondary sludge is gelatinous and hydrophillic. When compressed it has low permeability.

The repulping and deinking of used paper produces a deinking sludge that is typically composed of:

40% clay
30% carbon black
23% cellulosic fibres and fines, and
4% fatty acids (ink flotation aids)

As most recycled paper is composed of newsprint, the fibres in deinking sludge are lignified and biodegradable only under aerobic conditions.

Most mills combine primary and secondary sludge, and deinking sludge if present, prior to dewatering to a solids content in the range of 25 to 30%. This is done to reduce operational problems encountered with the dewatering of secondary sludge. The mixed sludge is a nuisance product and either landfilled or further dried and burned. The presence of deinking sludge in the mixed sludge is not expected to introduce an additional hazard. Combined sludges have excellent water retaining ability and have low permeabilities in the order of 10^{-10} ms^{-1} when consolidated.

In recent years, the pulp bleaching process has been modified to meet stricter limits on chloro-organic discharge in waste water. As a result, sludges produced today do not contain detectable levels of dioxins and are not expected to present environmental hazards.

Sludges produced in the past using earlier bleaching technology and now contained in landfills may contain parts per trillion of dioxins. The environmental impact of recovering and using old sludge as a dry cover material would, therefore, need to be evaluated. Old sludge may be found to be acceptable as in a Maine landspreading study referred to in the technical review (Appendix B).

Paper mill sludges are considered to be a nuisance waste and may be available, at their source, at no cost.

3.6 MOISTURE/INFILTRATION BARRIERS

3.6.1 Synthetic Liners

Synthetic liners or geomembranes have been extensively used as impervious barriers in tailings impoundment structures and continue to be suggested for use as dry covers. Common types of geomembranes are:

- polyethylene (PE)
- high density polyethylene (HDPE)
- chlorinated polyethylene (CPE)
- chlorosulphonated polyethylene (CSPE)
- polyvinyl chloride (PVC)
- ethylene propylene diene monomer (EPDM)
- butyl rubber

Geomembranes provide low permeabilities often 10^{-10} cm/sec or less. They also resist degradation due to chemical and bacterial action. Concerns with the application of synthetic geomembranes include:

uncertainty about the integrity of the geomembrane due to deterioration from ultra-violet light, ozone, cold weather cracking, root penetration, hot weather distortion, and mechanical damage;

difficulty in providing a suitable vegetative cover over the geomembrane;

uncertainty regarding geomembrane life and replacement costs; and

the performance of the geomembrane between replacements.

Synthetic geomembranes have been field and laboratory tested with encouraging results. Preliminary findings of recent research involving a 2 mm thick (80 mil) HDPE geomembrane undertaken at the Waite Amulet tailings site and in laboratory experiments at the Noranda Technology Centre (St. Arnaud et al. 1993) inferred that:

> the long term stability of the HDPE geomembrane may not be affected by acid leach effects, freeze-thaw effects, and tensile stresses. The potential negative effects of equipment, burrowing animals, root penetration, and ultra violet light remain as concerns.

A remediation program undertaken at the Wheaton tailings site, in the Province of Quebec, in 1993 involved the placement of a 1.5 mm thick HDPE geomembrane sandwiched between layers of sand. Two AMD tailings sites were covered - the largest site measuring approximately 250 m x 200 m. The remedial works were completed in September 1993. No instrumentation was installed to monitor the effectiveness of the geomembrane at inhibiting the sulphide oxidation process.

Synthetic membranes are probably effective as a dry cover but are costly (\$20 to \$40/m^2 range) and have questionable longevity. It is suggested, therefore, that the Waite Amulet HDPE geomembrane test plot continue to be studied; and that the Wheaton HDPE geomembrane be studied to evaluate its effectiveness and service life.

3.6.2 Asphaltic Liners

The application of asphaltic liners as sealing agents to the surface of reactive tailings has been suggested as a means of providing an impermeable dry cover. Sealing agents include readily available materials such as:

- asphaltic coatings; and
- spray on commercial waterproofing, corrosion protection, and soil stabilizing and caulking compounds.

These materials have been tested to a very limited extent in the laboratory and in the field over reactive tailings. Laboratory tests have indicated that asphaltic seals are effective in reducing radon flux. Effective diffusion coefficients for radon through various asphaltic seals were found to range from 0.12×10^{-6} to 31×10^{-6} $cm^2\ s^{-1}$. It was inferred that asphaltic covers would also be effective in reducing oxygen diffusion (SRK et al. 1989)

Key concerns with the use of these materials are:

- difficulty in maintaining the uniformity of the sealing agent across the tailings surface;
- uncertainty regarding the ability to maintain an impermeable seal across the tailings surface (as materials are susceptible to freeze/thaw, cracking, and mechanical damage);
- prohibitive capital cost;
- uncertainty about biodegradability, long term maintenance costs and performance; and
- leakage of polycyclic aromatic residues resulting from partial biodegradation.

3.6.3 Concrete Liners

The use of concrete in applied or shotcrete form has been suggested for use as a dry cover over tailings.

Concrete products may make use of local materials to some extent but a considerable and costly proportion will have to be transported to site. Concerns regarding the use of this material as a dry cover include:

- degradation due to settlement, freeze/thaw, and weathering;
- quality control during placement; and
- long term performance and reapplication requirements.

3.6.4 Waxes

Waxes consist of a broad group of materials having varied chemical composition some of which are natural in origin while others are synthesized. Unlike fats, which may have similar physical appearance, natural waxes are not glyceryl esters but are more complex blends of higher-molecular-weight esters, acids, alcohols, and hydrocarbons. Synthetic waxes have no particular chemical structure and are merely wax like in performance and appearance. They are designed for specific uses and unlike true waxes are often polymers.

There is no current large single volume market for waxes. Diverse applications of wax include: coatings for containers and wrappers, gloss control additives in varnishes, candles, cosmetic moisture retaining films, polishes, insulators, crayons, and other coatings.

It is estimated that a wax cover could be applied with a shallow cover at a cost of \$6 to \$8/m^2 (Davé 1993).

3.6.5 Biopolymers

The use of biopolymers has been suggested as a means of blocking interstitial pore spaces in a dry cover. In addition to producing an oxygen diffusion barrier, the highly organic environment is inhibitory to microbial sulphide oxidation. The technology to do this is as yet undeveloped and considerable research is required.

3.6.6 Desulphurized Tailings

Research into the use of desulphurized tailings as a dry cover is underway. The quantity of material available is more than adequate and transportation cost (to the mine site) is not a factor.

The ability to produce low sulphur tailings is expected to be site specific, and may be limited to ores which are not massive sulphides. Flotation facilities available at most mills could be modified to produce suitable low sulphur tailings. Limestone or phosphate addition could be used to buffer any residual sulphide content.

A typical flotation plant if operated as an add-on to the circuit with an operating cost of $1/t, could produce a 2 m dry cover of tailings at a cost of about \$3 to \$4/m^2 as compared with many other composite covers at more than \$25/m^2. Consideration would have to be given to costs for sulphide concentrate disposal. For non-operating sites, the production of low sulphur tailings would be less attractive and problematic. Many companies have considered the production of "clean tailings" caps but little work has been completed.

3.6.7 Tailings Slimes

As addressed in the Task 2 report, the use of tailings slimes is also an extremely promising concept. Many slimes produced at base metal mines are clay like gelatinous materials which have excellent water retaining abilities. A major problem with reclamation of slime ponds is surface trafficability as these materials will not readily drain. Falconbridge experience suggests slime cover can reduce oxidation rates in pyrrhotitic tailings by an order of magnitude because they act as an excellent oxygen barrier. The most attractive aspect is that the slimes are available at minimal to no cost if they can be applied directly without rehandling. Otherwise costs will be incurred to excavate and relocate the materials.

3.7 CHEMICAL AGENTS/INHIBITORS

3.7.1 Ashes

Several ashes are available for use in dry covers including wood ash produced by the forest products industry at a rate of 0.7 to 1.0 x 10^6 t/yr on a national basis. Ashes can provide both a source of alkalinity (pH 11 to 13) with considerable acid neutralization capacity (wood ash, 35% $CaCO_3$ equivalent), and moisture retention.

Concerns regarding the use of this material include:

- quality of cover leachate; and
- long term performance.

Ashes are expected to be available at their source at little or no cost.

3.7.2 N-Viro Soil

As discussed earlier in Section 3.5.5, N-Viro Soil is produced by processing dewatered sewage sludge and alkaline materials. This processed material provides several suitable qualities including water retaining ability, high levels of alkalinity, and high organic content. As such, it may also serve to inhibit the oxidation process.

3.7.3 Limestone

The use of limestone mixed into the upper reaction layer of tailings as been tested and continues to be suggested. Limestone used in this role has been found to be effective in assisting vegetation growth by controlling soil pH. This approach, however, has been shown to be ineffective as sites amended with limestone and revegetated continue to generate AMD.

The addition of crushed limestone to thickened tailings may provide uniform distribution.

Quantities of limestone are adequate although transportation costs present a constraint.

3.7.4 Phosphate Rock/Slag

As in the case of limestone, sufficient quantities of phosphate rock are available.

Phosphate rock is a mined mineral whose primary use is the production of elemental phosphate and phosphate fertilizers. The production of phosphate fertilizers produces gypsum as a primary by-product while phosphorus production leads to phosphate slag. Neither gypsum or phosphate slag are suitable materials for dry covers. Gypsum is acidic and unstable with a high permeability while phosphate slag is highly pervious and essentially inert.

Phosphate rocks like limestone can buffer acid solutions; but for cover application this property is of minor benefit as the material is only sparingly soluble.

It should be noted that elemental phosphorus slag has been widely used for a variety of purposes, in both the United States and Canada, however, because of its low level radioactivity such uses have been severely restricted in recent years. There are no specific disposal regulations in Canada for phosphate slag. In the Province of Quebec this slag is considered as hazardous waste because of its radioactivity.

Most phosphate deposits have small but measurable concentrations of uranium ranging from a few ppm to several hundred ppm. For instance, the uranium content of phosphate rock in the United States is often in the range of 100 to 150 ppm. The residue radioactivity levels in phosphate rock or phosphate slag would not likely pose a radioactive hazard if used as a component of a dry cover.

3.7.5 Alkaline Sludges/Solutions

Alkaline sludges, such as lime kiln rejects, produced by industry may be of use as they provide high alkalinity and moisture retention. The diverse source of sludges coupled with their small quantities would complicate their wide use in dry covers.

3.7.6 Inhibitors

Commercial inhibitors have been demonstrated to be effective in inhibiting bacterially assisted sulphide oxidation processes but only over the short term. Concerns with the use of these agents include:

- effects on the environment, and
- reapplication requirements.

3.8 SPECIAL APPLICATION

3.8.1 PHITO Layer

Phosphate rock is a component of the PHITO (Phosphate Heterotrophic Inhibition of Tailings Oxidation) layer being researched by Boojum Research Limited (Fyson, Kalin 1993). In this application, phosphate rock in combination with organic matter is worked into the near surface layer of fresh tailings. A vegetative cover is developed on the surface of the tailings and used to support heterotrophic bacteria. The resulting surface treatment, in theory, provides oxygen consumption through bacterial action and organic decay, and acid neutralization through reaction with the phosphate rock. Neutralizing reactions may result in the formation of a hardpan and increase moisture retention in the upper layer.

The research and the application of this technology is in the early stages of development. The likelihood of success is unknown.

The potential issues of this cover relate to the availability, cost, and long term performance of materials used in the cover design. Presently, there are no commercial sources of phosphate rock in Canada although deposits are known to exist. With the data available it is virtually impossible to predict the likelihood of success or the related costs.

PHITO layer test plots have been established at the Denison Stanrock tailings area, and at the INCO Copper Cliff tailings area.

Table 3.1

SUMMARY OF POTENTIAL DRY COVER MATERIALS

GENERAL CLASSIFICATION	NATURAL SOILS	PROCESSED SOILS
Potential Dry Cover Material	**Soils**	**Modified Soils**
Form	Natural clay, till, lake bottom sediments, and loess.	Natural soils modified by addition of materials such as bentonite, ashes and polymers.
Source and Quantity	May be found local to mine sites in sufficient quantities.	May be found local to mine sites in sufficient quantities.
Perceived Benefit/Concerns	Low permeability in the 10^{-7} to 10^{-10} ranges is useful in providing a moisture retaining cover. Long term performance may be affected by natural forces. Diffusion coefficient range: 10^{-6} to 5×10^{-3} cm^2 s^{-1}.	Low permeability (high moisture retaining cover). Low permeability in the 10^{-7} to 10^{-10} range is useful in providing a moisture retaining cover. Stable material both physically and chemically. Long term performance may be enhanced by additives. Diffusion coefficient 10^{-6} to 5×10^{-3} cm^2 s^{-1}.
Experience Related to Tailings Sites	Considerable research has been carried out on the use of natural soils as covers.	Research has been carried out to investigate bentonite, and polymer research is underway.
Stability of Material	Stable material.	Stable material.
Estimated Cost of Dry Cover	\$10 to \$40/m^2	\$15 to \$45/m^2
Guestimate of Effective Cover Life	Indefinite with maintenance.	Indefinite with maintenance.
Guestimate Care & Maintenance Requirements	Minimal.	Minimal.

GENERAL CLASSIFICATION	OXYGEN CONSUMER		
Potential Dry Cover Material	**Crumb Rubber**	**Wood Waste**	**Peat**
Form	Particles of rubber (+60 mesh) produced from tires.	Sawdust, bark, logs, and other wood waste.	Peat may be found in vicinity of mine sites in sufficient quantities.
Source and Quantity	Tire grinding plants produce relatively small quantities. There is at present a limited market for this material.	Produced by the forest products industry. Generally available in most mining districts.	Primarily peat bog material.
Perceived Benefit/Concerns	Large particle size prevents moisture retention. Biotoxicity and potential for combustion are major concerns.	Oxygen consumption. Concerns include variable feed, high porosity, poor quality control, and potential for combustion. Research indicates that wood waste layers can significantly reduce oxygen flux.	May be used to form an oxygen consuming/moisture retaining dry cover. Concerns include long term performance of the peat, maintenance of a perched water table within the peat, and high cost. Oxygen diffusion coefficient range: 10^{-4} to 10^{-2} cm^2 s^{-1}.
Experience Related to Tailings Sites	No experience.	Research at East Sullivan is ongoing. A pyrrhotite tailings pond covered by wood materials was studied from a site hydrological viewpoint.	Research has been carried out and continues (at University of Guelph). This work is in its early stages and suggests that peat or wood chips when mixed with tailings are a source of biomass which creates sulphate reduction and inhibits metals mobility.
Stability of Material	Unstable.	Unstable (decomposes).	Unstable (decomposes).
Estimated Cost of Dry Cover	>$30/m^2	<$30/m^2	<$30/m^2
Guestimate of Effective Cover Life	Unknown.	10 to 50 years.	Not established.
Guestimate Care & Maintenance Requirements	Unknown.	May require periodic reapplication.	Not established.

GENERAL CLASSIFICATION	OXYGEN CONSUMER		
Potential Dry Cover Material	**Sewage Sludge**	**N-Viro Soil**	**Other Industrial Sludges**
Form	Dewatered sewage sludge.	Processed dewatered sewage sludge and alkaline materials.	Sludges with a high biological oxygen demand.
Source and Quantity	Large quantities available nationally but not typically local to mines.	Small quantities may be created at a mine site, but cities are the source.	Sludges produced by various industries often in small quantities.
Perceived Benefit/Concerns	Expected to provide a bacterial seed and consume oxygen through biological processes. Limited quantities are a major concern as is resultant cover effluent quality Diffusion coefficient range 10^{-4} to 10^{-2} cm^2 s^{-1}.	Expected to provide a source of alkalinity, and high organic oxygen demand. Concerns include limited quantities and cost. Diffusion coefficient range 10^{-4} to 10^{-2} cm^2 s^{-1}.	Expected to provide high oxygen demand and be available at little or no cost. Concerns include limited quantities available and the diverse number of sludge sources. Diffusion coefficient range 10^{-4} to 10^{-2} cm^2 s^{-1}.
Experience Related to Tailings Sites	Limited scientific research has been carried out.	Limited laboratory research has been undertaken.	No relevant experience.
Stability of Material	Unstable (decomposes).	Unstable (partly decomposes).	Unstable (decomposes).
Estimated Cost of Dry Cover	<$30/m^2	<$30/m^2	<$30/m^2
Guestimate of Effective Cover Life	Not established.	Not established.	Not established.
Guestimate Care & Maintenance Requirements	Frequent reapplication.	Not established.	Frequent reapplication is a possibility.

GENERAL CLASSIFICATION	**OXYGEN CONSUMER**		
Potential Dry Cover Material	**Shredder Fluff**	**Compost**	**Municipal Refuse**
Form	Mixture of non-ferrous materials primarily polymers (rubber, plastic, fibres) produced as a by-product of the shredding of automobiles and appliances.	Immature or mature compost derived from organics such as food and yard waste. Mature compost is a humus-like material.	Municipal refuse excluding material sorted and diverted for recycling.
Source and Quantity	Produced in relatively small volumes at industrial sites typically located near the US-Canada border.	Large scale composting is just getting underway in large urban countries. Quantities of compost available within economic transport distance of most mines are expected to be insufficient.	Refuse produced in abundant quantities on a national basis but not regionally.
Perceived Benefit/Concerns	May be of some use in developing a tractable surface on soft tailings. Concerns include low level PCB contamination, and metal contaminated leachate.	Expected to provide a high biological oxygen demand and moisture retention. Concerns include contaminants, pathogens (and related public health issues), high cost and unknown long term performance.	Could offer significant cost savings if refuse disposal costs were applied to cover construction. Services concerns include leachate management, and complex permitting requirements.
Experience Related to Tailings Sites	No relevant experience.	Limited experience.	No scientific research undertaken using this material at AMD sites.
Stability of Material	Unknown stability.	Unstable (decomposes).	Unstable (decomposes).
Estimated Cost of Dry Cover	<$30/m^2	<$30/m^2	<$30/m^2
Guestimate of Effective Cover Life	Not applicable.	Not established.	Indefinite if landfill constructed at site.
Guestimate Care & Maintenance Requirements	Not applicable.	Frequent reapplication is possible.	Landfill monitoring.

GENERAL CLASSIFICATION	OXYGEN CONSUMER		
Potential Dry Cover Material	**Manure**	**Hay/Straw/Silage**	**Paper Mill Sludge**
Form	Animal and plant manure.	Farm products.	Paper mill sludge from both primary and secondary wastewater treatment.
Source and Quantity	Available in small quantities in the vicinity of mine sites.	Available in large quantities, often within 100 km radius of mining districts.	Available in moderate quantities - 1.1 x 10^6 t/yr nationally.
Perceived Benefit/Concerns	Perceived benefits are use as a soil conditioner, high oxygen demand and moisture retaining materials. Concerns include long term effectiveness.	Perceived benefits are use as a soil conditioner, high oxygen demand, and moisture retention. Concerns include relatively high cost, porosity, and poor compressibility.	Expected to provide high biological oxygen demand and moisture retention. Concerns include long term effectiveness.
Experience Related to Tailings Sites	Research has been suggested.	Research has been suggested.	Research has been suggested.
Stability of Material	Unstable (decomposes).	Unstable (decomposes).	Unstable (decomposes).
Estimated Cost of Dry Cover	<$30/m^2	<$30/m^2	<$30/m^2
Guestimate of Effective Cover Life	Not established (<5 years?)	Not determined (<5 years?)	Not determined.
Guestimate Care & Maintenance Requirements	Frequent reapplication may be required.	Frequent reapplication may be required.	Not determined.

GENERAL CLASSIFICATION	MOISTURE/INFILTRATION BARRIERS			
Potential Dry Cover Material	**Synthetic Liners**	**Asphaltic Liners**	**Concrete Liners**	**Waxes**
Form	Fabricated liners.	Typically spray-on type liners	Shotcrete, and poured concrete.	Liquid and solid form.
Source and Quantity	Commercially available.	Commercially available	These materials could be mixed on-site using both local materials and commercial products.,	Limited supply waste product.
Perceived Benefit/Concerns	Provision of an impermeable layer likely to be in service for at least 50 years. Concerns include replacement costs and cover deterioration.	Establishment of an impermeable layer. Concerns include ongoing maintenance, cover replacement, impact on the oxidation process, and high cost.	Concerns include deterioration of the cover due to settlement, freeze/thaw action, etc.	A pliable wax cover may be capable of providing a self-healing barrier. Long term effectiveness is a concern.
Experience Related to Tailings Sites	Significant experience regarding the properties and uses of synthetic liners has been obtained.	Limited research has been completed	No experience with respect to covering tailings.	Research has been suggested.
Stability of Material	Stable (may deteriorate).	Unstable (biodegrades, deteriorates).	Unstable (deteriorates).	Relatively stable (slowly decomposes).
Estimated Cost of Dry Cover	\$20 to \$40/m^2	<\$30/m^2	\$20 to \$100/m^2	<\$30/m^2
Guestimate of Effective Cover Life	>50 years	Short life (<5 years?)	Short life (<5 years?)	Not determined.
Guestimate Care & Maintenance Requirements	Scheduled inspections.	Ongoing inspection and repairs as required.	Ongoing inspection and repairs as required.	Not determined.

GENERAL CLASSIFICATION	MOISTURE/INFILTRATION BARRIERS		
Potential Dry Cover Material	**Biopolymers**	**Desulphurized Tailings**	**Tailings Slimes**
Form	Polymers	Tailings (processed to reduce sulphur content).	Tailings slimes (minus 200 mesh).
Source and Quantity	Dependent upon the type of polymers used.	Sufficient source created by processing tailings produced at a mine (or possibly at an adjacent operation).	Sufficient source created by the particle size separation of tailings produced at a mine (or possibly at an adjacent operation).
Perceived Benefit/Concerns	The principal concern is that the technology required for this approach is not yet available.	This material may provide advantages associated with the use of natural soils.	As per desulphurized tailings this material provides advantages associated with the use of natural soils.
Experience Related to Tailings Sites	Research is underway (Alberta Research council)	Research is underway (Ecole Polytechnique and INCO).	Research includes field measurements at Falconbridge, lab scale at Ecole Polytechnique.
Stability of Material	Unstable (decomposes).	Stable.	Stable (sulphides, if present in slimes, will react slowly).
Estimated Cost of Dry Cover	<$30/m^2	<$30/m^2	<$30/m^2
Guestimate of Effective Cover Life	Not determined.	Indefinite with maintenance.	Indefinite with maintenance.
Guestimate Care & Maintenance Requirements	Not determined.	Scheduled inspections.	Scheduled inspections.

GENERAL CLASSIFICATION	CHEMICAL INHIBITORS		
Potential Dry Cover Material	**Ashes**	**Limestone**	**Phosphate Rock**
Form	Boiler ash including wood ash. Coal bottom ash and fly ash including those from fluidized bed coal combustion operations.	Crushed limestone.	Crushed phosphate rock.
Source and Quantity	Available from diverse sources in various quantities.	Typically sourced outside mining districts and available as a commercial product.	Typically sourced form the United States and available as a commercial product.
Perceived Benefit/Concerns	Their alkaline content (wood ash 35% $CaCO_3$ equivalent) is expected to be useful along with moisture retention. Concerns include cover leachate quality and long term effectiveness.	Crushed limestone mixed in the reactive layer of tailings can buffer acid production. Concerns include quality control during mixing and cover leachate quality.	As per limestone, buffering capacity is provided. Concerns include cost, lower solubility, and availability compared to limestone.
Experience Related to Tailings Sites	Research has been suggested.	This concept has been adequately addressed by research	This concept has been adequately addressed by research.
Stability of Material	Unstable (reactive).	Stability dependent upon reactions.	Stability dependent upon reactions.
Estimated Cost of Dry Cover	<$30/m^2	<$30/m^2	<$30/m^2
Guestimate of Effective Cover Life	Not determined.	Variable life.	Variable life.
Guestimate Care & Maintenance Requirements	Not determined.	Possible reapplication as required.	Possible reapplication as required.

GENERAL CLASSIFICATION	CHEMICAL INHIBITORS		SPECIAL APPLICATION
Potential Dry Cover Material	**Alkaline Sludges/Solutions**	**Inhibitors**	**PHITO Layer**
Form	Sludges.	Commercial preparations.	Would be constructed at site using tailings, phosphate rock, organic material, and vegetative cover seed.
Source and Quantity	Small quantities of diverse sludges produced by various industries.	Available commercially.	Components that would need to be purchased are available commercially.
Perceived Benefit/Concerns	Buffering of acidity using low cost waste alkaline sludges. Concerns include availability and quality control if many sludge sources are involved.	Short term benefit.	Inhibition of the acid generation process through oxygen demand, and moisture retention. Concerns include long term effectiveness.
Experience Related to Tailings Sites	Research has been suggested	Considerable research has been undertaken in this area.	Test plots established at Stanrock and Copper Cliff.
Stability of Material	Stability dependent upon reactions.	Unstable.	Stability conditional on conditions and reactions.
Estimated Cost of Dry Cover	<$30/m^2.	<$30/m^2	<$30/m^2
Guestimate of Effective Cover Life	Not determined.	Short Life (<1 year)	Variable life.
Guestimate Care & Maintenance Requirements	Not determined.	Frequent reapplication required.	Possible reapplication of components.

4.0 SCREENING CRITERIA FOR PROPOSED DRY COVER ALTERNATIVES

4.1 GENERAL

There are a multitude of materials proposed for use in dry covers. These materials may be the bulk of the dry covers or simply an element of the cover. The potential attributes of each material can be described, but in many cases there are little to no data to assess the likely performance of the material.

In an effort to direct research funding for dry covers in an effective manner MEND has requested that a screening mechanism be developed. The following process has been proposed and is used to screen alternative dry materials discussed in Chapter 3.0.

4.2 SCREENING CRITERIA

4.2.1 Preliminary Screening

There are several general criteria which can be used as a screening mechanism for dry materials. There are three basic criteria that need to satisfied:

(1) Is the dry cover material likely to be cost effective? Research to date has indicated dry covers can be installed at a cost of perhaps \$15 to \$30 per square metre and less in some cases. Materials with higher costs should not be a high priority for research.

(2) Is there a broad based application? The MEND program is national and should focus on solutions with widespread application. A cover material which is only available to one mine or one region would be a low priority for research funding.

(3) Is there an adequate quantity of the cover material available within economic transportation distances to mining regions? There are two criteria that need to be met. These are total availability and mining regional availability. As a screening guideline 10^6 t/yr of a bulk dry cover material is suggested as a reasonable total

available quantity. Regional availability has been set at 10^5 t/yr. For a small tailings pond of 25 ha with 1 m of cover, there would be a requirement of 250,000 m^3 of material. At 1 t/m^3 (e.g. wood waste, sludge) it would take 2 to 3 years of regional production to cover the basin. Any quantity of $<10^5$ t is probably of minimal utility.

Any material that meets these initial screening criteria has potential to have broad based application as a dry cover material. This process is shown in Figure 4.1. The next step would then be to compare these high priority materials on the basis of many factors. These include:

i) cost (purchase and transportation)
ii) long term durability/performance
iii) care and maintenance
iv) biochemical/physical properties
v) constructability
vi) likelihood of success

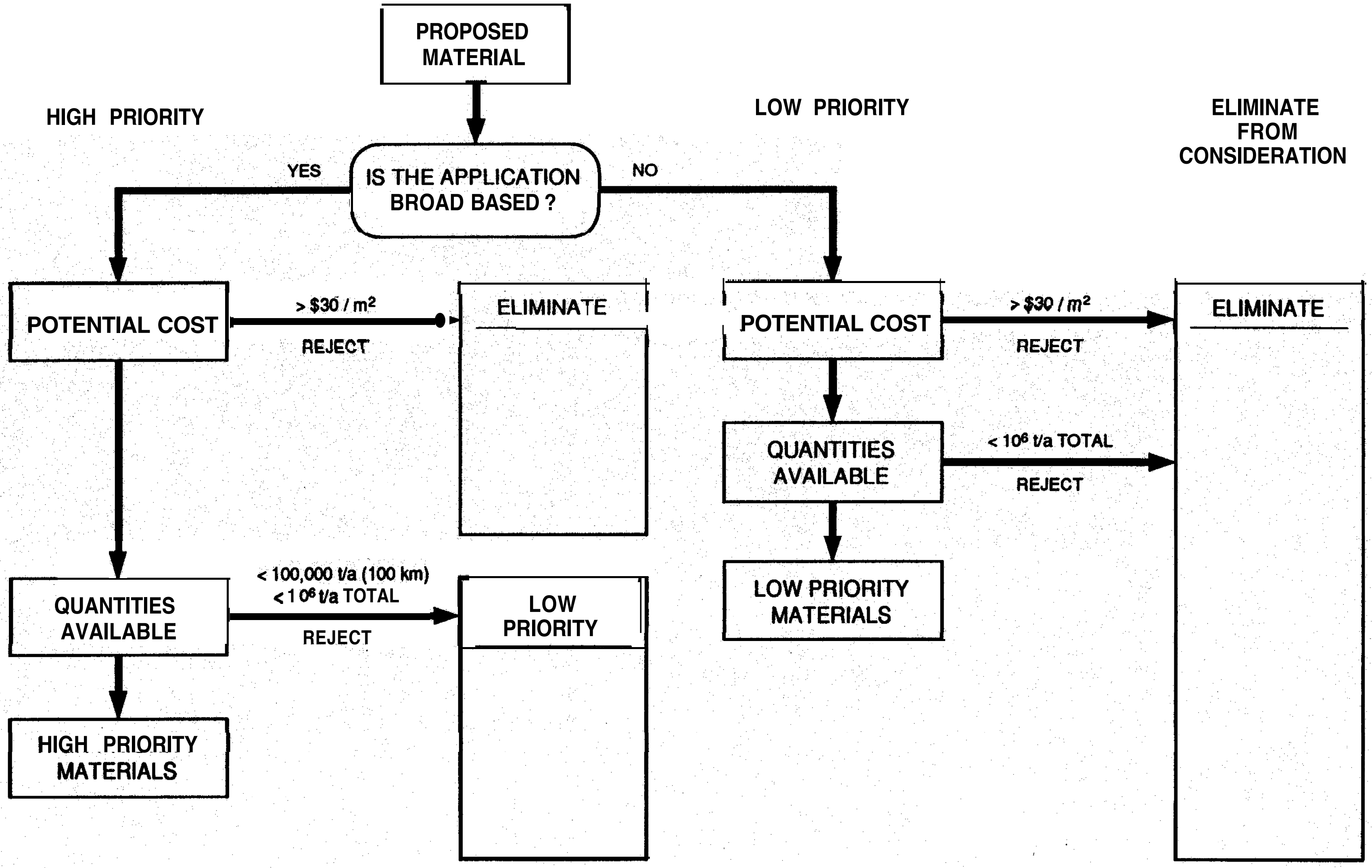
These criteria are both quantitative and qualitative:

i) The cost of materials will be highly regional and will depend in large part on purchase cost transportation and on-site processing cost. For materials such as a soil modifier (e.g. bentonite) costs will be highly dependent upon the application rate required.

ii) Long term durability and performance is essential as the cost to replace covers can be extremely prohibitive. As a general rule, it is unlikely that any dry cover will perform in perpetuity without some level of care and maintenance. As a screening guideline it is suggested that any cover which would not function for at least 50 to 100 years would not be a high priority for research. Therefore, an oxygen consumer must be effective and not require replacement, a chemical inhibitor must remain reactive, and a moisture or infiltration barrier must remain competent for 50 to 100

FIGURE 4.1

PRELIMINARY SCREENING



years. Materials with shorter lifespans may be of value in selected cases but are not likely to be of widespread interest.

iii) The objective of all decommissioning options is to minimize the need for long term care and maintenance. Any material which requires ongoing maintenance (e.g. an inhibitor which requires routine application) should be considered a low priority for research.

iv) The biochemical properties of many cover materials make them candidates for dry cover applications (e.g. wood waste); however, the properties can also lead to environmental concerns. They may add new contaminant and solve one problem only to create another. The biochemical properties are unlikely to eliminate cover materials for general application as site specific issues will likely dictate whether or not these problems are of concern. The biophysical properties are linked to constructability. The aspect of screening here is to determine if material has the biophysical properties to meet the stated objective. For example, does an oxygen consuming barrier have adequate levels of organics in a form which is degradable at a predictable rate? For a moisture retaining material, does the material have high water content, is it frost susceptible, does it have a low permeability?

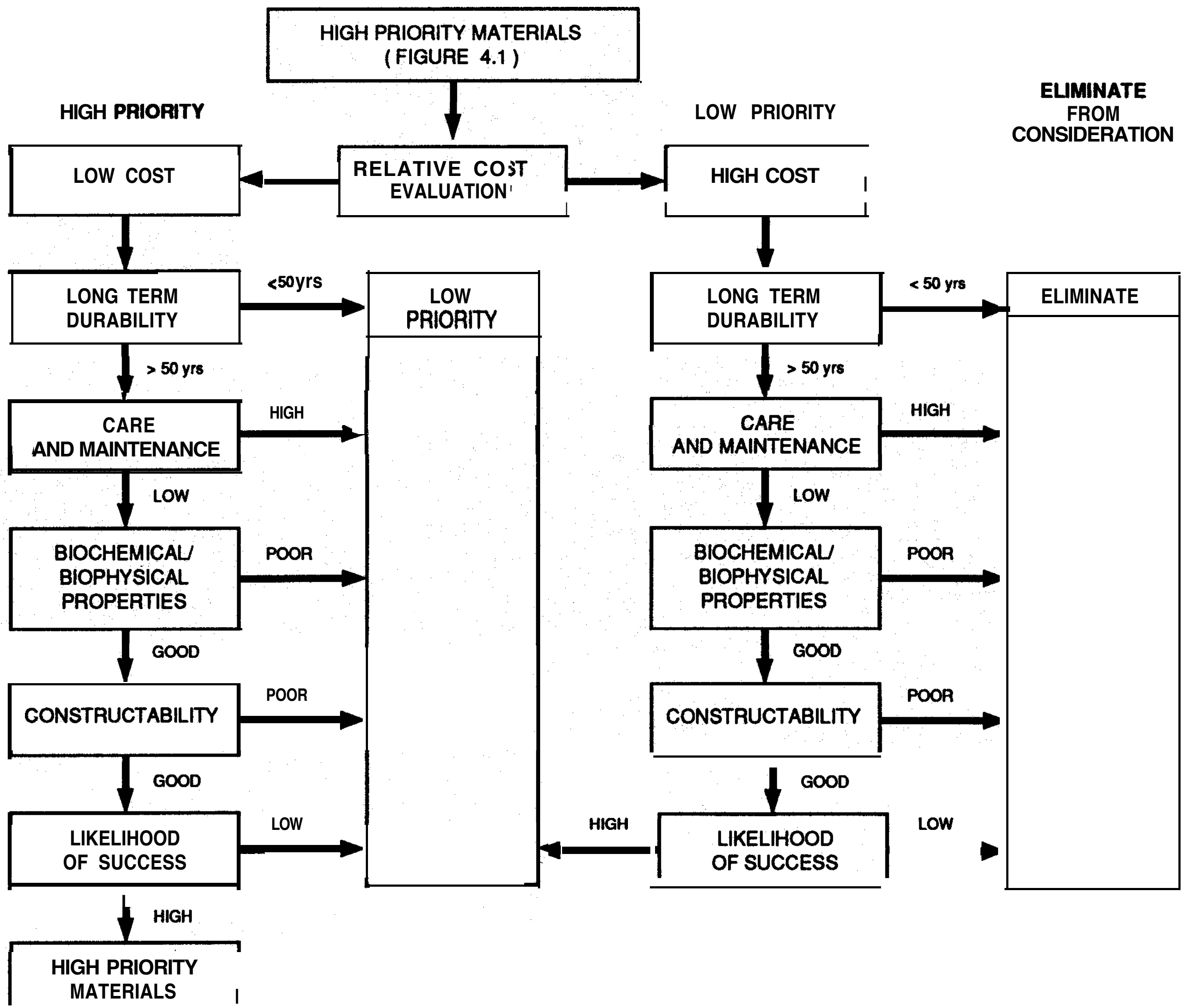
v) The ability to apply the dry cover using proven techniques is paramount. A sludge, for example, may have excellent moisture retaining properties but it if can't be uniformly applied and readily covered to protect the barrier from evaporation, freeze/thaw, etc., its utility is greatly diminished.

vi) Based upon all of the above information an informed opinion can be drawn as to the likelihood of success.

This overall process is shown in Figure 4.2. From this process a listing of high priority and low priority materials can be derived. One must be very cautious in being rigid and a great deal of

FIGURE 4.2

DETAILED SCREENING OF DRY COVER ALTERNATIVES



judgement must be applied to create these listings. Based upon the final list priorities can be established for those materials which have the most widespread application, low cost and likelihood of success.

The following section draws upon this methodology to review the potential alternative cover materials.

5.0 SCREENING ANALYSIS - ALTERNATIVE DRY COVER MATERIALS

5.1 PRELIMINARY SCREENING

As discussed in Section 3.0 potential dry cover materials are reviewed under six areas: natural soils, processed soils, oxygen consumers, moisture/infiltration barriers, chemical inhibitors and specific applications. The preliminary screening and detailed processes, as discussed in Section 4.0, were applied to derive a list of materials which have a high priority for further review.

The results of the screening analysis are provided in Figures 5.1 and 5.2 and a description of the analysis is provided below.

5.2 NATURAL SOILS

Natural soils such as clays and tills have been commonly applied as covers. There are numerous types of natural soils which effectively act as barriers to oxygen transport. The most effective barriers are soils with a high level of saturation. Other potential natural soils include lake sediments, marine clays, top soil, loess, silty sands, etc.

Work completed to date suggests that one or more of these materials would be available in the vicinity of a mining operation and therefore natural soils have excellent availability. Costs will be site specific, however, for a cover of 1 to 2 m deep and a cost of \$10 to \$20/m^3 the unit cost for development of an effective cover would be in the range of \$10 to \$40/m^2. Natural soil covers have excellent durability, require minimal maintenance and have no chemical or physical properties that would deter their use. As such, these materials are a high priority for research and development. In fact, much of this research is underway.

FIGURE 5.1

PRELIMINARY SCREENING

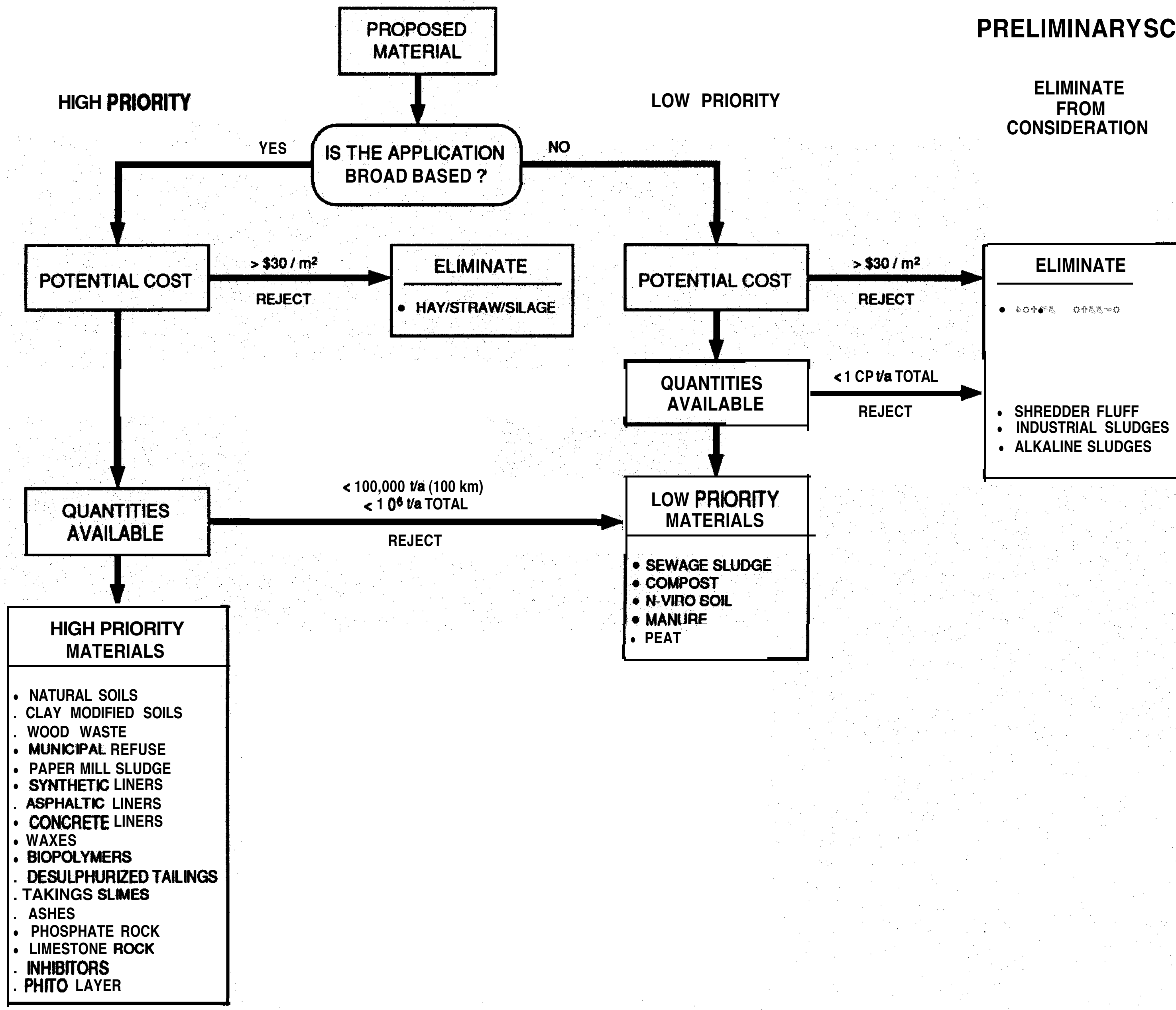
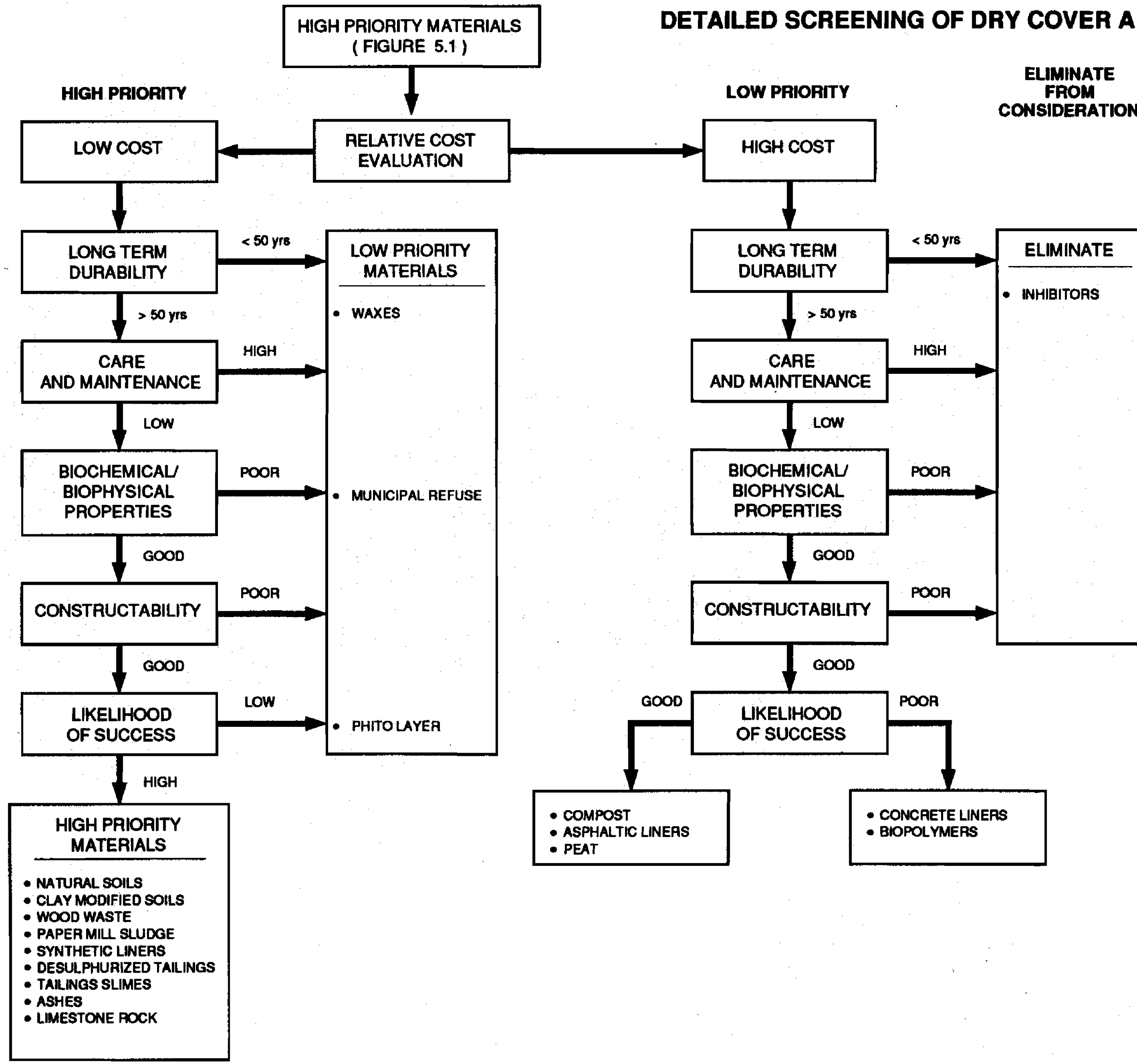


FIGURE 5.2

DETAILED SCREENING OF DRY COVER ALTERNATIVES



5.3 PROCESSED SOILS

5.3.1 Clay Modified Soils

There are three primary materials in this category. These are clay modified soils (bentonite or modified clays) or waste modified soils.

Bentonite addition to tills or silty sands has been commonly employed. The bentonite addition adds to the cost of the natural soil cover but typically with relatively small bentonite requirements (a few percent) the addition of the bentonite to a component layer of the cover probably would not add more than perhaps $5/m^2.

Recently modified clays have been prepared by researchers at the Alberta Research Council. Preliminary results are about to be released which suggest the polymer modified clays could provide for excellent moisture retaining zones in a composite cover. Details regarding costs are not available, however, one would only consider such an option if it was cost competitive with the use of natural soils or bentonite modified soils. As with natural soils, these materials have excellent durability, low maintenance, no deleterious chemical or physical characteristics and have a high probability of success.

5.3.2 Waste Modified Soils

Waste modified soils are for the most part ash modified soils. Ashes are available in reasonable quantities and at no cost other than transportation. If mixed with soils, ashes offer both water retention capabilities and alkalinity. The chemical stability and long term durability are not well known, however, one would expect these materials to remain as effective moisture retaining zones for more than 50 years. No field data are available and additional research is required to confirm the applicability.

5.4 OXYGEN CONSUMERS

5.4.1 Crumb Rubber

Crumb rubber is widely available but is costly, available only in small quantities and will produce potentially toxic leachates. Therefore, this material is eliminated as a candidate dry barrier.

5.4.2 Wood Waste

Wood waste is widely available to most mining areas. The waste is available at no cost other than transportation. In some cases even transport costs can be provided if the tailings area is closer than the wood waste disposal facility. Because of the inherent source variability, high porosity, poor quality control etc. wood waste is not an ideal cover material; however, given the potential major cost advantages it must be considered as a serious candidate as a dry barrier. There are concerns regarding combustion and leachate quality; however, these issues may not be significant.

5.4.3 Peat

Peat availability is somewhat more restricted than wood waste. As an organic material peat has some advantages in that it has excellent water retention capabilities, has less permeability when compressed, and is much more uniform production than wood waste. The major drawback is that there are costs for the purchase and excavation of the peat which could add to the overall cost. In addition, peat does not have a high oxygen demand. However, given the more uniform nature of peat it may well be possible to use less material than would be required for wood waste. Peat is a potential candidate for use in a dry barrier.

5.4.4 Sewage Sludge

Dewatered sewage sludges are available is small quantities in mining areas. Their use as a primary oxygen consuming layer is not likely for no other reason than availability. Small scale specific applications may develop, but sewage sludge is not a primary candidate as a dry barrier.

5.4.5 N-Viro Soil

N-Viro Soil has many attributes in that it has a high organic content for oxygen consumption, has good water retaining ability as a diffusion barrier and also contains high levels of alkalinity. As with sewage sludge the material is only available in small quantities and as such is unlikely to find a major role as a dry barrier.

5.4.6 Other Industrial Sludges/Wastes

A review of waste production records, waste exchange databases and waste registration databases did not uncover any large volume industrial wastes with potential for use as dry barriers.

5.4.7 Shredder Fluff

Shredder fluff is an alternative waste material because it is likely available at many mine sites at minimal to no cost. Quantities available are modest, however, sufficient material is produced annually to cover a small tailings area.

The primary concerns with shredder fluff are technical. The material is too porous and has insufficient organic content to be effective as a long term oxygen barrier. Other issues include the potential for low level PCB contamination and metal contaminated leachate. As such, this material is rejected from further consideration.

5.4.8 Compost

Composting of organic waste going to municipal landfill is becoming a more common practice. Compost is typically available at no cost at the point of production. To be applicable for use in mining areas compost has to be produced in adequate quantities within an economical transportation distance from the mine. Based upon the current and likely future availability, within the mining regions, compost will not find a major role as a dry barrier.

5.4.9 Municipal Refuse

As compared with compost, municipal refuse is available in much larger quantities. However, there are major concerns with leachate management and control and given the current hysteria over garbage disposal, municipal refuse is not a high priority candidate for use as a dry barrier.

5.4.10 Manure

Manure production is broadly dispersed and only available in small quantities. Manure as a soil conditioner or bacterial seed (like sewage sludge) could provide a limited role in other oxygen consuming covers. Based upon collection and transportation costs it is unlikely that manure will be a primary candidate as a dry barrier.

5.4.11 Hay/Straw/Silage

These materials as compared with wood waste have much better uniformity. They can be available in large quantities and likely within 100 km of many mining areas. Costs will be highly variable and most certainly will be higher than wood waste. It is unlikely that materials would be available at <$25 to $50/t and if more than above 0.5 t/m^2 were required this material would not be economical. These oxygen consumers have the added disadvantage of being poorly compressible and highly porous. As such, hay and other farm materials may have some potential application but its widespread use as a primary material in a dry barrier is unlikely.

5.4.12 Paper Sludge

Paper sludges are broadly available in moderate quantities. The sludges have a high clay content and high cellulose content. They will act as both diffusion barrier and an oxygen consuming barrier. The material has been used in reclamation and may prove to be useful. As a thin moisture barrier (0.3 m) about 0.24 t/m^2 of sludge would be required. For a 50 ha basin this equals about 1.2

x 10^5 t. This equals about 2 years productions of paper sludge in New Brunswick and 2 months production from Quebec. The massive use of paper sludge is unlikely but given its broad distribution, low cost and potential benefit it should be considered as a prime candidate for use in a dry barrier.

5.5 MOISTURE/INFILTRATION BARRIERS

5.5.1 Synthetic Liners

There is a multitude of synthetic liners that could be used as both an infiltration barrier as well as an oxygen barrier. Provided the liner is properly installed and protected, there is no reason to expect a liner to not function for 50 to 100 years or more. There are some concerns regarding punctures (roots, animals etc.) however these are not considered to be major concerns. An engineered liner installation would likely cost in the range of \$20-\$40/m^2 depending upon site conditions. Synthetics have to be considered as reasonable options for use as dry barriers. Having said this there is minimal need to demonstrate their viability as a well installed liner will function as designed.

5.5.2 Asphaltic Liners

There are a number of products which fall into the category of asphaltic liners. These include asphalt sheeting, asphalt pavements and spray on asphalt emulsions. Given the biodegradability of mass asphaltic compounds, durability and lifespan are substantial issues. Given there is no apparent cost advantage to these types of membranes over synthetic liners no immediate merit in research and development on the use of asphaltic membranes as dry barriers is seen.

5.5.3 Concrete Liners

A number of researchers have proposed the use of concrete (spray-on and applied) for capping waste dumps and pit walls. For fully consolidated materials, concretes may have application.

However, with high moisture materials, freeze/thaw action, long term settlement etc. it is highly unlikely that concrete will prove to be a viable dry barrier for tailings. As such, concrete was rejected as a likely material for dry barriers.

5.5.4 Waxes

Petroleum waxes are a by-product. They have limited uses and are available in limited supply. The concept of applying a pliable wax to the surface of a tailings pond as a water infiltration/oxygen diffusion barrier is intriguing and worthy of some scoping study. Data available suggests that a wax layer with a thin cover could be applied for $6-8/m^2 which is well below costs typically discussed for many conventional barriers (liners, clay).

Although availability will limit the use of waxes, these materials are potential candidates for use in dry barriers.

5.5.5 Biopolymers

Biotechnology is racing ahead and unique developments in bioengineering are continuously arising. One such concept was to develop a biopolymer or foiling agent which would result in plugging of the *in situ* tailings or soils causing a saturated barrier to form. Based upon the current state of knowledge it does not appear that such technology is currently economically or technically viable.

5.5.6 Desulphurized Tailings

Desulphurized tailings hold tremendous promise as dry barriers. They have all the advantages of natural soils and may be produced in many cases at a fraction of the cost. This application has been sadly overlooked in the industry and should be a major target for research as a candidate for use as a dry barrier.

5.5.7 Tailings Slimes

As with desulphurized tailings, tailings slimes show tremendous potential for cost effective use in dry barriers.

5.6 CHEMICAL AGENTS/INHIBITORS

5.6.1 Ashes

There are a number of ashes available (i.e. wood ash, bottom ash and fly ash) which could be used as additives or layers in dry barriers. The ashes can act as an alkalinity sink or a moisture retaining layer in a cover. Little is known about the use of ashes as moisture barriers, however, their alkaline content (e.g. wood ash 35% alkalinity as $CaCO_3$) may be beneficial. Leachate quality could be a concern as would be long term durability. Ashes are worthy of some preliminary screening for use as dry barriers but are not likely to find a major role. As such, some funding is warranted but only on a limited scale.

Future research (if any) into the use of bottom ash and fly ash in dry covers should include a review of the chemical constituents of Canadian ashes from an environmental perspective.

5.6.2 N-Viro Soil

N-Viro Soil has many attributes in that it has a high organic content for oxygen consumption, has good water retaining ability as a diffusion barrier and also contains high levels of alkalinity. As with sewage sludge the material is only available in small quantities and as such is unlikely to find a major role as a dry barrier.

5.6.3 Limestone

The incorporation of limestone into the unsaturated zone of the tailings to consume acid produced has been tested in several instances. Limestone incorporated into near surface acid tailings is effective in controlling soil pH for vegetation growth, and columns of tailings with limestone added as compared with other dry covers can be cost effective, however, additional methodology needs to be confirmed.

Crushed limestone if added to a thickened tailings should be uniformly distributed with the tailings. For a tailings with 10% sulphur, a limestone addition rate of about 350 kg/t would provide adequate alkalinity to consume any acid produced. If this unsaturated zone was 1.5 m deep, about 0.62 t/m^2 of limestone would be required. For an all found cost of $35/t for limestone, the dry barrier would cost about $\$22/m^2$ which is competitive with many other barriers. If sulphide levels are lower, costs would be reduced and vice versa.

5.6.4 Phosphate Rock

The incorporation of phosphate rock into the unsaturated zone of the tailings to consume acid produced may be of some merit. However, when reactivity, cost and availability are compared with limestone, there appears to be no merit in using phosphate rock.

5.6.5 Alkaline Sludges/Solutions

There are a large number of alkaline sludges and solutions produced by industry. The solutions are not viable options but the alkaline sludges (e.g. lime kiln rejects) may be beneficial. These sludges are produced in relatively small volumes but have both water retaining properties (pasty) and high available alkalinity (free lime and $CaCO_3$). These materials have been offered to the industry on many occasions with less than an enthusiastic response. Given the small supply and limited applicability no further study of these materials is warranted.

5.6.6 Inhibitors

There have been a number of commercial preparations (e.g. sodium lauryl sulphate, SLS) which can reduce oxidation rates in reactive materials. To date no material has shown to have long term benefits. At this time no funding of inhibitors appears warranted.

5.7 SPECIAL APPLICATION

5.7.1 PHITO Layer

The PHITO layer as proposed by Fyson and Kalin (1993) attempts to create an active biological environment in the near surface tailings. The process uses phosphate rock as a long term nutrient source and an organic (manure) to create an oxygen consuming layer. The combined biomass production/decay is hoped to effectively control acid production. The concept is not unlike many other oxygen consuming barriers and may have potential application. Given that at least two field programs are in place, funding of a limited monitoring program would appear warranted.

5.8 SUMMARY

The summary of the alternative dry barriers screening analysis is provided in Table 5.1.

Table 5.1

SUMMARY OF SCREENING ANALYSIS
ALTERNATIVE DRY BARRIERS

High Priority Materials	Low Priority Materials	Rejected Materials
Natural soils	PHITO layer	Crumb rubber
Clay modified soils	Waxes	Shredder fluff
Ash modified soils	N-Viro Soil	Industrial sludges
Wood waste	Compost	Alkaline sludges
Desulphurized tailings	Peat	Concrete liners
Tailings slimes	Asphaltic liners	Biopolymers
Limestone	Manure	Phosphate rock
Synthetic liners	Municipal refuse	Inhibitors
Paper mill sludge	Sewage sludge	
	Ashes	

6.0 CRITICAL REVIEW - HIGH PRIORITY DRY BARRIER MATERIALS

6.1 OVERVIEW

The high priority candidate dry barriers were summarized in Table 5.1. These potential barrier materials have been selected as being widely distributed at a cost competitive with proven dry barriers with potential biophysical properties that could make these materials excellent dry barriers.

The materials by function are listed below.

A) Oxygen transport barriers
- natural soils
- clay modified soils
- ash modified soils
- desulphurized tailings
- tailings slimes
- synthetic liners

B) Oxygen consuming barriers
- wood waste
- paper mill sludge

C) Reaction inhibiting barriers
- limestone

A critical review of each of these barriers is provided in this section.

6.2 OXYGEN TRANSPORT BARRIERS

6.2.1 Natural Soils and Synthetic Liners

Natural soils and synthetic liners have proven to be effective dry barriers. The primary concern to these barriers is cost. Detailed design data for composite soil covers is being developed and it is expected to be available in the near future. There are several concerns regarding weathering, durability etc. but these are generally not major issues at this time. The current research into natural soil barriers is the cornerstone of the dry barriers program and must be fully supported to its logical conclusion.

Natural soil barriers and synthetic liners are the standard upon which all other alternative dry barriers should be compared.

6.2.2 Modified Soils

Virtually no data are currently available in modified natural soils. Several additives have been proposed of which commercially available clays (bentonite), modified clays and ashes offer considerable promise. Little critical assessment of these materials can be completed as virtually no data are available. Certainly the potential for success with clay or modified clays is excellent. The potential for success of wood ash as an additive is unknown.

6.2.3 Tailings as Dry Barriers

All data which has been reviewed on the use of sulphur reduced tailings or tailings slimes is very encouraging. There appears to be no technical difficulties in the application and the potential benefits are enormous. The only drawback identified was the ability to produce a "clean tailings" which would not leach. The merits are obvious yet minimal research is ongoing.

6.3 OXYGEN CONSUMING BARRIERS

6.3.1 Wood Waste

Wood wastes and related lignocellulosics have been shown to be effective oxygen consuming barriers. These wastes comprise an abundant, renewable resource for cover application. There are, however, several concerns relating to:

- i) physical and chemical variability
- ii) long term stability
- iii) design criteria
- iv) undesirable leachates

i) Physical and Chemical Variability

Wood wastes are highly heterogeneous with regard to both physical and chemical composition. The suitability of wood wastes as a cover depends on their intrinsic oxygen demand. It is essential that the oxygen concentration approaches zero within the cover material. The oxygen consumption rate, in turn, is dependent on the interaction of a number of variables including the specific surface area, moisture content, cellulose, hemicellulose, lignin, terpene composition, temperature, and pH. It appears that the annual average oxygen demand should be in the range of 10^{-5} to 10^{-4} mol O_2 m^{-2} s^{-1} to deplete the oxygen concentration at the tailings surface. A higher intrinsic oxygen demand would significantly reduce the life span of the cover, while a lower demand would be inadequate to reduce the oxygen concentration to zero within 1 m cover depth. Current applications including the Sullivan mine wood waste cover (Germain et al. 1992) and the Falconbridge tailings sawdust cover require further monitoring. It seems that the oxygen consumption in peat covers is too low to have a significant effect as an oxygen consuming layer to curtail acid generation.

ii) Long Term Stability

Since wood wastes degrade under both aerobic and anaerobic conditions, these covers are expected to have a limited life span. Estimates of life span for 1 m cover are in the order of 10 years. As the biodegradable organic material in the cover is depleted, eventually oxygen concentration breakthrough is likely to occur with covers less than 1 m depth. To meet a lifespan of 50 years or more, a wood waste cover of 2-3 m depth would be required. The performance of such cover would depend on the moisture content and the degree of compaction as well as its capacity to consume oxygen. The diffusive barrier to oxygen content is expected to become the rate controlling factor as the moist organic matter compacts while the oxygen consumption rate declines.

iii) Design Criteria

Due to inherent physical and chemical variability, wood waste cover design is currently on a trial and error bases. Estimates of optimal cover depth, wood particle size (chips vs. sawdust), method of application (one-time vs. periodic) are conjectural at best, since they depend on number of variables discussed above. To date, there is no long term database for cover design.

iv) Undesirable Leachates

Wood waste covers are likely to result in dissolved organic material in the pore water. Organic acids, principally acetic, propionic and butyric acids, are well known terminal products of anaerobic metabolism. These acids readily complex with transition metal ions thereby increasing their mobility in the pore water.

Phenolics and polycyclic aromatic compounds in the pore water result from the biodegradation of lignins. Although lignin is more stable than cellulose, some aerobic degradation by fungi is likely to occur and affect water pore water quality. The significance of leachates, however, needs to be further evaluated.

6.3.2 Paper Mill Sludges

As previously discussed little data are available on either the moisture retention or oxygen consuming ability of paper mill sludges. Based upon the potential economic application, these materials warrant serious consideration as an alternative dry barrier.

6.4 REACTION INHIBITING BARRIERS

6.4.1 Limestone

Many tailings contain substantial quantities of acid producing and acid consuming materials. Tailings which contain excess buffering minerals (especially carbonate) have been shown in many cases to oxidize but not produce acidic drainage. Acid production is curtailed through precipitation reactions and free acid buffering. The economic viability of incorporating limestone into the near surface tailings is a function of many factors of which limestone addition rate is perhaps most critical. There are four major concerns regarding the use of limestone in dry barriers:

1) depth of the oxidation zone;
2) incorporation of method for limestone addition;
3) geochemistry of the tailings; and
4) rate of addition.

For a conventional tailings stack with existing perimeter dykes and low water tables, limestone addition is not a suitable long term method. Typically water tables within the shell are near the base of the dam and of all the reactive material present in the basin, perhaps 80% or more, is located within the shell. Limestone could be added to the near surface zone but no methodology exists to place material at depth.

For a standard valley dam repository water tables are typically near surface; therefore, limestone is only required in the near surface tailings. Addition can be accomplished at the mill, however, segregation of limestone presents a serious problem. Density and grain size distribution for crushed limestone can result in major segregation problems. To be applicable it is likely that tailings would have to be thickened to minimize segregation of the tailings/limestone particles.

Geochemically limestone may not be adequate to precipitate all metals (e.g. nickel). Therefore, although no free acidity is produced, substantial acidity in the form of dissolved metals can occur. This would only be a concern at some sites.

What constitutes an adequate level of addition is unknown. Rates of oxidation may be low as compared with the rate of limestone dissolution which could create a limestone depletion prior to the completion of sulphide oxidation. This is not likely a major concern. Excess reagent is likely required at perhaps 150 to 200% of stoichiometric demand. Depending upon site specific tailings characteristics this may or may not prove to be an economically attractive barrier.

Overall we conclude that limestone addition:

- may produce an economically effective dry barrier;
- little to no field data are available to record performance, however, extensive data are available on sulphidic tailings with naturally occurring levels of limestone;
- research into limestone incorporation is of secondary importance. The relative costs and benefits are simple to predict. Site specific laboratory testing is warranted for each potential application; and
- should always be considered as an alternative to conventional clay barriers.

The one potential disadvantage of a limestone barrier is that it does not prevent oxidation, but rather controls the rate of oxidation. Therefore, acid production will continue and reaction products ($CaSO_4$, $MgSO_4$) will be at elevated levels in drainage.

6.5 RESEARCH NEEDS

6.5.1 General

To date, a number of materials, both natural and synthetic, have been identified as potential covers for reactive (sulphidic) tailings. The research effort, particularly with non-conventional material, often lacked a systematic approach. Nevertheless, the intrinsic parameters for application (diffusion coefficient, permeability, oxygen consumption rate, reaction inhibition) have been studied quantitatively and at least the ranges of the parameter estimates are known. However, information is lacking on the long term (more than a few years) stability and the comparative economics of most covers. Therefore, continued monitoring of existing covers in the field is required to establish both the life span and the relative cost. It should be noted, that the economics depend, in part, on the maintenance cost and/or re-application of a particular cover.

Further research is needed to establish the cost-effective benefits of composite covers. For example, a thin clay zone below a soil cover may result in higher moisture retention, hence, a better barrier to oxygen transport to underlying tailings. Similarly, further research is required to evaluate the efficacy of organic (wood waste, paper mill sludge) material in combination with soils, either in layered, or mixed arrangement. The combination of synthetic geomembranes with soil covers provides a potentially viable alternative, however, the longer term stability of the synthetic membrane requires clarification.

Based upon the work completed as a component of this review, it is believed that there is a relatively sound knowledge regarding what might be termed the conventional dry barriers using natural soils or synthetic liners. Some clarification of design parameters is required and this should evolve from research which is currently funded by MEND.

Future research, we believe, must be directed at finding a more cost effective dry barrier. Synthetic liners are excellent candidates for dry barriers as they are virtually impervious. There are potential drawbacks of which long term performance is perhaps most significant. However, synthetic liners are likely to perform for at least 50 to 100 years. If a 75 year life was selected and the cost for application was $\$35/m^2$, the net cost to replace the liner in 75 years has only a net present value of $\$3.80/m^2$ at a 3% discount rate. Therefore, future costs are not significant. This order of cost represents the upset limit for dry barriers and any alternative material must be more cost effective to be a serious candidate as a dry barrier.

With the above discussion in mind the following are priorities for research.

6.5.2 High Priority Items

1) Completion of existing work programs. Engineered dry covers for tailings (Noranda) MEND project 2.21.2. This work represents the most comprehensive and useful information on the design of dry barriers using natural soils. These natural soil barriers have broad application and may be cost effective. This work is near completion and should be thoroughly reviewed as appropriate additional expenditures may well be justified.

2) Expansion of program research into the use of mine tailings as dry barriers. The field test results at the Falconbridge New Tailings showed that "non-engineered" slimes covers were effective at reducing rates by a factor of more than 100 times (David and Nicholson 1993; Elberling et al. 1993). The use of sulphide reduced tailings or tailings slimes offers major potential for application as dry barriers. All work completed to date shows incredible promise and this area would appear to have been neglected. Several MEND companies have projects in place such as MEND Project 2.22.2 (Ecole Polytechnique) which could be expanded to explore this area more fully.

3) Program research on wood waste should be continued. Of all the oxygen consuming wastes, only wood wastes are available in substantial quantities. The level of knowledge regarding many issues is still infantile and needs to be developed. The East Sullivan mine demonstration, although not engineered, is an excellent project which offers the potential to provide the data required to confirm the applicability of wood waste dry barriers.

4) Development of alternative oxygen barriers using processed natural soils. There were three candidate materials identified as potentially attractive materials for incorporation into natural soils to improve their moisture retention capability and/or weathering properties. These include commercial clays (bentonite), modified clays (University of Alberta) and ashes. The relative performance and costs of these materials as compared with natural soil barriers is not known. Furthermore, many mining areas have insufficient suitable natural soils for direct use as dry barriers and as such processed natural materials may have broad application. The initial study should involve laboratory screening of the above materials followed by field demonstration of one or more of the most promising additives for improving performance of natural soils.

5) Paper sludges are a waste available in relatively high quantities in mining districts. Little is known about the physical properties of these materials. Screening analysis with regard to moisture retention, permeability, organic content, durability etc. is proposed. Based upon this preliminary review, additional study may be warranted.

6.5.3 Lower Priority Items

A number of dry barrier materials have been proposed. Based upon this review, a number of these materials have potential economic application. The prime concern at this time is that the applications are not broad based, quantities are small and/or adequate data are not available to determine whether there is a high potential for success. These materials are listed below.

1) Alternative Oxygen Consuming Barriers

- peat is a poor oxygen consumer as compared with wood waste. However, peat is more uniform and may have application as a combined oxygen consuming/moisture retention barrier;
- sewage sludge, compost, N-Viro Soil and manure are all low volume materials which can act as oxygen consuming barriers. Applications will be limited but all material show some potential. These would be very low priorities for research but should be considered if adequate funding was available.

2) Moisture Retaining Barriers

- a screening analysis of several materials including waxes and ashes may be warranted. Applications will be limited, however, given the potential cost advantages, some level of funding should be considered.

3) Alternative Applications

- the PHITO layer proposed by Fyson and Kalin (1993) offers some potential and is worthy of some level of funding to confirm potential applicability.

6.5.4 Other Dry Barriers

The two other dry barriers which we believe will perform adequately and for which no further research is likely required are synthetic liners and limestone treated tailings. These are credible options for many sites and should not be overlooked.

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APPENDIX A

TASK 2 REPORT
LITERATURE REVIEW

DRY COVERS FOR SULPHIDE TAILINGS - REVIEW OF CONCEPTS AND CURRENT PRACTICE

A Report to SENES Consultants Limited

by: Ronald V. Nicholson
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APPENDIX A: TASK 2 REPORT LITERATURE REVIEW
DRY COVERS FOR SULPHIDE TAILINGS - REVIEW OF CONCEPTS AND CURRENT PRACTICE

A.1 INTRODUCTION

Numerous field studies have shown that sulphide mineral oxidation in mine tailings occurs in the shallow subsurface (Boorman and Watson 1976; Dubrovsky et al. 1984, 1985; Blowes et al. 1988, 1991, 1992; Elberling et al. 1993c). These studies have shown that oxygen concentrations in the partially gas-filled pore spaces decrease rapidly below the tailings surface and that detectable oxygen concentrations extend to greater depths in coarse-grained tailings than in similar fine-grained zones. Typical zones of oxidation are on the order of 0.3-3 m from the tailings surface. These field results are supported by modelling studies that confirm the link between oxidation rates and rate of diffusion of oxygen through the gas filled pores (Scharer et al. 1993; Elberling et al. 1993a). Diffusion rates are controlled by the proportion of gas and water in the pore spaces in the tailings. Oxygen moves readily by molecular diffusion through geologic materials that have high gas-filled porosity. In contrast, materials at or near water saturation exhibit reduced oxygen fluxes allowing only low rates of oxidation in the tailings because of the reduced diffusion coefficient for oxygen in water relative to that in air. This behaviour forms the basis for the concept of applying diffusion barriers at the surface of tailings to reduce acid generation (Nicholson et al. 1989). The application of such covers to reduce oxidation rates without placing the tailings underwater is generally referred to as "dry covers". This review will focus on the concepts involved in using covers as oxygen barriers and on the applications of such covers and their effectiveness in reducing oxidation rates and acid generation.

The concepts of covers as oxygen barriers is not new. Brown (1970) conducted experiments to determine the effectiveness of certain covers on pyritic coal spoils. It is evident that the physics of oxygen diffusion in covers was not well understood at this time. The following review considers those reports of covers and cover concepts that have been suggested and tested for application to sulphide mineral tailings to reduce rates of acid generation. Covers that reduce oxygen migration and those that act as oxygen consumption barriers are emphasized here. The results and implications of laboratory and field tests are summarized in an attempt to provide an evaluation of the various cover concepts reviewed.

A.2 BASIC CONCEPTS FOR COVERS

It is generally accepted that the most significant pathway for oxygen migration into tailings is by diffusion from the atmosphere through the partially gas-filled pores (Nicholson et al. 1989, 1991). Because this diffusion generally takes place from the surface downwards vertically, it can usually be described as a one-dimensional process where the flux of oxygen is governed by Fick's Law. The flux is given by:

$$F = - D_e \frac{\partial C}{\partial z} \qquad \text{(A.1)}$$

in which F is the diffusive flux of oxygen in the gas phase [$ML^{-2}T^{-1}$], D_e is the effective diffusion coefficient [L^2T^{-1}], C is the concentration of oxygen in the gas phase [ML^{-3}], and z is the depth [L]. It has been shown by others that D_e is controlled by the moisture content of the material and that values of D_e can be estimated readily when the moisture content or degree of saturation is known (Reardon, Moddle 1985; Nicholson et al. 1991; Elberling et al. 1993c). Using data obtained from tailings that can also be generalized for other porous media such as sands and silts, a useful expression to determine D_e from the degree of saturation is as follows (Elberling et al. 1993b):

$$D_e = D_a \tau (1 - S)^{\alpha} + \frac{D_w \tau S}{H} \qquad \text{(A.2)}$$

where D_a is the diffusion coefficient for oxygen in air, D_w is the diffusion coefficient for oxygen in water, H is the modified Henry's constant, S is the degree of saturation (volume of water/volume of pores), and α and τ are fitting parameters. A plot of the data and the equation shown above is given in Figure 1.

The relationship between the effective diffusion coefficient (D_e) and the degree of saturation (S) indicates that the diffusion coefficient can vary over five orders of magnitude. However, it is also evident that much of the decrease in D_e with increasing S values occurs at saturation values above 0.6. This means that effective covers or those that significantly decrease the diffusion of oxygen must remain nearly saturated to provide orders of magnitude decrease in the diffusion of oxygen into the tailings. Maintaining high degrees of saturation in soils and other prospective cover materials depends on the hydraulic properties of the material and the hydrology at the site. A brief review of hydraulic principles is presented below.

The basic hydraulic principles and physics of moisture retention in porous materials is presented by Nicholson et al. (1991). The highlights are presented here to provide a brief summary. In general, moisture retention is enhanced for fine-grained materials and decreases considerably as the grain size increases. In addition, the suction or negative pressure imposed on materials by gravitational forces above the water table also contribute to drainage of the material. In general terms, the greater degree of suction or greater elevation above the water table decreases the moisture retention and increases the proportion of gas-filled spaces that enhance oxygen diffusion. Figure 2 shows the response of moisture content (volume of water per total unit volume) to the decrease in pressure head (or increase in suction) for a fine-grained and a coarse-grained material. This diagram shows that the fine-grained material remains saturated under greater values of suction applied than does the coarser-grained material and that the fine silt looses moisture less rapidly than the sandy material as the suction pressure increases in the negative direction.

Given ideal homogeneous conditions in tailings, it is evident that even fine silty materials will not remain saturated near the tailings surface if the water table is deeper than a few metres below ground surface. However, as demonstrated by Nicholson et al. (1991), placement of a cover as a fine layer over the coarser-grained material provides a "capillary barrier" that will help to maintain high moisture contents in the fine-grained cover as shown in Figure 3. It is conceivable under these conditions that a cover could maintain near saturated conditions indefinitely if it is protected from evapotranspiration by a coarser cover layer.

High moisture retention in covers is the basis for diffusion barriers on sulphide mineral mine wastes. An alternate concept relates to covers as oxygen consumers that will block the movement of oxygen from the atmosphere into the tailings. An example of an oxygen consumer is wood waste as suggested by Reardon and Poscente (1984), who evaluated the potential use of wood chips and sawdust as a close-out alternative for pyritic tailings. If the uptake of oxygen is relatively rapid within the selected cover material, then isolation from atmospheric oxygen is possible for at least some finite period. Even though it is recognized that any oxygen consumers or interceptor will be consumed by the oxidation process, these types of barriers proposed as covers will be reviewed here.

A.3 OXYGEN MIGRATION BARRIERS

A number of laboratory studies investigating the effectiveness of soil-type covers on pyritic or sulphide wastes have been reported. One of the earliest reports is by Brown (1970) in which simple soil covers up to 40 cm thick were applied to coal wastes and oxygen uptake rates were measured. This study indicated that rates of oxidation decreased by only percentage values. However, evaluation of the materials used and the conditions applied suggest that the covers did not maintain high moisture contents and that the physics of diffusion and moisture content control were not well understood at the time of these experiments. In more recent studies, Nicholson et al. (1991) and Sydor (1992) showed experimentally that fine-grained materials layered above coarser-grained materials would remain nearly saturated and therefore could represent excellent diffusion barriers to oxygen above pyritic wastes. These results were confirmed by Yanful (1991). The effectiveness of clay covers in the laboratory was demonstrated by Yanful and Payant (1993). The results of that study indicated that acid release rates were on the order of three orders of magnitude less for covered tailings than for the uncovered materials. That study used dense clay material as a cover as opposed to the moist silt layers that were tested in previous work. The results of Sydor (1992) show that evaporation of water from a surface cover can significantly reduce the moisture content and hence reduce the effectiveness as an oxygen barrier. The modelling results in that study indicate that an evaporation barrier is required to reduce the loss of moisture from the cover surface. The covers behaved well in the laboratory and the resulting retention of high moisture contents at nearly saturated conditions suggested that oxygen flux through the cover could be reduced by a factor of 1000 or more. The properties of tailings for use as cover materials have also been studied in the laboratory (Aubertin et al. 1993a, b). The tailings materials were investigated as part of an ongoing laboratory study using column experiments and a proposed field study. Results of the diffusion related properties or evaluation of rate reduction in column studies are not yet available.

Some studies have taken cover testing beyond the laboratory into the field. Unfortunately, very few reports are available on this subject. However, the limited results generally suggest that covers can reduce oxidation of sulphide minerals significantly. A report by Yanful et al. (1993) on a field evaluation of composite covers at Waite Amulet indicates that oxygen fluxes through covers may be reduced by as much as 90-99% over non-covered sites. This means that the fluxes are reduced by a factor of 100 for certain cover scenarios. Some difficulties were encountered in assessing the oxidation rates by observed water chemistry. These difficulties relate to the existing water quality within the tailings when the study was initiated. Oxidation products already existed because of the ongoing reactions in these tailings and interpretation of water chemistry in terms of oxidation rates is made difficult. However, estimates of oxygen fluxes through the covers implied significant decreases in rates.

In general, the use of existing tailings to test covers is complicated by the water quality history at the site. It is, therefore, desirable in any field testing to attempt to use fresh tailings materials so that the oxidation products that occur as a result of oxidation below the cover can be easily evaluated. A major field test was initiated by Steffan Robertson Kirsten Ltd. (SRK) at the Faro mine site in the Yukon in 1986 (SRK Report 60644, 1992). This test consisted of six test plots that were constructed specifically to test cover designs (Figure 4). Data were collected semi-annually over a five year period. The results were critically reviewed by Nicholson and Scharer (1993). Some differences in rates were evident but the results were generally inconclusive. Although the original design of the test plots included control of the water table at the bottom of each pit, infrequent maintenance resulted in the occurrence of near surface water table conditions and hence all plots showed slow oxidation rates over the five year period. In addition, the data collected could not be used to differentiate oxidation rates specifically because of the large time lags involved for water moving from the surface of the test plots to the drain where water quality was tested. The presence of sulphate concentrations in the tailings when they were placed in the test pits also complicated the interpretation of water quality. The highest SO_4^{2-} concentrations in the top 50 cm of the tailings were replotted to compare rates in each pit (Figure 5). These showed slight differences over time with the control exhibiting the highest values. Further analysis by Nicholson and Scharer (1993) suggested that the rates were increasing in some of the test plots and that steady state conditions had not yet been achieved (Figure 6). Part of the difficulty at this site was the temperature that is quite low over most of the year. The cold weather conditions may have affected the onset of oxidation rates that are considered characteristic of uncovered, well-drained tailings. Further data collection is warranted at the test site with specific maintenance to improve data quality.

A field evaluation of a pyrrhotite tailings at Falconbridge, Ontario by David and Nicholson (1993), David (1993), and Elberling et al. (1993c) included comparisons between uncovered tailings and areas that were covered by thin layers of low sulphur slimes. Although this site was not originally designed to have a well-engineered slimes cover, the placement of the slimes in 1987 allowed testing of the effectiveness of these fine layers after five years of oxidation. The study measured oxidation rates using water chemistry near the surface and by measuring oxygen profiles and calculating oxygen fluxes through the shallow subsurface. Three scenarios were compared. The first was an uncovered tailings in a beach area that was well-drained over the top 1 m of tailings. The second was an area covered partially by low sulphur slimes with varying thickness of these layers. The third was a ponded area on site with about 0.5-2.0 m of overlying water. The results are summarized in Table 1 which shows that the slimes cover represented a decrease in oxidation rates by a factor of 200 compared to the uncovered site. Oxidation rates in the ponded area were a factor of 2000 less than those in the uncovered tailings. This means that the slimes cover may have been only a factor of 10 less effective than underwater disposal. Although this study did not evaluate a well-engineered cover, the results suggest that better placement control and erosion control would provide even more effective reduction in oxidation rates compared to uncovered tailings.

One of the most challenging aspects of cover evaluation will be the measurement of the reduction in acid generation rates below such covers in the field. The studies that have been reported suggest that covers do reduce oxygen consumption rates and that reduction of the generation of oxidation products is also achieved. However, the chemistry of acid generation is complex and evaluating the in situ field rates is not trivial. For example, a composite cover used at Rum Jungle reduced oxygen levels in the underlying waste rock (Harries, Ritchie 1984, 1988) but concentrations of pollutants did not decrease in drainage. It was estimated that it will require 10-15 years to flush existing oxidation products from the pile. In addition, if drainage quality is being measured at the edge of a tailings or in the downstream environment, long periods of time may be required before the oxidation products that are produced near the tailings surface reach the far field drainage areas. Travel times can be as high as 100 years or more depending on the hydrogeology of the site. Common travel times in the tens of years have been predicted at many tailings impoundments. This is one reason why a full scale test of four cover options in Sweden (Soddermark and Lundgren 1988; Lundgren 1992) did not definitively demonstrate a reduction in acid generation even though reduction in oxygen levels suggested rate reductions by a factor of 100.

Developing an appropriate testing strategy is very important in field studies of cover evaluation. Elberling et al. (1993b, c) have proposed methods to evaluate instantaneous oxidation rates that are appropriate to evaluate covers.

It is important in the evaluation of any cover design that the basic principles that cause reduction in oxygen flux and eventually reduction in acid generation rates are well understood. The principle may be based on high moisture contents to decrease diffusion of oxygen in the gas phase, or based on oxygen consumption so that the amount of oxygen moving into the tailings is restricted. If these principles are not considered, then materials may be tested that are inappropriate for cover design. The study by Hoving and Hood (1984) on the effects of different thicknesses of limestone layers and thicknesses of soil layers over pyritic materials is an example of such a study. Although this column study was performed in the laboratory, the results showed clearly what one might expect based on theory. Limestone was used as a cover layer and effectively had no impact on the rates of acid generation in the underlying pyritic material. This could have been predicted simply by assessing the buffer capacity that limestone has as it dissolves into the water infiltrating into the pyritic wastes and knowing the diffusion coefficient for this layer at the surface. The results of soil covers used on the pyritic wastes indicated a five-fold decrease in rates compared to uncovered wastes. No attempt, however, was made to maintain high moisture content in the soil and, overall, the concept of oxygen diffusion barriers was poorly understood at the time.

Another example of inappropriate cover evaluation is reported by Herbert (1992). This study presented numerical simulations results for flow and moisture characteristics of a cover designed for tailings. The results showed that infiltration would be significantly reduced and that cracking of the clay till was not likely. It was therefore concluded that the proposed design was appropriate. No evaluation of oxygen diffusion was performed, however, and therefore no evaluation of rate reduction could be made.

Oxygen Consumption Barriers

The most studied materials under this category are wood chips, wood waste, and peat used as covers over acid generating wastes. Some of the earlier studies on wood waste as an oxygen consumer and potential tailings cover were completed by Reardon and Moddle (1984) and Reardon and Poscente (1984). This work involved both laboratory and field measurements. Reardon and Moddle (1984) investigated the use of peat as an oxygen interceptor. The results of that study showed that peat used as a surface layer on pyritic tailings did not result in appreciative decrease in oxidation rates. Even when the peat was covered by a sand layer, the concentrations of oxidation products did not decrease significantly compared to uncovered columns (Figure 7). Some of these experiments were conducted over a period of one year or more and so the results represent a significant amount of data collection. However, it should be noted that the experiments did not consider the degree of moisture content or the oxygen concentration levels into the peat towards the tailings surface. The experiments were conducted to simulate six years of infiltration over a 100 day period. This means that excess water was being added to the columns and could have caused near-saturated conditions to exist through the tailings. Although differences among the columns were examined, it is possible that the overly wet conditions prevented the uncovered columns from oxidizing as they would under well-drained conditions representative of the field. So although the results indicate very little difference in the concentrations of oxidation products released from each of the columns, the test results may not have been representative of peat covers compared to well-drained tailings. The results are, therefore, somewhat questionable in comparing peat layers and composite sand over peat layers compared to no cover.

The study of sawmill wastes by Reardon and Poscente (1984) investigated the rate of oxygen consumption within a wood waste pile and oxygen diffusion through the waste itself. The results indicated that oxygen was consumed rapidly in fine wood waste but may not have been very effective at removing oxygen in very coarse materials. The pore gas concentration of oxygen in the fine wood waste decreased from atmospheric values to near zero values in the top 60 cm of the waste pile (Figure 8). Calculations showed that the wood material was being consumed at a rapid rate due to the oxidation process. It was estimated that the rate of degradation of this fine-grained waste was on the order of about 10 cm of waste per year caused by the high diffusion coefficients within the wood material itself. This led the authors to conclude that wood waste would be effective only for relatively short periods, perhaps tens of years, and to be an effective oxygen barrier would require an overlying material to reduce the flux of oxygen into the subsurface. It was also noted that about 2% of the degraded waste mass was transferred into dissolved organic carbon concentrations in the water that infiltrated to depth. The implication of this are uncertain, however, with high concentrations of DOC, mobility of some metals may be increased.

The preliminary results of a study of wood bark covers by Yanful and Payant (1992) in a bench-scale experiment suggested that the wood may have accelerated the rate of acid production by about 60% in the laboratory and 500% outdoors. The authors concluded that the organic material may have enhanced CO_2 production leading to increased activity of acidophilic bacteria. These results suggest that a 15 cm layer of wood bark does not act as an oxygen barrier and appears unsuitable as a potential cover material on sulphide wastes.

A field study of wood chips as a cover on mine tailings was reported by Germain et al. (1992). This field study at the East Sullivan mine in Québec focused on the gas concentrations in the wood wastes above the tailings. The results agree with those of Reardon and Poscente (1984) and suggest that oxygen is consumed rapidly in the subsurface with oxygen concentrations approaching near zero values at a depth of about 60 cm from the wood waste surface. The authors concluded that the wood waste layer prevents oxygen from entering the tailings and therefore represent an effective oxygen barrier on the tailings surface. Unfortunately, there is no direct evidence to show a reduction in the acid generation rates below the wood cover. This is not necessarily a shortcoming of that particular study, however, as noted previously, the evaluation of oxidation rates by examining water chemistry from the tailings is not trivial. Unfortunately, no estimates in the reduction of oxidation rates were given.

Other Applications

The work by Reardon and Moddle (1984) on peat layers as covers for tailings led to an investigation of the use of organic material within the tailings to enhance sulphate reduction processes. The study by Blowes et al. (1988) presented the theory of sulphate reduction when organic material is incorporated into reactive tailings. Although this process is widely known, it has not yet been successfully tested in the field. The concept put forward by Blowes et al. (1988) was to incorporate organic material below the water table in the tailings. This does not decrease the rate of acid generation or release of oxidation products above the water table, but provides an environment, at depth, where sulphate reduction can occur and metals can precipitate as metal sulphides as the pore water migrates through the organic-rich zone in the tailings. This provides a passive treatment method and the concept appears reasonable but may require further studies to develop an appropriate engineering design. It is doubtful that this concept could be applied in an effective manner to existing tailings unless further tailings deposition is warranted.

Wong et al. (1991) presented a concept of using shotcrete to control acid mine drainage in waste rock piles. The shotcrete was applied as a concrete mixture on the surface as would be used in mining operations to stabilize walls, etc. A test site was established at Westmin Resources, Myra Falls operation. Although the concept appears reasonable and testing is now in progress, no results on evaluation of the method to reduce acid generation rates have been presented.

Synthetic covers, including asphaltic, spray-on sealing agents, waxes, and polymers have been proposed for use as tailings covers. No reports on laboratory testings are available, however, and field testing is not warranted without an indication that bench-scale tests yield positive results.

Recent Cover Projects

There are four major projects where covers have been applied to reactive wastes in recent times. These are at Equity Silver, B.C.; Mount Washington, B.C.; Wheaton, Quebec and Heath Steele, N.B.

The Equity Silver project employed a two layer cover. The first layer was a compacted till with a permeability of 1 x 10^{-8} m/s. The second layer was an uncompacted zone of till which provides a surface for infiltration, erosion protection, frost protection and evaporation control of the till. The cover application has only been recently completed but early indications are the cover is performing well. There is extensive instrumentation (gas probes, thermometers, etc.) and detailed investigations are ongoing. The till layer has retained its high moisture content and should this continue, major reductions in ARD production are expected.

At Mount Washington a 1 m till cover was placed over the east dump. This till had a permeability of about 1 x 10^{-8} m/s. The cover has substantially reduced infiltration and has reduced oxygen flux. The relative effectiveness of the cover is unknown as it appears the dump was not a substantial source of acid drainage. The Mount Washington project has also used asphaltic membranes and concrete capping over waste materials. Monitoring data do not allow for an assessment effectiveness of these covers in reducing ARD production.

The Wheaton mine is located in the Eastern Townships (Quebec). The mine contained two small tailings areas covering about 7.5 ha. The basin was covered in 1993 with a 1.5 mm HDPE liner. The liner was installed over a sand cushion and contains 0.3 m of protective cover. Total installed costs were about $\$20/m^2$. It is understood that instrumentation was not installed to monitor the cover performance.

The Heath Steele project was initiated in 1991 with the covering of the pile. The engineered composite cover has included a layer of coarse drain material under a compacted till barrier. The pile is fully instrumented and data on the cover performance will be available in next 1 to 2 years.

A.4 CONCLUSIONS

The concept of oxygen barriers for use as covers on sulphide mine wastes is well developed. Our understanding of the problem allows us to model the systems to show the theoretical effectiveness of various types of covers proposed for use in the field. There has been a limited amount of laboratory testing to show that clay covers and silt (non-cohesive) covers can represent effective barriers to oxygen on acid generating tailings. Various studies on the effectiveness of peat and wood waste present encouraging results but are inconclusive as to the overall effect on acid generation rates in the underlying tailings or to the timeframe that the organic material will remain effective. The few field studies that have been reported on cover evaluation also provide encouraging results overall. Although a major test plot study was inconclusive, it may be possible to use that site in the future for further testing and to derive useful data. One major study of a highly engineered composite clay cover suggest that this is an effective means of decreasing acid generation rates in reactive tailings. One of the problems with such a cover is the large cost factor involved. A field study on a non-engineering slimes cover suggests that even under poorly designed conditions, thin slimes layers can reduce oxidation rates by a factor of about 200 or more compared to uncovered tailings.

One aspect of covers placed on existing tailings has not yet been fully investigated. Although it is generally considered that covers may be the only practical means of dealing with old or existing tailings, little consideration has gone into the effects of existing oxidation products within the tailings at the time when covers are applied. Preliminary modelling (Annable et al 1992) suggest that effluent quality from the tailings may not be significantly improved if covers are applied after a significant degree of oxidation has already occurred within the shallow tailings. This means that it may be necessary to apply covers to fresh tailings to receive the full benefit of oxygen barriers and hence older tailings may not exhibit the desired benefits after covering. Some preliminary results from underwater testing of old tailings provide similar conclusions (St. Arnaud 1993, pers. comm.).

The effect of the resident pore water concentrations after prolonged periods of oxidation may negate the effect of rehabilitation strategies such as flooding or covering when the effluent water quality is evaluated.

It is evident from this review that covers can be used to reduce acid generation rates in reactive tailings. This review has not revealed any startling or previously unknown information. It is also evident that there are few laboratory studies reporting results of testing of covers and even fewer field studies. The lack of field studies is evidently the result of high costs of such studies. It should also be evident that any new methods proposed should be examined first with available conceptual or mathematical models, some preliminary testing of characteristics of the materials, followed by bench scale testing of the concept if warranted. It is recommended that field testing only be applied when other evidence is encouraging and a reasonable probability of success is evident.

The results of this review also suggest that more specific field testing is required for simple inexpensive covers based on high moisture retention and low diffusion coefficients. Field testing may also be warranted for materials such as wood waste when included as composite covers if the economies of such covers is established.

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Table 1

SUMMARY OF OXIDATION RATES MEASURED IN THE FIELD FOR UNCOVERED, SLIMES COVERED, AND UNDERWATER PYRRHOTITE TAILINGS (from David, 1993)

	Oxygen Flux		Oxidation Product	
uncovered (4)[a]	23[b]	**(1)[c]**	2.4[b]	**(1)[c]**
slime cover (3)	0.09	**(0.004)**	0.02	**(0.008)**
underwater (2)	0.003	**(0.0001)**	0.004	**(0.002)**

Notes:

[a] number of measurements made in the field
[b] a values in moles - FeS $m^{-2}a^{-1}$
[c] values in brackets are ratios of flux values compared to the uncovered site

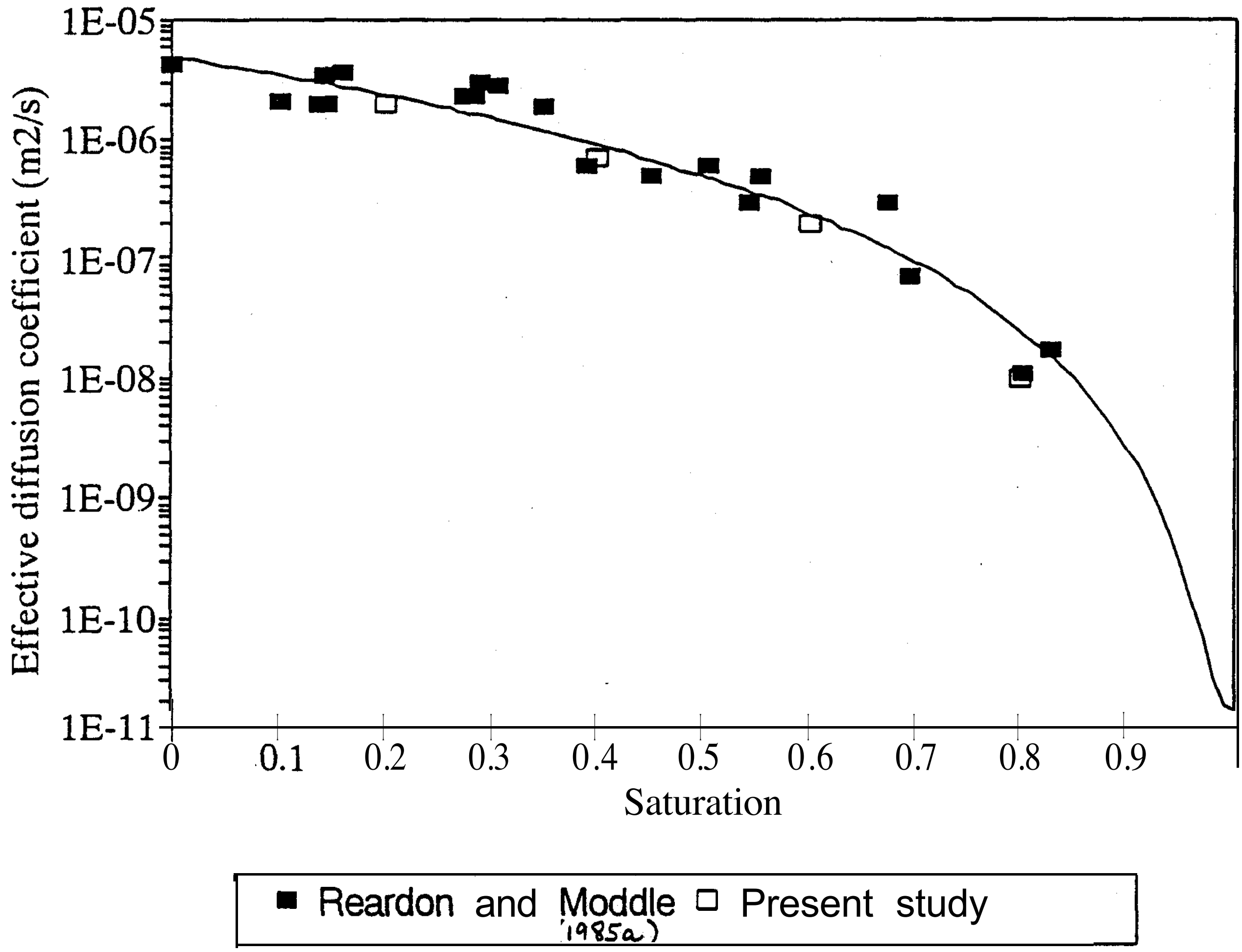

Figure 1: **Plot of effective diffusion coefficient (D_e) as a function of degree of saturation (S) (from Elberling et al., 1993c).**

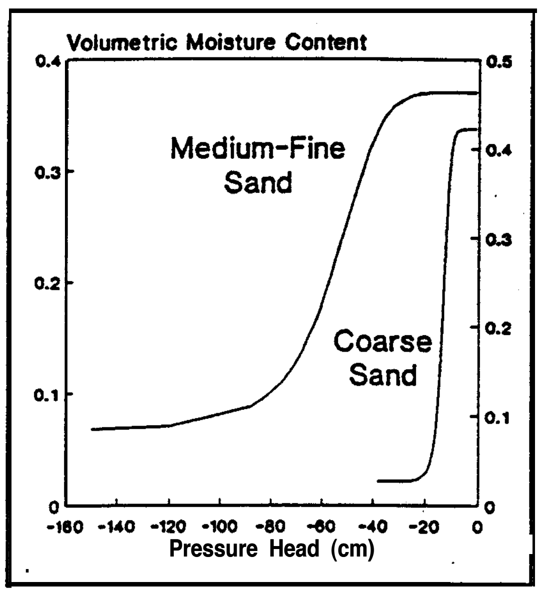

Figure 2: Drainage curves for a fine- and coarse-grained cover material. The pressure head (or suction) can be equated to height above the water table (from Nicholson et al., 1991).

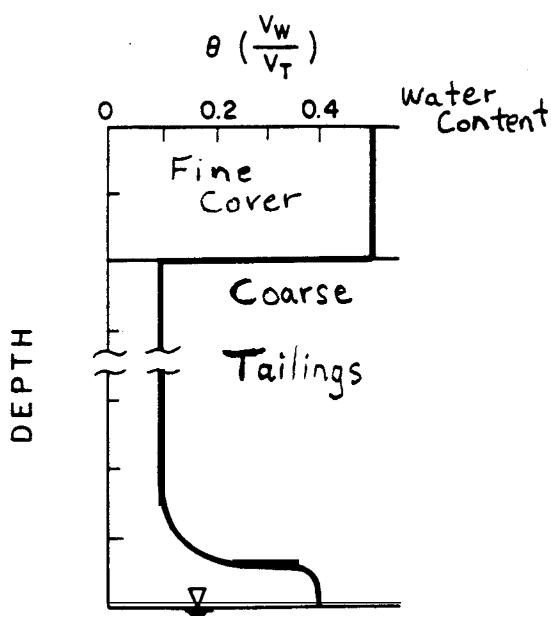

Figure 3: **Moisture content profiles in a fine cover over tailings (from Nicholson et al., 1991).**

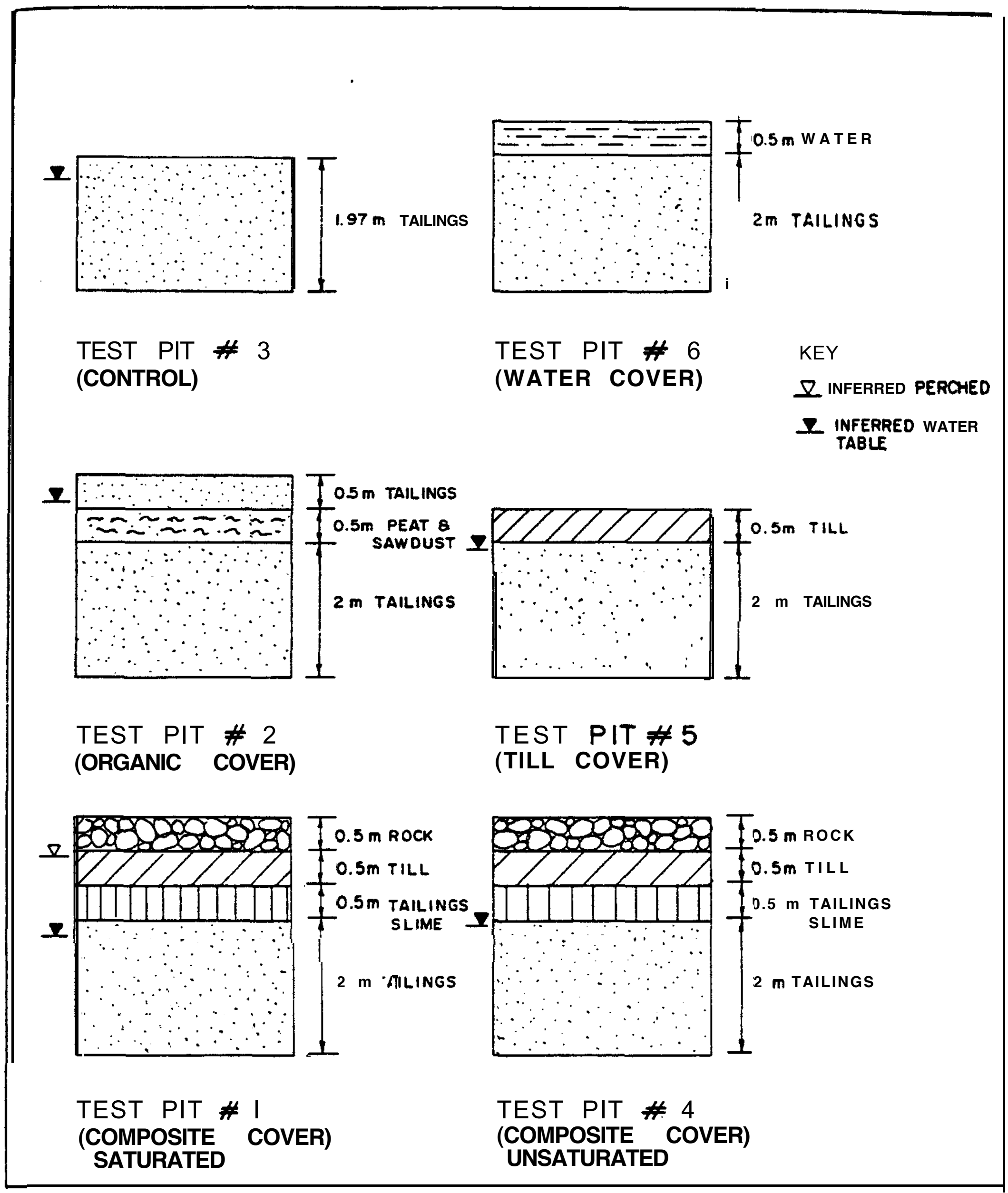

Figure 4: Cover designs tested by SRK in the test plot study at Faro, Yukon (from SRK, 1992).

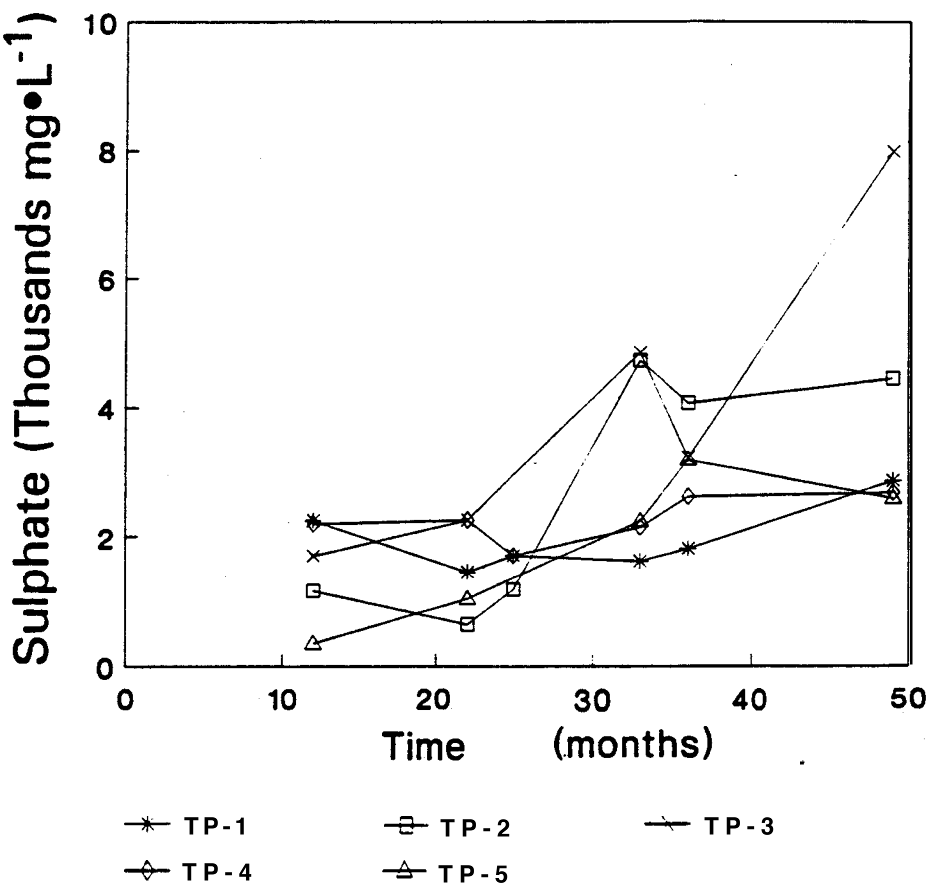

Figure 5: Highest sulphate concentrations in pore water in the top 50 cm of each test plot. The TP#'s refer to the cover scenarios in the previous figure (from Nicholson and Scharer, 1993).

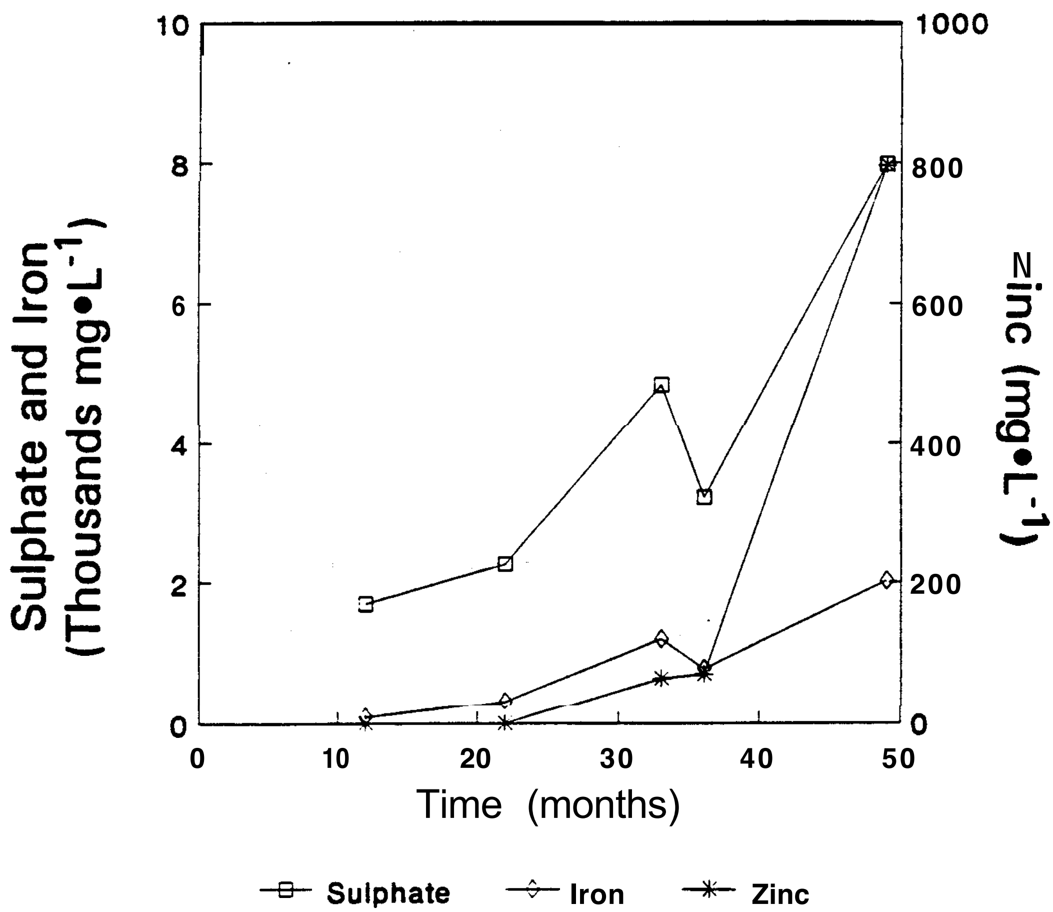

Figure 6: Plots of SO_4^{2-}, Fe, and Zn concentrations in pore water in the top 50 cm of the control plot over a four-year period (1988-91) (from Nicholson and Scharer, 1993).

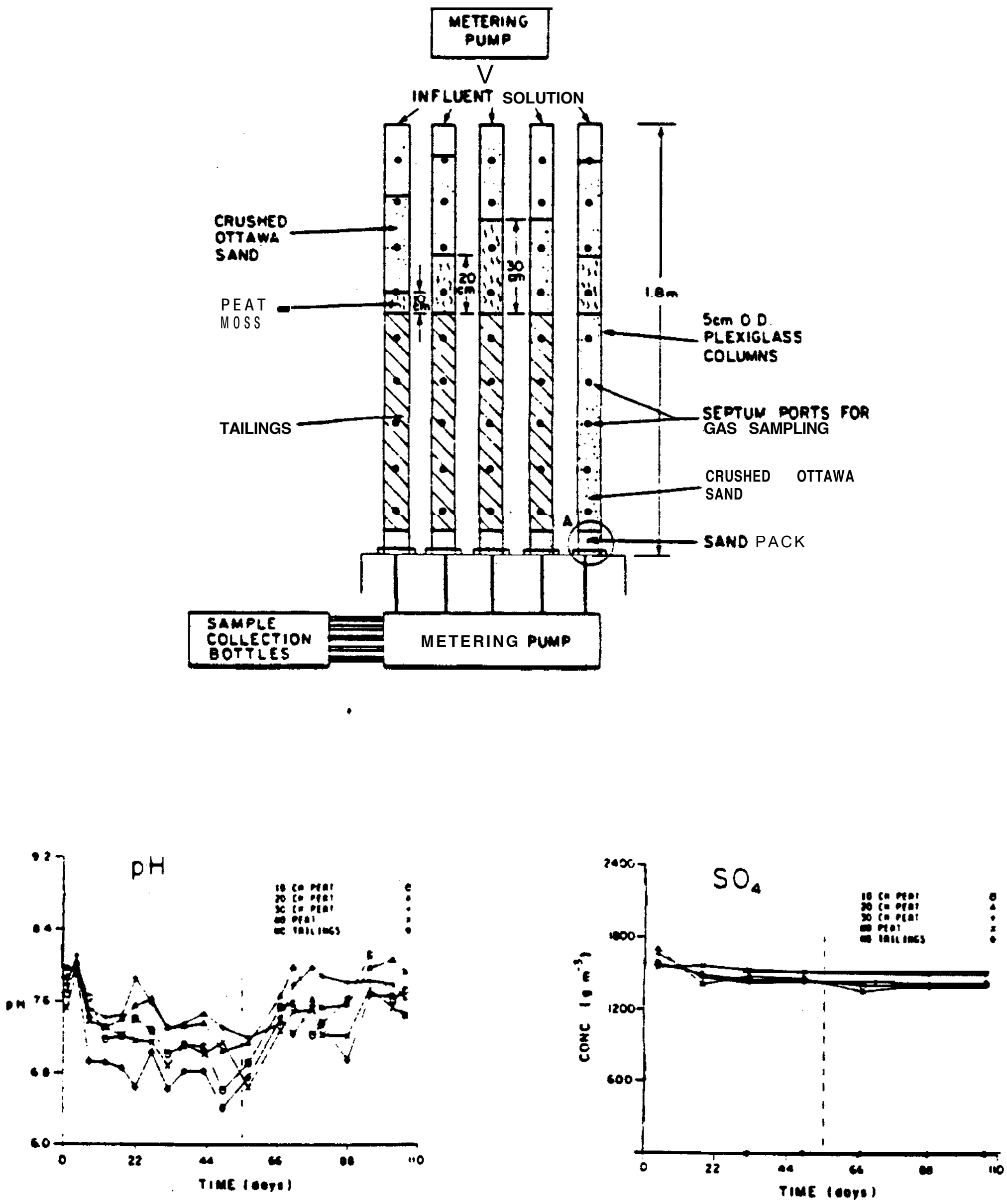

Figure 7: Column designs and effluent concentrations for peat cover testing on pyritic tailings **(from Reardon** and Moddle, 1985).

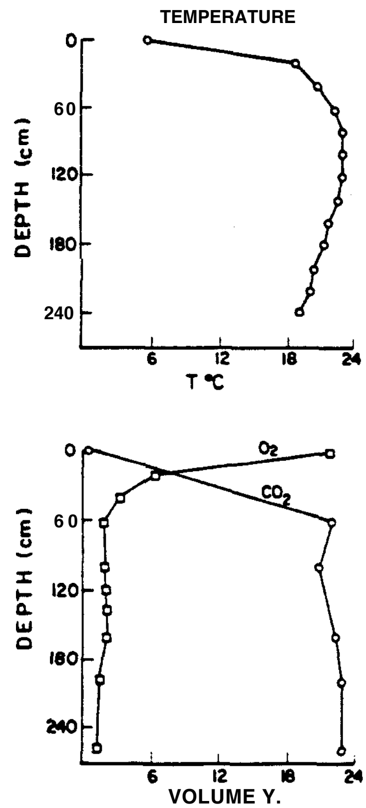

Figure 8: Oxygen profiles in fine wood waste (from Reardon and Poscente, 1984).

APPENDIX B

TASK 3 SUMMARY

WASTES PRODUCED BY THE FOREST PRODUCTS INDUSTRY

APPENDIX B: TASK 3 SUMMARY
WASTES PRODUCED BY THE FOREST PRODUCTS INDUSTRY

Wood wastes have been used to cover acid tailings areas. Their applicability is as an oxygen consuming layer. Based upon the review completed wood waste is likely to have a minimal role for use as a dry cover material.

There are two waste products which have excellent potential for use as cover materials. These are sludges from pulp operation ($\approx 1.1 \times 10^6$ t/yr) and boiler ash (0.7 to 1.0×10^6 t/yr). The overall quantity is substantial, however, the waste production is broadly distributed. Therefore, it is likely that these materials would only find a role as a component of a dry cover.

Paper sludges have excellent water retaining ability and when consolidated have only low permeabilities (1×10^{-10} m/s). The sludges are considered environmentally friendly and offer the added benefit of having a high organic content.

Boiler ashes are very alkaline (35% $CaCO_3$ equivalent) and are believed to have excellent water retaining capabilities. Little data are available respecting the physical properties of the ash.

Based upon the local availability to the mining industry and the potential applications for use in dry covers, both paper sludges and boiler ashes are excellent candidates for use in dry covers.

APPENDIX C

TASK 4 SUMMARY
POTENTIAL DRY COVER MATERIALS FROM MUNICIPAL AND INDUSTRIAL WASTE STREAMS

Prepared by

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February 1994

APPENDIX C: TASK 4 SUMMARY POTENTIAL DRY COVER MATERIALS FROM MUNICIPAL AND INDUSTRIAL WASTE STREAMS

1.0 INTRODUCTION

This document summarizes, in letter form, the findings of a search for alternate dry cover materials available from municipal or industrial solid waste streams (Task 4).

The search considered:

- Municipal Solid Wastes;
- Industrial/Commercial/Industrial Wastes;
- N-Viro Soil (essentially a product made by processing dewatered sewage sludge and alkaline materials);
- Shredder Fluff (produced as a by-product of automobile and appliance shredding);
- Crumb Rubber (produced by the grinding of used tires);
- Construction and Demolition Wastes;
- Phosphate Rock and Slag;
- Mining Wastes; and
- Coal Ash.

Waste materials such as pulp mill sludge, ash, wax, and salt are addressed in other task reports associated with this study.

The search identified seven waste materials which may provide basic requisite properties. Some of the materials were found to be unsuitable for use in dry covers. These unsuitable materials are also addressed in this document as their consideration raised a number of interesting issues which include but are not limited to:

Demand: the demand (and cost acquisition) for some waste materials has risen due as a result of recycling activity.

Processing Requirements: some waste materials require extensive and costly sorting and processing. This introduces quality control problems.

Limited Data: many waste materials are not technically well understood and extensive research is required to determine their properties and characteristics.

Undesirable Characteristics: some waste materials have undesirable characteristics (i.e. autocombustion, chemical contamination).

Approvals Process: the use of some waste materials could complicate the Closure Planning approvals process.

Aside from possibly identifying an alternate material with suitable properties and characteristics, there is a major cost incentive to evaluating the use of waste materials. The recycling of waste materials could be cost beneficial to both waste producers (who incur disposal charges) and owners of acid mine drainage (AMD) sites (who may get a low cost supply of cover materials).

2.0 BACKGROUND AND APPROACH

In broad terms, the concept of using a dry cover on acid generating tailings is based on reducing (to acceptable levels) the rates of oxidation of sulphide minerals within the tailings above the water saturated zone (if present). This can, in theory, be done using dry covers that have one or more of the following basic characteristics:

Low Permeability: The cover retains high levels of moisture sufficient to reduce oxygen flux. Clay and silt are examples of such material.

Oxygen Consumption: The cover has a high oxygen demand (chemical or biological) sufficient to reduce oxygen flux. Organic matter (decomposition) is an example of this type of material.

Reaction Inhibition: The cover has a pH buffering capability to neutralize acids generated by the oxidation of reactive tailings. Lime is an example of this type of material. Covers that contain compounds which inhibit the growth and metabolism of sulphate producing bacteria also fall under this classification.

A dry cover incorporating materials that naturally degrade and need to be replaced on a scheduled basis may be acceptable provided major maintenance is limited to low return frequencies of 100 years or so, or has an acceptable low cost.

These basic requirements for dry cover materials were used to identify potential materials. Specific information on the waste materials, when available, was obtained through literature review and discussions with researchers and other industry specialists.

Waste materials considered to be available in sufficient quantities for possible use as a dry cover (or a component of a cover) are addressed in the following section. It is expected that several waste materials will be rejected from further consideration for other reasons (i.e. environmental impact, costs).

As part of this search the estimated volume of each potential dry cover material produced each year, and available for use in dry covers, is compared to a reference volume of 2×10^6 m^3. The reference volume is an arbitrary figure. It was calculated based on the assumption that a typical tailings basin covers 100 ha at a depth of 10 m. If a 2.0 m thick dry cover is constructed over a combined area of 100 ha, the volume of dry material required to cover the area is 2×10^6 m^3. Therefore, if a waste material is produced at a level of 2×10^6 m^3/yr then it may be a candidate for a dry cover application. This is not to say other waste materials produced at lower volumes could not be used especially at locations whose progressive reclamation is possible.

The reference volume is useful as it provides an indication of the substantial volume of dry cover materials that could be required.

Another major criterion which must also be considered is cost. To put things into context a composite soil cover using about 2 m of material at $15/m^3 would cost $30/m^2 to apply. A composite cover with a synthetic liner added would have a similar cost of $25 to $35/m^2 depending on site conditions.

Therefore, to be competitive with generally known technologies, waste materials have to be delivered to the site at a cost in the range of $10 to $15/m^3 otherwise they would not be competitive.

Using 1993 Ontario Ministry of Transportation (MTO) hauling rates for gravel the following costs would be incurred for haulage:

$/t		$/m^3 at 1.8 t/m^3
10 km = 2.03	or	3.65
20 km = 3.34	or	6.01
50 km = 5.21	or	9.38
100 km = 8.10	or	14.58

Based upon road transport, it is unlikely that waste materials would be competitively shipped more than 50 to 100 km and still be cost competitive for use in a composite cover.

3.0 MUNICIPAL SOLID WASTE

For the purposes of this search, municipal solid waste includes residential and

Industrial/Commercial/Institutional (ICI) wastes.

It was found that reliable data on the quantity and characteristics of these wastes that take into consideration the effect of recycling/reuse programs is limited. The following data does, however, provide an overview of municipal solid waste production rates (by type of waste) and takes into account the influence of recycling.

Findings of a 1991 study (Proctor and Redfern, SENES 1991) into waste types and production rates for Metropolitan Toronto are summarized in Table C.1. In theory, the highest annual residential waste tonnage components, waste paper, and organics may be used as components in a dry cover due to high oxygen demand (through heterotrophic bacteria action). However, from an applied perspective these materials present serious problems (i.e. sorting and processing, quality control, contamination, combustibles).

3.1 WASTE PAPER

It is estimated that in 1991, the total quantity of waste paper generated in Canada was in the range of 5.7 to 7.5 x 10^6 tonnes (SENES 1993). A breakdown, by type, of the waste paper generated across Canada, is presented in Table C.2. It is estimated that even in the unlikely event that half the waste paper currently destined for landfills across Canada was diverted to tailings areas, it would take about a year to produce adequate quantities to cover a 100 ha basin with 2 m of materials. Given the broad based distribution of these materials it is highly improbable that adequate quantities of waste paper could be found in near vicinity to any tailings ponds.

Since 1982 the demand for some waste paper types such as fine paper, coated paper, and newsprint has increased, and has caused a corresponding rise in the prices for these waste paper types. Demand for these paper wastes may continue to increase due in part to additional de-inking facilities which are scheduled or proposed to come on-line in Canada. Therefore, future potential for use of waste paper will be even more limited.

3.2 COMPOST

Compost is produced by the biological decomposition of organic materials, in this case, clean organics such as food and yard wastes obtained from municipal waste streams.

In concept, organic wastes could be sorted and delivered to a composting facility near a major population centre. Compost would be produced under controlled conditions and once "mature", it could be transported to a tailings management area and placed as a dry cover. The mature compost, which resembles humus soil, may be suitable as a dry cover material primarily due its water retention capacity, and biological oxygen demand. Composting is not a necessary process and could be avoided if the sole purpose of the cover was for use as an oxygen consuming layer.

Due to the source of the organic materials, quality control may present operational difficulties. Other key concerns regarding the use of compost include:

- health impacts arising from the presence of pathogens, heavy metals, or other undesirable compounds in the compost;

- the rate of decomposition and unknown effective life of a dry cover using compost material; and

- expected high cost.

Composting of municipal organic wastes is not undertaken to a great extent in Canada today. At present, most raw materials which could be composted are landfilled. Extensive composting is, however, being promoted to reduce the amount of waste disposal in landfills. For instance, the Province of Ontario has legislated that 50 percent of municipal waste be diverted from landfills by the year 2000. This may make large quantities of compost available. It should be kept in mind that changing market forces could create other new demands for compost.

Table C.1

WASTE QUANTITIES PRODUCED IN METROPOLITAN TORONTO

Type of Waste Material	Residential Waste (Tonnes/Year)	ICI Waste (Tonnes/Year)
Paper	230,000[1]	291,000
Paperboard	--	267,000
Organics	194,000[2]	210,000
Plastic	49,000	131,000
Glass	33,000	38,000
Textile/Leather/Rubber	33,000	44,000
Diapers	24,000	--
Ferrous Metals	23,000	51,000
Non-Ferrous Metals	7,000	8,000
Wood	6,000	83,000
Inert Materials	9,000	44,000
Household Hazardous	3,000	--
Building Materials	--	12,000
Miscellaneous	23,000	7,000
	634,000	1,186,000

Notes:

(1) All quantities rounded to nearest thousand tonnes.

(2) Quantities exclude yard waste.

Table C.2

QUANTITIES OF WASTE PAPER

Type of Waste Paper	Range of Waste Paper Quantity Generated (Tonnes/Year)	Estimated Quantity of Waste Paper Recycled (Tonnes/Year)	Estimated Quantity of Waste Paper Landfilled (Tonnes/Year)
Fine Paper (Printing, Writing, Printouts)	819,000 - 1,390,000	61,340[1]	176,040[2]
Corrugated	1,474,100 - 1,759,600	257,340	187,920
Newsprint	1,037,200 - 1,321,700	401,790	137,360
Coated paper	409,400 - 625,300	260	39,800
Boxboard	928,100 - 1,166,900	--	77,800
Other (mixed)	1,010,100 - 1,308,700	525,980	5,172,730
TOTALS	5,677,900 - 7,572,200	1,246,710	5,791,650

Notes:

(1) Minimum recycled quantity.

(2) Takes into consideration the approximately 530,000 tonnes of waste paper incinerated each year.

Table C.3

CHARACTERISTICS OF CEMENT KILN DUST AND THE N-VIRO SOIL MADE FROM IT (Logan et al. 1989)

Parameter	CKD	N-Viro Soil*
pH (1:1 water)	13.0	11.1
Elements (% by wt.)		
N	<0.01	1.40
P	0.04	0.39
K	1.61	1.00
Ca	28.5	19.8
Mg	1.22	0.97
Na	0.60	0.20

* CKD was added to sludge at a 35% by weight of dry sludge solids.

GENERAL CHARACTERISTICS OF N-VIRO SOIL (Logan 1990)

Characteristic	Units	Value
CKD Content	% by wt.	35-75
Solids Content	% by wt.	50-75
Material > 2 mm	% by wt.	32
Mean Granule Size	mm	0.66
Bulk Density	g/cm^3	0.7-1.0
Volatile Solids	% by wt.	9.3
pH (1:1 water)		11-12
$CaCO_3$ Equivalent	% by wt.	50-80
Organic-C	% by wt.	12.2
Total Kjeldahl N (TKN)	% by wt.	1-1.5
NH_3-H	mg/kg	200
NO_3-N	mg/kg	50
P	% by wt.	0.39
K	% by wt.	1.0
Ca	% by wt.	20
Mg	% by wt.	1.0
Na	% by wt.	0.2

Table C.4

SUMMARY OF NATIONAL CONSTRUCTION AND DEMOLITION WASTE QUANTITY ESTIMATES - 1992

Description	**Generated**		**Diverted**		**Disposed**	
	(tonnes)	**% of Total**	**(tonnes)**	**% of Generated**	**(tonnes)**	**% of Generated**
Road & Bridge Related						
asphalt	3,875,623	34.7	2,808,559	72.5	1,067,064	27.5
concrete	2,348,138	21.0	1,702,074	72.5	646,066	27.5
Building Related						
wood*	1,630,968	14.6	88,162	5.4	1,542,807	94.6
rubble	1,700,987	15.2	0	0.0	1,700,987	100.0
paper	315,232	2.8	0	0.0	315,232	100.0
gypsum	355,118	3.2	117,042	33.0	238,076	67.0
building material	354,637	3.2	0	0.0	354,637	100.0
metal	330,174	3.0	0	0.0	330,174	100.0
other	275,828	2.5	0	0.0	275,828	100.0
Total	11,186,706	100.00	4,715,837	42.2	6,470,871	57.8

Note:

* Untreated, treated and painted wood.

Table C.7

COMPARISON OF POTENTIAL MATERIALS[1]

Potential Material	Relative Quantity Available	Anticipated Use of Material	Concerns						Costs	
			Effluent Quality	Material Transportation	Processing Costs	Long Term Effects	Auto Combustion	Radio-activity	Processing[1] $/t	Transpor-tation
Paper Waste	Declining due to recycling	Element of dry cover	✔	✔	✔	✔			low	high
Organic Compost	Small quantity	Element of dry cover	✔	✔	✔	✔			>100	high
Envirosoil	Small quantity	Element of dry cover	✔	✔	✔	✔			>50	high
Shredder Fluff	Small quantity	Element of dry cover	✔	✔	✔	✔	✔		0	(3)
Phosphate Rock	Large quantity	Element of dry cover	✔	✔	✔	✔		✔	10?	high
Crumb rubber	Small quantity	Element of dry cover	✔	✔	✔	✔	✔		?	high
Construction and Demolition (uncontaminated wood waste)	Large quantity	Element of dry cover	✔	✔	✔	✔	✔		?	high
Tailings	Large quantity	Element of dry cover	✔			✔			2	0
Bottom Ash, Fly Ash	Large quantity	Element of dry cover	✔	✔	✔	✔			?	high

Notes:

(1) Additional waste materials such as wax, pulp mill sludge, wood ash, and salt are addressed in other task reports.
(2) Many wastes are currently disposed at a cost. The disposal cost could offset transportation cost.
(3) This material would likely be delivered at no cost due to high disposal costs.

Table C.5

COMPOSITION OF COAL, BOTTOM ASH, AND ELECTROSTATIC PRECIPITOR ASH FOR SELECTED ELEMENTS (ppm)

Element	Coal[1]	Bottom Ash[1]	Fly Ash[1]
Al	21,800	110,000	129,000
Ca	1,350	8,390	6,970
Fe	29,300	223,000	176,000
Mg	1,030	6,870	6,600
K	4,780	18,600	24,100
Na	919	3,190	4,390
Ti	820	3,620	4,350
Cl	1,590	31	47
Zn	44	81	350
Cu	14	66	125
Pb	30	78	390
Cd	0.11	0.20	1.0
As	69	8	596

Note:

(1) At Lingan Generating Station.

Source: Table 5.8, Evans et al. (1985).

Table C.6

ANALYSIS OF A DEVCO THERMAL COAL ASH SAMPLE

Compound	% Weight
SiO_2	35.04
Al_2O_3	17.34
Fe_2O_3	37.94
TiO_2	0.83
P_2O_5	0.17
CaO	2.15
MgO	0.98
MnO_2	--
Na_2O	0.53
K_2O	1.55
SO_3	3.27
Total Determined	99.80
Undetermined & error	0.20

Note: The coal sample contained 7.77% ash (by wt.) on a dry basis.

Source: Nicholson, 1994.

It has been estimated that a population centre with a population of 50,000 could produce up to a maximum of 17,000 t of organic waste or 8,500 t of mature compost each year. Metropolitan Toronto could generate up to 212,000 t of compost on an annual basis (Molot 1992).

The Province of Ontario as a whole could produce about 6.8×10^5 t/yr of compost (Pierce 1992). At this rate, it would take in excess of several years to produce a 2 m layer of compost to cover a 100 ha tailings basin.

It is estimated that the unit cost of producing large quantities of mature compost in the Toronto area would be in the range of $100 to $126/t (Molot 1992). The costs of shipping the compost to a tailings management area and constructing the dry cover would be additional. However, if the material was not composted prior to shipping, there could be some cost incentive to using the organic waste. However, the use of compost in an "immature" form presents several concerns particularly regarding human health issues.

Other types of organic products could be substituted such as:

Organic Material	**Source**
Sewage Sludge	Population Centre
Forest Industry Waste including Paper Mill Sludge	Possibly in vicinity of mine
Peat	Possibly in vicinity of mine
Food Processing Waste	Population Centre or Agricultural District

The importing of waste materials, such as municipal organic matter compost, and its use as part of a dry cover may be prohibited or made unduly complex by present or proposed legislation. This issue along with the others indicated on the following table, should be addressed if further research in this area is undertaken.

Issue	Comment
AMD Inhibition	short and long term performance must be determined
Economics	lower cost methods of producing compost are required a cost benefits analysis is required
Quantity	evaluate the effects of limited compost production rates on cover construction/acid generation
Approvals	contaminated compost could be considered acceptable for use in tailings area reclamation. This should be resolved with regulatory authorities.

Overall, given the relatively low quantities available municipal compost is not likely to be an important component of dry covers.

4.0 N-VIRO SOIL

N-Viro Soil is a trade name used to describe "engineered soil" produced by mixing dewatered sewage sludge with an admixture such as current kiln dust, fly ash, or wood ash to produce a granular material with desirable soil property (Burnham, Logan 1993) see Table C.3. The product may, in theory, be useful as a component in a composite dry cover as it may increase the water retention capability and provide a short term supply of nutrients to heterotrophic bacteria and has substantial alkalinity to buffer acid production.

N-Viro Soil is essentially a process developed to provide an alternate disposal technique for sewage sludge. The process is claimed to destroy pathogens.

N-Viro Soil as a processed waste may be economically attractive as an alternative to conventional soil conditioners. However, large scale use for dry covers will be substantially limited by transportation costs from the major production centres and available quantities. A typical large city with 1 million people might produce on the order of 40,000 t/yr of dried sewage sludge. From this about 60,000 t/yr of dry N-Viro Soil could be produced or 100,000 t/yr of N-Viro Soil at 60% solids. Total quantities are therefore insufficient to supply large demands for cover application.

While this material is likely not to become available in sufficient quantities the basic process may be of interest to dry cover researchers.

5.0 INDUSTRIAL SOLID WASTE

There are large quantities of industrial waste produced in Canada. These wastes are for the most part disposed of in commercial landfills or private landfills operated by the companies. There has been an increasing trend in recent years to reducing waste production by 3Rs programs and there are very few large volume wastes remaining which are potential candidates for use in covers. Small volume wastes include:

- oily sludges
- food processing wastes
- waste product organics chemicals industries (monomers, fibres, sludges)

Potential materials for use as, or components of, dry covers that could be obtained from industrial wastes include:

- shredder fluff
- crumb rubber
- construction and demolition wastes
- phosphate rock and slag
- miscellaneous slags
- coal ash

5.1 SHREDDER FLUFF

Shredder fluff is a by-product of the mechanical shredding of automobiles, appliances and loose metal to recover ferrous materials. Shredder fluff is a mixture of materials primarily composed or organic polymers (plastics, rubber, fibres). It also contains lesser amounts of other nonferrous materials (i.e. glass, sand, cloth, copper) (Boeger, Braton 1985).

Shredder plants are located outside population centres and near steel making facilities.

At present, there are no established markets for shredder fluff. It is landfilled or used as a cover material at landfills (CH2M Hill 1990).

Quantities of this material are modest at 140,000 t/yr (440,000 m^3 at 0.32 t/m^3). Its potential application as a dry cover component is limited due to:

small quantities

concerns with concentrations of contaminants (i.e. metals, PCB's);

undesirable properties (i.e. autocombustion); and

expected high rates of diffusion of oxygen through voids in this material.

Note that the characteristics of shredder fluff are dependent upon the ever changing characteristics of the feedstock - primarily automobiles. As a consequence, shredder fluff characteristics may change over time.

Although shredder fluff is unlikely to have use as a dry cover, the material has potential as a general cover material for use in surface stabilization and reclamation.

5.2 CRUMB RUBBER

Crumb rubber is produced by the grinding of passenger vehicle and truck tires to small size particles (currently down to 60 mesh).

Disposal of used tires remains a problem and the rubber industry is looking for alternate disposal/recycle options.

Although the quantity of used tires is small in comparison with the demand for dry cover material, it is expected that crumb rubber would offer limited benefits as a component of a dry cover for reasons including concerns about biotoxicity (W. Baker 1993), autocombustion, and expected high rates of diffusion of oxygen.

5.3 CONSTRUCTION AND DEMOLITION WASTES

Construction and demolition wastes include waste from the clearing of land, construction, and demolition including road and bridge repairs. It is estimated that in 1992, a total of 5,871,000 tonnes of these wastes were produced across Canada (SENES 1993). A breakdown of wastes, by type, is provided in Table C.4.

One product with potential for use as a component in a dry cover is uncontaminated wood waste which typically consists of dimensional lumber. This material is expected to have limited applicability for use in dry covers as it would require processing prior to being applied as a cover. Wood waste should be easier to source local to a tailings area.

5.4 PHOSPHATE ROCK AND SLAG

Phosphate rock and slag were specifically identified as potential waste materials for use in covers. The potential issues to such a cover relate to the availability, cost, and long term performance of materials used in the cover design. Presently there are no commercial sources of phosphate rock in Canada although deposits are known to exist. With the data available it is virtually impossible to predict the likelihood of success or the related costs.

Phosphate rock is a mined mineral whose primary use is the production of elemental phosphate and phosphate fertilizers. The production of phosphate fertilizers produces gypsum as a primary by-product while phosphates production leads to phosphate slag. Neither gypsum or phosphate slag are suitable materials for dry covers. Gypsum is acidic and unstable with a high permeability while phosphate slag is highly pervious and essentially inert.

Phosphate rock does have some potential use however not in isolation as a dry cover material. Phosphate rocks like limestone can buffer acid solutions but for cover application this property of minor benefit as the material is only sparingly soluble.

Furthermore, it should be noted that elemental phosphorus slag has been widely used for a variety of purposes, in both the United States and Canada, however, because of its low level radioactivity such uses have been severely restricted in recent years. There are no specific disposal regulations in Canada for phosphate slag. In the Province of Quebec this slag is considered as hazardous waste because of its radioactivity.

Most phosphate deposits have small but measurable concentrations of uranium ranging from a few ppm to several hundred ppm. For instance, the uranium content of phosphate rock in the United States is often in the range of 100 to 150 ppm. The residue radioactivity levels in phosphate rock or phosphate slag would not likely pose a radioactive hazard if used as a component of a dry cover.

Phosphate rock is a component of the PHITO (Phosphate Heterotrophic Inhibition of Tailings Oxidation) layer being researched by Boojum Research Limited (Fyson, Kalin 1993). In this application, phosphate rock in combination with organic material is worked into the near surface layer of fresh tailings. A vegetation cover is developed on the surface of the tailings and used to support heterotrophic bacteria. The resulting surface treatment, in theory, provides oxygen consumption through bacterial action and organic decay, and acid neutralization through reaction with the phosphate rock. Neutralizing reactions may result in the formation of a hardpan and increase moisture retention in the upper layer.

The research on the application of this technology is in the early stages of development. The likelihood of success is unknown.

5.5 MINING WASTES

There are two materials produced in substantial quantities in mining areas. These are slags and tailings. Slags could be used as a component of a composite cover (e.g. drainage layer) but otherwise would have minimal benefit.

Tailings themselves can be used as a component of a cover. Two possibilities arise, one using a desulphurized tailings as the cover and second in using tailings slimes as a component of the cover material. Obviously there is no lack of material and transportation is not expected to be a major issue.

The ability to produce low sulphur tailings will be site specific and limited to ones which are not massive sulphides. The major benefit is that sulphur flotations almost uniformly practised at mining sites and many properties can readily add additional flotation capacity to produce a low sulphur tailings. Even if the tailings have residual sulphide, adequate buffering or limestone/phosphate addition could be considered.

A typical flotation plant if operated as an add-on to the circuit with an operating cost of \$1/t, could produce a 2 m dry cover of tailings at cost of about \$3 to \$4/m^2. As compared with many other composite covers at more than \$25/m^2. Consideration would have to be given to costs for sulphide concentrate disposal. For non-operating sites, the production of low sulphur tailings would be less attractive and problematic. Many companies have considered the production of "clean tailings" caps but little work has been completed.

As discussed in Task 2 (Appendix A) report the use of tailings slimes is also an extremely promising concept. Many slimes produced at base metal mines are clay like gelatinous materials which have excellent water retaining abilities. A major problem with reclamation of slime ponds is surface trafficability as these materials will not readily drain. Falconbridge experience suggests slime cover can reduce oxidation rates in pyrrhotitic tailings by orders of magnitude because they act as an excellent oxygen barrier.

5.6 COAL ASH

Bottom ash and fly ash are waste materials generated from coal combustion processes such as those used at coal-fired power stations. Bottom ash is obtained, as its name suggests, from the bottom of furnaces while fly ash is removed from flue gas.

The chemical composition of the ashes varies significantly and is a function of the composition and type of coal burned, and site specific coal preparation/combustion techniques and conditions. The elemental composition of a Canadian (Atlantic Region) bituminous coal and related bottom ash and fly ash are presented in Table C.5. Although not representative of all coal, Table C.5 indicates the wide range of elements present in ash. Results of an analysis of a Cape Breton thermal coal ash sample are provided in Table C.6.

Due to concerns regarding the quality of leachate from ash disposal areas, there is a move to permanently dispose of bottom ash and fly ash in engineered (lined, clay capped, etc.) landfills.

Coal ashes have been suggested as possible cover materials due, in part, to their alkaline nature and availability. The performance of an ash dry cover would, however, be dependent upon the ability of the cover to provide a moisture retaining, oxygen diffusion barrier. Given the concerns over the variable composition of ash, potential leaching, and surface erosion, this material is not likely to be an important component of dry covers.

6.0 CONCLUSIONS

The municipal and industrial wastes identified as having some potential for use as dry cover materials are summarized in Table C.7. The conclusion of this review is:

i) there are no large volume municipal or industrial wastes which are likely to find widespread application for use in dry covers.

ii) there are many municipal and industrial wastes which could have limited application. These materials include:

  waste paper as an oxygen consumer and high moisture retaining material
  compost as an oxygen consumer and high moisture retaining material
  N-Viro Soil as an oxygen consumer and high moisture retaining material

iii) desulphurized mine tailings or tailings slime are industrial wastes with a high potential to be cost effective dry covers for tailings.

iv) phosphate rock could find a role in providing neutralization capacity and nutrients as a component of a dry cover. If its use is simply as a buffering agent alternative materials such as limestone are likely more cost effective.

Consequences of Using Waste Materials:

As indicated in Table C.7, waste materials identified in the search present several concerns notably:

possible negative impact on cover effluent quality;

high costs of procurement and processing;

unknown long term performance and effects to the environment;

undesirable material characteristics (i.e. combustible materials).

Future dry covers research involving waste materials must consider these concerns.

Based upon this review we strongly recommend:

1) research funding of the use of desulphurized tailings and tailings slimes;

2) a technical review of the potential merits of the PHITO process.

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