Review of Soil Cover Technologies for Acid Mine Drainage – A Peer Review of the Waite Amulet and Heath Steele Soil Covers

MEND Report 2.21.3

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Review of Soil Cover Technologies for Acid Mine Drainage - A Peer Review of the Waite Amulet and Heath Steele Soil Covers

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EXECUTIVE SUMMARY

Prototype insitu covers were constructed at two mine sites, Heath Steele and Waite Amulet, as a part of the Mine Environmental Neutral Drainage (MEND) program. An independent study was undertaken by the Unsaturated Soils Group at the University of Saskatchewan to critically review the sites with respect to selection of soil materials, design, construction, instrumentation, performance, and economics. This work was funded by Cominco Ltd. The main objectives of the study were:

1. to undertake a literature review of fundamental processes and methods of analyses required for the evaluation and design of dry covers;
2. to identify the key aspects of the design of soil cover systems;
3. to complete an inventory of other "dry cover" sites and their performance;
4. to undertake a critical scientific review of the Heath Steele and Waite Amulet sites including the evaluation of the quality and completeness of the following:
   (a) field and laboratory tests;
   (b) site instrumentation systems and monitoring results; and
   (c) data analysis and interpretation.
5. to analyze alternative means that identify the essential components of soil cover systems, while at the same time, minimize the construction costs; and
6. to provide recommendations as to critical research needs in the areas of design, construction, monitoring, and analysis of soil cover systems.

The design objectives for the Waite Amulet and Heath Steele soil cover systems were to provide a low hydraulic conductivity barrier to minimize the influx of water and provide an oxygen diffusion barrier to minimize the influx of oxygen. The design of the two soil cover systems utilized the capillary barrier concept. Both these soil cover systems were extensively evaluated through laboratory, numerical modelling, and field studies. The results of the research indicated that the capillary barrier concept was attainable under field conditions and will result in a reduction of the influx of infiltration and oxygen, thereby reducing the potential for acid generation.

The soil cover systems installed at the Heath Steele and Waite Amulet sites performed satisfactorily. The design, construction, and monitoring programs for these soil cover systems provided a unique opportunity to evaluate the performance of engineered soil covers in Canadian climates.

In this report, apart from providing an independent review of Heath Steele and Waite Amulet projects, a brief state-of-the-art literature review is provided in Chapter 2. Several case histories of soil cover systems for various parts of the world are summarized in Chapter 3. The key laboratory tests and performance data for the Heath Steele and Waite Amulet soil cover systems are summarized in Chapter 4. A synopsis on the design and performance of these soil cover systems is provided in Chapter 5. Chapter 6 contains the conclusions and recommendations with respect to the design and analyses of soil cover systems.

An annotated literature review pertains to soil cover systems, liners, and related topics are provided in Appendix A. A methodology for numerical modelling of soil cover performance as prepared by Swanson (1995) is provided as Appendix B.

Over the course of this review it became apparent that a template for a rationale method of cover design for acid generating mine waste was emerging. The basic elements of this rationale method is outlined and provides a backdrop against which the design of covers can be developed.

The basic elements of this design approach can be summarized as follows:

- Design objectives/philosophy;
- Design principles;
- Methods of characterization;
- Methods of analyses;
- Monitoring; and
- General issues including economics, construction, long term performance.

Each case history was reviewed in terms of each of these design components. Based on the review of the existing literature, the various case histories and a detailed review of the Heath Steele and Waite Amulet sites a number of key recommendations were proposed:

Recommendation #1*: That research be conducted into the characterization of the soil water characteristic curve for soil cover and mine wastes materials. Of particular interest are the methods of characterizing and estimating the soil water characteristic curve and the prediction of the effect that weathering processes may have on this property.*

Recommendation #2*: That research be continued on the inter-relationships between micro-climatic conditions, vegetation, and soil as it pertains to cover performance.*

Recommendation #3: *That current methods of analyses for dry covers be reviewed including benchmark testing against documented case histories and that a methodology for analyses be developed which maximizes the capabilities of the various models.*

Recommendation #4: *That further work be encouraged to expand the capabilities of current models to include environmental coupling. Additional capability is required in the prediction of moisture movement during winter months, the influence of vegetation, multi-dimensional effects, and erosion.*

Recommendation #5*: That work be undertaken for the development and testing of a reliable method of measuring suction within covers and waste rock.*

Recommendation #6: *That a review of field lysimeter design and performance be undertaken with a view to the development of design procedures which take into account the complexities of unsaturated flow on field lysimeter performance.*

Recommendation #7: *That further work be undertaken on the development techniques for monitoring soil/environmental responses such as erosion, runoff and vegetation factors relevant to cover performance.*

Recommendation #8: *That design philosophy and objectives be encouraged which focuses on the development of long-term engineered cover systems which are fully coupled and integrated with the natural environment.*

Recommendation #9: *That full scale, long term, field case studies be developed and documented to increase the level of confidence in design principles, and methods of characterization, analyses and monitoring.*

Recommendation #10: *That studies be initiated to look at issues related to the ecological stability of covers. These studies will include a transfer of technology from the forestry, reclamation, and agricultural areas to the area of cover design and will provide a basis for predictions of long term cover performance.*

Recommendation #11: *Ongoing work should be supported into the use of economic design methods (1 material -multi-layer) and materials which consider innovations such as the development of multilayer performance with the use of one construction material, and the use of waste materials (tailings + waste rock) as potential cover materials.*

Recommendation #12: *That a state-of-the-art manual or handbook be developed which incorporates a rationale design method supported by documented case histories. This handbook should be prepared in an open-binder format so that it can be maintained as a current and dynamic summary of cover design methodology.*

Each of these recommendations are more fully discussed in Chapter 6.

SOMMAIRE

Des couvertures prototypes ont été aménagées dans deux sites miniers, Heath Steele et Waite Amulet dans le cadre du programme NEDEM (Neutralisation des eaux de drainage dans l'environnement minier). Une étude indépendante a été entreprise par l'Unsaturated Soils Group de l'University of Saskatchewan dans le but d'étudier de façon critique les sites sous les rapports suivants: choix des matériaux géologiques, conception, construction, instrumentation, rendement et aspects économiques. Les travaux ont été financés par la société Cominco Ltée. Les principaux objectifs de l'étude étaient les suivants :

1. procéder à une étude de la documentation des procédés et méthodes d'analyse fondamentaux requis pour l'évaluation et la conception de barrières sèches;
2. déterminer les aspects clés de la conception des systèmes de recouvrements géologiques;
3. dresser l'inventaire des autres sites à << barrière >> sèche, et de leur rendement;
4. procéder à un examen scientifique critique des sites Heath Steele et Waite Amulet, y compris l'évaluation de la qualité et de la réalisation des points suivants :
    a. essais sur le terrain et en laboratoire;
    b. systèmes d'instrumentation sur le site et résultats de la surveillance;
    c. analyse et interprétation des données.
5. analyser des solutions de rechange qui permettraient de déterminer la nature des composantes des recouvrements géologiques tout en réduisant au minimum les coûts d'aménagement;
6. formuler des recommandations relatives aux besoins cruciaux en matière de recherche dans le domaine de la conception, de l'aménagement, de la surveillance et de l'analyse des recouvrements géologiques.

Les objectifs se rapportant à la conception des recouvrements géologiques Waite Amulet et Heath Steele consistaient à aménager une barrière de faible conductivité hydraulique visant à réduire au minimum l'infiltration de l'eau et à aménager une barrière freinant la diffusion de l'oxygène pour réduire au minimum l'entrée d'oxygène. La conception des deux recouvrements géologiques faisait intervenir le principe de la barrière capillaire. Les deux recouvrements géologiques ont été évalués de façon prolongée en laboratoire, sous la forme de modèles numériques et par des études sur le terrain. Les résultats de la recherche indiquaient que la notion de barrière capillaire pouvait s'appliquer aux conditions sur le terrain et qu'elle aurait pour effet de réduire l'infiltration d'eau et d'oxygène, réduisant ainsi les risques de production d'acide.

Les recouvrements géologiques aménagés aux sites Heath Steele et Waite Amulet ont fait état d'un rendement satisfaisant. Les programmes de conception, d'aménagement et de surveillance pour ces recouvrements géologiques ont permis d'évaluer de façon unique le rendement de recouvrements géologiques aménagés dans des climats canadiens.

Dans le présent rapport, en plus d'un examen indépendant des projets de Heath Steele et de Waite Amulet, on trouve au chapitre 2 une brève analyse documentaire des connaissances les plus poussées. On trouve au chapitre 3 un résumé de plusieurs cas types de couvertures de sol aménagées dans différentes parties du monde. Au chapitre 4, on trouve des résumés des essais en laboratoire et des données relatives au rendement des recouvrements géologiques de Heath Steele et de Waite Amulet. Au chapitre 5, oį trouve un résumé de la conception des recouvrements géologiques de Heath Steele et de Waite Amulet. Au chapitre 6, on présente un résumé et des recommandations se rapportant à la conception et aux analyses des recouvrements géologiques.

Une analyse documentaire annotée concernant les recouvrements géologiques et d'autres sujets connexes est présentée à l'annexe A. À l'annexe B, on présente une méthodologie relative à la modélisation numérique du rendement des recouvrements géologiques préparée par Swanson (1995).

L'émergence d'un modèle de méthode raisonnée de conception des couvertures destinées aux déchets miniers produisant des effluents acides s'est clairement dessinée au cours de l'étude. Les grandes lignes des éléments de base de cette méthode raisonnée sont précisées, de même qu'un aperçu des éléments essentiels à la conception des différents recouvrements.

Voici un résumé des éléments fondamentaux de cette méthode de conception :

- Objectifs / philosophie de la conception ;
- Principes de conception;
- Méthodes de caractérisation;
- Méthodes d'analyse;
- Surveillance;
- Questions d'ordre général, y compris les aspects économiques, les aspects de l'aménagement, le rendement à long terme.

Chaque cas a été examiné d'après les composantes de la conception. D'après l'étude de la documentation portant sur le sujet, les différents cas types et un examen détaillé des sites de Heath Steele et de Waite Amulet, on a formulé un certain nombre de recommandations:

Recommandation n^o 1 *: Des travaux de recherche se rapportant à la courbe caractéristique de l'eau du sol devraient être réalisés pour les recouvrements géologiques et les déchets miniers. Les méthodes de caractérisation ainsi que l'estimation de la courbe caractéristique de l'eau du sol présentent un intérêt particulier, de même que la prévision des altérations atmosphériques et des effets qu'elles ont sur ces propriétés.*

Recommandation nº 2 : *Il faudrait continuer à effectuer des travaux de recherche portant sur la relation entre les conditions de micro-climats, la végétation et les matériaux de couverture en ce qui a trait au rendement de la couverture.*

Recommandation nº 3 : *It faudrait examiner les méthodes actuelles d'analyse des couvertures sèches, y compris la mise au banc d'essai et la comparaison avec des cas types documentés, et mettre au point une méthodologie relative aux analyses qui permettrait de maximiser les capacités de divers modèles.*

Recommandation nº 4 : *Favoriser la poursuite des travaux déjà en cours dans le but d'accroître la capacité des modèles actuels en vue d'inclure l'intégration au milieu. Favoriser d'autres propriétés se rapportant à la prévision de la migration de l'humidité pendant les mois d'hiver, à l'incidence de la végétation, aux effets multidimensionnels et à l'érosion.*

Recommandation nº 5 : *Voir à ce que des travaux soient entrepris en ce qui a trait à la mise au point et à la mise à l'essai d'une méthode de mesure fiable de la pression négative dans les couvertures et les stériles.*

Recommandation nº 6 : *Voir à ce qu'un examen de la conception et du rendement des lysimètres sur le terrain soit effectué dans l'optique de la mise au point de procédures de conception qui tiennent compte des effets de la complexité de l'écoulement non saturé sur les lysimètres placés sur le terrain.*

Recommandation nº 7 : *Voir à ce que d'autres travaux soient entrepris concernant les techniques de mise au point de la surveillance des réponses du sol/de l'environnement comme l'érosion, le ruissellement et la végétation qui sont des aspects pertinents du rendement des couvertures.*

Recommandation nº 8 : *Favoriser la philosophie et les objectifs de conception qui portent principalement sur la mise au point de l'installation à long terme de couvertures aménagées qui sont entièrement associées et intégrées au milieu naturel.*

Recommandation nº 9 : *Voir à ce que des études de cas sur le terrain, réalisées à l'échelle et à long terme soient mises au point et documentées pour accroître le niveau de confiance dans les principes de conception et dans les méthodes de caractérisation, ainsi que dans les analyses et la surveillance.*

Recommandation nº 10 : *Voir à ce que des études soient réalisées au sujet de la question de la stabilité écologique des recouvrements. Ces études devraient tenir compte du transfert de technologies provenant de la foresterie, de la réhabilitation et de l'agriculture pour la conception des couvertures et elles devraient constituer un fondement pour les prévisions du rendement à long terme des couvertures.*

Recommandation nº 11 : *Il faudrait soutenir la poursuite des travaux portant sur des méthodes de conception économiques (1 matériau - plusieurs/multi-couches) et sur l'utilisation de matériaux qui tiennent compte d'innovations telles que des systèmes multi-couches utilisant un seul matériau ou encore l'usage de déchets miniers (résidus et stériles) comme matériaux pour le recouvrement.*

Recommandation n^{o} 12 : *Il faudrait élaborer un manuel ou aide-mémoire des connaissances poussées qui devrait comprendre une méthode de conception raisonnée accompagnée de cas types documentés. Ce manuel devrait être préparé dans un format de reliure à courroies de sorte qu'on pourrait procéder régulièrement à des mises à jour de façon à ce qu'il demeure actuel; il devrait comporter un résumé des méthodologies relatives à la conception des recouvrements.*

Chacune de ces recommandations fait l'objet d'un examen plus approfondi au chapitre 6.

Acknowledgements

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CHAPTER 1

INTRODUCTION

1.1 GENERAL

The mining industry faces a major environmental challenge in the management of sulphide bearing waste rock and tailings. Acid mine drainage (AMD) or acid rock drainage (ARD) results from the exposure of sulphide bearing wastes to water and oxygen. Sulphide minerals oxidize upon contact with oxygen and water producing an acidic pore-water with high concentrations of dissolved sulphate, and heavy metals (Yanful and St-Arnaud 1992). Access to water and oxygen is provided by interactions of the waste rock or tailings with the atmosphere (Figure 1.1)

Studies conducted by Feasby and Jones (1994) indicated that an estimated 7 billion tonnes (41,000 hectares) of metal-mine and industrial mineral tailings exist in Canada. The cost of rehabilitation of these sites to meet current standards is expected to be from $ 3 to 5 billion. The cost of rehabilitating acid-producing mine waste could be in excess of $ 250,000 per hectare. Options are being studied to reduce this cost.

There are a number of sites world wide in which natural soil covers have been used to decommission potentially acid generating waste rock piles and tailings impoundments. An engineered soil cover may be effective in limiting the influx of oxygen and precipitation into the sulphide bearing material. Soil cover systems are designed as a function of the properties of the soil and waste materials, climatic and hydrologic conditions, and the response of the soil cover to atmospheric demands (O'Kane 1996).

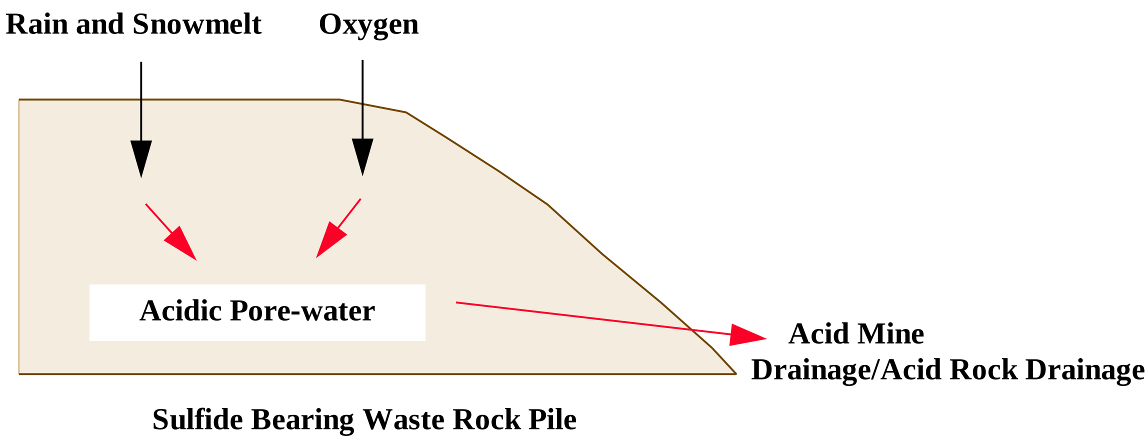


Figure 1.1 Definition of physical problem: development of acid mine drainage (from Swanson, 1995).

In general, the design objectives for these engineered soil covers vary; however, at most sites with reactive mine wastes, the objectives of the soil cover system are to provide:

- an oxygen diffusion barrier to minimize the influx of oxygen;
- a low hydraulic conductivity barrier to minimize the influx of water; and
- a stable soil surface on which vegetation can be established.

1.2 PROBLEM DEFINITION

The Heath Steele and Waite Amulet sites are two of the most prominent examples of soil cover designs that have been engineered to provide these benefits. The research at these sites focused on demonstrating the capability of "layered" soil cover systems to provide effective covers for mine waste materials. One of the objectives of this project was to provide an independent review of the design, construction, monitoring, and analysis of the performance of the soil cover systems installed at the Heath Steele and Waite Amulet sites.

A concern related to the Heath Steele and Waite Amulet soil cover system was the costs associated with the construction. There are, however a number of other sites at which less expensive alternatives have been utilized. For example, at Equity Silver Mines Ltd.

in British Columbia, Canada and at the Rum Jungle site in Australia, layered systems comprised of a single soil, densely compacted for the lower layer, and with a loosely compacted upper layer were constructed. At COMINCO’s Sullivan site near Kimberly, British Columbia, Canada, and at BHP’s Island Copper Mine on Vancouver Island, Canada, a single layer of till with a surface layer for revegetation were utilized. At Golden Sunlight Mines Ltd. in Montana, U.S.A., the soil cover systems consisted of waste rock; the lower layer being recompacted oxidized waste rock and the upper layer a recompacted waste rock top soil mixture. Many of these simple, less costly layered cover systems are still being evaluated.

1.3 SCOPE AND OBJECTIVES

In 1995, MEND requested the Unsaturated Soils Group, Department of Civil Engineering, University of Saskatchewan, Saskatoon to initiate a research project to scientifically review the Waite Amulet and Heath Steele soil covers. The objectives of this study are:

1. to undertake a literature review of fundamental processes and methods of analyses required for the evaluation and design of dry covers;
2. to identify the key aspects in the design of soil cover systems;
3. to complete an inventory of other "dry cover" sites and their performance;
4. to undertake a critical scientific review of the Heath Steele and Waite Amulet sites including the evaluation of the quality and completeness of the following:
   (a) field and laboratory tests;
   (b) site instrumentation systems and monitoring results; and
   (c) data analysis and interpretation.
5. to analyze alternative methods by which the essential components of soil cover systems could be utilized, while at the same time, minimizing construction costs; and
6. to provide recommendations as to critical research needs in the areas of design, construction, monitoring, and analysis of soil cover systems.

1.4 METHODOLOGY

The key to the design of a soil cover system for potentially acid generating mine waste lies in limiting the net moisture and oxygen flux to the underlying waste material. The oxidation of sulphide minerals and the production of acid mine drainage requires two key constituents, namely; water and oxygen. The development of acid mine drainage cannot proceed actively if either constituent is restricted. An understanding of these fundamental processes is necessary in identifying the critical design requirements for soil cover systems.

The design, construction, and monitoring of the soil covers completed for the Heath Steele and Waite Amulet sites were evaluated based on these principles in the context of the Canadian climate. The soil cover systems installed at Heath Steele and Waite Amulet site performed satisfactorily. Recommendations are provided for future research which will lead to the development of a rational design approach.

1.5 REPORT ORGANIZATION

This report is organized into six chapters. The scope, objectives, and methodology are outlined in this first chapter. The second chapter provides a brief review of background literature related to soil covers. Soil covers have been used in various parts of the world to control acid mine drainage. Some of these case histories are briefly discussed in the third chapter with reference to soil properties, design considerations, and performance. The cost of these soil cover systems were also discussed wherever information was available. In Chapter 4, key aspects of the Heath Steele and Waite Amulet projects were summarized with reference to site characterization, soil properties, design considerations, monitoring, and performance. Chapter 5 provides a critical review and discussion of the two sites with respect to the current state-of-the-art. A number of recommendations are offered with reference to the design, construction, monitoring, and economics of soil cover systems along with recommendations on future areas of research. These are outlined in Chapter 6. Information in other related areas of research are also appended to this report. There has been significant interest in the performance of soil cover systems and soil liners in recent years. Many of these studies are reported in various conferences and reports. The compiled information is available as Appendix A, entitled, "Annotated Literature Review on Soil Cover Systems and Soil Liners". A theoretical background by Swanson

(1995) for soil cover modelling entitled, "Predictive Modelling of Moisture Movement in Engineered Soil Cover Systems for Acid Generating Waste", is provided in Appendix B.

CHAPTER TWO

LITERATURE REVIEW OF SOIL COVER SYSTEMS

This chapter provides general background information on soil cover systems. The use of a layered engineered soil cover in controlling acid mine drainage is described and the key factors that control the integrity of soil cover systems are reviewed.

2.1 GENERAL BACKGROUND

Soil cover systems are commonly used on waste piles, municipal and chemical landfills, as well as mine wastes. The main objective of soil cover systems is to prevent or reduce the flow of water and gaseous oxygen into, and, in some cases, the transfer of toxic gases out, of the waste pile. Apart from this function, soil covers are expected to be resistant to erosion, and provide support for vegetation.

The ability of an engineered soil cover system to perform successfully over its design life is referred to as the cover's integrity (Haug, 1993). Figure 2.1 illustrates the key properties which influence cover integrity.

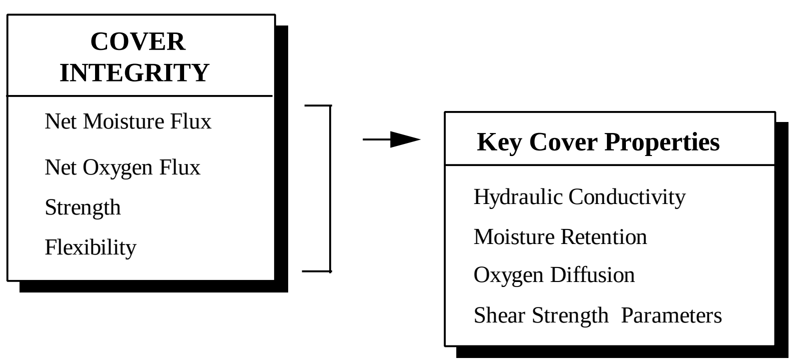


Figure 2.1 Categories describing the integrity of an engineered soil cover (modified from Haug, 1993 by Swanson 1995).

Figure 2.2 shows the factors which affect the integrity of soil cover and liner systems due to alteration of the initial structure of the materials. The physical factors are the key parameters which affect the performance.

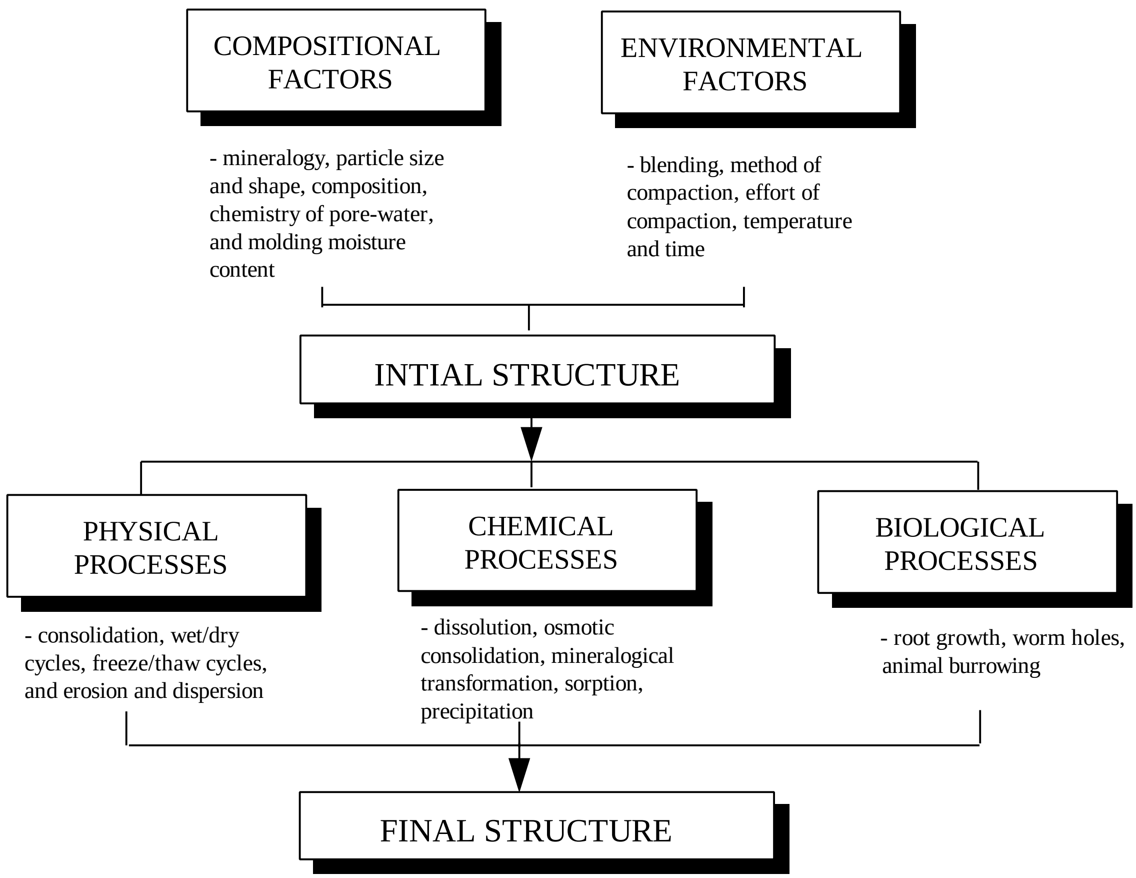


Figure 2.2 Factors controlling the initial and final structure of compacted soils (modified from Haug 1993 by Swanson 1995).

2.2 ACID MINE DRAINAGE/ACID ROCK DRAINAGE

One of the applications of a soil cover systems is for the decommissioning of potentially acid-generating mine waste. The dominant sulphide minerals present in tailings and waste rock are iron sulphides, pyrite and pyrrhotite. Oxidation processes occur when the sulphide mineral is exposed to water and oxygen. The chemical and bio-chemical reactions which cause the oxidation of sulphide are reasonably well understood. Several possible oxidation reactions with respect to these sulphide minerals are available in Nordstrom (1982).

The oxidation of sulphide minerals and the production of acidic drainage (i.e., acid mine drainage or acid rock drainage) requires two key constituents, namely; water and oxygen. If either constituent is not present, the generation of acid drainage cannot actively proceed. Thus, an efficient cover can be designed by limiting the net moisture and oxygen flux.

The rate of acid generation depends on several factors such as temperature, pH, specific surface area of the waste material, size of the waste pile, and availability of water and oxygen. An increase in the temperature and lowering of the pH (i.e., lower than 4), accelerates the process of acid generation by increasing the activity of the iron oxidizing bacteria. The greater the exposed surface of the waste (e.g. waste rock) the greater is the rate of reaction. A detailed review of the factors affecting the acid generation reaction are available in O'Kane (1996).

2.3 SOIL COVERS

The potential for acid generation may be reduced by placing the hazardous waste under a column of water (e.g., subaqueous disposal). This type of cover has been referred to as a "wet" cover. Wet covers may require construction and maintenance of structures which are costly and in some instances the topographical, and hydrological conditions may not be favorable.

"Dry" soil covers, are an alternative where flooding is not possible or feasible. Each layer in a soil cover has a specific function. A typical soil cover system is shown in Figure 2.3. The concept is to keep the central compacted fine grained soil near saturation and the sand layers on either side of this fine grained layer in an unsaturated condition.

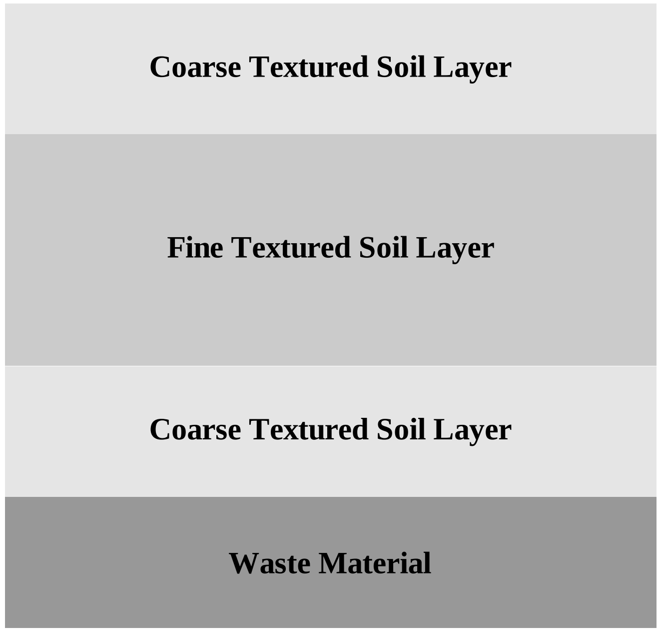


Figure 2.3 A soil-cover system over waste material (from O'Kane 1996).

2.3.1 Capillary Barrier Concept for Soil Cover Systems

A capillary barrier results when a fine grained soil overlays a coarse grained soil. The coarse textured soil may drain to a condition of residual water content if conditions allow. However, the residual suction for coarse textured material is relatively low (i.e., about 5 kPa for a 40/60 silica sand). At this low suction the overlying fine grained soil will not drain and consequently it remains in a saturated condition. This "capillary break" will occur during drainage whenever the residual suction of the lower coarse textured soil is less than the air-entry value of the upper fine-grained soil. Consequently, a layered soil system helps to maintain higher saturation levels in the fine grained layer. It also limits infiltration due to the low saturated hydraulic conductivity of the fine grained layer.

The ability of a soil cover system to limit the net flux of moisture is dependent mainly on the hydraulic conductivity properties of the soil materials. Thus, a capillary barrier (i.e., soil cover) can be designed based on the unsaturated hydraulic properties as predicted from the soil water characteristic curve. This aspect of soil cover behavior is described by Nicholson et al. (1989), Barbour (1990), Bruch (1993), Yanful et al. (1993), Swanson (1995) and O'Kane (1996) and others.

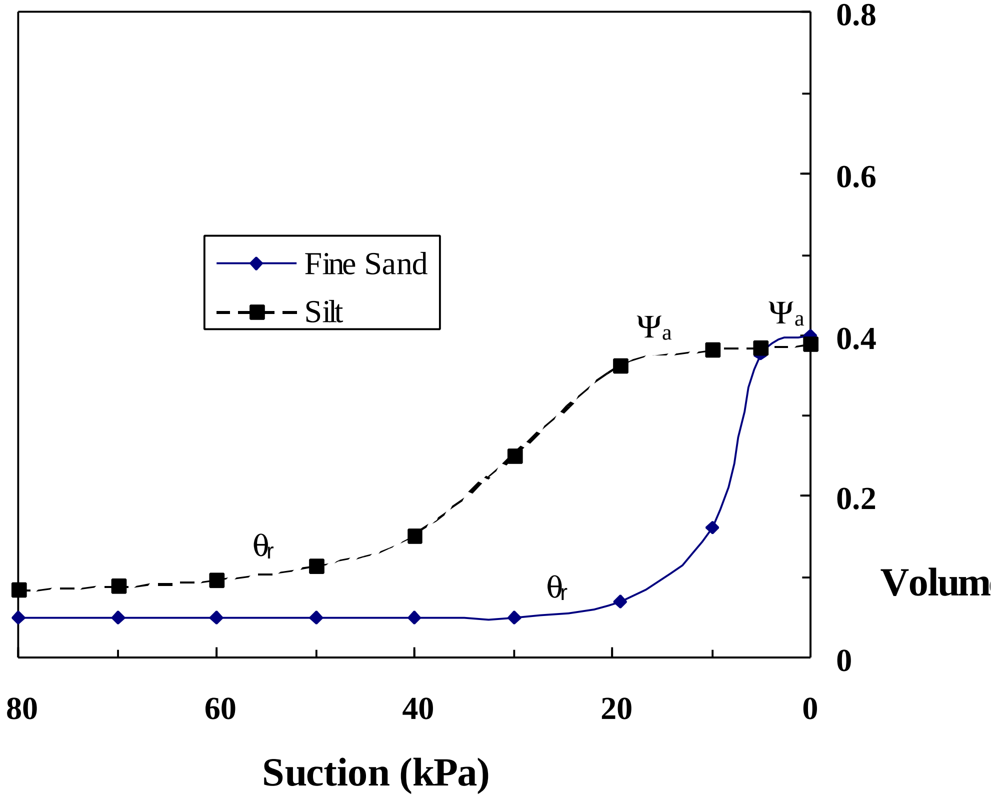


Figure 2.4 Typical moisture storage curves for soils (Modified after Ho, 1979).

Figure 2.4 illustrates the capillary barrier phenomenon using typical drainage curves from Ho (1979). The air entry value is the negative water pressure or matric suction required to initiate drainage of an initially saturated soil. The soil will not drain unless the applied suction exceeds the air entry value, ψ_a. When the fine sand (i.e., the coarse grained soil) is drained, the maximum suction that will develop is approximately equal to the suction at the residual water content , approximately 15 kPa. At this level of suction an overlying silt layer will not drain since air entry value of the fine grained soil is approximately 20 kPa. In addition, a coarse grained cover overlying the fine grained soil cover may be included in the design of the capillary barrier system to reduce evaporation from the fine grained layer. The upper coarse layer cover can reduce runoff since it provides for storage of water following infiltration, thereby allowing some water to reach the fine grained cover and satisfy any antecedent moisture losses. Selective layering of soils in soil covers also helps to prevent detrimental weathering processes such as alternate wet-dry cycles due to evaporation and infiltration in summer and freeze-thaw cycles in winter.

2.3.2 Diffusion of Oxygen

Composite soil cover systems are designed to control both oxygen and water flux to the underlying waste. The soil cover systems should be designed such that the fine grained layer maintains high degrees of water saturation under all climatic conditions. The relatively high degrees of saturation ensures that the effective coefficient of diffusion of oxygen is low which ultimately will lead to a control of the flux of oxygen to the underlying waste material.

The coefficient of diffusion for gaseous oxygen is a critical parameter for predicting the performance of a soil cover. The rate of oxidation within a waste rock pile is related to the amount of oxygen present in the waste. The net influx of oxygen into the waste is largely dependent on the ability of the cover to maintain a low effective oxygen diffusion coefficient. The supply, or transport of oxygen within waste rock dumps may also occur by convection and advection. More information on oxygen diffusion is available in Nicholson et al. (1989) and O'Kane (1996).

Figure 2.5 shows the effective coefficient of diffusion for oxygen as a function of the degree of saturation of uranium tailings and the Heath Steele till material. The effective diffusion coefficient increases significantly with a decrease in the degree of saturation of the materials. The effective coefficient of diffusion of the Heath Steele till decreased with an increase in the degree of water saturation, with decreases of nearly two orders of magnitude occurring in the 55% to 70% saturation range (Figure 2.5b).

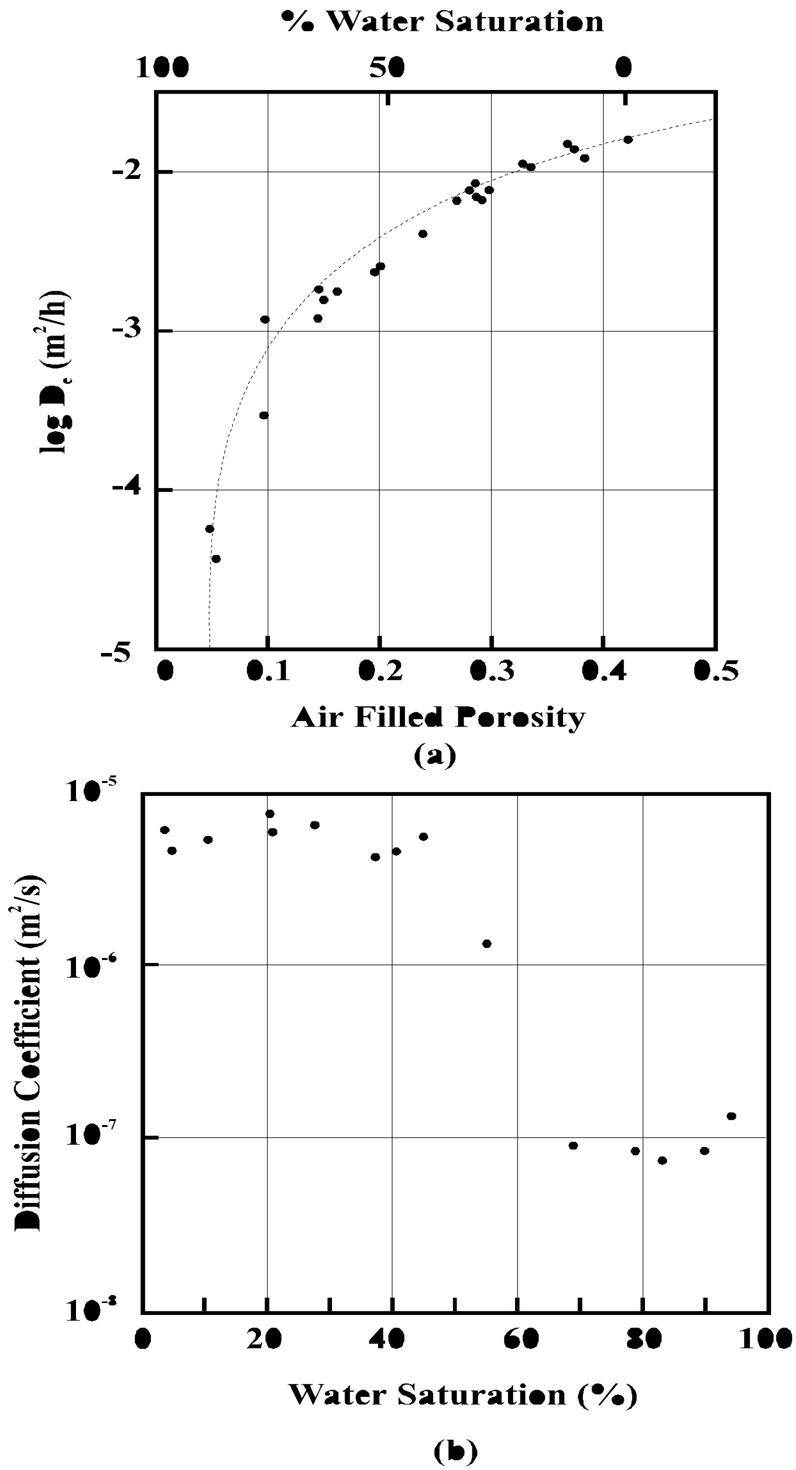


Figure 2.5 a) Relationship between effective diffusion for oxygen and the air filled porosity for a sample of tailings from the Elliot Lake uranium deposit (after Reardon and Moddle, 1985)
b) Effective diffusion coefficient of oxygen in Heath Steele Till versus degree of water saturation.

An effective barrier to oxygen diffusion will result if the degree of saturation of the fine grained layer can be maintained greater than approximately 85 to 90%.

2.3.3 Various types of Soil "Dry" Covers

SENES (1994) classified soil covers that control acid generation as: oxygen transport barriers; oxygen consuming barriers; and reaction inhibition barriers. An additional type of soil cover system are those designed to store and release moisture.

Table 2.1 Various types of soil covers

Dry Cover Classification	Primary Role of Cover in Inhibition of AMD
Oxygen Transport Barriers	Act to retain moisture and hence provides a low diffusion barrier to atmospheric oxygen
Oxygen Consuming Barriers	Act as an oxygen consuming sink to provide low oxygen concentrations at the interphase
Reaction Inhibiting Barriers	Act to inhibit reactions, neutralizes pH
Store and Release Infiltration Barriers	Act to minimize moisture flux by maximizing near surface storage of moisture with subsequent release by evapotranspiration

2.4 SOIL COVER DESIGN

The design of a soil cover system requires proper selection of soil materials to achieve a capillary break as discussed earlier. The soil water characteristic curve, the saturated and unsaturated hydraulic conductivity, and the oxygen diffusion properties of the soil are all important for the design of the soil cover system. General geotechnical tests such as the grain size analysis, Atterberg limits, specific gravity, and standard compaction tests will also be required for each material.

2.4.1 Selection of Soil Properties

Soil covers that are designed as moisture retaining covers use selective soil layers to achieve a capillary barrier. In a three-layer soil cover (as shown in Figure 2.3), the central layer is a fine grained material and the top and bottom soil layers are a coarse textured material.

2.4.2 Hydraulic Properties of the Soils

Moisture flow within the different layers of a soil cover system and across the interface of the layers can occur under both saturated and unsaturated conditions. A full understanding of the moisture and oxygen flux requires the measurement of the hydraulic conductivity of the soil under both saturated and unsaturated conditions. It is generally accepted practice to predict the unsaturated hydraulic conductivity of the soil using the soil water characteristic curve and the saturated hydraulic conductivity.

2.4.3 The Soil Water Characteristic Curve

The soil water characteristic curve is useful in understanding the capability of a soil to store and release water. It represents the relationship between water content and suction for a given soil. Suction is the negative water pressure in the soil. As the matric suction of the soil increases due to drainage or evaporation the water content of a soil will decrease. The soil water characteristic curve is obtained from a laboratory test in which the volumetric water content of a soil sample is measured at different applied suctions.

The laboratory measurement of the unsaturated hydraulic conductivity is costly, time consuming, and difficult. Empirical and analytical procedures are available to estimate the unsaturated hydraulic conductivity (Gardner, 1958; Brooks and Corey, 1964; Green and Corey, 1971; van Genuchten, 1980; Fredlund and Xing, 1994). These relationships usually require the soil water characteristic curve and the value of the saturated hydraulic conductivity as input data.

2.4.4 Oxygen Diffusion in Soil Cover System

The capillary barrier achieved by selective soil layering is designed to maintain a higher degree of water saturation in the fine grained layer which minimizes the effective oxygen diffusion coefficient. Several investigators have shown that diffusion properties can be related to the degree of water saturation (Troeh et al. 1982, Elberling et al. 1994). As a result the function for the coefficient of oxygen diffusion in the soil cover system can be predicted at varying degrees of saturation.

2.4.5 Other Properties

The performance of a soil cover system is significantly influenced by the weathering and erosion of the soil. Weathering and erosion properties are not generally taken into consideration in the design of soil cover system. The current design approach is to employ precautionary measures to control these natural processes.

2.4.5.1 Weathering

Alternate wet-dry and freeze-thaw cycles may alter the soil water characteristic curve and the hydraulic conductivity of the soil layers in the soil cover systems. However, these issues are rarely addressed and require further research.

2.4.5.2 Soil Erosion

Soil erosion and stability can also significantly influence the long term performance of a soil cover systems. The erosion phenomenon has not yet been systematically studied for soil cover systems. However, the literature provides valuable information on the erosion of agricultural top soil. Erosion is controlled by factors resulting from the interaction between the hydrologic system and the soil properties. Rainfall characteristics measured in terms of the velocity, size of droplets, intensity and total amount of rainfall, as well as flow properties influence soil erosion. The rate of the erosion is also influenced by other parameters such as the surface relief (both micro and macro), slope length, flow depth, and the surface roughness. Soil properties such as the type of the soil (cohesive or cohesionless), as well as size, shape and specific weight of particles are also of fundamental importance (Owoputi et al. 1995). One of the most important parameter for erosion is the presence of an adequate vegetation cover.

Owoputi et al. (1995) presented general recommendations for reducing erosion from a soil cover system that included providing a functional drainage system/network and ensuring an adequate vegetation cover. However, the role of the penetration of the plant roots into the cover system and the potential for the development of preferential pathways for oxygen and water need to be further studied. More importantly, the long term ecological stability of the soil cover system is an issue that has not been addressed and requires fundamental research.

More information about the influence of soil erosion on the performance of a soil cover system is available in Owoputi et al. (1995).

2.5 MONITORING

Instrumentation to monitor the performance of a soil cover system can be separated into two categories (O'Kane 1996): First, instrumentation to monitor temperature, gaseous oxygen and gaseous carbon dioxide within the waste material, and instrumentation to monitor the quality of seepage from the waste dump; Second, instrumentation installed directly into the soil cover system to monitor the effectiveness of the soil cover system as a hydraulic and oxygen barrier. The details of typical monitoring systems along with properties they measure are summarized in Table 2.2.

The local climatic conditions at a site will significantly affect the performance of the soil cover system and must be monitored. These include air temperature, precipitation, relative humidity, wind speed, and net radiation. In most cases it may be necessary to install a self-serving weather station at the site to gather the required site specific information. A weather station can include the following: rechargeable battery; solar panel; temperature probe; wind velocity monitor; ultrasonic depth/level sensor; relative humidity sensor; all season precipitation gauge; short wave radiation measurement; net radiometer; and, an evaporation pan (O'Kane 1996).

Table 2.2 Instrumentation details for monitoring the soil-cover system performance

Property	Instrument	Purpose/Notes
Moisture content	Time Domain Reflectometry (TDR)	3 rod probe system generally used. Apparent dielectric constant, k_a is measured .
Hydraulic head	Piezometers/Monitoring wells	PVC tubes; tips installed at known depths for sampling pore-water and for measuring water levels.
Suction	Thermal conductivity sensors/Jet fill tensiometers	Installed at the same depths as TDR probes
Flux properties	Field Lysimeter	Infiltration from the base of the soil cover system
Gaseous oxygen	Oxygen analyzer	Sampling ports installed during the placement of the piezometer.
Water quality	Laboratory tests using water collected from the base of lysimeters or piezometers	Properties such as pH, acidity, sulphate, and metal concentrations measured
Temperature	Thermocouple/ Thermistor	Secured to piezometers prior to installation.
Rainfall	Tipping-bucket rain-gauge	To collect rainfall data

2.6 NUMERICAL MODELLING FOR THE EVALUATION OF ENGINEERED SOIL COVERS

The performance of a soil cover can be predicted only if the moisture movement within the soil cover system is well understood. The moisture movement in the saturated and unsaturated zones can be predicted using unsaturated soil principles (Wilson et al. 1994). An accurate quantification of the surface water balance (i.e., storage and movement of moisture) is required to successfully analyze soil cover systems. Figure 2.6 shows the various components of the soil atmosphere interface. This is a dynamic zone in which the liquid and vapour movement of moisture as well as heat transfer occurs within saturated and unsaturated soil.

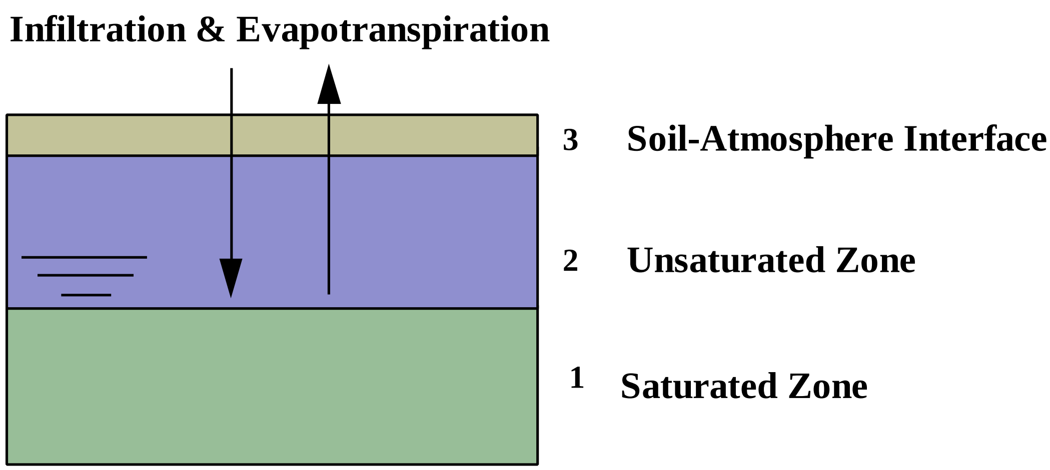


Figure 2.6 The three components of a natural soil system.

A physically based method for quantifying surface evaporation, transpiration, and evapotranspiration from an engineered soil is key to an accurate analysis of a soil cover system. The theoretical background with reference to the physically based model SoilCover (MEND 1993) is explained in detail by Swanson (1995). The theoretical formulations of this model, as prepared by Swanson (1995) is appended to this report (as Appendix B).

Predicting the performance of a cover system is a two-stage process involving field monitoring and numerical modelling (Swanson et al. 1995). Field monitoring provides data for evaluation of cover performance and also provides a basis for field response modelling using numerical predictions. In recent years a number of studies have looked at the long term performance of cover systems using numerical modelling techniques.

2.6.1 Numerical Modelling of Moisture Movement

The current methods of modelling moisture movement for soil covers in saturated and unsaturated zones of the soil profile are either largely empirically or physically based and consist of either one or two dimensional models (Swanson, 1995). Several flux boundary conditions such as infiltration, evaporation, and evapotranspiration are being included in new models in order to model the behavior as realistically as possible. These approaches appear to be useful in the design of soil cover systems.

Several one dimensional models to model the saturated-unsaturated flow conditions (Akindunni et al. 1991, Abdul 1985) using capillary barrier concepts are available. Complex boundary conditions such as atmospheric forcing and plant root uptake are also incorporated into some of the presently available one dimensional models, such as the SWIM model (Soil Water Infiltration and Movement: CSIRO, 1990). Atmospheric forcing models that incorporate the coupled solution of heat and water (liquid and vapour) transfer have been applied to the modelling of engineered soil cover systems (Swanson 1995). Wilson et al. (1994) proposed a one dimensional theoretical heat and water transport model coupled to the atmosphere through a modified Penman formulation which allows the calculation of evaporation from an unsaturated soil surface. Several modifications have been made (and are still being made) to this physically based computer model called SoilCover (MEND 1993) at the University of Saskatchewan (Wilson 1990, Joshi 1993, Machibroda 1994, Cook 1994, Newman 1996). Swanson et al. (1995) used SoilCover (MEND 1993) to model the performance of the soil cover system placed at Equity Silver Mines Ltd. located in British Columbia, Canada (see Chapter 3.2) and at Golden Sunlight Mines Ltd. located in Montana, U.S.A (see Chapter 3.3).

The application of two dimensional soil cover system modelling using coupled heat and mass transfer, saturated-unsaturated models would offer a distinct advantage of being able to account for lateral movement in and beneath the cover to provide a fully mechanistic description of flow in two dimensions.

The HELP model (Hydrological Evaluation of Landfill Performance: Schroeder et al. 1984) is one such model. Several researchers used this model for analyzing cover behavior (Hollingshead et al. 1985, Woyshner and Yanful 1993). The main disadvantage of the HELP model is that it is not capable of computing water contents.

SEEP/W (Geo-Slope 1993) is a two dimensional finite element saturated-unsaturated flow model. The SEEP/W model has been used in combination with the HELP model (Woyshner and Yanful 1993, and Bews et al. 1994). The estimates from the HELP model can be used as input into SEEP/W software to describe two dimensional flow in the vicinity of the cover (Bews et al. 1994). Woyshner and Yanful (1993) used a similar approach in the analysis of a composite soil cover for an acid generating tailings facility. Collin and Rasmusson (1990) utilized the two dimensional model, TRUST to illustrate the capillary barrier concept for oxygen limiting soil cover systems.

2.6.2 Oxygen Flux Modelling

The effective oxygen diffusion coefficient is related to the degree of saturation in a soil. Hence, modelling moisture flux is a prelude to the determination of oxygen flux rates in the soil cover system. The general methodology used to calculate oxidation rates in the evaluation of an engineered soil cover system is shown in Figure 2.7.

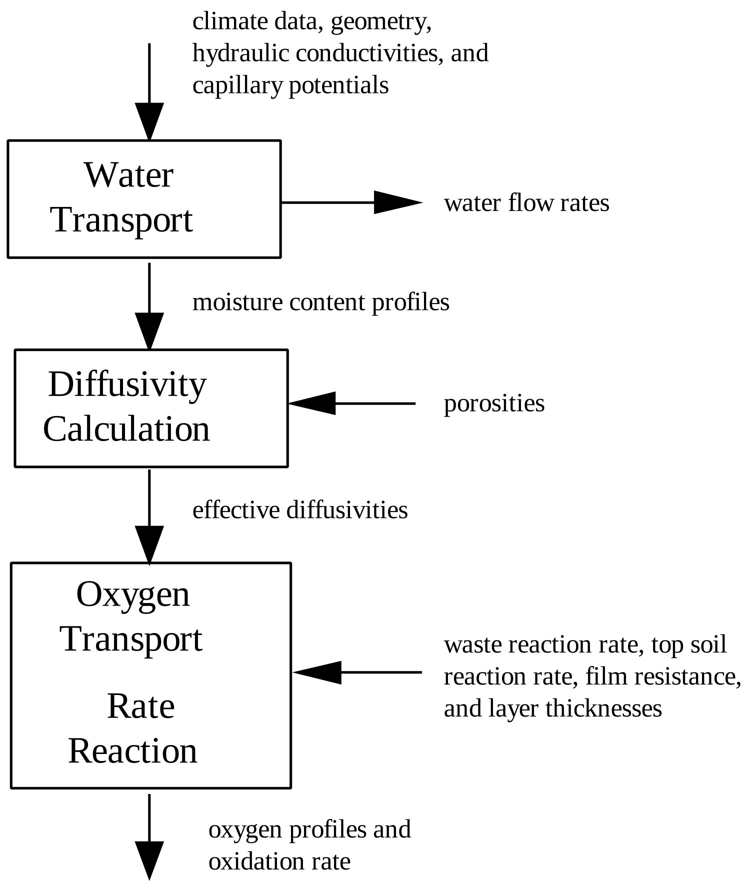


Figure 2.7 Methodology used to calculate oxidation rates in the evaluation of an engineered soil cover (from Collin and Rasmusson, 1990).

Water transport can be simulated by incorporating the appropriate boundary conditions, climate, soil properties, and geometry in one or two dimensional flow models. The estimated simulations of degree of saturations are then used to predict the oxygen diffusion coefficients throughout the period of simulation using empirical methods such as those established by Millington and Shearer (1971). Oxygen transport can be simulated using the mean diffusion coefficients for the entire soil cover system and assuming steady state diffusion in the soil cover system. Transient oxygen transport can also be simulated using mass transport programs such as POLLUTE (Rowe and Booker 1990).

2.7 SUMMARY

The analyses and design of engineered soil covers is summarized in the following steps:

- Measure key soil properties (e.g. soil water characteristic curve and saturated hydraulic conductivity) for candidate soils and waste materials.
- Select appropriate soil materials for selective layering to satisfy the capillary barrier concept.
- Identify, collect, and summarize climatic information such as air temperature, precipitation, evaporation, relative humidity, wind speed, and net radiation. These parameters significantly influence the performance of soil cover system.
- Monitor the cover performance insitu.
- Predict the storage and movement of moisture in the soil cover system in response to climatic conditions. An appropriate model is required to predict the performance of the soil cover. The moisture movement in the saturated and unsaturated zones can be predicted using the principles of unsaturated soil mechanics (Wilson et al. 1994). The data collected from steps 2, 3, and 4 above are necessary to predict the performance of an engineered soil cover systems. Figures 2.8 to 2.11 inclusive illustrate the various states in the generalized methodology outlined above for preliminary modelling, field response, and predictive modelling as summarized by Swanson (1995).

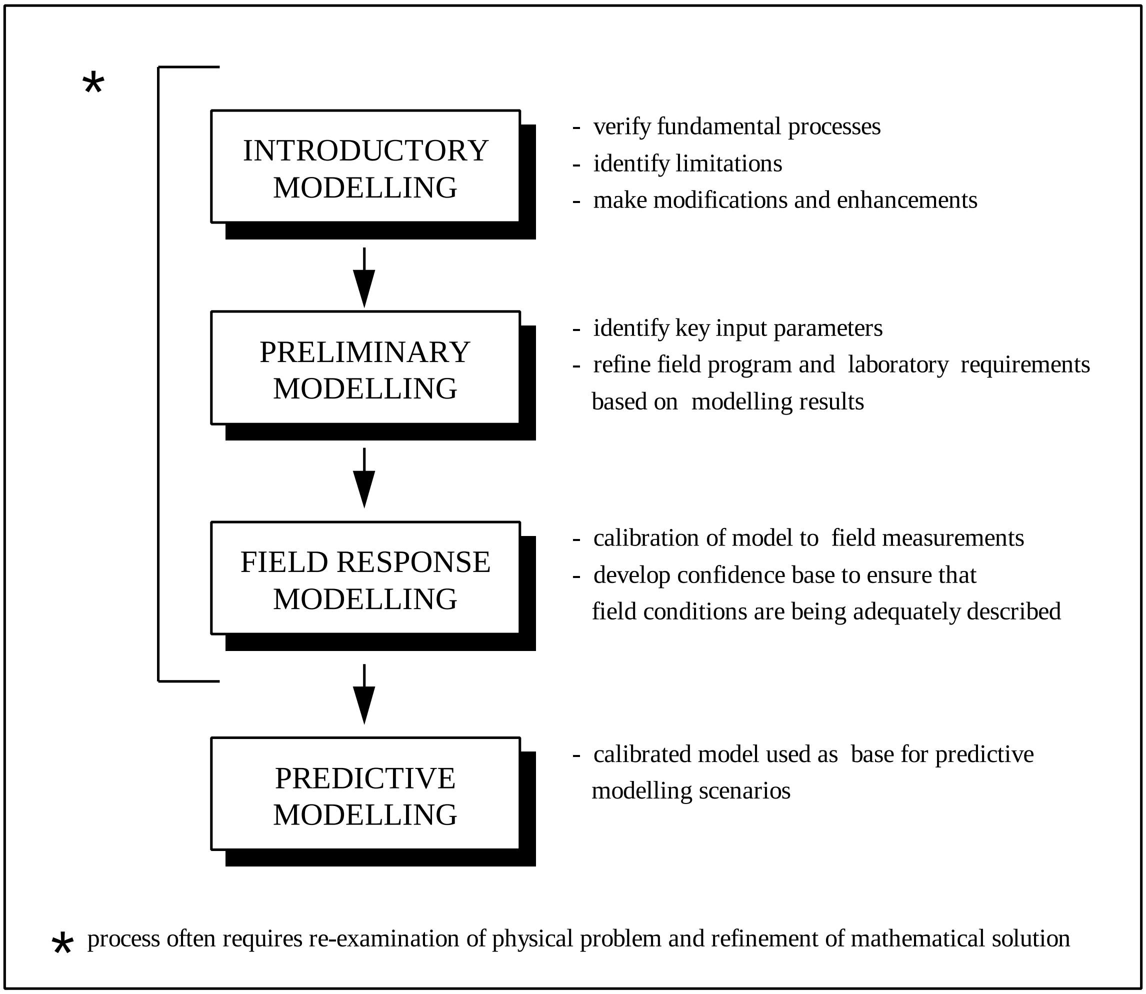


Figure 2.8 Generalized cover modelling methodology.

PRELIMINARY MODELLING

Initial Soil Property Estimation

- estimates of moisture retention and Ksat for coarse soils using "TheHyProS" (Tarnawski and Wagner, 1992)
- estimates of moisture retention and Ksat for compacted soils based on literature
- estimates of thermal properties for all soils using "TheHyProS" (Tarnawski and Wagner, 1991)
- estimates of oxygen diffusion coefficients using methods described by Collin and Rasmuson (1988)

Site Specific and Regional Climate Data Analyses

- review of available data to compare site to regional climate data if possible
- determine data requirements

Parametric Sensitivity Analyses

- identification of key soil properties, climate parameters, and boundary conditions
- may be based on previous experience or on quantitative analyses

Refinement of Laboratory and Field Program

- importance of various soil properties based on parametric sensitivity analyses
- may require more accurate soil, climate, or boundary condition data

Refinement of Model

- model may require modification or enhancement based on requirements of situation

Figure 2.9 Summation of preliminary modelling details and methodology recommended for soil-atmosphere modelling of engineered soil covers for acid generating mine wastes.

FIELD RESPONSE MODELLING

Soil Properties

Hydraulic Properties

- lab tests for moisture retention.
- Ksat from lab or field tests.
- Kunsat from Kcal (Geo -Slope Int, 1993) for low and medium Ksat soils and from Mualem (1976) as suggested by van Genuchten (1980) for high Ksat soils

Thermal Properties

- estimate using particle size and porosity/density as input to "TheHyProS" (Tarnawski and Wagner, 1993)

Oxygen Diffusion

- lab test required for compacted soils
- for uncompacted soils estimates can be made from empirical methods described by Collin and Rasmuson (1988)

Climate Data

Rainfall

- hourly site data or daily site data with regional intensity-duration curves

Net Radiation

- site data required where potential evaporation is expected to occurr the majority of simulated days
- regional estimates from daily sunshine hours or global solar radiation using the method of Maidment (1993) are adequate for regions where actual evaporation is expected to be less than potential evaporation for majority of simulated days
- where regional data used, calibration of Maidment (1993) method to site data recommenended for one summer

Average Wind Speed

- site data recomended. Regional data adequate if monthly average similar to site

Air Temperature

- max. and min. site data if detailed analysis of heat flow required.
- regional daily values are adequate for moisture flow analysis

Relative Humidity

- regional daily values adequate

Vegetation Data

Leaf Area Indices

- site measurements recommended to determine maximum LAI during growing season
- can use data from HELP manual for variation during growing season
- if site data not available, data from HELP User's manual can be used to define high and low ranges

Root Depth

- physical examination recommended
- examination of dried samples of seed mixture from local labs can provide intial model data

Boundary Conditions

Hydraulic Boundaries

- accuracy required depends on preliminary modelling results
- suctions should be used where data available
- if suction data unavailable can use water content data provided moisture retention properties are known with confidence.
- review of literature on similar materials can provide useful estimates

Thermal Boundaries

- rough estimate adequate for moisture flow analysis
- measurements required for detailed heat flow analysis
- surface temperature data required for at least two hot dry days to verify surface temperature calculation.

Field Response Measurements

Water Content Profiles

- essential for calibration
- readings once per two weeks where suction data not available and once per four weeks where suction data available
- readings required for vegetated and non-vegetated profile

Matric Suction

- recommeded for calibration of Ksat and essential for model development
- important near soil surface

Soil Temperature

- essential for model development and study of diurnal variations
- at least twice per month for calibration with emphasis near surface

Lysimeter Data

- highly recommended
- readings twice per month during snow melt and once per month otherwise

Runoff Data

- highly recommended
- measurements during spring snowmelt and after heavy rainfall events

Calibration Methodology

Potential Evaporation

- calibrate roughly to regional PE data through modification of net radiation

Moisture Retention

- adjust to field porosities
- adjust to fit field water content and suction readings

Saturated Hydraulic Conductivity

- calibrate to matric suction response with particular emphasis near the top 15 cm of the soil profile

Thermal Properties

- calibration not normally required for non-freezing conditions.

Figure 2.10 Field response modelling details and methodology recommended for soil-atmosphere modelling of engineered soil covers for acid generating mine wastes.

PREDICTIVE MODELLING

Determination of Extreme and Mean Years

- based on historical regional daily precipitation data base
- extreme dry year based on lowest amount of non-winter rainfall
- extreme wet year based on highest annual precipitation
- mean year depends on objective of analyses (either lowest non-winter rainfall where cover saturations of concern or most annual precipitation where cover infiltration of conern)
- evaporation climate parameters based on regional climate normals.
- net radiation estimates based on sunshine hours or global solar radiation using the method of Maidment (1993). For wet years, values for net radiation should be reduced by 50 % on days where rainfall occurs
- knowledge of the extent of snowpack development and snowmelt duration required for prediction of net moisture fluxes through cover
- review of site lysimeter data useful in evaluating percolation predictions

Predictive Modelling Scenarios

- simulations run for non-winter months
- predictive modelling scenarios should reflect parameters that are uncertain and parameters to which the model output is sensitive to. For example,
    - saturated hydraulic conductivity
    - vegetation thickness
    - amount and duration of snow melt
    - lower boundary condition

Coupling to 2-Dimensional Flow Models

- net percolation through cover should be used as input to regional model. The surface flux boundary determined from soil-atmosphere modelling is too dynamic for input into a regional model. Net percolation provides a more dampened boundary condition resulting in improved numerical stability and the use of larger time increments.

Figure 2.11 Predictive modelling details and methodology recommended for soil-atmosphere modelling of engineered soil covers for acid generating mine wastes.

CHAPTER 3

CASE HISTORIES

3.1 GENERAL

Chapter 3 provides information on soil cover systems at a number of mines throughout the world. The properties of the cover materials, the design considerations, construction techniques, monitoring data, and the performance of these cover systems are described. Cost details are also provided wherever information was available.

3.2 EQUITY SILVER MINES LTD.

3.2.1 Site Description

The Equity Silver Mine is located in north-central British Columbia, Canada in a sub-humid area, 35 km south east of Houston, British Columbia at approximately 56 degrees north latitude. The site is owned by Placer Dome Canada Ltd. and Equity Silver Mines Ltd., Canada (Figure 3.1) and was operated by Equity Silver Mines Limited. This region has an average annual precipitation of 570 mm per year and an estimated average annual evaporation of 300 mm. A detailed description of the Equity Silver Mine site is given by Swanson (1995) and O'Kane (1996).

3.2.2 Waste Material

Silver, copper and gold ore were extracted from open pit zones from 1980 to 1992 (Patterson 1992). The waste rock contains 2 to 3% pyritic sulphide and was estimated at 85 million tonnes by the end of 1991 (SENES 1991). The waste rock was deposited in three main areas; the Main dump, the Southern Tails dump, and the Bessemer dump.

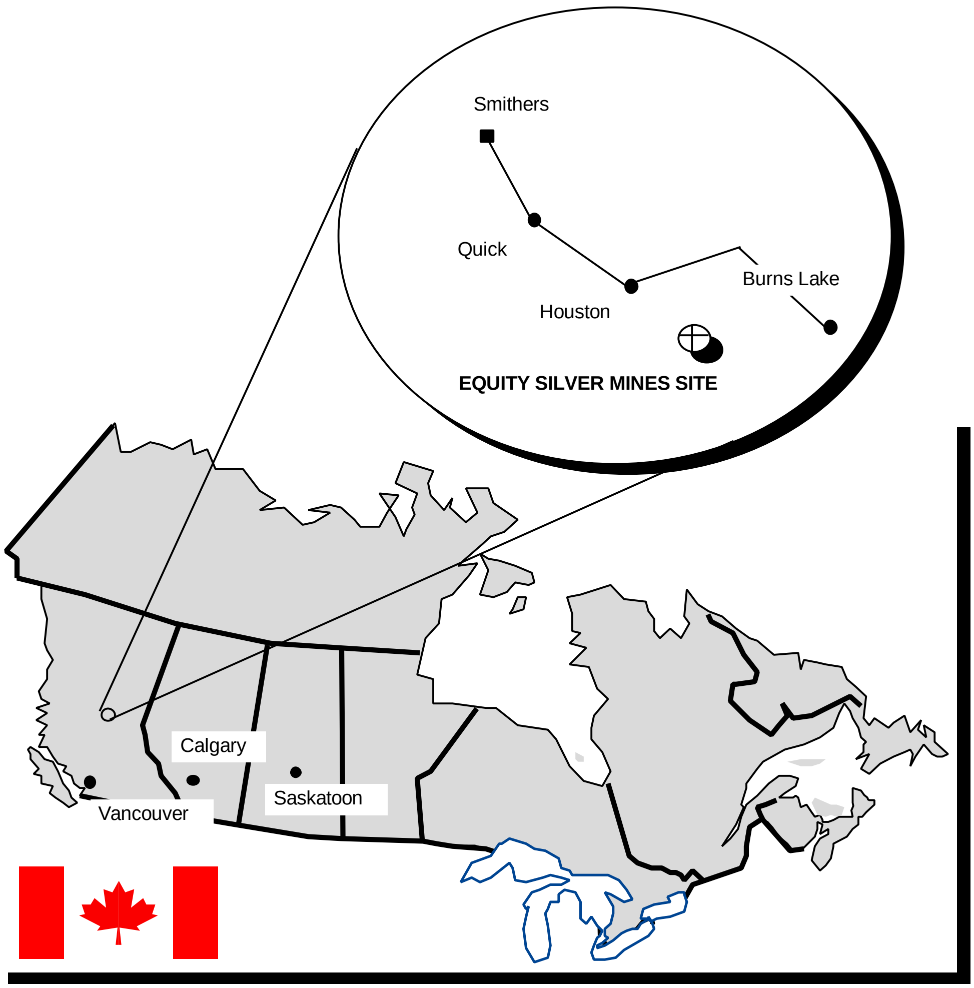


Figure 3.1 Location of Equity Silver Mine (from Swanson 1995).

3.2.3 History of the Soil Cover System

Full scale operation at the mine ceased in 1994. An effluent collection and lime treatment system has been in operation to treat the leachate over the last 10 years. The construction of the soil cover system on the Main dump was started in 1991. Thirty hectares of the Main dump was covered in the first year and the remainder of the dump was covered in 1994. Placement of the soil cover system on the Southern Tails dump started in 1990 with approximately 11 hectares being completed. The entire 26 hectare dump was completed in 1991.

Patterson (1992) estimated that the cost of soil cover system was approximately \$34,000/hectare. The relatively low costs were possible due mainly to the use of material available in large quantities in the vicinity of the site.

3.2.4 Design

The soil cover system relies on a low hydraulic conductivity and high moisture retaining layer. The cover consists of a 50 cm layer of compacted glacial till overlain by a 30 cm uncompacted glacial till layer. The two layers were placed directly over the waste rock surface. A thin compacted zone consisting of crushed waste rock from construction equipment is thought to exist beneath the cover and original waste rock (Swanson 1995) and acts as the lower capillary break layer. The upper non compacted layer was vegetated.

Reducing infiltration into the waste rock was the main consideration during the initial design of the cover. The effects of the potential reduction in oxygen influx due to the cover was later studied by SENES (1994) which used the RATAP model to perform a detailed acid generation study focusing on the geochemical aspect of acid generation. The University of Saskatchewan was contracted by Placer Dome Canada Ltd. to conduct a detailed study of the performance of the soil cover system taking into account the surface flux boundary conditions in 1993 (Swanson 1995). The research program included soil cover instrumentation and laboratory characterization as well as numerical modelling. The results of the laboratory tests and site investigations are reported by O'Kane (1996) and the numerical modelling analyses are reported by Swanson (1995).

3.2.5 Soil Characterization

O'Kane (1996) completed a detailed characterization of the soil cover material. The tests include the index properties of the cover material, standard compaction tests, consolidation-K_{sat}, and soil water characteristics tests. The till used for both layers of the soil cover system was classified as SC-CL. The material consists of 23% gravel, 28% sand, 40% silt, and 9% clay sized particles. The soil particle distribution curve for the till cover is shown in Figure 3.2.

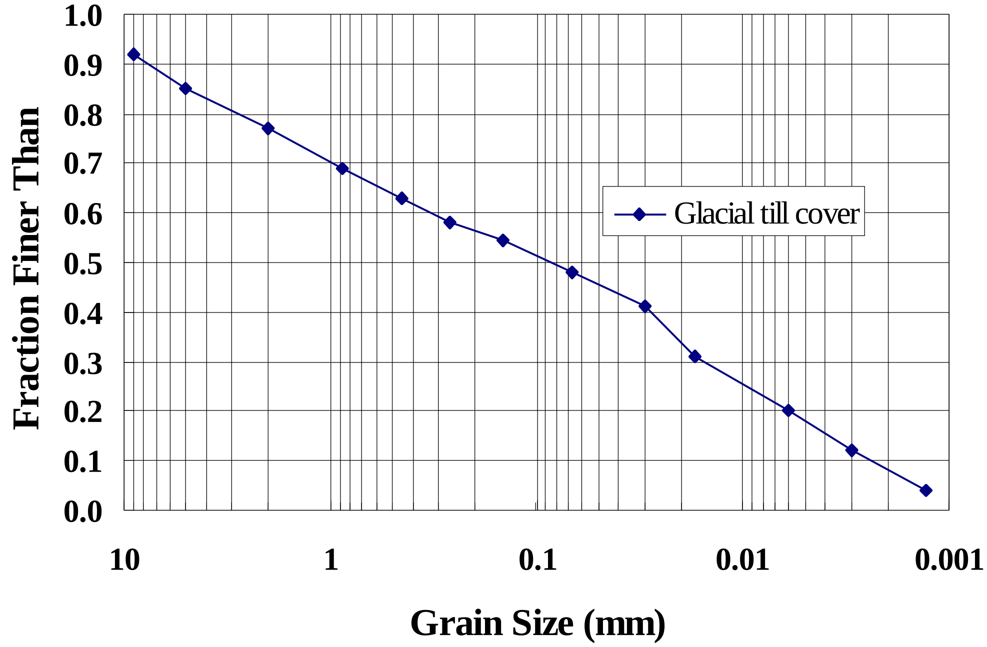


Figure 3.2 Grain size distribution of the glacial till cover material (from O'Kane, 1996).

The saturated hydraulic conductivity for the uncompacted and compacted till materials were reported by SENES (1991) as 5.7 x 10^{-7} cm/s and 2 x 10^{-8} cm/s respectively. O'Kane (1996) reported similar values for the compacted till based on laboratory testing. The soil water characteristic curves for the cover material tested by O'Kane (1996) at both 2% wet of optimum and 2% dry of optimum are shown in Figure 3.3.

3.2.6 Cover Monitoring and Performance

Several sets of instrumentation were installed by both the University of Saskatchewan and Equity Silver Mines to monitor the field performance of the constructed soil cover system. The instruments include gaseous oxygen and carbon dioxide probes, thermistors, thermal conductivity sensors for measuring the matric suction, and a neutron moisture probe for measuring water content within the soil cover system. An automated weather station, jet fill tensiometers as well as local surface runoff reservoirs and field lysimeters (Klohn Leonoff 1991) were also installed. A detailed summary of field instrumentation is available in O'Kane (1996). An important feature of the instrumentation was the installation of field lysimeters for measuring infiltration from the base of the soil cover system.

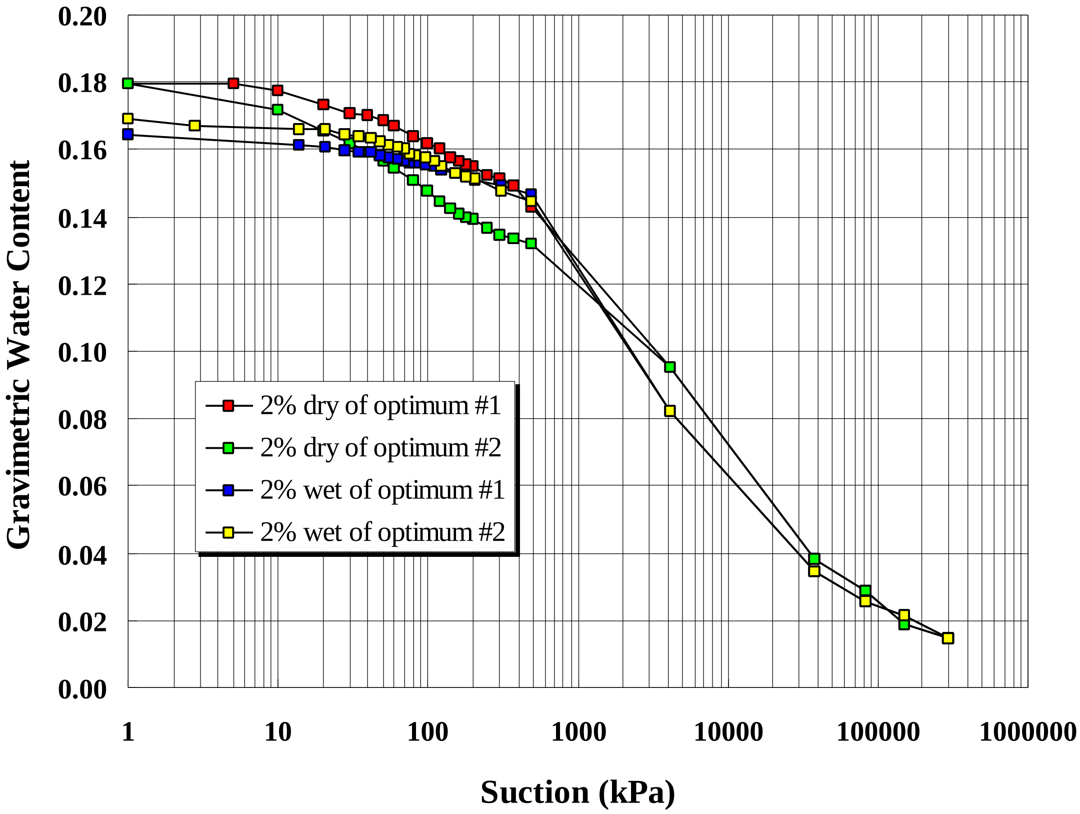


Figure 3.3 Soil water characteristic curves for the glacial till cover compacted both 2 % wet and 2 % dry of optimum (from O'Kane, 1996).

O'Kane et al. (1995) observed that the compacted till layer maintained a degree of saturation greater than 85% during the study period 1993. The moisture content of the upper non-compacted layer, however, fluctuated depending on the atmospheric demand and seasonal climatic condition. It was concluded that the atmospheric demand for soil moisture placed on the soil cover system was buffered by the non-compacted layer. This phenomenon was due to the higher hydraulic conductivity and storage available in the upper layer which allowed the movement of water to or from the soil atmosphere interface. The development of a capillary break at the interface of the waste rock and the lower compacted till layer prevented drainage of this lower layer.

The moisture contents of the upper half of the compacted layer (i.e., 1.0 to 1.4 m elevation in Figure 3.4) were close to 22% in the spring and 20% in the fall of 1993. The compacted soil was close to saturation at these moisture content values. A comparison between calculated and measured moisture contents is shown in Figure 3.4 and supports the existence of the capillary break phenomenon.

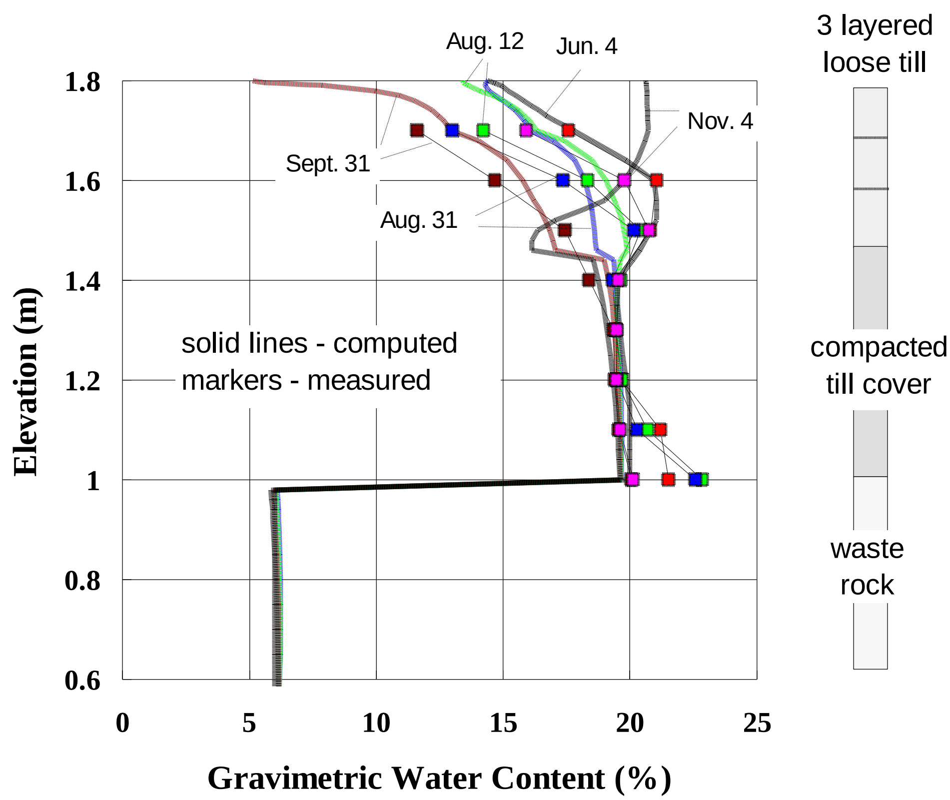


Figure 3.4 Comparison of gravimetric moisture contents measured and computed gravimetric moisture contents (from O'Kane 1996).

This soil cover system at Equity Silver Mines appears to be performing well under extreme climatic conditions (O'Kane et al. 1995 and Swanson 1995). Swanson's (1995) modelling predicted that the infiltration from the base of soil cover system was 3% of precipitation for an extreme wet year. The modelling studies also predicted that the oxygen flux to the waste rock material was reduced by 98% as compared to uncovered waste rock during an extreme dry year.

3.3 GOLDEN SUNLIGHT MINES LTD.

3.3.1 Site Description

The Golden Sunlight Mine is located in an arid alpine environment in Jefferson County, southwest Montana, USA (Figure 3.5). The mine is owned by Placer Dome Inc. and operated by Golden Sunlight Mines Ltd.

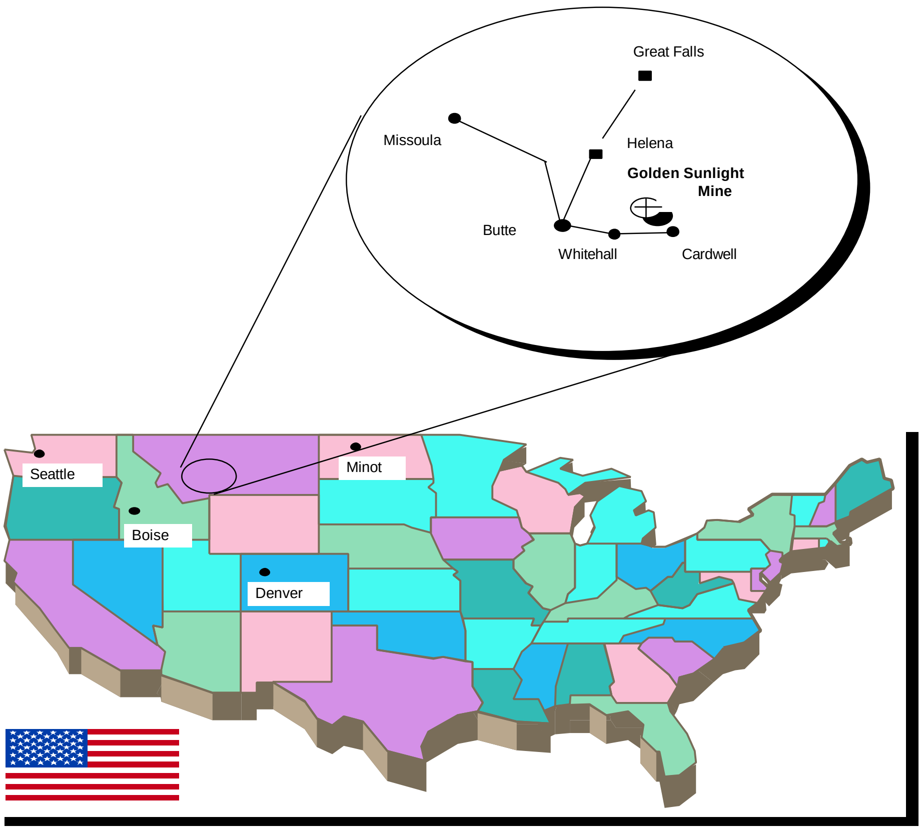


Figure 3.5 Location of Golden Sunlight Mine (from Swanson, 1995).

Open pit mining is used at this site and the waste rock is placed in dumps constructed by end dumping. The mine is expected to operate for at least 20 more years. The hilly topography of the mine site dictated that the waste rock dumps were constructed on fairly steep slopes. Revegetation, erosion control, and reduction of infiltration, were identified as the critical components in reclamation efforts. The current rehabilitation practices at the site include reduction of infiltration to the underlying waste rock, revegetation of the slope surface, erosion control through the use of a layered waste rock cover system (Swanson 1995). Field demonstration areas of the proposed soil cover system were built and monitored to verify the effectiveness of the proposed method. The soil cover system is shown in Figure 3.6.

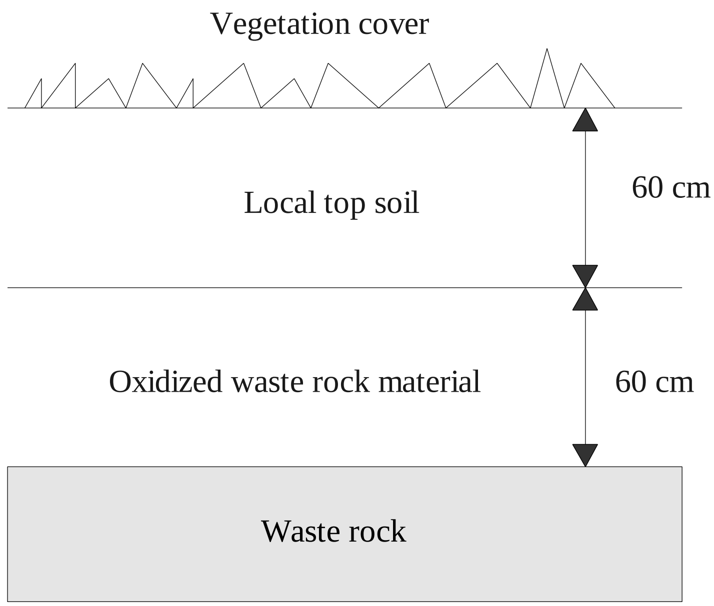


Figure 3.6 Soil cover system constructed at Golden Sunlight Mines Ltd.

3.3.2 Cover Design

Thermally driven air movement within the sulphide waste rock was thought to be one of the most important rate controlling factors in acid production at this site (Schaffer and Associates 1993). The infiltration of rain and snowmelt into the waste pile was another factor controlling the rate of acid mine drainage.

The rubble zone at the original dump toe was identified as a factor that led to an increase in gaseous oxygen concentrations into the pile. The slope of the waste rock dump was flattened in order to reduce the potential for advective air movement . The installation of the cover is expected to further reduce gaseous oxygen flux into the dump, increase runoff, and reduce infiltration rates (Schaffer and Associates 1993). The cover will also support the establishment of a vegetation layer which will reduce erosion of the soil cover system.

This mine is located in an arid climate with an average annual precipitation of 243 mm, where the yearly cumulative evaporation exceeds the annual precipitation. Since there was not a readily available source of fine grained material at the site the soil cover was designed as a moisture "store and release" system to take into account a moisture deficit that exists at the site (Swanson 1995).

The homogenization provided by reworking of the oxidized waste rock surface provides a benefit of removing surface openings for any preferential channels within waste rock which might allow rapid infiltration of oxygen and water.

3.3.3 Soil Characterization

A detailed soil characterization of the cover material was carried out by Yazdani (1996). The grain size distribution curves for the cover materials are shown in Figure 3.7.

These materials do not show a sharp contrast in grain size distribution. The saturated hydraulic conductivity of the oxidized waste rock (oxidized cap, bottom layer) was 1.10×10^{-5} cm/sec. The soil water characteristic curve for the waste rock, oxidized cap, and top soil materials are shown in Figure 3.8 (Yazdani 1996).

3.3.4 Details of the Soil Cover

The soil cover consists of a 60 cm layer of oxidized waste rock cap material overlain with another 60 cm layer of top soil. The top soil layer is seeded to provide a vegetation layer (Figure 3.6).

3.3.5 Monitoring and Model Performance

Two monitoring programs are currently in progress. The first is the West Dump Hydrological study started in 1992 to investigate the effects of reclamation efforts on infiltration rates, oxidation, and oxygen movement. The second is the High Grade Waste Test Plot study which was initiated to address concerns regarding erosion and vegetation failure on the proposed 2:1 slope of the waste dump (Swanson 1995).

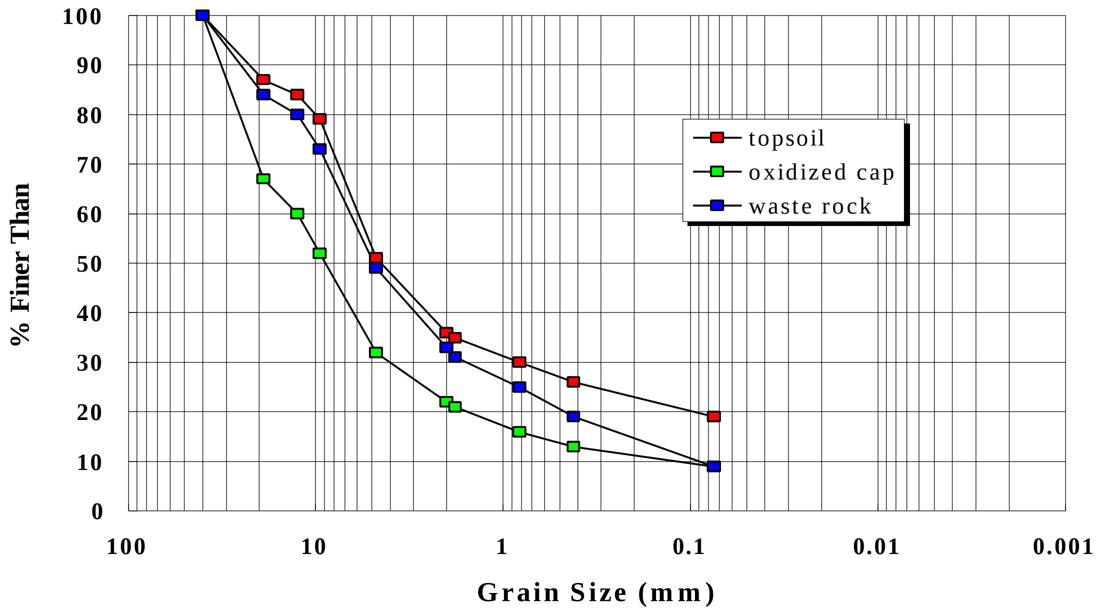


Figure 3.7 Grain size distribution for the topsoil, oxidized cap, and waste rock (from Yazdani, 1996).

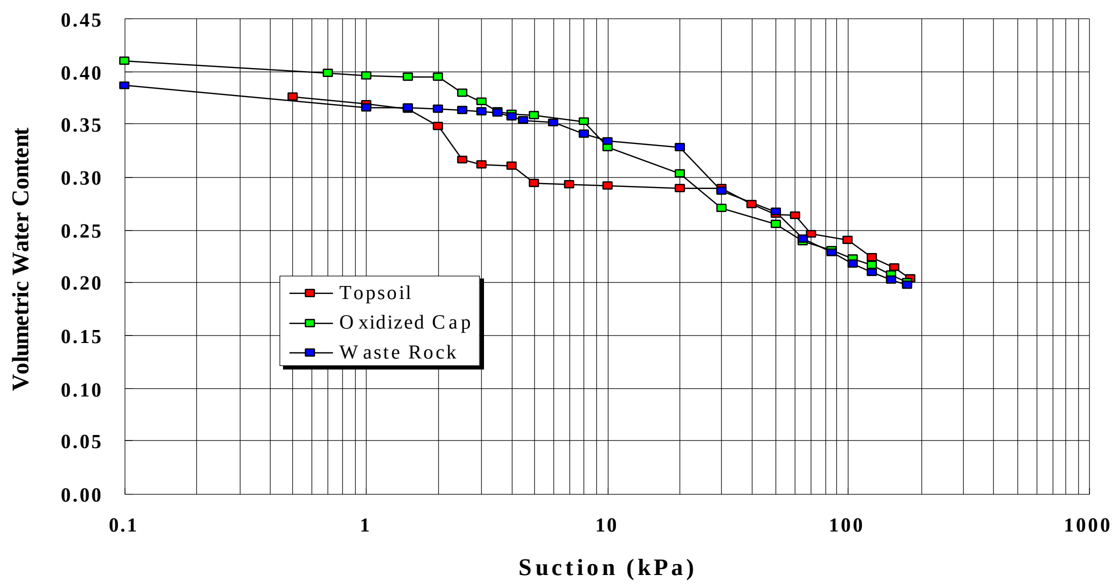
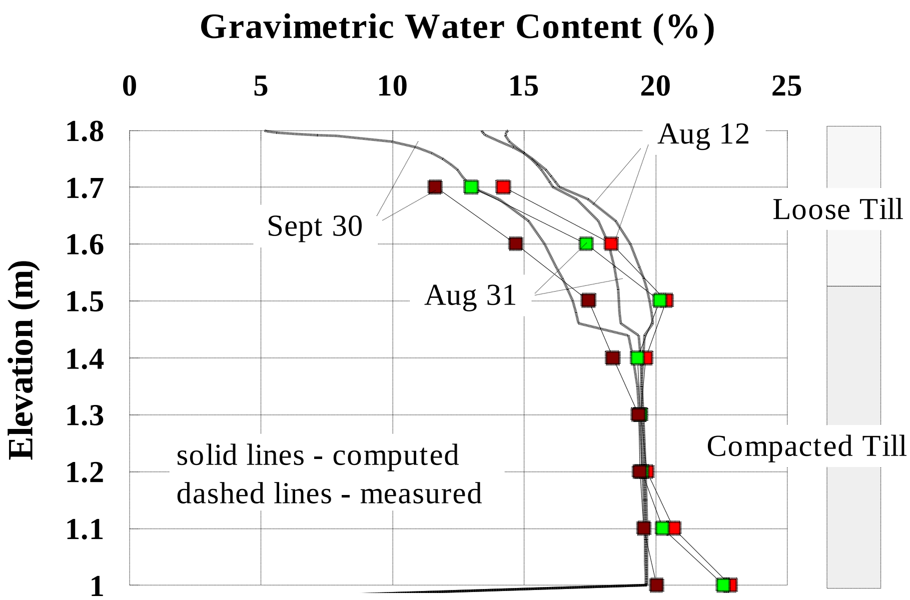
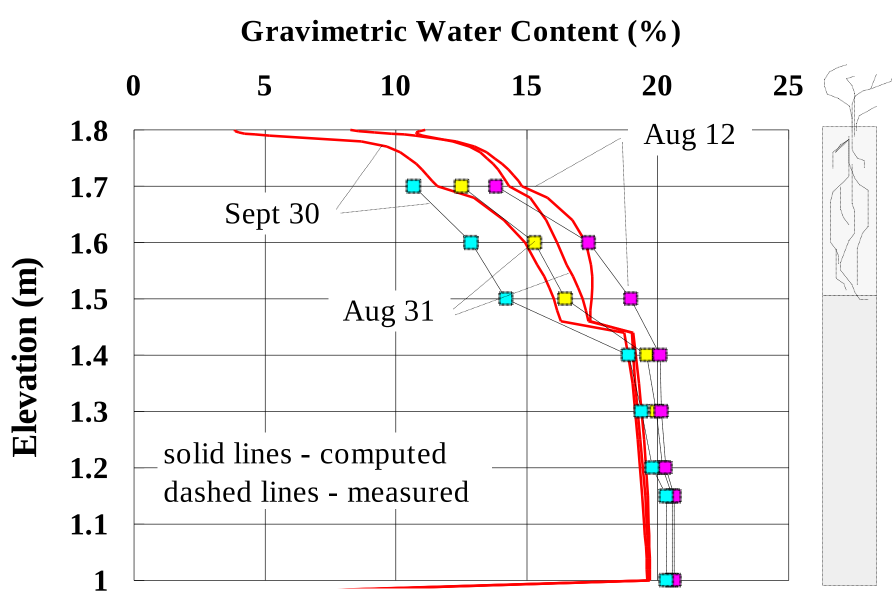


Figure 3.8 Soil water characteristic curves for the topsoil, oxidized cap, and waste rock (from Yazdani, 1996).

A study using the soil-atmosphere model, SoilCover (MEND 1993) demonstrated zero moisture flux from the base of the soil cover system, for both typical dry and mean year conditions. For an extreme wet year (assuming full snow pack development) the soil cover system limited the flux from the base of the soil cover system to 7% of annual precipitation (Swanson 1995). Figure 3.9 shows results for simulations of both bare soil and vegetated conditions (Swanson 1995).



a) Bare Soil



b) Vegetated cover

Figure 3.9 Measured and computed water content profiles for bare soil and vegetated covers (from Swanson, 1995).

3.4 HANFORD SITE

The U.S. Department of Energy (DOE) initiated an extended study program at the Hanford site near Richland, Washington, U.S.A. in 1985 to isolate and dispose of buried wastes over the long term. The Hanford site contains about 10.3% of all low level nuclear waste in the United States (Fisher 1986). Although it is not a acid mine waste site it provides valuable information on the use of layered soil systems and vegetation to control infiltration.

The site is located in south central Washington and has an arid climate with hot-dry summers and cool-wet winters. This area is characterized as a cool desert. The mean annual precipitation is about 162 mm which falls mainly in the winter. Long term extreme climatic analysis for 1000 years suggest that precipitation is bounded by three times normal precipitation limit and a maximum daily precipitation limit of about 70 mm (Petersen et al. 1995.)

3.4.1 Details of the Soil Cover

The key objective of the Hanford cover system was to isolate buried waste from environmental dispersion for at least 1,000 years. The Hanford Site Surface Barrier Development Program was initiated to design and test a soil cover system (barrier) that can be used to inhibit water infiltration, plant and animal intrusion, and wind and water erosion (Link et al. 1995).

The soil cover system consists of several layers of different soil materials such as fine soil, sand, gravel, rip rap, and asphalt to optimize barrier performance and longevity (Link et al. 1995). A typical cover system is shown in Figure 3.10.

The soil cover system at the Hanford site is essentially designed to control infiltration by partitioning precipitation into runoff and soil moisture storage (Petersen et al. 1995). Each layer has a specific purpose. The top vegetated fine soil layer acts as a medium in which moisture is stored until the processes of evaporation and transpiration return the water to the atmosphere. The coarse materials (e.g., sand, gravel and rip rap) below the fine soil layer provides a capillary break and restricts biointrusions. The asphalt concrete layer below the coarse materials is to divert any water that percolates through the capillary barrier from the waste zone.

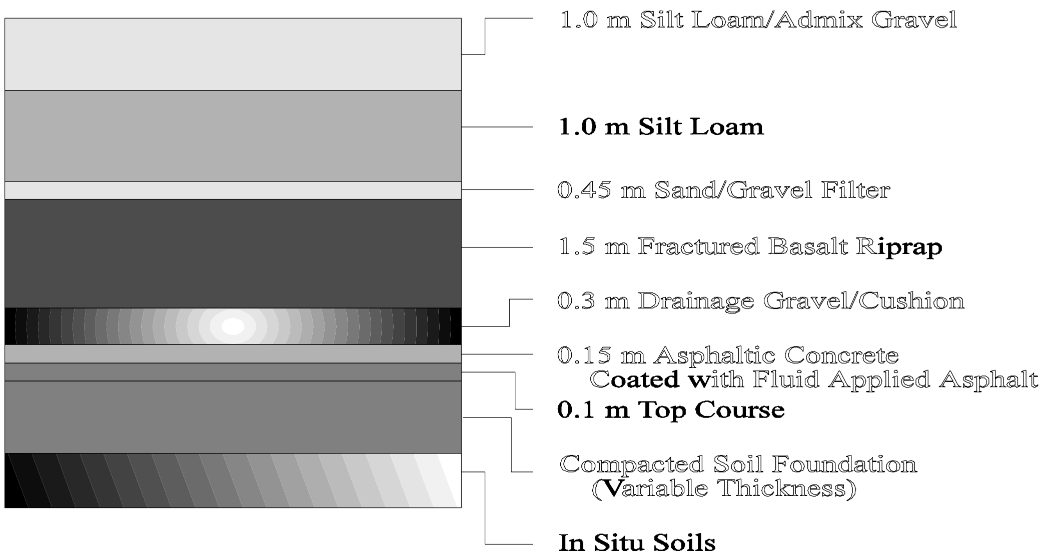


Figure 3.10 Cover system used at Hanford site

3.4.2 Performance of the Soil Cover

The effectiveness of the soil cover was studied using weighing lysimeters (Figure 3.11). These lysimeters were 1.5 x 1.5 x 1.7 m and contained 5,900 kg of soil (1.5 m deep). The soil was placed on a 0.2 m layer of sand in the lysimeter.

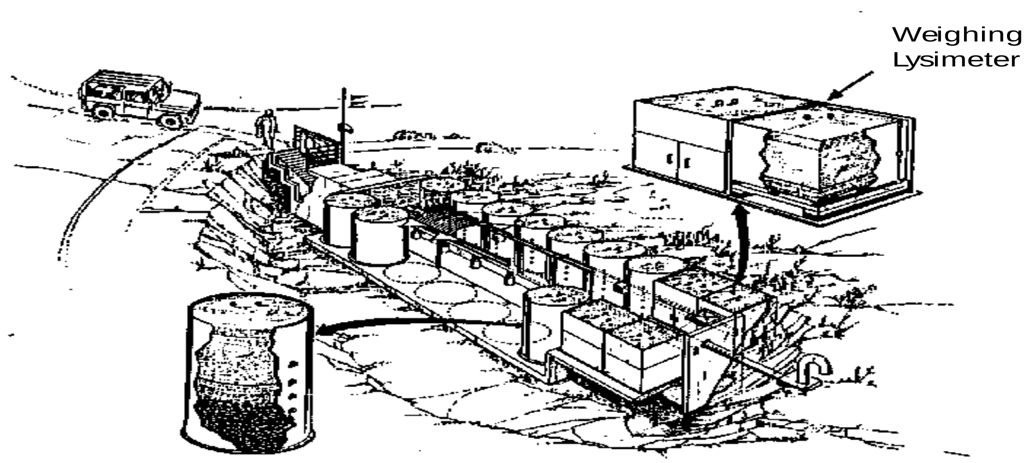


Figure 3.11 Weighing lysimeters at Hanford site (Petersen et al. 1995)

The bottom of the lysimeters were sloped with a drain port at the low point to measure discharge. Link et al. (1995) tested the hypothesis that a thick fine-grained soil layer over coarse sands would prevent drainage. Four treatment conditions were tested: ambient precipitation non-vegetated; ambient precipitation vegetated; additional precipitation non-vegetated; and additional precipitation vegetated. The additional precipitation used was two and three times the ambient precipitation which was 160 mm.

The key findings of the lysimeter studies conducted from 1987 to 1993 are as follows:

- The vegetated lysimeters maintained a smaller amount of storage (minimum values of around 90 mm) in comparison to non-vegetated lysimeters (i.e., minimum of 200 mm) for ambient precipitation conditions.
- The non-vegetated lysimeters always had more water stored in them than the vegetated lysimeters both under ambient precipitation conditions and precipitation conditions which were two or three times the ambient conditions.
- Drainage from the non-vegetated lysimeters was noticed only once in 1993 when the storage exceeded 500 mm (i.e., more than 3 times the ambient precipitation conditions).
- Vegetated lysimeters had minimum water storage which indicated that the plants used most of the water available to them.

Evapotranspiration at the site is able to return at least 480 mm/yr to the atmosphere. The success of the covers indicated that the capillary barrier phenomenon in conjunction with the use of vegetation to promote transpiration works well to prevent deep infiltration. These conclusions were derived from lysimeter results shown in Figure 3.12 and 3.13

The effect of surface conditions on soil water storage was also studied using small tube lysimeters made from 30 cm diameter plastic pipes with a length of 170 cm. The small tube lysimeter facility consists of an array of 21 rows of 5 lysimeters. Drainage is provided at the bottom end. The lysimeters were filled with silt loam overlying a capillary break consisting of sand on top of gravel (Link et al. 1995). The objectives of this study were to determine the optimum surface condition to minimize the potential for drainage and the effects of wind erosion.

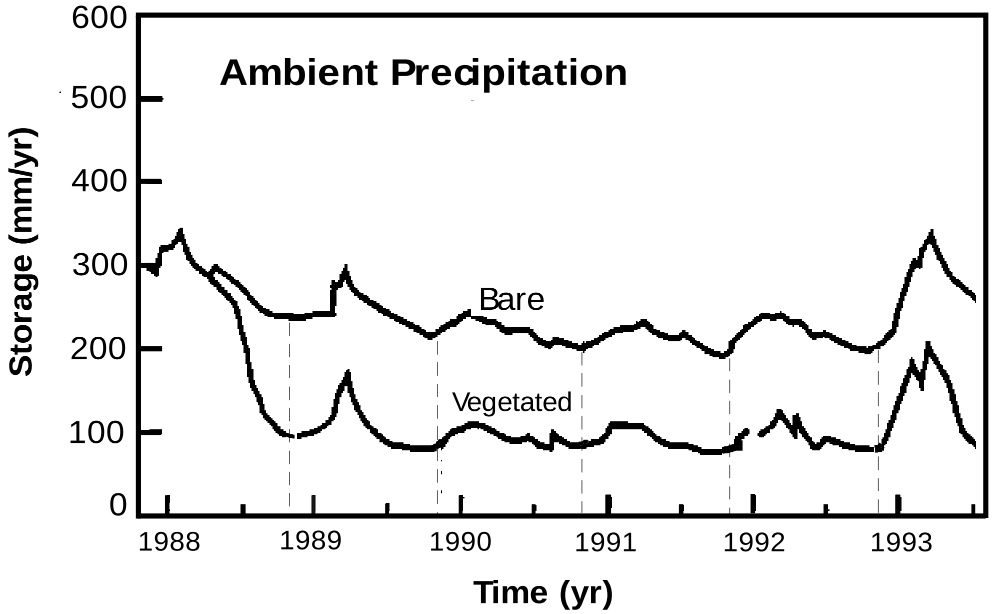


Figure 3.12 Water storage characteristics from weighing lysimeters (ambient precipitation conditions (from Link et al. 1995)).

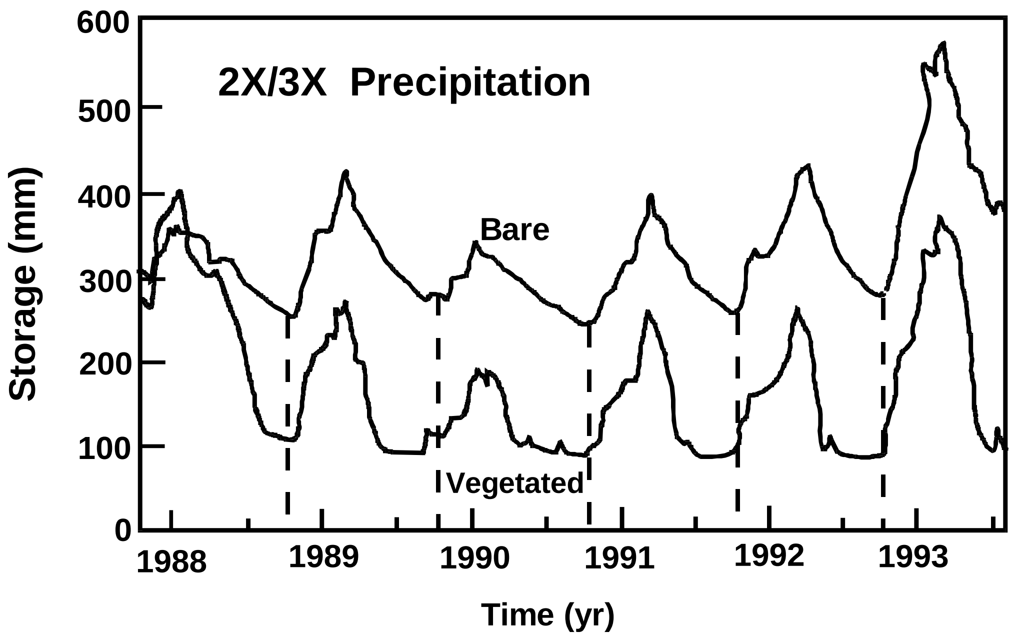


Figure 3.13 Water storage characteristics from weighing lysimeters (2X/ 3X ambient precipitation conditions (from Link et al. 1995)).

The simulated precipitation conditions were similar to earlier studies using weighing lysimeters having both vegetated and non-vegetated surfaces. Vegetation caused a greater decrease in storage than non-vegetated lysimeters. Link et al. (1995) have concluded that an admix surface (gravel mixed into the fine soil) with vegetation would also minimize the chance of wind erosion while not significantly the storage capability of the cover.

Studies to date at the Hanford site have shown that vegetation controls soil water storage and protects the soil cover system surface from wind and water erosion (Link et al 1995). The probability that roots will enter the buried wastes are remote since there will be a loose rock layer between the waste and surface soils. The roots will not enter under dry conditions, however under wetted condition the asphalt layer would prevent roots from entering into the waste below the asphalt. Burrowing small animals appear to have no significant consequences on soil water storage. Large animal burrows had some effect on storage during the winter, however, those increases in storage disappeared in the following spring or summer.

3.4.3 Modelling

Fayer (1995) (from Petersen et al. 1995) simulated the water movement in the soil cover system using six years of field lysimeter data. Two water balance models UNSAT-H and HELP were used. UNSAT-H is a physically based model while HELP is a model developed by the EPA to evaluate the performance of landfills. The following conclusions were derived from this study:

1. UNSAT-H modelling show little deviations from measured performances for different simulations using standard parameters, calibrated parameters, heat flow, and hysterisis.
2. Predictions of suctions were close to measured values using UNSAT-H modelling which included the effect of hysterisis.
3. Hysteristic behavior has a significant influence on the water movement behavior in soil covers. A closer examination of monitoring data from several field lysimeters also confirmed this behavior.

A comparison of measured (field) and simulated suctions with UNSAT-H is shown in Figure 3.14.

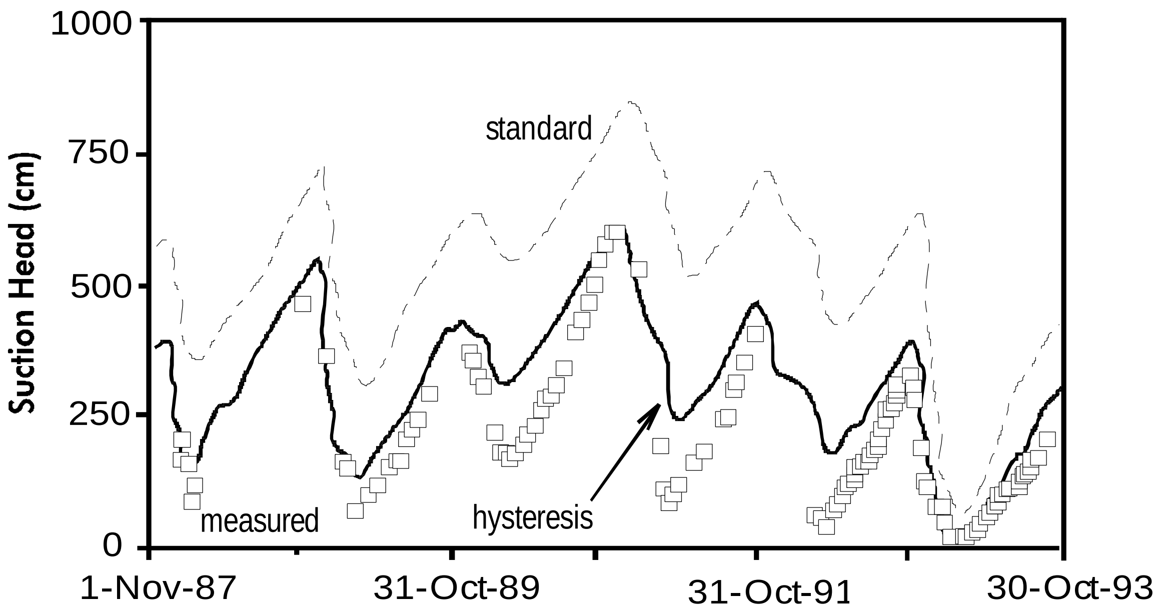


Figure 3.14 - Comparison of measured and suctions simulated with UNSAT-H (Petersen et al. 1995).

3.4.4 Prototype cover system

The program was extended to include building of a full-scale prototype soil cover system with a surface area of about 200 hectares. Petersen et al. (1995) detail the following objectives for the prototype cover:

- Obtain defensible probabilistic projections of the long term climate variability in the Hanford site .
- Develop several test-case climate scenarios that bracket the range of potential future climate.
- Use the climate scenarios to test (monitoring and instrumentation) and model the potential future climate.

A monitoring plan is proposed to collect data and information about the erosion behavior of the cover system under natural rainfall and snowmelt conditions. This will be used to evaluate the effectiveness of the pea-gravel admixture and vegetation in stabilizing the soil surface against erosive forces due to wind and weathering. The monitoring plan consists of the measurement of precipitation (rainfall and snow), run off of water-sediment mixtures, wind, water infiltration, creep, temperature, moisture content, and surface cracking. Figure 3.16 shows the layout of the surface grid and monitoring system. The construction cost of the system is estimated to be $ 300 K (US) per acre, which is approximately $100 (Canadian)/m^2 or $1,000,000 per ha.

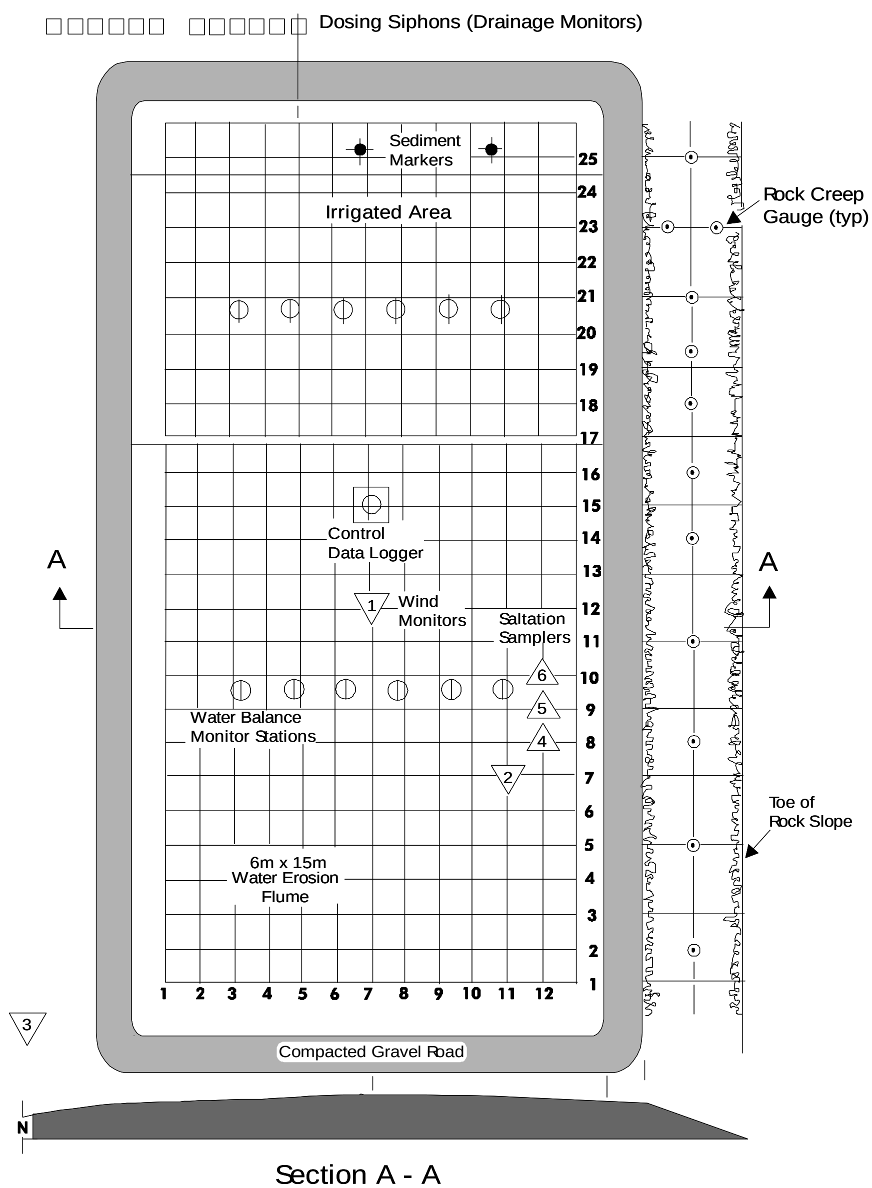


Figure 3.15 Layout of grid and monitoring system (from Petersen et al. 1995).

3.5 RUM JUNGLE

3.5.1 Site Description

The Rum Jungle mine is located in the Northern Territory, Australia, at a latitude of 13^{o} south. The mine was operational between 1954 and 1964 and was abandoned in 1971. The site is located in a tropical climate with a mean daily temperature of $25.1^{o}C$ in July and a maximum of $29.6^{o}C$ in November (MEND 1992).

3.5.2 Waste Material

Two waste rock dumps approximately 20 m high were constructed during the mining operation. The overall volume of waste was estimated to be approximately about 5 x 10^{6} m^{3} with an average sulphur content of 3%. The waste rock dumps and an abandoned experimental copper heap leach pile were identified as the major source of contamination at the site.

3.5.3 Design Details of the Cover

Reduction of acid mine drainage from the mine waste as well as the aesthetics of the site were considered the key issues to be addressed in the Rum Jungle mine rehabilitation program. The rehabilitation program focused on the reduction of the infiltration of air and water through the waste rock dumps. Prior to the placement of the cover the waste rock dumps were recontoured such that the top of the dumps were reshaped to a maximum slope of 5^{o} with a central drainage system. The sides were also recontoured to a maximum slope of 3H:1V with a berm half way down the slope. Engineered drop structures were provided to take water from the berms to the base of the waste rock dumps.

A composite cover consisting of a minimum of 22.5 cm of compacted clay overlain by a 25 cm thick sandy clay loam layer was constructed. The compacted layer was designed as a low hydraulic conductivity barrier and the upper layer was designed to retain moisture for vegetation and to prevent desiccation of the clay layer. The two layers were overlain by a gravelly sand with a minimum thickness of 150 mm to act as an erosion protection layer and to reduce evaporation. The top of the cover was vegetated for erosion protection as well as aesthetic purposes. The side slopes were covered with a minimum thickness of 30 cm compacted clay, 30 cm of sandy clay loam and 15 cm crushed rock.

3.5.4 Cover Monitoring and Performance

Temperature, gaseous oxygen and carbon dioxide concentrations were measured within the dumps prior to and after placement of the cover. The efficiency of the cover to reduce the infiltration of the water was studied using the lysimeters installed before the placement of the cover. A reduction in oxygen concentration in most regions of the dumps was observed following the placement of the cover (Bennett and Ritchie 1991). The decrease in oxygen concentration was attributed to a decrease in oxygen influx by convective air movement. The temperatures within the piles decreased and this trend was related to the decrease in the rate of acid production following construction of the soil cover system.

3.6 OTHER SOIL COVER SYSTEMS

The sites discussed earlier were complete soil cover systems. In this section other sites which provide information with respect to soil cover performance are summarized.

3.6.1 Mount Washington

The Mount Washington mine is located on Vancouver Island, Brtitish Columbia, Canada at an elevation of 1320 m. The mine site operated from December 1964 to March 1967. Two open pits (i.e., north and south) were developed during the life of the mine. Acidic drainage from the site and elevated copper concentrations seriously affected the fish stock for approximately twenty years after the mine was abandoned. Kwong and Ferguson (1990) suggested that acid generation was initiated by step wise oxidation of pyrrhotite, enhanced by the formation and dissolution of efflorescent minerals as well as the discharge of groundwater enriched in ferrous iron.

Loose waste rock was collected from the pit area and mixed with crushed limestone and spread over the East dump in 1988-89. This area was recontoured and covered with 1 m of glacial till. A branched diversion was also constructed upslope in the pit area to reduce water infiltration into the waste rock dump. Portions of the open pit were excavated to expose bedrock that was subsequently hydraulically cleaned in 1990-91.

Heavily mineralized areas were coated with an asphalt emulsion or a polyurethane sealant. The waste collected during the cleaning process was stockpiled with respect to sulphide content, and then contoured and encapsulated with a thin slab of concrete, a geotextile cover, or a compacted sand cover. The top layer was impregnated with asphalt emulsion or polyurethane sealant.

The monitoring results indicated that water quality has not improved since the start of the reclamation program. New information on the processes of acid generation and attenuation occurring at Mount Washington warrants a revision of the original abatement strategy to incorporate a more integrated approach to solving the acidic drainage problem. It was recommended that a series of wetland systems be developed downstream to complement the practice of controlling water and oxygen availability to acid-generating rocks in the North pit. Further abatement work at the minesite should take the local geology and mineralogy into consideration. Preservation and creation of reducing conditions in the pit area were highly recommended.

3.6.2 Saskatchewan Potash Tailings

Haug et al. (1991) describe the design and construction of a 20 m x 20 m experimental compacted till cover placed on potash tailings in Saskatchewan. The mean annual precipitation at the site varied from 350 to 450 mm (Haug et al. 1991). The soil cover system was designed as an infiltration barrier to prevent leaching of brine due to dissolution of salt from the potash tailings. The soil cover system is shown in Figure 3.16. A 50 cm coarse boulder capillary barrier was placed between a 100 cm compacted till layer and the potash tailings to prevent the movement of dissolved salt into the cover. The till layer was compacted in five equal lifts and overlain with 5 cm of granular material to minimize desiccation.

The coarse layer at the interface of the coarse layer and the till layer played a dual role in the design by preventing capillary rise of salt into the upper layers and providing a capillary break. The top layer acts as a storage layer. A 6 m x 6 m square lysimeter was installed under the soil cover system to measure infiltration. Water content, density, and hydraulic conductivity are measured periodically in the till layer.

The decision to separate the waste material from the till layer was based on the results of a three-year laboratory program to investigate potential cover materials for the potash tailings piles. Natural soil materials did not perform satisfactorily when place in contact with salt.

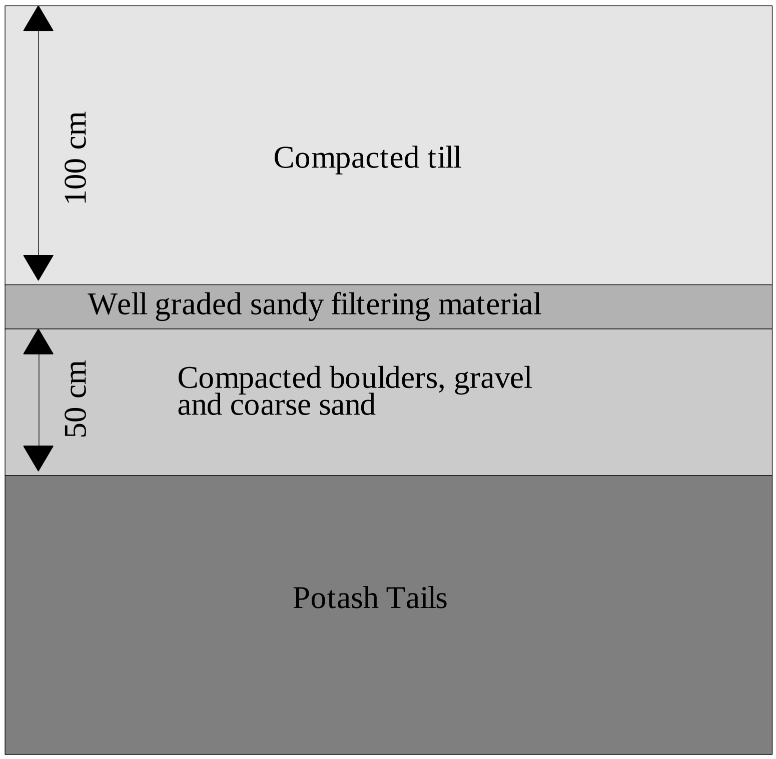


Figure 3.16 Glacial till cover at the Saskatchewan potash mine site.

3.6.3 NORWEGIAN MINES

Steffen, Robertson, and Kirsten (1991) have summarized recent Norwegian experience and technology on the remediation of acid rock drainage (ARD) at sulphide mines in Norway. The report provides information as to the immediate and long term effectiveness of the remediation measures taken by the Norwegian State Pollution Control Authority. The scope of the study was to provide a review of construction procedures, costs, and effectiveness and to evaluate the applicability of these remediation projects to Canadian mines.

3.6.3.1 Kjoli Mine

Copper was mined at the Kjoli mine in Norway, from 1766 to 1798 and from 1857 to 1868. Pyrite was exported during the early nineteenth century. A total of 80,000 m^3 of waste rock were deposited on an area of approximately 2 ha (Steffen, Robertson, and Kirsten 1991).

The final composition of the composite cover system is shown in Figure 3.17. Other construction details are available in Steffen, Robertson, and Kirsten (1991). The composite cover consisted of filter cloth placed directly on the waste rock pile followed by a 2 mm HDPE geomembrane. A geonet system was placed on top of the geomembrane to provide a drainage layer and was covered with a geofabric to serve as a filter. Two 50 cm lifts of till were then placed to provide a physical protective cover and a vegetation supporting layer (Steffen, Robertson, and Kirsten 1991). Riprap was placed on sloped areas to control erosion.

A total surface area of 27,000 m^2 was covered. The costs involved with this project was estimated at $ 10 (Canadian) per tonne of mine rock.

Three monitoring wells were installed to monitor temperature and oxygen within the waste rock pile in 1988. The gaseous oxygen concentration had remained at 20% during the 12-month period prior to construction of the cover. A rapid decrease in oxygen concentration was observed at all depths and locations following the installation of the cover. However, at some places higher oxygen concentrations were observed. It was concluded that the oxygen entry was due to a combination of 'barometric breathing' flows bypassing the edge of seals or convective flows along the base of the pile (Steffen, Robertson, and Kirsten 1991).

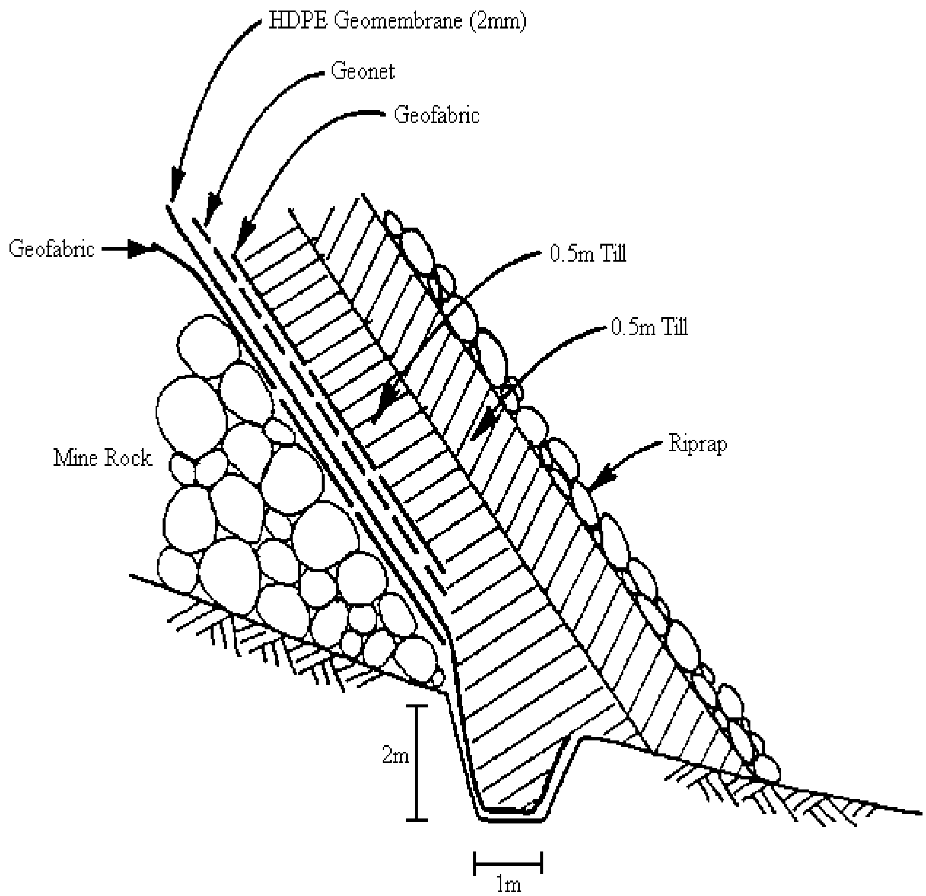


Figure 3.17 Cover composition and perimeter seal (from Steffen et al. 1991).

3.6.3.2 Lokken Mine

The first copper bearing pyrite was discovered in 1654 at the Lokken mine in Norway. The mine was located on the steep slope of the western embankment of the Raubekken stream near the village of Lokken Verk (Steffen, Robertson, and Kirsten 1991). The waste material was located at several sites on the property. A total of 2,000,000 tonnes of waste rock were deposited starting from 1920 (Steffen, Robertson, and Kirsten 1991). The southern piles oxidized more rapidly than the old pile.

The old pile was covered with 0.5 m till cover between 1975 and 1978. Steffen, Robertson, and Kirsten (1991) summarized the other remediative actions taken at the mine as:

- Providing a permanent water cover for the tailings dam;
- Placement of riprap on the slimes dam to the east of the Raubekken (for prevention of dust and erosion);
- Covering several acid generating waste rock piles with 0.5 m uncompacted sandy till;
- Revegetating the till covered mine rock piles; and,
- Construction of diversion ditching around subsidence zones in 1988 and 1989.

The remediation measures improved the water quality conditions at the mine site and the copper loading to the environment decreased from 73 tonnes to 48 tonnes per year. Further measures were being planned that will include modelling and laboratory studies. Extensive monitoring was planned to properly characterize existing conditions at the site including: water quality, dissolved oxygen with depth, COD, bacterial speciation, gas phase monitoring, tracer tests etc.

The remediation measures were designed based on the results of large scale studies which attempted to simulate the actual mine conditions. Changes in overall waste pile geometry and methods to improve future stability were designed to improve acid mine drainage. Economics associated with the cover and over all performance were not available.

3.7 SUMMARY

Several investigators have demonstrated that soil cover systems can be constructed in humid and arid environments to control acid mine drainage. There were no standard procedures or protocols developed in the literature for evaluating the construction and monitoring of soil cover system. Site and environmental conditions control the design specifications; however, no standard design methods for predicting the performance of soil cover systems has been utilized.

Detailed economics associated with the construction of soil covers are not available. However, actual costs are highly site specific. Feasby and Jones (1994) estimate the cost of rehabilitating acid-producing mine waste would be about $ 250,000 per hectare.

Williams (1995) estimated that soil cover systems for waste rock dumps cost up to \$50,000/ha in Australia. Progressive selective placement and covering can reduce this cost to between \$ 5,000 and \$ 10,000 per hectare. Reshaping of coal mine spoil piles cost in the range from \$ 15,000 to \$ 25,000. An upper range value of \$ 25,000 may be used as a guideline for wastes where acid mine drainage is involved. Vegetation costs are relatively small at about \$ 1,500 per hectare.

More full scale case studies are needed before any generalized recommendations can be made with respect to the economics of engineered soil covers.

CHAPTER 4

PRESENTATION OF DATA

4.1 INTRODUCTION

There are a number of sites around the world where natural soil cover systems have been used for rehabilitation of potentially acid generating waste rock and tailings. The design objectives vary from site to site; however, at most sites the soil covers were designed primarily to provide a low hydraulic conductivity barrier to minimize the influx of water, and to provide an oxygen diffusion barrier to minimize the influx of oxygen.

The studies related to the Heath Steele and Waite Amulet soil covers are well documented. A list of published studies pertinent to these projects are available in Appendix A.*

The primary objective of these two studies was to demonstrate the applicability of "multi-layered" soil cover systems for waste rock and tailings. The Heath Steele and Waite Amulet sites are the most prominent examples of soil cover designs engineered to provide these benefits. This chapter presents a synthesis of the pertinent details for these two sites including site description, soil properties, design considerations, cover performance and costs. Chapter 5 provides an independent scientific evaluation review of the design, construction, monitoring, and interpretation of the performance of these covers.

4.2 HEATH STEELE

4.2.1 Site Description

Heath Steele Mine (HSM) is located approximately 50 km northwest of Newcastle, New Brunswick (Figure 4.1). Sulphide ore deposits were discovered in 1953 and the mine has been operational since 1957 with the exception of two periods in 1958 and 1984 when operation was suspended as a result of low base metal prices and metallurgical problems encountered in the processing of oxidized portions of the ore (Yanful, Bell and Woyshner 1993). The site contains at least 756,000 tonnes of pyritic waste rock and reject ore, stockpiled in more than 20 piles ranging from 1,000 to 230,000 tonnes. Four waste rock piles were monitored to evaluate effective methods of long term management of acid generating waste rock.

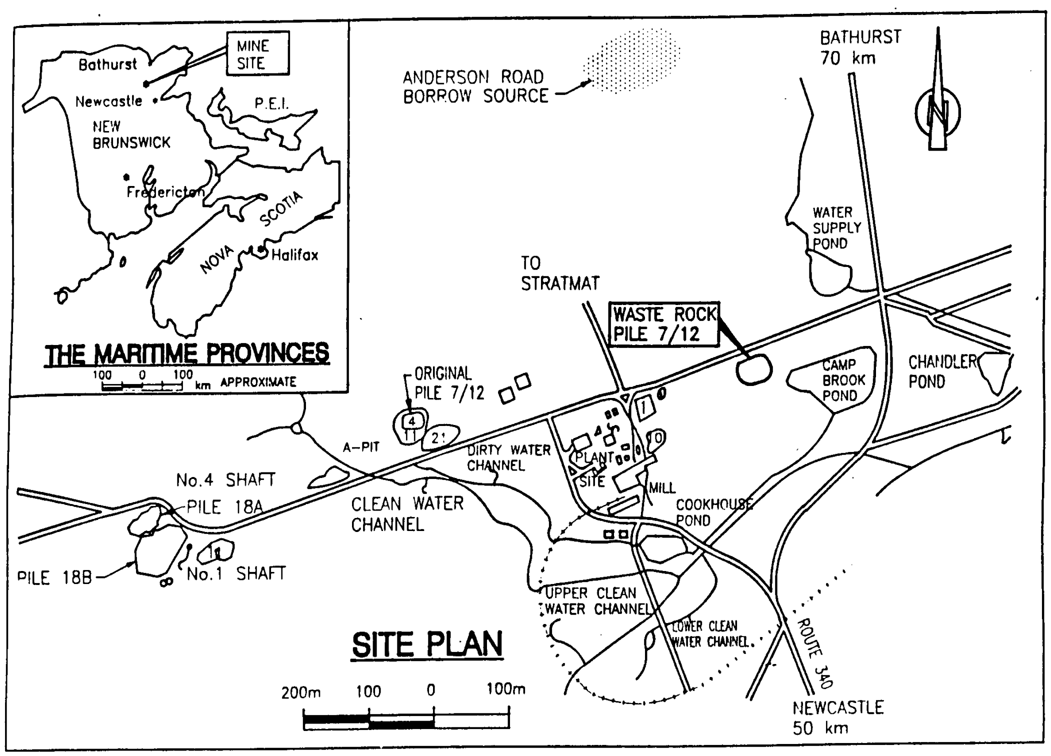


Figure 4.1 Site plan of Heath Steele Mines (from Yanful, Bell and Woyshner 1993).

4.2.2 Climate

The climate at the site is classified as Maritime continental. The mean annual precipitation at the Little River Mine AES station is 1134 mm with 762 mm as rainfall. An average of 135 days of precipitation per year is recorded at the station. Evaporation was measured at the site between June and November. The estimated potential evaporation at the Heath Steele site falls between a maximum of 35 mm in June to almost zero in November.

4.2.3 Study Program

The Heath Steele waste rock study is undertaken as a Mine Environment Neutral Drainage (MEND) program since 1989, and is sponsored by Brunswick Mining and Smelting (BMS), CANMET and the province of New Brunswick through the Canada /New Brunswick Mineral Development Agreement. This study was separated into four phases:

Phase (I) Selection of the waste rock piles suitable for monitoring and evaluation. (completed in the summer of 1988).

Phase (II) Installation of the monitoring equipment (completed in 1989).

Phase (III) Geotechnical and column testing of natural soils located in the vicinity of the HSM as potential cover materials (completed in 1990).

Phase (IV) Design, construction, and modelling at the soil cover system based on the results of Phase I, II, and III.

Four acid generating waste rock piles at HSM were monitored during the study. Detailed information is available in MEND (1992). The final phase of the HSM waste rock study included the construction of a multi-layer soil cover system based on the information collected in previous stages. Pile 7/12 was selected for construction of the soil cover system.

In 1989 Pile 7/12 was relocated to a 0.25 ha prepared sand base underlain by an impermeable synthetic membrane. The pile contained 14,000 tonnes of pyritic acid producing waste rock. The synthetic membrane isolated the waste rock pile from the effects of ground water and the oxygen flux from beneath the pile. Leachate was collected at the base of the pile before and after placement of the soil cover system to establish a water balance. Surface runoff was collected by a perimeter ditch. A maximum slope of 3:1 (H:V) was provided in the relocated pile. Table 4.1 summarizes the characteristics of Pile 7/12 and the waste rock

Table 4.1. Characteristics of relocated waste rock Pile 7/12 (from Yanful, Bell and Woyshner 1993)

Surface area	2100m^2
Average depth	2.9m
Maximum depth	5.0m
Sulphide mineralogy	
Pyrite	7-10%
FeS	5-7%
Pyrrhotite	<1%
Other sulphides (galena, sphalerite, etc.)	<1%
Total sulphur	5%
Theoretical acid production (as $CaCO_3$)	210.7 kg/t
Acid consumption (as $CaCO_3$)	0.4 kg/t

4.2.4 Soil Properties

The design of the experimental Heath Steele waste rock pile soil cover system, included the characterization of candidate cover materials in the vicinity of the mine with respect to their geotechnical and hydraulic properties. Sand and till material was located within 15 km of the site. Geotechnical tests such as grain size distribution, Atterberg limits, specific gravity, X-ray diffraction, chemical tests for defining mineralogy, and consolidation tests were performed on the sand and till materials. Hydraulic characteristics such as hydraulic conductivity, soil water characteristic curves and oxygen diffusion coefficients were also measured. Based on the laboratory tests a composite cover was selected for the site.

4.2.5 Design Considerations

The design of the soil cover system was based on the capillary barrier concept presented in Section 2.3.1. The final design consisted of a 30 cm thick sand base, a 60 cm thick compacted till layer, a 30 cm thick sand, and a final 10 cm thick gravel layer for erosion protection. Figure 4.2 shows the details of the soil cover system constructed on Pile 7/12. The compacted till layer and a sand base which form the soil cover are capable of providing a capillary barrier. The soil water characteristic curves of the soil cover materials shown in Figure 4.3 demonstrate that placing the compacted till on the sand base will create a capillary break at the interface of these two materials.

The sand material layer placed on the compacted till layer was to provide evaporation protection for the till material. The granular material reaches residual water content at a relatively low matric suction (e.g., 10 to 20 kPa) as shown in Figure 4.3.

Any threat to the integrity of the cover as a result of differential settlements were not considered to be critical because of the shallow depth of the pile. It was assumed that the cover was less susceptible to the effects of differential settlements since soils of low cohesion were used. The adverse effects of the climatic conditions such as wet-dry cycles and freeze-thaw cycles were moderated by using a multi-layer soil cover system as opposed to a single layer cover.

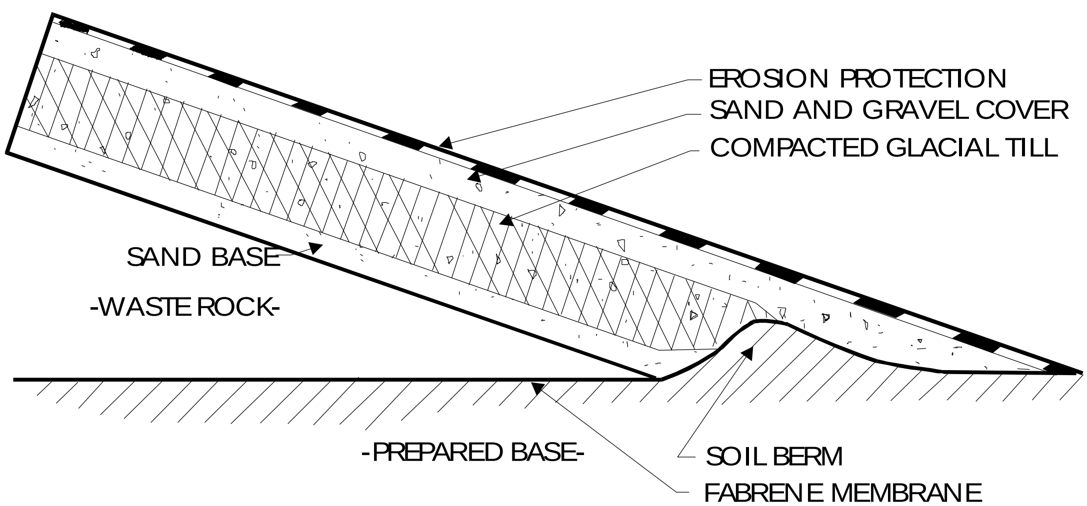


Figure 4.2 Soil cover system construction details at Heath Steele (Yanful, Riley, Woyshner and Duncan 1993).

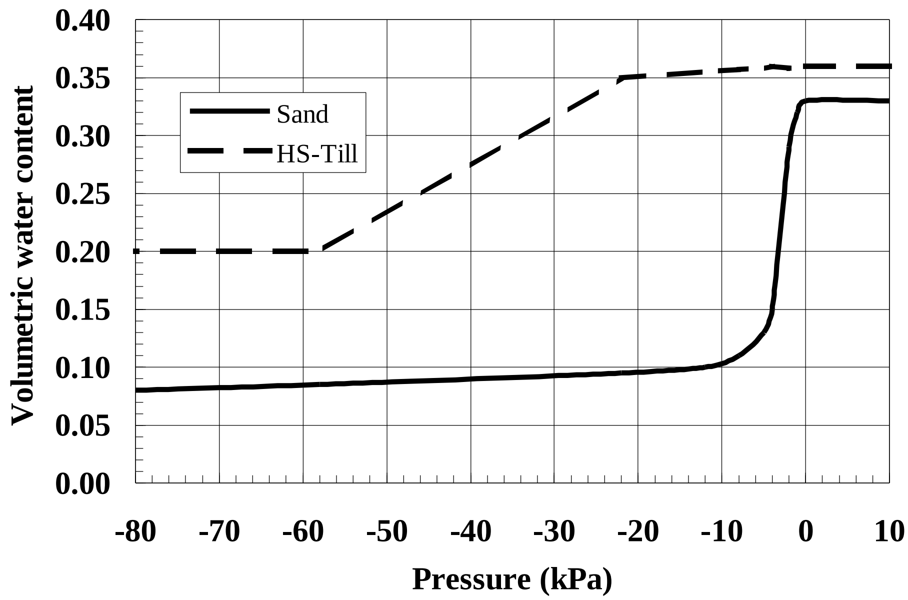


Figure 4.3 Soil water characteristics of Heath Steele till and sand (after Yanful, Bell and Woyshner 1993).

Elevated temperatures within waste rock piles could lead to desiccation of the compacted till layer in the soil cover system. Temperatures as high as 48^{o}C were measured within Pile 7/12 prior to placement of the soil cover system. This consideration prompted the use of a silty soil with low clay content for the compacted till layer. A highly plastic soil would be more susceptible to cracks due to volume changes associated with changes in water content, although a silty soil with low clay content may be more susceptible to frost action.

A field water content 2 to 3% above the optimum moulding water content and a compaction of 95% of Modified Proctor was specified for the construction of the compacted layer. This molding water content assures that this layer will have a low saturated hydraulic conductivity along with high degrees of saturation.

The results of saturated-unsaturated flow modelling for a 60-day dry period (i.e., no precipitation) using HELP for the three-layer cover design proposed for Pile 7/12 predicted a maximum evaporative flux of approximately 5 mm/day, which dropped gradually to negligible values during prolonged dry periods (Yanful et al. 1993). The modelling results demonstrated that in spite of development of high suctions in the upper layer, the till layer remained saturated. The top layer also provided an infiltration layer to store precipitation, thus providing for a reduction in runoff and a supply of water to the till layer to make up for any losses due to drying.

4.2.6 Construction

The construction specifications for the composite soil cover placed on Pile 7/12 are given in Table 4. 2.

4.2.6.1 Surface Preparation

Surface preparation of the waste rock pile for placement of the cover materials included infilling depressions and large voids with crushed rock from other areas of the waste rock pile. The levelling was completed using a Caterpillar 215 hydraulic excavator. A total of 50 tonnes of crushed waste rock from other piles on site was used for surface preparation.

Table 4.2. Construction specifications for composite soil cover (from Yanful, Riley, Woyshner and Duncan 1993)

Surface preparation

Grade identified high areas on side slopes (3H:1V), minimizing disturbance to pile Excavate two 3.5 x 3 x 1.2 m holes at identified monitoring stations at the top of the pile for lysimeters; provide sand cushion at bottom excavation and slope at 2% to promote drainage
Level top of pile filling voids and depressions with excavated waste rock or non-acid-generating crushed rock (-37.5 mm) or approved equivalent
Provide a tight seal between compacted till layer and pile

Sand base

Compact with several passes of a medium-size vibratory roller to 92% of maximum Modified Proctor density (ASTM 1987c)
Compact in two lifts to a finished total thickness of 30 cm
Ensure smooth surface of sand base to allow drainage
Ensure compacted surface is flat, with surface irregularity within ±25 mm of average grade
Finish final slopes at 3H:1V

Impermeable cover

Compact with medium-size vibratory roller or sheepsfoot roller (as approved by engineer) to achieve design specifications
Conduct demonstration test on a till pad using proposed equipment; pad to be compacted in a minimum of two layer and measure at least 5 x 10 m in plan
Engineer to determine minimum number of passes of compactor (from test pad) required for design densities
Compact till on sand base to at least 95% Modified Proctor density in three lifts (20 cm per lift) to a finished thickness of 60 cm
Apply water as necessary during compaction to maintain specified water content (-2 to +4% optimum); if cover is excessively dry add water, if it is too wet remove from site and let dry or replace
Engineer to perform field density tests on each lift before approving placement of next lift
In areas not accessible to rolling equipment, compact to specified density with approved mechanical tamper
Smooth top surface of cover to promote drainage

Granular cover

Place in maximum 15 cm lifts and compact to 92% of Modified Proctor to a finished thickness of 30 cm
Ensure compacted surface is flat, with irregularities within 50 mm of average grade

Erosion protection

Particle size to be maximum of 75 mm and 15% by weight finer than 4.75 mm
Place uniformly over entire pile surface of granular cover to a minimum thickness of 10 cm

4.2.6.2 Sand Base

The prepared surface of the pile was covered with a 30 cm thick layer of sand that was 4% gravel sizes, 90% sand size, 6% silt and clay size particles. The sand was compacted with a minimum of four passes of a 5-tonne vibratory compactor.

The base consists of an impermeable fabrene membrane, covered by a 15 cm thick protective layer of sand. An underflow leachate collection system was installed within the sand filter. The outlet was installed with a U-bend water trap to prevent air from entering the pile.

4.2.6.3 Low Hydraulic Conductivity Layer

The compacted till was placed on the sand base in three equal 20 cm lifts for a total thickness of 60 cm. The liquid limit of the till material was generally between 27 to 28% and the plasticity index was between 5 to 6%. The results of Modified Proctor compaction tests gave a maximum dry density of 1.96 Mg/m^3 at an optimum moulding water content of 13.5% as shown in Figure 4.4.

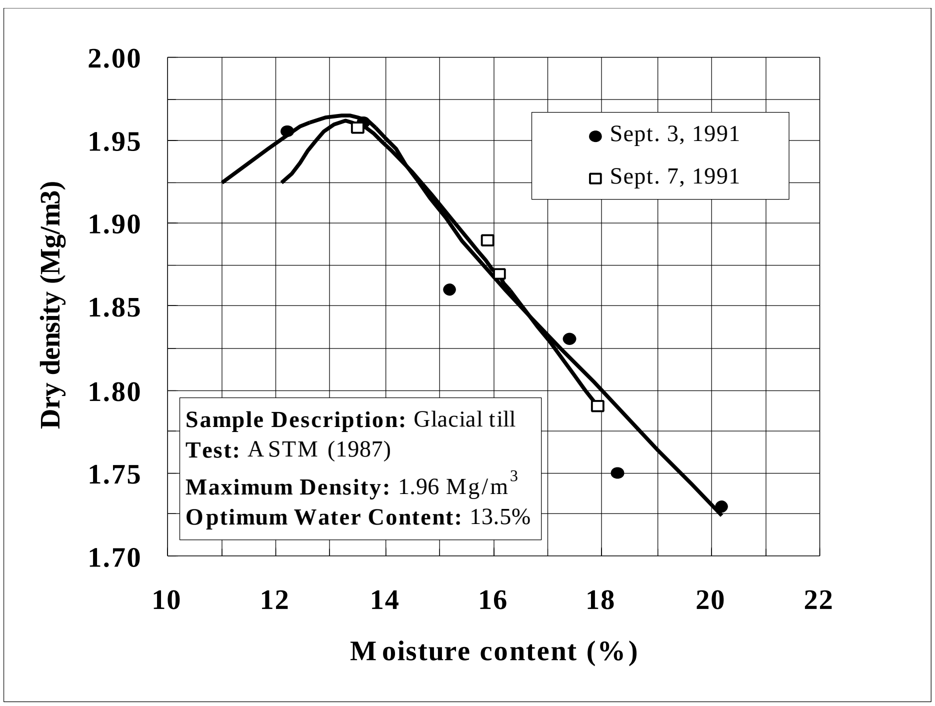


Figure 4.4 Test results of modified compaction test on Heath Steele till (after Yanful, Riley, Woyshner and Duncan 1993).

The grain size analysis indicated that the till consisted of 10 to 33% gravel, 18 to 45% sand, 28 to 44% silt, and 7 to 23% clay size particles. The grain size distribution envelope recommended for the till layer is shown in Figure 4.5.

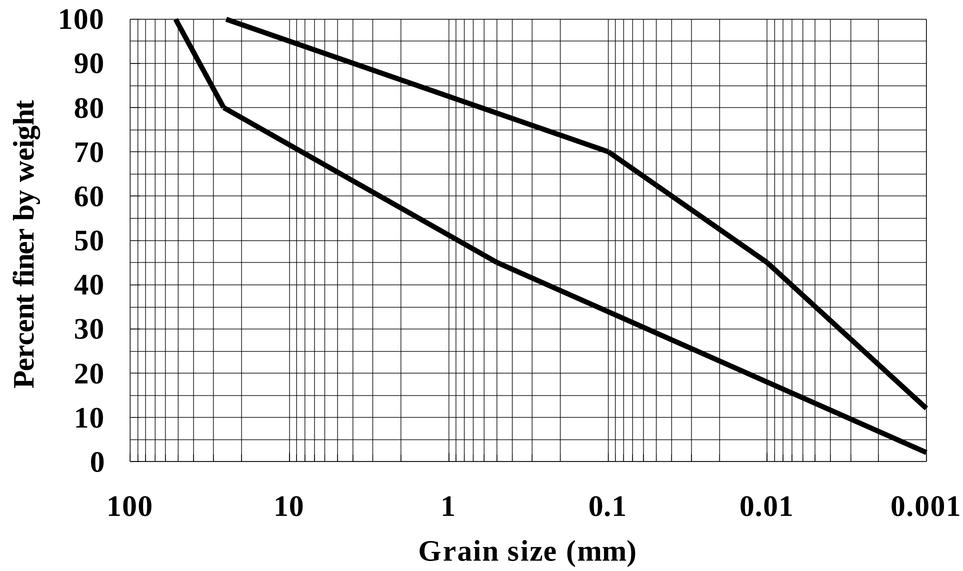


Figure 4.5 Grain size analysis results of Heath Steele till (modified after Yanful, Riley, Woyshner and Duncan 1993).

The till contained cobbles, boulders, and large tree roots, which were manually removed. In general, the natural water content of the till was approximately 5% greater than the optimum moulding water content, therefore the till was allowed to dry prior to placement. The till was then spread and compacted in three equal lifts using a smooth wheeled 5-tonne vibratory compactor. The quality control tests performed during the placement operation showed that a degree of compaction between 93-99% of the maximum dry density was achieved.

Field hydraulic conductivity tests performed after the placement showed results of the order of 10^{-6} and 10^{-7} cm/s.

4.2.6.4 Granular Cover

The granular cover was a clean sand and gravel consisting of 40% gravel, 58% sand, and 2% silt and clay size particles. The granular material was moistened to its optimum water content (6.5%) and spread in 15 to 20 cm thick lifts and compacted to at least 92% of the maximum dry density (2.24 Mg/m^3). The relationship between dry density and moulding water for the granular layer is shown in Figure 4.6.

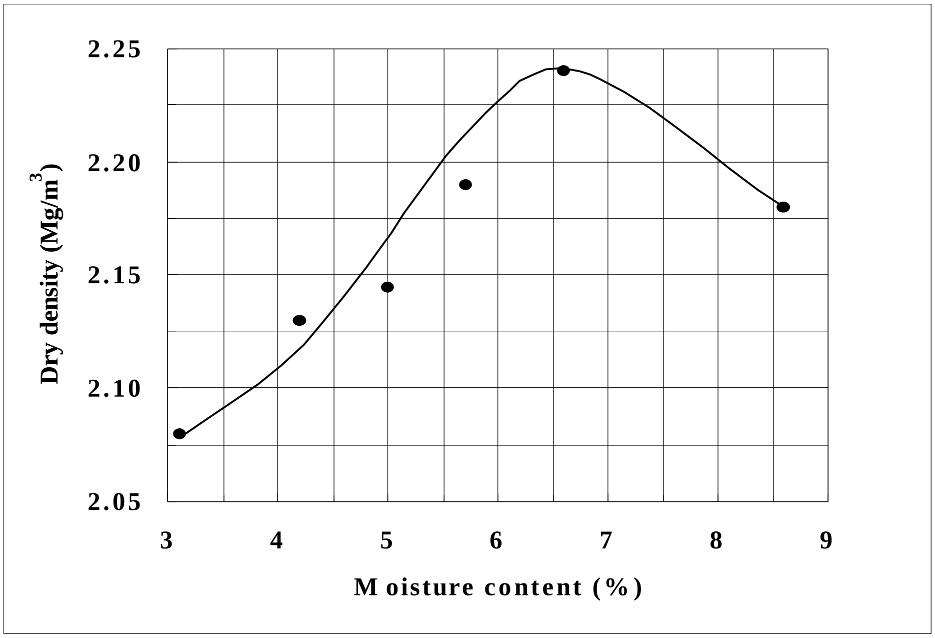


Figure 4.6 Test results of modified compaction test on the granular cover material (after MEND 1992)

4.2.6.5 Erosion Protection

The erosion protection layer consisted of a 10 cm layer of well sorted gravel which was compacted by several passes of the vibratory compactor.

4.2.7 Monitoring

Monitoring instrumentation were installed at several locations and depths within the waste rock pile and soil cover system to measure moisture content, suction, temperature, oxygen concentration, and piezometric pressure at the surface. The installation procedure was presented in detail by Yanful, Riley, Woyshner and Duncan (1993).

Two monitoring stations were installed at the top of the pile. Each monitoring station consisted of a lysimeter, and a vertical profile nest of five monitoring units (Yanful et al. 1993). The monitoring instruments consisted of gas sampling probes for gaseous oxygen, heat dissipation and electrical-resistance sensors for matric suction, a time domain reflectometry (TDR) system for water content, and thermocouples for temperature. The monitoring stations within the waste rock were operational two years prior to construction of the soil cover system. The gaseous oxygen concentrations within Pile 7/12 decreased from 20% prior to construction of the cover to about 1 percent after placement. The reduction in gaseous oxygen demonstrated that the oxidation reaction had used the available oxygen and the presence of the soil cover system limited oxygen diffusion from the atmosphere into the waste rock pile.

The average volumetric water contents at placement was 32% and the same high water content was measured approximately 7 months after cover installation. The water content data was verified with soil suction measurements which indicated near saturated conditions in the compacted layer. The temperatures in Pile 7/12 decreased following installation of the cover system but appeared to be more influenced by climatic variability than by a decrease in heat production and hence sulphide mineral oxidation. The seepage from the base at the soil cover system was collected using two lysimeters. The lysimeters indicated that infiltration into the waste rock pile was approximately 2% of precipitation during a 55-day period when rainfall was heavy. The volume of rainfall into Pile 7/12 has been reduced due to the presence of the soil cover system. However, leachate quality from the pile did not change significantly since cover installation due to stored acidity. Further monitoring is under progress until March 1997. These results will be used to confirm the reduction in acid production and to verify the long term performance of the cover.

4.2.8 Costs

The total cost for construction of the soil cover system for Pile 7/12 at HSM in 1991, excluding instrumentation was $60,000 (Canadian currency) or $ 22.5 per square meter ($ 225,000 per hectare) (ADI 1995).

4.3 WAITE AMULET

The site description along with the background and past history of the Waite Amulet tailings site described in this report were obtained from Yanful and St-Arnaud (1991) and a MEND report authored by Yanful et al. (1993).

4.3.1 Site Description

The Waite Amulet tailings site is located approximately 20 km west of Rouyn-Noranda, Quebec. The site is a decommissioned sulphide rich tailings impoundment. The tailings, derived from base metal sulphide ores, were deposited over a surface area of 41 ha and are mostly surrounded by a dam. Tailings disposal at the site started in the early 1920's and 1930's and ceased in 1962. In total, approximately 8.7 million tonnes of tailings were deposited. Sulphide oxidation and acid generation has occurred for at least 50 years, resulting in low pH seepage containing high concentrations of sulphate and iron. The seepage is collected in perimeter ditches and treated by lime neutralization to remove metals before being discharged into a natural stream.

4.3.2 Climate

Meteorological conditions were monitored in the fall of 1991 at the Waite Amulet site. The total rainfall during the period of June to October was 431.8 mm. A regional meteorological station is located at Duparquet approximately 25 km NNW from Waite Amulet. The rainfall characteristics and other meteorological conditions on the tailings of the regional station were similar to Waite Amulet, and were considered to be representative of the Waite Amulet site.

The total precipitation in 1991 and 1992 was 571.4 mm and 720.6 mm respectively. The normal precipitation (639.8 mm) is split evenly between rain and snow. The normal snowfall is 317.1 mm. The potential evaporation is 497.8 (using the Thornwaite method). The average annual maximum and minimum temperatures are 6.9^{o}C and -4.3^{o}C respectively. The average monthly maximum and minimum temperatures for 1992 were 20.6^{o}C and -23.1^{o}C respectively.

4.3.3 Study Program

The Waite Amulet project was initiated in July 1990 under the Mine Environment Neutral Drainage (MEND) program to assess the performance of pilot scale engineered soil cover systems on reactive mine tailings (MEND 1993). The principal objective of the project was to design, construct and evaluate the effectiveness of different soil cover systems made from locally available soil materials and a plastic or geomembrane cover, in reducing acid generation in reactive tailings. The decommissioned Waite Amulet tailings site was selected since information with respect to hydrogeochemistry and site instrumentation was available (MEND 1993). The site was also a typical example of acid generating tailings with well defined oxidized and unoxidized zones.

The study was completed in phases that consisted of a laboratory investigation, the construction of the experimental test cells in the field, performance monitoring, and evaluation of cover performance. Laboratory studies were used to develop a comprehensive design program for the field studies.

The location of the test plots are shown in Figure 4.7. Four 20m square test plots were constructed which included a control (without a cover) and three other plots with different cover profiles (Figure 4.8). The test plots were located on the crest of the groundwater divide where lateral subsurface drainage was thought to be minimal (Yanful et al. 1990).

4.3.4 Soil Properties

The Waite Amulet tailings were deposited on clay. The clay was deposited approximately 9000 years ago during the last phase of proglacial Lake Ojibway in the Abitibi area, Quebec (Quigley et al. 1985). The properties of the underlying clay are given in Table 4.3.

The clay content varied between 42% and 82%, with the silt content increasing with depth. The grain size distribution curves for the material used in the composite cover are shown in Figure. 4.9. The Modified Proctor curves for the clay is illustrated in Figure 4.10. The soil water characteristic curves and hydraulic properties of the cover materials as measured on column tests conducted by Woyshner and Yanful (1995) are illustrated in Figures 4.11 and 4.12 respectively.

Table 4.3. Properties of the Waite Amulet clay underlying the tailings impoundment (at Station WA-20) (from Yanful and St-Arnaud 1992)

Liquid limit	61%
Plastic limit	24%
Specific gravity	2.70
Bulk density (at depth)	1.70 Mg/m^3
Bulk density (near interface)	1.90 Mg/m^3
Void ratio (outside impoundment)	0.95
Average coefficient of consolidation	2.20
Saturated hydraulic conductivity (1.35 pore volumes)	9.0×10^{-8} cm/s

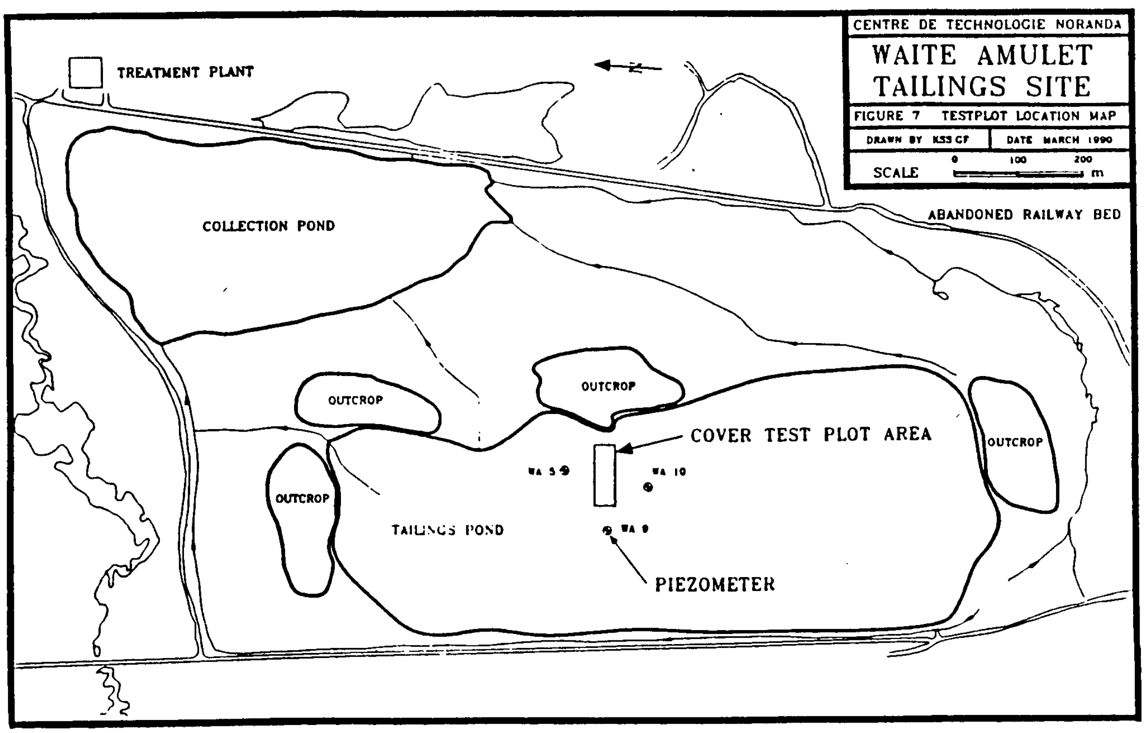


Figure 4.7 Site plan of Waite Amulet (after Yanful, Woyshner and Aube 1993).

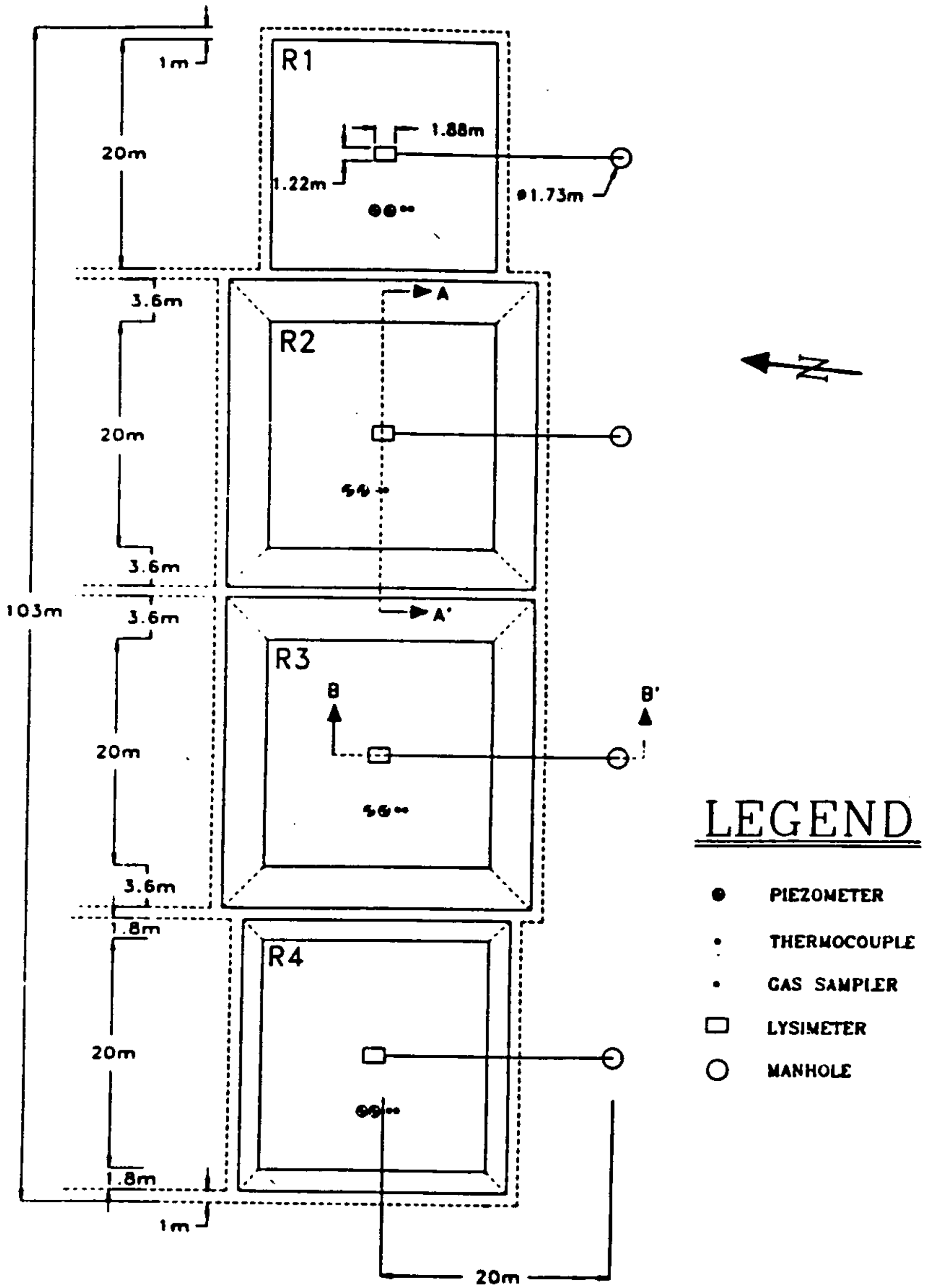


Figure 4.8 Test plots at Waite Amulet (after Yanful, Woyshner and Aube 1993).

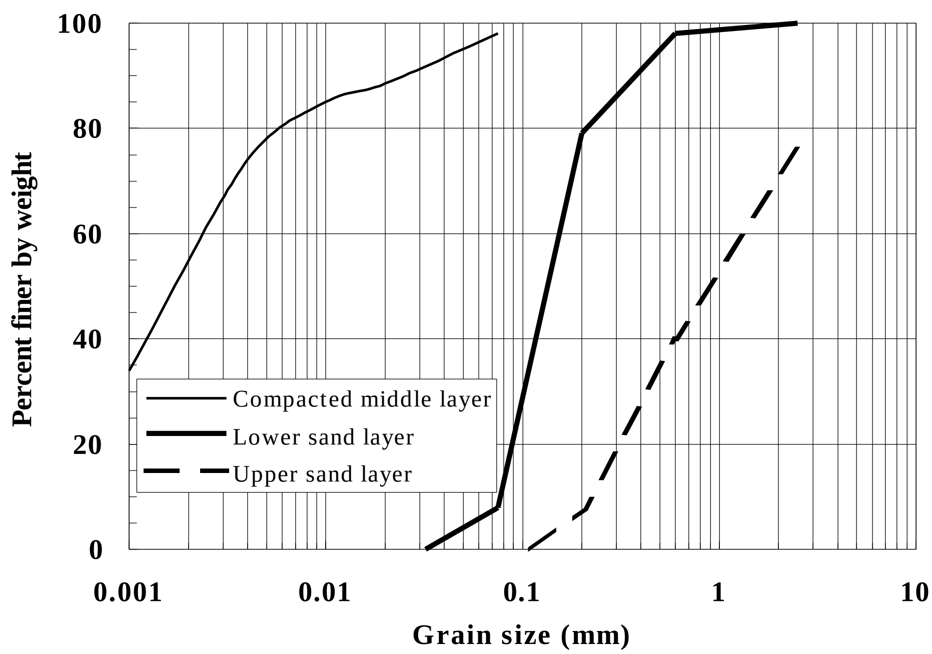


Figure 4.9 Grain size distribution of cover materials at Waite Amulet. (after Yanful, Woyshner and Aube 1993).

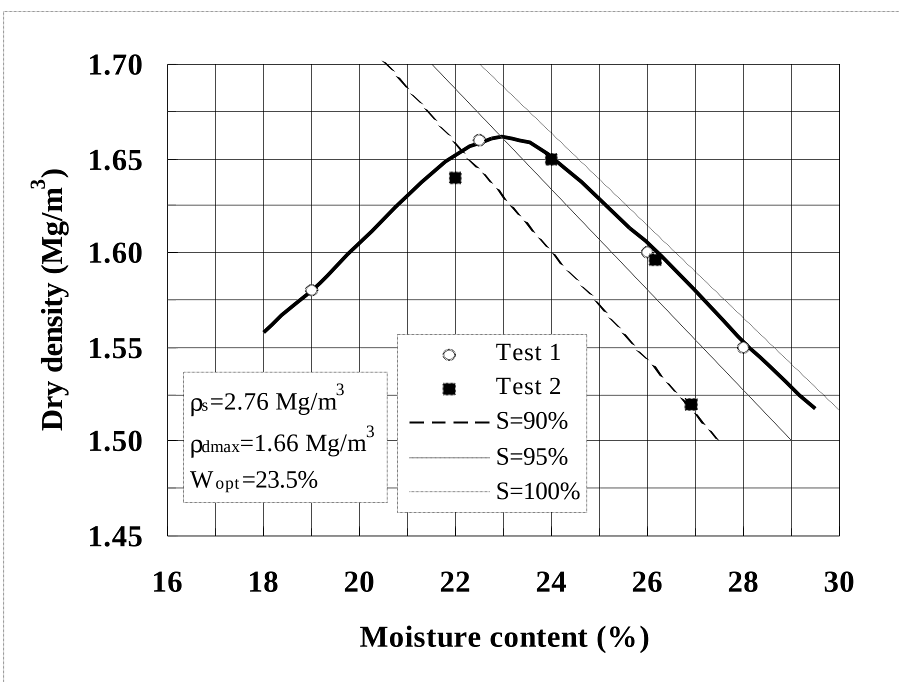


Figure 4.10 Modified Proctors curve for the clay layer at Waite Amulet (from MEND 1993 Report by Yanful, Woyshner and Aube 1993).

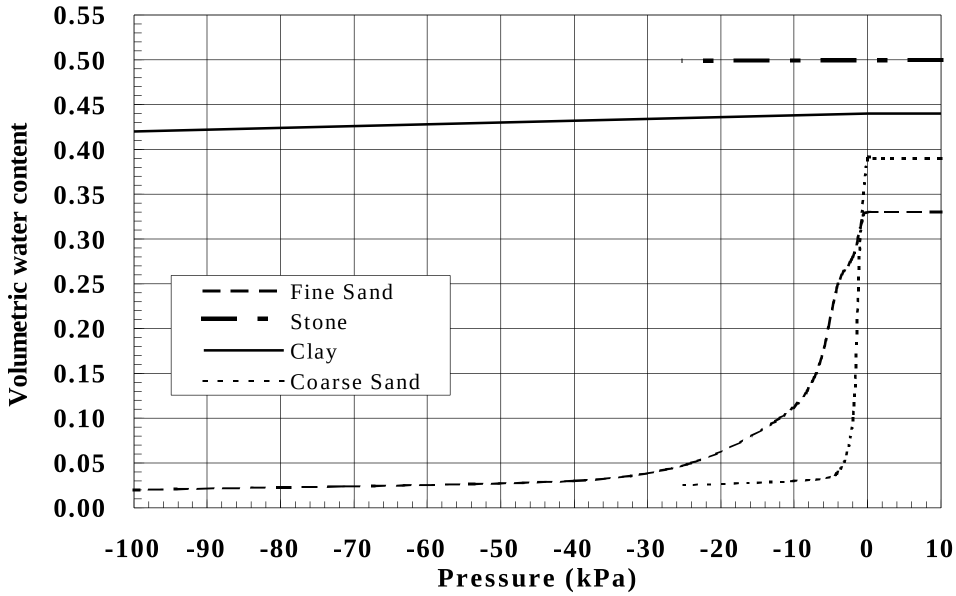


Figure 4.11 Soil water characteristic curves of column materials at Waite Amulet (Woyshner and Yanful 1995).

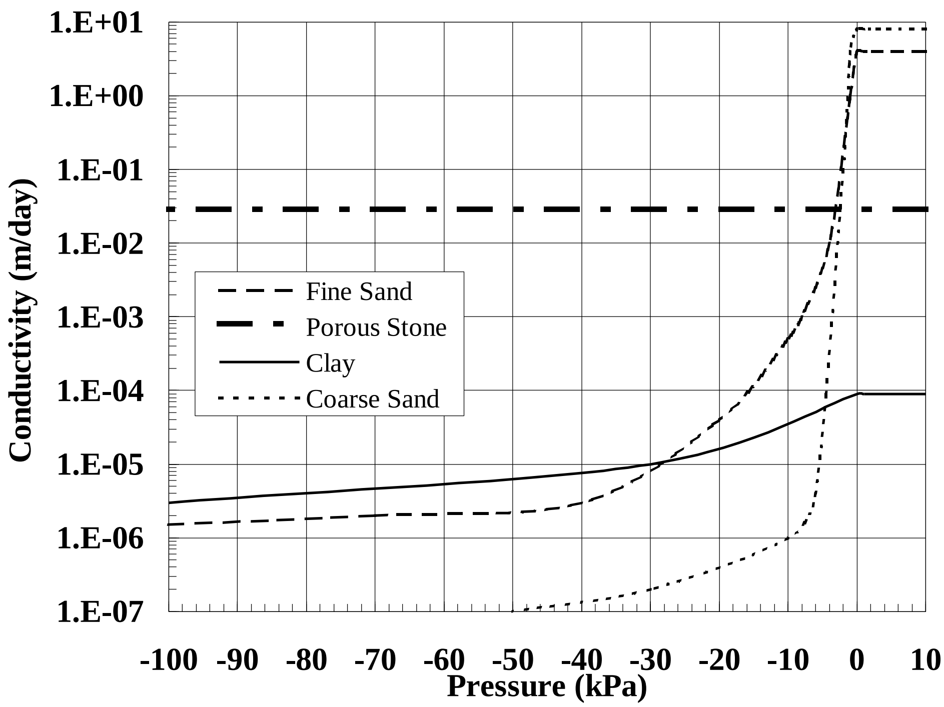


Figure 4.12 Column materials hydraulic conductivities for the Waite Amulet study (after Woyshner and Yanful 1995).

4.3.5 Design Considerations

The design of the soil cover system was based on the results of a previous laboratory study which concluded that the composite cover would be able to resist moisture losses over long periods. The layer thicknesses were selected to provide a reduction in the predicted oxygen flux and minimize the effects of adverse climatic conditions such as freezing, thawing and wet dry cycles (Figure 4.13).

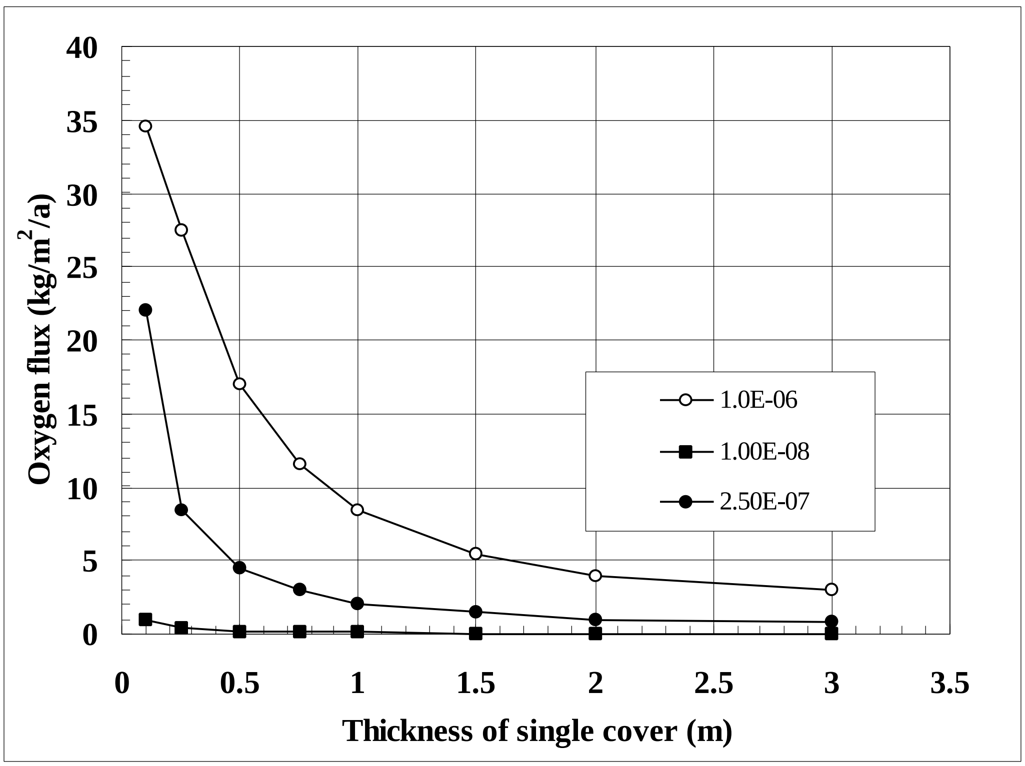


Figure 4.13 Variation of oxygen flux with cover thickness at Waite Amulet (after Yanful and St-Arnaud 1991).

The uppermost layer consisted of a fine sand which minimized evaporation from the underlying clay. An underlying coarse sand which would drain to residual saturation was provided as a capillary break from the clay layer. At elevated suctions both the fine and coarse sands have low hydraulic conductivities, less than the saturated hydraulic conductivity of the clay, and these would minimize both upward and downward fluxes.

The upper fine sand also reduced runoff, increased storage, and allowed more water to percolate into the clay.

The geomembrane cover consisted of an 80 mil (2 mm thick) high density polyethylene (HDPE) sheet placed between the upper fine sand and lower coarse sand.

4.3.6 Column Simulation Studies

Six column tests were conducted at Noranda Technology Centre (NTC) laboratory to simulate the test plots. The soil cover consisted of a 30 cm thick clay layer placed between two sand layers, each 15 cm thick (Figure 4.14).

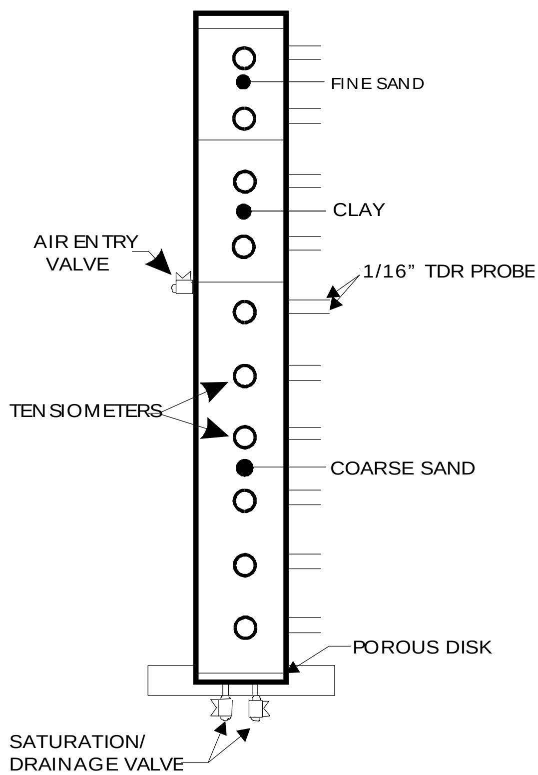


Figure 4.14 Column test setup at NTC laboratory (from MEND 1993 Report by Yanful, Woyshner and Aube).

The soils were similar to those used in the construction of the field test plots. They were also compacted to field specifications. Unoxidized tailings used in the laboratory experiments were collected from the deep saturated zone at the south end of the Waite Amulet tailings impoundment. The covered and uncovered tailings were subjected to cyclic wetting and drying at laboratory temperatures.

The tailings and sands were packed to a bulk density of approximately 1.9 Mg/m^3. The coarse and fine sand were placed at residual saturation which corresponded to a volumetric water content of about 0.08. The clay was compacted at 93% of the maximum Modified Proctor at a water content 2% higher than optimum. The compaction corresponded to a density of 1.53 Mg/m^3 and a gravimetric water content of 26%. It was estimated that the clay layer would have a degree of saturation of approximately 95% and a saturated hydraulic conductivity of less than 1.0×10^{-7} cm/s, based on the design procedures. Each column was instrumented to measure gaseous oxygen concentration, moisture content, and temperature. Time domain reflectometry was used to measure moisture content. Rainfall and snowmelt simulations were applied to each column. More details are available in MEND 1993.

The laboratory results demonstrated that the clay layer did not drain even though both the bottom coarse sand and fine sand were nearly drained to residual saturation. The clay was prevented from draining due to a capillary break (i.e., coarse sand) at the base of the layer. The presence of overlying fine sand considerably reduced evaporative losses from the clay. The high suction created by evaporation from the fine sand decreased the hydraulic conductivity of the sand significantly which, in turn, prevented further water flux from the clay. The data points of Figure 4.15 represent the experimental results whereas the lines show the results obtained from saturated-unsaturated flow modelling using SEEP/W (Geo-Slope International 1993).

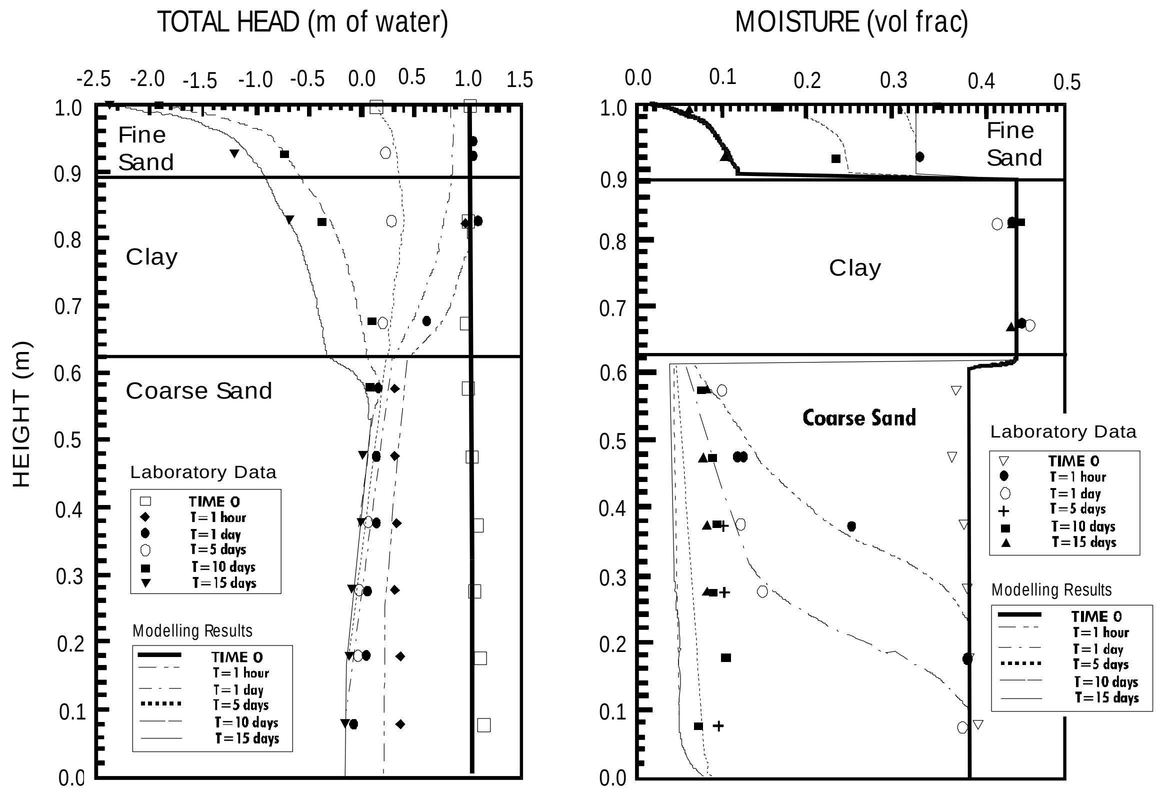


Figure 4.15 Column test results and drainage simulations (from MEND 1993 Report by Yanful, Woyshner and Aube).

4.3.7 Construction

The experimental plots were constructed as follows (Figure 4.8):

1. R1, control plot without a cover,

2. R2, composite soil cover consisting of upper and lower sand layers and a clay layer compacted at 93% Modified Proctors and a water content of 25%,

3. R3, second composite soil cover consisting of upper and lower sand layers and a clay layer compacted at 91% Modified Proctor and a water content of 26%,

4. R4, composite cover consisting of upper and lower sand layers and a middle 80 mil (2 mm thick) HDPE geomembrane.

The soil covers consisted of a 60 cm thick compacted silty clay layer placed between two sand layers, each 30 cm thick (Figure 4.16). A final 10 cm gravel was added later to the cover system to minimize erosion. Figure 4.9 shows the grain size distribution of the soils used in the test plots and the Modified Proctor curve for the clay is shown in Figure 4.10 (MEND 1993)

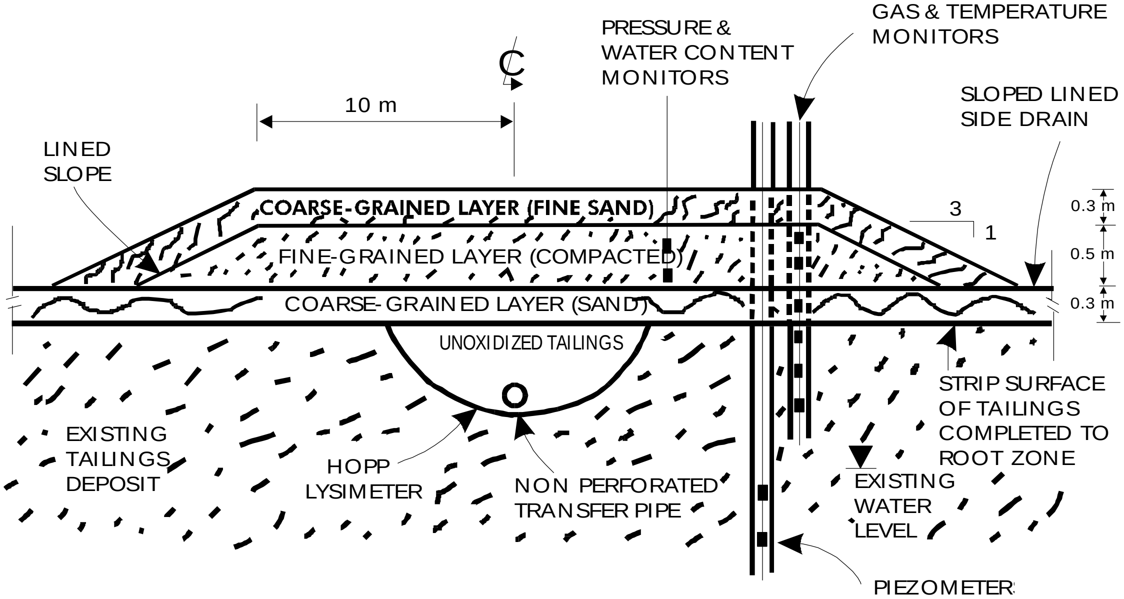


Figure 4.16 Composite soil cover at Waite Amulet (from MEND 1993 Report by Yanful, Woyshner and Aube).

The test plots were designed with 3:1 (H:V) end slopes and perimeter drainage ditches to ensure surface runoff away from the plots. The side slope of each plot was lined with 40 mil HDPE sheets at the clay and upper sand contact to prevent lateral transfer of gaseous oxygen into the system. Construction procedures are given in Yanful et al. 1993.

4.3.8 Instrumentation and Monitoring

Each test plot was instrumented to monitor gaseous oxygen concentrations, water content, suction, temperature, and pore water quality at various depths. In addition, a collection basin lysimeter, filled with unoxidized tailings, was installed below each cover to measure both the quantity and quality of percolating water.

The critical parameters for the assessment of covers for this project were identified by Yanful, Woyshner, and Aube (1993) as :

1. the moisture content, particularly that of the clay layer and the sand base;
2. the hydraulic heads in the cover/tailings;
3. the concentration of gaseous oxygen in the cover and in the tailings directly below the cover;
4. the water quality of the tailings pore water; and
5. the temperature of the cover materials and tailings.

The instrumentation devices installed for monitoring are listed in Table 4.4. The analyses of the performance of the tailings were carried out based on the monitoring data.

4.3.9 Effectiveness of the Cover

The covered tailings did not produce any drainage water during normal wetting or rain application because of the low hydraulic conductivity of the compacted clay layer from the laboratory studies. A majority of the applied water reported as runoff. The covered tailings were periodically flushed (soil cover was by-passed) to obtain water to assess the amount of acid produced from sulphide oxidation. The uncovered tailings were also flushed. Results of the laboratory, field and modelling studies indicated that the oxygen flux was reduced by 91 to 99% due to the presence of soil cover system (Yanful et al. 1993).

Table 4.4 Instrumentation details used at the Waite Amulet site

Property	Instrument	Location/Details
Moisture content	TDR	3 rod probe: measured dielectric constant, k_a during site visits in sand base and clay.
Hydraulic head	Piezometers	PVC tubes; tips installed at 2 and 4 m in saturated tailings zone for sampling pore water and for measuring water levels.
Suction	AGWA - II thermal conductivity sensors	Installed at the same depths as TDR sensors.
Gaseous oxygen	Oxygen analyzer	Teledyne model 340 FBS portable oxygen analyzer was used. Sampling ports were installed during the placement of the piezometer.
Water quality	Water collected from lysimeters	pH, acidity, sulphate, and metal concentrations were measured
Temperature	Thermocouples	Secured to piezometers prior to installation.
Rainfall	Tipping bucket rain gauge	Also collected rainfall data from Amos (which is 75 km ENE of Waite Amulet) and Duparquet (which is 25 km NNW of Waite Amulet) meteorological stations.

Two computer models HELP (1992) and SEEP/W (1993) were used to aid in the hydrologic analysis of the composite soil cover. The HELP model calculated that approximately 58% of the 904 mm of average annual precipitation evaporated and 16% reported as surface runoff. The net surface infiltration was therefore 240 mm per year or 26% of precipitation. SEEP/W flow modelling predicted 34.4 mm would percolate through the cover using the surface flux boundary condition calculated by HELP. The HELP and SEEP/W models predicted approximately 4% of precipitation percolated through the cover and into the tailings. The field lysimeter measurements indicated that approximately 6% or 54 mm per year of precipitation percolated through the soil cover system. This corresponded to a reduction of 80% in the total annual infiltration into the uncovered tailings.

HELP and SEEP/W modelling indicated that the sand base was drained and that the clay remained in saturation. Two years of field monitoring data confirmed these modelling results. The modelling and field monitoring results suggest that the soil cover system was properly designed and constructed and was capable of reducing acid production in reactive tailings (Woyshner and Yanful 1993).

4.3.10 Freeze-Thaw Effects and Long Term Performance

The effects of freeze-thaw cycles on the integrity of the compacted clay layer in the composite cover was also investigated. The results demonstrated that most of the negative effects occurred during the first two freeze-thaw cycles. The laboratory saturated hydraulic conductivity increased by one to two orders of magnitude after the first two freeze-thaw cycles and remained steady for subsequent freeze-thaw cycles. Field saturated hydraulic conductivity was measured in 1991 and 1992. The results indicated that the saturated hydraulic conductivity of the clay layer remained near the initial design value of 1.0×10^{-7} cm/s. It was determined that freezing and thawing had not adversely affected the clay layer and that no future negative effects need be anticipated.

The stability of the geomembrane cover was evaluated with respect to acid leachate, freeze-thaw, and tensile stresses. A tensile resistance of approximately 1.5 kN was obtained for both untreated and acid leached (pH of 3) specimens of 80 mil HDPE. A similar tensile resistance was obtained for specimens subjected to three freeze-thaw cycles. It was inferred that the long term stability of the HDPE cover was not a major concern except for the possible effects of equipment such as pleasure vehicles, burrowing animals, and sunlight.

Chapter 5

A SYNOPSIS ON THE DESIGN OF SOIL COVER SYSTEMS

5.1 INTRODUCTION

The primary objective of the Heath Steele acid waste rock cover study and the Waite Amulet tailings cover study was to demonstrate the ability of an engineered soil cover system to minimize the ingress of oxygen and infiltration of water to potentially acid generating mine wastes. Both studies met the principle objective using primarily an empirical design approach that was developed to decrease the production of acidic drainage.

In general, an empirical design approach leads to complex laboratory and field studies that attempt to include all possible conditions that may occur in the field. Analysis is relatively simple since it is essentially limited to the question of whether the prototype met the initial design objective under realistic field conditions. Two problems arise however when using an empirical design approach. First, the results cannot be extrapolated to take into account a change in field conditions. Therefore, to develop a design for a new set of site conditions, prototype testing must be developed again using the new field conditions. Second, an empirical design is usually conservative and therefore will tend to be expensive.

A theoretical design approach involves fundamental tests and characterization of design components and requires a more rigorous analyses and verification of the design. The empirical design process is a general approach undertaken before a theoretical approach is developed. The design of engineered soil cover systems for potentially acid generating mine wastes is moving from an empirical design approach to a theoretical one as the theoretical basis for design is improved and a better understanding for key design components is developed.

The approach taken in the Heath Steele and Waite Amulet studies was empirical and consistent with state-of-the-art technology at that time. The primary objective of the studies were achieved, and the proper approach was taken with respect to the evolution of engineering science. Current state-of-the-art soil cover system design technology has continued to advance the technology used in the Heath Steele and Waite Amulet studies. This chapter will present the current state-of-the-art technology with respect to the design of soil cover systems for potentially acid generating mine wastes, while briefly reviewing the work presented in Chapters one to four inclusive. A critical review and synopsis of the Heath Steele and Waite Amulet studies will also be provided.

5.2 PHILOSOPHY OF DESIGN

The philosophy used for the design of engineered soil cover systems based on current technology attempts to:

1. Minimize the flux of oxygen and water to potentially acid generating mine wastes,
2. Ensure that the soil cover system will maintain long term physical and ecological stability, where "long term" refers to the environmental liability associated with acidic drainage, and
3. Use a design that integrates all aspects of the ecosystem, climate, weathering effects, soil cover layers, and waste material.

The design philosophy described above integrates the waste material with the natural ecosystem, rather than attempting to isolate the waste from the environment in order to reduce acidic drainage. Alternate cover designs, such as the "moisture store and release" design employed at Golden Sunlight Mines (Swanson 1995) may provide an economic and technically feasible solutions to reducing acidic drainage in arid climates (Section 3.3). The waste rock rehabilitation scheme at Golden Sunlight Mines is an example of a soil cover system designed to be in hydrologic balance with the environment. The results to date also suggest that the first design objective listed above has been addressed satisfactorily at the Equity Silver Mines Ltd. and Golden Sunlight Mines Ltd. sites and work is in progress to address the second and third objectives.

The scope of the design objectives for Heath Steele and Waite Amulet was limited to minimizing acidic drainage by using the capillary barrier concept based on liquid flow analysis. The design did not include vegetation, or transient coupled heat and mass transfer, that is, the analyses was not fully coupled to the climate.

An integrated design approach can incorporate a variety of design variables that are not limited to soil cover material availability only. For example, a practical and economically feasible design of a soil cover system will require that site specific conditions with respect to the availability of appropriate soil cover materials is taken into account. In a similar manner the use of site specific climate conditions will allow for the proper evaluation of the performance of a soil cover system and may potentially lead to a more economic solution than the use of only regional climate conditions. The site specific conditions can be monitored using a weather station. The economic and environmental liability associated with potentially acid generating mine wastes is considerably greater than the cost of an automated weather station that monitors all key climate parameters, and is an important step towards an integrated design approach.

Heath Steele and Waite Amulet soil cover designs were based on the concept of minimizing infiltration and maintaining high degrees of saturation. These design objectives were addressed satisfactorily. The soil cover designs focused on the development of a capillary barrier as described in Nicholson et al. (1989). This is simple but reasonable analysis. This approach seems to work well in humid to semi-humid climates that are characteristic of many Canadian mines where fine grained materials are available.

The design approach used for the Heath Steele and Waite Amulet studies can be considered to be conservative based on the state-of-the-art practices available now. Consideration can be given to soil covers to maximize exfiltration while providing sufficient storage to retain climatic fluxes in arid or semi-arid regions. Using present state-of-the-art knowledge one can move towards a more general view of transient moisture fluxes by liquid and vapour movement under climatic conditions.

5.3 DESIGN PRINCIPLES

The fundamental design principles that must be included in the design of a soil cover system for potentially acid generating mine wastes require a fundamental understanding of the following processes:

1. Coupled heat and mass transfer in unsaturated soils,
    - the soil water characteristic curve,
    - saturated hydraulic conductivity,
    - storage and movement of water in unsaturated soils,
    - water vapour transport,

- diffusion of oxygen,
- the capillary barrier concept,

2. Ecosystem, climate, and soil interaction, defined
   - potential, actual, and pan evaporation,
   - vegetation,
   - transpiration,
   - actual evapotranspiration,
   - physical and ecological stability, and

3. General geotechnical behavior of unsaturated soils,
   - compaction,
   - shear strength,
   - swelling, and
   - settlement.

The Heath Steele and Waite Amulet studies have fully validated the principles of a capillary barrier and liquid flow under field conditions. Climate was used as a reference in these studies. For example, the Waite Amulet tailings column experiments were not designed to interact with the climate but rather were designed to minimize actual evaporation from the tailings, thus adopting a conservative but a reasonable approach.

The emphasis on oxygen movement in an unsaturated soil cover was a positive component of the Heath Steele and Waite Amulet studies. Oxygen transport is another significant issue which was addressed along with moisture movement and storage.

The scope of the Heath Steele and Waite Amulet design objectives did not include the analysis of transient heat and mass transfer in unsaturated soils, the effects of vegetation on the performance of the soil cover, and coupling of the climate to the soil profile. All these parameters can be taken into account however using more rigorous analysis which are currently being developed.

The present state-of-the-art understanding shows that the soil water characteristic curve is a key parameter in the design of soil cover systems. The soil water characteristic curve describes the fundamental relationship between the energy state in the pore water and the volume of water stored. It also helps to define the distribution of the water phases within the soil pores. Consequently, the soil water characteristic curve represents the ability of a soil cover system to retain water under various stress states and can be used to predict the hydraulic (hydraulic conductivity), mechanical (shear strength), and diffusion properties of the unsaturated cover and waste materials based on measurements of these properties at saturation (Barbour 1995).

Soil structure, aggregation, initial compaction moulding water content, method of compaction, void ratio, type of soil, soil texture, mineralogy, stress history, and weathering effects are all factors that influence the behavior of the soil water characteristic curve (Vanapalli, 1994). These factors also influence the hydraulic and mechanical properties of an unsaturated soil. However, stress history and initial moulding water content probably have the most influence on soil structure and aggregation. This is important since soil structure and aggregation are factors which dominate the nature of the soil water characteristic curve for fine grained soils. Specimens of a particular soil, in spite of having the same texture and mineralogy, can exhibit different soil water characteristics if they are prepared at different initial moulding water contents and possess different stress histories. The engineering behavior of each of the specimens will differ as a result. Thus, it is important to obtain a reliable soil water characteristic curve for the prediction of soil properties vital for the design of soil cover systems.

5.4 CHARACTERIZATION

A soil cover system includes the underlying waste material, each soil layer, the vegetation, and the atmosphere above the soil cover surface. It is therefore paramount to characterize each component of the soil cover system on a site specific basis.

5.4.1 Material Characterization

As stated earlier the present understanding shows that the key material characterization parameters with respect to the analyses of hydraulic performance of a soil cover system are the soil water characteristic curve and the saturated hydraulic conductivity. It is important to ensure that these properties be measured not only for each soil cover layer but also for the underlying waste material. Laboratory measurement of these two key parameters is often sufficient for preliminary design modelling. Other tests such as compaction, consolidation, oxygen diffusion coefficient, mineralogy, grain size, specific gravity, and index tests are also of importance.

Yazdani (1996), Newman (1996), and Herasymuik (1996) have demonstrated that it is possible to accurately measure the soil water characteristic curve of waste rock, although it is difficult. In general, research on characterization of the storage and transport of water (liquid and vapour) in waste rock is in its infancy and fundamental research is required. In addition, issues such as the transport of oxygen and oxidation products within waste rock material can be properly addressed only when the more fundamental issue of moisture flow and storage in waste rock is understood. Herasymuik (1996) illustrated the significance of this point as well as the importance of structure and segregation within a waste rock pile.

Care should also be taken to ensure that the soil water characteristic curves for fine textured soil layers of the cover system are measured such that the field stress state and soil structure are represented in the laboratory as much as possible. It is also imperative to verify these measurements in the field. Specimens of a particular soil will exhibit dissimilar soil water characteristics if they are prepared at different moulding water contents and possess a different stress history, in spite of having the same texture and mineralogy.

The effect of weathering on the soil water characteristic curve and the saturated hydraulic conductivity may also be included as part of the design of a soil cover system. This may be possible in future, however, the present understanding and the available information in this area is limited.

The effectiveness of a capillary break is a function of the difference between the soil water characteristic curves of the various layers in the soil cover system. Therefore, the soil water characteristic curve of each component of the soil cover system (i.e. waste materials and cover materials) must be determined in order to verify the presence of a capillary break. This would help to check the capillary break phenomenon and also lead to the development of economic alternatives. Such studies undertaken at Equity Silver Mines Ltd. were found to be useful (O'Kane, 1996).

The Heath Steele and Waite Amulet studies conducted a thorough investigation of the soil cover materials for grain size, specific gravity, Atterberg limits, mineralogy, compaction, consolidation, laboratory and field saturated hydraulic conductivity, and oxygen diffusion. However, some comments are necessary with respect to the soil water characteristic curves.

The soil water characteristic curve for the compacted till material at Heath Steele was not measured but was derived from literature as attempts to obtain a reliable drainage curve were unsuccessful (Yanful et al. 1993) (Figure 4.3). In several situations the soil water characteristic curve is assumed (or derived) but is eventually measured in the field for its validity. The derived soil water characteristic curve of the till material was not verified in the field. The soil water characteristic curve for the sand layer was measured. The soil water characteristic curve of the erosion protection layer used at Heath Steele was not measured.

The soil water characteristic curves of the coarse grained cover materials for the Waite Amulet study appear to be representative of field conditions. However, it was not clear whether the soil water characteristic curve of the clay material was representative of field conditions (i.e. was the laboratory sample compacted and then saturated prior to the soil water characteristic curve test or placed as a slurried specimen into the laboratory test apparatus). In other words, it is not stated whether soil structure was taken into account when measuring the soil water characteristic curve of the fine grained material.

In general, it appears that the soil water characteristic curves for the cover materials used in both studies were initially assumed and adjusted using a two dimensional saturated-unsaturated liquid flow model (SEEP/W) calibrated to laboratory column studies.

The Heath Steele and Waite Amulet studies did not attempt to measure the soil water characteristic curves of the underlying waste rock and tailings. In both cases, measurement of the waste material soil water characteristic curves may have demonstrated that the sand layer underlying the compacted fine layer was not required and that a capillary break will develop at the compacted layer and waste material interface. Eliminating the lower sand layer would have reduced the cost of the Heath Steele and Waite Amulet soil cover designs; however, there are also practical construction issues to be considered. For example, the use of a lower coarse layer may be required for a soil cover placed on tailings since it would be difficult to compact a fine grained soil on loose saturated tailings. The above discussion is offered in order to emphasize that an understanding of the performance of a soil cover system and its associated costs is possible only through complete preliminary studies.

5.4.2 Climate

Evapotranspiration is comprised of two components, evaporation and transpiration. The potential evaporation is the maximum rate at which a soil can evaporate and is a function of climate only. The evaporation rate will decrease as the soil surface becomes unsaturated and soil conditions will become the dominant factor controlling evaporation (Koliasev, 1941, Wilson et al. 1994). Plant transpiration is a result of root uptake within the soil profile and is a function of potential evaporation, the degree of plant development (Richardson and Ritchie, 1973), and soil suction (Wilson, 1990).

Atmospheric forcing on a soil cover system is represented by two main processes; evapotranspiration and infiltration (Wilson, 1990). Therefore, the climate parameters that should be measured on a site specific basis should reflect these two processes. The key measurements are precipitation, net radiation, air temperature, relative humidity, wind speed, and wind direction. Characterization of these climate parameters is important since they will influence the performance of a soil cover system. The key measurements that influence the performance of a soil cover system are site specific and in many cases will vary across the site based on slope angle, slope orientation, valley walls, and surrounding tree shading. However, the most important on site measurement is precipitation, which should be made as close as possible to a field test plot or experiment.

The relative influence of other measurements such as wind speed, air temperature, relative humidity, and net radiation will change depending on whether the soil cover system is evaporating at a potential rate or at the actual evaporative rate. For example, Swanson (1995) found in a climate parameter sensitivity analysis of the Equity Silver Mines Ltd. soil cover system that increasing wind speed caused an increase in evaporation from a saturated soil surface. However, if the soil surface was unsaturated a lower wind speed caused an increase in evaporation. Swanson (1995) concluded that under dry conditions high wind speeds cooled the surface resulting in a lower surface vapour pressure which reduced the actual evaporative rate. When the cooling effect of wind is not present the surface temperatures can get very high, resulting in increased vapour migration toward the surface (Swanson, 1995). Quantifying potential and actual evaporation on a site specific basis is paramount since overestimating evaporation will underestimate the ability of a soil cover system to perform as an oxygen barrier and overestimate its ability to function as a water infiltration barrier.

Daily rainfall, air temperature, relative humidity, wind speed, and wind direction was monitored on Pile 7/12 as part of the Heath Steele study. Pan evaporation was also measured at the site. The instrumentation demonstrated that the investigators recognize the importance of measuring these site specific climate parameters. Net radiation was not measured but is important since it is typically the predominant driving energy for evaporation. Ground heat flux can also be significant in many cases, especially if a heat source such as oxidizing waste rock is nearby.

A word of caution is necessary regarding the use of an evaporation pan to characterize evaporation at a site. Various types of pans are available such as sunken pans, floating pans, and surface pans. The most common pan is the surface type pan such as the Class A evaporation pan used at Heath Steele. Gray (1973) observed that a Class A evaporation pan overestimated the cumulative potential evaporation from a large fresh water reservoir near Weyburn, Saskatchewan by 1.25 times over a 6-month period. The difference was attributed to the energy provided by air movement and in general the influence of aridity as a result of the soil surrounding the evaporation pan. It is important to note that a Class A evaporation pan does not provide a measure of actual evaporation either since the actual evaporative rate decreases as the soil profile restricts the movement of moisture to the surface as a result of increased soil suction. Therefore, the Class A evaporation pan does not provide a site specific measure of potential evaporation or actual evaporation and its accuracy in characterizing either parameter will be site specific and more than likely change on a day to day basis.

The Waite Amulet site study did not adequately characterize site climate conditions. Site rainfall was measured from June to October of 1991. The data was compared to that measured at the Amos (75 km ENE of Waite Amulet) and Duparquet (25 km NNW of Waite Amulet) regional climate stations. The investigators concluded that site rainfall characteristics agreed reasonably well with Duparquet (Yanful et al, 1993). This may be true when comparing the total rainfall for the summer. However, Figure 5.1 illustrates that the monthly totals were significantly different. In addition, it is likely that the daily rainfall intensity and duration at the site is significantly different than at the regional climate station.

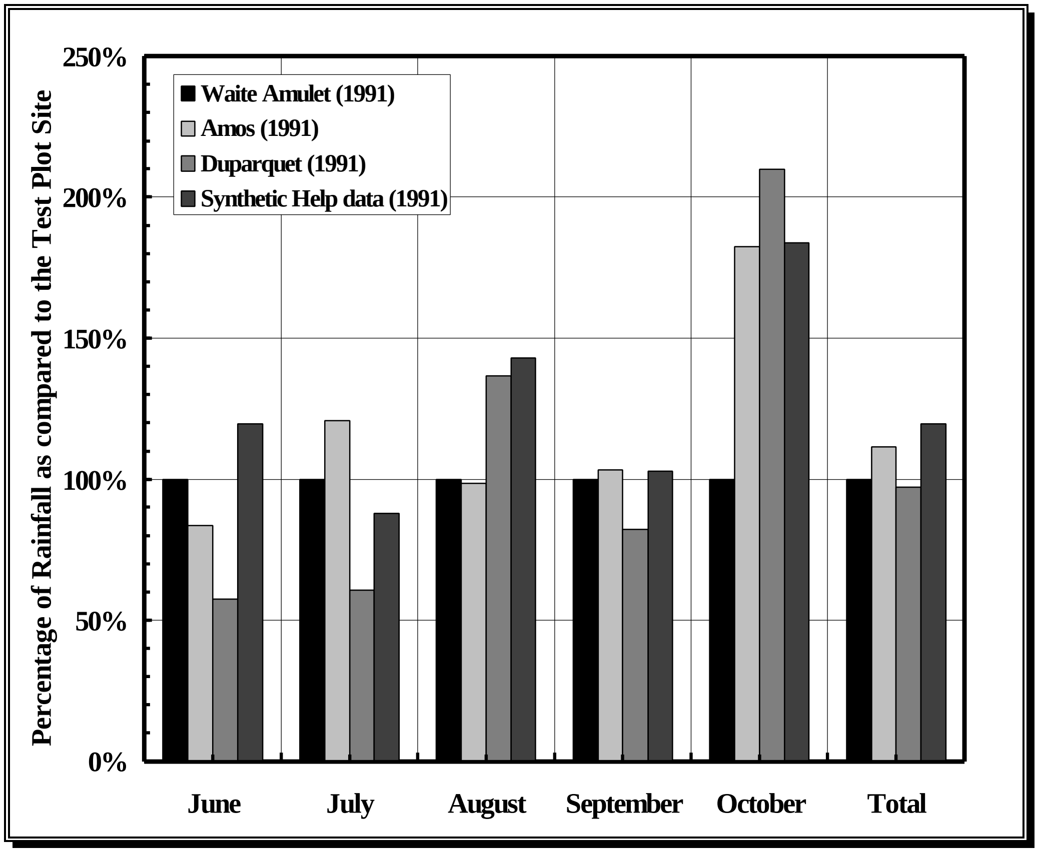


Figure 5.1 Monthly rainfall at the test site compared to the regional climate stations and the synthetic data generated by HELP.

The regional climate station was used to characterize rainfall and other meteorological conditions at the test plot site (Yanful et al, 1993). It may or not be reliable to assume that other regional meteorological conditions properly characterize the site when the regional climate station was not representative of site rainfall conditions. It is important to have a weather station at the site for proper characterization of the climate.

5.4.3 Vegetation

The Heath Steele and Waite Amulet studies did not include the effect of vegetation within the scope of the projects. An erosion protection layer was placed on the cover surface of Pile 7/12 to prevent the establishment of trees and shrubs on the cover so that the root system would not establish preferential pathways for oxygen and water (MEND, 1995). Vegetation was removed from the control plot tailings surface for the

Waite Amulet study and an erosion protection layer was placed on the surface of the upper sand layer.

Proper characterization of site vegetation conditions and designing for long term ecological stability is a fundamental research area that must be developed. In general, the end land use of the rehabilitated mine wastes site will determine the appropriate factors required for characterization in order to ensure the long term ecological stability of a soil cover system. Characterization is site specific and can be conducted on nearby undisturbed land forms.

The Heath Steele and Waite Amulet design philosophy was based on isolating the waste and soil cover layers from the environment rather than integrating the two components with natural vegetation. The objective of the studies was to limit the number of variables under investigation. However, in future it may be more appropriate to consider the effects vegetation has on soil cover systems. This is due to the fact that it is not possible to limit the natural succession of vegetation for the long term. The erosion protection provided by vegetation is a positive component to the long term performance of a soil cover system. It is assumed that root development will decrease the performance of a soil cover system as a result of preferential flow paths. However, this has not been verified in the field. Thus, there is a need to undertake fundamental research in this area to better understand the influence of vegetation on soil cover systems.

5.5 METHODS OF ANALYSIS AND PREDICTION

Methods for analyzing and predicting the performance of a soil cover system include the following:

1. Empirical approach,
    - capillary barrier relationships based on the soil water characteristic curve,
    - laboratory prototypes,
    - field test plots,

2. Single phase water movement,
   - steady state one-dimensional - Kisch analyses (Barbour, 1990),
   - two dimensional unsaturated flow analyses - SEEP/W (Geo-Slope International Ltd., 1993),

3. Uncoupled soil atmosphere modelling,
   - the Hydrologic Evaluation of Landfill Performance (HELP) model (Schroeder et al, 1984),
   - the Soil Water Infiltration and Movement (SWIM) model (CSIRO, 1990),

4. Fully coupled analyses,
   - the SoilCover model (MEND, 1993), and
   - the UNSAT-H model (Fayer and Jones, 1990).

The Heath Steele and Waite Amulet studies used an empirical design approach based on the capillary break concept and prototypes in the laboratory and field. The laboratory and field prototypes were extensive and the design objectives of limiting oxygen and water transfer to the waste material were achieved. The flow analysis carried out provided an understanding of the performance of the soil cover but is not rigorous.

The method used to simulate the Heath Steele project was conducted with a two-dimensional, liquid phase, saturated-unsaturated flow model that was calibrated to the laboratory prototype. The design modelling was based on a 60-day evaporation function to simulate dry climate conditions. This was based on a laboratory column test result rather than actual dry climate site conditions. As a result the soil cover design may be based on an extreme climatic condition that may not occur in the field and hence can be considered to be a conservative approach.

Numerical modelling of the Waite Amulet laboratory column tests and the field test plots was conducted using a two-dimensional liquid phase, saturated-unsaturated flow model. The surface flux boundary condition for modelling the laboratory columns was based on a similar 60-day evaporation function as used for the Heath Steele project. The surface flux boundary condition for the field test plots was predicted using the HELP model. Synthetic climate data was generated for Caribou, Maine (which was the most applicable site for Waite Amulet) and then corrected for the Waite Amulet latitude and Amos, Quebec using twenty year monthly temperature and precipitation normals

(MEND 1993). The total annual precipitation generated by the HELP model was 904 mm while the 30 year normal precipitation for the Amos regional climate station was 678 mm with a total precipitation for 1991 and 1992 of 654 mm and 653 mm respectively. The total precipitation for 1991 and 1992 recorded at the Duparquet regional climate station was 571 mm and 721 mm respectively. The normal precipitation for Duparquet was reported to be 640 mm.

The synthetic precipitation data generated by the HELP model is not truly representative of the regional climate stations. However, the subsequent analysis provided an understanding of the performance of a soil cover system. Some questions, as discussed earlier, can be raised with respect to using the synthetically generated data. Figure 5.1 compared the synthetically generated rainfall data to that measured during the summer of 1991 at Waite Amulet. The five month total of synthetically generated rainfall data overestimated rainfall at the site by 120% with a discrepancy of 185% for the month of October.

The same argument can be extended with respect to the HELP model analysis. This model predicted 39 mm (≈ 4% of the 904 mm) of the annual precipitation would infiltrate to the underlying tailings. It is difficult to compare this value to that measured by the field lysimeters installed in the tailings beneath the soil cover since the precipitation data used may or may not be truly representative of field conditions.

The surface flux boundary condition for the steady state SEEP/W modelling of the field test plots was predicted by the HELP model to be 240 mm/year. The SEEP/W modelling calculated that 34 mm (≈ 4% of the 904 mm) of the annual precipitation reported to the tailings. This value is a function of the applied steady state flux, and since the 240 mm/year calculated by HELP was a function of the synthetic precipitation data, the flux from the base of the cover predicted by SEEP/W cannot be assumed to be representative of field conditions either.

It is also important to note that one dimensional flow models may not represent the actual field conditions in many situations. The assumption of one dimensional flow may lead to large disagreement between the model results and actual field responses. Soil cover systems are placed on slopes in many situations and this two dimensional nature should be given consideration in the analysis. Studies to evaluate the influence of two dimensional moisture movement in the cover due to the presence of long slopes would be valuable.

5.6 INSTRUMENTATION AND MONITORING

All components of a soil cover system should be monitored to properly evaluate performance. Field instrumentation should therefore be installed to monitor the underlying waste material, each soil cover layer, the vegetation, and climate. In general, every instrument should be selected and installed to address a specific objective (Dunnicliff, 1996).

The general objectives of a field instrumentation program for monitoring the performance of a soil cover system designed to prevent acidic drainage are to:

1. Evaluate the performance of the soil cover system, and

2. Generate soil cover performance data to conduct field response modelling which will then produce a field calibrated model that can be used for predictive modelling.

The primary objective is to develop predictions of the long term performance of a soil cover system. The theoretical basis and mathematical solution of the predictive tool must be capable of properly representing the key design principles. The method used for predictive modelling will provide a basis for the selection of the boundary conditions, initial conditions, and field performance data (such as: soil suction and temperature profiles) that should be characterized in the field.

The key climate parameters that should be monitored were discussed earlier. Vegetation also plays an important role in the long term performance of a soil cover system and research is required to determine fundamental monitoring techniques and the effect of vegetation development on long term ecological stability.

5.6.1 Soil Cover Response and Instrumentation

The major objective of a soil cover is to act as a barrier against the influx of water and oxygen. The key soil cover response and characterization measurements are soil suction and soil temperature. The suction and temperature within the underlying waste material should also be monitored. The transfer and storage of heat within the waste material and soil cover can be monitored by installing temperature sensors.

Total suction is comprised of two components, matric suction and osmotic suction. Total suction corresponds to the free energy of the soil water, while the matric and osmotic suctions are components of the free energy (Fredlund and Rahardjo, 1993). Field matric suction values can be thought of as a measurement of the negative water pressure within the soil cover system. These measurements are important since matric suction describes the stress state of the soil cover system. In other words, a change in the degree of saturation or water content of the soil cover system is caused by a change in matric suction within the soil cover. Therefore, field measurements of matric suction describe the performance of the soil cover system. In addition, field matric suction values provide a means of verifying field water content measurements.

Evaluation of the response of the soil and waste material sensors to atmospheric forcing is a fundamental component of a field instrumentation program. A study on its effects should therefore be conducted prior to using the field data for field response modelling. The instrumentation should be installed in the correct location and orientation to allow for an accurate evaluation of its response to atmospheric forcing.

The Heath Steele and Waite Amulet studies included extensive field instrumentation programs. The investigators included the measurement of matric suction and this is a positive component of their field monitoring programs. However, the quality of the soil suction sensors used was not satisfactory. The investigators should not be faulted for this since the sensors used were the best available at that time. More importantly this also demonstrates the need for the development of a reliable sensor for field measurement of soil suction. A laboratory calibration curve for each soil suction sensor is required to increase the reliability and accuracy of the sensor. The laboratory calibration process will also detect sensors that will not function properly (as a result of poor quality) prior to installation in the field.

The investigators used the time domain reflectometry (TDR) method for measuring water content of the soil cover layers as well as the tailings material at Waite Amulet. The TDR method is widely accepted and many researchers and practitioners have reported success with its use. The calibration for laboratory and field conditions appears to be satisfactory for the TDR. The neutron moisture probe has also gained acceptance for measuring water content within a soil cover system although its use is not as popular due to difficulties associated with field calibration and the time consuming nature of data acquisition.

A word of caution is required regarding the measurement of water content in the field. All water content sensors must be calibrated in the laboratory and field to account for insitu density and material characteristics if a truly accurate measurement is to be generated. This is true regardless of the physics employed to indirectly measure the water content of a soil. For example, the Waite Amulet investigators reported that the TDR instrument did not give representative water content readings in the tailings as a result of high background conductivity. This observation should not necessarily imply that the TDR method cannot be used to measure the water content of all tailings. More precisely, the generic volumetric water content as a function of the apparent dielectric constant equation proposed by Topp et al. (1980) does not apply to the Waite Amulet tailings. In addition, the oxidizing Waite Amulet tailings produced an output wave that was difficult to interpret. Whether or not the TDR method can be used to accurately measure the water content of a soil or waste material can only be determined through calibration. In short, a field calibration curve should be developed for each soil under investigation, regardless of the water content measurement method employed, and should be based on insitu gravimetric water content and bulk density measurements to ensure that the sensor is providing a quantitative rather than qualitative measurement. However, achieving this goal is extremely difficult. For example, David and Nicholson (1995) showed that even gravimetric water contents and bulk density measurements were prone to error in "wet" fine-grained tailings above the water table. In addition, field calibration of a water content sensor is usually attempted by comparing a single field water content measurement to that predicted by the sensor and its “generic” calibration equation. A one point comparison does not suffice as proper calibration of a water content sensor. Researchers and practitioners have also developed field calibration curves by obtaining measurements at several depths and including all data in a single data base. However, the insitu density and material type will change as a function of depth for natural systems as well as tailings impoundments, waste rock piles, and soil cover systems. Therefore generating a larger data base by increasing the number of samples over the depth of measurement is also not adequate since it leads to poor curve fitting and an “average” field calibration curve. The ideal method for developing a field calibration curve is to build the data base by obtaining gravimetric water content and bulk density measurements for each depth of interest over time. In other words, the calibration data base should be developed over the entire measurement depth. Clearly this would be a time consuming and expensive effort and demonstrates that the more practical method of accurately monitoring moisture conditions is through the installation of soil suction sensors, which do not require field calibration. Installing a soil suction sensor and water content sensor (without the effort of field calibrating the water content sensor) at the same depth, will allow for the development of field soil water characteristic curves for each depth of interest and account for layering of soil types and density in natural and engineered soil systems.

In summary, measurement of suction, water content, gaseous oxygen, and temperature are key parameters necessary for properly monitoring and characterizing a soil cover system.

Field measurement of gaseous oxygen and carbon dioxide in the waste material and verification of insitu compaction and saturated hydraulic conductivity were positive components of the Heath Steele and Waite Amulet field programs.

5.6.1.1 Location, Orientation, and Installation of Instrumentation

The location, orientation, and installation of a sensor is as important to properly characterizing a soil cover system as the field and laboratory calibration curves discussed earlier. Sensors should be installed at key locations within a soil cover system to monitor the dynamic diurnal and seasonal response of a soil cover system. For example, sensors should be installed as close as possible to the soil surface to monitor this dynamic zone of heat and mass transfer and storage. Additional sensors should be installed at key locations such as at the interface of soil cover layers and at the interface of the waste material and the lower soil cover layer as well as in the underlying waste material.

A wave guide type sensor, such as the TDR sensor, should be installed horizontally since the zone of influence is focused around the wave guides. A wave guide type sensor installed vertically across the thickness of a soil cover layer will only provide an accurate measurement of the moisture conditions within the layer if the entire thickness is consistently at the same water content. This is highly unlikely in a layered soil cover system and is especially true of the upper layer of a soil cover system.

The Waite Amulet and Heath Steele investigators state that the TDR sensors at Heath Steele and Waite Amulet were installed horizontally (MEND 1996 and Yanful et al. 1993). However, it appears from the schematics and tables describing the TDR instrumentation, as well as from the figures presenting the TDR data, that the sensors were installed vertically. Therefore, it is difficult to determine if the high moisture conditions measured within the fine grained material at Heath Steele and Waite Amulet were a function of a high water content throughout the entire length of the wave guide or a "average" of moisture conditions along the length of the wave guide. Finally, the investigators compared the TDR measurements against gravimetric measurements although a field calibration curve was not developed. Fundamentally, the TDR measures the volumetric water content of a soil, therefore the measurements should be validated against volumetric water content rather than gravimetric water content.

All sensors should be installed with as little insitu disturbance as possible and with a thought to the predominant direction of flow. For example, a sensor should be installed laterally if the predominant direction of flow within the soil cover system is vertical, in order to minimize disturbance above the sensor.

5.6.2 Field Lysimeters to Monitor Flux into Waste Material

Installation of a field lysimeter introduces an artificial water table below the base of a soil cover. Care must be taken to ensure that this artificial phreatic surface does not influence the moisture flux into the waste material. The conceptual components of a lysimeter design shown in Figure 5.2 are defined as:

1. The depth of the field lysimeter,
2. The wall height of the field lysimeter,
3. The width of the field lysimeter,
4. The hydraulic properties (soil water characteristic curves and k_{sat}) of the materials within the field lysimeter as well as surrounding the field lysimeter, and
5. The flux from the base of the cover system.

The fact that an unsaturated soil system is being monitored is a key concept that must be taken into account when designing a field lysimeter to monitor the net infiltrative flux from the base of a soil cover. In general, the design of a field lysimeter for measuring reliable field drainage is not as simple as it initially may seem and can be quite complex.

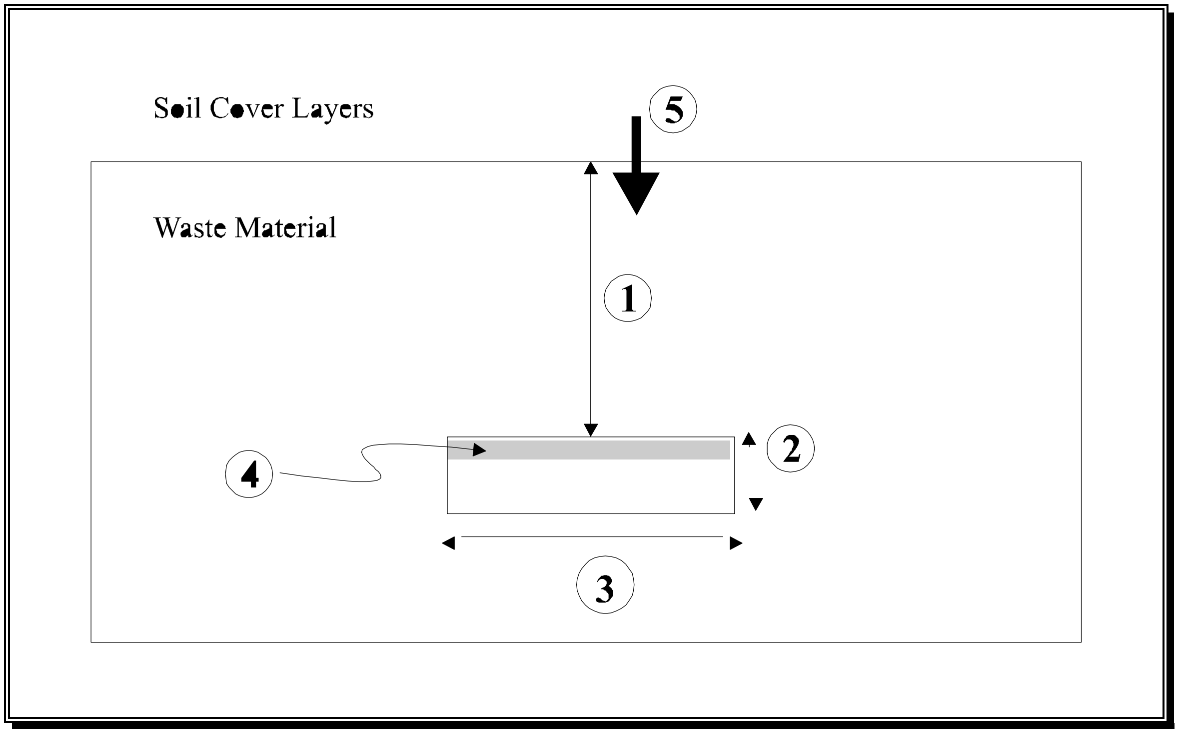


Figure 5.2 Key lysimeter design components.

The design must account for the soil water characteristic curve of the material placed in the field lysimeter. A field lysimeter designed to measure the flux into a waste rock pile will not give a true indication of the actual flux if the field lysimeter is backfilled with a finer soil such as a sand or coarser soil such as a gravel. The waste rock surrounding the field lysimeter will be drained to its residual suction as will the sand or gravel inside the lysimeter; however, more water will flow into the field lysimeter than the surrounding waste rock if the residual suction of the sand is higher than the waste rock. The opposite will occur if the residual suction of the gravel is lower than that of the waste rock.

In general, it is paramount that:

1. the lysimeter geometry does not influence the flux (in vertical or horizontal directions) entering the lysimeter, and

2. the lysimeter is backfilled with material representative of the surrounding waste material with respect to material type and structure.

The discussion provided here is to impress on the importance of measuring the soil water characteristic curves of the materials which are used in and outside the lysimeter.

The two lysimeters installed at the base of the composite soil cover placed on Pile 7/12 at the Heath Steele were backfilled with sand and gravel respectively. The lysimeter backfilled with gravel reported less flux from the cover compared to the lysimeter backfilled with sand. The earlier discussions would also support such a behavior. However, the flux measured by either of the lysimeters may or may not be representative of the actual flux entering Pile 7/12 since the soil water characteristic curve of the waste rock may be different than either the sand or gravel backfill. This observation highlights the importance of measuring the soil water characteristic curve of the waste rock material.

The lysimeters installed as part of the Waite Amulet study were backfilled with unoxidized tailings from the southern section of the existing impoundment where the tailings are known to be coarse (Yanful et al, 1993). The investigators specified coarse tailings rather than tailings that were representative of conditions under the test cover plots. However, the fact that the lysimeters were backfilled with similar material as the surrounding tailings was a positive component of the design. It was reported that the lysimeters were overtopped when the test plot area flooded. The explanation was provided to account for the poor water quality within the tailings. The piezometer data does not seem to support this explanation and an alternative explanation is shown in Figure 5.3. In this case the suction outside the lysimeter was less than that inside due to an artificial water table condition within the lysimeter. Moisture was drawn into the lysimeter from the surrounding tailings as a result. Water could also be drawn out of the lysimeter if the “water table” conditions inside and outside the lysimeter were opposite to that shown in Figure 5.3. In either case, the volume of water measured by the lysimeters at Waite Amulet may not be representative of the flux from the base of the cover.

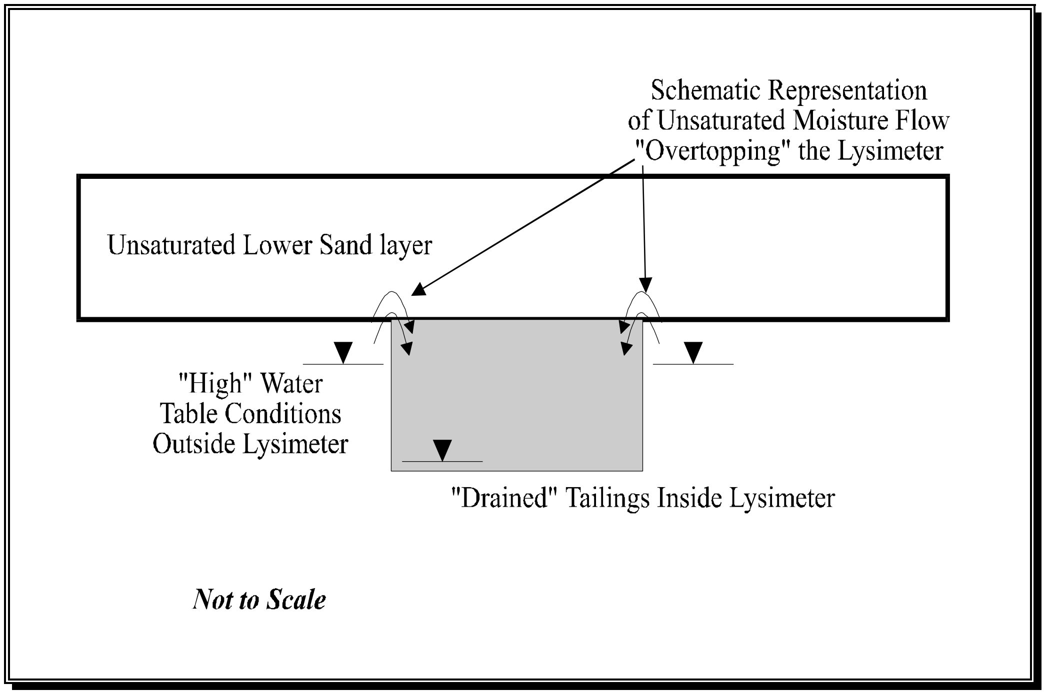


Figure 5.3 Conceptual schematic of the Waite Amulet lysimeter performance.

5.6.3 Future Research

The studies undertaken at Heath Steele and Waite Amulet provided insight into several research areas which are of importance towards the design of a soil cover system. The main concerns related to the soil cover systems is to provide a barrier to minimize the influx of water and provide an oxygen diffusion barrier to minimize the influx of oxygen.

One of the key research areas with respect to instrumentation and monitoring of a soil cover system is the development of a soil suction sensor that is reliable, accurate, and economically viable. In addition, characterization of waste rock piles with respect to moisture storage and transfer is a fundamental research area. At present, an accurate, reliable, and practical method, or "sensor" to monitor moisture storage and transfer in waste rock piles is not available. Finally, fundamental methods are required to characterize, monitor, and design for vegetation and its role in the long term performance of a soil cover system.

5.7 GENERAL PERFORMANCE, CONSTRUCTION, AND ECONOMICS

The validity of the capillary barrier concept under field conditions was strongly supported by the Heath Steele and Waite Amulet studies. The studies demonstrated that high degrees of saturation were maintained in the fine grained layer throughout the year resulting in a low rate of oxygen diffusion.

The layered soil cover system effectively isolated the water infiltration and oxygen ingress barrier from desiccation and freeze-thaw with no apparent increase in the saturated hydraulic conductivity of the fine grained material. A draft report with respect to oxygen diffusion data for a variety of sites is currently being prepared by Nicholson et al (1997).

The test plots were of limited scale but a high level of quality control with respect to placement geometry, water content, and density was demonstrated. The monitoring programs were comprehensive although some installation techniques were inadequate. The lack of a complete site weather station was the only key instrumentation and monitoring component missing from the studies.

The field test plot construction costs were in the range of \$20/m^2 to \$30m^2. These cost may be reduced if a large scale soil cover system were constructed.

There is a significant potential for reducing soil cover construction costs using methods such as the hydraulic placement of cover materials and construction of soil cover systems during winter. The latter construction method would take advantage of the improved subgrade conditions provided by frozen tailings that would otherwise be soft and wet in the summer. The development of these and other innovative material placement techniques are currently under investigation in other MEND studies.

Chapter 6

SUMMARY AND RECOMMENDATIONS

6.1 INTRODUCTION

Prototype insitu covers were constructed at two mine sites, Heath Steele and Waite Amulet, under the MEND program. The objectives of these soil covers was to minimize the influx of water and to provide an oxygen diffusion barrier by maintaining saturated conditions within the cover using the capillary barrier concept. The prototype covers provided an opportunity to verify that this design concept was effective under field conditions.

An independent review of these study programs has been conducted by the Unsaturated Soils Group, Department of Civil Engineering, at the University of Saskatchewan. The main objectives of this review were:

1. To undertake a literature review of fundamental processes and methods of analyses required for the evaluation and design of dry covers;

2. To identify the key aspects of the design of soil cover systems,

3. To complete an inventory of other "dry cover" sites and their performance;

4. To undertake a critical scientific review of the Heath Steele and Waite Amulet sites including evaluation of the quality and completeness of:
   a) field and laboratory tests;
   b) site instrumentation systems and monitoring results; and
   c) data analysis and interpretation.

5. To identify alternative design methods that provide for the essential components of a soil cover system, while minimizing costs; and

6. To provide recommendations as to critical research needs in the areas of design, construction, monitoring, and analysis of soil cover systems.

6.2 OVERVIEW OF RATIONALE METHOD FOR COVER DESIGN

Over the course of this review it became apparent that a template for a rationale method of cover design for acid generating mine wastes was emerging. The basic elements of this rationale method provides a backdrop against which the design of various covers can be evaluated and the lessons learned from these experiences can be catalogued.

The basic elements of this rationale method for design can be summarized as follows:

- Design objectives/philosophy;
- Design principles;
- Methods of characterization
- Monitoring;
- Methods of analyses; and
- General issues including economics, construction, long term performance.

Each site can be reviewed in terms of these design components. It needs to be understood at the outset that the scope of the Waite Amulet and Heath Steele projects was limited to only the field verification of the principles related to capillary barriers. Consequently one would not expect that they should be subjected to as rigorous a critique; however, there are important lessons from these sites which can be incorporated into the design method. Other sites of note have been reviewed in Chapter 3. This final chapter will focus on the major findings obtained from the review of the Heath Steele and Waite Amulet sites.

6.3 DESIGN OBJECTIVES AND PHILOSOPHY

There are two different views of cover design one can take; that of designing an engineered structure, the other of designing an engineered system.

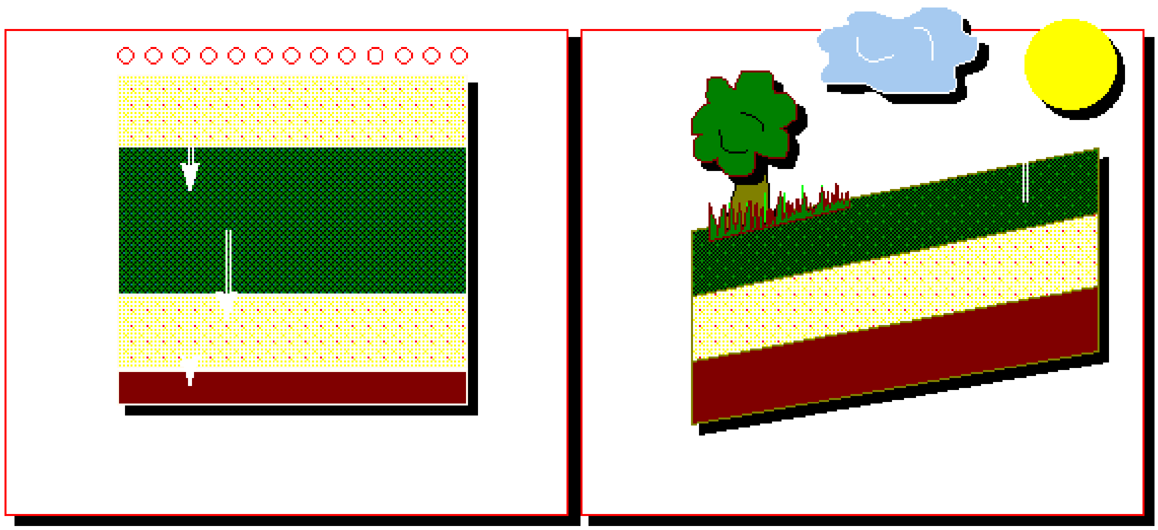


Figure 6.1. Objectives of dry cover design: Engineered Structures vs. Engineered Systems

In engineered structures, the design objectives of minimizing infiltration and the ingress of oxygen are obtained by providing an engineered multilayer system in which a low hydraulic conductivity barrier prevents infiltration while the capillary barrier phenomenon preserves a high degree of saturation. Additional elements of design such as surface cover layers are provided to isolate the structure from the effects of weathering (erosion, freeze-thaw, desiccation) and vegetation. The design is primarily one of engineered specification and is based on a view of long term average steady flux conditions.

The advantage of this approach is the simplicity of design. It does not require theoretical rigour or analyses but rather relies on empirical designs tested by experience and field prototypes. The disadvantage of this approach is that it is difficult to extrapolate the design into new conditions (climate, waste, geometry, etc.) without full scale prototype testing. In addition, it is often fairly conservative, and consequently may not provide economically viable designs.

The Heath Steele and Waite Amulet projects provided clear verification of the design principles, methods of characterization, and monitoring of dry covers, built using the engineered structure approach. The work has been well documented and has effectively used a design method which incorporates laboratory and field prototypes. It clearly supports the applicability of the capillary barrier concept to cover design and demonstrates that isolation can be provided which will preserve this structure from the effects of environmental influences in the short term.

Engineered systems on the other hand, are the design of dynamic soil/waste systems which are coupled to a site specific physical environment, including climate and vegetation. These systems have as a design goal the integration of the cover into the long term natural evolution of the site and consequently, they hold substantial promise for long term design. The disadvantage of these designs however, is that they require a high level of theoretical and analytical complexity, some of which is still being developed. These designs require that the interactions between the cover and the environment be dealt with in a dynamic, fully coupled manner. The advantage of this increased design complexity is that it provides for greater freedom, and hopefully a more economic design.

The danger in the development of cover design based only on the “engineered structure” approach is that we will rapidly move to the view that a soil cover system is an “up-side down liner”. This severely limits our ability to design and is also not consistent with observations of natural systems. An example is the comparison in the United States between the Resource Conservation and Recovery Act (RCRA, 1976) designs and those currently being considered for long term storage of nuclear waste at Hanford by the Department of Energy (DOE). The RCRA (1976) design is based on multiple engineered barriers and has been criticized for its short (30 years) design life, while the Hanford design is based on a “store and release” approach to minimizing infiltration by integrating the appropriate suite of soil layers with vegetation. This design provides a dynamic, transient, coupled, long term barrier to infiltration.

The objectives for Heath Steele and Waite Amulet were designed only to provide a field demonstration of the application of the capillary barrier concept to the design of dry covers for acid generating mine wastes. In this sense, they are a positive contribution to our understanding of some important processes in design. However, it would be a disservice to the Heath Steele and Waite Amulet work to allow soil cover design to de-evolve into the construction of “upside-down liners”.

6.4 DESIGN PRINCIPLES

It follows from the discussion on the philosophy and objectives for design that the key design principles are those associated with the movement of moisture and oxygen through unsaturated soils and the coupling of their response to the environment.

The key design principles have been reviewed briefly in previous sections of this report. The behavior of a soil system is controlled by the coupled response between the soil and the surrounding ecosystem. Consequently, the fundamental design principles include the inter-relationships between climate, vegetation, and soil in controlling surface phenomena such as actual evaporation, transpiration, runoff, infiltration, and erosion. The key component in the design of a soil cover system is the soil/atmosphere continuum.

It is important to highlight again that the fundamental behavior of unsaturated soils, whether it be in the cover materials or the underlying waste, is rooted in an understanding of the soil water characteristic curve. This function defines a fundamental relationship between the various stress and deformation states within an unsaturated soil, relating water storage to the total energy within the water phase. Consequently, it can be described as the fundamental property of an unsaturated soil that relates its ability to store and transmit water. It also forms the basis from which other material property functions, such as hydraulic conductivity and shear strength, can be predicted, as it also defines the distribution of the fluid phase in the soil pores.

Recommendations regarding further research as it pertains to the soil water characteristic curve and soil-ecosystem coupling will be combined with the following discussion on the Methods of Characterization.

6.5 METHODS OF CHARACTERIZATION

The key soil properties related to cover performance are the soil water characteristic curve and the hydraulic conductivity function. It is critical that in all soil cover designs these two properties be characterized both through laboratory testing as well as field verification testing. These two properties in particular are sensitive to changes in soil structure and consequently are sensitive to sample preparation in the laboratory or to construction procedures and the effects of weathering in the field.

It is also important to re-emphasize that all candidate soils for cover construction as well as representative samples of the waste materials (tailings or waste rock) must be fully characterized. In recent years a number of methods have been developed in which preliminary estimates of these properties can be made for analyses using the grain-size and geotechnical properties of the materials.

One area of ongoing study is on the effects of weathering processes such as chemical weathering, desiccation, freezing and thawing, and vegetation on the properties of the cover materials. In order to predict the long term performance of the engineered soil cover system it is imperative that these influences be understood.

Recommendation #1*: That research be conducted into the characterization of the soil water characteristic curve for soil cover and mine wastes materials. Of particular interest are the methods of characterizing and estimating the soil water characteristic curve and the prediction of the effect that weathering processes may have on this property.*

Characterization of environmental influences on cover performance include the study of climate effects, particularly micro-climatic effects, vegetation, and erosion. Regional weather stations are often insufficient in providing the level of detail required for site specific design. In addition, in many cases the micro-climatic conditions (wind speed, snow cover, radiation) can vary significantly across the site. Methods for characterizing the influence of vegetation as it pertains to cover performance still requires further development. Although a rich data base exists for agricultural soils and plants, little information is currently available on the characterization of vegetation required for cover design, particularly natural woodland systems which are the “real long term” systems for most of Canada. This characterization may include data on root depth, Leaf Area Index (LAI), and transpiration rates.

Recommendation #2: *That research be continued on the inter-relationships between micro-climatic conditions, vegetation, and soil as it pertains to cover performance.*

6.6 METHODS OF ANALYSES

Theoretical soil cover designs cannot occur without access to accurate and reliable predictive methods. Current practice seems to rely heavily on the application of analyses such as the HELP model which does not couple the soil and climate interaction. In addition, HELP does not predict stress states, the performance of capillary breaks or estimate oxygen flux. It is important to note that a series of linked applications, each with an increasing level of complexity, will be required for cover design. Research should be supported which helps to "benchmark" the various applications against documented case histories to highlight the applications and limitations of each method of prediction.

Further work is still required on expanding our analytical capabilities as they pertain to soil cover performance. Recommended areas of further study include consideration of multi-dimensional effects (moisture movement, climatic influences) and increased levels of sophistication as it pertains to processes such as snow accumulation and melt, freeze-thaw, vegetation, erosion, runoff, and weathering.

Recommendation #3: *That current methods of analyses for dry covers be reviewed including benchmark testing against documented case histories and that a methodology for analyses be developed which maximizes the capabilities of the various models.*

Recommendation #4: *That further work be initiated to expand the capabilities of current models to include environmental coupling. Additional capability is required in the prediction of moisture movement during winter months, the influence of vegetation, multi-dimensional effects, and erosion.*

6.7 MONITORING

The two case histories described (Waite Amulet and Heath Steele) along with others cited in this report (Equity Silver and Golden Sunlight) demonstrate the high level of confidence that exists with the current methods of monitoring the soil cover/waste response to environmental conditions at the sites. The experience at Equity Silver Mines Ltd. and other sites indicate that complete monitoring of climate and cover response can be undertaken at reasonable costs (≈ $50,000). Monitoring is of paramount importance not only to the initial characterization of site conditions, but also in providing field data against which analyses and predictions can be corroborated.

There are two areas of particular concern in monitoring soil cover/waste response: the measurement of soil suction and field lysimeter design.

We currently do not have an accurate, reliable, and durable means of monitoring suction. This stress state controls the flow of liquid water and water vapour as well as the storage of water. Soil suction also controls shear strength and volume change behavior within the soil cover system. Field monitoring of cover sites must include reliable methods of measuring suction.

Recommendation #5*: That work be undertaken for the development and testing of a reliable method of measuring suction within covers and waste rock.*

The second area of concern rising from the review was the lack of understanding in the design of lysimeters for measuring the net flux of water through covers. It is often assumed that if the fine grained layer remains saturated, the gradient through the cover is constant and equal to 1. In fact, the flux through the cover is a function of the properties of not only the fine grained layer but is also a function of the material underlying the cover, which in turn controls the suction at the base of the cover. The lysimeter establishes an artificial water table boundary below the cover which is not the same as that outside the lysimeter. The design of lysimeters requires that the geometry of the lysimeter (area and depth), hydraulic properties of the backfill (soil water characteristic curve and k_{sat}), and the cover response (flux) be integrated so that the suction at the base of the fine grained layer is the same both inside and outside of the lysimeter.

Recommendation #6: *That a review of lysimeter design and performance be undertaken with a view on developing design procedures which take into account the complexities of unsaturated flow on lysimeter performance.*

In addition to these areas of concern, there are also other areas in which new developments in monitoring and instrumentation systems are required. Concerns still arise as to the feasibility of monitoring key soil cover interactions such as runoff, sediment movement due to erosion, and vegetation (root depth, LAI, etc.). Studies on predicting the onset of erosion on soil covers is also underway.

Recommendation #7: *That further work be undertaken on the development of techniques for monitoring soil/environmental responses such as erosion, runoff, and vegetation factors relevant to cover performance.*

6.8 GENERAL CONCLUSIONS AND RECOMMENDATIONS

The recommendations given in the previous sections are quite specific and relate to particular issues that have arisen during the review. There are a number of more general issues regarding the future direction of research and practice as it pertains to cover design for acid generating mine wastes.

The discussion at the beginning of this chapter laid out the two types of design objectives/philosophy that can be adopted. Although Heath Steele and Waite Amulet illustrate that adequate designs can be obtained through the prototype based design of engineered structures, it is believed that the potential for long term, economic designs will require a greater degree of integration of the soil cover with the environment. This is the direction taken in the Hanford (DOE) program and is also supported through research by the Unsaturated Soils Group, University of Saskatchewan at a variety of mine sites.

Recommendation #8: *That a design philosophy and design objective be encouraged which focuses on the development of long term engineered cover systems which are fully coupled and integrated with the natural environment.*

It is evident that many of the most significant advances in our understanding of cover performance have come from field based studies. Although Heath Steele and Waite Amulet provide excellent examples of field prototypes they are of limited scale. For example, concerns arise at Waite Amulet due to the presence of lateral flow under the covers, a situation which would not occur at full scale. In order to develop a fully integrated environmental systems approach to cover design, it is imperative that the development of full scale and long term case histories be documented to incorporate both spatial and temporal rigour in the study. The case histories should be well documented so that the relationship between characterization, monitoring, and analyses is fully integrated. A high level of confidence in design adequacy and economics will not be established until we begin to document failures as well as successes.

Recommendation #9: *That full scale, long term, field case histories be developed and documented to increase the level of confidence in design principles, and methods of characterization, analyses, and monitoring.*

The long term evolution of the eco-system (pedological development, vegetation, bio-intrusion) associated with the performance of soil covers is of particular interest. Studies can be initiated which undertake a review of these areas as it has been studied with respect to agriculture and forestry. Historical analogues exist in areas which have been previously cleared or reclaimed. Existing full scale covers also provide an ongoing opportunity to study the long term ecological stability of soil cover systems.

Recommendation #10: *That studies be initiated to look at issues related to the ecological stability of covers. These studies will include a transfer of technology from the forestry, reclamation, and agricultural areas to the area of cover design, and will provide a basis for predictions of long term cover performance.*

The economics of soil covers has often been of concern. The Heath Steele and Waite Amulet studies demonstrate that small scale projects can be built for $20 to $30 per square meter. More sophisticated designs such as the Hanford cover will require as much as $100 per square meter. There is a need to develop economic applications associated with cover design and construction.

There are a number of promising developments in this regard. The cover at Equity Silver Mines Ltd. suggests that the 3-layer system can be constructed using the waste rock as the capillary break, densely compacted till as the moisture retention layer, and the same till placed in a loose condition as the upper storage and evapotranspiration barrier. The result is a multiple barrier constructed with only one imported material. Work at the Golden Sunlight Mine in Montana, and work being conducted in Quebec by the Ecole Polytechnique are looking at using mine wastes (waste rock and tailings) as components of the cover. The use of wood waste or municipal waste is also being considered. In addition, the use of new engineering materials (cementitious covers, or geosynthetics) is also under review. Innovative placement methods, such as the use of thickened tailings deposition techniques and winter construction are also being considered.

Recommendation #11: *Ongoing work into the use of economic design methods (i.e. 1 material - multi-layer) and materials should be supported.*

It appears that a consensus is developing as to the basic issues pertaining to design objectives and principles as well as methods of characterization, analyses and monitoring. Unfortunately this understanding has not been effectively disseminated to the mining and consulting industry. In order to facilitate this technology transfer it is important to develop a rationale design method, if only as a working draft, and to develop a guide which outlines the key issues pertaining to design. This guide should be prepared in such a way that it can include documented case histories and should also be in an "open-binder" format so that it can be updated regularly as the need arises.

Recommendation #12: *That a state-of-the-art manual or handbook be developed which incorporates a rationale design method supported by documented case histories. This handbook should be prepared in an open-binder format so that it can be maintained as a current and dynamic summary of cover design methodology.*

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Yanful, E.K., and Luc C. St-Arnaud. 1991. The Waite Amulet hydrogeochemical evaluation. Second International Conference on the Abatement of Acidic Drainage, Vol. 1, Montreal, September 16-18, pp. 91-114.

Yanful, E.K., Payant, S.C. 1991. Laboratory evaluation of the performance of engineered soil covers for decommissioning of sulphidic tailings. Proceedings: 44th Canadian Geotechnical Conference, 1991.

Yanful, E.K. and L. St-Arnaud. 1991. Design, instrumentation, and construction of engineered soil covers for reactive tailings management. Proceedings: Second International Conference on the Abatement of Acidic Drainage, Vol. 1, Montreal, September 16-18, pp. 487-504.

Yanful, E.K., and Aube, B. 1993. Modelling moisture-retaining soil covers. 1993 Joint CSCE-ASCE National Conference in Environmental Engineering. July 12-14, Montreal, Quebec.

Yanful, E.K., Bell, AV., and Woyshner, M.R. 1993. Design of a composite soil cover for an experimental waste rock pile near Newcastle, New Brunswick, Canada. Canadian Geotechnical Journal, Vol. 30, pp. 578-587.

Yanful, E.K., Riley, M.D., Woyshner, M.R. , and Duncan, J. 1993. Construction and monitoring of a composite soil cover on an experimental waste-rock pile near Newcastle, New Brunswick, Canada. Vol. 30, pp. 588-599.

Yanful, E.K. 1993. Oxygen diffusion through soil covers on sulphidic mine tailings. Journal of Geotechnical Engineering, Vol. 119, No. 8, pp. 1207-1228.

Yanful, E.K., and Payant, S.C. 1993. Laboratory acid fluxes from covered and uncovered sulphidic tailings. CIM Metsoc Meeting Symposium, Aug. 30-Sept. 1.

Yanful E.K., Shikatani, K.S., Quirt, D.H. 1995. Hydraulic conductivity of natural soils permeated with acid drainage. Canadian Geotechnical Journal, Vol. 32, pp. 624-646.

Yazdani, J. 1996. Soil water characterization of mine waste rock containing coarse material. Master of Engineering Thesis, Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada.

APPENDIX A

ANNOTATED LITERATURE REVIEW OF

PAPERS AND REPORTS

ON

SOIL COVERS AND LINERS

AND

OTHER RELATED TOPICS

Abu Hassanien, Z.S., and Benson, C.H. 1994. Using electrical resistivity for compaction control of compacted soil liners. Tailings and Mine Waste '94, Balkema, Rotterdam. pp. 177-188.

The authors of this paper measured electrical resistivity of two compacted clays at various molding water contents and compactive efforts. Electrical resistivity was found to be sensitive to molding water content and compactive effort. Lower electrical resistivity was obtained when the molding water content or compactive effort was increased. A distinct relationship between electrical resistivity and initial saturation (a parameter that combines molding water content and dry unit weight) was observed. This relationship was independent of compactive effort. A distinct relationship independent of compactive effort was also observed between hydraulic conductivity and electrical resistivity. The authors of this paper suggest that electrical resistivity measurements may prove useful in construction control of compacted soil liners based on the results of this paper.

Achib, M., Aubertin, M., and Chapius, R.P. 1994. Column tests investigation of milling wastes properties used to build cover systems. Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29. Vol. 2, pp. 128-137.

In this paper, the authors briefly review the basic principles behind the design of multilayer cover systems to control acid production. Some of the main components of an ongoing laboratory investigation are then presented. The emphasis is placed on column test procedures used to evaluate various cover configurations. Some analytical and numerical solutions to specific problems related to cover design are finally given.

The use of "dry covers" appears to be one of the most practical alternatives to control the production of acid mine drainage generated by reactive tailings (milling wastes). The purpose of such covers is to limit the flow of water and/or oxygen to the tailings so that reactions leading to acid generation can be prevented. Various types of materials have been considered to build such covers including geomembranes and fine grained soils because these materials are not always economically available. Authors of this paper have proposed the use of fine tailings that do not contain sulfide as a capillary material in a multilayer cover system. A research project is presently underway to investigate the potential efficiency of milling wastes. This research includes several different tests on homogenized tailings to determine some of the hydrogeological properties, such as hydraulic conductivity, capillary curves, and effective diffusion coefficients.

Akindunni, F.F., Gilham, R.W., and Nicholson, R.V. 1991. Numerical simulations to investigate moisture-retention characteristics in the design of oxygen-limiting covers for reactive mine tailings. Canadian Geotechnical Journal, Vol. 28, pp. 446-451, pp. 446-451.

Acid generation in reactive mine tailings is an oxidation process that is dependent upon the availability of molecular oxygen. The influx of atmospheric oxygen into a material at depth can theoretically be minimized by maintaining a protective cover layer at high moisture content. This can be accomplished because the diffusion coefficient of oxygen is several orders of magnitude higher in air than in water. Such oxygen-limiting covers are generally finer in texture than the material being protected. A numerical model was used to investigate the importance of moisture-retention characteristics in the transient drainage of such two-layer systems. The results show that the effectiveness of a material as a moisture-retaining cover is dependent upon the magnitude of its air-entry value and the pressure head at which the underlying coarse material approaches residual saturation.

The results of the numerical study proposed in this paper support the model of Nicholson et al. (1990); however, experimental verification is required. It should also be recognized that the simulations do not address all of the practical-design considerations for a fine grained cover. In particular, hysteritic effects caused by alternate cycles of wetting and drying, reduced moisture content caused by evaporation, and the effects of freezing and thawing on the integrity of the cover are important questions that need to be addressed.

Authors report that further laboratory modelling studies are in progress to better define the limitations of the concept. Preliminary results of the laboratory experiments show trends that are consistent with the aforementioned discussions.

Anderson, J.E., Nowak, R.S., Ratzlaff, and Markham, O.D. 1993. Managing soil moisture on waste burial sites in arid regions. Journal of Environmental Quality, Vol. 22, pp. 62-69.

In semi-arid regions, where potential evapotranspiration greatly exceeds precipitation, it is theoretically possible to preclude water from reaching wastes by providing a sufficient cap of soil to store precipitation while plants are dormant; and establishing sufficient plant cover to deplete soil moisture during the growing season, thereby depleting the soil moisture storage. The theory and rationale for such an approach is proposed and discussed using field study results in this paper.

The capacity of four species of perennial plants used to deplete soil moisture on simulated waste trenches was determined. In addition, the effective water storage capacity of the soil was examined. This data was then used to estimate the minimum depth of fill required to prevent deep drainage. It was shown that all of the species studied were capable of using all of the plant-available soil water, even during a very wet growing season. The water storage capacity of the soil studied was 17% by volume. A trench cap of 1.6 m thickness was found to be adequate to store precipitation received while plants were dormant. A fill soil depth of 2 m was however, recommended to provide a margin of safety in case water accumulated in local areas as a result of heavy snow fall, subsidence, or runoff. The authors suggest that fill soil requirements and the choice of plant specimens will vary, but the concepts and general approach are applicable to other shallow land burial sites in arid or semi-arid regions.

Applegate, R.J. and Kraatz, 1991. Rehabilitation of Rum Jungle Uranium Mine, Second International Conference on the Abatement of Acidic Drainage. Montreal, pp. 153-169.

Uranium and copper were mined at Rum Jungle in the Northern Territory, Australia between 1954 and 1971. During this period, a severe acid mine drainage problem developed. Following exhaustive investigations and studies in the 1970's a detailed strategy for rehabilitating the mine site was formulated. It was found that the ingress of water and oxygen from the major overburden heaps were contributing to the problem. The strategy developed therefore involved sealing of the overburden. This reduced pyrite oxidation and the transport of heavy metal pollutants.

A four year rehabilitation project funded by the Australian Government commenced in 1982 and cost $18.6 million. Since then an integral monitoring project has indicated that the rehabilitation operation has proved very successful. Oxidation of pyrites in the heaps has slowed and the quantities of heavy metals reaching the Finnis River have been greatly reduced. Conclusions reached include the following:

- Acid mine drainage and associated heavy metal migration is a world wide problem.
- Due to the complexity of the problem, there is increasing emphasis on establishing cost effective measures to combat it.
- The Rum Jungle rehabilitation project has shown the effectiveness of one such rehabilitation strategy for acid mine drainage affecting an abandoned mine.
- While it is too early to say that the entire operation has been 100% effective, the signs are that the concept of sealing the heaps to prevent the ingress of water and oxygen is a feasible and cost effective method of controlling acid mine drainage.
- The planning, design, implementation and monitoring of the Rum Jungle Rehabilitation Project is very well documented and because monitoring has been a large part of the project from well before the actual works commenced, the results have proven very useful for assessing a wide range of issues involved in the acid mine drainage process.

Aubertin M.M., Chapuis, R.P., Bussiere B., Aachib, M. 1993. On the use of tailings as a cover to prevent AMD. Proceeding of the 1993. Joint CSCE - ASCE National Conference on the Environmental Engineering, pp. 195-202.

The disposal of tailings containing reactive sulphides can be the source of serious environmental problems because of their potential for generating acid waters containing high level of toxic heavy metals. Traditionally, fine grained soils such as clay or till, have been considered to build such covers. However, fine grained soils are not always economically available for the construction of barriers over acid producing reactive tailings. The authors have proposed the use of tailings in the design of cover systems through this paper. Some of the hydrogeological properties of tailings relevant to cover systems are also presented. In addition, it is shown how a multilayered system can be used.

Aubertin, M., Chapuis, R.P., Aachib, M., Ricard, J.F., Tremblay, L., and Bussiere, B. 1994. Cover technology for acidic tailings: Hydrogeological properties of milling wastes used as capillary barrier. First International Congress on Environmental Geotechniques, Edmonton, Alberta, pp. 427-432.

Mining activities can be the source of various environmental problems. Among these, acid mine drainage (AMD) produced by sulfide tailings (milling wastes) is probably one of the most serious challenges to the mining community in Canada and around the world. AMD causes a lowering of the subsurface water pH, to values of 2 to 3, which in turn causes the dissolving of potentially toxic heavy metals. There are only a few alternatives available to reclaim such tailings, among which the use of covers appears to be the most practical. Covers aim to limit the flow of water and/or oxygen which are necessary elements for the production of AMD. These covers are traditionally built from fine grained soils; however, because these materials are not always economically available, the authors have proposed to use the fine tailings themselves as capillary material in a layered cover systems. In this article, some of the basic mechanisms controlling the efficiency of such cover systems are presented together with recent hydrogeological laboratory tests on mine tailings including consolidation, permeability and the soil-water characteristic curve.

Baker, R.S., and Hillel, D. 1989. Laboratory tests of a fingering during infiltration into layered soils. Soil Science Society of America Journal, Vol. 54, pp. 20-30.

A theory has been presented by Hillel and Baker to explain and predict infiltration into layered soils in terms of measurable hydraulic properties. When the conductivity of a coarse textured sublayer, at its effective water-entry suction, is greater than the rate of transmission through a fine textured top layer, the flow velocity increases across the interlayer plane. A spatially-distributed flow field in the top layer will then tend to constrict, forming spatially separated streams (fingers) in the sublayer. To test this hypothesis, ponded infiltration experiments were conducted in transparent laboratory chambers packed with air-dry sands. The hydraulic properties of the media were determined by equilibrium capillary rise, parameter estimation, and horizontal absorption experiments. Dynamic measurements of flux and suction at the inter layer plane during infiltration revealed that the water entry suctions are a function of the predominant pore size in the sublayer and can be predicted from its median particle size (r^2 = 0.99). Predictions regarding the onset of fingering and the wetted fractional volume of fingers were both validated for the mono-disperse and poly-disperse sublayers studied.

Barbour S.L., Wilson, G.W., and St-Arnaud, L.C. 1993. Evaluation of the saturated-unsaturated groundwater conditions at a thickened tailings deposit. Canadian Geotechnical Journal, Vol. 30, pp. 935-946.

The method of thickened tailings disposal has been in use at an active copper-zinc mine near Timmins, Ontario, for approximately 25 years. Field and laboratory tests were conducted to determine particle-size distribution at various horizontal locations, in situ values of hydraulic conductivity, moisture retention characteristics, and in situ water contents. The results of the investigation show that the thickened tailings deposit is relatively homogeneous and that groundwater levels follow the gently sloping topography of the tailings surface. Upward-seepage analyses were conducted for various steady-state evaporative fluxes. These analyses showed that the ability of tailings to maintain saturation can be attributed to their high air entry value and to the shallow ground water levels. Saturated conditions minimize the diffusion of atmospheric oxygen into the tailings which aids in the prevention of acid generation.

Barbour S.L., and Yanful, E.K., 1994. A column study of static nonequilibrium fluid pressures in sand during prolonged drainage. Canadian Geotechnical Journal, Vol. 31, pp. 299-303.

A key concern in the design of liners or covers over unsaturated soil, is the magnitude of negative fluid pressure that will develop along the base of the liner or cover. In the absence of evaporation or vapour migration, maximum negative fluid pressures will develop near the cessation of drainage. Previous theoretical analyses and numerical modelling of these systems have indicated that this pressure will be equivalent to the pressure at which an underlying sand reaches its residual water content. The hydraulic conductivity at these pressures is so small that "static" non-equilibrium pressures are sustained over long periods of time.

In this paper drainage of a fine and coarse layered sand column is monitored in the laboratory. These column results provide confirmation that the maximum negative pressures that will develop in a coarse grained soil during drainage are approximately the same as those developed at the residual water content. Although not at equilibrium, this condition will persist for long periods of time in the absence of other mechanisms of moisture movement such as vapour flow. Measurement of the moisture-retention characteristics for these materials will provide a reasonable estimate of the maximum negative pressures that will develop along the base of liners or covers during prolonged periods of low leakage or infiltration.

Barbour, S.L., Wilson, G.W., Arnaud, L.St., Salvas, R.J., and Bordin, D. 1993. Aspects of environmental protection provided by thickened tailings disposal. Innovative Mine Design for the 21st Century. Proceedings of the International Congress on Mine Design, Aug. 23-26, 1993. Published by A.A. Balkema/Rotterdam/Brookfield 1993.

This paper describes the enhanced environmental protection provided when the thickened tails disposal method is used. Non-thickened disposal facilities rely on "engineered" control structures such as water retention dams, cutoffs, and liners. In thickened tailings disposal, the properties and placement of the tailings themselves are "engineered" in order to minimize effluent seepage rates and prevent acidification of the tailings. Key features of thickened tailings disposal are the low hydraulic conductivity, high capillarity and spatial homogeneity of the tailings. These key features are illustrated using the data from the Falconbridge Kidd Creek Division mine tailings in Timmins, Ontario, Canada.

Bell, A. V., Surges, L., and Groskopf, G.R. 1990. An update on the acid waste rock field trials at Heath Steele Mines, New Brunswick. Acid Mine Drainage Conference, GAC-MAC Annual Meeting, Vancouver, British Columbia, May 16-18 .

This paper describes an experimental program used to evaluate the performance of alternate covers for existing acid waste rock piles at Heath Steele Mines in New Brunswick, Canada. Including in the description are the selection of experimental piles, installation of instrumentation, definition of back-ground conditions, and the design of covers to be installed and monitored during the final phase.

Bell, A. V., Riley, M.D., and Yanful, E. K. 1994. Evaluation of a composite soil cover to control acid waste rock pile drainage. Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, 1994. Vol. 2, pp. 113-121.

Acid mine drainage (AMD) research under the MEND program has been ongoing since 1988 at the Heath Steele Mines, near Newcastle, NB, Canada. In 1989 approximately 10,000 mt of waste rock was placed on a prepared sand base with an underlying impermeable membrane. The waste rock pile was heavily instrumented to measure oxygen concentrations and temperatures. In September 1991, a composite soil cover was designed using local soils and considering local climatic conditions. This cover was placed over the waste rock pile, creating a totally enclosed system. Moisture content and oxygen probes were installed within the composite soil cover to monitor changes over time, while two large-size lysimeters were installed below the cover to monitor the hydraulic conductivity of the cover.

Analyses of the waste rock monitoring data shows that the placement of the composite soil cover has had a major impact on the generation of AMD. Major reductions in temperature and oxygen concentrations within the waste rock pile indicate that the cover has significantly inhibited the oxidation reaction that generates the AMD. In addition performance data has shown that the cover has maintained its integrity under the climatic conditions of the area.

Bennett, J.W. and Pantelis, G. 1991. Construction of a waste rock dump to minimize acid mine drainage - A case study. Second International Conference on the Abatement of Acidic Drainage, Vol. 3, Montreal, September 16-18, pp. 299-318.

Construction of a waste rock dump at a zinc, lead and silver mine in northern Australia was completed at the end of 1986. Efforts were made to isolate the pyritic waste by placing it on top of a thick base of clay and non-pyritic material. Waste rock with a pyrite fraction greater than 5 percent was selectively placed in a pit which had been left in the centre of the other pyritic waste. There was no effective seal against water or gas transport on the dump surface.

By 1990 there were signs that pyritic oxidation was occurring, generating metal sulphates which were being transported to the environment. Probe holes were installed in the dump to enable the measurement of temperature and pore gas oxygen concentrations. These measurements could then be used as indicators of the location of and rate at which pyritic oxidation was occurring.

The measured data was used to calibrate the parameters in Ansto's mathematical model of heaps undergoing pyritic oxidation. This model showed that diffusion through the dump surface was the dominant oxygen supply mechanism and that 1300 tonnes of sulphate was being generated per year at the time of measurement in 1990. Modelling of the future behavior of the dump indicated that it would take 14 years for the sulphate generation rate in the rehabilitated dump to fall to half of the current value.

The model was also used to assess the effect that varying the size of the surface cover would have on limiting the pollution generation rate. The covers were presented as being impermeable to oxygen. Covering only the high-pyrite zone reduced the sulphate generation rate to 25 percent of the rate in the rehabilitated dump, and covering the whole surface reduced the rate to 4 percent.

Bennett, J.W., and Ritchie, A. I. M. 1991. Measurements of the transport of oxygen into two rehabilitated waste rock dumps. Second International Conference on the Abatement of Acidic Drainage, Vol. 3, Montreal, September 16-18, pp. 289-298.

Two pyritic waste rock dumps at the abandoned Rum Jungle mine site in northern Australia were rehabilitated between 1983-1986. In the past, these dumps were major sources of environmental pollution. Rehabilitation involved reshaping the dumps and capping them with a three-layer cover that included a compacted clay layer.

Long term monitoring of oxygen levels in a waste rock dump provides a sensitive indicator of changing conditions in the system. The monitoring of additional data such as gas diffusion coefficients, oxidation and pollution generation rates, allows the stability of site to be assessed and quantified. Lysimeter measurements have shown that the covers on both waste rock dumps continue to meet the rehabilitation design specifications for water infiltration.

This paper presents data from the monitoring of oxygen concentration levels data in the dumps since rehabilitation. The behavior of the oxygen profiles in "White's dump" follow an annual cycle. Oxygen concentrations increase during the dry season and return to a minimum during the monsoonal wet season. There is no such seasonal variation in oxygen levels in the "Intermediate dump", where it appears that the integrity of the covers, with respect to oxygen transport, is being maintained. The data from White's dump will enable the evaluation of oxygen consumption rates, pollution generation rates and gas diffusion coefficients. Until the data are further analyzed, it is not possible to say whether the seasonal increases in oxygen levels in White's dump mean that the cover is now as effective in limiting oxidation rates as it was immediately after installation.

Benson, C. H., and Daniel, D.E. 1990. Influence of clods on the hydraulic conductivity of compacted clay. Journal of Geotechnical Engineering, ASCE, Vol. 116, No. 8, pp. 1231-1248.

The laboratory measured hydraulic conductivity of a highly plastic, compacted clay soil is significantly influenced by the size of the clods used in preparing the soil for compaction. For soil compacted dry of optimum, the hydraulic conductivity is 1,000,000 times less when prepared from small (4.6 mm) rather than large (19 mm) clods. For soil compacted wet of optimum, clod size is unimportant. In addition, large differences are seen in the hydraulic conductivity of soils compacted with standard versus modified

Proctor procedures. The conclusion reached is that the clods and interclod pores which exist during soil processing and compaction, control the hydraulic conductivity of the compacted soil. To achieve low hydraulic conductivity, it is necessary to destroy the clods and to eliminate large interclod pores either by wetting the soil to a high water content or by using a large compactive effort.

Benson, C.H., and Othman, M. 1993. Hydraulic conductivity of compacted clay frozen and thawed in-situ. Journal of Geotechnical Engineering. ASCE, Vol. 199, No. 2, pp. 276-294.

A large specimen of compacted clay (diameter = 298 mm; thickness = 914 mm) was subjected to freeze-thaw in the field for 60 days. The hydraulic conductivity of the sample was then measured and found to be essentially unchanged except for increases of 1.5 to 2 orders of magnitude above the freezing plane. The increase in hydraulic conductivity was highest at the top of the specimen and decreased with depth. Changes in hydraulic conductivity also occurred at depths of 150 mm below the freezing plane, where desiccation had occurred because of water redistribution. Numerous horizontal and vertical cracks had formed in the soil mass. Dissection of the sample after permeation revealed that the cracks were laden with water. Cracking was greatest at the surface and became less frequent with depth. The frequency of cracks was consistent with the principles of mechanistic models of freezing.

The results of laboratory tests were used to predict the hydraulic conductivity of the large specimen. Numerous tests were conducted on specimens subjected to various freeze-thaw cycles, temperature gradients, and states of stress. It was found that the predicted overall hydraulic conductivities were lower than those measured on the large specimen, but the general trend of varying hydraulic conductivity with depth was the same.

Benson, C.H., Zhai, H., and Wang, X. 1994. Estimating hydraulic conductivity of compacted clay liners. Journal of Geotechnical Engineering, Vol. 120, No. 2, pp. 366-387.

A database is described that contains laboratory measurements of hydraulic conductivity and associated soil properties extracted from construction reports on compacted soil liners. The data base contains measurements conducted on a wide variety of soils from 67 landfills in North America. The data base was used to evaluate relationships between hydraulic conductivity, compositional factors, and compaction variables. It was also used to identify minimum values of soil properties that are likely to yield a geometric mean hydraulic conductivity of less than 1×10^{-7} cm/s. A graphical analysis suggests that a geometric mean hydraulic conductivity of less than 1×10^{-7} cm/s can be achieved if the following conditions are met: liquid limit is greater than 20, the plasticity index is greater than 7, the percent fines (< No. 200 sieve), greater than 30%, and the percent clay (< 2 μm) is greater than 15%.

A multivariate regression equation was also developed that can be used to estimate the geometric mean hydraulic conductivity as a function of soil composition and compaction conditions.

Benson, C.H., Bosscher, P.J., Lane D.T., and Pliska, R.J. 1994. Monitoring system for hydrologic evaluation of landfill covers. American Society for Testing and Materials.

Three test sections were constructed and instrumented to assess the hydrologic behavior of final soil covers at two municipal solid waste landfills. A traditional design using a "resistive barrier" was used for two of the test sections, while an alternative design using a "capillary barrier" was used for the third section. The test sections were built in two distinctly different climates. The first was humid with high precipitation (Atlanta, Georgia) and the second arid (East Wenatche, Washington). Each test section was instrumented to measure climatologic variables, overland flow, percolation, soil temperature, and soil water content. This paper concentrates on the construction and instrumentation of the test sections.

A data acquisition and control computer (DACC) was used to collect data and control various components of the monitoring system. Commercially available equipment sold by a variety of vendors was used. The system in Atlanta is powered by 115 volt alternating current (VAC) batteries. Telecommunications are established via traditional telephone lines or by cellular transmission. After approximately two years of operation, maintenance requirements for the systems have been minimal.

The authors have found that a DACC used to remotely monitor the hydrology of final covers must permit system control and remote access. Selection of robust instruments that require minimal calibration and maintenance is also essential. Experience has shown that it is best to initially sample often and then, after a time, adjust the sampling frequency to obtain representative data. Periodic manual measurements have also been useful in error checking and in ensuring confidence in the data.

Benson, C.H., Hardianto, F.S., Motan, E.S. 1994. Representative specimen size for hydraulic conductivity assessment of compacted soil liners. ASTM STP 1142. Hydraulic conductivity and waste contaminant transport in soils, D.E. Daniel and S.J. Trautewin, eds, ASTM, Philadelphia, pp. 3-29.

An alternative to field measurement of hydraulic conductivity is to conduct laboratory hydraulic conductivity tests on specimens large enough to simulate field-scale conditions. Laboratory tests can be performed rapidly using standard procedures and with accurate control of stress and gradient. The objective of this research program was to identify how large a specimen must be to yield an accurate field-scale hydraulic conductivity. This objective was accomplished through field testing, laboratory testing, and statistical modelling.

Field hydraulic conductivity tests were performed on test pads at four sites that represented construction conditions ranging from poor to excellent. One test pad was deliberately constructed using poor construction methods to demonstrate "worst" case conditions. Field tests were performed with sealed double-ring infiltrometers (SDRI's) having inner ring widths of 0.61, 0.92, 1.2, or 1.5 m. Laboratory tests were performed on block specimens with diameters ranging from 0.07 to 0.46m.

For the range of construction conditions that were evaluated, the test results showed that a hydraulic conductivity at or near field-scale can be measured using block specimens with a diameter of 0.3 m and a thickness of 0.15 m. A probabilistic model was designed to simulate macroscopic defects in compacted soil. Results obtained with the model supported the results of the experimental study.

Benson, C. H., and Daniel, D.E. 1994. Minimum thickness of compacted soil liners: I. Stochastic Models. Journal of Geotechnical Engineering, ASCE, Vol. 120, pp. 129-152.

Regulatory agencies often specify a minimum thickness of compacted soil liners that will ensure that the liner performs adequately. No consensus has been formed however, on an appropriate minimum thickness. In some states, soil liners may be as thin as 60 cm (2 ft), while in others states soil liners are required to be at least 360 cm (12 ft) thick. Difficulties encountered in the analysis of soil liners such as uncertainties in construction, flow in macropores, spatial variability of hydraulic properties, and variability in past experiences of regulatory agencies are the most likely reasons for the lack of consensus on minimum thickness.

In the present paper, the first in a two-part series, two models of fluid flow in compacted soil liners are described. These models incorporate flow in macropores, spatial variability, and uncertainty with respect to probability theory, but they also consider advective transport in saturated soil. In the second paper, the models are used to identify an appropriate minimum thickness of soil liners.

Benson, C. H., and Daniel, D.E. 1994. Minimum thickness of compacted soil liners: II. Analysis and case histories. Journal of Geotechnical Engineering, ASCE, Vol. 120, pp. 153-172.

The stochastic models described in a companion paper were used to analyze compacted soil liners with a variable number of 15 cm (6 in.) thick lifts. No optimum number of lifts could be defined based on first passage time when the liquid, originally covering the liner, first emanates from the base of the liner. The first-passage time increased as the thickness increased. Both models showed that the flux through the liner and the equivalent hydraulic conductivity of the lifts, modelled as a log normally distributed random variable, decreased. There was little benefit to increasing the number of lifts beyond four to six. An analysis of case histories of insitu hydraulic conductivity also confirmed this. Based upon hydraulic conductivity considerations, the recommended minimum thickness of compacted soil liners is four to six lifts, or 60 cm to 90 cm (2 to 3 ft).

Benson, C.H., Abichou, T.H., Olson, M.A., and Bosscher, P.J. 1995. Winter effects on hydraulic conductivity of compacted clay. Journal of Geotechnical Engineering, Vol. 121, No. 1. pp. 69-79.

A field test was conducted to determine if freeze-thaw cycles cause increases in hydraulic conductivity in the field, as has been observed in laboratory tests. A test pad of compacted clay was partially insulated and instrumented for monitoring temperatures and climatic conditions. The measurements indicated that up to 10 cycles of freeze-thaw occurred in the uninsulated portion of the test pad, however, no change in the overall hydraulic conductivity occurred in the uninsulated region because the depth of frost penetration was only 30% of the thickness of the test pad. However, tests on block specimens collected from near-surface soil that underwent freezing and thawing increased in hydraulic conductivity by factors of 50 - 300. Similar increases in hydraulic conductivity were measured using laboratory freeze-thaw tests.

Blight, G.E., Ball, J.M., and Blight, J.J. 1992. Moisture and suction in sanitary landfills in semiarid areas. Journal of Environmental Engineering, Vol. 118, No. 6, pp. 865-876.

Waste-disposal practices in the third world countries can have extreme adverse environmental impacts, especially with regard to ground-water pollution. A water-budget method has been developed and used to predict leachate production from sanitary landfills. This study examines the details of moisture profiles in three landfills located in semi-arid climates in a third world country. This information is most important for the design of low-cost, environmentally acceptable landfills for these communities. The study also investigates whether soil moisture suction in the landfills is sufficiently low enough to enable uninhibited bacteriological activity to take place.

The detailed examination of moisture and suction profiles in landfills situated in semi-arid climates has enabled the following conclusions to be drawn:

1. The overall average storage of a landfill is not a useful concept as it is very difficult to predict. It depends a great deal on the properties and disposition of the intermediate cover layers. The emission of leachate from a landfill may be greatly affected by either the channeling or sealing effect of the intermediate cover layers.
2. Even in semi-arid climates, landfills contain sufficient moisture to sustain uninhibited bacteriological activity.
3. There is promise that by careful cap design and careful disposition of intermediate cover layers in semi-arid climates it may be possible to avoid the installation of underliners by maintaining a perennial water deficiency in landfills. However, more research is needed to substantiate this.

Bonaparte, R., and Gross, B.A. 1994. Field behavior of double-liner systems. Waste Containment Systems, Construction, Regulation, and Performance. GSP, No. 26, ASCE, New York. pp. 52-83.

This paper presents field data on the flow of liquid from the leakage detection layers of double-liner systems at 30 landfill and surface impoundment facilities. For each facility, information on design and operation is presented, as is an evaluation of the sources of the measured flow. Potential sources include leakage through the top liner, precipitation that percolates into the leakage detection layer during construction, ground-water infiltration, and consolidation of any clay component of the top liner. From the evaluation, several conclusions are drawn. Double-liners in general were found to be suitable.

Breitenbach, A. 1993. Rockfill placement and compaction guidelines. Geotechnical Testing Journal, GTJODJ, Vol. 16, March, 1993. pp. 76-85.

The purpose of this article is to establish general guidelines for rockfill placement and compaction procedures. The guidelines are based on experience gained from the design and construction of several large rockfill tailing dams in the western United States. Valuable rockfill information was obtained from construction test fills using test procedures similar to those developed by the Corps of Engineers in the 1960's and modified for modern-day compaction equipment. The rockfill guidelines establish basic procedures that can be readily adapted to site specific conditions.

Broman G., 1991. Use of sludge for sealing purpose in dry covers: Development and field experience. Proceedings: Second International Conference on the abatement of acidic drainage. Montreal, September 16-18, Vol. 1, pp. 515-528.

Acidic drainage is the largest single environmental problem facing the Canadian mining industry today. Technologies to prevent acidic drainage from occurring in waste rock piles and tailings sites, and on the walls of open pits, need to be developed and proven. In response to this need, the Mine Environmental Neutral Drainage (MEND) program was established in Canada to initiate and co-ordinate research efforts. MEND is a co-operative program financed and administered by the Canadian mining industry; the Canadian government through Energy, Mines and Resources Canada (CANMET); Environment Canada; Indian and Northern Affairs Canada; and the governments of British Columbia, Manitoba, Ontario, Quebec and New Brunswick, where most of Canada's sulphide minerals are mined.

MEND sponsored research programs have been under way since the beginning of 1988. To date, some 34 projects have been initiated. In terms of technical progress, 21 projects have been completed spanning all the research program areas. Some of the most promising results have been obtained through the studies into the prevention and control of acidic drainage using wet barriers and solid covers. This paper summarizes the present, proposed and completed activities of the MEND program including budget proposals.

Cartwright, K. and Krapac, I.G. 1994. Construction and performance of a long-term earth liner equipment. Waste Containment Systems, Construction, Regulation and Performance, GSP. No. 26, ASCE, New York.

In land burial schemes, compacted soil barriers with low hydraulic conductivity are commonly used as cover and liner systems to control the movement of liquids and prevent groundwater contamination. An experimental liner measuring 8 x 15 x 0.9 m was constructed to simulate soil liners built at waste disposal facilities. The surface of the liner was flooded with a 29.5 cm deep pond on April 12, 1988. Infiltration of water into the liner has been monitored for two years using 4 large-ring (1.5 m OD) and 32 small-ring (0.28 m OD) infiltrometers, and a water balance method that accounts for total infiltration and evaporation. Average long-term infiltration fluxes based on two years of monitoring are 5.8 x 10^{-9}, 6.0 x 10^{-8} cm/s and 5.6 x 10^{-8} cm/s for the large-ring, small-ring, and water-balance data, respectively. The saturated hydraulic conductivity of the liner based on small-ring data, estimated using Darcy's law and the Green-Ampt Approximation, is 3 x

10^{-8} and 4 x 10^{-8} cm/s, respectively. All sets of data indicate that the liner's performance exceeds that which is required by the U.S. EPA.

Collin, M., and Rasmusson, A. 1988. A comparison of gas diffusivity models for unsaturated porous media. Soil Science Society of America Journal, Vol. 52, pp. 1559-1565.

In this paper, comparisons are made between experimental diffusivity data for different materials at various moisture contents, using estimation methods from the literature. The estimation methods proposed by R.J. Millington and R.C. Shearer in 1971 give the best predictions of the effective diffusivity. The methods are extended here to account for the contribution of diffusion in the water-filled pores. The method for aggregated media should be used for undisturbed clayey soils, while the method for non-aggregated media may be used for sandy soils as well as other non-aggregated materials, e.g., laboratory packed clayey soils. The experimental data show that very low effective diffusivities may be obtained in practice in soils with high moisture content.

Daniel, D.E. 1983. Shallow land burial of low-level radioactive waste. Journal of Geotechnical Engineering, ASCE, Vol. 109, no. 1, pp. 40-55.

Low-level radioactive waste has been produced since the early 1940's in the U.S.A. Most of it has been buried in shallow pits at 11 existing sites which have to date performed poorly. Inability to control the flow of surface groundwater into and out of disposal pits has been the most important problem. Lack of attention to design of earthen covers over the waste and improper placement of the waste in the pits have also contributed to the poor performance.

Several steps are recommended for improving disposal practices:

(1) Waste settlement can be minimized by stacking wastes neatly into pits rather than dumping them randomly;

(2) The performance of the earthen cover could be improved by making it thicker and by maintaining it properly; and,

(3) Groundwater contamination can be minimized by placing disposal facilities at locations with favorable geohydrologic characteristics.

Ultimately, improved designs are needed for earthen covers. As well, the technology for predicting groundwater contamination in the saturated/unsaturated soils underlying the waste needs improvement.

Daniel, D.E. 1984. Predicting hydraulic conductivity of clay liners. Journal of Geotechnical Engineering, Vol. 110, No. 2, pp. 285 - 300.

Data is presented from four projects in which rates of leakage from ponds lined with clay significantly exceeded the rates that would have been predicted on the basis of laboratory permeability tests. The four projects had certain features in common:

(1) All cases involved comparatively high rates of leakage;

(2) The liners were relatively thin (less than 24 in. or 0.6 m thick);

(3) With only one exception, all of the liners were subjected to some desiccation; and,

(4) In all cases, the construction inspection was not as extensive as it might have been.

The actual hydraulic conductivities of the clay liners were generally found to be 10 to 1,000 times larger than values obtained from laboratory tests on either undisturbed or recompacted samples of the clay liner. The main source of difficulty with laboratory permeability tests is the problem of obtaining a representative sample of soil for testing. Neither recompacted samples nor small, undisturbed samples are likely to contain a representative distribution of desiccation cracks, fissures, slickensides, or other hydraulic defects that may be present in the liner. Field permeability tests were performed on three of the four case histories and yielded results that compared well with field performance. It was found that field permeability tests seem to produce much better results than laboratory tests.

Daniel, D.E. 1989. In situ hydraulic conductivity tests for compacted clay. Journal of Geotechnical Engineering, ASCE, Vol. 115, pp. 1205-1226.

This paper summarizes the state-of-the-art in insitu conductivity testing of compacted clay soils. Nine methods of testing were reviewed:

(1) The Boutwell permeameter;
(2) Constant-head borehole permeameters, e.g., the Geulph permeameter;
(3) Pore probes, e.g., the BAT device;
(4) Open, single-ring infiltrometers;
(5) Open, double-ring infiltrometers;
(6) Closed, single-ring infiltrometers,
(7) Sealed, double-ring infiltrometers;
(8) The air-entry permeameter; and,
(9) Lysimeter pans.

Installation procedures are given, equations for calculating hydraulic conductivity are presented, simplifying assumptions are listed, and case histories are reviewed. Each type of testing equipment has advantages. The Boutwell permeameter is especially convenient for the measurement of vertical and horizontal hydraulic conductivity. It was also found that borehole permeameters and porous probes provide data relatively quickly but permeate a relatively small volume of soil. Finally, of the permeameters that can permeate a large volume of soil, the sealed double-ring infiltrometers and pan lysimeter were found to be the most versatile.

Daniel, D.E., and Benson, C.H. 1990. Water content-density criteria for compacted soil liners. Journal of Geotechnical Engineering, ASCE, Vol. 116, No. 12, pp. 1811-1830.

Soil liners have traditionally been compacted in the field to a minimum dry weight over a specified range in water content. The approach evolved from the practice of placing structural fills where strength and compressibility were of primary concern. With soil liners, the hydraulic conductivity is usually of greatest importance. The approach used to ensure adequate strength and compressibility is therefore not necessarily applicable to the construction of soil liners. Data is presented to show that the water content-density relationship for compacted soil liners can be formulated in a manner that is different from the approach currently used by many engineers. The recommended approach is based on defining water content-density requirements for a broad, but representative range of compactive energy, and relating those requirements to hydraulic conductivity and other relevant factors.

A case history illustrates the recommended procedure and implementation. Hydraulic conductivity measurements were performed on three soils to develop an "acceptable zone" on the compaction curve that was used for quality control during construction. As a result of implementing the recommended procedure, construction operation significantly improved.

Daniel, D.E. and Wu Y-K. 1993. Compacted clay liners and covers for arid sites. Journal of Geotechnical Engineering, ASCE, Vol. 119, No. 2, pp. 223-1460.

Tests were performed on a clayey soil from a site in Texas to define ranges of water content and dry unit weight at which compacted test specimens would have:

(1) low hydraulic conductivities;

(2) minimal potential for shrinkage upon drying; and,

(3) adequate shear strength.

Test specimens were compacted with three compactive energies over a range of water contents. It was found that low hydraulic conductivity could be achieved over a broad range of water contents, but often wet specimens underwent large shrinkage upon drying. A range of water contents, near the optimum value measured and tested with the highest compactive energy proved to be most suitable in meeting the objective of low hydraulic conductivity and minimum shrinkage potential. The dry unit weight had to be greater than 96-98% of the maximum value from modified compaction (ASTM method D1557) to meet the hydraulic conductivity, shrinkage, and strength objectives. A similar approach is suggested in the development of compaction criteria for other projects in which low-hydraulic conductivity liners for covers must be constructed in relatively arid regions or for other situations in which potential cracking caused by desiccation is of concern.

Daniel, D.E. 1993. Case histories of compacted clay liners and covers for waste disposal facilities. Proceedings: Third International Conference on Case Histories in Geotechnical Engineering, St. Louis, Missouri, June 1-4, Vol. 2, pp. 1407-1425.

Compacted clay liners and covers are widely used in waste containment units. Case histories in three categories are presented as follows:

(1) Case histories illustrating compaction, construction, and quality assurance difficulties;

(2) Case histories involving field hydraulic conductivity testing of large-scale test pads; and,

(3) Case histories involving final cover systems.

These case histories illustrate that:

- The compaction criteria should be chosen carefully and with consideration given to how the compaction be controlled in the field;
- Regulatory roadblocks may defeat sound technical approaches in terms of developing compaction criteria;
- One can follow ASTM procedures and still get into difficulty if sample preparation procedures are not given special attention;

- Data on the field performance of test pads provides valuable insight concerning the relationship between hydraulic conductivity and field performance; and,
- Problems with differential settlement, desiccation, and freeze-thaw make use of compacted clay liners a challenge in final cover systems. Geosynthetic clay liners offer an attractive alternative.

David, D.J. and Nicholson, R.V. 1995. Field measurements for determining rates of sulphide oxidation. Paper presented at Sudbury '95 Conference on Mining and the Environment, Sudbury, Ontario, May 28th - June 1, 1995.

A field study was conducted at the Falconbridge "New Tailings" site during 1990 and 1991 to assess the rate at which tailings were oxidizing under different physically-controlled environments. Three tailings disposal scenarios were evaluated: a poorly engineered, fine grained (slimes) covered area; an uncovered area, and a shallow water-covered area. Two methods of estimating oxidation rates were used. The first related the mass of iron and sulphate in pore water to the rate of pyrrhotite oxidation (Solute Method). The second method related the oxygen gradient in the near-surface pore gas to the downward diffusion of oxygen driven by pyrrhotite oxidation (Gradient Method).

Results suggest that the uncovered site was oxidizing at rates 100 times faster than the slime-covered areas and 100-1000 times faster than the underwater area. The shallow water-cover appeared to provide a favorable environment for reducing oxidation rates. The fine grain cover provided some degree of protection against oxidation by its ability to retain moisture thereby reducing the flux of oxygen. Uncovered, run-of-the-mill tailings were typically well-drained and provided minimal resistance to the influx of oxygen. Consequently, the areas were susceptible to substantially higher rates of oxidation and rapid degradation of water quality.

Davis, B.S., Fortin, D., and Beveridge, T.J. 1995. Acidophilic bacteria, acid mine drainage and Kidd Creek mine tailings. Proceedings, Conference on Mining and the Environment, Sudbury, Ontario, May 28-June 1, 1995, pp. 69-77.

The 1200 hectare Kidd Creek site deposited in a well-engineered tailings impoundment by utilizing the thickened tailings discharge method represents one of the single largest concentrations of sulfidic mine tailings in Canada. Field microbiology and geochemistry results were obtained from two sampling locations within a reactive toxic zone at the Kidd Creek site. To determine the microbial ecology of the toxic zone, seasonal populations of acidophilic iron-oxidizing chemolithothropic (e.g., thiobacilli) and non-iron oxidizing tereotrophic (e.g., Acidiphilum spp) bacteria were correlated to physicochemical conditions (i.e., Eh, pH, pore-water geochemistry and sequential soil extraction) within the tailings. These results were compared with those from a nearly abandoned AMD-generating Cu-Zn mine typical of the 500,000+ ecologically detrimental sites present in North America today. The authors results demonstrated the importance of bacteria in the formation and possible amelioration of acidic heavy metal-rich leachates.

Dubrivsky, N.M., Cherry, J.A., Reardon, E.J., and Vivyruka, A.J. 1985. Geochemical evolution of inactive pyritic tailings in Elliot Lake uranium district. Canadian Geotechnical Journal, 22:110-128.

Geochemical data obtained between 1979 and 1983 from a network of piezometer nests and cores from three inactive uranium tailings impoundments in the Elliot Lake district indicate that oxidation of pyrite taking place in the shallow part of the zone above the water table is causing the chemistry of the pore water above and below the water table to change. A two-layered hydrochemical zoning has developed in which infiltrating water from rain and snow has resulted in an upper zone of low-pH water with a high concentration of SO_4, Fe, and heavy metals. This zone is gradually expanding downward at rates generally between 0.2 and 2 m/year, causing displacement of the original mill process water, which has neutral pH and low concentrations of heavy metals. High concentrations of Fe (III) at shallow depths in the zone above the water table indicate that ferric iron is an important oxidizer of pyrite in the presence of free oxygen.

The pH of the groundwater is controlled by the ferric-ferrous redox couple. Trends in the data indicate iron solubility is controlled by siderite at high pH, by ferric hydroxide at moderate to slightly acid pH values, and possibly by jarosite at low pH. Aluminum solubility controls are complex, and precipitation of amorphous aluminum hydroxide, allophane, and basic aluminum sulfates may occur over different pH ranges. The transport of low-pH conditions is retarded relative to the rate of groundwater flow in the tailings, because of the buffering effect of small amounts of carbonate minerals added during tailings neutralization; primary aluminosilicates such as sericite; and secondary aluminum hydroxides.

Field data show that the flux of dissolved iron from the vadose zone to the groundwater zone in the Nordic Main tailings has been decreasing in recent years. However, mass-balance calculations indicate a potential for the generation of high-Fe groundwater for several decades to several hundred years. A long-term potential for acid and iron production is also shown by data from two tailings impoundments that have been inactive for 8-10 years longer that the Nordic Main area. Presently, only a small portion of the Noridc Main and West Arm tailings areas has become acidic throughout the entire tailings thickness; however, under existing infiltration conditions more extensive acidification will occur in future decades.

Elberling, B. and Nicholson, R.V. (accepted Dec. 1995). Sulphide-oxidation rate determination in mine tailings in the field. Water Resources Research.

A field study was conducted by authors to assess the rates of oxygen consumption in the vadose zone of sulphide mine tailings. Oxygen uptake rates were measured directly at the ground surface and were compared to rates of sulphate production in the tailings profile. A non-reactive tracer was also used to assess effective diffusion coefficients in the shallow sub-surface. The 26 measurement sites were located within a 0.1 km^2 area in tailings with water table depth ranging from 0.6 m to ponding at the surface. Ambient oxygen consumption rates in the eight year-old tailings were compared to measurements through 0.2 m thick covers of fine sand and 0.2 m layers of fresh tailings replacing oxidized tailings at the ground surface.

The following conclusions were derived from this research study:

1. The field measurements revealed that the oxygen flux represents combined effects of oxygen diffusion and oxygen uptake by oxidation of sulphide minerals and that the oxygen flux measurements are consistent over time and space. The relatively good agreement between oxygen consumption and sulphate production in the pore water confirmed that oxygen flux measurements over a range of more than two orders of magnitude consistently represents the rate of oxygen consumption in the subsurface profile.
2. Comparisons between oxygen consumption rates and gas diffusion rates for a non-reactive gas species revealed that the order of magnitude variations in oxygen consumption rates could be explained solely by the near-surface soil diffusivity regardless of the heterogeneous sulphide content, or the potential reactivity of the tailings. Results from the 26 sites indicated that spatial variation in soil diffusivity over a three orders of magnitude range was due to either the presence of moist fine grained layers at the tailings surface or a shallow water table.
3. Oxygen consumption rates were used as a mapping tool in an existing tailings area of 0.1 km^2 and found to correlate well with the depth to the water table.

Elberling, B., Nicholson, R.V., Reardon, E.J., and Tibble, P. 1994. Evaluation of sulphide oxidation rates - A laboratory study comparing oxygen flux rates of oxidation product release. Canadian Geotechnical Journal, vol. 31, pp. 373-383.

A series of column experiments were conducted to evaluate three methods of determining sulphide oxidation rates in mine tailings. Measurements were made of

(i) the flux of oxygen across the surface of the tailings;
(ii) the oxygen consumption rates at the tailings surface; and,
(iii) the total sulphate produced in the pore water over time.

Two columns were prepared with a mixture of quartz sand and pyrhotite and well overlain with varying thicknesses and grain sizes of a non-reactive layer. The impact of varying the water table depth within the nonreactive layers on the overall oxidation rate was also evaluated. Modelling was completed to verify the importance of diffusive and kinetic control on the different column configurations. The results indicate that the overall rate of oxidation is reduced when fine grained layers are applied. This is due to the high degree of saturation generated by the fine material regardless of the depth to the water table. As a zone depleted of sulphides develops on top of the tailings over time, the oxidation rate decreases and modelling indicates a shift from kinetic to diffusive control of the overall oxidation rate after some years of tailings of exposure. The consistency and precision of the methods used to measure relative oxidation rates were noted and a new practical field mapping tool was recommended. Many years of monitoring and data collection are often necessary to estimate the rate of acid generation and oxidation-product release (Dubrovsky et al. 1985). This new method provides rapid, inexpensive and precise measurements of relative oxidation rates that can be applied to existing tailings sites with soil-type covers to show spatial and temporal trends.

Elsbury, B.R., Daniel, D.E., Sraders, G.A., and Anderson, D.C. 1990. Lessons learned from compacted clay liner, Journal of Geotechnical Engineering, ASCE, Vol. 111, No. 4, pp. 465-478.

A highly plastic clay liner was compacted in the field with full-sized equipment to an average of more than 100% of standard Proctor maximum dry density. The average field permeabilities of two sections of the liner, as measured with four sealed double-ring infiltrometers and a 16 x 16 ft (4. 88 x 4. 88 m) pan lysimeter, were 3 x 10^{-5} and 10 x 10^{-5} cm/s, respectively. Laboratory permeability tests were conducted on samples compacted in the laboratory by three procedures, only one of which gave a reasonable prediction of the permeability of the liner. The high permeability of the liner was caused by the failure to achieve compaction objectives that govern the permeability of compacted clays. Several basic factors that influence the permeability of compacted clays and the performance of the liners are explained in this paper.

EPA 1989. Final covers on hazardous waste landfills and surface impoundments. Technical Guidance Document. EPA/530-SW-89-047. Office of Solid Waste and Emergency Response, U.S. Environmental Protection Agency, Washington, DC 20460.

The owner or operator of a landfill or a surface impoundment called as landfill, must meet the closure requirements specified under 40 CFR 264.310 (permitted units) or 40 CFR 265.310 (interim status units).

This guidance report document addresses landfill covers and recommends a multilayer final cover design that includes the following elements from top to bottom:

- A top layer consisting of two components: (1) a vegetated or armored surface component, either of which is selected to minimize erosion and, to the extent possible, promote drainage of the cover, and (2) a soil component with a minimum thickness of 60 cm (24 in.) comprised of top soil and/or fill soil as appropriate, the surface of which slopes uniformly at least 3 percent but not more than 5 percent;
- A soil drainage layer with a minimum thickness of 30 cm (12 in.) and a minimum hydraulic conductivity of 1 x 10^{-2} cm/sec that will effectively minimize water infiltration of at least 3 percent after settlement and subsidence or may consist of geosynthetic materials with equivalent performance characteristics. The drainage layer also serves as a protective cover for the flexible membrane layer (FML) component of the underlying low permeability layer;
- A two component low permeability layer, that limits water infiltration into the underlying wastes to a rate less than or equal to the rate of leachate migration out of the bottom liner system and consists of (1) a 20-mil minimum thickness [or greater depending on the material and design] FML component and (2) a 60-cm [24 inch] minimum thickness compacted soil component with an in-place saturated hydraulic conductivity of no less than 1 x 10^{-7} cm/sec. It should be noted that the requirement for FMLs in the cover are for all permitted units and interim status units with an FML in the bottom liner. A FML however may not be required.

Optional layers that may be used on a site-specific basis include (1) a gas vent layer to remove gases produced within the water, and/or (2) a biotic barrier layer to protect the cover from animal or plant intrusion.

The agency recommends a detailed construction quality assurance (CQA) program for each layer of the final cover system. CQA records should document quality and demonstrate compliance with plans and specifications. The cover design process must consider many site-specific factors such as precipitation, construction materials, freeze-thaw phenomena, waste characteristics, potential subsidence, and other environmental factors.

Fayer, M.J., and Rockhold, M.L., and Campbell, M.D. 1992. Hydrologic modelling of protective barriers: Comparison of field data and simulation results. Soil Sc. Society of America Journal. Vol. 56, pp. 690-700.

Protective barriers, which consist of layers of silt loam over sand and gravel, have been proposed as covers for waste sites located in the semiarid south-central sate of Washington. The ability of an uncalibrated model to predict water contents, water storage, and drainage in barriers was tested for durations as long as 1.5 yr. Eight nonvegetated sites containing the barrier layering sequence have been monitored using lysimeters since November, 1987. The lysimeters were subjected to one of three precipitation treatments: ambient, 2 times average, and break through (i.e., until drainage occurred). Distributions of measured and simulated water contents with depth were similar. Maximum differences ranged from 0.023 cm^3/cm^3 for the ambient treatment to 0.089 cm^3/cm^3 near the soil-sand interface for the breakthrough treatment. Simulated storage followed the trend in the measured values, although differences as much as 5 cm were observed at certain times. Generally, the model over predicted evaporation in the winter and under predicted it in the summer. Root-mean-square errors were 1.47 and 2.21 cm for the ambient and 2 times average treatments, respectively. Sensitivity tests revealed that the hydraulic conductivity function, snow cover, and potential evaporation were most important to the successful modelling of storage in a protective barrier. When the above parameters and processes were adjusted although not optimized, the root-mean-square error for the 2 times average treatment was reduced 63% to 0.81 cm. For the breakthrough treatment, simulated drainage was obtained only by using field measured sorption and saturated conductivity data. This result indicates that hysterisis is important to the successful modelling of drainage through protective barriers.

Gee, G.W., Wierenga, P.J., Andraski, B.J., Young, M.H., Fayer, M.J., and Rockhold, M.L. 1994. Variations in water balance and recharge potential at three western desert sites. Soil Science Society of America Journal, Vol. 58, No. 1, pp. 63-72.

Radioactive and hazardous waste landfills exist at numerous desert locations in the U.S.A. At these locations, annual precipitation is low and soils are generally dry, yet little is known about recharge of water and transport of contaminants to the water table. Recent water balance measurements made at three desert locations, Las Cruces, NM, Beatty, NV, and the U.S. Department of Energy's Hanford Site in the state of Washington, provide information on recharge potential under three distinctively different climate and soil conditions. All three sites show water storage increases with time when soils are coarse textured and when plants are removed from the surface, the rate of increase being influenced by climatic variables such as precipitation, radiation, temperature, and wind.

Lysimeter data from Hanford and Las Cruces indicate that deep drainage (recharge) from bare, sandy soils can range from 10 to greater than 50% of the annual precipitation. At Hanford, when desert plants are present on sandy or gravelly surface soils, deep drainage is reduced but not eliminated. When surface soils are silt loams, deep drainage is reduced but not eliminated. At Las Cruces and Beatty, the presence of plants eliminated deep drainage at the measurement sites. Differences in water balance between sites are attributed to precipitation quantity and distribution and to soil and vegetation types. The implication for waste management at desert locations is that surface soil properties and plant characteristics must be considered in waste site design in order to minimize recharge potential.

Gillham, R.W. 1984. The capillary fringe and its effect on water-table response. Journal of Hydrology, 67 pp. 307-324.

Shallow water tables are often observed to respond in a highly disproportionate manner to precipitation events. That is, the magnitude of the response is often much greater than would be predicted on the basis of the specific yield of the geologic material and the amount of rainfall. Nevertheless, in most hydrogeological investigations, the effect has been ignored, or discounted as being of little significance, and few detailed field investigations have been reported.

The physical arguments presented in this paper indicate that in fine grained geologic materials, the capillary fringe, and thus the zone of saturation, may extend for several metres above the water table. In addition, the results of the field study indicated that the water table response under natural conditions was consistent with the physical basis of the capillary fringe (the zone of tension saturation) phenomenon. Therefore, it appears that the capillary fringe can indeed have a major influence on the response of shallow water tables to precipitation.

If the capillary fringe extends to the ground surface, then the addition of a very small amount of water can result in an immediate and large rise in the water table. These arguments are supported by a field experiment in which the addition of 0.3 cm of water caused the water table to rise 30 cm in 0.25 min., thus demonstrating the large and highly transient influence of the capillary fringe on the position of the water table.

The evidence in this study, as well as the recent work of others, suggests that the capillary fringe could be an important consideration in the analysis of several hydrologic processes. Examples include recharge and consumptive use calculations, stream-flow generation, migration of contaminants to surface waters and contaminant transport in shallow water table regimes. Additional studies are required in order to evaluate the effect of the capillary fringe on the water table response in a wider range of geologic materials, and to evaluate its importance in hydrologic processes associated with shallow water table regimes.

Haering, K.C., Daniels, W.L., and Roberts, J.A. 1993. Changes in mine soil properties resulting from overburden weathering. Published in Journal of Environmental Quality. Vol. 22, pp. 194-200.

Hard rock overburden is often used as a top soil substitute for reclamation in the southern Appalachian surface mining region because of the limited availability of natural topsoil. In relatively unweathered overburden materials, soil forming processes are accelerated and the resulting mine soils form rapidly. Morphological, physical, and chemical properties related to overburden weathering in mine soils from siltstone and sandstone overburden were observed for 6 to 8 years. Distinct subsurface soil horizons, enriched with organic matter occurred within two growing seasons after mine soil construction, and a discernible subsurface horizon developed within four growing seasons. Although pH and extractable Ca and Mg levels decreased during the first three growing seasons, apparently due to the rapid leaching of exposed carbonates, these properties rebounded to near initial levels after six growing seasons due to the release of Ca and Mg from continued carbonate weathering and photocycling. Levels of extractable Fe tripled between the first and second growing seasons and then remained relatively constant for the rest of the study. The changes in soil properties in these mine soils indicate the difficulties involved in predicting the chemical weathering and development processes as well as all eventual mine soil properties from premining overburden analysis.

Harries, J.R. and Ritchie, A.I.M. 1981. The use of temperature profiles to estimate the pyritic oxidation rate in a waste rock dump from an open cut mine. Water, Air, and Soil Pollution, 15, pp. 405-423.

Temperature distributions were measured in a dump of waste rock from an old open cut mining operation at Rum Jungle in the Northern Territory of Australia. The 20 yr. old dump contained pyritic material, averaging about 3% sulphur. The pyrite is known to be oxidizing. These temperature distributions were used to evaluate the heat source distributions which identify oxidation sites and are a direct measure of rates of oxidation within the dump. Temperatures measured ranged between 32 to 37^{o}C for most of the dump, but increased to 56^{o}C in one region. As temperature is essentially a macroscopic property of the dump, the picture obtained of pyritic oxidation sites and their rates is also macroscopic. Such a picture is appropriate to modelling the leaching process in a field situation because it describes oxidation rates over a large volume of the material rather the rate at a particular particle in the material. Oxidation occured in the top 5 m of the dump and, at some sites, down to 15 m from the surface. Oxidation rates at the deep sites did not change over the 8 month period from the end of one wet season to the beginning of the next.

The existence of oxidation sites at depth, as well as those near the surface of the dump, provides a good test for any model purporting to describe the pyritic oxidation process in similar dumps. Diffusion of O_2 from the surface of the dump through the pore space to the oxidation sites deep in the dump appears to be a possible mechanism for O_2 transport. The O_2 supply rates predicted by the simple model are somewhat lower than those required by the deep sites with the highest oxidation rates for the site conditions.

Harries, J.R. and Ritchie, A.I.M. 1985. Pore gas composition in waste rock dumps undergoing pyritic oxidation. Soil Science. Vol. 140, No. 2. pp. 143-152.

These investigators measured oxygen and carbon dioxide concentrations in the pore space of two waste rock dumps located at the abandoned Rum Jungle mine in the Northern Territory, Australia. These dumps are significant sources of acid and trace metal pollutants to a local river system. The release of these pollutants is a consequence of the oxidation of pyritic material within the dumps.

Comparison of oxygen concentration distributions indicates that oxygen supply is the oxidation-rate-limiting mechanism in most regions of these dumps. Gas transport into the dumps is by diffusion and advection due to both thermal effects and atmospheric pressure changes. The extent to which one transport mechanism dominates depends upon the proximity of the area studied to edge of the dump and differences in the properties of the material in different regions. In some areas, at least two transport mechanisms determine the pore gas composition. It was also found that carbon dioxide levels which were generated were one to three orders of magnitude higher than atmospheric levels. This indicates that the bacteria that catalyze pyritic oxidation have a plentiful supply of carbon dioxide which is essential for their metabolism.

Harries, J.R. and Ritchie, A.I.M. 1987. The effect of rehabilitation on the rate of oxidation of pyrite in a mine waste rock dump. Environmental Geochemistry and Health, 9(2), pp. 27-36.

Temperature profiles were taken from within a mine waste rock dump undergoing pyritic oxidation. The waste rock dump located at the abandoned Rum Jungle mine site in Northern Australia, was a major source of pollution to the local river system. The dump was rehabilitated in 1983-84 by reshaping to reduce erosion and by placing a clay and soil cover to reduce the infiltration of water. Heat production at the dump is directly related to the rate of oxidation of pyritic material. Hence, changes in the rate of heat production can be interpreted as changes in the rate of pyrite oxidation. Heat source distributions were derived from temperature profiles measured in the dump. The heat source distributions have shown that heat production, and hence oxidation, was occurring at depth before rehabilitation and that it has been greatly reduced, and perhaps stopped, since the cover was placed on the dump. With the possible exception of one location (hole C as described in the paper) the heat source distribution since rehabilitation is consistent with a zero oxidation rate.

The technique of obtaining heat source profiles from measured temperatures were found to be useful for optimizing the rate of oxidation in commercial heap leaching operations. The heat source profiles in such leaching dumps provided information about the uniformity of oxidation through out the dump and the efficiency of leaching.

Harrop-Williams, K. 1985. Clay liner permeability: Evaluation and variation. Journal of Geotechnical Engineering, ASCE. pp. 1211-1225.

The primary criterion used in evaluating the suitability of hazardous waste landfills for containing hazardous wastes is permeability. Many regulatory agencies have adopted regulations requiring clay-lined hazardous waste landfills to have a coefficient of permeability no greater than a fixed value. The measurement of the in-situ permeability of compacted clay is however, time consuming and difficult. If used to monitor construction, it slows the construction rate. Another equally important problem is that the clay-liner permeability is extremely valuable. Solutions to both of these problems are presented. Firstly, a relationship is developed between permeability and easily measured dry unit weight and moisture content. This would allow for the immediate monitoring of clay liners during construction. Secondly, an alternative is provided to the conventional approach in which permeability is treated as a single valued quantity. A probabilistic description of the permeability of clay liners is developed from considerations of the heterogeneity of the soil. This would improve the design of clay liners by establishing confidence levels associated with possible ranges of permeability.

Haug, M.D., Wong, L.C., Johnston, K. 1991. Design and construction of a compacted earth test cover for a potash tailings pile. Proceedings of the First Canadian Conference on Environmental Geotechnics 1991, May 14, pp. 185-192

This paper describes the case history of the design and construction of a 20m x 20m glacial till test cover. This cover was constructed as part of a capping research program being conducted by the University of Saskatchewan in conjunction with the Saskatchewan Potash Producers Association. Potash mines produce large quantities of waste salt which are stored in tailings piles adjacent to the mines. Covers are one method of decommissioning being considered by the potash industry. The function of these covers is to shed rainwater off the tailings to prevent the generation of brine caused by the dissolution of the salt. The till test cover constructed at the site is composed of a coarse boulder capillary barrier of approximately 0.5m in thickness. The function of this barrier is to prevent the upward movement of salt to the overlying till. A layer of approximately 1 m of till compacted in five lifts overlies the capillary barrier. The till layer was designed to be flexible and to have a minimum permeability of 1×10^{-7} cm/s. The surface of the till cover was overlain with a 0.05 m granular layer to minimize desiccation. A 6m x 6m lysimeter was installed under the cover to measure infiltration. The test cover is being monitored for changes in water content, dry density, and permeability.

Haug, M.D., Wong, L.C., Reid, K.W. 1991. Potash tailings field test covers. Proceedings, 15th Annual British Columbia Mine Reclamation Symposium and 16th Annual Conference on Reclamation and Sustainable Development, Kamloops, British Columbia, pp. 265-275.

This paper describes the results of a research program into the design and construction of covers for potash tailings piles. This work began with a three year laboratory testing program and investigation of potash tailings covers in other countries. The laboratory program was primarily directed towards evaluating the use of potash thickener slimes as a potential cover material. In this study, the impact of the addition of various soil liner materials to slimes was examined. The first phase of this research exposed many of the difficulties associated with covering potash tails piles and provided information on which a field test cover program could be based. The second phase of the research was followed by the design, construction and instrumentation of two field test covers. These test covers were placed on an abandoned potash tails pile located near Saskatoon, Saskatchewan. The first test cover constructed was composed of glacial till overlaying a layer of boulders. The second cover was constructed of polymerized bentonite and sand.

In the case of potash tails covers, some site specific conclusions were drawn. The difficulty in excavating abandoned tailings suggested that any substantial grading required to shape the tailings prior to decommissioning will be difficult. Almost immediately after the construction of the cover, problems developed during an intense precipitation event. The "clean" water running off the surface of the till cover dissolved deep holes in the salt tailings on the downslope edge of the cover. A lysimeter monitoring trench partially collapsed permitting some till cover material to cave in. Plans have been designed to collect the cover runoff and direct it downslope over the tails away from the test site because of this incidence.

Herasymuik, G.M., Wilson, G.W., Barbour, S.L., and Smith, T. 1995. The characterization of hydrologic properties and moisture migration pathways of a waste rock dump. Abstract for the Nineteenth Annual British Columbia Mine Reclamation Symposium, Dawson Creek, B.C.

A multiphase research program has been initiated on a large waste rock pile which has undergone partial excavation. The focus of the research is to define the distribution of moisture migration pathways in the waste rock and to develop a conceptual model of the heat and mass transfer processes within the pile. The first phase of the research program was conducted simultaneously with the excavation process. This phase included visually logging the exposed rock and taking insitu measurements of matric suction, temperature, relative humidity and water content. As well, samples were taken from the exposed waste rock in numerous test pits for further analysis. The test pits were excavated along the predetermined transect lines established on the benches of the waste rock pile which were exposed during the excavation process.

The second phase of research includes a laboratory testing program to determine saturated and unsaturated hydraulic and thermal properties of the rock. The properties being measured include grain size, porosity, moisture retention characteristics, saturated hydraulic and thermal conductivity and specific heat capacity. In summary this paper outlines the research program to date and discusses the initial findings of the field program.

Jamie, Y-W., and Norum, D.I. 1980. Heat and mass transfer in a freezing unsaturated porous medium. Water Resources Research, Vol. 16, No. 4, pp. 811-819.

A numerical simulation of a laboratory experiment involving coupled heat and mass transfer has been carried out. The laboratory experiment involved a horizontal porous medium column with one end subjected to a temperature below 0^{o}C. The model is essentially that of Harlan (1973) and is solved numerically by the finite difference method using the Crank-Nicholson scheme. The solution yields temperature, liquid water content, and ice content profiles along the column as a function of time. A comparison of the experimental results and the simulated Harlans model results shows that with some modification in the hydraulic conductivity of the frozen medium, the numerical model can be used successfully to simulate the coupled heat and mass transfer processes when ice lensing does not occur.

Jones, C.E., and Wong, J.Y. 1994. Shotcrete as a cementitious cover for acid generating waste rock piles. Paper presented at the International Land Reclamation

and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, Vol. 2, pp. 104-112.

A research program supported by both Westmin Resources and the Canada-British Columbia Mineral Development Agreement (MDA) has evaluated the use of cementitious dry surface covers for the prevention of water and oxygen infiltration into acid generating waste rock piles. The objectives of this study were to apply the cementitious cover in the most cost effective manner and to evaluate the material properties and the long-term efficacy of the system. This paper presents the results of a field trial of a dry cover over a large test area on a waste rock pile at the Westmin Myra Falls site near Campbell River, BC, Canada. This study indicates that shotcrete dry covers can be a viable option for sealing prepared waste rock dumps.

An area of approximately 3,500 m^2 was covered using the shotcrete process. Prior to shotcrete application, the surface of the dump was stabilized through resloping and surface compaction. The application, using a robotic spray boom, resulted in high productivity and therefore contributed to a low application cost. A major proportion of the cost involved the importation of aggregate. The use of a local aggregate course such as mine tailings would make this option more cost effective when compared to other types of covers. The test area was instrumented with survey markers to monitor settlement in the rock slope. In addition, the performance of the test area was monitored for one year to evaluate the durability of this cover when subjected to field conditions. Compressive strength increased over the one year period, and all samples achieved or exceeded the design criteria. Some plastic shrinkage cracks were observed in the shotcrete immediately after application but after one year of exposure, these cracks did not appear to have expanded.

This study did not evaluate the effectiveness of the cover in restricting acid generation in a waste rock pile. It is recommended that this cover technology be applied in a controlled field trial on a designed waste rock test pile to evaluate its effectiveness in restricting the infiltration of oxygen and surface water in to the reactive waste rock.

Joshi, B., Barbour, S.L., Krause, A.E., and Wilson, G.W. 1993. A finite element model for the coupled flow of heat and moisture in soils under atmospheric forcing.

The Galerkin weighted residual method has been applied to develop a one-dimensional finite element formulation for the coupled equations of heat and moisture flow in soils. The formulation considers pressure and temperature as the dependent variables and is sufficiently general to accommodate various types of initial and boundary conditions. The specific theoretical postulations made in the light of experimental evidence so far can be readily incorporated into the formulation.

The formulation has been successfully implemented. The computer model named Vap1 is interactive and portable. It has been verified for various simple cases of uncoupled moisture and heat flow. The simulated results have been compared with available analytical and numerical solutions for these simple cases. The model has also been verified for a fully coupled nonlinear system. For this case, the model results have been compared with measured data available from laboratory experiments on such a system, as well as with results from a finite difference model.

Comparisons with measured data indicate that the model is capable of predicting actual evaporation over prolonged time periods with good accuracy. It also predicts the water content and temperature to a fair degree of accuracy. The inconsistencies at advanced stages of drying can plausibly be explained in view of the uncertainty in soil property relationships and the limitations of experimental techniques.

Khanbilvardi, R.M., Ahmed, S., and Gleason, P.J. 1995. Flow investigation for landfill leachate (FILL). Journal of Environmental Engineering, Vol. No. 121, No. 1, pp. 45 - 57.

A two-dimensional unsteady state moisture flow model has been developed in order to describe the leachate flow process in a landfill. The unsteady variation of leachate head has also been considered in the saturated zone of the landfill to compute the time-varying leachate flow rates in both the lateral and vertical directions. The contribution of precipitation to the landfill leachate has been investigated by computing evapotranspiration and surface runoff due to side slope. The model was used to simulate the leachate flow rates in section 6/7 of Fresh Kills landfill, situated in Staten Island, New York. A comparison of the results was made with the Hydrologic Evaluation of Landfill Performance (HELP) model, which is based on a quasi-two-dimensional approach. Comparisons were also made with the results obtained from previous studies using the Environmental Protection Agency (EPA) water-balance model and by investigating the real field condition. It was found that the HELP model underestimated the surface runoff. The simulated leachate flow rates by the new model were found to be less than those obtained by HELP. The effects of varying boundary conditions, which depend on surface runoff and evapotranspiration, were examined to arrive at a better representation of the two-dimensional unsteady state mechanism of leachate flow in the landfill.

Khire, M.V., Meerdink, J.S., Benson, C.H., and Bosscher, P.J. 1995. Unsaturated hydraulic conductivity and water balance predictions for earthen landfill final covers. Presented at the 1995 ASCE National Convention, San Diego, CA, September 1995.

The influence of the unsaturated hydraulic conductivity function on water balance predictions for landfill final covers is presented using predictions made with a water balance model and field data. The field data was obtained from an instrumented test section that is being used to collect field-scale data describing the hydrology of final covers. The components of the water balance were precipitation, overland flow, soil water storage, lateral intra-layer flow, percolation, and evapo-transpiration. Gardners, Haverkamps, van Genuchten and Fredlund and Xings models were used in the analysis. The water balance equation was first published by Benson et al. (1994) in GTJODJ, Vol. 17, No. 2.

Knapp, R.A., Petit, C.M., Martin, J.C. 1995. Waste rock sampling techniques for acid rock drainage ARD assessment. Proceedings of '95, Conference on Mining and the Environment, Sudbury, Ontario, May 28th-June 1, 1995. pp. 587-594.

Acid Rock Drainage (ARD) is a major environmental issue at virtually all types of mining operations across Canada. Over the past twenty years, a series of monitoring

techniques has been developed to predict the potential for ARD at mining sites and to monitor the acid generating characteristics of mine rock piles. There are many techniques available, but not enough of information regarding the effectiveness of the various techniques exists. This paper is based on the results of a recent international survey of industry, government and researchers as well as experts workshop held to discuss sampling techniques. It summarizes the available techniques and presents those that are preferred and most commonly used, those that are the most cost-effective and those that provide the best data for decision making and modelling. Various waste rock sampling categories and cost information statistics are summarized in this paper.
In summary:

- There are no accepted standard techniques. Most techniques are suitable.
- There is a need for standards to better compare the techniques. It is understood that work is progressing in this area.
- The key areas of discussion/deficiency have been identified.

Koerner, R.M. and Daniel, D.E. 1992. Better cover-ups. Civil Engineering, May 1992, pp. 55-57.

Defining the final cover for a soil-waste landfill or remediation site is often more difficult than designing its lining because a cover will undergo more unpredictable stress and distress during its life span. The authors of this paper discuss several factors that engineers must pay special attention to in the design of the barrier component.

Konrad J-M., and Morgenstern, N.R. 1980. A mechanistic theory of ice lens formation in fine grained soils. Canadian Geotechnical Journal, Vol. 17, pp. 473-486.

This study reveals that a freezing soil can be characterized by two parameters, the segregation-freezing temperature, T_s, and the overall permeability of the frozen fringe, K_f. During unsteady heat flow, the variation of these parameters with temperature produces rhythmic ice banding in fine grained soils. At the onset of steady state conditions, freezing test conducted at a fixed warm end temperature showed that T_s was independent of the cold side step temperature. In addition, a model is presented that indicates how the overall permeability of the frozen fringe can be calculated without detailed measurements at the scale of the frozen fringe.

Kwong, Y.T.J. 1992. Generation, attenuation and abatement of acidic drainage in an abandoned minesite on Vancouver Island, Canada. Second International Conference on Environmental Issues and Waste Management in Energy and Minerals Production. *Eds*. Singhal et al. Balkema, Rotterdam. Sept. 1-4. ISBN 90 5410 0796.

Twenty years after the abandonment of the Mount Washington Mine in central Vancouver Island, Canada, acidic drainage entrenched in copper was found to be emanating from the site and seriously affecting the fish stock in a river down-stream. At the abandoned minesite, acid generation is initiated by oxidation of pyrrhotite and enhanced by the formation and dissolution of efflorescent minerals, as well as the discharge of groundwater enriched with ferrous iron.

In a small pond receiving acidic drainage however, natural attenuation of acidity is effected through dilution and sulfate reduction. Reclamation activities conducted to date focus on reducing the supply of oxygen and water to an acid-generating waste rock dump and apparent "hot spots" in the open-pit. Since shallow bedrock still contains much sulfide, an integrated abatement strategy is deemed more appropriate. New information on the processes of acid generation and attenuation occurring at the Mount Washington abandoned minesite warrants a revision of the original abatement strategy to incorporate a more integrated approach to solving the acid rock drainage problem. The natural acid and metal attenuation capacity of a series of wetland downstream from the site should perhaps be developed and utilized. Further abatement work at the minesite should take the local geology and mineralogy into consideration. Preservation and the creation of reducing conditions in the pit area are highly recommended.

Link, S.O., Wing, N.R., and Gee, G.W. 1995. The development of permanent isolation barriers for buried wastes in cool deserts:Hanford, Washington, Journal of Arid Land Studies, Vol. 4, pp. 215-224.

The Hanford Site Surface Barrier Development Program has been developed to design and test an earthen cover system (barrier) that can be used to inhibit water infiltration, plant and animal intrusion, and wind and water erosion. The barrier is designed to isolate buried wastes from environmental dispersion for at least 1,000 years. The Hanford Site is located in south-central Washington, which is characterized as a cool desert. Yearly precipitation averages 160 mm, falling mostly in the winter.

The prototype barrier design includes a fine-soil surface with a relatively high infiltration rate to limit infiltration below the fines by inducing temporary storage near the surface. Transpiration by vegetation and evaporation will return stored water to the atmosphere. A capillary break created by the interface of the fine-soil layer and coarser textured material below will further limit infiltration and promote evapotranspiration. Should water pass the interface, it will drain laterally on a low permeability asphalt layer through a coarse textured sand/gravel filter layer.

Water infiltration control is a key component in barrier design. Lysimeter studies indicate that a surface layer of fine soil with deep-rooted plants precludes drainage even with three times normal precipitation. Drainage on the Hanford Site occurs when soils are coarse textured even when plants are present.

Studies at the Hanford Site have shown that plants and animals will significantly interact with the barrier. Plants serve to transpire soil water into the atmosphere. Native deep-rooted (down to 3 m) perennials such as sagebrush and bunch grasses will best recycle water, while shallow-rooted (about 60 cm) annuals introduced such as cheatgrass can potentially lead to infiltration. Deep-rooted tumbleweeds potentially could intrude into the waste, but coarse rock layers and a redundant asphalt layer will prevent penetration. Animal intrusion studies indicate that small animal burrows have no significant effect on soil water storage, and that large animal burrows have a small effect in the winter and disappears in spring or summer.

Current work tests integrated scientific and engineering concepts on a large prototype barrier to determine if it can isolate buried wastes from environmental dispersion.

Lundgren, T. 1990. Bersbo - The first full scale project in Sweden to abate acid mine drainage from old mining activities. Acid Mine Drainage: Designing for closure. Presented: GAC/MAC Joint Annual Meeting, Vancouver, B.C. Bitech Publishers Ltd.

The abatement of acid mine drainage (AMD) in Sweden has recently started with some full scale projects: the Bersbo Project, the Dalalven Project and the Rantad Project. The general strategy adopted in Sweden is the reduction of oxygen and water transport by covering "impermeable" layers. This paper reports the recently completed covering operations in Bersbo, Sweden.

Lundgren, T., and Lindahl, L-A. 1991. The efficiency of covering the sulphidic waste rock in Bersbo, Sweden. Second International Conference on the Abatement of Acidic Drainage, Montreal, Vol. 3, September 16-18, pp. 239-255.

The waste rock piles in Bersbo, Sweden were mainly produced in the 19th century although mining in the area was active from medieval times until the year 1900. In remedial actions carried out in 1987-1989, the waste rock and a small tailings pond were concentrated in two dumps which were covered. The total amount of waste, 1.4 M metric tons, had been substantially reduced by filling the old shafts. The covers of the dumps consist of a sealing layer and a protective layer (2 m of glacial till). On one of the dumps, the sealing layer was constructed using a compacted, dry clay. On the other dump, the sealing layer was made by grouting cement-stabilized coal fly ash (Cefill) in a 0.25 m thick layer of crushed rock aggregate. Instrumentation was placed during the construction of the cover so that the efficiency of the sealed layers could be monitored. There is also a conventional monitoring program running on the cover surface to monitor ground water quality.

The covers were completed in the spring of 1989. Although it may be too early to predict the total effect that the covering operations has had on the metal transport from the Bersbo area, some important observations have been made. The oxygen concentration in the dumps reduced very rapidly after the completion of the cover and is still low. The ground water levels above the sealing layers confirm that the diffusion barrier exists and that the seepage of water is very low. The oxygen diffusivity and the hydraulic conductivity of the cover are measured to be very low. At this point, the clay liner seems to be the most efficient oxygen barrier while the Cefill liner seems to be the most efficient water barrier. However, it also reveals the existence of local deficiencies in the cover. As long as the layers are not fully saturated, it is not possible to assess the long term efficiency. Despite the fact that there still is a washing out of weathering products from the waste dumped in the mine shafts, the metal transport to the main recipient, Lake Risten, has been measured to be lower than that which existed before the remedial actions were started. The acidic drainage of the area is slightly reduced since the remedial actions took place.

Lundgren, T., and Lindahl, L-A. 1991. Remedial action programs for sulphidic wastes from ancient mining in Central Sweden. Second International Conference on the Abatement of Acidic Drainage, Montreal, Vol. 3, September 16-18, pp. 403-416.

The prosperity of Sweden in the 17th and 18th centuries was based on the production of copper and silver. The mines were at that time almost all situated in central Sweden. Presently, only three of them are still in operation. One, the Falun Mine, is probably more than 1000 years old. More than 200 heaps of waste rock and slag have been mapped and classified that this site and the total production of acid mine drainage (AMD) from the heaps corresponds to an annual flow of about 500 tons (metric) of zinc, 25 tons of copper and 600 kg of cadmium all of which are carried to the Baltic sea by the River Dalaven.

A special investigation conducted in 1989-1990 has revealed that the waste from the city of Falun is responsible for about 90% of the total AMD discharged to River Dalalven. Of the remaining 10%, less than 2% comes from another mining area in operation, the Garpenberg area. The rest of the AMD is produced by some 200 small heaps or minor mining areas in the region. Some remedial action programs suggested to the authorities include:

- (Re-)concentration of waste rock and tailings
- Collection and treatment of AMD
- Wet cover
- Dry cover
- Diverting surface and ground waters by trench wall sealing

In total, some 20 reclamation projects are planned in Sweden. The aim is to reduce AMD to the River Dalaven and other major streams by 75-80%. The total cost of the programs is estimated to be approximately 100 million dollars U.S.

Lundgren, T. and Soderblom, R. 1985. Clay barriers - A not fully examined possibility. Engineering Geology, 21 (1985), pp. 205-208.

Due to their low hydraulic conductivity and resistivity against mineralogical changes, clays should be very useful as sealing material when constructing barriers around hazardous waste. Mechanisms like surface diffusion, phase transitions and syneresis may however, cause unstable conditions or may enhance the mobility of the ions in the system. In this paper, these mechanics are discussed and a way of studying some of them is suggested.

The conclusion of the discussion is that present knowledge is insufficient to evaluate the efficiency of clay barriers in the long term. It is therefore important to increase the knowledge of the processes concerned.

Mac G. Roberston, A., Kent, D.D., Williams, D.R. and Skermer, N.A. Frost action in uranium tailings - Canadian Uranium Mill Waste Disposal Technology. Prepared by Steffen Robertson and Kirsten (B.C.) Inc., Clifton Associates Ltd., and EBA Engineering Consultants Ltd.

Canadian uranium tailings impoundments, specifically those in Saskatchewan, are located in climatic zones that have severe cold winter climates which result in seasonal freezing or permafrost effects in tailings. Frost effects may be disruptive to tailings reclamation measures following closure. An understanding of the potential effects of freezing on the long-term containment of the tailings and of possible solutions to the problems presented by freezing are prerequisites for the successful design and implementation of close-out measures.

This report discusses Saskatchewan conditions, presents the available technology for the prediction of frost effects, together with example analyses and a proposed assessment methodology. Three representative sites were selected for evaluation. These were Gunnar, Key Lake and Rabbit Lake. Frost heave features have been reported at the Gunnar and Key Lake tailings sites. Two items of concern which have been identified at these sites include the heaving of covers, with the consequent disruption in surface drainage, and the potential for 'frost pumping' of pore fluid. The 'frost pumping' mechanism is speculative at this point in time. Further investigation and research is needed to clarify the significance of this mechanism. Substantial depths of frozen tailings have been encountered in the tailings deposit at Rabbit Lake, raising concerns over the possibility of thaw in the tailings and resulting tailings water yield and surface settling.

Machibroda, R.L., Wilson, G.W. and Barbour, S.L. 1993. Evaluation of the net infiltrative fluxes across the surface of exposed mine tailings. 46th Annual Geotechnical Conference, Saskatoon, SK, September 27-29, pp. 167-175.

Leakage production rates from disposal sites, such as municipal landfills or mine tailings facilities, depend on the net infiltrative flux of water across the surface of the waste disposal site. The net infiltrative flux entering the ground surface is controlled by both the climate and soil condition. In general terms, the net infiltrative flux may be computed as total precipitation less runoff, change in surface water content and evaporation. Calculation of the actual rate of evaporation is difficult because it is a coupled process which depends on both atmospheric conditions and soil properties such as soil water potential, hydraulic conductivity and groundwater levels.

A wide variety of methods are available for calculating evaporation rates; however, most of these methods provide an estimation only of the potential rate of evaporation. Potential evaporation may be defined as the upper limit or maximum rate of evaporation that would occur from a free water surface given the climatic conditions. The actual rate of evaporation from unsaturated soil surfaces is however, frequently much less than the potential rate.

A modification to the Penman method for calculating the actual rate of soil evaporation is proposed in this paper. The modified method is used in the calculation of the net infiltrative flux into the surface of exposed mine tailings. This flux is then compared to the net infiltrative flux computed using the original Penman method. The analysis shows that significant error in the net infiltrative flux may occur when using the original Penman method for potential evaporation.

Malhotra, V.M. 1991. Fiber-reinforced high-volume fly ash shotcrete for controlling aggressive leachates from exposed rock surface and mine tailings. Proceedings: Second International Conference on the abatement of acidic drainage. Montreal, Sep. 16-18, 1991., pp. 507-513.

The authors describe the nature of the problems associated with aggressive leachate from exposed rock surfaces and mine tailings sites in this paper. A discussion is presented on the various available capping systems to cover these types of exposed surfaces in an effort to reduce or eliminate the leachate. As well, the drawbacks of these systems are mentioned. An alternative capping system, which involves the use of polypropylene fibre in high-volume fly ash shotcrete, is proposed. The proposed CANMET-developed technology appears to be promising and is likely to provide cost-effective, long-term solution to a serious environmental problem. The results of limited field trials of this technology in Canada have been encouraging. It is recommended that additional large scale field trials be conducted to obtain more data on the long-term effectiveness of the proposed capping systems.

Manassero, M. and Pasqualini, E. 1993. Design and construction of Barricalla hazardous waste landfill. Geotechnical News, December, 1993, pp, 23-29.

Barricalla landfill is the biggest and most important waste landfill of IIc category in Italy with a final capacity of more than 600,000 m^3. The most important features of this landfill, from a geotechnical standpoint, have been described in this paper, referring in particular, to the bottom and sidewall mineral sealing layers. As far as the side wall sealing layer is concerned, an original blended material and related construction approaches have been used for the first time in the authors knowledge, in order to overcome the difficulties due to the requirement for steep side slopes. This construction procedures have resulted in satisfactory safety factors as far as stability is concerned and good insitu sealing properties considering the expected long-term hydraulic conductivity values. The importance of the insitu tests to check the actual full-scale hydraulic conductivity and shear strength of the mineral sealing layers has been illustrated by showing some results and by doing comparisons with the laboratory tests.

McCormick, G. 1991. Freezing and thawing indices in northern Canada. Canadian Geotechnical Journal, Vol. 28, pp. 899-903.

A method for determining the return period values for thawing and freezing indices is presented. Data are based on published temperature records from 48 weather stations in northern Canada. The method described in this note can be applied to any place where there are temperature records covering a period of more than 20 years. The method could also be applied where there is a lesser period of record, but caution should be exercised, since the possibility of error exists with limited or non-continuous weather records.

McWhorter, D.B., and Nelson, J.D. 1979. Unsaturated flow beneath tailings impoundments. Journal of Geotechnical Engineering. ASCE. Vol. 115, pp. 1317-1344.

A model is presented to estimate the seepage under tailings impoundments in partially saturated soils for a variety of conditions. The value of this paper is in the presentation of engineering solutions that do not require impractical quantities of data or the use of numerical methods and computer applications. To achieve this, only those aspects of the flow phenomena that have first order effects on seepage rates have been accounted for in the analyses.

MEND Project 2.20.1. 1994. Evaluation of Alternate Dry Covers for the Inhibition of Acid Mine Drainage from Tailings.

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 focused on evaluating potential barrier materials. This has produced a multitude of suggestions with regard to alternate barrier materials and the direction of future dry cover research. This study reviews dry cover theory and current research for use in covers including several which have not yet been evaluated, 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 consuming, or reaction inhibiting. Potential barrier materials are identified through a technical literature search. As well, a literature review which focuses on forest product industry wastes and a search for potential materials that may be obtained from municipal and industrial waste streams is presented. A short list of potential materials has been developed applying a two stage screening process which takes technical aspects, cost, and practical application into consideration. Potential barrier materials considered to provide a broadly based (country wide) benefit and a good likelihood for success are listed. Finally, 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.

MEND Project 2.31.1(a). 1992. Heath Steele Waste Rock Study Phase 1 to 3.

Sulphide ore mining at the Heath Steele property developed in the late 1950's in Northeast New Brunswick has produced waste piles containing acid generating pyritic rock. The generation of acidic drainage from these highly pyritic waste rock piles create immediate environmental control problems in addition to long-term reclamation challenges.

A proposal was submitted to various federal and provincial agencies to use several of the waste rock piles at Heath Steele to develop and test strategies for the long-term management of acid generating waste rock. A four phase program was developed, and on December 16, 1988, an agreement to fund the first three phases was signed. This report describes the work comprising the first three phases of the project.

1) Phase I of the study involved the selection of four acid generating waste rock piles most amenable to monitoring and evaluation of remedial measures.

2) Phase II involved the installation of monitoring equipment to define the detailed characteristics and background data for the four piles identified in Phase I.

3) In Phase III, the performance characteristics of natural soils in the vicinity of Heath Steele mine site were evaluated to determine their potential as engineered covers for the waste rock piles were determined. This study also developed the most appropriate cover design scenario for the waste rock piles through geotechnical laboratory testing and column studies.

Phase IV will be the installation of an engineered cover on one of the piles which has been designed on the basis of the results from Phase III's work.

A composite soil cover was designed using natural soil materials. The proposed 3-layer composite cover consisting of a fine grained saturated till, sandwiched between two coarse grained layers, will be an effective oxygen barrier. If the till is compacted and placed at a water content slightly wet of optimum, it can be expected to have a low hydraulic conductivity and be an effective water barrier as well. Computer modelling indicated that much lower oxygen fluxes can be expected from this composite system than from a single till layer.

MEND Report 2.31.1b. 1996. Monitoring Report. Phase IV - Composite Soil Cover Acid Waste Rock Study - Heath Steele Mines.

The Heath Steele Waste Rock Study was initiated in the Spring of 1988 at the Heath Steele Mines (HSM) site in New Brunswick. The project was carried out under the Mine Environment Neutral Drainage Program, with funding provided by Brunswick Mining Smelting Corporation, Noranda Technology Centre, the New Brunswick Department of Natural Resources, and Natural Resources Canada through the Canada/New Brunswick Mineral Development Agreement.

The objectives of the study were to develop strategies for the long term management of acid generating waste rock, to evaluate the performance of a soil cover placed over an existing acid waste rock pile at HSM, and to assess the effectiveness of the cover to determine a method for long term management of acid generating waste rock. Phase IV of the program constituted the placement of soil cover and performance monitoring at Pile 7/12 (July 1991 to December 1994).

The data collected over the 72 month period of the project demonstrated that in the uncovered piles, relatively uniform increases in temperature existed towards the centre bottom of the piles

MEND Report. 1995. Engineering Design and Construction, Phase IV - Composite Soil Cover, Acid Waste Rock Study Heath Steel Mines, New Castle, NB. File No. 28-3562-001.1 by Nolan Davis ADI .

A 130 cm thick composite soil cover was constructed on an experimental waste-rock pile at the Heath Steele Mines site near Newcastle, New Brunswick. The cover consists of a 30 cm thick sand base, a 60 cm thick compacted glacial till layer, a 30 cm thick granular layer, and a final 10 cm thick gravel layer for erosion protection. The till was compacted on the sand base in three finished lifts each of 20 cm thickness. Results of a preconstructed pad test indicated six passes of a 5 tonne vibratory compactor were required to attain the design specifications of 95 percent of the Modified Proctor maximum dry density at a moulding water content of 2-3 percent wet of the optimum. These compaction specifications also ensured that the till had a degree of water saturation of at least 95 percent, which is required to reduce oxygen and acid fluxes in the underlying pile. Quality control measures were taken during the construction of the soil cover to ensure that the specifications were followed and monitoring instrumentation installed.

Results indicate a reduction in gaseous oxygen concentrations in the pile from 20 percent before cover to about 1 percent after cover placement. The decreased oxygen penetration implies reduced oxygen flux and acid production. Volumetric water-contents averaged about 32 percent in the till immediately following cover installation and 7 months later. The water-content data are corroborated by soil suction measurements. Temperatures in the pile have decreased following cover installation but appear to be more influenced by climatic variability than by a decrease in heat production and hence sulphide mineral oxidation. Observed discharge from two lysimeters installed below the cover indicate infiltration of 2 percent of precipitation during a 55-day period when rainfall was heavy. The volume of the water seepage from the piles has been reduced but the quality has not changed since cover installation. Further monitoring will be required to confirm the reduction in acid production.

MEND Report. 1995. Draft Final Report on the Acid Waste Rock Study at Heath Steel Mines, New Castle, NB. File No. 28-3562-001.1. Submitted to Heath Steele Mines on behalf of the Mine Environmental Neutral Drainage by Nolan Davis ADI.

A waste rock study was initiated in the Spring of 1988 at the Heath Steele Mines (HSM) site in New Brunswick. The objectives of the study were to develop strategies for the long term management of acid generating waste rock, to evaluate the performance of a soil cover placed over an existing acid waste rock pile at HSM, and to assess the covers effectiveness as a method for long term management of acid generating waste rock.

The project was carried out under the Mine Environment Neutral Drainage (MEND) Program, with funding provided under the program by Brunswick Mining and Smelting Corporation, Noranda Technology Centre, the New Brunswick Department of Natural Resources, and Environment Canada.

The project was developed and conducted in the following four phases:

- Phase I: Selection of four waste rock piles for monitoring and evaluation;
- Phase II: Installation of monitoring equipment in the four piles identified in Phase I to define waste rock characteristics and background data;
- Phase III Geotechnical and column testing to evaluate the performance characteristics of potential covers;
- Phase IV Placement of soil cover and performance monitoring at Pile 7/12.

The Noranda Technology Centre reviewed and tested a range of cover options and recommended for Pile 7/12, a composite cover of a 30 cm base granular layer, a 60 cm saturated glacial till layer, a 30 cm overlying coarse grained granular layer, and a 10 cm erosion protection layer. A cover of this specification was placed in the late summer of 1991.

After the placement of the cover, monitoring of oxygen and temperature continued monthly at all piles. At Pile 7/12, infiltration rates and quality were also measured as was the moisture content of the glacial till layer.

The project confirmed that uncovered acid waste rock piles provide an ideal environment for oxidation of the sulphide material and thus the generation of acid leachates. The cover also resulted in a depletion of oxygen within the pile and a reduction in pile temperatures. In addition, the volume of acid leachate escaping from the pile was drastically reduced representing only two percent of total precipitation on the pile. The glacial till layer within the cover maintained the moisture content at which it was placed over the 36 months of evaluation.

Ultimately, composite soil covers were found to be an effective way to reduce the oxidation reaction in acid waste rock piles and thus significantly lessen their impact on the environment. To achieve this, the active layer must be designed, constructed and maintained so that its integrity and moisture content are maintained. Composite soil covers are suitable for areas only where precipitation enables the active layer to maintain its moisture content, such as at the Heath Steele site. Ongoing maintenance would also be required to prevent the establishment of trees or shrubs on the cover, the roots of which could threaten the integrity of its sealing ability.

Miller, C. J. and Mishra, M. 1989. Hazardous waste containment using clay liners. Groundwater Management: Quantity and Quality, Proceedings of the Benidrorm Symposium, Oct. 1989, pp. 191-199.

The use of clay liners is prevalent in the waste disposal industry. The liner is expected to perform the most critical function of providing a barrier between the natural environment and the deposited waste. Unrestricted migration of the waste could lead to soil, ground water, and surface water contamination. It has become evident that such environmental problems are also prevalent in the vicinity of landfills constructed with clay and/or synthetic liner barriers. This situation, and the continuing increase in hazardous waste production, suggests a need for further investigation of hazardous waste containment. The present investigation focuses on failure mechanisms and fluid transport through clay liners. Management decisions regarding landfill design should incorporate these considerations.

Millington, R.J., and Shearer, R.C. 1971. Diffusion in aggregated porous media. Vol. 111, No. 6, pp. 372-378.

Aggregation or under-dispersion of either the solid or void components of a porous medium imposes additional restriction on the flow of fluid through the medium. A model is presented which permits calculation of diffusion coefficients in aggregated porous solids, either saturated or partly saturated with fluid. Calculated gas diffusivities are compared with experimental data and reasonable agreement is found.

Mitchell, J. K. 1994. Approach to closure designs for mine sites with severe AMD. Proceedings of the First International Congress on Environmental Geotechnics, Edmonton, Alberta, pp. 951-962.

Insitu containment of wastes by means of barrier walls and covers within already contaminated ground can be a viable means for environmental protection. Contained land disposal is likely to remain a major technology for safe disposal of newly generated hazardous and municipal wastes for many years to come. Vertical barriers include slurry walls, grouting, sheet pile walls, deep soil-mixed walls and geomembranes installed within slurry trenches. Bottom barriers include natural soil and rock formations, grouted barriers, composite liner systems, jet grouting, and some recently devised special systems. Covers are usually constructed in layers of compacted soil, geosynthetic and drainage materials. Materials, construction methods, interactions with the surrounding environment and with wastes of various types, the advantages and limitations, and permittivity of different types of physical barrier systems are all considered. More data on the long-term effectiveness of barriers is needed.

Unfortunately, sufficient long-term performance case histories are not yet available for many types of systems at the time of construction. Collection and promulgation of such information could go a long way towards changing public perception that all contaminated ground must be completely cleaned and that new wastes should never be stored below ground.

Mitchell, J. K. and Jaber, M. 1994. Factors controlling the long-term properties of clay liners. Waste Containment Systems: Construction, Regulation, and Performance, GSP, No. 26, ASCE, New York.

The properties of clay liners and their susceptibility to changes with time are major concerns in the design of waste repositories. Both the desired and required properties of clay liners are reviewed in this paper as well as the factors affecting their long-term stability. These factors fall into four major groups:

(1) Soil composition including gradation, plasticity index and type of mineral;
(2) Placement conditions and construction effects including moisture content and density, compaction method and effort, size of clods, bonding between lifts, excessive wetting, desiccation and frost conditions;
(3) post-construction changes including change in confining stress, clogging due to fine particle migration or biological activity, piping, differential settlement below the liner, the effects of freezing and slope instability; and
(4) Chemical compatibility between the clay liner and the contained waste.

Mohamed, A-M.O., Yong, R.N., Caporuscio, F., Yanful, E.K., and Bienvenu, L. 1993. Chemical interaction and cyclic freeze-thaw effects on the integrity of the soil cover for Waite Amulet tailings. Joint CSCE-ASCE National Conference on Environmental Engineering. Montreal, July 12-14, Vol. 1, pp. 259-268.

In this study, two cases regarding water availability during freezing were investigated. The first case adopts a positive water head to assess the maximum alteration to the clay cover during freeze-thaw. The second case adopts a negative water head during cyclic freeze-thaw to simulate field conditions during the fall season at the Waite Amulet site.

It was demonstrated that the integrity of the clay cover was considerably reduced due to the induced positive water head during freeze-thaw. This was attributed to:

(1) Aggregation of clay particles;
(2) Chemical interactions between the generated acidic solutions and heavy metals from the tailings and the clay residence pore fluid. This in turn results in a reduction of the thickness of the double layer and increases the tendency of flocculation of the clay particles; hence an increase in permeability occurs; and,
(3) Reduction in the buffering capacity of the clay due to reduction pHs.

For the case of the negative water head, the integrity of the clay cover is slightly reduced due to:

(1) Limited amount of water intake during freezing; and,
(2) Limited amount of chemical interaction. Due to further leaching however, the residence pore fluid cations in the clay will be reduced. The thickness of the double layer will then be increased and the clay tendency for dispersion increased. This in turn will reduce the permeability of the clay cover to water.

Nevertheless, the negative water head used in this study was less than the air entry value of the clay obtained from soil suction experiments (Yong et al. 1991). Therefore, the clay layer will remain unsaturated. This is not recommended for the decommissioning of the site (i.e., protection against oxygen and water infiltration.)

Murray, E.J., Rix, D.W., and Humphrey, R.D. 1992. Clay linings to landfill sites. Quarterly Journal of Engineering Geology, Vol. 25, pp. 371-376.

Seepage of leachate or the migration of noxious gases from landfill sites can pollute the ground and groundwater to a considerable distance from the source of the problem. Current trends and legislation dictate that future practice at waste disposal sites will be to provide a liner capable of eliminating or minimizing the migration of contaminants. Geotechnical considerations in the design and construction of low permeability clay liners are addressed and laboratory test results for a range of clay types are presented in support of the arguments. The use of the moisture condition value (MCV) test in the selection of acceptable materials and the control of earthworks operations is discussed. A permeability requirement of no greater than 10^{-9} m/s for the clay liner dictates the upper limit to the acceptable MCV range while the shear strength dictates the lower limit.

Newman, G. 1995. Heat and mass transfer of unsaturated soils during freezing. M. Sc. Thesis. Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada.

Experimental and field data have shown that large amounts of water can be redistributed from warmer soils to and behind an advancing freezing front. The mechanisms by which this occurs are becoming more understood, but the most appropriate method for analyzing these mechanisms is not yet known. Various researchers have developed soil freezing models, but they are all limited to some extent and are not practical tools from a design or predictive modelling perspective. The objective of this research program was to develop an unsaturated soil freezing and thawing theory and to verify this theory by modifying an existing non-freezing soil heat and mass transfer model. In this study, the SoilCover (MEND, 1993) model is modified to verify the freeze-thaw theory and numerical solution.

SoilCover is a one dimensional soil/heat flow transfer computer model used for designing protective covers over waste rock and tailings. These covers, if they remain saturated, prevent oxygen infiltration into the waste material where it can combine with water to produce acid mine drainage. SoilCover is not capable of modelling through the winter months when upper regions of the covers become subject to negative temperatures. This thesis discusses the theoretical background for freeze-thaw analysis and it presents a modified numerical model capable of analyzing soils which are subjected to freezing temperatures.

Unique to this soil freezing model is the method by which the coupled heat and mass equations are combined and solved. The numerical model uses a single, unique expression which describes the heat flow, mass transfer, and phase change phenomenon in the frozen or partially frozen soil zones. To derive the modified equation, the dependent suction variable in the mass transfer equation is re-written as a function of negative temperature using a Claperyon type relationship which comes from combining soil freezing curve data with soil water characteristic curve data. The mass transfer equation is then re-written as a function of the change in ice content and substituted into the ice content term of the heat transfer equation. The result is one heat transfer equation and one unknown variable, i.e., temperature. Once new temperatures are solved for over the current time step, suctions and ice contents are computed using back-substitutions.

The modified freeze-thaw model was verified using laboratory freezing test data collected at the University of Saskatchewan in 1977, and field freeze-thaw data collected over the winter of 1993/1994 from a silver mine near Houston, B.C. The agreement between measured data and computed results was quite good in all cases. Some discrepancies between measured and computed results were evident, but these were primarily due to slightly incorrect soil thermal and hydraulic property functions. In addition, during the field data simulations, the soil surface temperature beneath the snow pack had to be estimated as the numerical model does not account for heat and mass flux through snow layers. Daily infiltration during the spring thaw was also estimated based on averaged meteorological data provided by the Equity Silver Mine.

Results from the laboratory freezing test simulations indicate that the permeability versus suction relationship for an unsaturated soil also applies as the soil pore-water freezes. This finding is contrary to the findings of other researchers who had to introduce an arbitrary ice impedance factor to make computed and measured ice contents agree. The ice impedance factor has the effect of reducing the permeability by several orders of magnitude as the volumetric pore-ice content increases. In this study, excellent agreement between computed and measured ice contents was obtained without the use of an impedance factor. This is most likely due to an accurate prediction of the permeability versus suction relationship.

Nicholson, R.V., Gilham, R.W., Cherry, J.A., Reardon, E.J. 1989. Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. Canadian Geotechnical Journal, Vol. 26, pp. 1-8.

Acid production in sulphidic tailings can cause severe degradation of water quality in both subsurface and surface systems. The availability of gaseous oxygen and the rate of diffusion of oxygen through the open pore spaces in the upper zone of the tailings are the critical factors controlling the rate of acid generation. Acid generation can be reduced by applying a fine grained, cover layer to the tailings surface. The key process involves moisture retention by capillary forces so that near-saturated conditions can be maintained even when the cover layer exists at several metres above the water table. Textured layering of fine over coarse materials improves moisture retention in the fine layer when infiltration exceeds evaporation. The application of such a cover layer can theoretically reduce oxygen diffusion coefficients and rates of acid generation by up to four orders of magnitude. This can represent a substantial difference in the potential treatment costs of tailings seepage. Preliminary laboratory measurements of the diffusion characteristics of potential cover materials can be evaluated on the basis of their effectiveness in decreasing acidification using simplified calculations based on Fick's first law. These concepts and methods provide an initial evaluation of cover performance before field-scale testing .

(Note: There are is a discussion on this paper by Barbour, S.L. in the Canadian Geotechnical Journal, vol. 27, pp. 398-401 and reply by authors in the same issue pp. 402-403).

Nicholson, R.V., Akindunni, F.F., Sydor, R.C., and Gilham, R.W. 1991. Saturated tailings covers above the water table: The physics and criteria for design. Proceedings, Second International Conference on the Abatement of Acidic Drainage, Montreal, Quebec, September 16-18.

Fine granular materials such as silty sands or desulphurized tailings have been identified as possible candidates for tailings covers to reduce acid generation. The concept is based on minimizing the diffusion of oxygen through the cover by maintaining a high water content. Under most conditions, granular materials would be expected to drain to residual saturation allowing a significant portion of air to enter the voids. However, by selective layering of fine grained over coarse grained materials, the upper layer may be maintained in a saturated condition regardless of the depth to the water table.

Numerical simulations indicate and laboratory measurements confirm that under specific contrasts of grain size, an upper layer will be prevented from draining by a well drained underlying material's impedance to further water movement. Criteria for cover design are based on simple laboratory tests of the candidate materials.

The results of preliminary modelling and laboratory studies have suggested that moisture retention in a cover layer is enhanced by the selective matching of material properties with the underlying medium. The properties of interest in the selection of candidate cover materials include the pressure head at which the tailings or underlying medium approaches residual saturation and the air-entry value of the cover. In order to avoid drainage and maintain full saturation of the upper layer, the sum of the absolute value of residual saturation and the thickness of the cover should be less than the air-entry value of the cover.

The concept of maintaining a high degree of saturation in fine covers above the water table appears promising under ideal conditions. Further study of the hydraulic processes contributing to this phenomenon is required. This includes the simulation of processes such as evapotranspiration and wetting-drainage cycles to evaluate the sensitivity of the moisture levels in the cover to such perturbations. Further laboratory experiments with various scenarios are also required to provide more substantial verification of the model results. Field trials should then build on the results of these studies for the purpose of developing a cost effective cover scheme for existing reactive tailings impoundments.

Nicholson, R.V., Elberling, B., and Williams, G. 1995. A new oxygen consumption technique to provide rapid assessment of tailings reactivity in the field and the laboratory. Paper presented at Sudbury '95, Conference on Mining and the Environment, Sudbury, Ontario, May 28th-June 1, 1995.

The rate of sulphide mineral oxidation in tailings is affected by chemical kinetics at the particle surface and the transfer of oxygen from the atmosphere into the tailings. When sulphide mineral waste is the only oxygen consuming material present, the rate of oxidation within the tailings can be estimated by measuring the flux of oxygen through the tailings surface.

A technique has been developed by the authors to measure the oxygen consumption at the surface. The method involves insertion of a 20 cm diameter thin-walled aluminum tube into the tailings, placement of a cap to temporarily seal the head space from the atmosphere, and measurement of the oxygen concentration in the air volume above the tailings over a one to two hour period. The observed rate of oxygen depletion is used to calculate the oxygen flux through the tailings surface. Laboratory and field measurement of oxygen consumption agree well with oxidation rates estimated from sulphate release rates. This method provides a simple and rapid measurement technique that can be used to monitor tailings oxidation and identify relative "hot-spots" that may require immediate intervention to reduce loadings from acidic drainage. This method can also be applied to the evaluation of non-oxygen-consuming covers by comparing pre- and post-construction oxidation rates across the tailings.

Nixon, J.F. 1991. Discrete ice lens theory for frost heave in soils. Canadian Geotechnical Journal, Vol. 28, pp. 843-849.

The existing segregation potential (SP) method for frost heave prediction in soils is semi-empirical in nature and does not explicitly predict the relationship between heave rate, temperature gradient, and other more fundamental soil properties such as the water movement in a freezing soil. The SP method assumes that the heave rate is directly related to the temperature gradient at the frost front but acknowledges that the SP parameter is dependent on pressure, suction at the frost front, cooling rate, soil type, etc. This paper extends and modifies an approximate analytical theory of frost heave by Gilpin (1980) and accounts for the effects of distributed phase change within the freezing soil. Assuming that independent measurements of the hydraulic conductivity of frozen soils can be made, the proposed theory can be used for more basic and fundamental prediction or understanding of the physics of frost heave. This method can also be used to predict the effects of changing overburden pressure on the predicted heave rate. The solution can be carried out quickly on a microcomputer to obtain the heave, suction at the frost front, ice lens temperature, and other results of interest with time. This discrete ice lens model for predicting heave provides more insight into some other common problems and misconceptions with frost heave test interpretation.

O'Kane, M., Wilson, G.W., Barbour, S.L., and Swanson, D.A. 1995. Aspects on the performance of the till cover system at Equity Silver Mines Limited. Paper presented at Sudbury '95, Conference on Mining and the Environment, Sudbury, Ontario, May 28-June 1, 1995.

The prevention of acid rock drainage (ARD) from mine wastes has received a great deal of attention in recent years. Many ARD control options are available; however, the technical and economic feasibility of each ARD control option is site specific.

Engineered soil covers over waste rock were employed as an ARD control method at the recently decommissioned Equity Silver Mines Ltd. open pit operation at Houston, British Columbia. Climate and soil cover conditions were monitored over a two year period. The cover consists of 50 cm of compacted till overlain by 30 cm of uncompacted till. The main objective of the soil cover system was to limit flux of water and oxygen into the underlying waste rock by making use of a high degree of saturation within the compacted layer.

O'Kane, M., Wilson, G.W., Barbour, S.L. 1993. SoilCover, a new computer model to aid in the design of SoilCover systems for acid generating waste rock and tailings. Proceedings of the 17th Annual British Columbia Mine Reclamation Symposium, May 4-7.

Evaluation of the flow of water across the soil/atmosphere boundary is an essential component in the design of soil cover systems. The design of soil cover systems as oxygen barriers for the long term closure of sulphidic tailings and waste rock requires the accurate prediction of moisture fluxes between the cover surface and the atmosphere.

SoilCover (MEND, 1993) is a new software package which uses a theoretical method for predicting the exchange of water between the atmosphere and a soil surface. The theory uses the well known principles of Darcy's Law and Fick's Law to describe the flow of liquid and water vapour in both the soil profile and the soil/atmosphere boundary. SoilCover predicts the actual rate of evaporation from both saturated and unsaturated soil surfaces. The model accounts for atmospheric conditions, soil properties, and the effects of vegetation. In addition, SoilCover performs a water balance on the basis of infiltration, evapotranspiration, surface runoff, surface ponding, and the soil profile. The change in water content, suction, vapour pressure, temperature, and hydraulic conductivity with respect to time and depth within the soil profile are also calculated.

SoilCover provides a one dimensional, transient analysis which can be used interactively with other commercially available software packages for modelling ground water flow in mine tailings and waste rock. The two dimensional flow system can be modelled using the transient flux boundary conditions from the soil cover/atmosphere boundary predicted by SoilCover.

O'Kane M. 1995. Instrumentation and monitoring of an engineered soil cover system for acid generating mine waste. M.Sc Thesis. Department of Civil Engineering, University of Saskatchewan, Canada. 246p.

Engineered soil cover systems are often used as a control method for acid rock drainage. Acid generation occurs when sulphide bearing waste material is exposed to oxygen and water. The oxidation process results in acid rock drainage as acidic water leaches heavy metals from the waste material. Placement of engineered soil cover systems in humid climates is an at source control method since it controls the acid generation process limiting the oxygen and water to the waste material. Soil cover systems can also be used as water infiltration barriers. In either climate, the ability of the soil cover to perform as designed is a function of the properties of the soil cover and waste materials and their response to atmospheric demands. In reality, closure of mining operations usually involves collection and treatment of acid rock drainage. However, limiting oxygen and water to sulphide bearing waste material through the use of engineered soil cover systems will significantly reduce current and long term treatment costs.

The research presented in this thesis describes a laboratory characterization for potential soil cover materials as well as a field instrumentation program that together provide a methodology for evaluating the insitu performance of engineered soil cover systems. The methodology was developed for soil covers placed over acid generating mine waste. However, the methodology can be applied to uranium tailings and landfills as well as to many tradition geotechnical problems such as slope stability and the evaluation of groundwater systems since the same physical parameters are evaluated.

This thesis is part of a five year soil cover research program that includes: field response and predictive modelling using the physically based soil/atmosphere SoilCover (MEND, 1993) model. Extension of SoilCover to include the effect of freeze-thaw on moisture movement in the cover system (Newman 1995, Zhou 1996 and Yazdani 1995); and an investigation of the potential for water induced erosion to cause degradation of the soil cover system (Owoputi 1995) are also discussed.

In this thesis, an engineered soil cover system placed over the waste rock material at Equity Silver Mines Ltd was studied. The cover consisted of 30 cm of non-compacted till material placed over 50 cm of compacted till material and was evaluated on the basis of its ability to perform as an oxygen and water limiting barrier to the underlying waste rock material. Field instrumentation was installed to monitor temperature, gaseous oxygen, and gaseous carbon dioxide in the waste rock material. Lysimeters were installed at the base of the soil cover system to monitor soil suction, soil temperature, and water content. Finally, a fully automated weather station was installed to monitor climate conditions at the mine site.

The field data illustrated that the lower compacted layer maintained a high degree of saturation (i.e., 90% or higher) during the three years of data collection. The high degree of saturation was due to a capillary break at the interface of the lower compacted layer as well as the higher hydraulic conductivity in the upper layer and its response to atmospheric demands. This is a positive result since the lower compacted layer was designed as an oxygen limiting barrier. In addition, field data verified that water infiltration to the underlying waste material was limited due to the low hydraulic conductivity of the compacted layer.

Patterson, J.P. 1987. Environmental and reclamation measures at Equity Silver Mines Ltd., AMD Second Workshop, Halifax. pp. 457-477.

Acid Mine Drainage (AMD) of disposed pyritic wastes presents a potential pollution hazard for Equity Silver Mines Ltd. and the mining industry in general. Failure to collect and treat these acidic effluents can eventually affect the quality of receiving streams and endanger aquatic life forms. Treatment and discharge to the receiving environment must comply with stringent anti-pollution laws.

Wastes mined at Equity Silver Mines Ltd. are predominantly acid generating and must be handled according to a materials management plan to minimize impact on the environment. Effluent collection and treatment facilities have been constructed to address the short term environmental concerns while reclamation and research programs are being developed to address and monitor abatement measures for control over the long term.

The purpose of this paper is to offer a brief overview of these measures. Key topics for discussion are: kinematics of AMD, acid generating potential, water treatment and sludge handling, special wastes, waste dump construction, waste rock amendments, bacteriode research, and reclamation measures. Although programs designed to evaluate impact on the receiving environment form an extensive part of the program, they were not discussed in this paper.

Control measures at Equity Silver Mines Limited have been effective in minimizing the environmental impact of AMD. Reclamation practices appear to have reduced oxidation rates at confined sites, although considerably more monitoring will be required to fully evaluate control measures on the larger disposal site. Although alternate methods tested for suppressing acid generation processes initially appeared encouraging, they have since been stopped because of their questionable long term benefit. With existing reserves to last approximately 5 years, plans are now being developed to prepare for mine abandonment. This will require a host of studies associated with sludge disposal and tailings pond abandonment, as well as further research into AMD mitigation for the waste dump.

Payant, S., St.-Arnaud, L.C., and Yanful, E.K. 1995. Evaluation of techniques for preventing acid rock drainage. Proceedings, Conference on Mining and the Environment, Sudbury, Ontario, May 28-June 1, 1995. pp. 485-494.

Cover techniques for preventing acid rock drainage were investigated through column experiments. The cover techniques investigated included a 1 m water cover; a soil cover consisting of a 150 mm thick water-saturated clay layer sandwiched between two 75 mm thick sand layers; and a 150 mm thick wood bark layer. Limestone and phosphate were added at 1 and 3% dosages to test their ability to reduce acidity. Control experiments, using waste rock without cover and additive, were also installed for comparison. Potentially acid-generating waste rock samples used in the investigation contained approximately 19% pyrite and were obtained from the Stratmat site, located on the Heath Steele Mine property, near Newcastle, New Brunswick. The rock samples were crushed to particle sizes between 25 and 50 mm.

Monitoring of the effluent water quality indicated that the control waste rock started producing acid very early in the tests (about the 5th week). After 3 years, the average cumulative acidity from the three water covered columns was 1.2 g of $CaCO_3$. This represents an efficiency of 99.7% in reducing acidity in the effluent. The effectiveness of the soil cover was 98.3%. Limestone addition reduced the acid production by 99.7% and 82.7% at dosages of 3% and 1%, respectively. Finally, phosphate addition reduced the acid production by 64.04% and 9.95 % at dosages of 3% and 1%, respectively.

Parallel outdoor lysimeter tests showed trends for acid reduction which were similar to the laboratory column tests. The difference was explained by the effects of adverse natural climatic conditions (for example, freezing and thawing) which were not present in the laboratory. It was also believed that oxygen and water entered the soil covered waste rock by the side walls of the lysimeters.

The woods bark accelerated acid production by about 30% in the laboratory and 150% outside. Oxidizing bacteria (Thiobacillus ferrooxidans) was used to accelerate the reaction. The habitat of the bacteria might have been improved by keeping the waste rock wetter and warmer. Under the conditions tested, the wood bark cover was not a good technique for reducing acid generation.

Pederson, T.A., Rogowski, A.S., and Pennock Jr. R. 1980. Physical characteristics of some mine soils. Soil Science Society of America Journal, vol. 44, pp. 321-328.

Studies were conducted to evaluate the physical properties of soils from surface coal mining and reclamation operations in Clearfield County, Pennsylvania. Bulk density, evaporation, water retention, infiltration, and hydraulic conductivity values were determined at 10 sites randomly located within a 4 ha experimental area. The average bulk density of the surface 0.5 m layer of mine soil was 1,763 kg/m^3 while the specific surface at most sites averaged 31 m^2/g. Micro-lysimeter data indicated that evapotranspiration (ET) from mine soil could be approximated by class A pan evaporation or by model results. A large amount of spatial variation was observed in infiltration, water retention and hydraulic conductivity values. In the uppermost 0.75 m of profile, most mine soils on the average retained 35 mm of water between 10 and 1,500 kPa, compared to 136 mm for the adjoining soils.

The findings of this study have the following hydrologic implications. Where geology is similar to that of the study area, surface mining will generally result in a mine soil with low infiltration rates (high density and low porosity). While evapotranspiration may approach potential rates when water is available, hydraulic properties of mine soil may result in droughty conditions and periods of plant stress. However, hydrologic changes resulting from mining can be highly variable from site to site and will also vary over time as a result of weathering processes.

Peterson, K.L., Link, S.O., Gee, G.W. 1995. Hanford site long-term surface barrier development program: Fiscal Year 1994 Highlights. Prepared for the U.S. Department of Energy Contract DE-AC06-7RLO 1830.

The Hanford Site Surface Barrier Development Program was organized in 1985 to test the effectiveness of various barrier designs in minimizing the effects of water infiltration; plant, animal and human intrusion; and wind and water erosion on buried wastes, plus preventing or minimize the emanation of noxious gases.

The purpose of the prototype barrier was to provide insights and experience with issues regarding barrier design, construction, and performance that have not been possible with individual tests and experiments conducted to date. Additional knowledge and experience was gained in 1994 on erosion control, physical stability, water infiltration control, model testing, Resource Conservation and Recovery Act (RCRA) comparisons, biointrusion control, long-term performance, and technology transfer.

The barrier is designed to control water by partitioning it into runoff and temporary storage. Evapotranspiration will return stored water to the atmosphere. A capillary break created by the interface of the fine soil layer and coarser textured materials below will further limit the downward migration of surface water. Low permeability asphalt layers, placed below the capillary break, will be used to divert water away from the waste zone should any water get through the capillary break. Tested barrier designs appear to work adequately to prevent drainage under current and postulated wetter climate conditions. The prototype barrier allows this design to be assessed in an integrated test.

Wind erosion will be minimized with a pea-gravel admix soil and vegetation. Wind erosion monitoring was initiated on the prototype barrier in August 1994. Water erosion studies were initiated in August 1994 to evaluate the effectiveness of the admix and vegetation in stabilizing the soil surface under natural rainfall and snowmelt conditions.

Physically disruptive forces that could occur during +1000-year design life of the Hanford Protective Barrier are being assessed. These include tornadoes, high winds, high intensity precipitation, earthquakes, and volcanic ash deposition.

Water infiltration control tests were done at the Field Lysimeter Test Facility (FLTF). Tests at the FLTF continue to show the advantages of using silt loam as a surface material. Silt loam soil has the largest storage capacity of any material tested. When incorporated in a capillary barrier design, this material is capable of storing at least three times the annual average precipitation before drainage occurs. For vegetated, silt-loam surfaces no drainage has occurred since testing began, even under the most extreme climate regime tested (i.e., 480 mm/yr precipitation, three times the annual average). Tests with bare silt loam surfaces have shown that under the extreme climate conditions, modest amount of drainage have occurred over the past 2 years. For ambient treatments, there has not been any drainage from silt loam soils under any treatment. When vegetation is present, barriers at Hanford with silt-loam surfaces are not expected to drain.

An asphalt layer is an important component of the barrier. This layer provides a RCRA- equivalent backup to the overlying earthen layer in the unlikely event these layers cannot prevent drainage. Studies were done on RCRA equivalency, physical properties, aging characteristics, and ancient asphalt analogs.

Simulation models of the hydrology of protective barriers were compared to evaluate their performance for a minimum of 1000 years. The UNSAT-H code was compared with the EPA's HELP code, with the conclusion that the HELP code is inadequate for Hanford conditions.

RCRA equivalency of the Hanford Protective Barrier is being tested at Hill Air Force Base near Ogen, Utah. The use of an existing lysimeter facility simplifies construction and allows comparison of the Hanford Protective Barrier with an existing clay cap at the site. The clay cap was designed to meet EPA-RCRA guidelines. This site also allows testing in a wetter and colder environment, similar to the upper bound of predicted climate change at Hanford in the next +1000 years.

Plant studies focused on efforts to revegetate the prototype surface. Seeds of native shrubs were collected at McGee Ranch in December 1994. Seedlings were grown for transplanting onto the prototype barrier's surface.

Climate change studies indicate that the long-term mean annual precipitation in the Columbia River Basin is estimated to have ranged between 50% and 75% of modern and 130% of modern levels, while temperatures have ranged from 7^{o}C to 10^{o}C below to 2^{o}C above modern levels. There is no evidence that the long term precipitation averages ever reached three times the normal precipitation limit and were limited to a daily precipitation maximum of about 70 mm at the Hanford Site.

Technology transfer efforts have centered on publishing and distributing research information. Documents produced through barrier development activities continue to be published and provided to interested individuals and organizations both onsite and offsite. Over 90 barrier-related documents have been published so far.

The completion of fiscal year 1994 marks a transition point for the program; one in which the functional principles upon which the design of the long-term surface barrier is based have been shown to be technically sound. With the completion of the prototype barrier, full-scale performance issues can be addressed to ensure technical suitability, public confidence, and regulatory acceptance of the barrier for the long-term isolation of hazardous and nuclear contaminants.

Peyton, R.L., and Schroeder, P.R. 1988. Field verification of HELP model for landfills, Journal of Environmental Engineering, ASCE, Vol. 114, No. 2, pp. 247-269.

Long term simulations of 17 landfill cells from six sites are performed using the Hydrological Evaluation of Landfill Performance (HELP) computer model. Results are compared with field data from a variety of landfills to verify the model and to identify shortcomings. The sites are located in California, Kentucky, and Wisconsin. Since site data is not available for some of the model input parameters, default values are used in many instances. It is found that model predictions are generally bracketed by field measurements. Good agreement between the predicted and measured results is obtained by calibrating the hydraulic conductivity of the cover materials but staying within the range of hydraulic conductivity values reported in the literature for these materials.

The results indicate that the HELP model can be a very useful tool for designing and evaluating landfills. However, additional data is required to rigorously test many of the model assumptions and mechanisms.

Pufahl, D.E., and Haug, M.D. 1991. Cover materials for potash tailings piles. Proceedings: 44th Canadian Geotechnical Conference 1991, Paper No. 66.

Saskatchewan's potash industry produced in excess of 300 million tonnes of tailings since it began operation in 1962. While much of the immediate concern for environmental damage has focused on the containment of leakage from the brine ponds, more attention is now being given to the reduction of the enormous volumes of waste salt and to its long term stabilization. The surface of these piles must be sealed if brine generation is to be controlled and damage to the environment reduced. This paper describes the procedure for assessing potential cover materials and reports the results of a laboratory program. The most promising materials have been found to be the geopolymerized clay and admixtures.

Pusch, R. and Alstermack, G. 1985. Experience from preparation and application of till/bentonite mixtures. Engineering Geology, 21, pp. 377-382.

Clay-based layers have been found to minimize infiltration of surface water into waste piles in Sweden. This can be accomplished since the hydraulic conductivity of these layers can be kept so low that the net effect of cyclic drying and wetting will be that of no water penetration. Problems may arise, however, from physico-chemical processes as well as from swelling. One example is discussed in this paper.

Rastoji, V., Scharer, J.M., C.M. Pettit 1995. Factors affecting ARD production: Size and configuration of the waste rock piles. Proceedings, Conference on Mining and the Environment, Sudbury, Ontario, May 28 - June 1, 1995. pp. 597-603.

Waste rock pile size and configuration have been found to be significant factors affecting the production of ARD. It has been a practice in industry to use small piles of pyritic materials (e.g., 30 m^2 to 500 m^2 at the base and 1m to 5 m high) to test the acid producing capabilities of various materials, as well as to investigate acid prevention or pile treatment technologies. These small test piles have demonstrated the potential for "runaway" acid production which on a unit mass basis, may exceed anticipated rates. In some instances, these tests have led to incorrect conclusions regarding prediction methodologies, and management or treatment technologies.

The results of a field study with coal refuse test piles are presented. The effects of pile size were investigated using mathematical (computer) modelling of the test piles and the actual large pile. Recommendations are made as to how to carry out small scale tests. Considerations of scale will hopefully lead to more accurate predictions of acid production and better evaluation of acid prevention technologies.

Ramsey, D.L., and Brannon. 1988. Predicted acid mine drainage impacts to the Buckhannon river, WV, USA. Water, Air, and Soil Pollution. Vol. 39, pp. 1-14.

This study was conducted to determine acid, Al, Cd, Cu, Fe, Mn, and Zn loads originating from coal mines in the Buckhannon River watershed in central West Virginia, U.S.A. It was also used to predict the impacts of those loads should they enter the river as un-neutralized acid mine drainage.

It was found that net alkaline loads at the river mouth would decrease from 3341 to 1014 and 7488 to 1463 kg day^{-1} $CaCO_3$ during the summer and spring sampling periods, respectively, causing the pH to decrease below the level required for the survival of warm water fish species in the affected study area and for a viable trout fishery in a 12 km segment of the river. In addition, aluminum could have major impacts through much of the study area. Zinc could impact the existing cold water fishery and may cause deleterious effects on the warm water fishery. It was not possible to draw accurate conclusions about the impacts of Fe because of the uncertainties of toxicity data and rates of oxidation. It appears that Cd and Cu would probably not impact the river; however, manganese may cause a water treatment problem for the city of Buckhannon.

Rasmuson, A. and Eriksson, J-C. 1986. Capillary barriers in covers for mine tailing dumps. Royal Institute of Technology, Stockholm, Sweden

The possibility of using capillary barriers to reduce water infiltration into mine tailings is explored. A detailed account of the hydrological and physico-chemical basis for the phenomenon is given. The capillary barrier concept involves the principles of unsaturated flow between soils of different texture. A capillary barrier system is constructed such that a fine textured soil overlies a coarse textured soil. Fine soils tend to have a distribution of small diameter pores while coarse soils tend to have a distribution of larger diameter pores. Since the capillary forces are higher in a fine textured soil than in a coarse textured soil, at a particular value of pressure head, more water would be retained in the fine textured soil.

When an infiltration event occurs, the smallest pores in the fine soil begin to fill. Capillary flow can only occur to the coarse layer when the pore size just filled in the fine material matches the smallest pore size in the coarse material. If this system was designed in such a manner that the fine textured material could drain, while maintaining negative pressures at the interface with the coarse material, then the coarse textured soil would remain essentially dry. This may be the case, if the slope of the interface is sufficient to establish a lateral hydraulic gradient.

It is established that the capillary barrier will, in practice, only function if the fine layer remains somewhat unsaturated (i.e., the upper menisci exists and no ponding over the fine layer occurs). Accordingly, water reaching the fine layer must be transported laterally within this layer. The pressure conditions are dependent on the length and slope of the interface, the thickness and types of soil in the fine layer, the water influx at the surface, and the total volume of water infiltrated during a storm event. A simple calculation shows that, using optimistic parameters values, the hydraulic conductivity of the fine material must be larger than 10^{-4} m/s. A hydraulic conductivity of this magnitude is found only in coarse materials with low capillarity. To keep the fine layer at a high moisture content, and to reduce the inward diffusional transport of oxygen, a high capillarity is needed. In practice, it will be difficult to avoid ponding above the fine layer in this situation thereby eliminating the capillary barrier effect.

In conclusion, the capillary barrier effect of reducing infiltration is deemed to be of little importance for the distances and slopes which are characteristic of waste rock covers. However, the low hydraulic conductivity of the fine layer together with the higher hydraulic conductivities of the layers above it, could diminish infiltration to the waste rock significantly. On the other hand, keeping the fine layer at a high moisture content and thereby significantly reducing inward diffusional transport of oxygen seems quite feasible. If this is the case, the weathering of the pyrite will be very low and some water movement through the waste could be tolerated.

(Note: This paper has a good summary of the application of capillary barrier concepts.)

Ross, B. 1990. The diversion capacity of capillary barriers. Water Resources Research. Vol. 26, No. 10, pp. 2625-2629.

An arrangement of unsaturated fine grained soil overlying unsaturated coarse grained soil along a sloping contact can, under appropriate circumstances, divert infiltrating water away from the coarser material. Such an arrangement is called a capillary barrier. The water diverted by a capillary barrier follows downdip above the contact. The volume of water moving laterally increases in the downdip direction as additional infiltration is diverted by the barrier. Sufficiently far downdip, the laterally moving water wets the contact to the point that an amount of water equal to the infiltration flows downward through the coarse soil. The lateral flow, at such a point, represents the diversion capacity of the capillary barrier because this flow will not increase farther downdip. If the width (measured in the direction of dip) of the system is large enough that total infiltration exceeds the diversion capacity, the downdip portion of the barrier will not be effective. The diversion capacity can be calculated exactly in the quasi-linear approximation where the relationship between relative permeability, K_{rel}, and pressure potential 'y' takes the form $K_{rel} = e^{\alpha y}$. This calculations show that an upper bound on the width of capillary barriers is $K_s \tan\phi / q\alpha$, where K_s is the saturated hydraulic conductivity of the fine soil, ϕ is the dip angle of the contact, and q is the infiltration rate.

Rowe, R.K., 1988. Contaminant migration through ground water - the role of modelling in the design of barriers. Eleventh Canadian Geotechnical Colloquium, Canadian Geotechnical Journal, Vol. 25, pp. 778-798.

The role of analysis in the evaluation and design of barriers is discussed. Factors considered include:

(i) The mechanisms controlling contaminant migration through barriers;
(ii) The determination of diffusion and distribution coefficients;
(ii) Leachate mounding and the effect of the clogging of leachate collection systems upon contaminant migration through barriers;
(iv) The importance of considering the finite mass of contaminant available for transport into the soil and a method of modelling the effect of the fine mass of contaminant; and
(v) Examples of how analysis may improve the geotechnical engineer's feel for the effect of the potential contaminant attenuation mechanisms in both glacial till deposits and fractured rock.

Rowe, R.K., Caers, C.J., and Chan, C. 1993. Evaluation of a compacted till liner test pad constructed over a granular subliner contingency layer. Canadian Geotechnical Journal. Vol. 30, pp. 667-689.

The construction and evaluation of a compacted clayey-till test pad constructed over a stone layer are described. The evaluation of the clayey liner involved :

(i) The excavation of six test pits through the liner, followed by careful visual inspection for defects in the liner;
(ii) Sampling of the liner using standard 75 mm diameter Shelby tubes, a 150 mm diameter piston sampler, and block sampling;

(iii) Triaxial hydraulic conductivity tests on samples of liner material consolidated to a number of stress levels relevant to the proposed design; and

(iv) Diffusion tests on samples of liner material.

Based on the results it is concluded that it was possible to construct a low-permeability liner where the hydraulic conductivity was less that 1.4 x 10^{-8} cm/s under expected field stress conditions. Geotextiles from above and below the compacted liner were carefully exhumed and subjected to a series of laboratory tests to examine:

(i) The effect of construction damage on the geotextile's strength;

(ii) The effectiveness of the geotextile in minimizing the extrusion of the clay liner through the geotextile and into the stone layer(s) under expected field stress conditions; and

(iii) The friction angle between the geotextile and clay, and the geotextile and stone.

The geotextile exhumed from the test liner showed some evidence of construction damage; however, based on the field observations and subsequent laboratory tests, it is concluded that it performed adequately.

Ryan, P. and Joyce, C. 1991. Prevention and Remediation of Acid Drainage from Mine Waste Rock in Australia. Second International Conference on the Abatement of Acidic Drainage. Montreal. pp. 221-245.

Investigation into the occurrence and significance of acid drainage from sites in Australia has received a large degree of attention in recent years. For contemporary and future projects, particularly those in higher rainfall areas, the focus on prediction and resolution of acid drainage issues is likely to increase.

This paper describes the preventative and remedial measures adopted at three metalliferous mines in northern Australia at which acid drainage was identified as a key issue with respect to project environmental management and rehabilitation.

The three case studies include an active, a recently decommissioned and an abandoned operation which was rehabilitated in the mid 80's (Captains Flat Copper Mine in New South Wales, Rum Jungle Copper/Uranium Mine in the Northern territory of Australia, Gold Mine of Carpentaria, Queensland). The control objectives and remediation works implemented at each mine are described, the success of the works is assessed, and a procedure for the evaluation of acid drainage significance at future projects is presented.

The Rum Jungle rehabilitation project stands as an example of a precisely engineered approach to AMD/ARD cleanup. Monitoring data suggests that on projects of this nature there is a substantial lag period before the major objectives of cleanup can be realized. It also suggests that there is room for the full consideration of alternative rehabilitation strategies. The two other case studies demonstrate the need for, and advantages of, a proactive approach to AMD/ARD assessment. They also demonstrate the key roles that correct implementation and ongoing auditing of control measures play in the success of this approach. Fundamental to the successful implementation of control measures is an increase in the level of understanding of the processes involved in AMD/ARD and in the remedial options potentially available by industry and associated services and regulators.

The correct use (as opposed to the misuse) of acid base accounting and kinetic test work to assess AMD/ARD potential remains a valuable tool to mine planners. However, it should be viewed in isolation when planning, designing and initiating control measures. Consequently, the authors have proposed that seven key variables require AMD/ARD assessment in the design of control strategies (Ryan and Joyce, 1990). This approach is summarized in the paper.

Saile, L. 1985. Some aspects of sandwiched soil cover design for toxic waste repositories. Engineering Geology, 21 pp. 321-326.

The environmental industry generally favors "dry" waste management systems as compared to the more common practice of shallow land burial. With the former, sandwiched soil covers are usually employed. A double barrier concept is presented and discussed for the sandwiched construction. The critical matrix potentials of the two barrier materials appear to have a significant influence on the performance of the system. Despite some practical problems, the concept appears promising.

Safety of the environment against pollution through seepage and leaching is increased greatly by the dry waste management system. With this technique, unsaturated flow of moisture within the soil cover can be maintained throughout. Therefore, in addition to the more common hydraulic barriers, capillary barriers may also be employed to impede moisture movements. In addition, the combined effect may lead to a double barrier which may be built single-stage or multi-stage, depending on the prevailing circumstances. There is also an added advantage in that a capillary barrier acts as a bio-barrier controlling root penetration and burrowing animals.

Analysis has indicated that the double barrier concept is strongly dependent on the difference between the critical matric potentials of the upper and lower barrier. The hydraulic barrier should preferably be self-sealing, impermeable and with sufficient stability. If the material has a less sharp wetting front (diffusion-type flow) and the capillary barrier is of negligible suction, achievements could be significant.

Scharer, J.M., Garga, V., Smith, R., and Halbert, B.E., 1991. Use of steady state models for assessing acid generation in pyritic mine tailings. Proceedings, Second International Conference on the Abatement of Acidic Drainage, Montreal, Quebec, September 16-18. pp. 211-229

Steady state models have been developed for assessing the oxidation of pyritic minerals and the resulting acidic flux in tailings groundwater. Oxygen transport through the tailings have been regarded as a rate limiting process which depend upon the effective diffusion coefficient of oxygen in the oxidizing zone. The steady state solutions are compared with dynamic solutions obtained by solving second order partial differential equations.

The diffusivity coefficients used in this study were calculated by taking into account the porosity of unconsolidated tailings material. The primary cause of the high sulphate flux in unsaturated tailings is the higher diffusion of oxygen in the pore space. If this pore space is fully occupied with water, as in the case of flooded tailings, the diffusion of oxygen, hence, the sulphate generation rate, is substantially reduced.

Laboratory investigations were performed to determine oxygen uptake and sulphide ore oxidation under various environmental conditions. Of the factors studied, the temperature, pH and the presence of thiobacilli were proven to be the most important. The derived acid flux for unconsolidated, porous tailings depended on the square root of the product of the oxygen diffusive transport and oxygen utilization rate (OUR). The results were applied to determine the acid generation potential at a base metal mining operation in subarctic Canada. As part of the water licensing procedure, the mine operator was required to study the environmental impact of various tailings abandonment options. Of the options considered, submerging the tailings by flooding with fresh water gave the least adverse effects in terms of acid generation and toxic metal (copper, zinc) release.

The steady state models in this study allow for the effects of alternative tailings management strategies on pyrite oxidation to be assessed As with any modelling exercise, the predictions are subject to uncertainties and assumptions. For example, the pyrite oxidation rates reported for the cited base metal mine tailings were derived from short-term laboratory studies. These rates would not be maintained indefinitely under the field conditions.

Scharer, J.M., Kwong, E.C.M., Nicholson, R.V., Petit, C.M., and Chambers, D.W. 1995. Factors affecting ARD production: Kinetics of sulphide oxidation. Proceedings, Conference on Mining and the Environment, Sudbury, Ontario, May 28 - June 1, 1995. pp. 451-458.

The significance of the intrinsic kinetics of sulphide mineral oxidation and acidic rock drainage (ARD) from waste rock has been evaluated. The intrinsic reaction rates were established on a unit surface area basis (mol m^{-2} s^{-1}) and yet depended on the temperature, pH, and oxygen concentration. Kinetic studies with pyrhotite (Fe_{1-x} S) at acidic pH were performed. The sulphide oxidation rate consisted of a biological and an abiological component. The abiological surficial reaction rate ranged from 2.6 x 10^{-9} mol $m^{-2}s^{-1}$ at pH = 4 and 10^{o}C to 3.5 x 10^{-8} mol m^{-2}/s^{-1} at pH = 2 and 30^{o}C. The temperature dependence of the oxidation rate gave an Arrhenius activation energy of 57 kJ mol^{-1}. The biological rate was evaluated assuming a steady state population of chemolithotropic bacteria (Thibacillus ferroxidans) on the sulphide surface and in the pore water. At pH values below 4.0, the reaction rates were consistently higher in the presence of bacteria.

Oxidation and diffusion rates were determined for both fine and coarse (rock) particles by combining the intrinsic kinetic rates with mass transfer. The size dependent rates were then employed in a computer model to simulate acid generation in waste rock piles. Kinetic control was appropriate and better suited for modelling the oxidation of larger particles.

By coupling the fundamental kinetic data with the transport processes the potential dominance of each process in the oxidation of sulphide particles in typical mine wastes could be evaluated. The resulting models, together with the transport equations for oxygen and water flow through the porous matrix of mineral waste deposits, could then be used to predict acid generation under field conditions. The analysis identified the need for the accurate measurement of both the oxidation kinetics and the mass transfer characteristics. Although the application of short-term kinetic data to long-term processes in the field remains to be proven, it is evident that the prediction of sulphide mineral oxidation in the field should include the effect of the combination of kinetic and transport controls as well as the chemical feedback (oxygen concentration, pH, temperature effects) on the oxygen flux, in the kinetic parameters. These modelling results suggest that it is critical to characterize the dimensions of exposed reactive surfaces in mine wastes.

Senft, J.P. and Baker, D.E. 1991. Reclamation of a very acid mine waste site in Pennsylvania, USA. Second International Conference on the Abatement of Acidic Drainage, Montreal. pp. 211-219.

Great strides have been made in mine site reclamation since the passage of the U.S. Mine Reclamation Act of 1977. However, many lands have as yet to be reclaimed in the Eastern U.S.A. Among these, an especially difficult problem is reclamation of very acidic mines.

Reclamation of mines lands can be successful when appropriate attention is given to the conditions necessary for reestablishing vegetation. If optimum water-air-soil relationships are met and optimum essential and nonessential mineral element levels are maintained, good revegetation will develop. While general ranges of conditions for attaining these optima have been established, the unique qualities of a given site require that competent application of the general theoretical principles be applied if successful reclamation is to be attained in a timely, cost effective, and environmentally sound fashion. Methods for determining appropriate air-water-soil relationships have been established. The Baker Soil Test, when combined with other standard soil tests, provides the necessary information for determining soil-plant ion availability relationships. When the desired conditions, indicated by these tests, are met for a specific reclamation site, appropriate plant species for initial and permanent revegetation can be selected.

A demonstration project for reclamation of such a site, with a soil pH of less than 2, was developed cooperatively among the Bureau of Mines, Greenley Energy Holidays, Inc., and Land Management Decisions. The theory of ion availabilities in soil solutions developed by Baker (Baker Soil Test$_{TM}$ (BST), Baker and Amacher, 1981) over the past two decades was applied to develop a surface cover which combined fly ash, agricultural lime, and fertilizer with the mine spoil. Development of good ground cover in conjunction with positive soil and plant analysis results confirmed the effectiveness of the protocol for the development of a synthetic soil without the utilization of valuable top soil. The protocol developed included assessment of the slopes and hydrology of the site, characterization of the synthetic soil by the BS, and assessment of the treatment for short and long term acid neutralization. The protocol permits coal utilization and fly ash disposal in a way which has great economic benefit. In the process, vegetatively nonproductive land is returned to productivity. Summary data which documents successful application of the protocol is presented.

Shelp, G., Southam, G., Spiers, G., Liu, L., and Chesworth, W. 1994. An evaluation of a peat - wood chip - microflora admixture to act as an ameliorant for acid mine drainage. Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage. Pittsburgh, PA, April 24-29, Vol. 2, pp. 356-362.

Peat was investigated as a potential source of indigenous microflora capable of:

(1) Providing a suitable source for sulfate-reducing bacteria (SRB) through the anaerobic degradation of black spruce (Picea mariana) and trembling aspen (Populus tremuloides) wood chips;

(2) Complexing metals to from relatively insoluble sulphide minerals through the reduction of sulfate to sulphide; and

(3) Surviving exposures to extremely acidic conditions.

Enumeration studies, combined with measurements of dissolved organic carbon, indicated that sufficient available carbon was generated by anaerobic degradation of cellulose to support a viable population of SRB. The bacterial systems showed signs of recovery within 2 to 3 weeks following acidification to a pH of 3.0. The re-establishment of active microbial systems was indicated by the formation of a black iron sulphide precipitate.

Shikatani, K.S., and Yanful, E.K. 1993. An Investigation for the design of dry covers for mine wastes. CIM Metsoc Meeting Symposium, Aug. 30 -Sept. 1.

The most important environmental problem facing the mining industry today is the generation of acidic drainage from sulphidic waste piles and tailings impoundments. Collection and treatment costs associated with the management of this drainage can be significant and a long term liability. Engineered dry covers provide effective means of reducing acid generation from mine wastes. The principal function of these covers is to minimize the transport of oxygen and water into the underlying tailings or waste rock. The two key parameters that give an indication of the ability of a soil to fulfill this function are oxygen diffusion characteristics and hydraulic conductivity.

This paper describes the laboratory techniques used in the evaluation of candidate cover materials (Heath Steele till, Waite Amulet till, Yukon till). Results obtained from the assessment of composite dry cover materials involving clays, tills and sand-bentonite mixtures are also presented and discussed.

The study consisted of an evaluation of the pertinent geotechnical properties, a determination of gaseous oxygen diffusion coefficients and measurements of oxygen fluxes through nearly saturated candidate soils. The geotechnical properties investigated include grain size distribution, moisture-density relationships, liquid and plastic limits. The soils were evaluated for their ability to retain moisture under various draining conditions in the laboratory.

From the data presented, it was possible to design a soil cover capable of reducing water infiltration and oxygen diffusion into sulphide-bearing mine wastes. It was found that a three-layer system incorporating a fine grained soil placed between coarse grained soils would be effective in minimizing sulphide oxidation and acid generation.

The methods described in this paper enable suitable candidate soil materials to be selected. In addition oxygen diffusion and fluxes can be determined for prediction of long-term cover performance.

Steffen, Robertson and Kirsten (B.C.) Inc. 1991. Acid Rock Drainage Remediation at Four Norwegian Mines. pp. 62.

The purpose of this report is to transfer the recent Norwegian experience and technology on the remediation of acidic rock drainage (ARD) at four sulphide mines in Norway to Canada and to provide an opinion of the immediate and long term effectiveness of the remediation measures to the Norwegian State Pollution Control Authority. The sulphide mines were: 1) Kjoli mine 2) Skoravas mine 3) Lokken mine and 4) Killingdal mine. In general the scope of the study was to provide a review of construction procedures, costs and effectiveness and to evaluate the applicability of this projects to Canadian mines.

Strachan, C. 1994. Covering tailings - Some theoretical and practical aspects. Tailings and Mine Waste '94. Balkema, Rotterdam, pp. 189-193.

Tailings undergo a significant change in stress regime, density, and shear strength at the end of the operating life of a tailings impoundment. The solids that at one time are settling out of an aqueous slurry may later support the weight of construction equipment and other materials. These materials change by consolidation as a result of the stresses imposed by fill placement and reduction in pore water pressures within the tailings.

The measures selected for tailings covering are primarily a function of the stress and consolidation history of the tailings. In some cases, climatic conditions and time since operation have allowed the tailings for covering. At other sites, climatic conditions and shorter periods since operation require thick lifts of fill or special equipment, methods or geotextiles to cover the tailings without significant tailings displacement.

In addition to the immediate effects of tailings covering, significant tailings settlement can have an effect on cover cracking and final slopes. Tailings settlement is primarily dependent on the thickness of the tailings, the method of impoundment operation, and the stress and consolidation history of the tailings.

This paper discusses the theoretical and practical aspects of these tailings covering issues. Although many factors affecting tailings covering and reclamation are site-specific, there are a few general principles that have been observed from reclamation experience. These include an understanding of the tailings characteristics and stress history, and adapting reclamation methods to meet these conditions.

Suter II, G.W., Luxmore, R.J., and Smith, E.D. 1993. Compacted soil barriers at abandoned landfill sites are likely to fail in the long term. Journal of Environmental Quality, Vol. 2, No. 2, pp. 217-226.

At innumerable sites in the U.S.A and around the world, buried waste has been isolated from the environment by barriers constructed entirely or in part of compacted soil. The chief concern in barrier design has been to isolate the waste in the short term by preventing movement into and through the waste. However, in the long term, a variety of mechanisms can act to compromise this isolation. The mechanisms of long-term failure include initial flaws in barrier construction, shrink-swell cycles, freeze-thaw cycles, erosion, subsidence, root intrusion, and small animal intrusion. Evidence of action for all of these mechanisms is summarized.

Clearly, natural phenomena, both physical and biological, may cause long-term failure of earthen barriers. To avert adverse consequences of the failure of earthen liners and caps, monitoring and maintenance of inactive hazardous waste burial sites should be continued indefinitely (not just 30 yr). A few jurisdictions (e.g., State of Wisconsin in a law passed in 1979) have established trust funds to cover the cost of remedial measures in the event of failures at regulated waste facilities following the required care period. The Federal Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) of 1980 provided for a study on the possible establishment of such a funding mechanism for federally permitted hazardous waste facilities, but the Post-Closure Liability Trust Fund discussed in the Act was never established.

The following measures should be considered to reduce adverse consequences from barrier failures:

(1) 0.15 m of soil cover with a low-permeability infiltration barrier should be regarded as bare minimum criteria; and

(2) Infiltration barriers should be covered by a soil layer sufficiently thick to extend below the frost line and to accommodate the typical rooting depths of native plants expected to invade the site (i.e., at least 3 m in most areas). This has been recommended previously (Lutton et al., 1979) but is seldom practiced.

Swarbrick, G.E., and Fell, R. 1992. Modelling desiccating behavior of mine tailings. Journal of Geotechnical Engineering, ASCE, Vol. 118, No. 4, pp. 540-557.

A one-dimensional model of the sedimentation and desiccation of high clay content, subaerially deposited tailings is described. The method employs both geomechanical and soil physics principles. The approach is semi-empirical and predicts the average density and water content of a layer of tailings during sedimentation, first stage-evaporation, and finally second-stage evaporation when desiccation occurs. Five tailings are analyzed, and model parameters are determined for each. The laboratory equipment developed to provide parameters for analysis and the methods used to obtain model parameters for other tailings are described. Comparisons of recent experimental field data and the predictive model show good agreement. The model allows the effects of different initial layer depths, different initial water contents, and different available evaporation potentials to be compared with total drying time and resulting final dry density. Some examples of this are also shown in this paper.

Swanson, D.A., 1993. Desiccation of soil covers - Processes and Prediction. A Project Work submitted to fulfill the course requirements in "New Developments in Geoenvironmental Engineering", offered by M.D. Haug at the University of Saskatchewan.

Soil covers are being used as the decommissioning option for many mining and landfilling operations. In addition to minimizing the infiltration into the waste, the successful covering of wastes can also limit the diffusion of oxygen into acid generating waste and limiting the diffusion of radon from uranium tailings into the atmosphere. Limiting the diffusion processes requires that the cover maintain a high degree of saturation.

Desiccation is a process that has a major impact on the integrity of a soil cover. The process is characterized by drying and potential cracking in the soil cover. Numerical models have been developed that simulate drying in a soil based on the processes of heat and mass transfer and soil-atmosphere coupling. Such models can be used to assess the long term performance of a soil cover by predicting the variations in water content in the cover with time. Such information can be used to evaluate the performance of a soil cover based on the cover's ability to maintain a high degree of saturation and to exhibit minimal volumetric shrinkage strain that can result in potential cracking, which can in turn effect both degree of saturation and infiltration rates.

This paper describes the processes involved in the desiccation of soil covers and the technologies being developed to model both drying and cracking processes. Emphasis is put on the application of predictive technology for the evaluation of the long term performance of soil covers.

Swanson, D.A., Barbour, S.L., Wilson, G.W., and O'Kane, M. 1995. Modelling the performance of an engineered soil cover for acid generating mine waste. Paper presented at Sudbury '95, Conference on Mining and the Environment, Sudbury, Ontario, May 28th - June 1, 1995.

Soil covers are often used as a closure option for the decommissioning of acid generating mine waste. The objective of the cover is to reduce the influx of water and oxygen into the waste material in an attempt to limit the acid generating process. Predicting the performance of an existing soil cover or evaluating various design options is of interest to both facility owners and regulatory agencies. Mine owners must provide effective and economical decommissioning strategies, and regulatory agencies must be able to assess these decommissioning strategies to determine their effectiveness and acceptability.

Prediction of cover performance involves both field monitoring and numerical modelling efforts. Field monitoring of the responses of the in-place cover (i.e., net infiltration and variations in degree of saturation) is required as a direct evaluation of the cover performance. Numerical modelling techniques can then be utilized to predict the future performance of the cover system under extreme climatic conditions. The ability of the model to adequately describe field conditions must first be demonstrated before predictions regarding future performance can be made.

The numerical model "SoilCover" developed under the MEND (1993) program has been used to evaluate an in-place cover system over mine waste rock at the Equity Silver Mine located in British Columbia, Canada. Examples from this analysis are used to illustrate the modelling process in this paper.

Swanson, D.A., Barbour, S.L., Wilson, G.W. 1995. The modelling of moisture movement in engineered soil covers for mine waste rock dumps. Phase II of a Cover Modelling Research Program.

A two-phased cover instrumentation and modelling research program has been initiated at a waste rock dump site. The first phase of the research program involves field instrumentation and monitoring of the inplace cover. The second phase involves modelling infiltration and evaporation in the cover system using a soil-atmosphere flux model that has been developed at the University of Saskatchewan. The soil-atmosphere model used is a one dimensional, transient, finite element, water and heat transport model that uses a physically based method to predict the exchange of water between the atmosphere and a saturated or an unsaturated soil surface. This paper describes the application of the soil-atmosphere model in predicting the field responses of in-place cover system at a waste rock dump site.

Swanson, D.A. 1995. Predictive modelling of moisture movement in engineered soil covers for acid generating mine waste. M.Sc. Thesis. Dept. of Civil Engineering. University of Saskatchewan, 241p.

Engineered soil covers are often used as a closure option for the prevention of acid mine drainage from waste rock dumps and tailings facilities. The primary purpose of a cover system for acid generating mine waste is the prevention of both water and oxygen flux into the sulfide bearing waste.

The ability to evaluate various design options and to predict the future performance of in-place cover systems is of interest to both mine owners and regulatory agencies. Mine owners must be able to develop effective and economical decommissioning strategies. Furthermore, regulatory agencies must be able to assess these decommissioning strategies to determine their effectiveness and acceptability.

The research presented in this thesis describes the evaluation and application soil-atmosphere cover model, SoilCover (MEND 1993), as a tool for predicting the movement of moisture in engineered soil covers for acid generating mine waste. The research represents the second phase of a cover instrumentation and modelling research program. SoilCover is a one-dimensional, finite element, water (liquid and vapor) and heat transport model that couples the atmospheric supply and demand of moisture to moisture movement within the soil profile. The model was developed at the University of Saskatchewan through the Mine Environmental Neutral Drainage program (MEND). Two sites were selected in order to evaluate the model for a wide range of climatic conditions and cover designs. A compacted glacial till cover constructed on a waste rock dump at the Equity Silver Mine located in north-central British Columbia, Canada, was selected to represent wet site conditions. A layered top soil and oxidized waste rock cover constructed on a waste rock dump at Golden Sunlight Mine located in southwest Montana, USA, was selected to represent arid site conditions.

Characterization of the wet site cover material and field responses (i.e., the variation in matric suction, moisture storage, and soil temperature) was carried out during phase one research by O'Kane (1995). Computed and measured field responses for the wet site revealed good agreement for a five month period from June to November, 1993. Calibration of the soil hydraulic properties to field conditions was required for the evaluation. The wet site cover system was designed to function as a moisture and oxygen barrier and relies on low hydraulic conductivity and high moisture retention characteristics to provide these capabilities. Predictive modelling revealed that the cover system performed well under extreme climate conditions. Moisture flux through the cover should not exceed 21 mm per year for an extreme wet year (i.e., 3% of extreme wet year precipitation). Oxygen flux through the cover, under extreme dry conditions, should be reduced by 98% from uncovered conditions.

Field responses for the arid site were well characterized in a reclamation monitoring program carried out by Schafer Associates (1994). Characterization of the arid site cover materials was carried by Yazdani (1995). Computed and measured field responses for the arid site (i.e., variations in moisture content and moisture storage) revealed good agreement for two seven month periods during 1992 and 1993. Calibration of the saturated hydraulic conductivity of the cover materials and waste rock, as well as the vegetative parameters was required for the evaluation. The arid site cover system is designed to function as a moisture barrier and relies on moisture retention and vegetation to provide these capabilities. Predictive modelling revealed that the cover system performed well with regard to limiting moisture flux under extreme and mean climate conditions. There will be zero moisture flux through the cover, for extreme wet conditions assuming a full snowpack development, should not exceed 35 mm (i.e., 7% of extreme wet year precipitation). Oxygen flux through the cover, under extreme dry conditions, should be reduced by approximately 30% from uncovered conditions.

Szymanski, M.B., and MacPhie, H.L., 1994. Approach to closure designs for mine sites with severe AMD. Proceedings of the First International Congress on Environmental Geotechnics, Edmonton, Alberta, pp. 569-576.

The approach to closure for mine sites with severe acid mine drainage (AMD) is discussed from the practitioners perspective. Designing for mine closure is a relatively new discipline and there is a need to exchange the experience gained from actual mine closure design projects. The paper focuses on those aspects of the approach to closure designs which are characteristic of mine sites with severe AMD. The need for a site specific approach to closure designs and for investigations of all plausible closure design options is discussed and emphasized throughout the paper.

Tratch, D. 1995. A geotechnical engineering approach to plant transpiration and root water uptake. M.Sc thesis. Department of Civil Engineering, University of Saskatchewan.

In recent years, the field of geotechnical engineering has identified the significance of the surface mass flux boundary condition on the soil water flow conditions through the vadose zone of the soil profile. This thesis investigates the soil surface flux which is directly a result of the vegetative cover in the form of transpiration. Application of transpiration theory may be extended to any geotechnical engineering problems which involves vegetated surfaces. Typical applications include moisture redistribution evaluation for volume change and stress analyses, contaminant transport and evaluation of the performance of soil over hazardous waste site.

Historical literature on the available methods to predict transpiration and root water uptake were consulted. Methods available varied between highly empirical method which lack accuracy, to physically based methods which are too complicated for practical use. A semi-empirical method of evaluating the transpiration rate by the potential evaporation rate, degree of vegetative cover and matric suction profiles through the root zone was determined to be reasonable for use by geotechnical engineers. The method was incorporated into an existing one-dimensional heat and mass transfer, finite element computer program named SoilCover (MEND 1993).

A laboratory program was conducted to measure the evapotranspiration flux rate from a vegetated soil column placed in an environmental chamber. The surface of the soil column and the soil column profile were instrumented for matric suction, temperature and manual water content determinations. Climatic variables measured in the environmental chamber included pan evaporation rates, evaporating pan and ambient temperature, and ambient relative humidity.

Data from the laboratory program were used to verify the proposed methodology to predict transpiration. As well, a field data set from the Matador Site Program, was used to verify the predictive methodology using typical field data. In both cases, the analytical solution provided by SoilCover was in agreement with the measured data trends. The predictive methodology appears to be a simple method with variables which are relatively easy to define and measure. The most difficult factor in the predictive methodology involves the definition of the boundaries of the active root zone. In the laboratory program, the upper limit of the active root zone did not perform in a reproducible fashion. In addition, the field data simulation results show the lower root boundary behaves in a relatively unpredictable manner. However, the active root boundaries could be calibrated using measured surface flux and water content profiles for both the laboratory and field cases. Relatively minor changes to the definition of the active root zone resulted in significantly modified results for both data sets. The unpredictable behavior of the active root zone is of particular concern to predictive modelling attempts, if a detailed data set is not available.

In summary, this thesis demonstrates the ability to incorporate knowledge based theories which were developed by soil scientists. With this knowledge, geotechnical engineers can be successful in providing analytical solutions to the problem of the surface flux transpiration boundary condition.

Tratch, D.J., Wilson, G.W., and Fredlund, D.G. 1995. The prediction of moisture uptake in the root zone due to transpiration for problems in geotechnical engineering. 48th Geotechnical Conference, Vancouver, B.C., pp. 771-780.

Historically, geotechnical engineers have been concerned with groundwater flow, particularly within the saturated zone. More recently, geotechnical engineers have identified the importance of unsaturated flow and the flux boundary condition with respect to water flow across the soil atmosphere interface. Plant transpiration is an important component of the surface flux rate.

This paper outlines a theoretical approach for the prediction of transpiration rates. A laboratory experiment was conducted to measure evapotranspiration rates and analytical modelling was performed to simulate the laboratory data. The experimental results identify the significance of including the transpiration flux in the surface boundary condition. The analytical modelling results show the proposed methodology for the prediction of transpiration to be reasonably accurate.

Tremblay, R.L. 1994. Controlling acid mine drainage using an organic cover: The case of the East Sullivan Mine, Abitibi, Quebec. Paper presented at the International Land Reclamation and Mine Drainage Conference and the Third International Conference on the Abatement of Acidic Drainage, Pittsburgh, PA, April 24-29, 1994. Vol. 2, pp. 122-127.

The East Sullivan site holds 15 million tonnes of tailings which generate significant acid mine drainage. The tailings pond covers a surface area of 150 hectares, and spillage extends over an additional 70 ha. The interstitial water at the centre of the pond is characterized as follows: pH = 2.3, Cu = 261 ppm, Zn = 23 ppm, SO_4 = 13,500 ppm, and Fe = 3200 ppm.

In order to stop acid drainage from being generated, plans have been made to cover the entire tailings pond with an organic blanket comprised of two metres of softwood and hardwood bark. This type of covering has proven effective in preventing oxygen from reaching the tailings. A grass cover planted on top of the bark will reduce water seepage. Sludge from municipal waters treatment plant is incorporated into the first 30 cm of the organic material as a conditioner and then seeded. A containment dike will be built around the entire site (6 km) to divert fresh water and carry drainage from the pond to a water treatment system. The containment dike will be completed within the next three years, and the water treatment system should be operational the following year.

Since the initial cover has been placed, oxygen concentrations have been dropped from 16.1% near the surface to less than 1.5% some 70 cm below it, while the CO_2 concentrations at the same depth rose from 8.2% to 50.8%. Studies have shown that some organic contamination results from bark decomposition. Phenol and tannin concentrations of 5.7 ppm and 95 ppm, respectively have been measured to date. Tests are under way to determine the best passive treatment system for controlling both organic and mineral contamination caused by the tailings. A multimedia filter was installed a year ago and work will begin this year on experimental wet lands.

The ultimate objective of the East-Sullivan mine site reclamation plan is to abandon the site as quickly as possible in an environmentally benign manner. So far, 30% of the mine site is under organic cover and the remaining 70% should be covered within five years at most.

Troeh, F.R., Jabro, J.D., and Kirkham, D. 1982. Gaseous diffusion equations for porous materials. Geoderma, Elsevier Scientific Publishing Company, Amsterdam. Vol. 27, pp. 239-253.

Commonly used equations of gaseous transport by diffusion are examined and the two parameters required for each equation are obtained from the literature. The advantages and limitations of the commonly used linear $D/D_o = a(S-b)$ and curvilinear, $D/D_o = KS^m$ equations are considered and a new diffusion equation is proposed to combine the advantages of the previous equations. This new equation, like the others, requires only two parameters. It takes the form $D/D_o = [(S-u)/(1-u)]^v$ and may serve as a basis for studying and more accurately modelling gas transport in porous media.

Waugh, W.J., Thiede, M.E., Bates, D.J., Cadwell, L.L., Gee, G.W., and Kemp, C.J. 1994. Plant and Environmental Interactions: Plant cover and water balance in gravel admixtures at an arid waste-burial site. Journal of Environmental Quality, Vol. 23, No. 4, July-August 1994, pp. 676-685.

Isolation of radioactive waste buried in unsaturated zones will require long-term control of recharge and erosion. Soil covers control recharge at arid sites by storing rainwater close enough to the surface to be removed by evapotranspiration. Surface layers of rock or gravel control erosion at sites with sparse vegetation can alter plant habitat and cause recharge through interred waste. As an alternative, gravel mixed into the uppermost soil layer may control erosion over the long-term better than surface gravel layers. The authors postulate that gravel admixtures would not influence plant establishment or soil water balance in waste site covers. They measured the interactive effects of gravel admixture concentration, vegetation, and precipitation on soil water content and plant cover at the U.S. Department of Energy's Hanford Site in Washington state.

Coupled with the results of erosion studies (Finely et al. 1985; Ligotke and Klopfer, 1990) and lysimeter studies of soil water balance (Waugh et al. 1991), authors data favor the use of gravel admixtures as an alternative to surface gravel layers for controlling erosion on waste sites in arid regions. Gravel can be mixed into the uppermost soil layer without influencing vegetation establishment or the water balance of waste-site covers. Admixture designs should be tailored to local site conditions. Consideration should be given to site geometry, soil and gravel physical properties, plant ecology, and possible long-term changes in these factors. Tools such as tractive shear stress analyses (Temple et al., 1987) and physical models can be used to help determine permissible slope lengths and gradients for site specific soils and climate.

Authors data also illustrate the important role vegetation plays in controlling water storage and recharge on waste site. With vegetation present, soil water storage was consistently depleted to an annual lower limit even under conditions of twice the average precipitation. Without vegetation, soil water continued to rise annually even at depths greater than 200 cm, a leading indicator of recharge (Gee et al., 1992). Choice of plant species is important to accelerate development of vegetation that maximizes soil water extraction (Anderson et al., 1993).

Webb, J. A. and Sasowsky, I. D. 1994. The interaction of Acid Mine Drainage with a carbonate terrain: Evidence from the Obey River, north-central Tennessee. Journal of Hydrology 161, pp. 327-346.

The production of acidic drainage from active or abandoned coal mines is controlled by a complex series of reactions triggered by the oxidation of sulphide minerals. Limestone is frequently used as a neutralizing agent. Neutralization occurs both through dissolution of the limestone and exsolution of carbon dioxide from the water.

A demonstration of these processes in a natural system is provided by the East Fork of the Obey River where acidic mine waters travel through conduits in limestone bedrock for several kilometers. Application of the discharge-concentration relationships allow for the tracking of the evolution of these waters within the karst aquifer. Several trends are evident. Virtually all of the iron in the acid mine drainage is precipitated along the flow path within the limestone, the H^+ released during this reaction, together with the H^+ generated by pyrite oxidation, is largely neutralized by both exsolution of CO_2 and dissolution of calcite/dolomite in the carbonate bedrock (releasing calcium and magnesium). Nevertheless, the pH is still sufficiently low that all bicarbonate is converted to carbonic acid. The leaching of clay minerals by the acidic water releases small amounts of Al and Si. The species Cl^-, F^-, and NO_3^- are however more or less inert. The sulphate concentration substantially increases during the evolution of acid drainage. This seems to be related to an input of sulphate-enriched water that has dissolved gypsum/anhydrite as it follows deep flow paths within the limestone.

Calculations of the relative proportions of H^+ removed by reaction with calcite/dolomite and CO_2 degassing show that the latter is important in acidic water that has reacted significantly with limestone and can readily lose CO_2 to the atmosphere. These results indicate that acid neutralization through carbonic acid dissociation, in addition to neutralization through dissolution of carbonates, is a useful method for the commercial abatement of acid mine drainage.

(Note: This paper provides a good review of the geochemistry of acid mine drainage.)

Wilson, G.W., Barbour, S.L., Swanson, D., and O'Kane, M. 1996. Instrumentation and modelling for saturated/unsaturated performance of soil covers on acid generating waste rock.

A research programme involving field instrumentation, laboratory testing and numerical modelling for the evaluation of soil covers installed on waste dumps at two mine sites in Canada and the United States, has been reviewed in this paper. One site is located in a humid environment, and the other site is situated in an arid climate. The objective of the research was to evaluate the performance of soil covers with respect to water and oxygen fluxes. A newly developed soil-atmosphere flux boundary model was used to predict mass transport rates. The analysis showed that the cover constructed at the humid site functions as an oxygen and infiltration barrier. The cover at the arid site reduces infiltration reduces to values approaching zero.

Wilson, G.W. and Barbour, S.L. 1995. The prediction of evaporative fluxes from unsaturated soils surfaces. First International Conference on Unsaturated Soils, Paris, France.

The analysis of problems such as volume change in expansive soils or groundwater flow through saturated/unsaturated soils requires an evaluation of the flow of moisture between the soil surface and the atmosphere. This paper presents a theoretical approach for the evaluation of soil evaporative fluxes from unsaturated soil surfaces on the basis of potential evaporation and total suction at the soil surface.

Soil evaporation tests were conducted in the laboratory for sand, silt, and a highly plastic clay. Saturated soil surfaces evaporate at a rate approximately equal to the potential rate. The rate of evaporation begins to decrease when the values of suction exceed approximately 3000 kPa and the rate continues to decrease as suctions increase. The actual rate of evaporation was found to be a function of total suction for all three soil types. This suggests that the theoretical method of computing evaporation for the columns can be used for other soil types such as silt and highly plastic clay.

Wilson, G.W., Fredlund, D.G., Barbour, S.L. 1991. The evaluation of evaporative fluxes from soil surfaces for problems in geotechnical engineering. Proceedings: 44th Canadian Geotechnical Conference.

Evaluation of the flow of water across the soil-atmosphere boundary is an essential component in the analysis of many problems in geotechnical engineering. For example, the design of soil covers systems as oxygen barriers for the long-term closure of sulphitic mineral tailings requires accurate prediction of moisture fluxes between the cover surface and the atmosphere. The flow of water across the ground surface is also important for problems in classical soil mechanics. These include the analysis of pore water pressure for slope stability analysis and the prediction of volume change in expansive soils.

The flow of water across the soil-atmosphere boundary occurs as two separate processes. Liquid water due to precipitation enters the soil below the ground surface through the process of infiltration. Alternately, water vapour leaves the ground surface through the process of evaporation. The physics of liquid flow during infiltration has been widely discussed in the literature and many suitable methods of analysis are available. However, the physical processes which govern evaporation from soil surfaces are poorly understood. Extreme difficulties are encountered when attempting to predict evaporation from unsaturated soil surfaces.

The traditional methods of evaluating evaporation from a theoretical basis provide only an estimate of potential evaporation. These methods assume that the evaporating surface is fully saturated. This approach is appropriate for predicting evaporative rates from ponds and water reservoirs. However, actual rates of evaporation from unsaturated soil surfaces are often much less than the potential rate of evaporation. A mechanistic approach for predicting evaporation from unsaturated surfaces that is suitable for applications in geotechnical engineering is not available in the literature. Several empirical methods for estimating evaporation from unsaturated soil surfaces are available; however, the reliability and accuracy of these methods are questionable.

This paper presents a theoretical model for predicting the rate of evaporation from unsaturated soil surfaces. The theory is founded on the well-known principles of Darcy's Law and Fick's Law to describe the flow of liquid water and water vapour in the soil below the soil-atmosphere boundary. Dalton's Law and a modified Penman formulation are used to describe water vapour transfer above the soil-atmosphere boundary.

A column evaporation test was carried out in the laboratory. The laboratory test results have shown that evaporative fluxes from a soil surface are controlled by the soil suction at and below the soil-atmosphere boundary. Furthermore, soil evaporative fluxes are also strongly dependent on groundwater conditions and the flow properties of the soil.

The theoretical model for soil evaporation was then used to simulate the evaporative fluxes measured from the soil columns during the laboratory evaporation test. The theoretical model provided good agreement with the evaporative fluxes measured in the laboratory over a six week test period.

Wilson, G.W., Fredlund, D.G., Barbour, S.L. 1994. Coupled soil-atmosphere modelling for soil evaporation. Canadian Geotechnical Journal, Vol. 31, pp. 151-164.

Traditional methods of evaluating evaporation provide an estimate of the maximum or potential rate of evaporation determined on the basis of climatic conditions. Methods such as these are appropriate for open water or fully saturated soil surfaces. Actual rates of evaporation from unsaturated soil surfaces are generally greatly reduced relative to the potential rate of evaporation. A theoretical model for predicting the rate of evaporation from soil surfaces is presented in this paper. The model is based on a system of equations for coupled heat and mass transfer in soil. Darcy's Law and Fick's Law are used to describe the flow of liquid water and water vapour, respectively. Heat flow to the atmosphere is based on the suction at the soil surface. The soil-atmosphere model was used to predict soil evaporation rates, water-content profiles, and temperature profiles for a controlled column evaporation test over a 42 day period. The values computed by the soil-atmosphere model agreed well with the values measured for two columns of Beaver Creek sand in a laboratory evaporation test.

Wilson, G.W., Machibroda, R.T., Barbour, S.L., and Woyshner, M.R. 1993. Modelling of Soil Evaporation from Waste Disposal Sites. 1993 Joint CSCE-ASCE National Conference on Environmental Engineering, Montreal, July 12-14, Vol. 1, pp. 281-288.

The production of leachate from waste disposal sites such as mine tailings or domestic landfills depends on the net infiltrative water flux across the surface of the site. Soil cover systems are frequently used in the closure of waste disposal sites to control water fluxes at the ground surface. The design and performance of soil cover systems depends on the ability to predict net infiltrative fluxes under various climatic events. The net infiltrative fluxes at the ground surface are controlled by climate conditions such as precipitation and evapotranspiration along with the characteristics of the surface. Evaporative fluxes are difficult to predict in that soil evaporation is a coupled process which depends on both atmospheric conditions and soil properties such as soil water potential at the ground surface, hydraulic conductivity and groundwater conditions.

Numerous methods of calculating evaporation are available. The vast majority of these methods provide only an estimate of potential evaporation. The actual rate of evaporation from unsaturated soil surfaces is generally much less than the potential rate of evaporation. A modified Penman method for the prediction of actual soil evaporative fluxes is proposed in this paper. The modified formulation calculates soil evaporative fluxes on the basis of the actual vapor pressure at the soil surface and coupled heat and mass transfer processes in the soil profile below the soil-atmosphere boundary.

The actual soil evaporative fluxes from a large nonvegetated surface of mine tailings are calculated using the modified Penman formulation for a period of several weeks during the summer months. The predicted soil evaporative fluxes are compared with the evaporative fluxes evaluated by the measured Bowen Ratio energy balance method. The soil evaporative fluxes computed using the Modified Penman formulation agree reasonably well with the values of actual field evaporation measured using the Bowen Ratio method.

Wilson, G.W. 1995. Assessment of protective covers and dump behavior. In, Proceedings of the 2nd Australian Acid Mine Drainage Workshop, Charters Towers, Australia, March 28-31, 1995.

A research program involving field instrumentation, laboratory testing and numerical modelling for the evaluation of soil covers installed on waste dumps at mines sites in Canada and the United States, has been completed. One site is located in a humid environment, while, the second site is situated in an arid climate. The objective of the research was to evaluate the performance of soil covers with respect to water and oxygen fluxes. A newly developed soil-atmosphere flux boundary model was used to predict mass transport rates. The analysis shows that the cover installed at the humid site functions as an oxygen and infiltration barrier. The cover at the arid site reduces infiltration to values approaching zero.

Excavation of a large section of the waste dump (15 Mt) at the arid site has also been carried out. The dump was found to be well structured with respect to particle size distribution. This structure appears to strongly influence the heat and mass transport processes within the dump.

Wing, N.R. and Gee, G.W. 1994. Quest for the perfect cap, Civil Engineering.

Engineers and scientists at the Department of Energy's Hanford site in Washington believe they have developed a maintenance free waste site surface barrier made from natural materials that will last for 1,000 years. They are ready to monitor a 5 acre prototype recently constructed over a decommissioned waste water disposal facility. If it performs as expected, this cap could have a significant impact on waste disposal systems nation wide.

Wong, L.C. and Haug, M.D. 1991. Cyclical closed-system free-thaw permeability of soil liner and cover materials. Canadian Geotechnical Journal, Vol. 28, pp. 784-793.

The impact of closed system freeze-thaw cycles on the permeability of clay, till, and sand-bentonite mixtures was examined in a laboratory test program. The bentonite content of the sand-bentonite mixtures varied from, 4.5 to 25%. Test samples were prepared by dry mixing, moisture conditioning, and compacting materials according ASTM D698, method A specifications. The molding water content of these samples was at or slightly wet of optimum. Trimmed test samples were placed in a triaxial permeameter and their unfrozen or initial permeability was established. These permeability tests were conducted for approximately 10,000 min. using low hydraulic gradients and confining stresses. Changes in specimen volume were also measured during the permeability test. This process of alternating permeability tests with freeze-thaw cycles was continued until the change in permeability between the freeze-thaw cycles became insignificant. The following results were obtained from this test program:

(1) The permeability of the clay liner material increased significantly with increasing numbers of closed system freeze-thaw permeability cycles. The rate of this increase diminished with additional freeze-thaw cycles.

(2) The permeability of the till liner material increased with the number of cycles due to closed system freezing and thawing; however, the increase in permeability occurred

primarily during the first freeze-thaw cycle. The magnitude of the permeability increase for the till and the degree of continued permeability increase with freeze-thaw cycles was less than that for the clay.

(3) Closed system freeze-thaw cycles were found to have no deleterious effect on the permeability of compacted Ottawa sand and sodium bentonite. These samples contained bentonite concentrations varying from 4.5% to 25% and were confined under an average vertical effective stress of 17.5 kPa.

(4) The permeability of the 6% bentonite and Ottawa sand specimen after five freeze-thaw cycles was approximately equal to the long-term permeability (over 120, 000 min.) of a second identical unfrozen specimen.

(5) The inclusion of up to 25% bentonite (particles smaller than 0.02 mm in diameter) in an Ottawa sand matrix did not increase frost susceptibility in this test program.

(6) Flexible and fixed wall sample confinement produced similar results during freeze-thaw triaxial permeability tests conducted on sand-bentonite specimens.

Woyshner, M.R. and Yanful, E.K. 1993. Hydrologic analysis and prediction in a soil cover. 1993 Joint CSCE-ASCE National Conference in Environmental Engineering. July 12-14, Montreal, Vol. 1, pp. 289-296.

A 3-layer soil cover constructed on acid producing tailings was evaluated for its long-term ability to retain high water saturation and low hydraulic conductivity. The Hydrologic Evaluation of Landfill Performance (HELP) model and a finite-element flow model (SEEP/W) were applied and the results corroborated with field measurements of percolation and soil water content.

The HELP Modelling showed that approximately 58% of the 904 mm of average annual precipitation evaporates and 16% runs off. The amount available for subsurface flow is therefore 240 mm per year or 26% of precipitation. Using that value as a surface boundary condition in SEEP/W flow modelling, it was determined that 34.4 mm would percolate through the cover. HELP modelling determined that 39 mm would percolate through the cover. The modelling exercises therefore predicted that 4% of precipitation infiltrates and percolates through the cover. Both modelling methods also indicated that the sand base will drain and the clay will remain at a high degree of water saturation. Two years of monitoring data confirm the modelling results. Field lysimeter measurements indicate that approximately 6% of precipitation infiltrates and percolates the cover. These results suggest that a properly designed and constructed soil cover can reduce acid production in reactive tailings.

Woyshner, M.R. and Yanful, E.K. 1995. Modelling and field measurements of water percolation through an experimental soil cover on mine tailings. Canadian Geotechnical Journal, Vol. 32, pp. 601-609.

A composite soil cover constructed on acid producing tailings was evaluated for its ability to retain a high degree of water saturation and low hydraulic conductivity. The cover consisted of a 60 cm thick, compacted, nearly saturated, varved clay placed between two sand layers, each 30 cm thick. A final 10 cm thick gravel layer was placed on the upper sand layer to minimize erosion. The Hydrologic Evaluation of Landfill Performance

(HELP) model and a finite-element flow model (SEEP/W) were applied. The results corroborated with field measurements of percolation and soil water content.

The HELP model was used to evaluate the effectiveness of the cover at four meteorological stations surrounding the site within a 400-500 km radius. The HELP modelling showed that approximately 56% of average annual precipitation evaporates and 11% runs off. The amount available for subsurface flow is therefore 33% of precipitation. Using 33% of the precipitation at Amos, Quebec, as a surface boundary condition in saturated-unsaturated flow modelling, it was determined that 34.4 mm of water would percolate through the cover. HELP modelling determined that 38 mm would percolate through the cover. The modelling exercises predict that 4% of precipitation percolates through the cover. Both modelling methods also indicate the sand base will drain and the clay will remain at a high degree of water saturation. Four years of monitoring data confirm the modelling results. Field measurements of hydraulic conductivity over 3 years did not reveal any increase in the hydraulic conductivity of the clay (Yanful et al. 1993). These results suggests that a properly designed and constructed soil cover can reduce acid production in sulphide-bearing mine tailings located in the region of eastern Ontario and western Quebec.

The modelling and field experiments were conducted with a nonvegetated cover; therefore, the effect of revegetation was not evaluated. Reclamation of tailings ponds using soil covers may, however, require the inclusion of sustainable vegetation. This could affect the overall water percolation and should be considered in the analysis.

Yanful, E.K. 1991. Engineered soil covers for reactive tailings management: Theoretical concept and laboratory development. Proceedings: Second International Conference on the abatement of acidic drainage. September 16-18, Montreal.

A preliminary assessment of the performance of engineered soil covers with respect to oxygen transport in sulphidic mine tailings was undertaken through laboratory experiments and computer modelling. Oxygen transport through fine grained soil covers on reactive sulphide tailings is mainly by molecular diffusion thorough gas-filled pores. If these covers are placed in a nearly saturated state, resulting oxygen fluxes can be expected to be very low and will lead to reduced acid production in the covered sulphide tailings.

Empirical relations between the diffusion coefficient and moisture saturation were reviewed. The grain size and pore size distributions and the moisture-pore pressure and moisture-hydraulic conductivity relationships were shown to be critical for determining the hydraulic behavior and diffusion coefficients of saturated soil covers.

The capillary barrier concept is discussed and evaluated in laboratory column experiments using candidate soils from two Canadian mine sites (Heath Steele and Yukon). Observed moisture contents and pressure heads indicated that saturated, fine grained soils placed over coarse grained layers will remain saturated for about 100 days when the coarse layer has drained to its residual water content. Oxygen diffusion coefficients estimated from the laboratory measured moisture contents and porosities decreased with increasing moisture contents.

It is concluded from the modelling and laboratory results that the developed methodology and equipment constitute important tools for future evaluations of natural soils, siliceous tailings, and blends (sand bentonite mixtures) for the design of effective covers for sulphide tailings.

Yanful, E.K. and Luc C. St-Arnaud. 1991. The Waite Amulet hydrogeochemical evaluation. Second International Conference on the Abatement of Acidic Drainage, Vol. 1, Montreal, September 16-18, pp. 91-114.

The Waite Amulet project was initiated with the aim of developing a better understanding of the hydrogeochemical process controlling sulphide oxidation and subsequent pore water evolution in an acid generating tailings area. This paper reviews the project, discusses the extent of sulphide mineral oxidation at the site, and provides profiles of unsaturated and saturated zones pore water chemistry. A summary of the geotechnical behavior of the clayey subsoil is also presented.

Gaseous oxygen concentration profiles show that oxygen is an important control on the extent of pyrite oxidation. Key conclusions, drawn from the study of acid pore water generation and movement in the Waite Amulet tailings are:

1) Acidic pore water is partly neutralized by buffering reactions occurring in the deeper unsaturated zone. The remaining acidity and dissolved metals will flow downwards with the pore water in the unsaturated zone until the water table is reached.
2) Acidic conditions are found in the shallow saturated zone. These conditions become more neutral with depth due to buffering reactions, such as mineral dissolution and precipitation.
3) Pore water in the saturated zone flows in a direction which varies across the area of the tailings. Flow in the central part of the tailings is vertically downwards while flow along the perimeter of the tailings is horizontal.
4) Anisotropy in the hydraulic properties of the tailings is a major control on the flow of pore water in the tailings. This anisotropy is produced by the presence of fine grained, horizontal "slime" layers. It has the effect of promoting horizontal flow over the vertical downward flow.
5) Analysis of pore water quality and calculation of groundwater velocity in the clay suggests that tailings pore water does not penetrate deep into the clay layer on the south side of the tailings. Sulphate levels above background values, observed in the deeper layer of the clay, may be attributed to migration by diffusion.
6) Acid generation will last longer along the tailings dam and in the south section of the impoundment. In these areas, coarser tailings grain sizes induce lower water table levels and larger volumes of unsaturated tailings are available for oxidation.

Yanful, E.K., and Payant, S.C. 1991. Laboratory evaluation of the performance of engineered soil covers for decommissioning of sulphidic tailings. Proceedings: 44th Canadian Geotechnical Conference, 1991. Paper no. 69.

Decommissioning of sulphide mine tailings in an environmentally acceptable manner continues to pose a challenge to the mining industry. These sulphides oxidize when exposed to air and, in the presence of moisture, generate acidic drainage with high metal levels. It is recognized that reducing gaseous oxygen transport and water infiltration into such tailings is critical to the success of any prevention and control technology.

The rationale behind the design of laboratory column experiments involving engineered soils covers is presented. The experiments consisted of layered soil covers from the Waite Amulet tailings site near Rouyn-Noranda, Quebec. The columns were monitored for oxygen concentration, water content, temperature, and drainage water chemistry. Control columns containing unoxidized tailings without covers were similarly monitored for comparison. Moisture was supplied to the surface of the covers and to the exposed tailings by means of a simulated rain. The covers were placed in the columns in accordance with compaction specifications used in the field test plots.

Yanful, E. K. and St-Arnaud, L. 1991. Design, instrumentation, and construction of engineered soil covers for reactive tailings management. Proceedings: Second International Conference on the Abatement of Acidic Drainage.

The design and installation of 20 m x 20 m test plots, consisting of engineered composite soil covers on sulphidic tailings at the Waite Amulet site, are presented. The soil covers consist of a compacted saturated clay layer sandwiched between gravelly sand and medium sand layers. The clay layers serve as an infiltration and oxygen barrier while the sand layers function as capillary barriers. Two test plots consisting of the clay/sand composites were installed with the clay layers compacted and placed at different modified Proctor densities. A composite system in which a high density polyethylene (80 mil HDPE) sheet replaced the clay layer and a control plot without a cover were also installed for comparison. All four test plots were instrumented to monitor gaseous oxygen, moisture content, suction, temperature, and the quality of pore water in the tailings saturated zone. Field lysimeters were installed beneath the covers to collect water leaching through a volume of unoxidized tailings.

Preliminary results obtained during the first two months after the installation indicated an attenuation of gaseous oxygen and elimination of infiltration by the covers as was expected. Moisture contents in the covers did not change from their placement values. Temperature profiles showed increases in depth with the actual values controlled by air temperature. All lysimeter underneath the covered test plots were dry. The control plot reported large volumes of water during October and November, 1990. The quality of water reflected tailings oxidation and acid generation.

Continued monitoring of the test plots will provide comprehensive data for assessing the effectiveness of engineered soil covers in the abatement of acidic drainage from tailings impoundments.

Yanful, E. K. and St-Arnaud, L. 1992. Migration of acidic pore waters at the Waite Amulet tailings site near Rouyn-Noranda, Quebec, Canada. Canadian Geotechnical Journal, Vol. 29, pp. 466-476.

Pore waters found in the unsaturated zone of the Waite Amulet tailings have been modified by sulphide mineral oxidation, resulting in an acidic pH (near 4) and high concentrations of dissolved iron and sulphate at about 5 and 12 g/L, respectively. These pore waters have been displaced down into the shallow saturated zone of the tailings by infiltrating water. Most metals are removed from the pore water as a result of pH buffering before they reach the deeper saturated zone. However, some dissolved metals still remain in solution and are transported with the pore water through the tailings.

Numerical flow modelling shows that anisotropy in the hydraulic conductivity (ratio of K_x/K_y is estimated to be 100) exists in the tailings, most likely due to the presence of horizontal fine grained "slime" layers. Anisotropy in hydraulic conductivity has the effect of promoting horizontal flow over vertical flow in the model. The estimated horizontal pore-water velocity is almost 20 times higher than the vertical velocity. The geometry of the tailings impoundment and the assumed impermeability of the varved clay soil underlying the tailings also contribute to increased horizontal flow.

To verify that a preferred horizontal flow exists and that the clay subsoil is indeed impermeable, the geotechnical properties and hydrogeochemistry of the clay are also evaluated. Analysis of pore-water quality and calculation of groundwater velocity in the clay unit underlying the south portion of Waite Amulet tailings impoundment suggests that tailings pore water does not penetrate deep into the clay layer on the south side of the tailings but rather flows predominantly laterally in the tailings towards the limits of the impoundment and reaches AMD interception ditches. Overconsolidation ratios reach a maximum value of 2.0. In the clay-tailings interface zone, the soil is characterized by lower insitu water contents and slightly higher undrained shear strengths, C_u, than the deeper clay. The water contents of the near interface clay average about 40% and a C_u value of only 20 kPa occurs in the clay at greater depths.

These geotechnical properties confirm the presence of a desiccated oxidized upper zone identified in previous studies. It is hypothesized that fractures that could have appeared in the oxidized zone before the tailings deposition would have then closed due to consolidation by the tailings mass. Above back ground sulphate concentrations observed in the clay layer at a depth of 1 m are believed to be controlled by diffusion and advection. The presence of fractures in the oxidized zone and excess pore-water pressures generated during consolidation of the clay by the tailings mass could have also influenced chemical transport.

Yanful, E. K., and Aube, B. 1993. Modelling moisture-retaining soil covers. 1993 Joint CSCE-ASCE National Conference in Environmental Engineering. July 12-14, Montreal, Quebec.

A composite soil cover, consisting of a clay soil placed between two sand layers, was evaluated in a laboratory column under conditions of evaporation and no evaporation. Moisture contents and pressure heads which developed at various depths during drainage were modelled using a saturated-unsaturated flow model. Long term predictions indicated that the clay layer would retain high water saturation.

Yanful, E.K., Woyshner, and M.R. Aube, B.C. 1993. Field evaluation of the effectiveness of engineered soil covers for reactive tailings. Final Report. DSS Contract Number: 23440-0-9061/01-SQ.

A project was initiated in July 1990 under the MEND (Mine Environmental Neutral Drainage) program to assess the performance of engineered covers. The project was funded by Noranda Inc., Canada Centre for Mineral and Energy Technology (CANMET) and Centre de recherché minerales of Ministere de l'Energie et Des Resources of Quebec.

The principal objective of this project was to design, construct and evaluate the effectiveness of soil covers and plastic or geomembrane covers in reducing acid generation in reactive mine tailings. The evaluation consisted of performance monitoring of field test plots at the decommissioned Waite Amulet tailings site and laboratory experiments at the Noranda Technology Centre (NTC).

A total of four test plots, consisting of two composite soil covers, one geomembrane cover and a control (tailings without cover) were constructed at the Waite Amulet site. Each test plot was instrumented to measure gaseous oxygen concentrations, water content, suction, temperature and pore water quality at various depths. In addition, a collection basin lysimeter, initially filled with unoxidized tailings, was installed below each cover to measure both the quantity and quality of percolated water.

The composite soil cover consisted of a 60 cm thick, compacted, silty clay layer placed between two sand layers, each 30 cm thick. A final 10 cm gravel crust blanketed the cover system to minimize erosion. These thicknesses were selected to provide maximum reductions in the predicted oxygen flux and a sufficient safety factor to minimize the effects of adverse climatic conditions such as freezing and thawing. The design of the cover was based on the results of a previous laboratory study which concluded that this composite cover would be able to resist significant moisture losses for a long time.

The geomembrane cover consisted of an 80 mil (2 mm thick) high density polyethlene (HDPE) placed between upper fine sand and bottom coarse sand. Six column tests were installed in the laboratory to simulate soil-covered and uncovered tailings. The soil cover consisted of a 30 cm thick clay layer placed between two sand layers, each 15 cm thick. The soils were similar to those used in the construction of the filed test plots. Unoxidized tailings used in the laboratory experiments were collected from the deep saturated zone of the south end section of the Waite Amulet tailings impoundment. The cover and uncovered tailings were subjected to cyclic wetting and drying, at laboratory temperature. Gaseous oxygen concentration, water content, temperature and drainage and water quality were monitored. The covered tailings did not produce any drainage water during normal wetting or rain application because of the low hydraulic conductivity of the compacted clay layer. Most of the added water reported as run off. The covered tailings were periodically flushed (by by-passing the soil cover) in order to obtain water to assess the amount of acid produced from sulphide oxidation.

Results of the laboratory, field and modelling studies indicated that the oxygen flux is reduced by 91 to 99% by the soil cover. Hydrologic modelling indicated that water percolation through the cover is about 4% of precipitation. Field lysimeter data gave 6% or 54 mm per year which indicates a reduction of 80% in the total annual infiltration into the uncovered tailings. Based on field results and results from the laboratory freeze-thaw studies, it was concluded that freezing and thawing did not adversely affect the cover and that no future negative effects would be anticipated. It was also found that the long-term stability of the HDPE cover is not a major concern except for the possible effects of equipment, burrowing animals and sunlight.

It was recommended that the tailings in each test plot lysimeter be sampled and examined for signs and extent of oxidation. This would involve detailed pore water analysis and a mineralogical investigation. The water balance of the two soil-covered test plot should be confirmed by further field monitoring through the fall of 1993. The results presented and discussed in this study and the results from the recommended additional monitoring should then be integrated into a set of design and construction protocols for soil covers for use by mining companies and consultants. In addition, a new project should be initiated to investigate the effects of root penetration on the soil covers.

Yanful, E.K., Bell, AV., and Woyshner, M.R. 1993. Design of a composite soil cover for an experimental waste rock pile near Newcastle, New Brunswick, Canada. Canadian Geotechnical Journal, Vol. 30, pp. 578-587.

The Heath Steele Waste Rock Project was initiated in 1989 under Canada's Mine Environment Neutral Drainage (MEND) program. This program was developed to test strategies for managing acid generating waste rock. The multiphase project involved the identification and selection of a few waste rock piles for field evaluation at the Heath Steele mine site located approximately 50 km northeast of Newcastle, New Brunswick. As part of the evaluation, a 0.25-ha acid generating pile, pile 7/12, was relocated and reconstructed on an impermeable synthetic membrane by end dumping from the perimeter and pushing into the middle section. The pile, which contains about 14, 000 t of mine waste rock, has been producing an acidic seepage characterized by high dissolved iron (3.5 - 13.5 g/L) and sulphate (12.7- 43.4 g/L) concentrations.

Following the definition of the baseline acid generating characteristics of the pile and a laboratory investigation of potential soil cover materials in the vicinity of the site, a three-layer cover design is proposed. The design calls for a 60 cm thick saturated impermeable cover sandwiched between a 30 cm thick sand base and a 30 cm thick overlying granular layer. The coarse layers serve as capillary barriers to minimize moisture losses in the fine layer due to evaporation and drainage. The principal objectives of the design are to obtain a low gas diffusion coefficient to minimize oxygen fluxes and, also, to attain a low hydraulic conductivity to reduce infiltration into the pile. Both objectives can be achieved by compacting the impermeable cover at a maximum dry density of 95% Modified Proctors with wet of optimum water content conditions.

The three-layer cover system has been extensively evaluated in laboratory, by modelling, and with field studies involving acid generating mill tailings. The results of these evaluations all indicate that the system is effective in reducing acid generation by at least 90%. The potential for the impermeable layer to remain nearly fully saturated, even under an evaporative flux, is demonstrated by flow modelling. It is noted that the assessment of the durability of the cover, with respect to variable climatic conditions (drying, freezing, and thawing), is a critical component of the performance evaluation.

Although differential settlements in the 5 m high pile could be much smaller than those associated with large piles (of several metres high), other aspects of the performance evaluation of the cover, such as the effects of freezing and thawing and reductions in temperature resulting from cover placement would be applicable to other piles.

Yanful, E.K., Riley, M.D., Woyshner, M.R., and Duncan, J. 1993. Construction and monitoring of a composite soil cover on an experimental waste rock pile near Newcastle, New Brunswick, Canada. Canadian Geotechnical Journal, Vol. 30, No. 4, pp. 588-599.

A 130 cm thick composite soil cover was constructed on an experimental waste-rock pile at the Heath Steele mine site near Newcastle, New Brunswick. The cover consisted of a 30 cm thick sand base, a 60 cm thick compacted glacial till, a 30 cm thick granular layer, and a final 10 cm thick gravel layer for erosion protection. The till was compacted on the sand base in three finished lifts each of 20 cm thickness. Results of a preconstruction pad test indicated six passes of a 5 t vibratory compactor were required to attain the design specifications of 95% of the Modified Proctor maximum dry density at a moulding water content of 2 - 3% wet of optimum. These compaction specifications also ensured that the till had a degree of water saturation of at least 95%, which is required to reduce oxygen and acid fluxes in the underlying pile. Quality control measures were taken during the construction of the cover.

Results indicated a reduction in gaseous oxygen concentrations in the pile from 20% before cover to about 3% after cover placement. The decreased oxygen penetration implied reduced oxygen flux and acid production. Volumetric water contents averaged about 32% in the till both immediately following cover installation and 7 months later. The water content data is corroborated by soil-suction measurements. Temperatures in the pile have decreased following cover installation but appear to be more influenced by climatic variability than by a decrease in heat production and, hence, sulphide mineral oxidation. Observed discharge from lysimeters installed below the cover indicates infiltration of 2 - 2.5% of precipitation during a 55 day period when rainfall was heavy. The quality of seepage from the pile has not changed since cover installation. Further monitoring will be required to confirm the reduction in acid production.

Yanful, E.K. 1993. Oxygen diffusion through soil covers on sulphidic mine tailings. Journal of Geotechnical Engineering, Vol. 119, No. 8, pp. 1207-1228.

Engineered soil covers are being evaluated under Canada's Mine Environmental Neutral Drainage (MEND) program for their effectiveness in preventing and controlling acid generation in sulphidic mill tailings. A critical parameter for predicting the performance of these covers is the diffusion coefficient of gaseous oxygen in the cover materials. Laboratory experiments conducted to determine the effective diffusion coefficient of a candidate cover material, a glacial till from an active mine site, are described. The diffusion coefficient is determined by fitting a semi-analytical solution of the one-dimensional, transient diffusion equation to experimental gaseous oxygen concentration versus time graphs. Effective diffusion coefficients determined at high water saturations (85-95%) were in the order of 8×10^{-8} m^2/s. The diffusion coefficients decreased with an increase in water saturation as a result of the low diffusivity of gaseous oxygen in water relative to that in air and the low solubility of oxygen in water. Placement of soil covers in high saturation conditions close to maximum compaction density ensures that the flux of oxygen into tailings underneath such structures is low, resulting in low acid flux. This is confirmed by combined laboratory, field, and modelling studies.

The results of column tests designed to evaluate the effectiveness of a three-layer soil cover on sulphidic tailings from a decommissioned mine site are discussed. The cover consists of a compacted clay layer sandwiched between a fine and coarse sand layer. The sands function as capillary barriers in preventing the clay from losing moisture by drainage and evaporation. This is corroborated by water content measurements. Theoretical fluxes, obtained from simulations of observed oxygen concentration profiles over a 65 day period, indicate a 97% reduction of the maximum acid flux by the cover. These results are found to be similar to those obtained from covered and uncovered tailings in laboratory columns. Oxygen profiles measured in the covered field tailings also gave a predicted flux that indicates a 99% effectiveness in the exclusion of gaseous oxygen. The effective diffusion coefficient of the clay layer is determined from the simulations to be 3.9 and 9.9 x 10^{-9} m^2/s in the laboratory and field, respectively.

Further simulations confirm that, in both the laboratory and field, the thickness of the clay layer required to minimize the theoretical acid flux does not need to exceed 30 cm. However, a thicker layer (60 cm) was used in the field as a safety factor against possible increases in the diffusion coefficient of the clay due to adverse climatic conditions such as freezing and thawing.

Yanful, E.K., and Payant, S.C. 1993. Laboratory acid fluxes from covered and uncovered sulphidic tailings. CIM Metsoc Meeting Symposium, Paper # 69, Aug. 30-Sept. 1.

Recent interest in the use of engineered soil covers for managing sulphidic mill tailings has resulted in a series of research interests under the MEND program. A laboratory study has been undertaken to investigate the effectiveness of composite soil covers in reducing acid generation in tailings at Waite Amulet. Gaseous oxygen and moisture content profiles obtained during cyclic wetting and drying periods are presented for covered and uncovered tailings. Total acid production for specific periods is presented as cumulative acidity and mass of sulphate. The rate of acid production is deduced from this data.

Yanful E.K., Shikatani, K.S., Quirt, D.H. 1995. Hydraulic conductivity of natural soils permeated with acid drainage. Canadian Geotechnical Journal, Vol. 32, pp. 624-646.

Three different soils from Canadian mine sites namely Waite Amulet clay, Heath Steele till, and Yukon till, were evaluated in the laboratory for their compatability with acid mine drainage (AMD). The key parameter evaluated was the hydraulic conductivity, *k*, measured with a flexible wall triaxial permeameter at low hydraulic gradients ranging from 15 to 60. The test soils comprised of a slightly over consolidated silty clay of medium to high plasticity with about 80% of the particles <2 µm (Waite Amulet clay) and two fairly sandy tills. The Yukon till was nonplastic and had a silt content of 40% and a sand content of 35% whereas the Heath Steele till had a low plasticity and had both sand and silt contents of 25%.

The undisturbed Waite Amulet varved clay gave a *k* value of 1-1.5 x 10^{-7} cm/s when permeated with simulated pore water and two pore volumes of AMD. The Heath Steele and Yukon test soils consisted of -No. 4 mesh (<4.75 mm) samples that were compacted at approximately 2% wet of optimum using the modified Proctor method (ASTM 1987). The Yukon till, having a higher silt content, gave a higher *k* (2-3 x 10^{-7} cm/s) than the Heath Steele till (2 x 10^{-8} cm/s) in both reference permeant (1 N $CaSO_4$) and AMD.

Detailed geochemical analysis and equilibrium speciation modelling were conducted on the effluents obtained during the *k* tests. Mineral stability field diagrams and species activity data were used to aid in the interpretation of the complex geochemical and mineralogical changes that occurred in the soils as they were permeated with AMD. X-ray diffraction analysis was performed on the natural and AMD permeated soils to confirm the mineralogical changes. Mass balance calculations of species concentrations in both effluent were used along with post *k* testing and measured exchangeable cations to evaluate processes affecting the effluent chemical profiles. The data indicated that while AMD did not change *k*, it may have dissolved primary minerals such as chlorite, smectite, plagioclase feldspars, illite, and K-feldspar in a decreasing order of susceptibility. The dissolution and accompanying precipitation of secondary minerals appeared to have maintained or preserved the soil void ratio resulting in no net measurable volume change during *k* testing. The degree of AMD attack was found to be related to its contact time with the soil. One of the tills produced acidic effluents after 5.5 pore volumes or 243 days of permeation, the longest testing time used. The AMD permeation also reduced the tills cation exchange capacity by more than 50%. There was clear evidence that AMD permeation could eventually deplete soil buffering capacity to the extent that heavy metals such as Zn would no longer be attenuated. Immobile contaminants such as Cu were strongly retarded even at low pH. Soils intended to be used in the design and construction of barriers (for example, slurry walls and dam cores) against AMD seepage should, therefore, be tested for compatability with the intended AMD. Such compatability testing should be conducted over a long period of time to establish chemical equilibrium of key mobile contaminants such as Zn. This will improve design confidence and also avert or minimize detrimental, postconstruction changes requiring costly remedial actions.

Yazdani, J. 1995. Soil water characteristic curve for mine waste rock containing coarse material. M. Engg. Thesis. Department of Civil Engineering, University of Saskatchewan, Saskatoon, Canada.

A key component in the design of decommissioning facilities is characterization of the soil water characteristic curve (SWCC) for mine waste rocks which consist of material containing a wide range of grain sizes, including a significant portion of cobble size material. Determining the soil water characteristic curve for such a material is expensive and time consuming. Often, the job becomes impossible. Larger tempe cells proportional to the particle sizes should be used for developing the SWCC. This testing could be simplified if the finer portion of the waste rock were used to estimate the SWCC instead of using the entire material.

This report proposes a procedure which utilizes the results obtained for the fine fraction of waste rock passing through 4.75 mm sieve only. It bypasses direct testing of the entire material which includes both fine and coarse fractions. The test results show that the SWCC of rock particles (coarse fraction) do not have significant effect on the overall SWCC of the mixture. Rather, it changes the SWCC of the mixture by a factor proportional to the volume of the coarse fraction. These studies have also shown that the air entry value of the mixture is controlled by the fine fraction and that the residual water content remains almost the same for all three fractions (coarse, fine and mixture) and is independent of the coarse and fine fractions of the mixture.

The conclusion of this study was that in order to characterize the SWCC of mine waste rock, tests need only to be conducted on the fine fraction passing through 4.75 mm sieve. The final SWCC of the mixture can then be predicted based on a volumetric percentage of the coarse fraction.

APPENDIX B

Chapter 3

THEORETICAL BACKGROUND

from

PREDICTIVE MODELLING OF MOISTURE MOVEMENT IN ENGINEERED SOILS COVERS FOR ACID GENERATING WASTE

M.Sc Thesis
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Chapter 3
THEORETICAL BACKGROUND

The software used to simulate moisture movement in the cover systems is based on the SoilCover Version 1.0 model (Mend, 1993). SoilCover is a one-dimensional, transient, finite element, heat and water transfer (liquid and vapour) model which uses a physically based method for predicting the exchange of moisture between the atmosphere and a soil surface. The theory is based on the well known principles of Darcy's, Fick's, and Fourier's laws which are used to describe the movement of liquid water, water vapour, and heat respectively, within the soil profile. The water and heat flow equations were developed within the framework of continuum mechanics by Wilson (1990) as put forth by Fredlund and Dakshanamurthy (1982). The coupling of the soil profile to the atmosphere is accomplished using a modified Penman formulation developed by Wilson (1990) which allows for the calculation of evaporation from a saturated or an unsaturated soil surface.

The original formulation of the soil-atmosphere model was developed by Wilson (1990) as an explicit finite difference scheme which utilized Dalton's mass transfer method for the calculation of evaporation at the soil surface. A finite element formulation of the original program was later developed by Joshi (1993). The conversion of the Joshi (1993) formulation for use on a personal computer was performed and documented by Cook (1994). A modified Penman method proposed by Wilson (1990) was incorporated into the Joshi (1993) finite element formulation by Machibroda (1994). The SoilCover Version 1.0 (Mend, 1993) is a culmination of all these efforts. Tratch (1995) developed and formulated an algorithm for the simulation of plant transpiration which is utilized in this research.

This chapter presents the theoretical background for the SoilCover model used in this research.

3.1 WATER AND HEAT FLOW COUPLING

The water and heat flow equation as developed by Wilson (1990) is shown in Equation 3.1. Total head is evaluated through the application of Darcy's law to describe liquid water flow, Fick's law to describe vapour flow, and the conservation of mass for a representative elementary soil volume.

$$\frac{\partial h_w}{\partial t} = C_w^1 \frac{\partial}{\partial y}\left(k_w \frac{\partial h_w}{\partial y}\right) + C_w^2 \frac{\partial}{\partial y}\left(D_v \frac{\partial P_v}{\partial y}\right) \qquad [3.1]$$

where:

h_w = total head (m)

t = time (s)

C_w^1 = coefficient of consolidation with respect to the liquid water phase

$= \dfrac{1}{\rho_w g m_2^w}$

ρ_w = mass density of water (kg/m^3)

g = acceleration due to gravity (m/s^2)

m_2^w = slope of the moisture retention curve (1/kPa)

y = position (m)

k_w = hydraulic conductivity (m/s)

C_w^2 = coefficient of consolidation with respect to the water vapour phase

$= \dfrac{(P+P_v)}{P\rho_w{}^2 g m_2^w}$

P = total gas pressure in the air phase (kPa)

P_v = the actual vapour pressure within the pore-air (kPa)

D_v = diffusion coefficient of water vapour through the soil (kg m/kN s)

$= \alpha\beta(D_{vap}\dfrac{W_v}{RT})$

α = tortuosity factor of soil

$= \beta^{2/3}$ (Lai et al, 1976)

β = cross sectional area of soil available for vapour flow

D_{vap} = molecular diffusivity of water vapour in air (m^2/s)

$= 0.229 \times 10^{-4} (1 + \dfrac{T}{273.15})^{1.75}$ (Kimbal et al, 1976)

T = temperature (K)

W_v = molecular weight of water (0.18 kg/kmole)

R = universal gas constant (8.314 J/mole/K)

Temperature is evaluated on the basis of conductive and latent heat transfer according to Equation 3.2. A Fourier diffusion equation is used to simulate the transfer of heat within the soil (Wilson, 1990).

$$C_h \frac{\partial T}{\partial t} = \frac{\partial}{\partial y}\left(\lambda \frac{\partial T}{\partial y}\right) - L_v\left(\frac{P+P_v}{P}\right)\frac{\partial}{\partial y}\left(D_v \frac{\partial P_v}{\partial y}\right) \qquad [3.2]$$

where:

T = temperature (°C)

C_h = volumetric specific heat of the soil as a function of water content ($J/m^3/^\circ C$) $= C_v \rho_s$

C_v = specific heat of the soil (J/kg/°C)

ρ_s = mass density of the soil (kg/m^3)

λ = thermal conductivity of the soil (W/m/°C)

L_v = latent heat of vapourization of water (J/kg)

The coupling of water and heat flow is accomplished through the soil vapour pressure term (Pv) which is common to both Equations 3.1 and 3.2. The vapour pressure within the soil (Pv) is calculated on the basis of total suction in the liquid phase (Equation 3.3) using the relationship developed by Eldefson and Anderson (1943).

$$P_v = P_{sv} h_r \qquad [3.3]$$

where:

P_v = actual vapour pressure within the soil

P_{sv} = saturation vapour pressure of the soil at a temperature, T

h_r = relative humidity of the soil surface as a function of total suction and temperature

$$= e\left(\frac{\psi g W_v}{RT}\right)$$

ψ = Total suction in the soil (m)

Some of the key assumptions inherent in the above coupled water and heat flow equations as summarized by Machibroda (1994) and Wilson (1990) are as follows:

- The soil particles, water and air form a continuum, the behavior of which may be described using a representative elementary volume.
- The flow of liquid water in the soil due to osmotic suction gradients is neglected
- Hysteresis in the moisture content versus matric suction and the hydraulic conductivity versus matric suction relationships is ignored.
- Heat flow due to convection is negligible.
- The temperature in the soil remains above freezing and below the boiling point at all times.

3.2 ATMOSPHERIC COUPLING

Boundary conditions are required at the surface in order to solve the water and heat flow equations. Atmospheric coupling provides the upper boundary conditions in the form of evaporation and infiltration rates and surface temperatures. Evaporation is calculated from a modified Penman formulation that utilizes climate parameters that are varied on a diurnal basis. On days where rainfall occurs evaporation can either be allowed to occur simultaneously or set to zero for the day. The surface temperature can either be specified (provided data is available) or calculated by the program.

3.2.1 Evaporation

Evaporation from the soil surface is determined using a modified Penman formulation proposed by Wilson (1990) and implemented by Machibroda (1994). The formulation is given in Equation 3.4.

$$E = \frac{\Delta Q + \nu E_a}{\Delta + A} \qquad [3.4]$$

where:

E = vertical evaporative flux (mm/day)

Δ = slope of the saturation vapour pressure versus temperature curve at the current temperature of the air (kPa/°C)

Q = net radiant energy available at the surface (mm/day)

ν = psychrometric constant

E_a = $f(u)e_a(B - A)$

$f(u)$ = function dependent on wind speed, surface roughness, and eddy diffusion

= $2.63 \times (1.0 + (0.864 / 3.6) \times Ua)$ (Doorenbos and Pruit, 1977)

U_a = wind speed (km/hr)

e_a = vapour pressure in the air above the evaporating surface

B = inverse of the relative humidity of the air

A = inverse of the relative humidity at the soil surface = $\frac{1}{h_r}$

Thorm and Oliver (1977) note that the Penman formulation (i.e., original formulation) promotes an understanding of the physical processes of evaporation from natural surfaces. The formulation, aside from being both simple and realistic, requires only routine meteorological data. The main disadvantage is that the formulation only predicts evaporation from saturated surfaces. The modified Penman formulation allows for the calculation of evaporation from an unsaturated soil surface provided the vapour pressure at the soil surface is known. The original formulation is modified through the terms Ea and A. Under saturated conditions the term (A), which is the inverse of the relative humidity of the soil surface, has a value of 1.0. The value E_a then becomes equal to the original formulation (i.e., $f(u)\ (e_s - e_a)$) and Equation 3.4 becomes equal to the original Penman formulation. The relative humidity at the soil surface is determined from the vapour pressure at the soil surface as calculated from the coupled water and heat flow equations.

Diurnal fluctuations in air temperature, relative humidity, and net radiation are accounted for by using a sinusoidal function. The diurnal variations were implemented by Machibroda (1994) to provide a more accurate daily quantification of the evaporation from the modified Penman formulation. Air temperature varies from a minimum value that occurs in the morning and midnight to a maximum value occurring at solar noon. Similarly, relative humidity varies from a maximum in the morning and at midnight to a minimum value at solar noon. Daily net radiation is input as a total for the day and is then varied from a value of zero at daybreak and sundown to a peak value occurring at solar noon. Net radiation, and evaporation is assumed to be zero during the nighttime.

3.2.2 Infiltration

Precipitation is applied by specifying a positive value for the surface boundary condition. Infiltration excess (i.e., runoff) is accounted for by modifying the surface boundary condition from the specified rainfall flux value to a zero suction boundary at the moment the surface pore-water pressure becomes equal to or greater than zero (i.e., soil suction equal to or less than zero). This condition assumes that no surface retention (i.e., ponding) is allowed to occur. The infiltration excess is then quantified by subtracting the actual flux through the top element from the specified rainfall rate. The calculation is shown schematically in Figure 3.1.

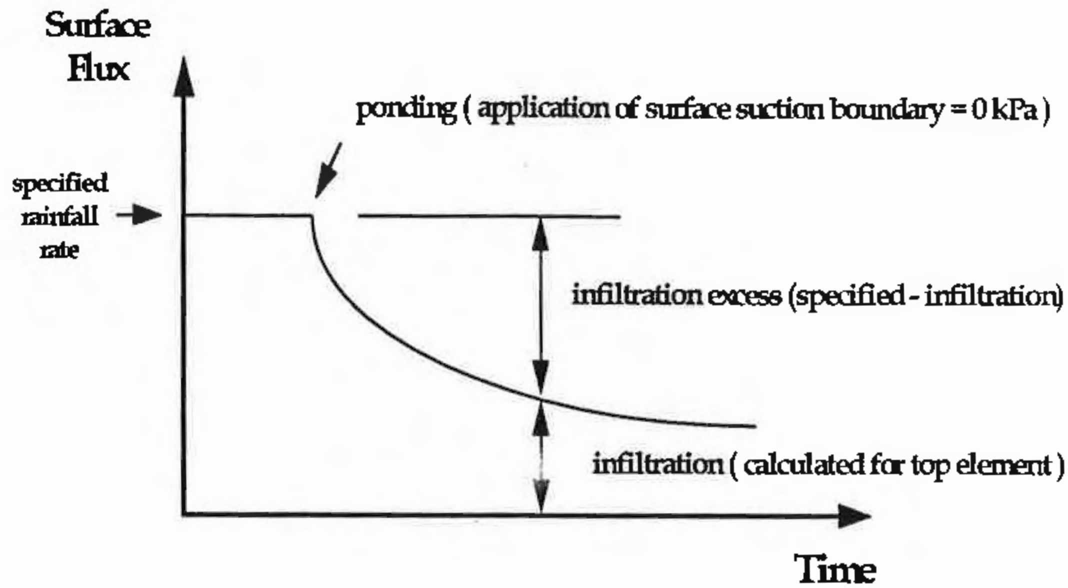

Figure 3.1 Quantification of infiltration excess (i.e., runoff) using a modified surface boundary condition

Differences in runoff for flat surfaces and sloping surfaces are accounted for by considering the duration of the rainfall event. For flat surfaces the total amount of rainfall is distributed evenly over the entire day (i.e., 24 hours). The reasoning behind this methodology is based on the local surface retention that occurs over a regional flat surface. Few surfaces are completely flat, but rather have local topographic lows and highs. These highs and lows are capable of retaining rainfall from high intensity-short duration rainfall events that would otherwise been lost to runoff. This ponded water is then allowed to infiltrate throughout the day. Distributing the rainfall evenly throughout the day simulates the condition of ponding without having to know topographic details of the flat surface to average surface retention.

Runoff for slopes is accounted for in a general way by considering the actual intensity of the rainfall event. For sloping surfaces, any infiltration excess will be lost immediately to runoff. This is opposite to the flat surface which can store the infiltration excess until complete infiltration can occur. By specifying the amount and duration of a rainfall event, runoff for a sloping surface can be adequately described. This description does not however, account for varying degrees of slope. In general, both the methods adopted for flat and sloping surfaces have significant limitations. However, a more rigorous physical account of runoff would require a detailed two dimensional analysis. This would require solution of a two dimensional head distribution along the slope face while accounting for runoff from the upper slope regions which could become potential infiltration for the lower slope regions. The effects of vegetation on the sloping surface is not taken into account.

3.2.3 Surface Temperature

The temperature of the soil surface must be known in order to solve the heat flow equation. The surface temperature can either be specified (if data is available) or calculated by the program using a relationship proposed by Wilson (1990). The relationship is given in Equation 3.5.

$$T_s = T_a + \frac{1}{\nu f(u)}(Q - E) \qquad [3.5]$$

where:

T_s = temperature at the soil surface (°C)

T_a = temperature of the air above the soil surface (°C)

ν = psychrometric constant (kPa °C^{-1})

$f(u)$ = function dependent on wind speed, surface roughness, and eddy diffusion (mm day^{-1} kPa^{-1})

= $2.63 \times (1.0 + (0.864 / 3.6) \times U_a)$ (Doorenbos and Pruit, 1977)

U_a = wind speed (km hr^{-1})

Q = net radiant energy available at the surface (mm day^{-1})

E = vertical evaporative flux (mm day^{-1})

3.3 FINITE ELEMENT FORMULATION

The finite element formulation of the SoilCover model was developed by Joshi (1993) and is based on the Galerkin weighted residual approach. The finite element formulation required replacing vapour pressure terms in the heat flow and moisture flow equations with equivalent water pressures. The result is two equations with two dependent variables; namely, pressure and temperature. The global equation for moisture flow is given in Equation 3.6.

$$[K_W]\{\Psi_N\} + [K_{WH}]\{T_N\} + [C_1]\{\dot{\Psi}_N\} = \{F_W\} \qquad [3.6]$$

where:

$[K_W]$ = global stiffness matrix associated with suctions
$[K_{WH}]$ = global stiffness matrix associated with coupling
$[C_1]$ = global moisture storage mass matrix
$\{\Psi_N\}$ = nodal suction vector
$\{T_N\}$ = nodal temperature vector
$\{\dot{\Psi}_N\}$ = time derivitive of the nodal suction vector.
$\{F_W\}$ = global moisture load vector

Equation 3.7 gives the global equation for heat flow:

$$[K_H]\{T_N\} + [K_{HW}]\{\Psi_N\} + [C_2]\{\dot{T}_N\} = \{F_H\} \qquad [3.7]$$

where:

$[K_H]$ = global stiffness matrix associated with temperatures
$[K_{HW}]$ = global stiffness matrix associated with coupling
$[C_2]$ = global heat storage mass matrix
$\{\dot{T}_N\}$ = time derivitive of the nodal temperature vector
$\{F_H\}$ = global heat load vector

Equations 3.6 and 3.7 are then combined and written as a single system of simultaneous equations for coupled moisture and heat flow:

$$\begin{pmatrix} K_W & K_{WH} \\ K_{HW} & K_H \end{pmatrix}\begin{pmatrix} \Psi \\ T \end{pmatrix} + \begin{pmatrix} C_1 & 0 \\ 0 & C_2 \end{pmatrix}\begin{pmatrix} \dot{\Psi}_N \\ \dot{T}_N \end{pmatrix} = \begin{pmatrix} F_W \\ F_H \end{pmatrix} \qquad [3.8]$$

An adaptive time stepping scheme is used by SoilCover to automatically calculate the size of the time step during each day. Time step control parameters implemented by Joshi (1993) are used to calculate the initial size of the time step for the beginning of each day. Cook (1994) modified the original time stepping scheme to provide improved numerical stability. In the new scheme, suctions and temperatures from the previous time step are used to back calculate what the time step should have been based on the Crank Nicholson marching forward in time method.

SoilCover utilizes a relative convergence scheme for the dependent variables of suction and temperature which is evaluated at every node in the system (Cook, 1994). The original Joshi (1993) formulation utilized a relative convergence scheme which was evaluated for the norm of the nodal head and temperature vector (i.e., essentially evaluated for averaged nodal conditions). The modified method provides a more stringent control over system convergence.

3.4 SOIL PROPERTIES

Hydraulic and thermal soil properties are required for coupled heat and mass transfer modelling. They are described in the following sections.

3.4.1 Hydraulic Properties

The hydraulic properties required solution of the water flow equations include the volumetric water content versus suction and the hydraulic conductivity versus suction relationships.

The *storage function* describes the relationship between the soil suction (negative pore-water pressure) and the volumetric water content and is fundamental to the water flow formulations. The ability of the soil to store water will be a function of both the soil suction and the physical characteristics of the soil (i.e. grain size distribution, porosity, structure, etc.). Figure 3.2 shows a typical storage function. The slope of the curve in the negative pore-water pressure range is referred to as m_2^w and m_v in the positive pore-water pressure region and describes the volume of water taken on or released by a change in pore water pressure. The volumetric water content at zero suction (i.e., zero pore-water pressure) is equivalent to the soil porosity. The suction corresponding to the point where the curve realizes a sharp drop in water content is referred to as the air entry value (AEV). The AEV indicates the suction at which the soil will begin to desaturate and may or may not be well defined depending on the soil type. Fine grained soils tend to have flat functions with high air entry values whereas coarse grained soils tend to have steep functions with low air entry values.

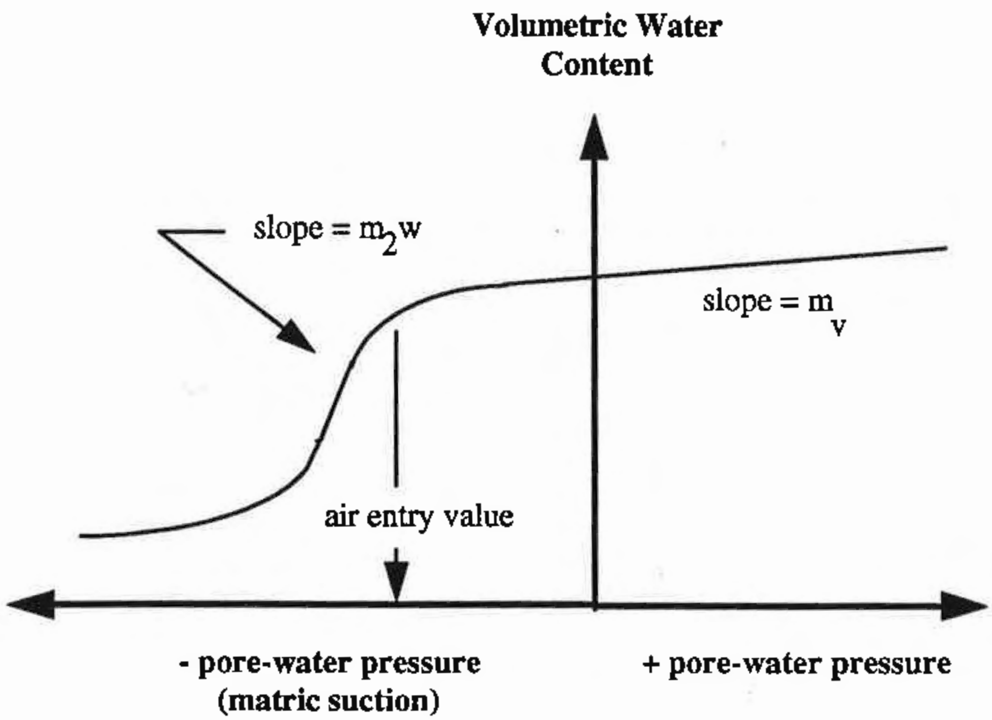

Figure 3.2 Volumetric water content versus suction relationship

Storage curves are obtained through a relatively simple laboratory procedure using a pressure plate apparatus for suctions up to 500 kPa and an osmotic desiccator for suctions greater than 500 kPa. Details regarding the theory and procedures involved with the determination of the storage function are described by O'Kane (1994).

The *hydraulic conductivity* refers to the soil's ability to transmit water. Water in soils can be thought of as flowing through a series of water filled conduits. Under saturated conditions all of the conduits are filled with water and subsequently all pathways are available for flow resulting in the hydraulic conductivity being its highest value.

3.5 PLANT TRANSPIRATION AND ROOT WATER UPTAKE

The theoretical development for the modelling of vegetation is provided by Tratch (1994). The formulation provided by Tratch (1994) is used in place of the original formulation used in SoilCover Versions 1.0 and 1.1 for the reason that it provides a much more accurate description of the physical processes of root water uptake and cover conditions. Details of the theoretical development are documented by Tratch (1994). A general description of the theory is given in the following paragraphs.

The vegetation characteristics are described by the Leaf Area Indices (LAI) typical for the vegetation being studied. LAI is the ratio of the green leaf surface area to the ground surface area and is a function of plant species, vegetation density, and growth stage. Potential transpiration is calculated as a function of the potential evaporation and the LAI.

The calculated potential transpiration is then partitioned into a potential root uptake profile. The root flux is distributed linearly between the top and bottom nodes of the root system. The actual root uptake for each node in the root system is a function of the moisture availability and is calculated on the basis of a defined plant limiting factor.

Vegetation effectively intercepts incoming radiation which will reduce actual evaporation rates. The net radiation is modified on the basis of LAI.

3.6 OXYGEN DIFFUSION

The flux of oxygen through a cover layer is determined on a daily basis. The flux of oxygen can be determined using Fick' First law. Assuming that a condition of steady state exists for each day with regard to oxygen movement and knowing the oxygen concentration above and below the cover the mass flux of oxygen can be calculated as follows:

$$J = De\frac{\Delta C}{\Delta x} \qquad [3.12]$$

where J = mass flux of oxygen ($\frac{g}{m^3}$)

De = coefficient of oxygen diffusion ($\frac{m^2}{s}$)

ΔC = change in oxygen concentration ($\frac{g}{m^3}$)

Δx = change in elevation (m).

The coefficient of oxygen diffusion can be determined experimentally or can be estimated using an empirical relationship. Nicholson (1991) provides a linear regression equation that can be fit to laboratory tested data (Equation 3.13)

$$D_{eff} = D_{oa}\ \beta\ (1-S)^{a} + \beta\, D_{ow} \qquad [3.13]$$

where,

α and β = curve fit parameters

D_{oa} = diffusion coefficient of oxygen in air

D_{ow} = diffusion coefficient of oxygen in water

S = degree of saturation.

An empirical relationship developed by Millington and Shearer (1971) and modified by Collin and Rasmussen (1988) is given in Equation 3.14. The effective diffusion coefficient can be estimated knowing the degree of water saturation, the porosity, and the coefficient of oxygen diffusion in free air. Collin and Rasmussen (1988) evaluated several methods of diffusion coefficient estimation techniques and indicate the Millington and Shearer equation to be reasonably accurate throughout the range of dryness to saturation.

$$De = D_{oa}(1-S^2)\bullet(n(1-S))^{2xa} + HD_{ow}S^2(nS)^{2xw} \qquad [3.14]$$

where De = effective oxygen diffusion coefficient ($\frac{m^2}{s}$)

Doa = oxygen diffusion coefficient in free air ($\frac{m^2}{s}$)

Dow = oxygen diffusion coefficient in water ($\frac{m^2}{s}$)

S = degree of water saturation

n = porosity.

x_a = empirical coefficient: $[n(1-S)]^{2x} + [1-n(1-S)]^{x} = 1$

x_w = empirical coefficient: $(nS)^{2x} + (1-nS)^{x} = 1$

H = equilibrium constant.

In order to calculate the steady-state mass flux of oxygen for each day the overall oxygen diffusion coefficient for the cover layer must be determined. This can be calculated using a series equation (Equation 3.14) in the same manner as used to calculate the overall vertical hydraulic conductivity for a layered system as described by Freeze and Cherry (1979).

$$D_{cov} = \frac{d}{\sum_{i=1}^{n} \frac{d_i}{D_i}} \qquad [3.14]$$

where D_{cov} = series diffusion coefficient for the cover ($\frac{m^2}{s}$)

d = layer thickness

D_i = nodal diffusion coefficient ($\frac{m^2}{s}$)

n = number of layers.

A steady-state oxygen concentration profile (i.e., concentration at each node in the cover) for each day can then be back-calculated from Equation 3.12. Starting from a known concentration at the surface of the cover the incremental change in oxygen concentration across an element can be calculated using the average oxygen diffusion coefficient for that element. The average oxygen diffusion coefficient can be calculated from the degree of water saturation and porosity known for each node.

Collin and Rasmuson (1990) describe a similar methodology for the calculation of oxygen flux through a cover layer. They note that the assumption of steady-state conditions result in oxygen flux being overestimated during periods of increasing transport rate of oxygen and underestimated during periods of decreasing tansport rate of oxygen. In this study complete oxygen consumption is assumed at the base of the cover. For most situations this methodology will result in conservative estimates (i.e., higher than actual).