DESIGN, CONSTRUCTION AND PERFORMANCE MONITORING OF COVER SYSTEMS FOR WASTE ROCK AND TAILINGS

VOLUME 5 – CASE STUDIES

MEND 2.21.4e

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CASE STUDIES

Prepared for MEND

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SUMMARY

This manual includes a summary volume (Volume 1) and the following four supporting technical documents:

- Volume 2 – Theory and Background;
- Volume 3 – Site Characterization and Numerical Analyses of Cover Performance;
- Volume 4 – Field Performance Monitoring and Sustainable Performance of Cover Systems; and
- Volume 5 – Case Studies.

This volume presents a compilation of case studies that have previously been presented in publications such as the CETEM manual (CANMET, 2002), the MEND manual (MEND 5.4.2d), and the INAP long-term cover performance monitoring report (INAP, 2003). Depending on the objective of the original report, the case studies in these reports were written to highlight different aspects of the cover design process. The case studies have been re-formatted from their original presentation so that each case study is presented in a similar format. This volume has been divided into four sections based on the reports from which the case studies were taken: CETEM Manual Case Studies, MEND Manual Case Studies (a section each for tailings and waste rock), and INAP Report Case Studies.

The case studies in this manual are presented in terms of the successes and design objectives achieved. However, where appropriate, considerable emphasis is also placed on identifying the "lessons learned" as a result of the work having been undertaken. The objective will be to determine whether the cover system would have been designed, constructed, or monitored differently (i.e. would an amended methodology have been utilized), if the lessons learned had been known at the start of the project.

A potential fatal cover system design flaw is simply applying a successful design from one site to a second site, when in fact material properties, slope angles, slope lengths, and in particular climate conditions are in fact much different at the second site. Hence, the key idea(s) behind presentation of the case studies is that it is the design methodology that is transferable from one site to the next, and not the actual design itself, and that the methodology should be updated constantly as new information is developed.

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1 CETEM MANUAL CASE STUDIES

Two case studies are presented in this section. The first is for a waste rock storage facility located in a seasonally humid climate. The specific site cannot be disclosed in order to gain access to the site's information and associated data. The second case study (Myra Falls) is a waste rock storage facility located in a humid location. A third case study (Mt. Whaleback) was presented in both the CETEM manual and the INAP report. This case study is discussed in the INAP report section.

1.1 Seasonally Humid Climate Cover System Design Case Study

Data and information presented in the oxygen ingress summary, soil-atmosphere numerical modelling summary, and 2D cover performance modelling summary sections of Volumes 2 and 3 were based on information from the this case study. Hence, the focus of discussion in this case study will be on other key aspects of the cover system design such as clay mineralogy.

1.1.1 Background

At closure of the mine, a detailed site characterization was carried out to identify existing mining impacts and to provide a basis for the development of a closure plan. It was determined that sulphide oxidation products from the tailings storage facilities and a waste rock pile had significantly impacted the local aquifer system. The closure plan called for relocation of the tailings into the open pit (under water) to prevent future oxidation and acidic drainage from this source. The waste rock storage facility, the only remaining potential long-term source of acidic drainage, was to be rehabilitated *in situ* using a cover system.

The climatic conditions at the site could be generally defined as tropical savannah characterized by a long dry season from April to October, followed by a humid wet season from November to March. The wet season is characterized by heavy thundershowers that deliver about 90% of the annual precipitation. The average annual precipitation measured at the site is 1,435 mm, with a maximum and minimum annual rainfall of 2,644 and 1,025 mm, respectively. Annual potential evaporation is approximately 2,500 mm.

The maximum temperatures for the region are fairly consistent throughout the year, ranging from 28 °C to 33 °C. November and December are the hottest months, with a mean maximum of 34 °C and a mean minimum of 27 °C. July is the coolest month, with a mean maximum and minimum of 30 °C and 19°C, respectively.

1.1.2 Material Characterization

1.1.2.1 Waste Material

The evaluation of the primary rock in the waste storage facility indicates that approximately twenty-five to thirty percent of the primary rock either contains high sulphide material, or has been impacted by acidic drainage resulting from the presence of the sulphide material. The zones of high concentration sulphide material were observed while trenches were developed in the waste storage facility primary rock. In addition, localized acidic seeps emanate from the waste storage facility.

A significant percentage of the primary rock in the waste storage facility is acid consuming. However, it is fundamentally incorrect to form a conclusion with respect to the long-term, or short-term, acid rock drainage potential, simply on the basis of balancing acid consuming and acid forming material. Preferential flow paths exist in all waste rock dumps and therefore acidic drainage resulting from the presence of high concentration sulphide zones may not have the opportunity to be neutralized by the acid consuming material. In addition, the characterization work completed as part of this study indicates that any “circum-neutral” drainage from the primary rock will likely possess elevated zinc, manganese, and iron concentrations because the neutralized drainage will not reach a level of pH for “complete” precipitation of zinc. Elevated sulphate concentrations in the seepage are also predicted.

1.1.2.2 Cover Material

An area near the waste storage facility was identified as the most promising source of fine textured potential cover material. Illitic clay was encountered during field investigations that extended from the surface of the potential borrow area to a depth of approximately two metres. A layer of smectitic clay approximately one metre thick was observed below the overlying illitic clay layer.

It is important to note the different clay mineral types (i.e. illite and smectite) because the two materials possess significant differences that will impact on their long-term performance as cover materials. In general, an illitic clay is considered to be relatively stable clay mineral, while a smectitic clay would be termed as an “active” clay, with potential for swelling, shrinkage, and the potential for alteration of the clay crystal structure (i.e. become dispersive and subject to piping and erosion) in the presence of pore-water possessing elevated metal concentrations. These characteristics are not desirable cover material characteristics. However, use of the smectitic clay potential cover material is desirable, provided it is used in a judicious manner, because it possesses significantly higher moisture retention capability and lower permeability than the illitic clay. Both of these characteristics are desirable for developing a cover system that has a long-term ability to limit water infiltration and control oxygen ingress in the climate conditions prevalent at the site. This is not to say that the illitic clay cover material does not possess appreciable moisture retention and low hydraulic conductivity, just that the smectitic clay material does possess different material properties. For example, the laboratory measured saturated permeability of a compacted layer of the illitic clay is approximately

1 x 10^{-6} cm/s, while the smectitic clay was measured at between one and one-half to two orders of magnitude lower for the same conditions. Figures 1.1 and 1.2 show the hydraulic conductivity and SWCCs for the waste and cover materials.

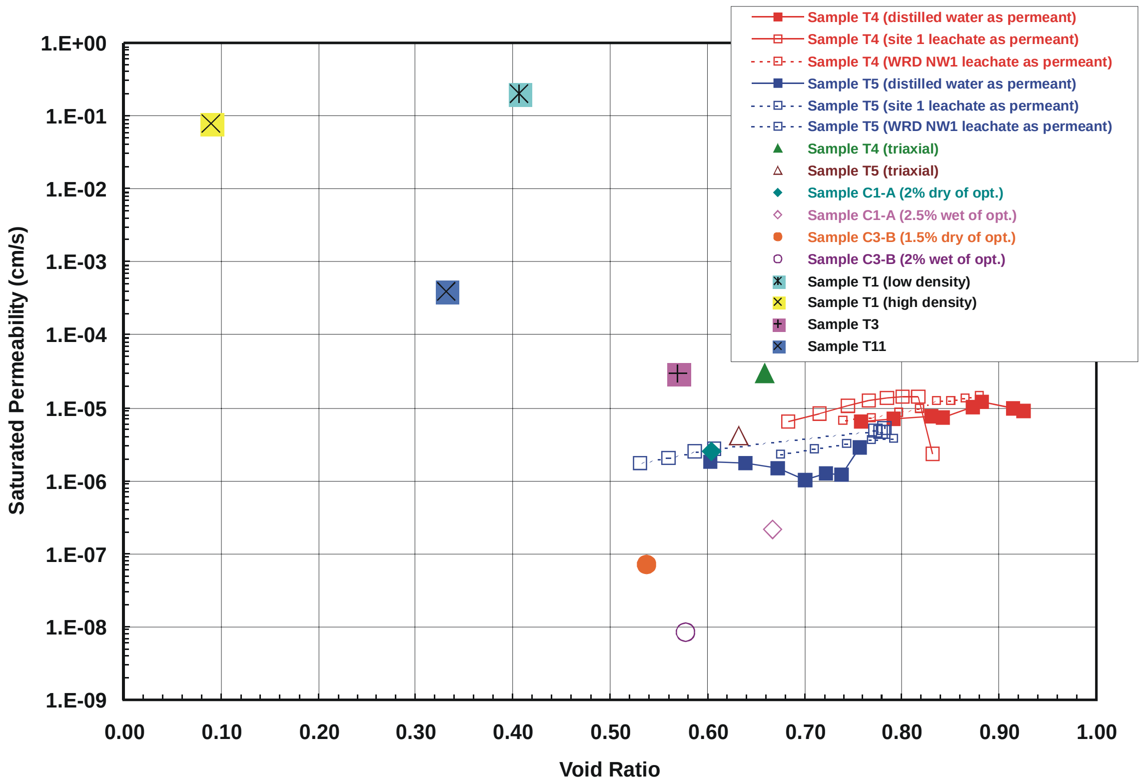

Figure 1.1 Hydraulic conductivity laboratory data for the seasonally humid site.

1.1.3 Cover Design

The cover system design is based on characterization of the underlying waste rock material and potential cover material, numerical modelling of alternate cover system scenarios, and a qualitative assessment of the impact that physical, chemical, and biological processes will have on long-term performance. Issues such as geochemical evolution, erosion, landform evolution, water infiltration, and oxygen ingress were addressed in a quantitative or semi-quantitative manner. However, it is only possible to address many of the chemical and biological processes that will impact long-term performance from a qualitative perspective. The soil-atmosphere cover design numerical modelling completed for this case study was presented as Example 1 for 1D SoilCover modelling and for 2D soil-atmosphere modelling in Volume 3 of this manual.

The general arrangement of the cover system is a one-half metre layer of compacted clay cover material placed directly on the waste rock material, overlain by a two metre layer of non-compacted clay material that would eventually function as a growth medium. Furthermore, competent “coarser” cover material would be “tilled” or worked into the upper twenty to thirty centimetres of this non-compacted layer on an approximately fifteen percent by mass basis. This latter component is critical to the proposed general arrangement to ensure that erosion and gullying does not occur before vegetation has been well established and can be relied upon to control erosion.

The non-compacted growth medium layer would consist of the illitic clay located in the borrow area. A soil-atmosphere numerical model predicted that approximately one percent of average annual rainfall would percolate to the underlying waste rock if the smectitic clay were used as the compacted layer on the upper gently sloping surface of the waste storage facility. This model also predicted that oxygen ingress would be controlled throughout the year as a result of the compacted smectitic clay layer. The thickness of the overlying non-compacted layer was critical to the model predictions to ensure that moisture cycling (i.e. infiltration and evapotranspiration) took place in this layer, as opposed to the underlying compacted layer. This was required to minimize the impact of wet-dry cycles on the mineralogical structure of the compacted smectitic clay material.

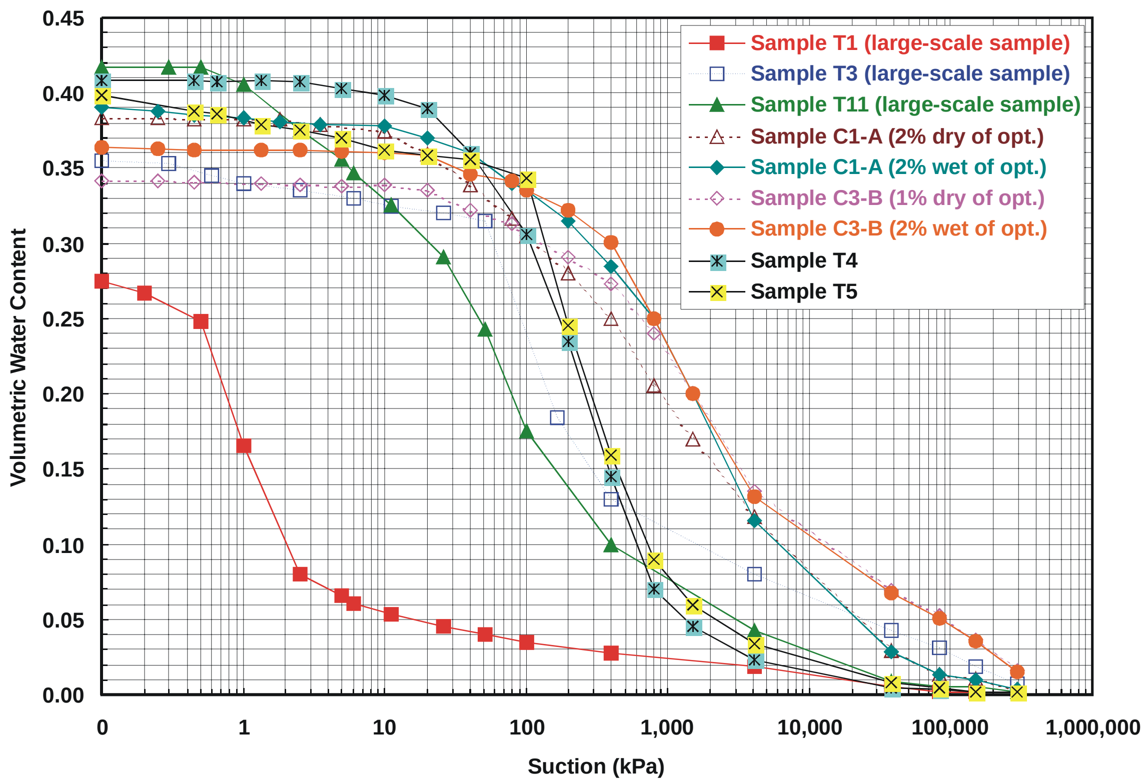

Figure 1.2 Soil water characteristic curve laboratory data for the seasonally humid site.

Numerical modelling of the cover system on a sloped surface gave a positive benefit to cover system performance. A compacted layer of the stable illitic clay potential cover material could be placed on the slope and shed water that infiltrated across the non-compacted compacted layer interface. This "shedding" phenomenon is not possible for the compacted illitic clay placed on gentle slopes, as would be encountered on the top of the waste storage facility. The use of the compacted smectitic clay material on the outer batter slopes would not be prudent because of the potential for lateral seepage from the waste storage facility that would lead to dispersion of the clay material, and failure of the cover system. In essence, the predicted performance of the illitic clay compacted material on the outer batter slopes was the same as for the smectitic clay compacted material on the relatively horizontal, even though the former material possesses higher hydraulic conductivity and lower moisture retention characteristics as compared to the latter material. This predicted performance was a direct result of the sloping surface conditions that were modelled and exist at the waste storage facility. The slope length and slope angle of the outer sloping surface of the waste storage facility, coupled with the hydraulic characteristics of the compacted and non-compacted layers were such that any accumulation of moisture towards the lower end of the slope did not result in an increase in net percolation in this region.

1.1.4 Summary

This case study outlines the design of a cover system based on material characterization, numerical modelling, and a qualitative assessment of the impacts of physical, chemical and biological processes on long term performance. The key lessons learned from this case study involving development of a cover system design for the acid forming waste rock were:

- The importance of 2D modelling for development of the preferred cover system design for the sloping surfaces of the waste storage facility; it was found that the preferred cover material for a sloping surface differed from that preferred for the relatively flat surfaces of the waste storage facility;
- The importance of considering and understanding clay mineralogy of potential cover materials as part of the material characterization program to ensure that issues potentially impacting long-term performance of the cover system are understood; and
- The importance of landform development; the final landform design was crucial to ensure that deterioration of the cover due to erosion was acceptable, while also providing a slope angle and length that did not compromise hydraulic performance of the sloping cover system (i.e. control of net percolation and oxygen ingress), while also providing visually aesthetic features compatible with surrounding natural landforms.

1.2 Boliden - Myra Falls Operation

This case study is based on a cover system design designed to control oxygen ingress and water infiltration to the underlying waste within a waste rock storage facility. The case study involves cover system design, test plot construction, and test plot performance monitoring.

1.2.1 Background

Boliden's Myra Falls Operation is a copper, zinc, gold, and silver mine located in the temperate rainforest of the central interior of Vancouver Island, British Columbia. The site is situated in a hanging glacial valley and typically experiences about 2,400 mm of precipitation. In general, 75% of this precipitation occurs during the months of October to March, inclusive. Waste rock dumps from mining at the site are producing acid rock drainage. Currently, collection and treatment systems handle this water prior to release to the environment. A long-term solution is required for ultimate mine closure.

1.2.2 Material Characterization

1.2.2.1 Waste Material

The acid base accounting and hydrogeological modelling at this site determined that active oxidation is occurring in the upper 10 m of the waste rock dumps and in deeper zones of high sulphide content materials. The mean net neutralization potential (based on acid-base accounting) for all waste rock samples tested was -88.1 t $CaCO_3$ per 1,000 t of waste and varied from +25.7 t to -423.6t $CaCO_3$ per 1,000 t of waste.

1.2.2.2 Cover Material

The till cover material was a sandy, non-plastic silt matrix till with a trace of clay. It was oxidized with angular cobbles and boulders up to 15 cm with a specific gravity of 2.82. The maximum dry density was approximately 2.1 Mg/m^3 for a standard Proctor compaction effort and the corresponding optimum moulding water content was 10%. The oxidized waste rock was well graded with coarse angular rock and a significant portion of silty material as a result of physical, chemical, and biological weathering. The saturated hydraulic conductivity of each sample was measured using a falling head apparatus during consolidation testing. The samples were prepared using material less than 4.75 mm (i.e. passing the No.4 sieve). The laboratory saturated hydraulic conductivity of a sample of compacted native till cover material varied between 1×10^{-6} cm/s and 1×10^{-7} cm/s. The laboratory saturated hydraulic conductivity of the waste rock samples varied between 1×10^{-5} cm/s and 1×10^{-7} cm/s because the coarse particles were screened out. In addition, significant silt size material was present in the waste rock within the upper few meters of the waste rock pile at the location where the sample was collected.

A key component of the laboratory program was the measurement of the soil water characteristic curve (SWCC). The saturated hydraulic conductivity and the relationship between the effective diffusion coefficient for oxygen and the degree of saturation are also key parameters for soil cover design. The SWCC is central to the design of an unsaturated soil system and the most fundamental characterization required for design.

The measured SWCCs of the waste rock, compacted till, and non-compacted till are shown in Figure 1.3 and represent the materials evaluated during the soil-atmosphere modelling conducted to design the test plots. The SWCCs of the non-compacted and compacted till samples illustrate the coarse but well graded nature of the potential cover material. The non-compacted till possesses a low air entry value (i.e. ≈ 1 kPa) with a gradual slope at suctions greater than the air entry value.

The air entry value increased to approximately 10 kPa as a result of compaction and the porosity decreased from 0.34 to 0.31, although the slope of the SWCC was similar. The small percentage of fine textured material within the till sample, and as a result the non-plastic behaviour of the till, led to the relatively small increase in the air entry value following compaction. The SWCC of the waste rock is bi-modal as a result of the presence of coarse material as well silty material “created” by physical, chemical, and biological weathering of the waste rock. The waste rock is gap graded with two distinct air entry values, as shown in Figure 1.3. The first occurring at a suction near zero and the second at approximately 7 kPa.

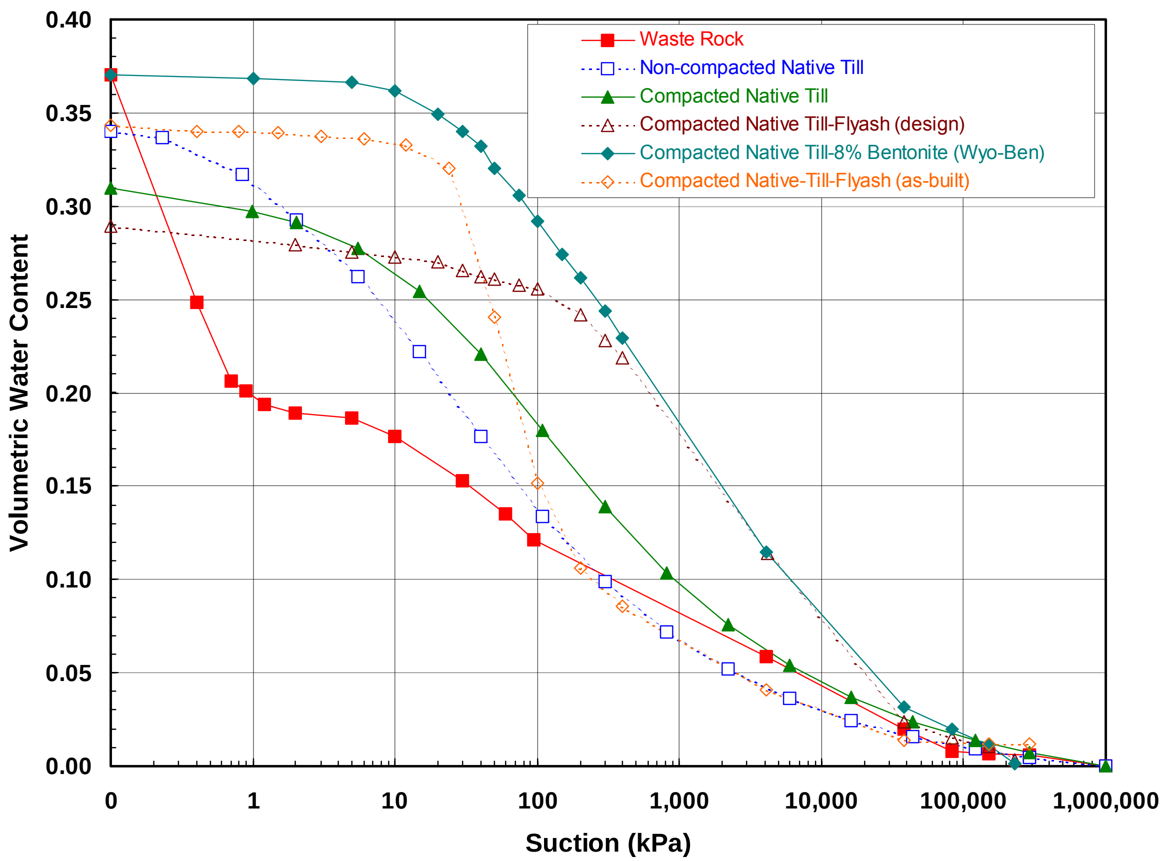

Figure 1.3 Soil water characteristic curve of the run-of-mine cover material for Myra Falls.

1.2.3 Cover Design Modelling and Test Plot Design

The test plot cover system alternative designs modelled were evaluated on the basis of their ability to perform as oxygen diffusion and water infiltration barriers. Initially, a cover system consisting of a compacted native till layer overlain by a non-compacted native till layer was considered. However, the computed degree of saturation of the compacted native till layer was less than the desired minimum of 85% during the simulation period. In general, the oxygen flux across the soil cover system is limited if the degree of saturation of the compacted layer is greater than 85%.

The soil-atmosphere numerical modelling showed that a compacted layer of till, ameliorated with bentonite or flyash, and placed between an upper non-compacted layer of till and the underlying waste rock provided an oxygen ingress and water infiltration barrier for the waste rock material (O'Kane *et al.*, 1997). The SWCCs of compacted till ameliorated with either bentonite or flyash are shown in Figure 1.3 and represent the materials evaluated during the soil-atmosphere modelling conducted to design the test plots. The model predicted that the ameliorated compacted till layer remained at a degree of saturation greater than 95% during the historical "dry" year growing season. The predicted net percolation from the base of the compacted layer into the underlying waste rock was approximately 1% of the historical "wet" year modelled precipitation.

The addition of 15% by mass of precipitate catch, or flyash, increased the air entry value of the compacted till to approximately 100 kPa, although little change in the porosity of the sample was observed. The air entry value of the compacted till sample ameliorated with 8% bentonite was approximately 30 kPa. However, the porosity of the compacted till ameliorated with 8% bentonite by mass increased by 20% as compared to that measured for the native compacted till sample.

Figure 1.4 shows the physical layout and materials of each test plot, which were constructed based on the modelling results. Test Plot No.1 (TP-1) is a control test plot with a bare waste rock surface. All three of the remaining test plots were constructed in a similar manner. That is, each test plot had approximately 50 cm of compacted material placed directly on the waste rock platform surface, overlain with 30 cm of non-compacted native till. A seed mix of grasses and legumes applied to the three test plots.

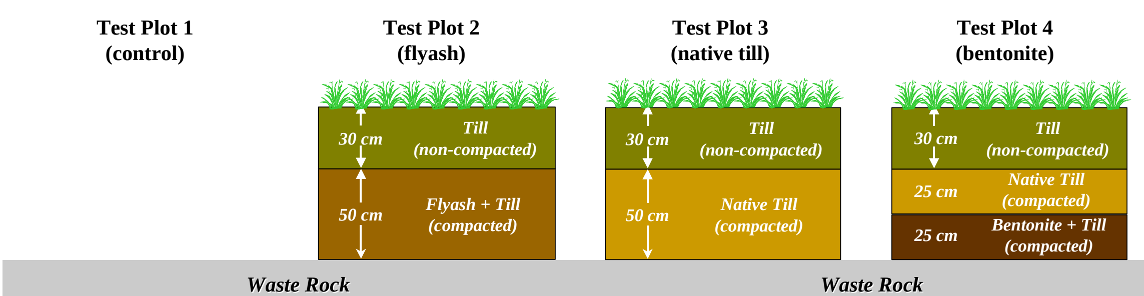

Figure 1.4 Test plot configuration for Myra Falls.

Test Plot No.2 (TP-2) and Test Plot No.3 (TP-3) were constructed with two 25 cm lifts of compacted material. The TP-2 compacted layer consisted of a mixture of flyash and native till. The flyash was added to the native till on a 25% mass basis. The flyash was dry mixed with the native till using a pulvi-mixer. The flyash-till mixture was moisture conditioned using the pulvi-mixer, and then mixed repeatedly until consistent moisture conditions were achieved throughout the depth of the lift. Each lift was compacted using a smooth drum vibratory roller. The TP-3 compacted layer was constructed from native till only.

The Test Plot No.4 (TP-4) compacted layer was also placed in two lifts. However, the two lifts were constructed from different material. The lower lift placed directly on the waste rock platform surface consisted of a mixture of bentonite and native till. The bentonite was supplied by Wyo-Ben Incorporated located in Montana, USA and mixed on an 8% by mass basis using the same procedure as described above for the flyash and native till in TP-2. The upper compacted lift of TP-4 was constructed from native till without the addition of fine textured ameliorating material.

1.2.4 Field Performance Monitoring System

The field performance monitoring system included instruments to measure climate conditions, net percolation, moisture storage and transport, temperature, and oxygen concentration.

<u>Net Percolation:</u>

Four lysimeters were installed following completion of the waste rock test plot platform. Each lysimeter was installed using the same procedure and materials, and is shown schematically in Figure 1.5. The pressure transducer in each lysimeter is located at the base of the lysimeter inside the centrally located piezometer. The TP-1 and TP-2 lysimeter pressure transducers are connected to the TP1-TP2 data acquisition system (DAS). The pressure transducers installed in the TP-3 and TP-4 lysimeters are connected to the TP3-TP4 DAS.

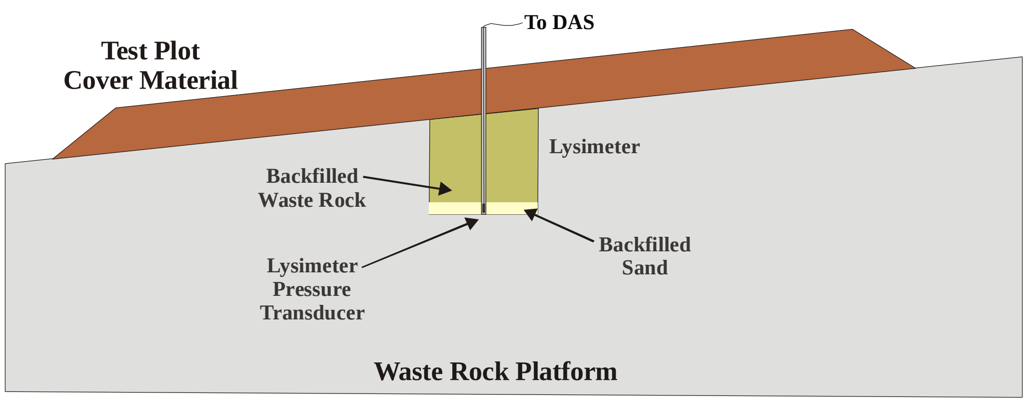

Figure 1.5 Schematic of the Myra Falls lysimeter configuration.

Moisture Storage and Transport:

Moisture storage and transport are monitored using matric suction sensors and volumetric water content sensors. Nests of eight suction sensors were installed up-gradient and down-gradient of the TP-2, TP-3, and TP-4 lysimeters. A sensor was installed in the underlying waste rock at each location, followed by four sensors in the compacted layers, and three sensors in the overlying non-compacted layer. Single nests of eight volumetric water content sensors were installed at the up-gradient location of TP-2, TP-3, and TP-4. The TP-1 sensors are connected to the TP1-TP2 DAS, and the TP-3 and TP-4 sensors are connected to the TP3-TP4 DAS.

Temperature:

In situ temperature was measured using the matric suction sensors. These sensors are actually thermal conductivity sensors operating under the principal of heat dissipation. Therefore, the initial temperature obtained before heating the sensor can be used to measure *in situ* temperature.

Oxygen Concentration:

Gas sampling ports were installed at the down-gradient nest location just below the material layer interface of each test plot. For example, at TP-2, gas-sampling ports were installed just below the interface of the non-compacted till material and the compacted till-flyash material, as well as just below the interface of the compacted till-flyash material and the waste rock material. All of the gas-sampling ports were connected to small diameter flexible tubing that extended to a sequencer and analyzer that are controlled by the TP3-TP4 DAS. The setup allowed for automated measurements of oxygen concentrations at TP-2, TP-3, and TP-4, although the system is shut down during the winter.

1.2.5 Analysis

Field performance monitoring data presented focuses on oxygen ingress and net percolation.

Net Percolation:

The test plot net percolation values shown in Tables 1.1, 1.2, 1.3, and 1.4 are for a "monitoring period" basis (i.e. October to September) because precipitation occurring in the late fall and winter contributes to percolation during the following spring. A negative value implies that gradients within the lysimeter were upward and no percolation reported to the lysimeter.

The net percolation measured at TP-1 is displayed in three-month segments or "seasons" in Table 1.1. October to December is the fall season that generally receives high amounts of precipitation both in the form of rainfall and snow. Over 320 mm of net percolation was calculated from the water level measurements recorded by the pressure transducer during the October to

December 1999 period. The winter months are considered to be January, February, and March. Few changes in the net percolation are expected during this period as the upper part of the profile is likely frozen. April to June is classified as the spring season; some net percolation is expected due to the melt of the winter snow pack and any spring precipitation events that occur. The net percolation during this period will also be influenced by the climate; the early onset of the summer season (i.e. an increase in evapotranspiration rates) might reduce the amount of downward net percolation experienced. Net percolation calculated from the pressure transducer for the winter and spring season was 5.8 mm and 4.2 mm, respectively. The summer season months of July, August, and September are often hot and dry at the site. Generally, an upward movement of water, or negative percolation, is expected during this period such as in 2000 when an upward movement of 107 mm of percolation was measured. However, large rainfall events have the potential to produce downward net percolation.

Table 1.1 also presents the net percolation as a percentage of the total precipitation for the manual and pressure transducer measurements. The percentage net percolation values are calculated in six-month segments, the “cold” six months (October to March) and the “warm” six months (April to September), and for the entire year. The manual and pressure transducer net percolation values were 11% and 20%, respectively, in the 1999-2000 period, and 21% (pressure transducer) and 4.3% (manual measurement) for the 2000-2001 monitoring period.

Table 1.1

Net percolation measured at TP-1 for Myra Falls.

Season	Year	Net Percolation (mm)		Precipitation (mm)	Net Percolation (%)	Net Percolation (%)
		Pressure Transducer	Manual Measurement			
Oct - Dec	1999	320.2	320	1,434	% Percolation (P.T.) = 23%	Over 1 Year Period: Precipitation 2,065 mm % Percolation (P.T.) = 11% % Percolation (M.M.) = 20%
Jan - Mar	2000	5.8			% Percolation (M.M.) = 22%	
Apr - Jun	2000	4.2	91.1	631	% Percolation (P.T.) = -16.3%	
Jul - Sept	2000	-107.4			% Percolation (M.M.) = 14.4%	
Oct - Dec	2000	389.3	34.6	1,345	% Percolation (P.T.) = 30%	Over 1 Year Period: Precipitation 1,957 mm % Percolation (P.T.) = 21% % Percolation (M.M.) = 4.3%
Jan - Mar	2001	15.2			% Percolation (M.M.) = 2.6%	
Apr - Jun	2001	-25.5	48.8	612	% Percolation (P.T.) = 1.8%	
Jul - Sept	2001	36.4			% Percolation (M.M.) = 8.0%	

MM = Manual Measurement

PT = Pressure Transducer Measurement

Table 1.2
Net percolation measured at TP-2 for Myra Falls.

Season	Year	Net Percolation (mm)		Precipitation (mm)	Net Percolation (%)	Net Percolation (%)
		Pressure Transducer	Manual Measurement			
Oct - Dec	1999	6.9	49.0	1,434	% Percolation (P.T.) = 0.2%	Over 1 Year Period:
Jan - Mar	2000	-3.6			% Percolation (M.M.) = 3.4%	Precipitation 2,065 mm
Apr - Jun	2000	-70.1	27.6	631	% Percolation (P.T.) = -1.9%	% Percolation (P.T.) = -0.4%
Jul - Sept	2000	57.8			% Percolation (M.M.) = 4.4%	% Percolation (M.M.) = 3.7%
Oct - Dec	2000	-10.6	29.2	1,345	% Percolation (P.T.) = -0.5%	Over 1 Year Period:
Jan - Mar	2001	4.3			% Percolation (M.M.) = 2.2%	Precipitation 1,957 mm
Apr - Jun	2001	7.6	17.9	612	% Percolation (P.T.) = 2.8%	% Percolation (P.T.) = 0.6%
Jul - Sept	2001	9.7			% Percolation (M.M.) = 2.9%	% Percolation (M.M.) = 2.4%

MM = Manual Measurement
PT = Pressure Transducer Measurement

Table 1.2 shows the net percolation calculated from manual and pressure transducer measurements at TP-2, the compacted flyash-till test plot, for the October 1999 to September 2001 monitoring period.

TP-2 does not show the same distinctive net percolation patterns as shown in the uncovered TP-1. The net percolation from October 1999 to September 2001 was approximately 2 mm for the pressure transducer readings and 124 mm based on the manual measurements. The net percolation as a percentage of the precipitation was low for both years of the monitoring period. Net percolation was –0.4% of the annual precipitation as measured by the pressure transducer, and 3.7% based on the manual measurement during the 1999-2000 period. Net percolation was slightly less in the 2000-2001 period; percolation calculated from the pressure transducer measurements was 0.6%, while the manual measurement percolation was 2.4%.

Table 1.3 presents the net percolation calculated from manual and pressure transducer measurements at TP-3, the compacted native till material test plot, for the October 1999 to September 2001 monitoring period.

The net percolation based on the pressure transducer and manual measurements are not as similar at TP-3 when compared to the other test plots. The net percolation from the pressure transducer over the two-year monitoring period was –46 mm, compared to 202 mm calculated from manual measurements. The pressure transducers show increased upward movement of water in the July to August fall months in both 2000 and 2001. The net percolation obtained from the manual measurements is approximately 5% of the total annual precipitation for both years of the monitoring period.

Table 1.3
Net percolation measured at TP-3 for Myra Falls.

Season	Year	Net Percolation (mm) Pressure Transducer	Net Percolation (mm) Manual Measurement	Precipitation (mm)	Net Percolation (%)	Net Percolation (%)
Oct - Dec	1999	-3.9	55	1,434	% Percolation (P.T.) = -0.2% % Percolation (M.M.) = 3.8%	Over 1 Year Period: Precipitation 2,065 mm % Percolation (P.T.) = -0.8% % Percolation (M.M.) = 4.6%
Jan - Mar	2000	1.1				
Apr - Jun	2000	-0.8	40	631	% Percolation (P.T.) = -2.1% % Percolation (M.M.) = 6.3%	
Jul - Sept	2000	-12.8				
Oct - Dec	2000	1.2	52	1,345	% Percolation (P.T.) = -0.1% % Percolation (M.M.) = 3.8%	Over 1 Year Period: Precipitation 1,957 mm % Percolation (P.T.) = -1.5% % Percolation (M.M.) = 5.5%
Jan - Mar	2001	-1.9				
Apr - Jun	2001	-9.1	56	612	% Percolation (P.T.) = -4.8% % Percolation (M.M.) = 9.1%	
Jul - Sept	2001	-20.2				

MM = Manual Measurement
PT = Pressure Transducer Measurement

Table 1.4
Net percolation measured at TP-4 for Myra Falls.

Season	Year	Net Percolation (mm) Pressure Transducer	Net Percolation (mm) Manual Measurement	Precipitation (mm)	Net Percolation (%)	Net Percolation (%)
Oct - Dec	1999	-28.9	-120	1,434	% Percolation (P.T.) = 0.8% % Percolation (M.M.) = -8.4%	Over 1 Year Period: Precipitation 2,065 mm % Percolation (P.T.) = 3.0% % Percolation (M.M.) = -4.5%
Jan - Mar	2000	40.7				
Apr - Jun	2000	52.2	27.0	631	% Percolation (P.T.) = 7.8% % Percolation (M.M.) = 4.3%	
Jul - Sept	2000	-3.1				
Oct - Dec	2000	-20.5	-1.8	1,345	% Percolation (P.T.) = -0.1% % Percolation (M.M.) = -0.1%	Over 1 Year Period: Precipitation 1,957 mm % Percolation (P.T.) = 1.8% % Percolation (M.M.) = 0.7%
Jan - Mar	2001	18.8				
Apr - Jun	2001	29.8	14.7	612	% Percolation (P.T.) = 6.0% % Percolation (M.M.) = 2.4%	
Jul - Sept	2001	7.0				

MM = Manual Measurement
PT = Pressure Transducer Measurement

Table 1.4 presents the net percolation calculated from manual and pressure transducer measurements at Test Plot No. 4, the compacted processed till and bentonite test plot, for the October 1999 to September 2001 monitoring period.

The results from the TP-4 vary in a similar manner as described for TP-3. The net percolation from the pressure transducer over the two-year monitoring period was 96 mm, compared to -80 mm calculated from manual measurements. The results calculated from the pressure transducer readings fluctuate between upward (negative) percolation and downward percolation. The annual net percolation measured from the pressure transducers was 3.0% of the annual precipitation in 1999-2000 and 1.8% in 2000-2001.

Moisture Storage and Transport:

The average degree of saturation of the compacted till-flyash layer and the non-compacted layer at TP-2 is shown in Figure 1.6. The data shown in Figure 1.6 is calculated by averaging the response of the individual sensors in each layer that were installed across the thickness of the layer. For example, the average degree of saturation values calculated for the compacted till-flyash layer is based on the response of four sensors. Note that the data shown is based on the response of both the suction sensors and the volumetric water content sensors. The non-compacted material has lower moisture conditions than the compacted till-flyash layer, which is to be expected as it is exposed to the atmosphere. In addition, the response to the demand for moisture during the summer is more significant. The till-flyash compacted layer does not maintain tension saturation conditions during the hot dry summer months at the site. The average degree of saturation of the compacted till-flyash layer dropped to approximately 50% during the summers of 1999 and 2000 in response to the demand for moisture from the atmosphere. This is not a desirable performance characteristic because it implies an increase in oxygen diffusion coefficients and ultimately an increase in oxygen ingress during these hot dry periods. However, it should be noted that in each case the degree of saturation of the compacted till-flyash layer "recovers" to tension saturated conditions during wet climate conditions.

There are three key reasons for the performance of the compacted till-flyash layer shown in Figure 1.6, all of which contribute to the measured performance. First, the till-flyash material itself does not possess sufficient moisture retention to "oppose" the demand for moisture and thus significantly limit the reduction in moisture content. Second, the overlying non-compacted growth medium does not possess sufficient moisture storage and retention such that this layer alone satisfies all of the atmospheric demand for moisture. This simplest solution for this problem is to increase the thickness of the non-compacted layer, which would also be more consistent with rooting depths of undisturbed areas at the site. Finally, the hot dry summers that are prevalent at the site contribute to the decrease in moisture conditions of the compacted till-flyash layer. This is important to note because it is a common mistake during cover system design to assume that if there is a moisture surplus on an annual basis, then limiting oxygen ingress will be possible. However, the data shown for the past three years at this site clearly demonstrates that performance of a cover system should be based on at least a seasonal basis, if not a monthly or daily basis. There are essentially two prevalent climate “regimes” at the site; namely, wet falls, winters, and springs, followed by hot dry summers. It is important to note that these climate characteristics are very common at mine sites across Canada, which is an issue that should be addressed as part of the cover system design.

The performance of the compacted till-flyash layer was not as designed. The primary reason for the difference in performance between that anticipated and that measured during the past three years is illustrated in Figure 1.3. A SWCC of a compacted till-flyash sample collected after construction of the test plots is shown in Figure 1.3. The SWCC of the compacted till-flyash layer used during the design stage of the project is significantly difference than that measured on the till-flyash mixture obtained during construction of the test plots. The latter material possesses significantly less ability to retain moisture as suction increases. The performance of the compacted native till layer and the non-compacted native till at TP-3 was similar to that described for TP-2, in that the demand for atmospheric moisture during the summer was satisfied by the compacted native till layer. This performance was anticipated based on the soil-atmosphere cover design modelling.

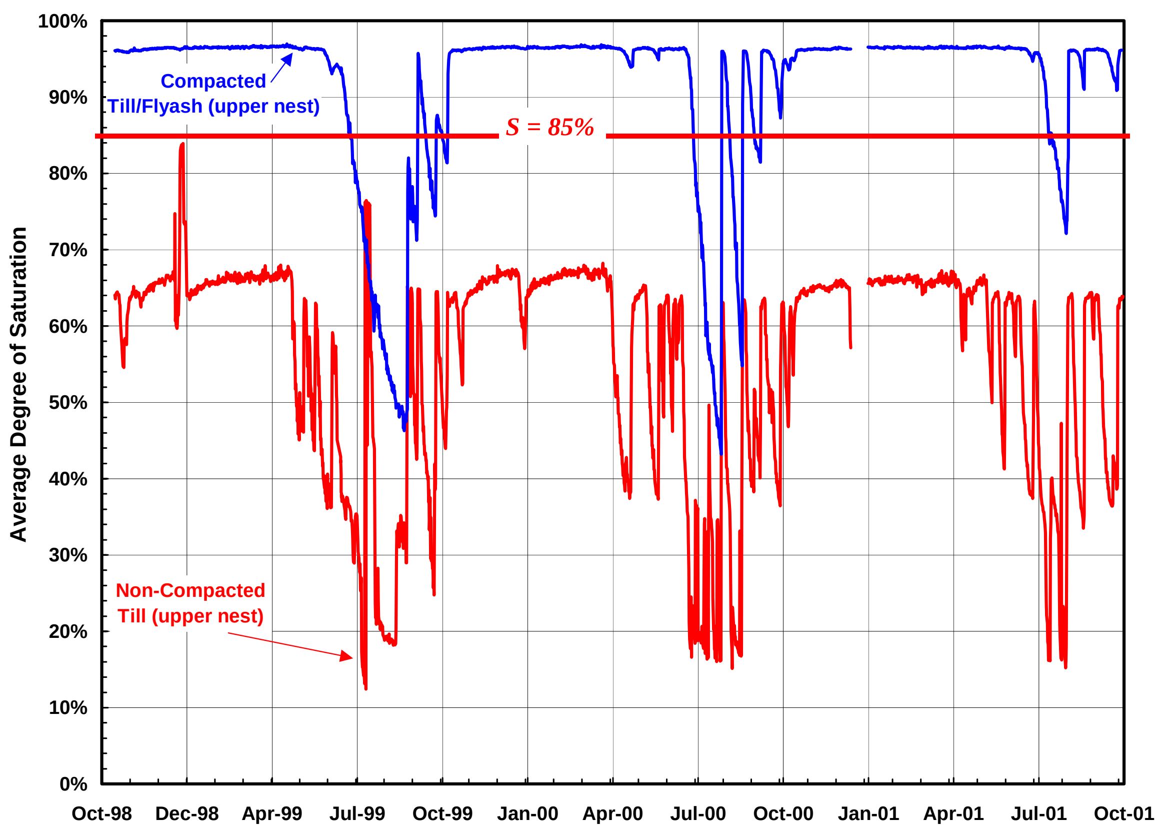

Figure 1.6 Average degree of saturation of the compacted till-flyash and non-compacted native till at TP-2 for Myra Falls.

Figure 1.7 shows the average degree of saturation for the compacted till-bentonite layer, the compacted native till layer, and the non-compacted till layer at TP-4. The performance of the compacted till-bentonite layer is characteristic to that discussed earlier for the till-flyash and native till compacted layers at TP-2 and TP-3, respectively. However, the compacted till-bentonite material possesses significantly more moisture retention as suction increases (see Figure 1.3), and therefore the average degree of saturation of the compacted till-bentonite layer during the summer remains above or just below 85%. This is a positive performance results, as is the ability of this layer to "recover" and increase in moisture content is response to wet climate conditions. Figure 1.8 clearly shows that the decrease in moisture content within the compacted till-bentonite layer is a function of the demand for atmospheric moisture during the summer. The sensor installed near the upper interface of the compacted till-bentonite layer decreases in moisture content during the summer, while the sensor at the base of the layer maintains tension saturated conditions throughout the summer.

Temperature:

The temperature data collected during the monitoring period illustrates that any overlying snow pack and the presence of the non-compacted layer provided insulation for the compacted layers at each of the test plots.

Oxygen Concentration:

The oxygen concentration data collected during the monitoring period agrees with the moisture content data presented earlier. Gaseous oxygen concentration measured below the compacted till-bentonite layer was consistently near zero, while the measurements below the compacted layers at TP-2 and TP-3 were variable in response to the seasonal change in moisture conditions of the compacted layers.

Hydraulic Flow Gradients:

The *in situ* matric suction conditions were indirectly measured with thermal conductivity sensors within the test plot cover layer and underlying waste rock material. The *in situ* matric suction at each sensor was measured at two-hour intervals. The sensors were installed above each other during construction of the test plots to create a vertical nest of sensors, one nest located up-gradient of the lysimeter and one located down-gradient.

The vertical and horizontal gradients can be evaluated from the *in situ* matric suction data. The vertical gradient was calculated from the difference in the matric suction values between the 0.75 m deep sensor in the test plot cover material and the 0.85 m deep sensor in the waste rock material for TP-2, TP-3, and TP-4. The horizontal gradient was calculated from the difference in the average *in situ* suction condition of the 0.45 m, 0.60 m, and 0.75 m deep sensors located up-gradient and down-gradient of the lysimeter tank.

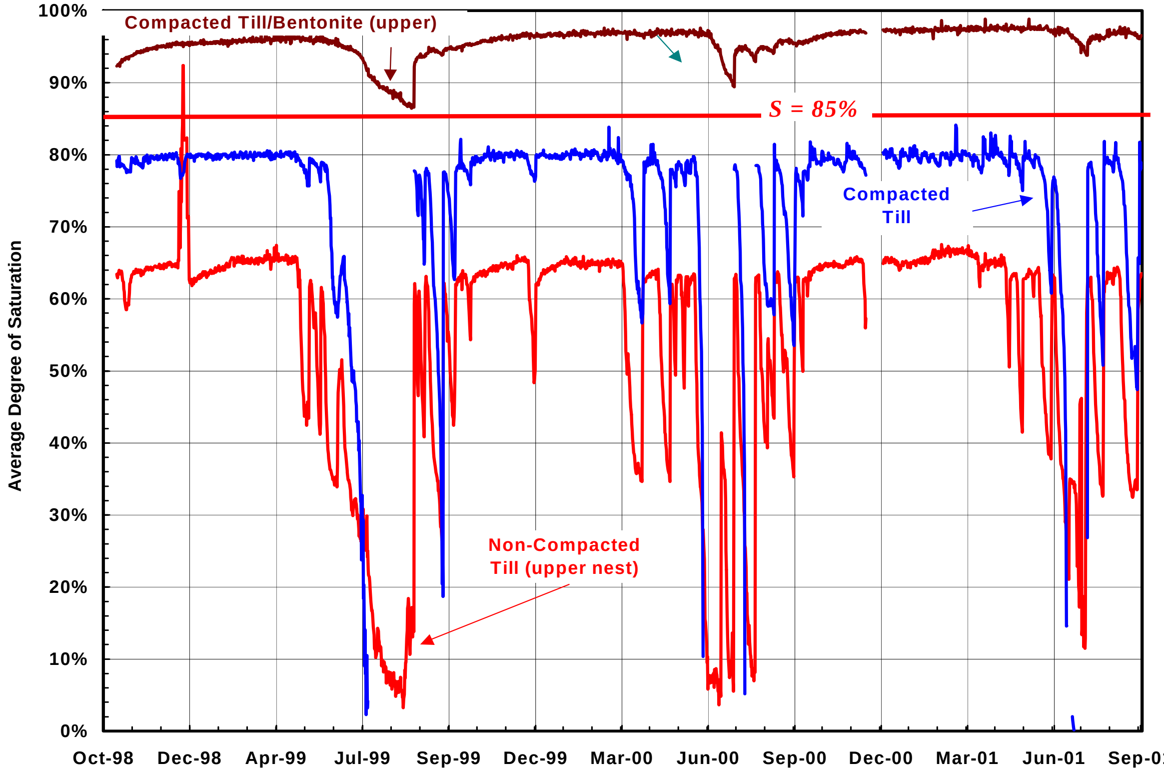

Figure 1.7 Average degree of saturation of the compacted till-bentonite and non-compacted native till at TP-4 for Myra Falls.

The vertical gradient between the 0.75 m and 0.85 suction sensors in the upper suction sensor nest of TP-3 is shown in Figure 1.9, together with the cumulative net percolation. A positive gradient indicates the potential for downward percolation, whereas a negative gradient implies upward flow. The gradient is negative or upward for the majority of the year, which is unexpected especially during the fall and spring seasons. This could be due to the low *in situ* suctions being measured at the cover layer / waste rock interface, and the small distance between the sensors. For example, if one sensor reads 7 kPa suction when the suction condition is actually 5 kPa, then it could lead to inconsistencies in the calculated vertical gradients. The significant trend shown on Figure 1.9 is the strong upward gradient produced in the summer months at TP-3. The conditions suggest that the lysimeter is “drying out” as water is “pulled up” from the lysimeter into the cover layer in response to atmospheric forcing. This response is shown in the pressure transducer readings as an upward net percolation is measured during the summer months in 2000 and 2001.

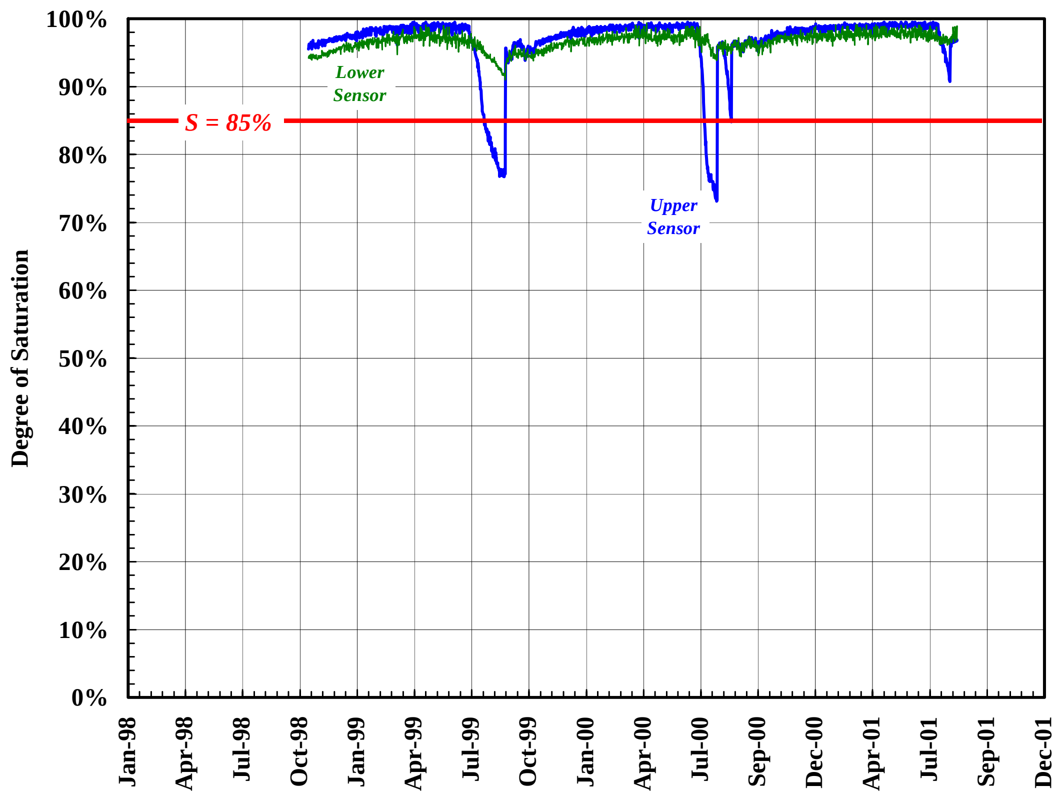

Figure 1.8 Degree of saturation of the upper and lower sensors installed in the compacted till-bentonite layer at TP-4 for Myra Falls.

The horizontal gradient defines the direction of lateral flow within the test plot cover layer. A positive gradient indicates a flow from the upper area of the cover layer to the lower area. A high lateral gradient suggests the compacted cover layer is diverting flow from percolating vertically into the underlying waste rock material. Figure 1.10 compares the lateral gradient to the vertical gradient for up-gradient nest of suction sensors. The gradients mimic each other and an up-slope lateral gradient is seen in the summer months when there is a strong upward vertical gradient. However, the lateral gradient is approximately 100 times smaller than the vertical gradient indicating that the lateral gradient has a small influence on flow for the conditions being monitored. It is important to note however, that for longer slope lengths, and in particular for a steeper slope angle than is being monitored, the lateral hydraulic gradient could be significant. Note also that a calibrated model could be developed for the conditions being monitored, and once developed could then be used to model alternate slope lengths and slope angles to evaluate the impact on performance.

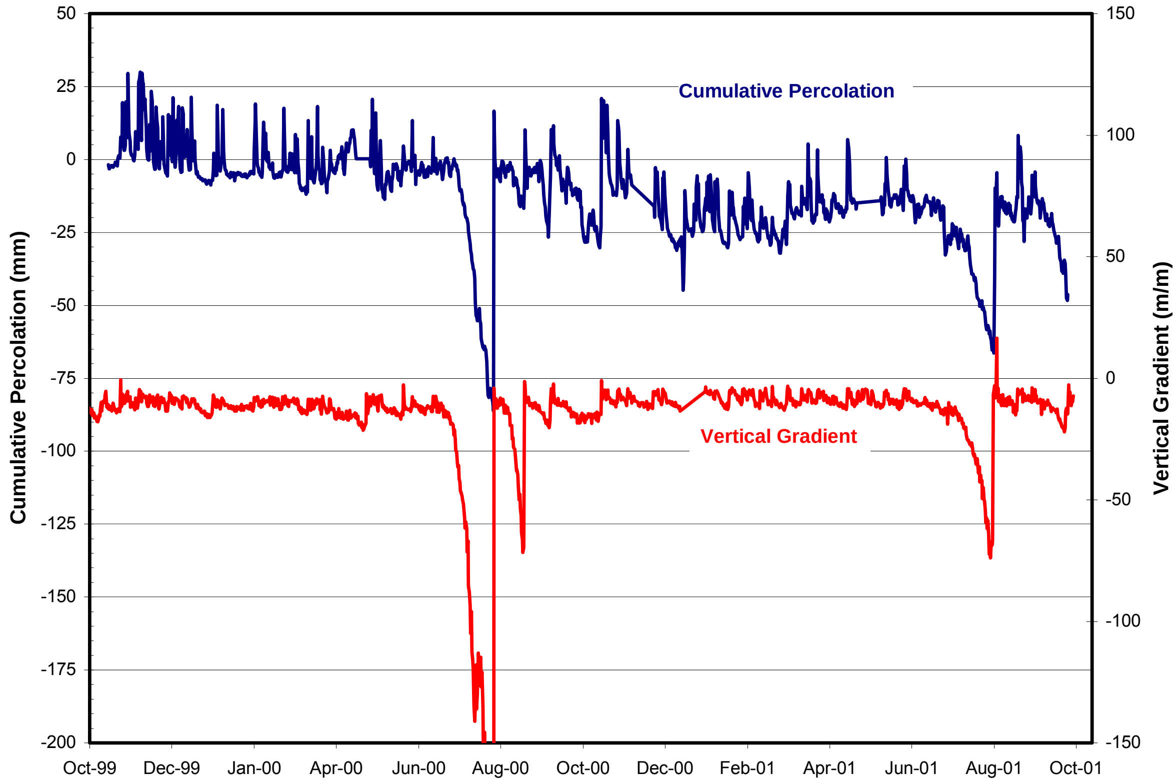

Figure 1.9 Cumulative percolation and vertical gradient measured at TP-3 for Myra Falls.

1.2.6 Summary

The Boliden Myra Falls case study outlines the design of a cover system, construction of test plots, and test plot performance monitoring. The results of the performance monitoring shows that the compacted till-bentonite cover system has been most successful in limiting the infiltration of meteoric water and oxygen ingress to the underlying waste rock material. The compacted till-flyash and compacted till cover systems have produced similar net percolation results and neither have functioned well in maintaining an oxygen ingress layer throughout the year. The amelioration of till with bentonite to produce a compacted barrier layer shows promise in reducing water and oxygen ingress at the MFO site, while the incorporation of flyash with the till did not result in a significant increase in performance.

It is important to note however that desired performance of a full-scale cover system placed over waste rock storage facilities at the site should be put into context of all the closure works planned for the entire MFO site. In other words, the preferred cover system for the waste storage facility should not just be based on arbitrary cover design objectives for net percolation and / or oxygen ingress. The preferred cover system should be based on considering the costs and benefits, as well as predicted impacts to the receiving environment and potential for collection and treatment of any seepage.

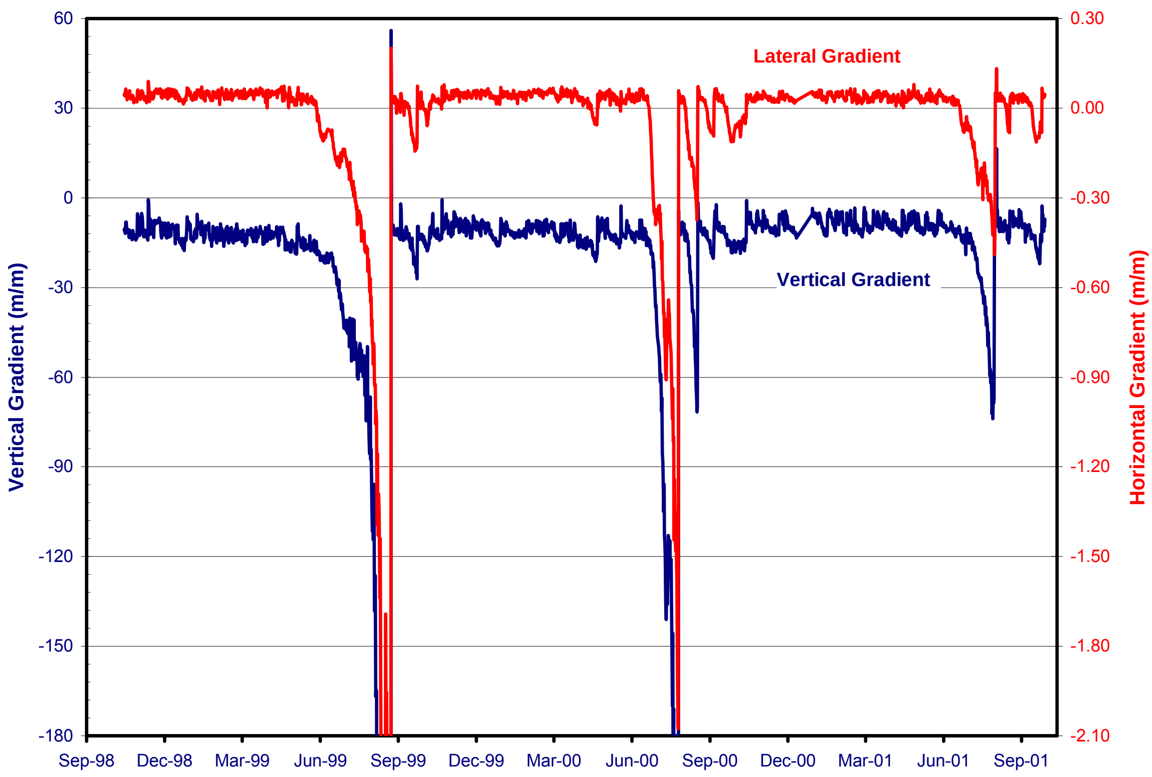

Figure 1.10 Horizontal and vertical hydraulic gradients measured at TP-3 for Myra Falls.

The key lessons learned from this case study were:

- The importance of basing final cover system design on field performance monitoring, as opposed to solely relying on numerical modelling and laboratory based material properties.
- The importance of addressing climate on a seasonal basis as opposed to annual averages to determine cover system performance. Assuming that limiting oxygen ingress is possible simply on the basis that the site has an annual moisture surplus can lead to undesirable cover system performance because of the hot, dry summer conditions that are prevalent at numerous mines sites.
- Caution is required when designing a cover system that utilizes a by-product or waste material such as flyash as there is a high potential that the as-built characteristics of the material will differ from the characteristics during the design phase, especially due to the time frame typically required for a cover design project.

- Considerable attention is typically focused on the placement of the compacted layer during design and construction of a cover system, ensuring proper water content and compaction to produce a low hydraulic conductivity material. While the importance of the "barrier" layer should not be discounted, neither should the importance of the overlying growth medium. Field performance monitoring for this case study shows that the thickness of the overlying growth medium was not adequate to limit de-saturation of the underlying compacted material during hot, dry summer conditions. The numerical modelling completed for the test plot design indicated the thickness was adequate; however, the precipitation and evaporation conditions during monitoring clearly illustrate this is not the case. A growth medium with a greater depth would not only provide an increase in moisture storage capability above the compacted layer, but would also provide rooting depths more consistent with vegetation species native to the area.

2 MEND MANUAL CASE STUDIES – TAILINGS

2.1 Waite Amulet (MEND 2.21.1, 2.21.2)

The evaluation of cover system for the Waite Amulet tailings area consisted of performance monitoring of field test plots at the decommissioned tailings site and laboratory experiments at the Noranda Technology Centre, as well as several universities (MEND 2.21.1, 2.21.2).

2.1.1 Background

The Waite Amulet project was initiated in July 1990 under the MEND program to assess the performance of pilot scale engineered soil cover systems on reactive mine tailings. The principal objective of the project was to design, construct and evaluate the effectiveness of different soil cover systems in reducing acid generation in reactive tailings. The Waite Amulet site was selected for the study.

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.

The normal precipitation at the site is 640 mm, split evenly between rain and snow; the potential evaporation is approximately 500 mm (estimated using the Thornthwaite (1948) method). The average annual maximum and minimum temperatures are 6.9 ^{o}C and –4.3 ^{o}C, respectively.

2.1.2 Test Plots

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 underlying the cover layers, cover material moisture conditions, *in situ* 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 seepage water.

The composite soil cover consisted of a 60 cm thick, compacted, silty clay layer placed between two sand layers, each 30 cm thick. Different proctor densities and moulding water contents were used for the two compacted layers. A final 10 cm gravel crust blanketed the cover system to minimize erosion. Figure 2.1 is a cross section through the Waite Amulet tailings test plots.

These cover layer depths were selected to provide maximum reduction in oxygen ingress 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 laboratory study that concluded the composite cover would be able to resist significant moisture losses during dry climate conditions. The geomembrane cover consisted of an 80 mil (2 mm thick) high-density polyethylene (HDPE) liner material placed between a fine sand and underlying coarse sand layers.

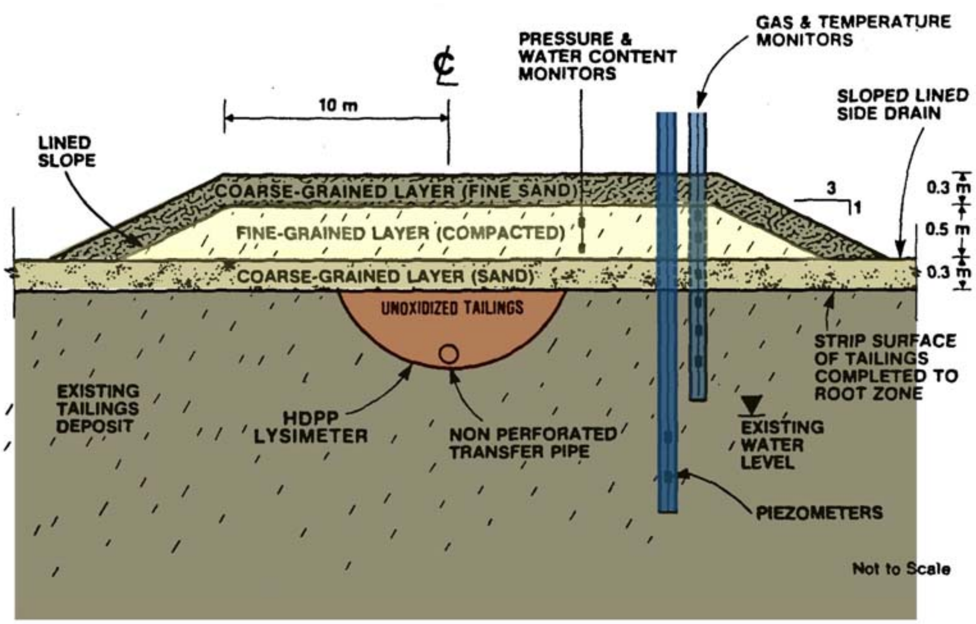

Figure 2.1 Cross-section through composite soil cover test plot at Waite Amulet tailings (from Yanful and St-Arnaud, 1991).

2.1.3 Laboratory Study

The laboratory study consisted of six column tests to simulate covered and uncovered tailings. The covered tailings 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 field test plots. Un-oxidized 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 covered and uncovered tailings were subjected to cyclic wetting and drying, at laboratory temperatures. Gaseous oxygen concentration, moisture conditions, temperature, and drainage water quality were monitored during the laboratory study. The covered tailings did not produce any seepage during normal wetting or rain application because of the low hydraulic conductivity of the compacted clay layer. A large majority of the water applied to the surface of the covered tailings during the column test reported as runoff. The covered tailings were periodically flushed (by-passing the soil cover) to collect pore-water and assess the degree of sulphide oxidation.

2.1.4 Summary

Results of the laboratory, field and modelling studies indicated that ingress of oxygen was reduced by 91% to 99% due to the presence of the cover material as compared to the uncovered tailings. Hydrologic modelling indicated that water percolation through the composite cover was approximately 4% of the incident precipitation. Field lysimeter data indicated that 6% of the annual incident precipitation percolated to the underlying tailings. This represented a reduction of 80% in the total annual infiltration as compared to the uncovered tailings. It was concluded that freezing and thawing did not adversely affect the cover and that no future negative effects would be anticipated, based on the field results, as well as results from the laboratory freeze-thaw studies. It was also found that the long-term stability of the HDPE cover was not a major concern except for the possible effects of equipment, burrowing animals, and sunlight.

The MEND 2.21.3a report, which provides a critical, peer review of this project, states that the soil cover system installed at the Waite Amulet site performed satisfactorily. It was also stated that 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. One concern raised in the MEND 2.21.3a report was the costs associated with the construction of the Waite Amulet cover system.

The lesson learned from this case study was the importance of using site specific climate data. The data used for the Waite Amulet modelling had similar total monthly precipitation, but different frequency and duration of precipitation events.

The key lessons learned from this case study were:

- The importance of a systematic approach to demonstrating new technology while moving from a theoretical basis, to laboratory scale tests, and finally to field trials.
- Field demonstration of the capillary barrier concept for conditions prevalent at mine sites in Canada.
- The importance of utilizing site specific climate for the a cover system design project. The data used for the Waite Amulet modelling was from a regional meteorological station, which had similar total monthly precipitation as the site, but different frequency and duration for the precipitation events.

The reader is referred to the MEND reports referenced in this section, as well as Yanful (1991), Yanful and St-Arnaud (1991, 1992), Yanful and Aubé (1993), Woyshner and Yanful (1993), and Yanful *et al.* (1993a) for additional details on the Waite Amulet project.

2.2 Les Terrains Aurifères (MEND 2.22.4)

2.2.1 Background

Les Terrains Aurifères (LTA) is a mining property located about 8.5 km east of the city of Malartic in Abitibi, Québec. The property consists of a mine, closed since 1965, a mill, and a tailings impoundment. The mine was operated during two distinct phases. During mining operations in the 1930's, roughly 10 Mt of non acid-generating tailings, having a buffering capacity of 100 kg/t ($CaCO_3$ equivalent), were deposited in a 5 m layer over the entire site. The mine reopened in 1977 and approximately 7.7 Mt of acid generating tailings (200 kg/t $CaCO_3$ equivalent) were placed over half the surface of the old site, to a thickness of 12 m.

Several laboratory and field studies were carried out under MEND prior to the design and construction of a full-scale cover system for the tailings facility at the Les Terrains Aurifères (LTA) site (MEND 2.22.4). The results of the studies conducted prior to the LTA project were instrumental in the final design of the tailings cover system, and are summarized briefly below, followed by an update on the field performance of the constructed full scale cover system.

2.2.2 Laboratory Study

Laboratory studies were completed between 1991 and 1996 at l'École Polytechnique de Montréal on the feasibility of using clean (i.e. non-acid generating) tailings for the moisture retention layer in a multi-layer cover system (MEND 2.22.2a, 2.22.2b). The impetus for this research was to find a lower cost alternative for the fine-textured layer for sites where clean cover material is not available near the site. Clean tailings can be obtained from milling sulphide-free ore, or by using a desulphurization process, which has been investigated by Bussière *et al.* (1997), Benzaazoua *et al.* (1998), and others. The studies have shown that if high saturation ($\geq$ 90%) can be maintained in the cover through capillary barrier effects, then a layer of fine material (i.e. tailings) sandwiched between two sand layers will effectively reduce the oxygen flux to the reactive tailings materials by a factor of 1,000 of more. Theoretically, the efficiency of a cover system then becomes comparable to that of a water cover of the same thickness (MEND 2.22.2a).

2.2.3 Experimental Cells at Norebec-Manitou

Six experimental cells were constructed in 1995 at the Norebec-Manitou site near Val d'Or, Québec to evaluate, on a larger scale and under more realistic conditions, the performance of multi-layer covers built with clean tailings (MEND 2.22.2c, Aubertin *et al.* 1997a). A laboratory study was conducted in parallel to this field program to characterize the material properties and evaluate, under controlled conditions, the behaviour of the same cover systems constructed in the field. MEND 2.22.2b presents the material properties and the content of the various laboratory columns. Preliminary results from the column testing revealed the various layered cover systems had a similar hydraulic behaviour to the layered system evaluated in MEND 2.22.2a.

MEND 2.22.2c and Bussière and Aubertin (1999) describe the experimental cells and the instrumentation installed in each test cover, as well as present and discuss the results of nearly four years of monitoring. Each of the five test covers (one cell was a control plot) had three layers placed on reactive tailings. The top and bottom layers consisted of 0.3 m and 0.4 m of relatively coarse sand, respectively. The fine material layer, placed between the two sand layers, was either made of clean tailings with different thicknesses (three cells: 0.3, 0.6 and 0.9 m), of a natural silty soil (one cell: 0.6 m), or a mixture of bentonite and clean tailings (one cell: 0.3 m). The field performance monitoring program consisted of routine measurements of volumetric water content, matric suction, oxygen flux, and chemical composition of the leachate.

The key monitoring results from the MEND 2.22.2c field project include the *in situ* water content profiles and oxygen fluxes measured through the various test covers. The water content profile showed that the degree of saturation in the fine-textured layer of each test cover remained high (usually above 85%). The oxygen consumption tests demonstrated that after the first year, the oxygen flux through the covers became very low compared to the control (uncovered) cell. The conclusion from all the different monitoring results is that clean tailings can be used as fine-textured material in a multi-layer cover system to control the production of AMD from sulphidic tailings (MEND 2.22.2c; Bussière *et al*., 2000).

2.2.4 LTA Cover Construction

The design, construction and instrumentation of the cover system built on the LTA tailings impoundment and the external slopes is described by MEND 2.22.4a, MEND 2.22.4b and Ricard *et al.* (1997, 1999). A multi-layer cover system, using clean tailings for the moisture retention layer, was selected as the closure option based on the promising results obtained from MEND 2.22.2a,b,and c. The goal was to assess the large-scale performance of a composite cover placed on the acid-generating tailings impoundment (MEND 2.22.4).

The LTA project is a landmark tailings cover system construction project because it was likely the first large-scale multi-layer cover system implemented in Canada. Approximately 60 ha of reactive tailings were covered with 0.5 m of sand placed directly on the tailings (Figure 2.2). This capillary barrier layer was overlain with 0.8 m of locally available compacted clean tailings. The compacted clean tailings were overlain with an upper layer capillary barrier material consisting of 0.3 m sand and gravel. The optimum configuration was calculated using a simplified one-dimensional cover design model and a two-dimensional saturated-unsaturated numerical model. Input data was based on laboratory characterization tests.

Construction of the 1.6 m thick composite cover on top of the LTA tailings impoundment proved to be a challenge due to the elevated phreatic surface in the tailings. The Zone 1 layer (Figure 2.2) required placement and compaction during winter while the underlying tailings surface was frozen. This enabled movement of heavy equipment on the tailings surface and prevented migration of LTA tailings particles into the Zone 1 layer (MEND 2.22.4a). Cover construction was completed during the winter of 1995/1996 and the summer of 1996 using a comprehensive QA/QC program. The final cost of the LTA composite cover, an area of almost 60 hectares, was $3.9M or approximately $65,000/ha.

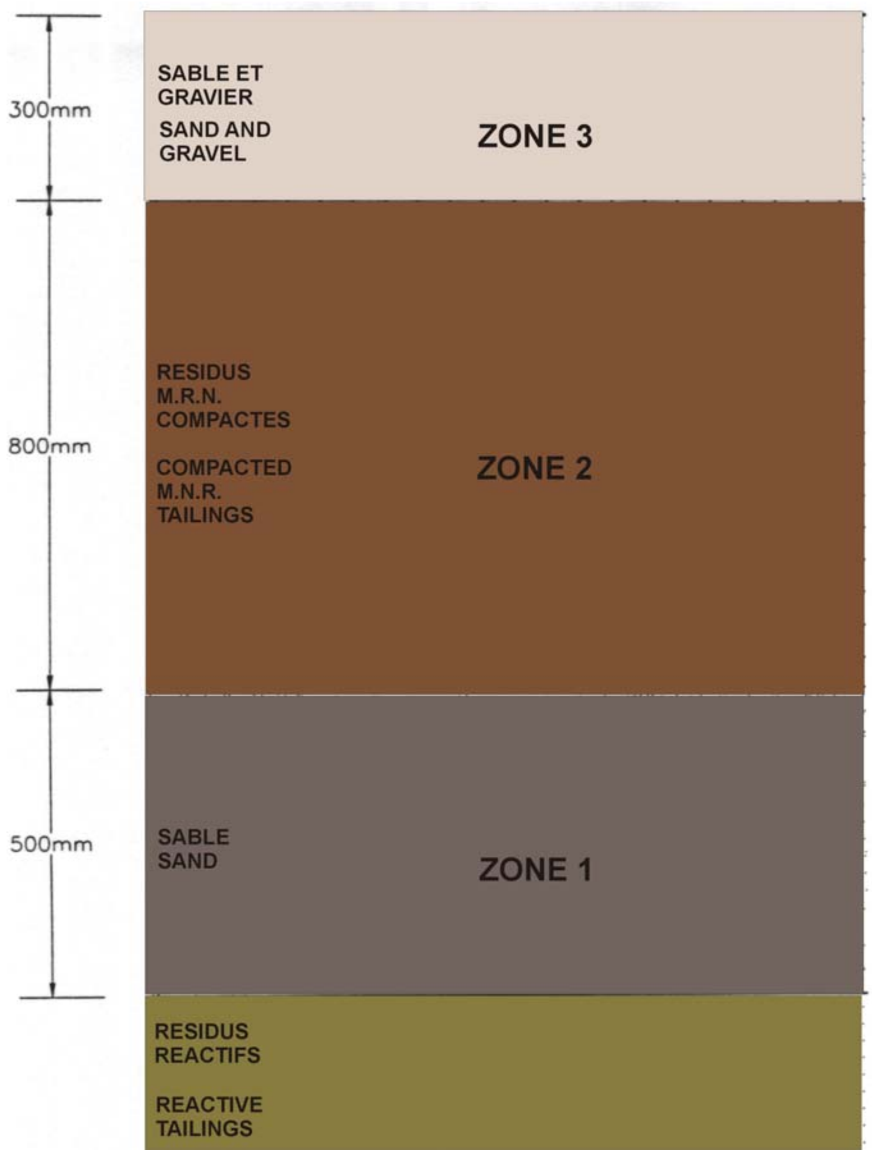

Figure 2.2 Stratigraphy of the LTA cover system (from MEND 2.22.4a).

2.2.5 Field Performance Monitoring

Field performance monitoring of the constructed cover system commenced in the fall of 1996 and has continued for a seven-year period (Bussière *et al.*, 2003). Several instrumented stations were installed on top of the impoundment and in the outer slopes of the dykes for monitoring *in situ* volumetric water content, *in situ* matric suction, and oxygen fluxes through the cover system

(MEND 2.22.4b). The results of the field performance monitoring are presented in Bussière *et al.* (2003), and are summarized in the following.

The aim of the cover is to use capillary barrier effects (CCBE) to maintain a high degree of saturation in the moisture-retaining layer. A typical volumetric water content profile in an effective CCBE corresponds to low water contents in the two coarse-grained materials and high water contents in the moisture retaining layer (e.g. MEND 2.22.2a, Aubertin *et al.*, 1996; Bussière and Aubertin, 1999). With the exception of the CCBE south section where the phreatic surface is located in the cover, the volumetric water content values measured at the different stations since 1996 are typical of those expected for an effective CCBE. As an example, Figure 2.3 shows the evolution of volumetric water content measurements since 1996 at Station CS 96-1 (located on a flat section of the cover in the northwest corner). In this figure, CS 96-1-T1 corresponds to the volumetric water content in the bottom sand layer (capillary break layer) while CS 96-1-T3 and CS 96-1-T5 correspond to volumetric water content measured at the bottom and at the top of the moisture-retaining layer, respectively. The water content values measured by TDR probes CS 96-1-T3 and CS 96-1-T5 are usually greater than 37% (corresponding to degree of saturation values greater than 84% for a porosity of 0.44), while the conditions measured by CS 96-1-T1 are usually between 12% and 18% (corresponding to degree of saturation values between 34% and 51% for a porosity of 0.35). The fact that the volumetric water content in the bottom sand layer (CS 96-1-T1) is much lower than those measured by the probes in the moisture-retaining layer clearly indicates the creation of the desired capillary barrier effects.

The results of the monitoring on the sloping surfaces of the cover showed that the upper slopes have a tendency to de-saturate during prolonged drying events. However, precipitation events have been shown to quickly recharge the moisture retaining layer on the sloping surfaces. The lower slopes have similar behaviour to the flat surfaces of the full scale cover system.

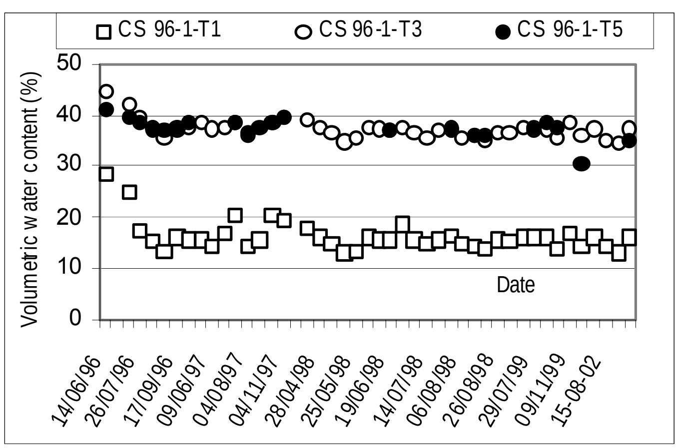

Figure 2.3 Moisture content results from the CS 96-1 T1 station showing capillary barrier effects (Bussière *et al.*, 2003).

2.2.6 Summary

The LTA site is one of the first mine tailings impoundment sites that has been rehabilitated with a cover with capillary barrier effects. The site has been continuously monitored since its construction in 1996. The main results from the seven-year monitoring program are:

- Overall, the cover is performing as designed where the degree of saturation in the moisture-retaining layer is well above the design criteria of 85%.
- It has been demonstrated that it is more difficult on the sloping cover to maintain the desired volumetric water content in the moisture-retaining layer, which can influence the performance of the cover system with respect to control of oxygen ingress. The upper part of the slopes is more affected by the de-saturation process than the lower part, particularly during prolonged dry periods; however, recharge occurs during precipitations events. While it is now understood how to mitigate such effects, it is not considered necessary to modify the cover system as the overall performance has shown the cover system is achieving the original objectives.
- In the south section of the site, the phreatic surface is located in the cover system, which explains the high water content values in the capillary break layer and moisture-retaining layer.
- In the areas where the phreatic surface is well below the cover, capillary barrier effects are produced.

Even if the upper part of the slope may, under specific situations (prolonged dry periods), temporarily not meet the design criteria of a minimum 85% degree of saturation, the overall performance of the CCBE on the 60 ha site exceeds expectations from the design stage. More work is presently being done to evaluate the performance of the LTA cover by integrating the slight reactivity of the MRN tailings, which may have a positive impact on its ability to limit gas diffusion (Bussière *et al.*, 2002; Mbonimpa *et al.*, 2003), and by performing other tests such as long-term oxygen consumption tests (Mbonimpa *et al.*, 2002).

The lessons learned from this project are

- It is fundamental to take into account slope effects (i.e. slope length, slope angle, contrast between the two materials, and surface flux boundary conditions) when designing cover systems with capillary barrier effects. For more information on slope effects see Ross (1990); Stormont (1996); Miyazaki (1993); Aubertin *et al*. (1997); Bussière (1999); MEND 2.22.4b, and Bussière *et al.* (2001, 2003).
- Winter construction is beneficial for cover placement over tailings with a high phreatic surface.

- Using appropriate waste material produced at the site, or a nearby site (even from another industry), is the most logical source of potential cover material. The LTA project demonstrated that locally available material (i.e. non-reactive tailings) for cover construction is a technically and financially viable component of a closure plan.

Further details on certain aspects of this project can be found in McMullen *et al*. (1997), Aubertin *et al*. (1997a, 1997b), and Bussière *et al*. (1997, 1998).

2.3 Oxygen Consuming Organic Cover Systems: Background Studies (MEND 2.25.1)

2.3.1 Background

Large quantities of organic material are now stockpiled, or may be available in the near future, from urban and industrial sources. Cities in Ontario are capable of producing approximately 680,000 tonnes of municipal solid waste (MSW) compost annually and create comparable amounts of sewage sludge, which is currently landfilled (MEND 2.25.1a). Peat from bogs in the Canadian Shield region, although not a waste material, represent a vast renewable source of organic matter. Peat bogs are often found near base metal and precious metal mines.

These materials may provide effective and affordable solutions to the reclamation of acidic mine tailings. In essence, a source of waste from one industry could be used to resolve problems associated with wastes from another industry (i.e. “two wrongs make a right”). A literature review of the physical and chemical characteristics of MSW compost and other organic materials (MEND 2.25.1a) illustrated that an organic cover on sulphide tailings could be beneficial in suppressing tailings oxidation and consequently AMD as a result of:

1. *A Physical Oxygen Barrier:* the organic layer may be saturated with water over at least part of its depth;
2. *An Oxygen Consuming Barrier:* the continued decomposition of organic material may create a large biological oxygen demand which can act as a sink for meteoric oxygen and dissolved oxygen within infiltrating water;
3. *Chemical Inhibition:* compounds and decomposition products in the organic material that leach into the tailings may inhibit the growth and metabolism of sulphate producing (acidifying) bacteria;
4. *Chemical Amelioration:* organic compounds in the organic material may cause the reductive dissolution of iron oxides (either directly or indirectly by providing metabolic substrates for bacteria), the reduction of sulphate, and the prevention of indirect ferrous sulphide oxidation and acid generation; and
5. *By Reduced Water Infiltration:* the decomposition and resultant compaction of an organic cover layer may result in the decrease of the hydraulic conductivity of the cover. This would decrease infiltration, thus decrease seepage of tailings pore-water to groundwater.

MEND 2.25.1a stated that MSW compost or other organic wastes will be useful for the mining industry only if they provide a permanent, socially acceptable, and cost-effective solution to tailings abandonment. Transportation costs from the major MSW sources to remote tailings sites may be prohibitive for a mining company even if the MSW compost is provided at no charge or is subsidized (MEND 2.25.1a).

2.3.2 Summary

MEND 2.25.1b summarizes the results of a laboratory study of using MSW compost as a sulphide tailings cover material, which was conducted based on the positive findings of MEND 2.25.1a. Column studies of mature and fresh MSW compost over sulphide tailings were conducted. MEND 2.25.1b concluded that:

1. There is strong evidence of a reversal of AMD processes in the oxidized tailings;
2. The observed mobilization of iron and sulphate was enhanced by the establishment of strong reducing conditions and the availability of organic substrates for the reductive dissolution of iron oxides by reducing bacteria;
3. The compost and sand cover layer models were more effective at maintaining anoxic or other ameliorative conditions in the tailings than was the ploughed model during the nine-month simulation;
4. Fresh compost treatments are much more effective than mature compost in maintaining high water content and strong reducing conditions at the compost-tailings interface;
5. Fresh compost cover layers showed a greater resistance to the conduction of water that, along with high water content, would seal off the tailings from infiltration of atmospheric oxygen, precipitation, and surface water thus forming a physical oxygen barrier; and
6. Compost quality tests showed that leachate from mature and fresh compost present a low environmental risk for use on mine lands.

The study results from MEND 2.25.1a and MEND 2.25.1b have provided much of the basis for continued work on the area of oxygen consuming organic cover systems. Key issues that need to be addressed further are degradation of the organic material (Tassé, 2000) and potential replenishment of the organic matter. The potential for remobilization of metals also requires further consideration.

Two studies involving the use of organic matter in a cover system for reactive tailings (Strathcona – MEND 2.25.3 and East Sullivan Mine) are discussed below.

2.4 Strathcona Tailings: Organic and Inorganic Cover Materials (MEND 2.25.3)

MEND 2.25.3 summarizes an evaluation of the effectiveness of organic covers in reducing acid generation from sulphidic tailings. Stogran and Wiseman (1995) and Elliot *et al.* (1997) also provide details of the study. The materials evaluated were lime-stabilized sewage sludge (LSSS), MSW compost, and peat. An inorganic material (desulphurized tailings, DST) was also evaluated as part of the project for comparative purposes because of potential production of this material at operating mines. The evaluation included physical and chemical characterization of the tailings and potential cover materials, salt migration column tests, and pilot-scale tests.

The main objective of the study was to comparatively evaluate the effectiveness of various organic cover materials at limiting or reducing the impacts of acid generation on the environment from acid generating tailings. The organic cover materials tested demonstrated that there were significant differences in the ability of each material to provide a beneficial tailings cover. The compost and LSSS were found to be good oxygen barriers as a result of acting as an oxygen sink. In contrast, the peat cover, which had a high humus component and was therefore resistant to further decomposition, was observed to be very susceptible to oxygen diffusion (MEND 2.25.3).

The test results reported illustrate that the LSSS performed best as a tailings cover (i.e. limiting ingress of oxygen to the underlying sulphidic tailings). The peat showed the least favourable cover material characteristics. The desulphurized tailings also performed well but as a fine textured physical barrier for oxygen diffusion, as opposed to an oxygen sink with the LSSS cover material. MEND 2.25.3 recommended that field trials were required to properly evaluate the potential of the two promising cover materials, whether on their own, or blended to improve economics. Longevity is one of the concerns for the LSSS as a potential cover material (i.e. at what point would the organic matter have to replenished).

2.5 East Sullivan Mine: Oxygen Consuming Organic Cover Material

2.5.1 Background

The East Sullivan Mine is located near Val d'Or in northwestern Québec. Metals extracted from the mine between 1949 and 1966 included copper, zinc, gold, and silver, resulting in approximately 15 Mt of tailings (3.6% sulphur) with a surficial area of 1.36 km^2 (Tassé *et al.*, 1997). A variety of organic wastes (bark, fiberboard, pulpwood, and sanding dust) were deposited on the tailings since 1984. Historically up to 6 m of organic waste material was placed although more recently material placement was limited to 2 m and fiberboard excluded.

Comparison of water quality from covered and uncovered portions of the tailings illustrated the potential of the organic cover material in mitigating ARD. Measured pH increased from 4.5 to 7 from 1988 to 1992, respectively, with a corresponding order of magnitude decrease in zinc concentrations (Tremblay, 1994). Oxygen and nitrogen decreased while methane and carbon increased within the one metre cover (Tremblay, 1994).

Field test plots 2 m high and 20 m^2 were constructed based on the promising water quality results (MEND 2.25.2). Pore gas monitoring revealed that oxygen concentrations were reduced to 4% at depth with a corresponding increase of carbon dioxide to over 10%. Pankewich *et al.* (1998) provides a summary of the isotopic geochemistry of biogenic gases released by the East Sullivan cover system.

2.5.2 Cover Performance

The placement of the wood-waste cover has continued so that, to date, 85% of the 136 ha impoundment is covered. The tailings pile, its wood-waste cover, and the acid and heavy metal-rich pore and surface waters have been surveyed since the early 1990s. Germain *et al.* (2003) present the results of the cover performance from 1998 to 2002, which is summarized in the following.

Placement of an organic barrier does not create an immediate cessation of acid mine drainage. The pore-water will still contain oxidation products that must be first flushed out of the tailings. The acid generated near the surface of the tailings is neutralized as it passes through the mineral medium in the saturated zone. At emergence, once oxygen is readily available again, rapid Fe^{2+} oxidation can occur. This mechanism can continue well after the placement of an oxygen barrier, until a balance of acidity and alkalinity in the effluent is reached. Samples of discharged pore-water around the impoundment have shown that the pore-water under the oldest parts of the cover (pre-1992) have high alkalinity and low Fe^{2+}. However, acid prone samples are found elsewhere and are typically located next to spigotted dikes and former dikes, now enclosed in finer tailings.

The acidic effluents around the impoundment are collected into four reservoirs. Between May and October, the effluents are pumped back over the organic cover, to use the organic cover as a biofilter. Since the beginning of the recirculation operation, the maximum concentration of Fe_{total} in the effluent has decreased from over 400 mg/L in 1998 to 70 mg/L in 2002. For the past three recirculation periods, pH of the feed-water (effluent being pumped over the cover) was below 3.5 most of the time.

To determine the efficiency of the cover as a biofilter, the quality of the feed-water was compared to groundwater samples collected in a nearby observation well. It was determined that feed-waters would require 30 days to reach the observation well. The residence time was sufficient such that Fe^{2+} concentrations were reduced from more than 200 mg/L to 1.5 mg/L.

Alkalinity, pH, and Fe^{2+} have been monitored in the groundwater since 1998. Despite a five-year feed of acid and ferrous waters, no acid or ferrous front has developed under the dispersal zone. The pH of all the groundwater samples underlying the zone varies between 5.0 and 8.0 for the entire 1998 – 2002 database, which suggests efficient H^+ neutralization by local alkalinity and / or adsorption by colloidal and particulate wood waste.

2.5.3 Summary

Since 1998, recirculation has been used to treat the acid and acidogenic effluent waters from the East Sullivan mine impoundment. According to Germain *et al.* (2003), Fe^{2+} concentrations measured in an observation well near the dispersal zone, compared to the concentrations of the feed-water, have shown an increase in removal rate from 86% in 1999 to 97% in 2001. The system has also been shown to neutralize acid pore-waters, with the pH of all eight nearby shallow observation wells being maintained above 6, despite acidic feed water. Evolution of surface water quality suggests that the contaminated groundwater flush is completed in the north and northwest area of impoundment, the east sector is under recovery, and the southwest sector is still flushing contaminated pore-waters.

Tassé (1999, 2000) concluded that the long-term efficiency of a wood waste cover strongly relies on the water saturation that can be reached and maintained at the base of the wood waste cover. The anaerobic environment would then help to keep the amounts of nutrients and readily metabolizable organic substrates at a high level for favourable oxygen consumption. The implication is that an oxygen consuming organic cover system may be better suited for “wet” climate environments where the term “wet” implies that annual precipitation meets or exceeds potential evaporation. Tassé (1999) stated that old wood wastes are less efficient than recent ones and that well drained woodpiles (i.e. wood waste covers) are much less efficient than those with a water saturated base. This is a positive result with respect to the use of wood waste as a cover material for tailings. However, this could imply that a well-drained waste material such as waste rock may not be a suitable long-term underlying material for oxygen consuming organic covers. MEND 2.35.2b concluded that a wood bark cover is not a good technique for reducing acid generation in sulphide-bearing waste mine rock. Alternatively, an organic layer could be one component of a waste rock cover system. However, as with all “alternate” cover materials the feasibility is closely associated with transportation of the organic material to the mine site.

The main lessons learned from this case study are the importance of maintaining high moisture conditions in a wood-waste cover, such as from a humid climate or from the saturated base of a tailings impoundment, and the improved efficiency of recent wood wastes compared to old wood-wastes.

2.6 Mine Poirier, Québec

2.6.1 Background

Poirier was an underground copper and zinc mine located in northern Québec near Joutel that operated between 1965 and 1975. Milling of the ores produced approximately 5 million tonnes of high sulphide tailings, which were deposited in a surface impoundment spanning an area of nearly 46 hectares. A thin layer of spilled tailings had accumulated at several locations external to the main impoundment, having a combined volume of about 0.3 million tonnes and covering an area of nearly 28 hectares. Seepage from the tailings impoundment and spill areas has contributed acidity and metals to two nearby creeks (Lewis *et al.*, 2000). An important feature of the site, however, is the presence of a low permeability clay layer beneath the main tailings deposit, which acts as a barrier to limit groundwater contamination.

2.6.2 Reclamation Plan Development

Rio Algom undertook an assessment of the property in 1996 for the preparation of a reclamation plan. Lewis *et al.* (2000) provide details on the reclamation plan, which represents the culmination of a series of studies directed at developing an environmentally sound method of returning the site to a natural state. The primary objective of the reclamation plan was to reduce chemical loadings from the tailings basin in order to reduce ecological risk to an acceptable level and allow sections of the nearby creeks to recover naturally (Lewis *et al.*, 2000). The following five options were considered to reduce loadings from the site:

1. *Soil cover:* a 1 m cover of clay;
2. *Geomembrane liner with a protection layer:* 0.5 m of clay and 1 to 1.5 m of till;
3. *Collect and treat:* collection ponds, treatment plants and sludge disposal;
4. *Clay cover with frost protection:* 1 m of clay and 1.5 m of till; and
5. *Bury tailings:* in the muskeg adjacent to the site.

Option 2 became the preferred option following discussions with the Provincial Government and the prediction of loadings from the tailings basin to the receiving environment for each option. This option involves a cover consisting of a geomembrane liner over the main tailings deposit and relocated mine waste materials, together with a 1 m thick soil layer to protect the liner. The purpose of the liner is to substantially reduce (essentially eliminate) infiltration through the cover (Lewis *et al.*, 2000). The cover is also designed to function as an oxygen barrier to prevent further oxidation of the tailings.

2.6.3 Cover Construction

Construction of the cover system over the Poirier tailings basin began with preparatory works in the fall of 1998 (Lewis *et al.*, 2000). The internal tailings beach was graded and compacted in preparation for the application of the geomembrane liner, which required removal of tree stumps, as well as some rock and decant structures. A support layer of sand was placed below the liner in several sections. Installation of the geomembrane liner was completed in 1999, and consisted of placing two different types of liner. A smooth 60 mil high-density polyethylene (HDPE) liner was used on the beach and over the central waste piles (surface area of 37 ha), while a textured 80 mil HDPE liner was used on the slopes, with a geonet drainage layer above the textured liner. A 0.5 m thick layer of clay was placed on all of the liner for protection, and to provide a secondary natural sealing media for any imperfections that may occur in the liner (Lewis *et al.*, 2000). A layer of till, ranging in thickness from 0.5 m on the beach and waste pile area to 1.5 m on the slopes, was subsequently placed over the clay layer. This layer provides physical protection of the clay by inhibiting frost penetration and provides a suitable medium for vegetation (Lewis *et al.*, 2000). Completion of cover system construction and commencement of field performance monitoring occurred in 2000.

2.6.4 Summary

The Poirier mine site has the distinction of being the first full-scale demonstration project in Canada of utilizing a geomembrane in a cover system. The reclamation plan for the Poirier site will provide considerable improvements to the surrounding habitat (Lewis *et al.*, 2000). Further research is required with respect to the longevity of geomembrane liners as a component of a cover system.

2.7 Other Case Studies Using Alternate Cover Materials

Pulp and paper (P&P) residues were used as capillary barrier material in a field test cover system for reactive tailings at the Eustis mine site near Sherbrooke, Québec (Cabral *et al.*, 1997). The P&P residues originated from paper de-inking processes and were described as a spongy, partially saturated material, capable of absorbing large quantities of water. The de-inking residue layer acts as an oxygen barrier in two ways: 1) due to its high moisture retention capacity, it maintains a high degree of saturation; and 2) due to the high organic content of the de-inking residues and microbial activity, the barrier consumes atmospheric oxygen (Cabral *et al.*, 1999). The approximate stratigraphy of the field test plot consisted of non-oxidized tailings of variable thickness, overlain by 1.5 m of compacted, fresh de-inking residues and finally, a 0.2 m layer of a compost-de-inking residue mixture (Cabral *et al.*, 1997). The field performance monitoring program consisted of measurements of volumetric water content, temperature, gaseous oxygen concentrations and hydraulic conductivity. The key monitoring results are the oxygen profiles and hydraulic conductivity measurements, which show the cover system is functioning as both an oxygen barrier and water infiltration barrier. Additional monitoring results and details on this test cover project are reported in Cabral *et al.* (1997). A field application of utilizing de-inking residues for the moisture retention layer in a waste rock cover system is reported in Cabral *et al.* (1999).

McGregor (1997) reported on a field investigation of a "self-sealing/self-healing"(SS/SH) barrier undertaken at Falconbridge Ltd.'s East Mine tailings near Sudbury, Ontario. The test barrier was installed in four stages by first excavating the overlying oxidized tailings, then reactive material was placed and compacted followed by high Fe-S material (mill washings), and finally reapplication of a layer of overlying oxidized tailings. The interface of the overlying mill washings and the underlying reactive material forms the SS/SH barrier. The reaction of dissolved compounds form precipitates at the interface of the two materials. The aqueous concentrations decrease, thereby creating a concentration gradient, which leads to diffusion of additional reagents and further precipitation until the pores of the parent materials are filled. The field measured average vertical hydraulic conductivity of the interface was four orders of magnitude lower that the surrounding tailings (McGregor, 1997). The pore gas diffusivity of oxygen across the SS/SH barrier was less than 1/1000 of the overlying tailings. This resulted in nominal gaseous oxygen concentrations of 3.4% below the barrier, as compared to 18.5% above the barrier. McGregor (1997) reported that the cost for installation of the SS/SH barrier would range from $30,000 to $50,000 per ha. It is noted, however, that a native cover material would likely be required to establish vegetation for long-term closure considerations using this technique, thus adding to the unit cost per hectare. No further work has been reported on the SS/SH barrier system.

3 MEND MANUAL CASE STUDIES – WASTE ROCK

3.1 Heath Steele (MEND 2.31.1)

3.1.1 Background

Heathe Steele Mine (HSM) is located approximately 50 km northwest of Newcastle, New Brunswick. 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 due to low base metal prices and metallurgical problems. The site contains approximately 756,000 tonnes of pyritic waste rock and reject ore, stockpiled in more than 20 piles ranging from 1,000 to 230,000 tonnes.

A waste rock study was initiated in the spring of 1988 to develop strategies for the long-term management of the acid generating waste rock, to evaluate the performance of a soil cover, and to assess the cover effectiveness as a method for long-term management of ARD.

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

Phase I: Selection of four waste rock piles for monitoring and evaluation (MEND 2.31.1a);

Phase II: Installation of monitoring equipment in the four piles identified in Phase I to define waste rock characteristics and develop background data (MEND 2.31.1a);

Phase III: Geotechnical and geochemical column testing to evaluate the performance characteristics of potential cover system designs (MEND 2.31.1a);

Phase IV: Placement of a soil cover system on Pile 7/12 and performance monitoring (MEND 2.31.1b); and

Phase V: Continued monitoring at Pile 7/12 (MEND 2.31.1c).

3.1.2 Cover Design and Construction

The Noranda Technology Centre reviewed and tested a range of cover options and recommended the following composite cover for Pile 7/12 (surface area of 0.25 hectares):

- 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 system with these specifications was constructed in late summer of 1991. Figure 3.1 shows the construction details of the soil cover system used on Pile 7/12.

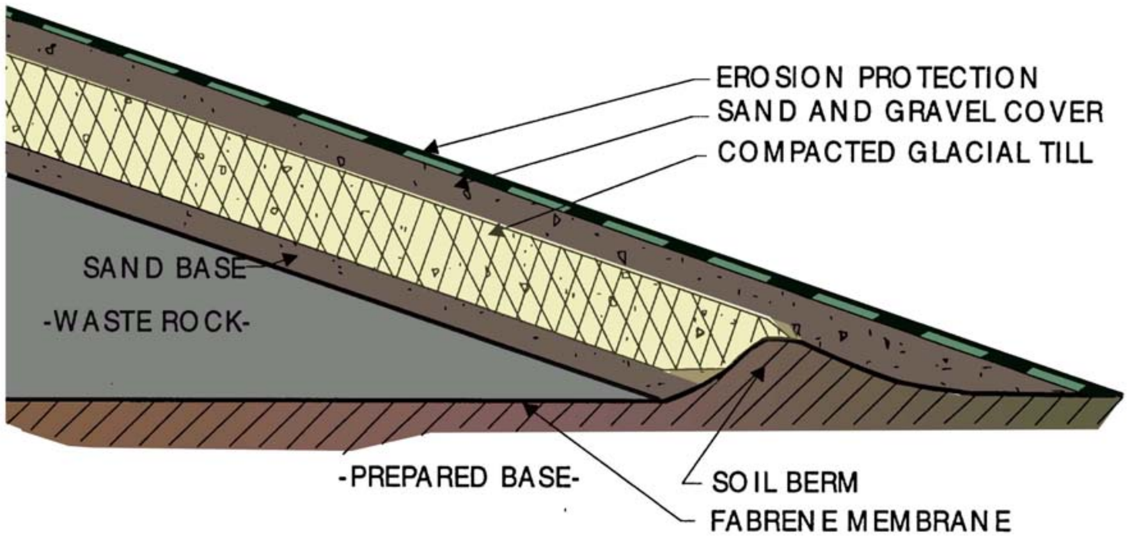

Figure 3.1 Soil cover construction details at Heath Steele (from Yanful *et al.*, 1993c).

Monitoring of oxygen and temperature conditions continued monthly at all four piles after the placement of the cover on Pile 7/12. Infiltration rates and water quality were also measured at Pile 7/12, as was the moisture conditions of the compacted till layer.

3.1.3 Summary

The following conclusions were made after the completion of Phase V (1995-1996 monitoring program):

- The influx of oxygen to the pile was minimized, with internal waste rock gaseous oxygen concentrations typically being well below 1% (20.9% represents atmospheric conditions);
- The volume of acid leachate escaping from the pile was drastically reduced representing only two percent of total precipitation incident on the pile;
- The loading of metals and sulphate decreased by 99%;
- The potential cost of lime for treatment was reduced by $187/yr per 1,000 tonne of waste rock due to reduced seepage volume, and a further $8.70/yr per 1,000 tonne of waste rock due to gradual seepage quality improvement;
- It will take many decades to flush out the stored oxidation products resulting from the Pile 7/12 material being exposed to atmospheric conditions prior to the start of the project (one pore volume was estimated at 30 years);

- Evidence exists that de-watering of part of the cover system is a concern for the long-term effectiveness of the cover.

Ultimately, composite soil covers were found to be an effective method for reducing the oxidation reaction in sulphidic waste rock piles, thus significantly reducing their impact on the environment. The active layer (i.e. compacted layer) must be designed, constructed, and maintained so that its integrity and moisture content are maintained to achieve this objective. 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.

MEND 2.31.1c reports that the cover system has resulted in a cost savings for lime in the range of $196/yr per 1,000 tonnes of waste rock. Approximately 94% of the savings were observed shortly after construction of the cover due to reduced flushing flows through the cover. Other benefits for treatment include a low volume of flow to be treated and effluent water quality consistency.

The MEND 2.21.3a report, which provides a critical, peer review of this project, states that the soil cover system installed at the Heath Steele site performed satisfactorily. It was also stated that 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 lessons learned from this project include:

- Consolidation of mine waste to reduce the surface area of material requiring a cover system, preferably during operations, will significantly reduce overall closure costs for a site.
- It is fundamental to take into account slope effects (i.e. slope length, slope angle, contrast between the two materials, and surface flux boundary conditions) when designing cover systems with capillary barrier effects.
- Long-term performance monitoring is required to understand whether preventing establishment of trees or shrubs on the cover system is practical.

Yanful *et al.* (1993b), Yanful *et al.* (1993c), Bell *et al.* (1994) and Bennett *et al.* (1995) also reported detailed summaries on certain aspects of this project.

3.2 Bersbo, Sweden Pilot Project

3.2.1 Background

The Bersbo, Sweden pilot project was the first full-scale project in Sweden of remediating sulphide wastes using state-of-the-art cover system design methodologies. Performance has been monitored since 1989. The 700,000 m^3 of waste rock covered was between 90 and 600 years old. It was relocated from various historic mines in the area into two locations with surface areas of 2.8 ha and 3.5 ha, respectively. The two deposits were covered with a sealing layer and a protective layer designed to control the ingress of oxygen and infiltration of water to the underlying waste rock (Lundgren, 1997).

The sealing layer of the smaller deposit consisted of a concrete like product made of pulverized coal flyash, cement and water. The mixture was blended into a paste, and grouted into a 0.25 m thick layer of crushed rock aggregate. A 0.5 m layer of compacted till was placed on a thin filter layer of tailings, which had been placed directly on the larger deposit. The two sealing layers were overlain by 2 m of non-compacted till.

3.2.2 Summary

Percolation through the covers was monitored with collection lysimeters installed beneath the covers. Percolation through the grout cover system decreased to 12% of incident precipitation as compared to before placement of the cover system. The compacted till cover system decreased net percolation to 3%, as compared to the uncovered condition. The latter “natural” cover system also performed well as an oxygen ingress barrier because the compacted till layer maintained a reasonable high degree of saturation, although problems associated with the upper areas of the sloped surfaces were noted. The cementitious compacted layer did not maintain a high degree of saturation, and as a result it did not perform as an oxygen ingress barrier to the same extent as the compacted till cover system.

Oxygen transport was governed by advective transport processes before placement of the cover material (Lundgren, 1997). Oxygen supply did not become a limiting factor for oxidation of the potentially acid forming waste material until the cover material was applied. Gaseous oxygen concentrations were near atmospheric conditions prior to placement of the cover material. The mean gaseous oxygen concentration within the waste rock piles during the period covering 1991-1995 following placement of the cover was 3.2% for the first pile and 0.4% for the second pile.

3.3 Rum Jungle Mine, Northern Territory, Australia

The Australian Centre for Mine Environmental Research (ACMER) initiated a project to study the 18 year-old cover systems at the Rum Jungle Mine. The project was funded by INAP, the Queensland Department of Natural Resources and Mines, and the Queensland Environmental Protection Agency. The project was conducted by ANSTO and CSIRO. The following case study is taken from the final report of the investigation (Taylor *et al.*, 2003).

3.3.1 Background

The Rum Jungle mine is located approximately 85 km south of Darwin in the Northern Territory, Australia. The uranium and copper mine operated between 1954 and 1964 and was abandoned in 1971. The climate at the site is monsoonal with an average annual rainfall of 1,600 mm, which falls mostly between October and May. High intensity rainfall events occur during thunderstorm activity in the early wet season, and steady rainfalls occur during the latter part of the wet season (January to March). High daily maximum temperatures are experienced throughout the year (annual average 34 ^{o}C) as well as high annual evaporation rates (>2,600 mm at Darwin).

Four waste rock piles, tailings, a heap leach pile, an acid dam, and open cuts contributed to the acidic drainage from the mine site. In the mid-1960's, acidic leachate high in heavy metals was found running off the heaps and springs and elevated temperatures (as high as 36.5^{o}C) were measured at the base of the heaps midway through the wet season. An investigation was carried out during the 1973/74 wet season, which led to the initiation of a rehabilitation strategy for the waste rock piles.

The objective of the rehabilitation plan was to reduce infiltration into the waste rock piles to less than 5% of incident rainfall. It was also intended that the rehabilitation plan minimize the long term maintenance required. A 100-year design life was used.

A four-year rehabilitation project, funded by the Australian Government, commenced in 1982 and cost $18.6 million (AUD). The project involved covering three waste rock dumps at the site. The cover systems were designed to reduce the water infiltration to less than 5% of incident rainfall by both water shedding and moisture storage-and-release mechanisms.

3.3.2 Cover Design and Construction

The cover system was designed to meet the following objectives:

- Possess low hydraulic conductivity;
- Be well drained and prevent ponding;
- Support a vegetative cover;
- Be resistant to erosion even on the slopes prior to full vegetation growth;

- Be the minimum thickness that meets the performance objectives (minimize cost); and
- Construction should be simple and make use of locally available materials.

To meet the objectives outlined above, a three-layer cover was designed, with construction varying depending on the location of the cover—side or top slopes. On the top slopes the cover consists of a minimum of 22.5 cm of compacted clay overlain by a 25 cm thick sandy clay loam layer (also compacted). The compacted layer was designed as an infiltration barrier and the upper layer was designed as a growth medium layer and to prevent desiccation of the clay layer. The two layers were overlain by a gravelly sand with a minimum thickness of 15 cm to act as an erosion protection layer and to reduce evaporation. 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. The layers were thicker on the side slopes due to the greater tendency for erosion.

The waste rock piles were reshaped prior to cover placement to create a stable landform with a formal drainage system that would maximize runoff and minimize erosion. The side slopes of the waste rock piles were reshaped to a more stable slope of 3H:1V, with the top surface of the piles reshaped to a slope ranging from 1% to 10%.

Once the covers were in place, the waste rock piles were revegetated. The key objective of revegetation was to prevent erosion. A variety of species were selected for revegetation consisting of pasture grasses and legumes.

3.3.3 Field Performance Monitoring

Five pairs of barrel lysimeters (200-litre drums) were installed in one of the waste rock piles (White's heap) in 1983 to monitor infiltration through the cover. Four lysimeters were installed in Intermediate heap following reshaping in 1985. Probe holes were drilled in all three waste rock piles for measurement of internal temperature and oxygen concentration.

Additional monitoring has been carried out to monitor the condition of the vegetation, erosion, chemical activity within the piles, the pile water balance, groundwater hydrology in and around the piles, and pollutant loadings on surface water.

The average net percolation measured by the five pairs of lysimeters is presented in Table 3.1. The measurements between the various lysimeters varied widely so the data presented represents the average of the measurements of 9 – 10 lysimeters over a particular season. The measurements should only be used as a qualitative indicator of long term changes in cover performance. The lysimeters are too shallow (i.e. the base of the 200-litre drums are not far enough away from the interface of the underlying waste and overlying cover material), and as a result the presence of the lysimeters influence the net percolation measured. Taylor *et al.* (2003) do not report the range of net percolation values measured by the lysimeters over the past 18 years, nor does any historic report or literature for the site. Only the average net percolation measured by the five pairs of lysimeters is reported, which makes it difficult to independently understand the measured range of performance of the cover systems. Taylor *et al.* (2003) report that based on the average net percolation measured by the five pairs of lysimeters, that over the first decade, cover performance was relatively stable and consistent year to year. Starting in 1994, the average net percolation measured by the five pairs of lysimeters increased, indicating a change in cover performance (Taylor *et al.*, 2003). Taylor *et al.*, (2003) concluded from the lysimeter measurements that infiltration through the cover has likely increased over the 18-year monitoring period.

Measurements of oxygen concentration and temperature profiles through the cover system were used to estimate sulphate generation in the piles. The measurements showed that following cover placement sulphate generation rate was reduced by a factor of two to three compared to the uncovered waste. Despite the reduction, sulphate generation is still shown to occur at a significant rate (e.g. 750 t SO_4/yr for White's heap) indicating production of oxidation products is occurring within the piles.

Table 3.1

Lysimeter measurements (averaged from 9 – 10 lysimeters) for White's waste rock pile.

Period	Rainfall (mm)	Average lysimeter infiltration (% of rainfall)
Nov 84 – May 85	1072	2.2%
May 85 – May 86	1087	2.2%
May 86 – Jun 87	1289	2.8%
Jun 87 – Jun 88	1057	1.5%
Jun 88 – Aug 89	1625	3.5%
Aug 89 – Oct 90	1008	2.5%
Oct 90 – May 91	1587	3.9%
May 91 – May 92	1008	2.6%
May 92 – Jun 93	1421	2.6%
Nov 94 – Jun 95	1484	6.0%
Jun 95 – Jun 96	998	8.7%
Jun 96 – Jun 97	1763	10.2%
Jun 97 – Jun 98	1821	5.1%
Jun 98 – Jun 99	1887	9.8%
Jun 99 – May 00	1716	10.3%
May 00 – Jun 01	1912	6.9%
Jun 01 – Jun 02	1269	7.6%

Monitoring of the flora and fauna resident on the cover system showed the following trend over five to ten years following cover placement: following revegetation, the seeded pasture grasses grew, along with various species of colonizing grasses. Shrubs (*Acacia holosericea*) then moved in gradually. Several species of ants and one species of termite colonized the cover system, with more than 20 termite mounds observed on White's heap.

The pasture grasses remained generally healthy until 1993, when weeds started to compete with the grass species. Over the following decade, the weeds have been controlled with herbicide, although not eradicated. Numerous wildfires have occurred on the piles, with both White's pile and Dyson's piles experiencing at least one complete burn over the entire cover surface. Erosion has generally been minimal, although sufficient erosion typically occurs in the drainage channels, which requires some annual maintenance.

The cover systems were investigated in 2002 to evaluate their performance since placement. Investigations were made during both the wet and dry season to determine seasonal changes in performance. The investigations involved six major study sites, as well as other sites of casual observation. At the major study sites, vegetation and surface analyses were performed, and trenches were excavated to investigate each layer of material. The trenching involved typical site characterization components such as a photo log, material sampling, and *in situ* measurements of infiltration rates and oxygen flux.

In general, the site investigation determined that the cover varied widely in thickness, with some areas as thin as 2 – 5 cm. Testing of the material samples revealed that some characteristics of the cover materials fell outside of the specified design parameters. Roots, termite and ant activity, and desiccation cracks (dry season) were found throughout the entire cover thickness. Measurements of infiltration determined that the saturated hydraulic conductivity of all the layers ranged between 10^{-5} to 10^{-6} m/s during the wet season, and 10^{-4} to 10^{-5} m/s at the end of the dry season. Oxygen flux measurements through the entire cover thickness were found to be four times greater at the end of the dry season (1.9×10^{-7} kg/m^2 s) compared to the wet season (0.44×10^{-7} kg/m^2 s).

3.3.4 Summary

Performance monitoring of the Rum Jungle mine cover system provides an invaluable resource for learning about the long-term performance of cover systems. Many observations from this cover can be used to highlight areas of importance for future cover designs.

The lessons learned from 18 years of performance monitoring at the Rum Jungle site are (Taylor *et al.*, 2003):

- A cover system design based on material properties available in the immediate vicinity and cost is not necessarily appropriate. It was determined that the variations in cover thickness were likely due to a shortage of cover material;
- Adequate quality assurance and quality control are essential during construction of a cover system;
- Adequate instrumentation should be installed at the time of construction to enable the performance of a cover to be quantified with respect to infiltration rates (lysimeters) and oxidation (oxygen concentration and temperature profiles);
- Instrumentation should be monitored periodically for many years. Major changes in cover performance were not observed at Rum Jungle until after the first decade of monitoring;
- Cover system designs must account for the invasion of local species of flora and fauna. Termites and ants are inevitable in the Australian tropics and should have been evaluated as part of the cover system design;
- Cover system designs must account for changes in hydraulic conductivity resulting from root penetration and voids due to termite and ant galleries;
- Comprehensive physical and geochemical testing of potential cover materials is required to ensure that they meet specifications. It is critical to either find cover materials that meet the design specifications or to include the properties of the available materials in the cover design modelling. The material samples of the Rum Jungle cover showed that some of the materials used in cover construction fell outside the specifications for the cover design;
- Cover system designs should include revegetation with native species to reduce high cost, long-term maintenance requirements and to improve cover performance (e.g. increase evapotranspiration rates); and
- The importance of evaluating cover system performance on a seasonal basis to determine the optimum cover design for the site's climate conditions. In retrospect, it was unrealistic to design a high moisture content, low infiltration layer at Rum Jungle where deep-rooting tropical plants and extreme wet and dry seasons prevail.

3.4 Kidston Gold Mine, Queensland, Australia

Durham (1999) and Durham *et al.* (1999) reported on the performance of two cover system trials constructed at the Kidston Gold Mines in the state of Queensland, Australia. Average annual potential evaporation for the site is approximately 1,900 mm and exceeded average annual precipitation by almost 1,200 mm. Three years of monitoring demonstrated the promise of a moisture store-and-release cover system designed for the site, as well as the importance of maintaining good vegetation. The field trial cover systems were constructed using well-graded, non-acid forming run-of-mine waste. A field test plot consisting of 2.5 m of non-compacted oxidized run-of-mine waste was constructed. A second test plot was constructed with a 0.5 m compacted layer and an overlying 1 m layer of non-compacted material. Run-of-mine oxidized waste was used as the construction material for both of the cover materials in the second test plot. No moisture has reported to the lysimeters (see Bews *et al.* (1997) for design details) installed to measure percolation to the underlying waste material during the three-year monitoring period (Durham, 1999).

A progressively longer period of time was required to reduce moisture conditions in the run-of-mine cover material to pre-wet season conditions following the wet season precipitation. Vegetation is not as well established as compared to earlier in the monitoring period and appears to be a key factor for successful performance of the moisture store-and-release cover system trials. Transpiration is a key component of the water balance and appears to significantly reduce moisture conditions in the run-of-mine cover material. It is postulated that nutrient deficiency is the likely contributor to the vegetation problems and is being addressed (Durham, 1999).

3.5 Hanford Site: Low Level Nuclear Waste

The U.S. Department of Energy (DOE) initiated an extended study program at the Hanford site near Richland, Washington 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 Unites States (Fisher, 1986). Although it is not an acid mine waste site it provides valuable information on the use of layered soil systems and vegetation to control infiltration.

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 could be used to inhibit water infiltration, plant and animal intrusion, and wind and water erosion (Link *et al*., 1995).

The cover system consists of several layers of different soil materials such as fine soil, sand, gravel, riprap, and asphalt to optimize performance and longevity. A typical cover system is shown in Figure 3.2. The top vegetated fine soil layer acts as a medium in which moisture is stored until the process of evaporation and transpiration return the water to the atmosphere. The coarse materials (e.g., sand, gravel, and riprap) below the fine soil layer provide a capillary break that restricts biointrusion. The asphalt concrete layer below the coarse materials is designed to divert any water that percolates through the capillary barrier.

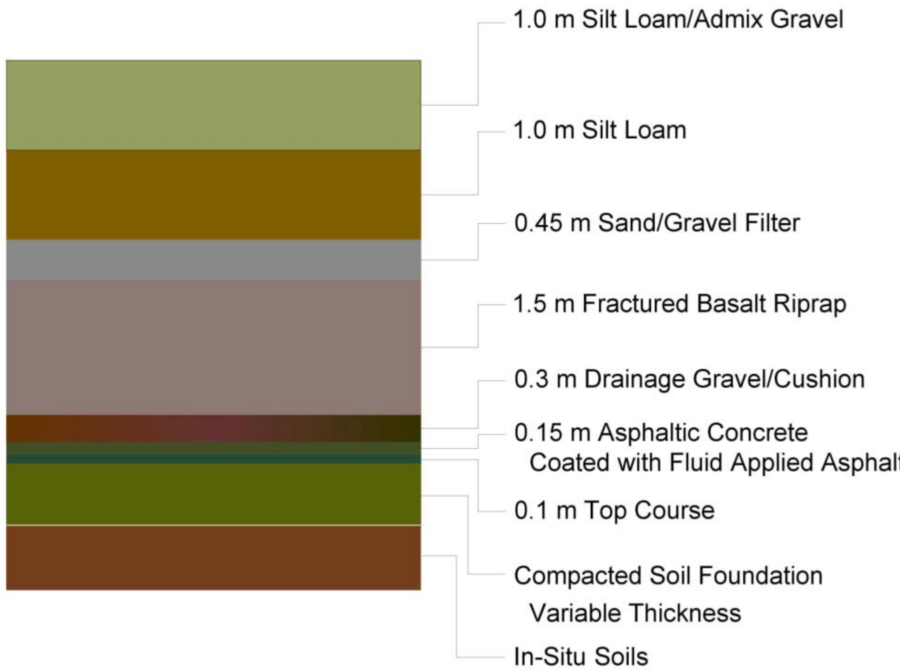

Figure 3.2 Cover system used at Hanford site (from MEND 2.21.3a).

The effectiveness of the soil cover was studied using weighing lysimeters. The results indicated that the capillary barrier in conjunction with the use of vegetation to promote transpiration worked well to prevent deep infiltration.

The effect of surface conditions on soil moisture storage was also studied with the use of small tube lysimeters. It was found that vegetation caused a greater decrease in storage than non-vegetated plots. Link *et al.* (1995) have concluded that an admix surface (gravel mixed into the fine soil) with vegetation would minimize the potential for wind erosion, while not significantly affecting the moisture storage capability of the cover.

The program was extended to include building of a full-scale prototype soil cover system with a surface area of approximately 200 hectares. The monitoring plan consisted of the measurement of, runoff of water-sediment mixtures, water infiltration, creep, moisture content, and surface cracking (Petersen *et al*., 1995). The construction cost of the system is estimated to be $300,000 (US) per acre, which is approximately $100 (CND) per m^2. This cost makes such a system unrealistic for use in the mining industry. However, the results of the study are extremely useful for predicting long-term performance of cover systems typically found in the mining industry, in particular with respect to biointrusion and capillary barriers.

4 INAP REPORT CASE STUDIES

4.1 BHP-Billiton Iron Ore Pty Ltd., Mt. Whaleback Operation

4.1.1 Background

The Mt. Whaleback Operation is located in the Hamersley Iron Province in the northwest of Australia, approximately 1,200 km north-northeast of Perth, WA. The mine was started in 1968 with the first railing of iron ore in 1969. The mine currently produces approximately 18 million wet tonnes (Mt) and moves approximately 53 Mt of overburden per annum. The current projected life of the mine is approximately 25 years.

Mt. Whaleback is the largest known continuous high-grade iron ore deposit in the world and originally contained over 1.7 billion tonnes of iron ore and nearly 4 billion tonnes of overburden (van der Hayden, 1993). The ore consists mainly of the mineral hematite, an iron oxide containing up to 70% iron. Overburden materials at the mine consist primarily of Banded Iron Formations (BIF) and shales, but also small amounts of chert and dolerite.

The climate of the Pilbara region is semi-arid, tropical with a mean annual rainfall of approximately 320 mm. There are two distinct seasons, a hot, wet summer (December to April), and the rest of the year, which is more temperate and generally has lower rainfall. Typically, rainfall occurs in high intensity, short duration events, usually associated with cyclonic events during the summer. The annual potential evaporation typically exceeds 3,000 mm (O'Kane *et al.* 2000).

4.1.2 Summary of Cover System Test Plots

BHP Billiton Iron Ore Pty Ltd. (BHPBIO) has installed five acid rock drainage field test plot performance monitoring systems for cover systems placed over overburden material at their Mt. Whaleback operation. Details of the test plots are summarized below.

Test Plot 1 and Test Plot 2:

- Surface area: ≈ 1 ha each
- Location: W22 overburden storage area
- Constructed: January 1997
- Performance monitoring started: August 1997
- Surface characteristics: no vegetation, generally horizontal with block dumped hummocks

Test Plot No. 3:

- Surface area: ≈ 0.75 ha
- Location: W31 overburden storage area (south slope)
- Constructed: January 1998
- Performance monitoring started: January 1998
- Surface characteristics: minimal vegetation, sloping surface (≈ 3.3H:1V)

Test Plot 4 and Test Plot 5:

- Surface area: ≈ 0.25 ha each
- Location: W29 overburden storage area
- Constructed: June 2001
- Performance monitoring started: June 2001
- Surface characteristics: approximately 20 cm of topsoil placed and seeded late 2001, relatively horizontal surface (≈ 2%), paddock area created using large bund walls

Test Plot 1 and Test Plot 2 are constructed immediately adjacent to each other on a horizontal overburden storage area (OSA) surface at W22. Well-graded run-of-mine overburden material with little or no potential to consume or produce acid was used as the cover material. The cover material was block dumped on the surface of W22 creating an undulating surface with low and high points as well as short surface runoff paths to reduce erosion during the life of the test plots. Test Plot 1 had a minimum of 2 m of cover material at the aforementioned low points while Test Plot 2 was constructed in two lifts with a minimum of 4 m of cover material at the low points. The performance of the two horizontal surface field test plots is monitored using a system designed to measure climate conditions at the test plot area (rainfall, potential evaporation, and actual evaporation), moisture and temperature conditions within the cover and waste material, and net percolation from the base of the cover layer into the underlying overburden material.

Test Plot 3 was constructed on a historic OSA sloped to approximately 17^{o}. The objective was to quantify the difference in performance of the Mt. Whaleback moisture storage-and-release cover system design constructed on a sloping surface as compared to a horizontal surface. Test Plot 3 was created by battering down a 45 m wide historic reclaimed area to a uniform surface extending approximately 160 m from the crest to the toe of the slope. Sensors extending laterally from six instrument access culverts monitor the performance of the sloped surface field test plot. The objective of the patterned instrument nests was to replicate monitoring laterally and longitudinally to the sloped surface.

Test Plot 4 and Test Plot 5 are located on the re-vegetated surface of the W29 OSA. Both of these test plots are located entirely within the run-of-mine banded iron formation (BIF) material. The objective of the test plots is to quantify the effect of vegetation on the cover system water balance in comparison to the bare surface cover system water balance measured at the W22 test plots.

4.1.2.1 Overview of the Field Performance Monitoring Systems

State-of-the-art monitoring systems were installed to monitor various parameters that will influence the field performance of each test plot cover systems. Climatic data collected at the central mine weather station includes: rainfall, wind speed and direction, temperature, pan evaporation, relative humidity, and net radiation. Tipping bucket rain gauges were installed at the W22 OSA, which is adjacent to W29, as well as at the W31 OSA. The lysimeters at Test Plot 1 and Test Plot 2 are being monitored manually to record the quantity of net percolation through each cover system field trial. The *in situ* moisture and temperature conditions within the cover and waste materials at each test plot are being monitored with thermal conductivity and volumetric water content sensors. These sensors are connected to automated data acquisition systems powered by solar panel/rechargeable battery sources. The parameters monitored by the Bowen ratio station installed at W29 provide an assessment of evapotranspiration rates from the vegetated surface. Prior to construction of the W29 field trials, the Bowen ratio station was set up at the W22 field trial area to monitor bare surface evaporation.

4.1.3 Analysis of the Mt. Whaleback Operation

The cover system test plots installed at Mt. Whaleback have information for characterising one-dimensional (1D) and two-dimensional (2D) flow within the cover system, as well as the effect of vegetation on cover system performance. Analysis of the performance monitoring data has led to insights or “lessons learned” pertaining to the long-term performance of the cover system. The “lessons learned” at Mt. Whaleback include:

- The effect of extreme climate events, such as successive above average rainfall years, on the performance of a cover system;
- The importance of field performance monitoring and the measurement of *in situ* material properties in the calibration of a numerical model to site conditions;
- The positive influence of vegetation on the performance of a cover system in semi-arid tropical climates; and
- The adverse effect of segregation, which can occur during material placement, on cover system performance.

Volume 4 identified extreme climate events as one of the physical processes that can affect the long-term performance of the cover system. Mt. Whaleback experienced three consecutive years in which the total annual rainfall was equal to or greater than the annual rainfall recorded at the site in the previous 30 years. The performance of the cover system during this period was not as originally predicted, which at first glance could be attributed to the consecutive periods of extreme rainfall (that were not modelled during the Mt. Whaleback test plot design phase). This aspect of the performance of Mt. Whaleback's moisture store-and-release cover system field trials is discussed below, and clearly has led to higher net percolation than predicted. However, a contributing factor could also be the use of the laboratory SWCC during the design phase of the field trials, which is often a poor representation of field conditions. The propensity for segregation of well-graded run-of-mine cover material to occur during cover material placement is also discussed as a potential reason for net percolation being higher than predicted.

4.1.3.1 Measurement of *In Situ* Material Properties

In situ field properties of the BIF cover material at Mt. Whaleback site developed using the field performance monitoring data. *In situ* temperature, matric suction, and volumetric water content are measured at each test plot using sensors connected to an automated data acquisition system. The sensors are located at the same depth (up to 4 m deep) in close proximity to each other. In addition, sensor measurements are taken at the same interval.

For the purposes of this case study, the *in situ* suction and volumetric water content readings are of primary interest. Simultaneous measurement of these parameters produces the field soil-water characteristic curve (SWCC), which details the moisture retention characteristics of the BIF cover material. The moisture retention characteristics of the cover material are vital to the performance of the moisture store-and-release cover system constructed at Mt. Whaleback, which relies upon storing meteoric waters during the wet season rainfall events for release during subsequent prolonged dry periods.

The SWCC and the hydraulic conductivity functions are the most important functions in a soil-atmosphere numerical model. Figure 4.1 compares the *in situ* SWCC measured in the field at the W22 OSA (Test Plot 1) to the SWCC measured in the laboratory prior to construction of the test plots. The field SWCCs show a "double hump", or are bi-modal, which is typical of field SWCCs. The bi-modal SWCC is indicative of a gap-graded material in which the coarse materials de-saturate first at a low suction value producing the function's first steep downward slope. The second hump is produced when the finer-textured materials start to de-saturate. This point is rarely well defined in field measurements due to the inherent heterogeneity of the cover materials. Figure 4.1 shows that there was a significant difference between the shape of the laboratory and field SWCCs, even though the laboratory test was completed on a sample prepared to *in situ* density and moisture content conditions, which were measured during the potential cover material sample collection phase of the project.

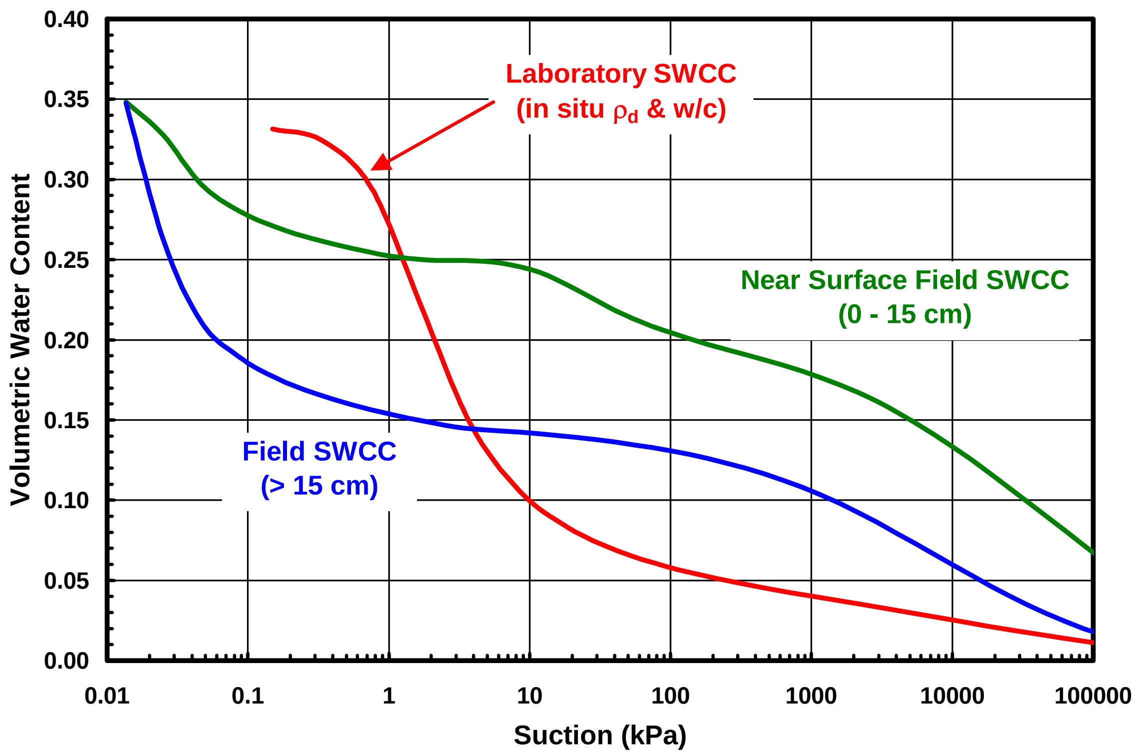

Figure 4.1 Comparison of the laboratory and *in situ* field SWCCs for the BIF cover material.

4.1.3.2 Calibration of the Numerical Model

The 1D SoilCover soil-atmosphere model was calibrated to a set of field conditions measured at Test Plot 1 at Mt. Whaleback. Figure 4.2 shows the results from the calibrated SoilCover model compared to the actual measured field data.

The correlation coefficient between the measured field data and the model results are relatively high for the monitoring period. The numerical model responded at the same time and with a similar magnitude to the measured field conditions, which is critical in the calibration of a numerical model. Future performance of the in-place cover system or alternative cover system designs can be predicted with reasonable confidence with the calibrated numerical model.

It is important to note that the results shown in Figure 4.2 and discussed above were generated on the first attempt of the numerical simulation with minimal changes to the numerical model. The field SWCCs were input to the model as well as estimated hydraulic conductivity functions based on the field SWCCs and field saturated hydraulic conductivity testing. Very few of the model inputs were "tweaked" or varied in successive model runs to better fit the data. This exercise showed the value of field-based material properties such as the SWCC and the value of accurate, detailed performance monitoring systems, which are used to generate the field SWCC.

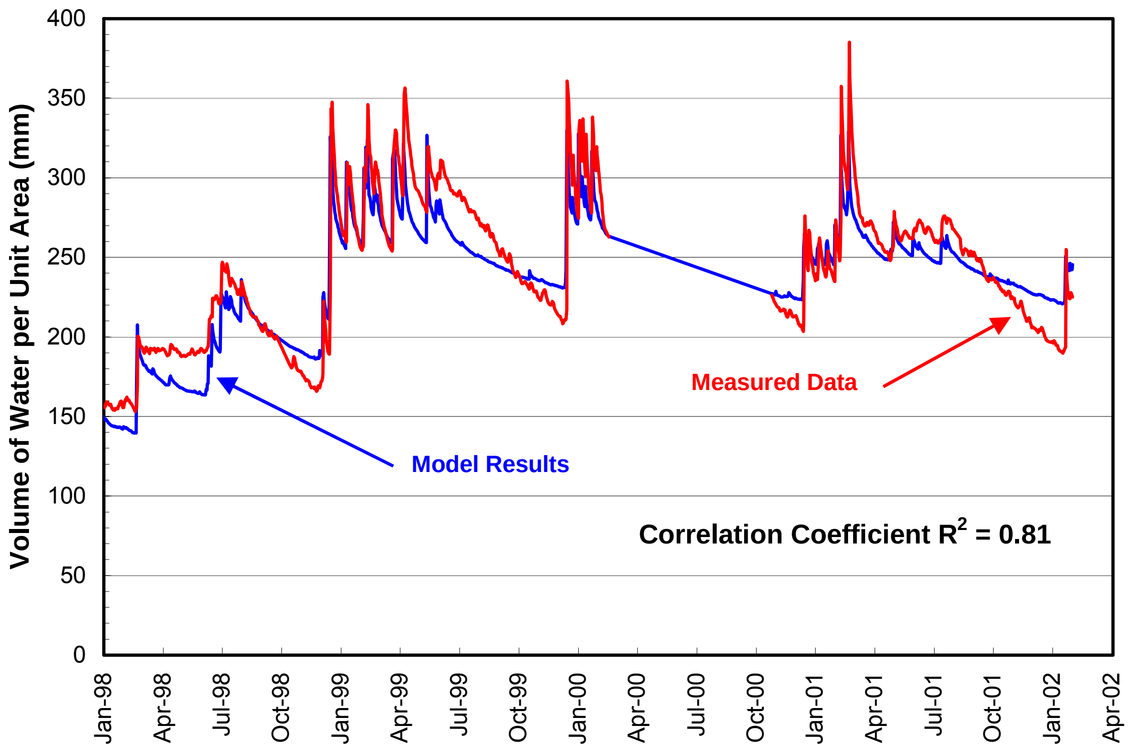

Figure 4.2 Comparison of the calibrated numerical model results to actual measured field data covering the period from January 1998 to February 2002.

4.1.3.3 <u>Effect of Extreme Climate Events</u>

The original modelling completed for the Mt. Whaleback cover system design used 300 mm for the average annual rainfall based on 30 years of climate data for the site. No net percolation into the underlying waste was predicted using this annual rainfall data. The highest recorded annual rainfall in the 30 year database was approximately 500 mm, which when modelled in 1996 (before construction of the field trials) indicated that net percolation in the 2.0 m BIF cover system would be less than 1% of annual rainfall.

The annual rainfall for the first year of monitoring (October 1997 to September 1998) at Test Plot 1 was 295 mm. No net percolation was recorded during this monitoring period. Rainfall was significantly higher in the next three years with 870 mm recorded in 1998-99, 1,160 mm in 1999-2000, and 497 mm in 2000-01. Net percolation through the cover system was recorded because the storage capacity of the cover system was exceeded by the successive wet years. Figure 4.3 shows the calculated volume of water within the cover system, as well as the net percolation recorded in each year, expressed as a percentage of annual rainfall.

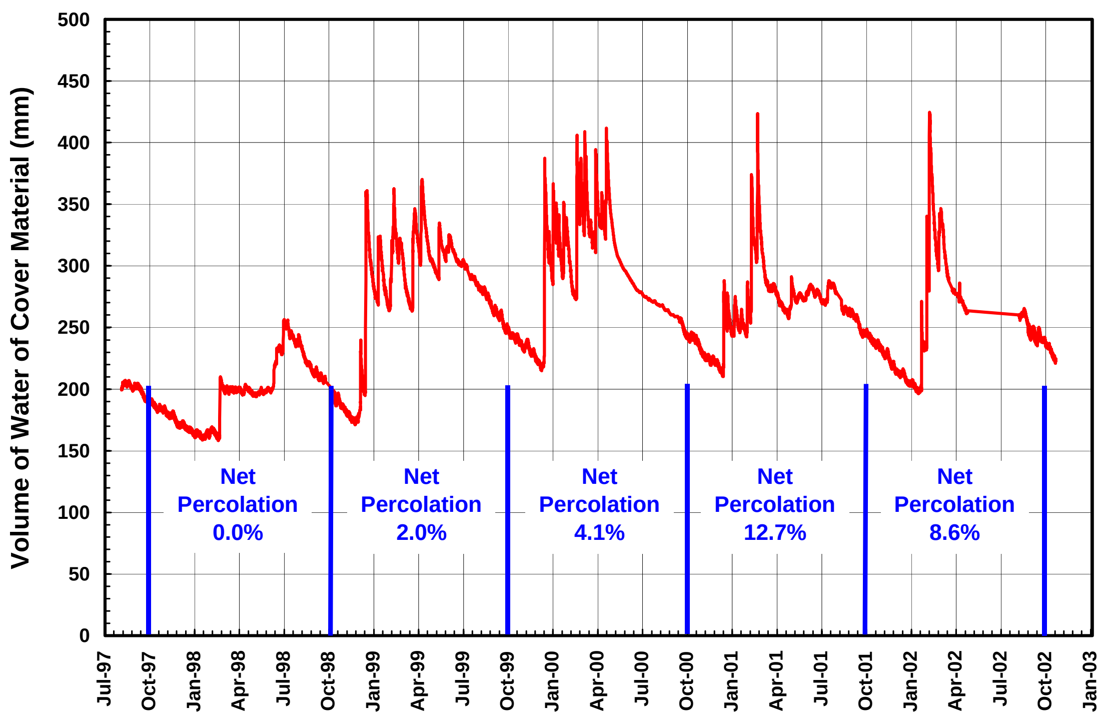

Figure 4.3 Net percolation and change in cover material storage at Test Plot 1.

Net percolation was greatest in 2000-01 when net percolation was approximately 13% of the annual rainfall. This is a significant amount of net percolation compared to the negligible net percolation predicted by the numerical model. The high net percolation in 2000-01 was likely due to the high rainfall in 1999-2000; as there is a lag time required for the infiltrating water to penetrate to the base of the cover system and further to the base of the lysimeter used to monitor net percolation. It is more appropriate to view net percolation over an extended time period to reduce the lag effects and develop an average net percolation value. The net percolation for the time period shown on Figure 4.3 was 5.0% of the rainfall recorded.

The fact that the 2 m of cover material was able to significantly buffer the extreme consecutive wet seasons is a positive aspect of the performance of the Mt. Whaleback field trials, particularly in light of the fact that bare surface conditions are being monitored (i.e. no transpiration). However, the results do illustrate an aspect of predicting cover system performance that was not included in the design phase of the Mt. Whaleback field trials. Typically, and certainly at the time the Mt. Whaleback field trials were designed, cover design modelling would only include modelling of a single extreme wet year. However, the Mt. Whaleback cover system field performance monitoring data clearly illustrate the importance of modelling consecutive extreme wet seasons to ensure that the impact of these conditions on long-term cover system performance is understood.

4.1.3.4 Effect of Vegetation on Cover System Performance

Vegetation provides the opportunity for a cover system to evapotranspirate moisture back to the atmosphere. Moisture stored within a cover system is "pulled" back to the surface through the vegetation root systems. The Mt. Whaleback site currently has two 1D field plots (Test Plots 4 and 5) to examine the effects of native vegetation on cover system performance.

The calibrated SoilCover model was used to predict the effect of "poor" vegetation (in terms of transpiration rates), with root development to 1 m, on the performance of a 2 m thick layer of Mt. Whaleback run-of-mine cover material. The model was completed for three consecutive years using the 1998-99 climate data. One set of simulations incorporated a bare cover system surface while another set of simulations added "poor" vegetation with root development to 1 m. The results of the modelling programme are shown in Figure 4.4.

The cumulative net percolation for the bare cover system simulations was 125 mm or 4.8% of the cumulative rainfall for the period. This percolation rate is similar to the 5.0% measured value at Test Plot 1. The net percolation predicted for a vegetated surface was 37 mm, or approximately 1.4% of the cumulative rainfall.

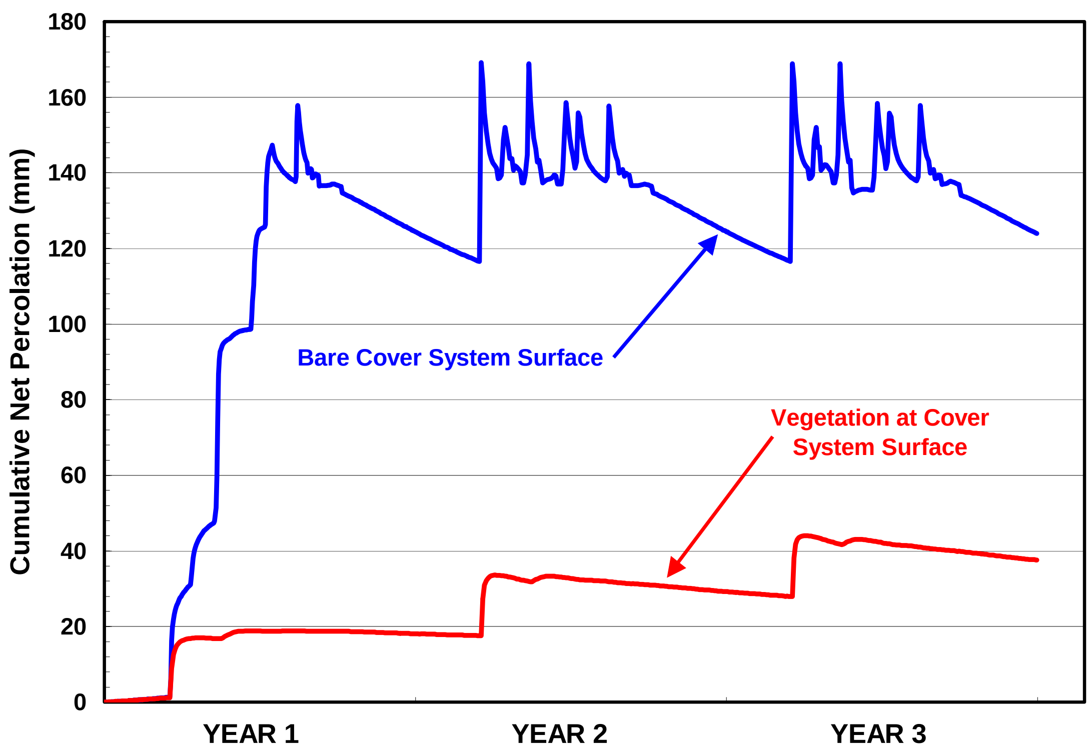

Figure 4.4 Net percolation predicted for consecutive wet year simulations.

The presence of vegetation improves the performance of all cover systems and in particular, moisture store-and-release cover systems. Vegetation increases evapotranspiration and “pulls” moisture back to the atmosphere that would otherwise report as net percolation. Once meteoric water infiltrates past the upper layers of the cover system (i.e. 30 cm), it takes prolonged dry periods to generate a sufficient suction gradient within the surface cover material to “pull” up the stored moisture to the surface by evaporation alone. Once a subsequent rainfall event occurs the suction gradient is reduced and infiltration from the first rainfall event cannot be removed from the cover system by evaporation. The rooting systems of most vegetation will develop to reach available moisture sources at depths greater than 30 cm; implying vegetation with a deep root system has a positive impact on cover performance. The modelling results shown in Figure 4.4 illustrate this impact. Test Plots 4 and 5 at Mt. Whaleback were implemented to quantify this effect for species native to the area.

4.1.3.5 The Effect of Segregation on Cover System Performance

The cover system at the Mt. Whaleback site was constructed by block dumping from large haul trucks to create a hummocky cover surface. Some segregation of the cover material is possible during placement due to the coarse nature of the material. Segregation of well-graded material, which describes most run-of–mine material, can lead to preferential flow paths, or macro-pore flow, within the cover system and possibly increase net percolation to the underlying waste material.

Macro-pore flow was observed in the field following a rainfall event where approximately 280 mm of rain was recorded over a 36-hour period. Sensors at a depth of 10 cm responded immediately following the start of the rainfall event. Sensors installed at 100 cm responded in the range of 36 to 48 hours after the start of the event, which was reasonable assuming flow through the matrix of the cover material. However, the sensors at a depth of 190 cm responded to the significant rainfall event less then six hours after the event started. This implies that a macro-pore flow path, which was not active for any other previous rainfall event, became a preferential flow path as a result of the extreme rainfall condition.

It was hypothesized that segregation of the cover material during placement caused a coarse textured zone, which only became active under high flow conditions (i.e. under all conditions before as well as after this event the preferred flow path was the finer textured matrix and homogeneous surrounding material). VADOSE/W, a 2D soil-atmosphere numerical model, was used to verify this hypothesis while also illustrating the effects of segregation on performance of a moisture store-and-release cover system.

The numerical simulation included an analysis of the net percolation of a 2.0 m BIF cover system with a hummocky surface, with the addition of a segregated layer within the cover system. Figure 4.5 shows the two meshes used in the numerical analysis.

The results of the simulations are summarized in Figure 4.6. Minimal net percolation was predicted for the hummocky cover system with no segregation layers. Net percolation was highest (between 5 to 6 mm) below the depressions on the undulating surface. Surface runoff collected in these depressions during the high intensity rainfall events of the simulated climate year driving water into the cover system and resulting in the higher net percolation values. The average net percolation for the cover system was minimal. The cover system with segregation layers showed high net percolation in the two areas where the segregated layer connected with the surface of the overburden. Net percolation was approximately 180 mm in these areas, significantly increasing the average net percolation across the entire cover system modelled (i.e. the mesh shown in Figure 4.5).

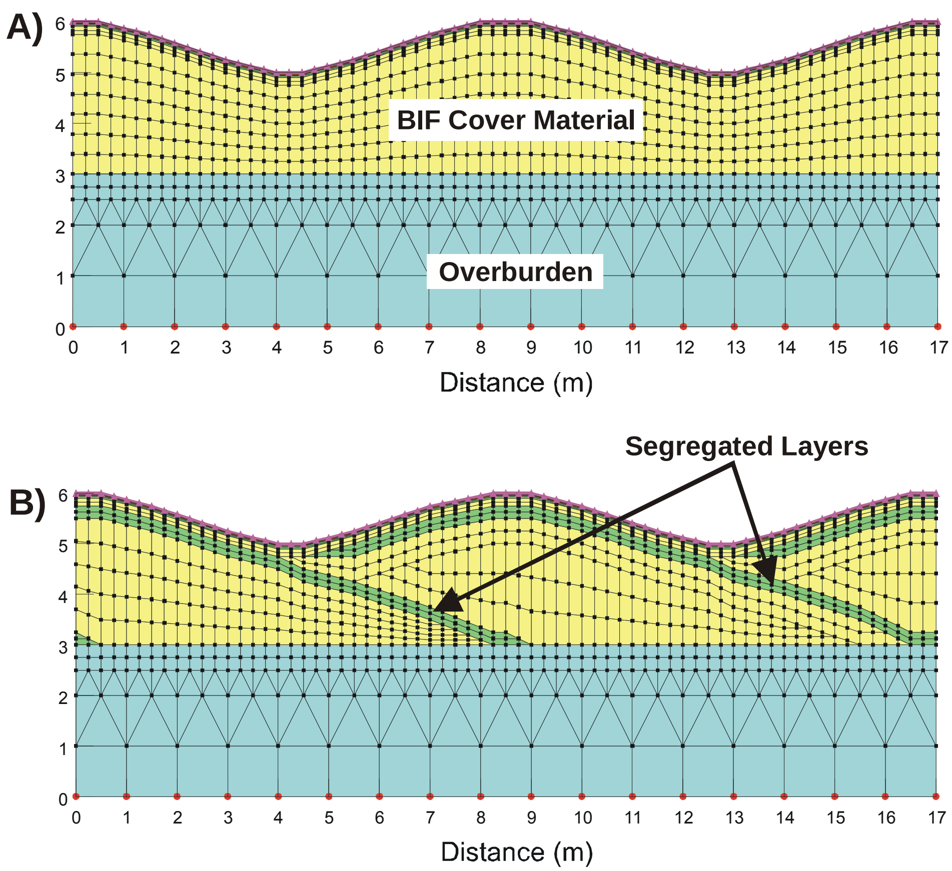

Figure 4.5 a) Mesh used in the 2-D analysis of the Mt. Whaleback hummocky cover system.
b) Coarse-textured segregation layers added to the 2-D mesh.

The VADOSE/W model, together with the field performance monitoring data, illustrated a key characteristic with respect to the performance of a moisture store-and-release cover system under high rainfall conditions. Namely; simply place cover material to the required depth is not sufficient. It is equally important to ensure that a homogeneous layer of material is placed to ensure that segregation of the cover material does not lead to near surface coarse zones, which have the potential to transmit infiltration deeper into the cover profile than would otherwise have occurred for a homogeneous layer of material.

The segregation layer produces a preferential, or macro-pore, flow path for meteoric waters to infiltrate to the underlying overburden material during extreme climate events. Macro-pore flow occurs in these areas resulting in high hydraulic conductivity rates causing rapid percolation to the underlying overburden material. The effects of segregation have also been observed at Test Plot 2. Volumetric water content sensors will show quick responses to rainfall events at depths up to two or three metres, suggesting high hydraulic conductivity flow paths exist within the test plot. Note however that these flow paths only become "active" during the extreme rainfall events or when surface runoff promotes accumulated surface flow to the area of segregation. Once the meteoric waters percolate to depth, it is an extremely slow process to "pull" the moisture back to the surface because flow occurs in the matrix of the cover material. In addition, if rainfall events occur prior to exfiltration of the moisture to the surface (or transpiration of the moisture), then unsaturated "piston" flow will "push" the moisture deeper into the profile, and potentially to a depth where moisture cannot be removed as evapotranspiration. Segregation has an adverse effect on moisture store-and-release cover systems because the macro-pore flow paths allow infiltration of moisture deep into the cover profile during the wet season where it might not be removed before the start of the next wet season. This can result in the deeper moisture reporting as net percolation.

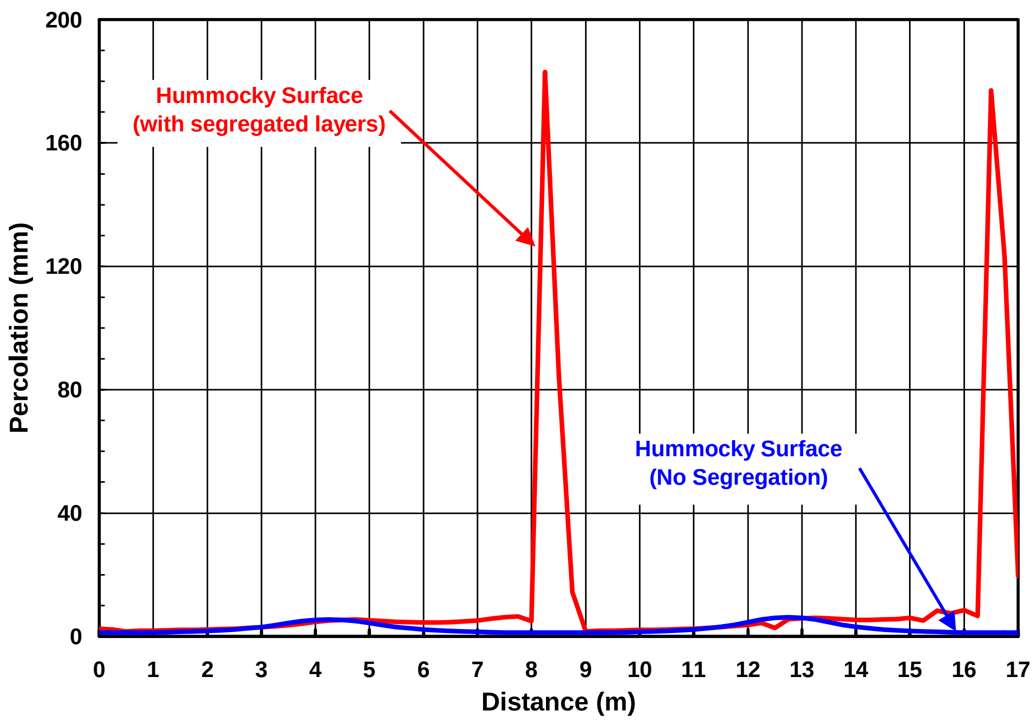

Figure 4.6 Net percolation results predicted for the homogeneous and segregated cover systems.

4.1.4 Summary

The Mt. Whaleback operation possesses a significantly long detailed performance monitoring system of five large-scale cover system field trials. Data has been collected at two of the test plots for more than six years, with little interruption in data due to equipment malfunction. The high data capture rates are a testament to the BHPBIO's commitment to the research project. The field data generated has allowed for the evaluation of the effects of extreme climate events on cover system performance, the definition of field material properties, the calibration of a numerical model to site conditions, an examination of the potential positive impacts of vegetation on cover system performance, and the assessment of the adverse effects of cover material segregation on cover system performance. It is expected that field performance monitoring data will continue to be collected for use in the development of a mine site closure plan.

The key lessons learned from the field performance monitoring are the impact of consecutive extreme climate events on cover system performance, the significant difference between field and laboratory cover material properties, the importance of a sustainable vegetation cover for long-term performance of moisture store-and-release cover systems, and the importance of limiting the segregation of cover material during placement. In short, for a moisture store-and-release cover system, it is not sufficient to simply place the required thickness of a material with no quality control. This is particularly true for well-graded or gap-graded material, which describes most run-of-mine waste.

4.2 Equity Silver

4.2.1 Background

Equity Silver is located in the Central Interior of British Columbia, within the Omineca Mining Division, 35 km southeast of Houston and approximately 575 km north northwest of Vancouver. During the life of the operation, copper, silver, and gold were mined within a window of interbedded volcanic and minor sedimentary rocks. Equity Silver is situated on an alpine plateau in a humid alpine environment. The average annual precipitation at Equity Silver is approximately 650 mm, with rainfall accounting for approximately 300 mm. Annual potential evaporation is approximately 500 mm.

Equity Silver worked an open pit mining operation from 1980 to the scheduled end of mining activities in the spring of 1992. Mining activities were continued past the scheduled closure date as underground mining was initiated to follow the ore body. A tailings facility containing waste from the milling operation and covering an area of 120 ha was constructed to the north of the mine plant site. In addition, three waste rock dumps were constructed during the life of the mine. Over 80 Mt of waste rock were placed in the Main dump, the Southern Tail dump, and the Bessemer dump. The final closure of the mine occurred in the spring of 1994.

4.2.2 Summary of Full-Scale Cover System

The Main dump was constructed first by placing waste rock directly on the cleared ground surface. The natural ground surface consisted of a thin topsoil mantle over glacial till that varies in thickness from 2.5 meters to greater than 20 meters. The Main dump, which contains about 52 Mt of waste rock, has a surface area of approximately 41 ha. The Southern Tail dump, for which construction was started in 1985, contains approximately 18 Mt of waste rock. The surface area of the Southern Tail dump is approximately 31 ha. The Bessemer dump is the smallest of the three waste rock dumps and contains approximately 10 Mt of material. The Bessemer dump is located north of the Main dump between the mine plant site area and the Main dump. The surface area of the Bessemer dump is approximately 29 ha.

The cover system for the waste rock dumps was constructed over the period of 1990 to 1994, starting with the Southern Tail dump, followed by the Main dump, and finally the Bessemer dump. The side slopes of the Main dump were graded to a constant slope with a maximum grade of 21° (2.6H:1V). The entire Main dump was covered with a compacted till layer 0.5 meters thick. A non-compacted layer of till, 0.3 m thick, was placed over the compacted layer. The Southern Tail dump consists of two distinct sections, the northern flat portion which is directly east of the Main dump and the sloped and tiered southern section. Both dumps were covered with a layer of compacted till 0.5 m thick that was placed directly on the waste rock and overlain with a layer of non-compacted till 0.3 m thick. The Bessemer dump was active until final closure of the mine site. An engineered soil cover system similar to that placed on the Main dump and the Southern Tail dump was completed on the Bessemer dump.

The cover system was designed to limit net percolation of meteoric waters to the underlying waste, with any reduction in oxygen ingress seen as an additional benefit. Swanson *et al.* (2003) demonstrated that significant benefit was also realized in terms of controlling oxygen ingress due to the presence of the cover system. The compacted till barrier layer possesses a low hydraulic conductivity that limits the percolation of meteoric waters to the underlying waste material. The compacted barrier layer is also capable of maintaining a high degree of saturation to reduce the ingress of oxygen. The design takes advantage of the low diffusion coefficient of oxygen through water as compared to air. Maintaining a degree of saturation of approximately 85% ensures that diffusion through the cover system will be low.

4.2.2.1 Overview of the Field Performance Monitoring Systems

Performance monitoring systems were installed to monitor various parameters that will influence the performance of field-scale cover systems. A weather station on the top of the Main dump (TMD) collects rainfall, wind speed, temperature, relative humidity, and net radiation data. The *in situ* moisture and temperature conditions within the cover and waste materials are being monitored with thermal conductivity sensors at the TMD, southwest face of the Main dump (SWF), and at the

Southern Tail dump (STD). These sensors are connected to automated data acquisition systems powered by solar panel/rechargeable battery sources. Volumetric water content is measured manually with a neutron water content probe. There are 14 neutron access tubes installed around the mine site with the majority clustered near the three automated monitoring sites.

4.2.3 Analysis of Equity Silver

The full-scale cover systems installed at Equity Silver have been in-place for approximately 10 years. The site has provided insight on the evolution of a full-scale cover system and the effects of changing cover material properties on cover system performance. The “lessons learned” at the Equity Silver site include:

- The importance of monitoring changes in the field saturated hydraulic conductivity of the cover materials;
- The proper design of the growth medium layer within a cover system to protect the compacted barrier layer; and
- The need to periodically re-evaluate the performance monitoring data and its value in developing a site-specific calibrated numerical model.

4.2.3.1 <u>Evolution of Cover System Materials</u>

Volume 4 summarized the physical, chemical, and biological processes that affect the long-term performance of a cover system. The processes were related to changes in the key properties of the cover materials such as hydraulic conductivity, the SWCC, and the physical integrity of the cover system. A field programme was completed as part of the INAP project at Equity Silver to measure the *in situ* saturated hydraulic conductivity of both the compacted till barrier layer and the non-compacted till growth medium.

The objective of the field programme was to evaluate changes in hydraulic conductivity of cover material with time. Soil structure controls the hydraulic properties of well-graded and fine-grained materials. The alteration of soil structure with time can significantly change the hydraulic conductivity of the cover materials. The field programme was a unique opportunity to evaluate the change in hydraulic conductivity of the Equity Silver cover materials over time. This was possible because a consistent borrow source was used to construct the cover systems for three different waste dumps. The cover systems at the Main and Southern Tail dumps have been in-place for approximately 12 years while the Bessemer dump cover system has been in place for approximately nine years. The results of the field *in situ* saturated hydraulic conductivity test programme were compared to the as-built and laboratory material properties.

Twelve measurements of the *in situ* saturated hydraulic conductivity (K_{fs}) were made at a depth of 18 cm with the Guelph permeameter for each of the three cover systems at the site. In addition, three measurements of K_{fs} were obtained at depths of 2 cm, 30 cm, and 70 cm with a pressure infiltrometer. Four measurements of K_{fs} taken with the pressure infiltrometer at a depth of 70 cm "failed" indicating that the hydraulic conductivity of the material at 70 cm was less than the measurement limits of the instrument. The measurement limit of the instrument is 1 x 10^{-7} cm/s. Additional pits were excavated to a depth of 70 cm for hydraulic conductivity testing until three successful infiltration tests were completed. Lastly, dry density measurements were obtained with a sand cone at depths of 2 cm, 30 cm, and 70 cm. These measurements were taken in pits similar to the ones excavated for hydraulic conductivity testing. Table 4.1 summarizes the results of the pressure infiltrometer and Guelph permeameter hydraulic conductivity tests.

Figure 4.7 show the field saturated hydraulic conductivity (geometric mean) and density as a function of depth for the sloped cover systems at the Main dump and the Southern Tail dump. Measurements of hydraulic conductivity taken at depths of 30 cm and 70 cm were within the compacted "barrier" layer. In general, the hydraulic conductivity decreased one order of magnitude from the 2 cm depth to 30 cm depth and decreased two additional orders of magnitude from 30 cm to 70 cm. The dry density was lowest at a depth of 2 cm and increased sharply at 30 cm. These results were anticipated as the 30 cm density measurements were made within the compacted layer. Dry density decreased marginally in the Southern Tail dump cover system as the depth increased to 70 cm. The density was fairly constant from 30 cm to 70 cm in the Main dump cover system.

Table 4.1

Summary of Guelph permeameter and pressure infiltrometer tests at Equity Silver (geometric mean (M), standard deviation (σ), dry density (ρ_d)).

Depth (cm)	M (10^{-4} cm/s)	σ (10^{-4} cm/s)	ρ_d (g/cm^3)	Failed Tests	M (10^{-4} cm/s)	σ (10^{-4} cm/s)	ρ_d (g/cm^3)	Failed Tests
	Southern Tail Dump (Slope)				**Main Dump (Slope)**			
18	0.28	0.62	Guelph Perm.		0.40	1.14	Guelph Perm.	
2	3.37	4.60	1.96	0	3.24	1.65	1.74	0
30	0.32	0.10	2.20	0	0.19	0.19	2.03	0
70	0.006	0.002	2.01	1	0.006	0.002	2.04	0
	Main Dump (Horizontal)				**Bessemer Dump (Horizontal)**			
18	0.49	0.46	Guelph Perm.		0.15	0.34	Guelph Perm.	
2	5.63	2.10	1.69	0	2.59	2.37	1.66	0
30	0.38	0.036	1.75	0	0.29	0.10	2.01	0
70	0.004	0.002	1.78	2	0.004	0.003	1.81	1

Note: M is the mean value of the field hydraulic conductivity tests conducted
σ is the standard deviation of the field hydraulic conductivity tests conducted
ρ_d is the dry density measured at the same depth and location

Based on the relationship between density and hydraulic conductivity, it was anticipated that values of K_{fs} measured at 30 cm would be as low or lower than those at 70 cm due to the higher *in situ* density. However, values of K_{fs} at 30 cm were two orders of magnitude greater than at 70 cm. It would seem likely that the increase in hydraulic conductivity is a result of a change in soil structure. Two possible physical processes that could lead to a change in structure at the site are freeze-thaw cycling and wet-dry cycling. Temperature sensors installed in the compacted layer indicate that this region of each cover system is not undergoing freeze-thaw cycles at any of the automated monitoring locations.

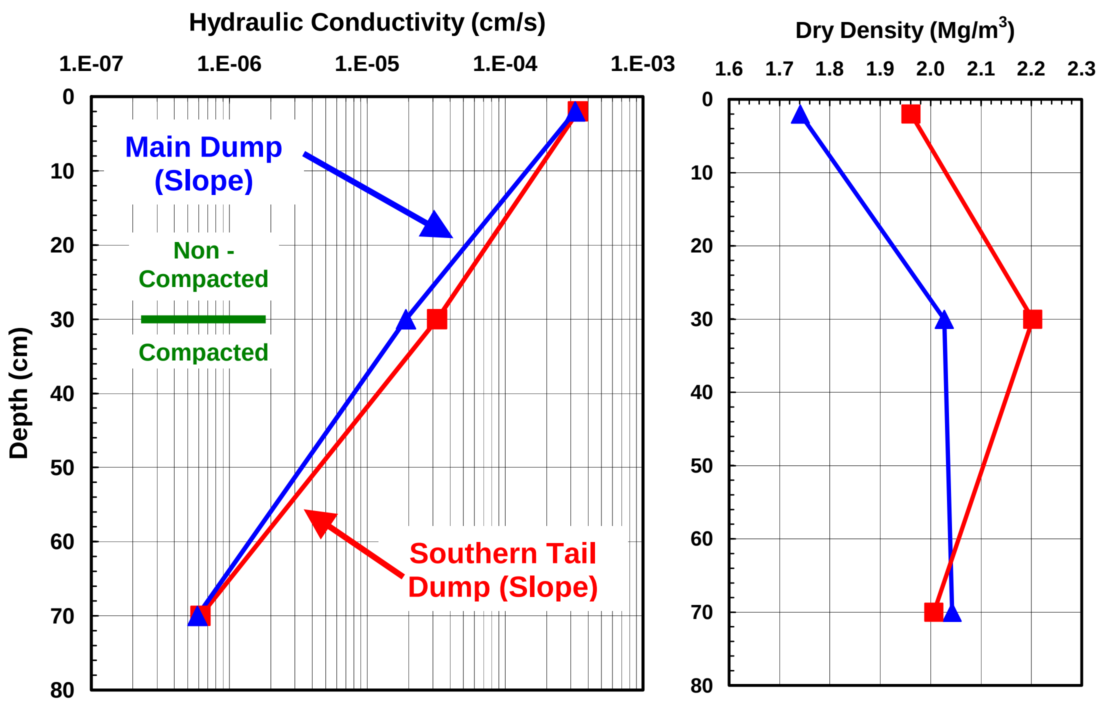

Figure 4.7 Saturated hydraulic conductivity and density measured for the sloping cover systems at Equity Silver.

The matric suction sensor data indicate that wet-dry cycles started occurring within the top 10 cm of the compacted material in approximately 1999 or 2000, and have continued in each subsequent summer. The increased levels of matric suction have only been recorded in the uppermost matric suction sensor in the compacted layer and were not experienced in the three sensors installed lower down in this layer. This suggests that only the top portion of the compacted layer has experienced wet-dry cycles, which might explain the increased field saturated hydraulic conductivity measured at the top of the layer, as compared to the lower values measured at a depth of 70 cm. Matric suction values measured by the uppermost sensor in the compacted layer during the summer have fluctuated between 400 kPa and 1,000 kPa, significantly higher than the AEV of the compacted cover material.

The residual water content for this material likely corresponds to a suction higher than that measured, however, this level of suction would still represent significant drying conditions.

The field saturated hydraulic conductivity testing at Equity Silver found that the upper region of the compacted barrier layer (approximately 10 cm) possesses a field saturated hydraulic conductivity value more similar to the overlying growth medium. It is likely that the thickness of the growth medium at the Main and Southern Tail dumps was not sufficient to prevent evaporation of moisture from the underlying compacted layer (for the period commencing in 1999 or 2000). It is important to note, however, that the lower region of the compacted layer ($\approx$ 40 cm) appears to be "intact" in the sense that it is similar to as-built conditions and has not been affected by wet-dry cycling. In short, for the limited number of areas tested, it would appear that rather than the growth medium layer and compacted barrier layer having a thickness of 30 cm and 50 cm, respectively; the split is approximately 40 cm and 40 cm. Whether the cover system has come into equilibrium with its surroundings and the evolution of the upper region of the compacted barrier layer is complete (in terms of "changing" to become part of the growth medium); or whether the layers will continue to evolve, will require additional field performance monitoring to further understand the evolution of the cover system.

O'Kane (1996) reported that the laboratory measured saturated hydraulic conductivity values for the compacted till and non-compacted till used in the cover system design were 1×10^{-8} cm/s and 1×10^{-6} cm, respectively. Field measurements taken approximately 10 years later found the field saturated hydraulic conductivity of the growth medium in the range of 1×10^{-4} cm/s, which is a difference of two orders of magnitude. The upper region of the compacted till has a field saturated hydraulic conductivity of 2×10^{-5} cm/s while the lower depth of the compacted layer is 5×10^{-7} cm/s, or lower (recall the failed *in situ* K_{fs} tests, which indicate values less than 1×10^{-7} cm/s for the field saturated hydraulic conductivity of the lower region of the compacted layer).

As part of a cover system research programme undertaken by the site over the period covering approximately 1992 to 1995, Swanson *et al.* (2003) developed field calibrated model parameters that were similar to the laboratory values noted above. The numerical modelling completed for the Equity Silver cover system as part of the INAP project did not predict a higher net percolation, as compared to that predicted using the Swanson *et al.* (2003) field calibrated model parameters. This is despite using higher saturated hydraulic conductivity values, as compared to Swanson *et al.* (2003). The modelling comparison was completed for the period subsequent to the first occurrence of the wet-dry cycling measured in the upper 10 cm of the compacted layer (i.e. 1998 to 2002). One rationale for explaining this counter-intuitive result is the contrast between the growth medium and compacted layer, in terms of moisture retention and saturated hydraulic conductivity. This key aspect of the performance of the Equity Silver cover system exists, whether the material properties are as per those modelled by Swanson *et al.* (2003), or as utilized in the modelling completed for the INAP study. The higher saturated hydraulic conductivity and reduced moisture retention of the overlying growth medium (i.e. the non-compacted layer) increases the potential for atmospheric demand for moisture to be satisfied to a much greater extent by this layer, as compared to the underlying compacted material. In addition, the saturated hydraulic conductivity of the lower 40 cm of the compacted material appears to be sufficient to control net percolation for the period from 1998 to 2002 inclusive when evaporation was low (i.e. during late fall and spring freshet). Note also that while a higher saturated hydraulic conductivity for the growth medium increases surface infiltration, it should also imply that exfiltration rates would be higher.

The saturated hydraulic conductivity of a cover material is not the only material property likely to change with time; the SWCC will also likely change as the material evolves. The change in moisture retention characteristics of the material will affect the saturation levels of the cover system, which will, in turn, affect the rate of oxygen ingress to the underlying waste material. The modelling completed for this study predicted higher oxygen ingress for the hydraulic material properties assumed to represent current conditions, as compared to that predicted using the hydraulic material properties developed by Swanson *et al.* (2003).

Note that all numerical modelling on Equity Silver's cover system and reported herein was completed using the SoilCover model (Geo-Analysis 2000 Ltd., 2000).

4.2.3.2 Design of Growth Material Layer Thickness

Often in the design and construction of a compacted barrier layer – growth medium cover system the focus of the design is on the compacted barrier layer. Considerable attention is paid to the placement of the compacted layer, ensuring proper water content and compaction to produce a low hydraulic conductivity material. While the importance of the barrier should not be discounted, neither should the importance of the overlying growth medium. The growth medium layer serves as protection against physical processes, such as wet-dry cycling and freeze-thaw cycling, as well as chemical and biological processes. An inadequate growth medium layer will not properly protect the compacted barrier layer, leading to possible changes in the barrier layer performance. Concurrent to these considerations is that the growth medium must possess sufficient available water holding capacity to ensure a sustainable vegetation cover, which would be a function of the underlying material as well as the moisture retention and thickness of the growth medium.

The full-scale cover system design at Equity Silver incorporated a 0.5 m compacted till barrier layer with a 0.3 m overlying non-compacted till growth medium layer. As discussed in the previous section, the compacted barrier layer has experienced an increase in saturated hydraulic conductivity resulting from a change in soil structure, which in turn was caused by wet-dry moisture cycling. This suggests that the growth medium layer did not provide adequate protection for the upper region of the underlying barrier layer in terms of ensuring that atmospheric demand for moisture was limited to the growth medium layer. The emergence of different vegetation species and changes in the moisture requirements of the vegetation would likely have also influenced the measured performance.

The performance monitoring data collected at the site suggests that the 0.3 m growth medium layer does adequately protect the compacted layer from freeze-thaw cycling, when combined with the insulating effects of the winter snowpack at the site. Suction data recorded within the compacted layer does show moisture cycling with elevated suctions being measured in the summer season and low suctions during the winter and spring. This indicates wet-dry cycling, most likely driven by the vegetation established on the cover system.

It is generally thought, that plants do not establish their rooting systems in barrier layers due to the high density conditions within the layer, although this report does not make that contention. An alternate hypothesis (Barbour, 2003) might be that root development does not extend into these layers due to the low oxygen levels within the compacted layer because these layers are most often compacted wet of optimum, which corresponds to a high saturation level. If the growth medium does not possess the capacity to supply the moisture required to meet vegetation and atmospheric demand throughout the summer season, this demand for moisture will extend to the barrier layer. The moisture condition of the upper region of the barrier layer will be reduced, which will increase oxygen concentration in the pore space. It is hypothesised that the vegetation could then establish a "toe-hold" within the barrier layer and continue to penetrate to the depth required to satisfy its moisture demands.

Equity Silver is an example of the importance of the design of the growth medium layer to long-term performance. The upper 10 cm of the compacted barrier layer functions in a similar manner to a growth medium layer rather than a compacted barrier layer. It is possible that a thicker growth medium layer, which would appear to be the direction in which the cover system is evolving, may provide better protection for the barrier layer and limit the evolution of the material within the barrier layer.

4.2.3.3 Periodic Evaluation of Performance Monitoring Data

The operational status of the performance monitoring system should be reviewed annually to ensure that it is still meeting its objectives with respect to the long-term closure plan. The objectives of field performance monitoring are to:

1) Develop an understanding for key processes and characteristics that control performance;
2) Verify the predicted performance of the cover system;
3) Develop credibility and confidence with respect to performance of the proposed cover system from a closure perspective; and
4) Develop a database with which to calibrate numerical modelling tools and optimize the cover system design.

For example, if one of the objectives of the performance monitoring programme at the mine site is to collect *in situ* field measurements for the calibration of a site-specific numerical model then the automated instrumentation must be maintained to ensure that the required data is collected. There is minimal value in maintaining a performance monitoring system that does not suit the closure objectives of the mine site.

Field performance monitoring systems were installed at three locations at Equity Silver in 1993. Data has been collected continuously since the onset of monitoring with automated temperature and matric suction readings and periodic manual measurements of volumetric water content. Gradually, over the 10 years of operation, some sensors have stopped operating or do not record accurate data. For example, only one of the original eight suction sensors at the top of the Main dump monitoring location is currently providing useful data. Note, however, that this is a function of the quality of the sensors installed. At the time of installation the sensors installed were state-of-the-art. More robust sensors are now available, which were not available at the time of installation of the monitoring system.

As part of the INAP project, numerical modelling was completed on selected mine sites. Equity Silver was one of the selected sites and time was spent to create a database of *in situ* conditions, material properties, and climate data. The soil-atmosphere model was calibrated to the field data. However, it should be noted that it was more difficult to calibrate the model to the site's field performance monitoring data (i.e. *in situ* suction), as compared to the BHP Billiton Mt. Whaleback site.

The difficulty in calibrating the model to Equity Silver's field performance monitoring data is due in part to the lack of a continuous record of *in situ* conditions, as discussed above. An additional issue associated with the difficulty in developing the calibrated cover system model for the site was the manual, periodic measurements of volumetric water content. Neutron probe water content measurement was the state-of-the-art technology at the time of installation. However, recent research has shown that manual monitoring does not provide timely enough measurements for use in model calibration nor provide the required "real-time" data to develop a thorough understanding for the response of the cover system to precipitation and evaporation at the site. Volumetric water content should be measured automatically at the same intervals as soil suction. As discussed in the previous section, this would allow determination of the *in situ* field SWCC, which significantly enhances the ability to develop a calibrated numerical model.

4.2.4 Summary

Equity Silver possesses the oldest, in-place full-scale cover systems of the Canadian sites summarized herein. Data has been collected at three monitoring stations for approximately ten years; however, there have been considerable interruptions in data collection due to equipment malfunction.

A field testing programme conducted found that the saturated hydraulic conductivity of the non-compacted till growth medium material and the upper 10 cm of the compacted till barrier layer are higher than the laboratory measured values used in the numerical modelling completed by Swanson *et al.* (2003) and the original design work completed for the cover system. Examination of the field data collected found that wet-dry cycling is likely occurring in the upper 10 cm of the compacted layer and might be a possible cause of the change in cover material properties. The INAP study highlighted the importance of a properly designed growth medium cover layer and the value of accurate, automated, and continuous cover system performance monitoring data.

The key lessons learned from the field performance monitoring and field testing completed at the Equity Silver are the significant difference between the current saturated hydraulic conductivity of the cover materials and the original laboratory tests (i.e. the evolution of the cover material); and the importance of timely, accurate performance monitoring data. This includes the collection of automated volumetric water content data. The site's historical data and research work on cover system design at the site represents a tremendous opportunity to evaluate the long-term performance of cover systems.

4.3 Teck Cominco Ltd., Kimberly Operations

4.3.1 Background

The Teck Cominco Ltd. Kimberly Operations site is located in Kimberley, British Columbia, within the Purcell range of the Rocky Mountains. During the life of the operation, iron, lead, and zinc were mined from the underground ore body. The climate at Kimberly Operations is classified as semi-arid due to an annual moisture deficit, however the site typically experiences hot, dry summer conditions and can experience humid fall and winter conditions. The average annual precipitation at the site is 402 mm calculated from mill site weather records, with rainfall accounting for approximately 240 mm. The average annual potential evaporation for the site is approximately 700 mm.

The underground mining operation at the site ran continuously from 1909 until closure in 2001. A tailings facility was constructed in 1923 and contains 90 million tonnes of waste material within its 373 ha area. The tailings were deposited on a relatively flat area directly on a bedrock / till surface.

4.3.2 Summary of Cover System Test Plots

A total of seven test plots were constructed on the siliceous tailings storage facility. This study focuses on three test plots constructed in 1994; consisting of a compacted barrier cover system, a moisture store-and-release cover system, and a coarse rock “control” cover system. The reader is referred to Gardiner *et al.* (1997) for additional details. The test plots were constructed using a coarse low-density reject rock from the mill (float rock) and a cobbly, non-plastic till. The float rock was originally placed on the tailings for dust suppression. However, as an understanding for the use of this material as a component of a cover system was developed, the float rock layer served as a capillary break to limit the upward movement of salts from the underlying tailings into the cover system materials. The depth of the float rock layer in the test plots ranges from 20 to 60 cm.

The compacted barrier cover system (Test Plot #2) included a 25 cm compacted till layer and an overlying 25 cm non-compacted till growth medium layer. The measured laboratory saturated hydraulic conductivity of the compacted and non-compacted till material was 1×10^{-6} cm/s and 1×10^{-3} cm/s, respectively. The moisture store-and-release cover system (Test Plot #3) was constructed from 45 cm of non-compacted till over the float rock. The final “control” cover system consisted of the bare float rock material.

4.3.3 Overview of the Field Performance Monitoring Systems

Meteorological conditions monitored in the test plot area include air temperature, precipitation, and relative humidity. Information on global radiation and sunshine hours are recorded at nearby regional meteorological stations and was used to supplement site measurements. Snow depth measurements were obtained on the test plots subsequent to the onset of winter conditions and up to the spring freshet. The suction and temperature at the mid-depth of the non-compacted and compacted till layer of each test plot, as well as the underlying tailings, have been monitored since construction. Field lysimeters monitor net percolation into the underlying waste tailings material from the base of the cover systems and are used to evaluate the performance of the cover system field trials.

4.3.4 Analysis of Kimberly Operations’ Test Plots

The cover system test plots installed at Kimberly Operations have been in-place for approximately nine years. The site has provided insight on the relative influences of snow and rain on the performance of the cover systems, the evolution of cover system materials, and the effects of changing cover material properties on cover system performance. The “lessons learned” at Kimberly Operations include:

- The tendency for higher net percolation during years when snowfall is a large percentage of the total annual precipitation; and
- The importance of monitoring changes in the field saturated hydraulic conductivity of the cover materials.

4.3.4.1 <u>The Influence of Precipitation Distribution on Cover System Performance</u>

The comparative performance of the compacted barrier cover system and the moisture store-and-release cover system has been evaluated at the site since 1994. Figure 4.8 summarizes the performance of the three cover systems from 1995 to 2001. The average net percolation through the compacted barrier cover system was 6.6% of the average annual precipitation over the monitoring period, which is slightly less than the 8.8% average net percolation recorded at the moisture store-and-release cover system. The performance of the "control" float rock cover system was distinctly higher; on average the control plot allowed 52% of the annual precipitation through as net percolation.

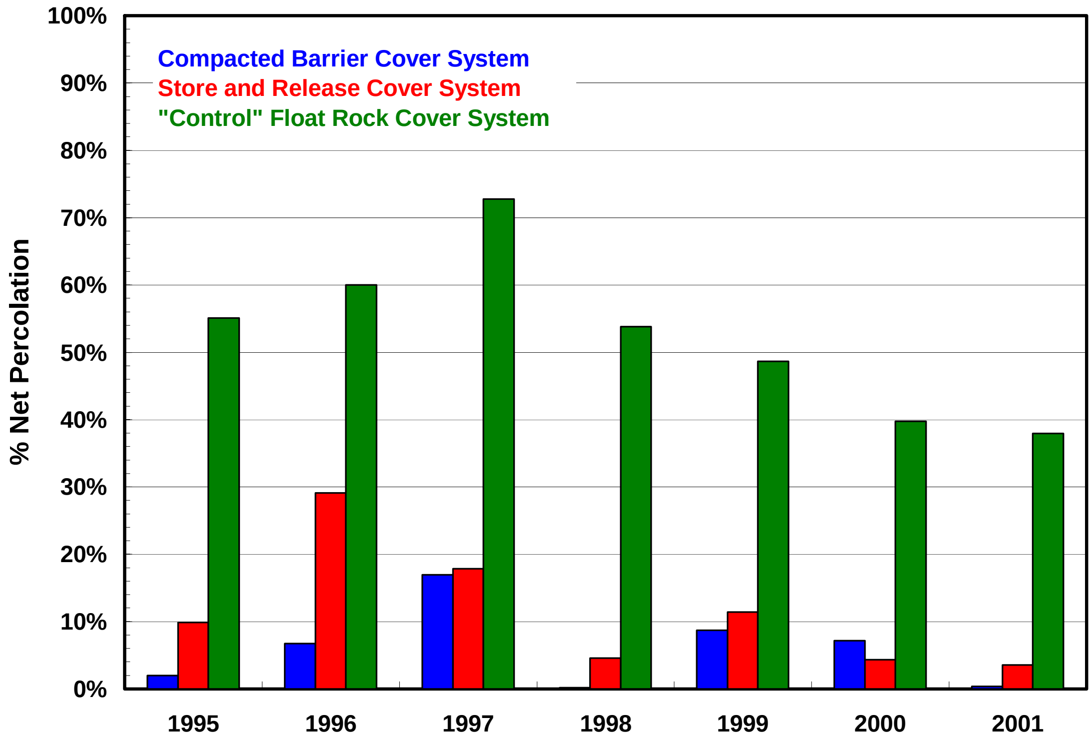

Figure 4.8 Comparison of the performance of the cover system test plots at Kimberly Operations (1995-2001).

Further analysis of the precipitation and snow depth survey data was completed to examine the relative influence of snowfall and rainfall on cover system performance at the site. The timing of precipitation at the site is a significant factor on cover system performance due to the varying climate conditions at the site. For example, rainfall occurring during the hot, dry summers at the site is not likely to percolate through the cover systems. However, during the late fall, winter, and early spring, precipitation is more likely to result in net percolation. This is due to the low evaporative demand during these periods and the low storage capabilities of the cover systems. Freezing conditions do not usually develop within the cover system profile because of snow cover and climatic conditions, which allow net percolation into the underlying waste material during these periods.

Figure 4.9 separates the annual precipitation into rainfall and snowfall and includes the total net percolation recorded at the compacted barrier and moisture store-and-release cover systems for each year of the monitoring period. In the first two years of monitoring, the compacted barrier cover system performed better than the moisture store-and-release cover system allowing less net percolation. The increase in net percolation from 1995 to 1996 is comparable to the increase in total precipitation and snowfall for the two years. The highest total precipitation and snowfall was recorded in 1997, which led to the highest net percolations measured during the monitoring period, if the results for the two test plots are averaged. A significant increase in net percolation was recorded for the compacted barrier cover system while net percolation through the moisture store-and-release cover system decreased. Minimal net percolation was measured at the test plots in 1998; this year had the lowest snowfall measured during the monitoring period. In the following year, snowfall and total precipitation increased leading to above average net percolation measured at the test plots. Finally, the net percolation recorded in 2000 and 2001 was low, with 2001 recording the lowest net percolation for the monitoring period.

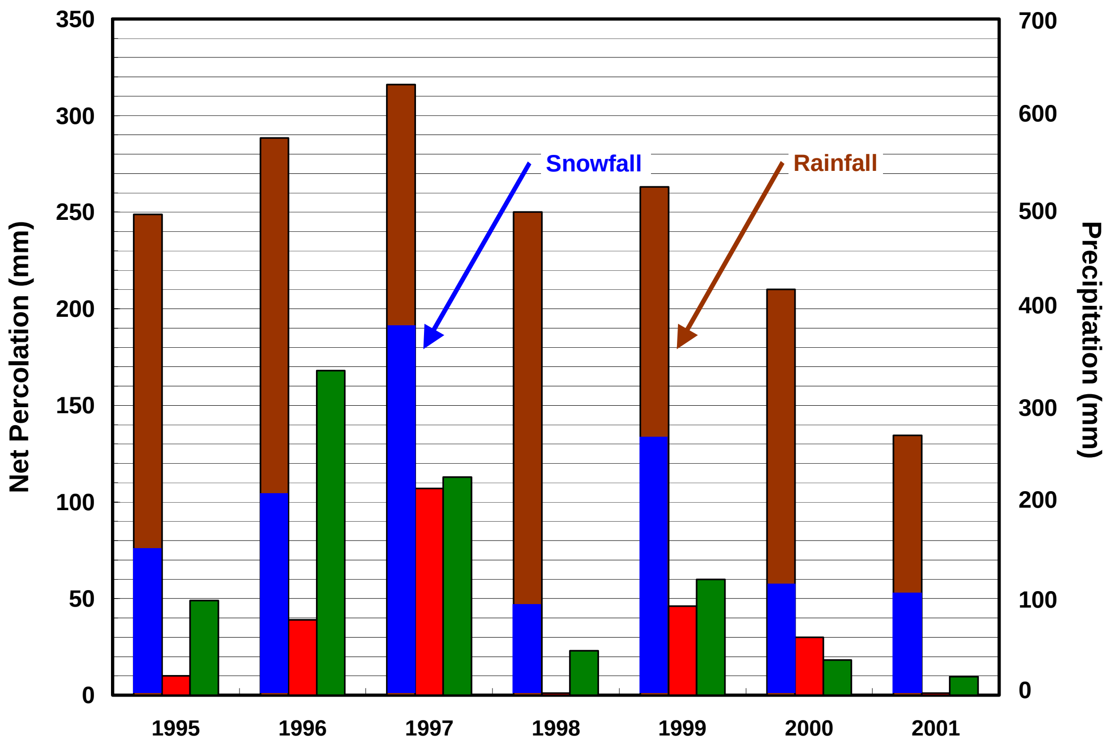

Figure 4.9 Net percolation and precipitation recorded at the compacted barrier and moisture store-and-release cover systems (1995-2001).

It should be noted that precipitation was above the long-term average for the majority of the monitoring period. In the first five years (1995 to 1999), total precipitation was at least 100 mm greater than the long-term average. Precipitation recorded in 2000 was similar to normal conditions, and total precipitation was only 65% of the long-term annual average in 2001.

The best example of the relative influence of snowfall and rainfall is shown in the net percolation results measured in 1998 and 1999. These years had roughly equivalent total precipitation as approximately 25 mm more precipitation was recorded in 1999 (526 mm compared to 500 mm).

However, net percolation during the two years was quite different. Less than 1 mm was measured at the compacted barrier cover system in 1998 with 23 mm recorded at the moisture store-and-release cover system. In comparison, 46 mm and 60 mm were recorded at these test plots in 1999. The difference in performance is likely due to the precipitation that occurred as snowfall during the years. Only 90 mm of precipitation fell as snowfall in 1998 as compared to 270 mm in 1999. The results from 1995 are also similar to 1998 and 1999. Total precipitation was roughly equivalent and total snowfall was in between the results from 1998 and 1999. The net percolation measured at both test plots was also in between the values recorded in the other years.

Climate conditions appear to be the key factor controlling performance of the test plots. Higher annual incident precipitation will generally lead to an increase in percolation to the tailings underlying the test plots, which is intuitive, but often not appreciated when predicting long-term performance. However, not so intuitive is the influence on performance due to the time of year in which precipitation occurs and the form of precipitation (i.e. snow or rain). In general, precipitation that contributes to snowpack, or occurs during the winter, will increase net percolation to the underlying tailings material while summer rainfall is buffered by the presence of cover material and net percolation is reduced as a result of the hot dry conditions during this time. Hence, the impact on performance due to than average annual precipitation can only be properly understood within the context of whether the higher precipitation was due to rainfall, snowfall, or some combination of rainfall and snowfall.

4.3.4.2 Evolution of Cover System Materials

A field *in situ* saturated hydraulic conductivity testing programme was completed at Kimberly Operations in 2002 as part of the INAP study. The testing methodology was identical to the procedure incorporated at Equity Silver. Figure 4.10 shows the field saturated hydraulic conductivity and density as a function of depth measured at the compacted barrier cover system (Test Plot #2). Measurements of field saturated hydraulic conductivity obtained at a depth of 30 cm and 50 cm were within the compacted barrier layer. In general, the hydraulic conductivity decreased one order of magnitude from the 2 cm depth to a depth of 30 cm, and decreased slightly less than one order of magnitude from 30 cm to 50 cm. The dry density was lowest at a depth of 2 cm and increased sharply at 30 cm. These results were anticipated as the 30 cm density measurements were obtained within the compacted layer. Dry density increased further as the depth increased to 50 cm. The results are similar to conditions measured at Equity Silver with the upper 10-15 cm of the compacted barrier having higher field saturated hydraulic conductivity as compared to the lower region of the compacted layer.

The 25 cm compacted barrier layer at Test Plot #2 was constructed in two lifts. The same compaction procedure was used during construction making it unlikely that either the initial saturated hydraulic conductivity or initial density would differ between the layers. This suggests that a physical, chemical, or biological process has occurred at the site within the last nine years to alter the properties of the upper lift of the compacted barrier layer. Possible processes that could lead to a change in structure at the site are freeze-thaw cycling, wet-dry cycling, and the influence of plant roots identified from the performance monitoring data collected at the site. Temperature sensors installed in the compacted layer indicate that this region of the cover system is not undergoing freeze-thaw cycles.

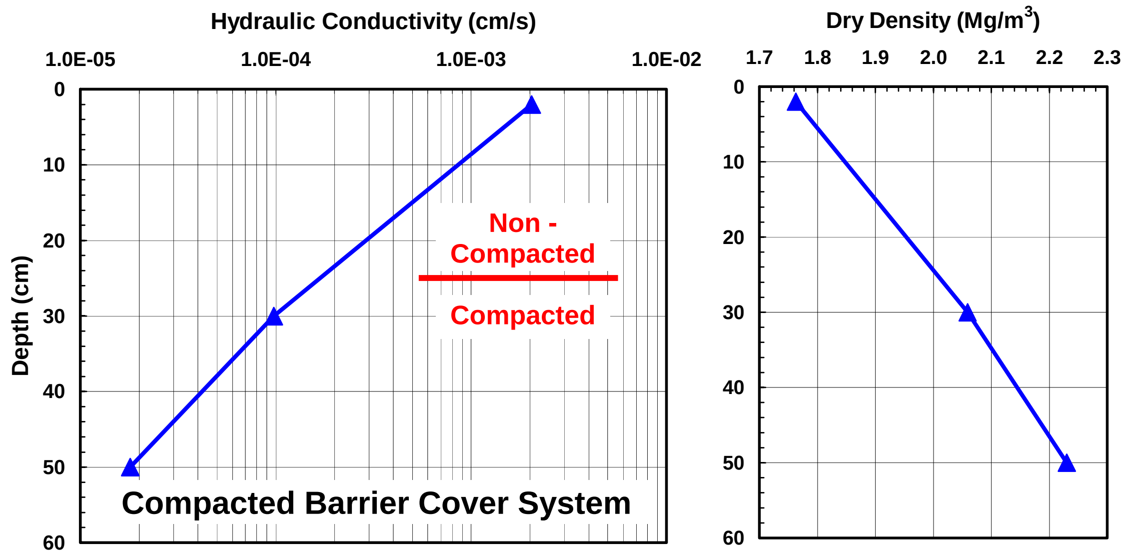

Figure 4.10 Results of *in situ* saturated hydraulic conductivity tests on the compacted barrier cover system at Kimberly Operation.

Examination of matric suction sensor data indicates that wet-dry cycles have occurred in the compacted material in each summer since installation. Matric suction values measured during the summer in the compacted layer are typically greater than 1,000 kPa, significantly higher than the AEV of the compacted cover material and likely close to residual water content conditions. The dry conditions are typically experienced from June to October of each year. In the remainder of the year, the average suction condition in the compacted layer is approximately 30-40 kPa, but levels in 1998 and 1999 only dropped to 100 kPa. Matric suction is only measured at the center of the compacted layer so it is unclear whether the increased suction condition is typical of the entire compacted layer, but based on field observations, it is reasonable to assume this is the case.

Preparation of the test covers for *in situ* hydraulic conductivity testing at Kimberley Operations found that a large amount of plant roots extend into the upper lift of the compacted barrier layer. It is possible that plant roots have "broken up" the compacted layer and caused the increase in field saturated hydraulic conductivity and decrease in density. Very few traces of root development were found upon examination of the lower lift of the compacted layer, suggesting that the moisture demand resulting from vegetation is satisfied by the growth medium and upper compacted layer. It is also possible that the vegetation has not had sufficient time to fully penetrate the lower lift, which could be determined through monitoring during future growth seasons.

It is likely that the overlying growth medium of the cover system at the compacted barrier test plot was not sufficient to limit atmospheric demand for moisture from impacting on the underlying compacted layer. Whether or not the cover system has come into equilibrium with its surroundings and the evolution of the upper region of the compacted barrier layer is complete (in terms of “changing” to become part of the growth medium) remains to be seen. Additional field performance monitoring is required to further understand the evolution of the cover system.

Note that observations and measurements obtained during excavation of Kimberley Operations’ test plots provide credence to the hypothesis presented earlier with respect to high density conditions and root development. It is clear that the upper lift of the compacted layer has not limited root development, and that this layer does possess low saturation conditions. This would theoretically provide for more suitable conditions for root development, in terms of oxygen concentration of the pore space, as compared to a tension saturated compacted barrier layer.

O’Kane *et al.* (1999) reported that the laboratory saturated hydraulic conductivity values for the compacted till and non-compacted till used in cover system design were 1 x 10^{-6} cm/s and 1 x 10^{-3} cm, respectively. Field measurements approximately nine years later indicate that the average field saturated hydraulic of the growth medium is approximately the same value (2 x 10^{-3} cm/s), which is an insignificant change from the initial measured value. It would appear that there is little difference between the laboratory and field based measurements, which could be a result of the non-plastic properties of the material. The upper area of the compacted till has a hydraulic conductivity of 1 x 10^{-4} cm/s while the lower depth of the compacted layer is approximately 2 x 10^{-5} cm/s. Both values represent higher field saturated hydraulic conductivity values as compared to laboratory measurements, and based on the results presented for previous case studies, it is also likely these values are higher than compared to the as-built conditions. It should be noted that the hydraulic conductivity of the material is not the only material property likely to change with time, the SWCC will also likely change with material evolution. The change in moisture retention characteristics of the materials will affect the saturation levels of the cover system, which will, in turn, affect the rate of oxygen ingress to the underlying waste material.

4.3.5 Summary

The Kimberly Operations possesses one of the oldest (approximately nine years) instrumented test plots analysed summarized herein. The performance monitoring data collected at the site provides an opportunity to quantify the relative effects of snowfall and rainfall on cover system performance. The climate of the site is semi-arid, however, the winter season is cool and wet while hot and dry conditions persist in the summer. The analysis found that the amount of snowfall occurring during the year has the largest effect on cover performance. Field testing conducted as part of the INAP project found that the field saturated hydraulic conductivity of the compacted till barrier layer is higher than the original laboratory tested values used in the field response numerical modelling completed in 1996 and the original test plot design work. Examination of the field data collected found that wet-dry cycling is likely occurring in the compacted layer and might be a possible cause of the change in cover material properties. Also possible is the development of roots into the compacted barrier layer. The INAP study also highlighted the importance of a properly designed growth medium cover layer to satisfy the demand for water by vegetation and ensure that root development does not extend into the underlying compacted layer.

In essence, if a significant effort is put forth to create an engineered compacted layer, then it is paramount that an appropriate growth medium layer is placed over the compacted layer. The objective is to ensure that the financial resources committed to creating the barrier layer are fully realised (in addition to the design objectives), and that the barrier layer does not evolve to a growth medium layer.

The key lessons learned from the field performance monitoring and field testing are the relative influence of snowfall and rainfall on cover system performance and the difference between current saturated hydraulic conductivity of the cover materials and the original laboratory tests.

4.4 Historical Site in Western United States

4.4.1 Background

A field testing programme was completed at a site in the western United States as part of the INAP study. In order to gain access to the site, an agreement was made to keep the site of the field tests anonymous.

4.4.2 Summary of Cover System Test Plots

Four cover systems were investigated at the historical site, each placed at different dates in a semi-arid environment. Generally, each cover system was constructed with the same design consisting of a single layer of non-compacted cover material. Cover systems #1 and #2 were constructed approximately 18 and 14 years ago, respectively, from coarse sand with trace amounts of silt and clay. Cover systems #3 and #4 were constructed using a material with a finer sand silt content and trace amounts of clay. Cover system #3 is approximately 6 years old while cover system #4 has been in place for 3 years. No automated field performance monitoring data is currently being collected at the site.

4.4.3 Analysis of the Historical Site

The site provides the opportunity to examine the field saturated hydraulic conductivity of comparatively older (to the other cast studies) cover systems. The waste material in the area was covered with a monolithic, variable thickness cover system. The "lesson learned" at the historical site was:

- The potential for large changes in field performance due to evolution of cover materials.

4.4.3.1 Evolution of the Cover System Materials

Sixteen measurements of K_{fs} were obtained with the Guelph permeameter at a depth of 12 cm for each of the four cover systems at the site. Table 4.2 summarizes the average saturated hydraulic conductivity measured for each of the four cover systems.

The coarse textured material cover systems were constructed in 1985 and 1989. The field saturated hydraulic conductivity measured at the site is approximately 1 x 10^{-3} cm/s for each cover system. The field saturated hydraulic conductivity measured for cover systems #3 and #4 are similar, which suggests that either the cover material has evolved to its final condition or that the material did not evolve any appreciable amount from the condition in which it was placed. The data collected in the field study programme cannot make this distinction, although it could be argued that based on the coarse texture of this cover material the latter hypothesis is more likely.

Table 4.2
Summary of the average saturated hydraulic conductivity measured at the historical site (geometric mean (M), standard deviation (σ), dry density (ρ_d)).

Cover Designation	*M* (10^{-4} cm/s)	σ (10^{-4} cm/s)	Cover Designation	*M* (10^{-4} cm/s)	σ (10^{-4} cm/s)
Coarse Cover Material			***Fine Cover Material***		
#1	**9.39**	**2.90**	**#3**	**7.37**	**2.61**
#2	**9.94**	**2.39**	**#4**	**4.89**	**2.08**

Note: M is the mean value of the field hydraulic conductivity tests conducted
σ is the standard deviation of the field hydraulic conductivity tests conducted
ρ_d is the dry density measured at the same depth and location

The newer cover systems were constructed in 1997 and 2000. The average hydraulic conductivity for each of these cover systems is within one-half of an order of magnitude of the coarse material cover systems at 7 x 10^{-4} cm/s and 5 x 10^{-4} cm/s for cover systems #3 and #4, respectively. Note that all field saturated hydraulic conductivity measurements at this site were obtained within the upper 20 cm of the surface of the cover systems.

Figure 4.11 is a cumulative histogram of the field saturated hydraulic conductivity values measured with the Guelph permeameter in the summer of 2002. There is a small difference in the field saturated hydraulic conductivity measured at the test plots. If the results of cover systems #3 and #4 are compared, it appears that the finer cover materials are evolving towards the older, coarser cover materials. In the long-term, there may be little difference in behaviour of the cover materials. This is significant because effort was made in the newer cover systems to place a finer-textured material in order to improve cover system performance. The results suggest that in terms of field saturated hydraulic conductivity there will only be marginal difference in the performance of the newer cover systems (constructed with the finer textured material) as compared to the older cover systems (constructed with the coarser textured cover material).

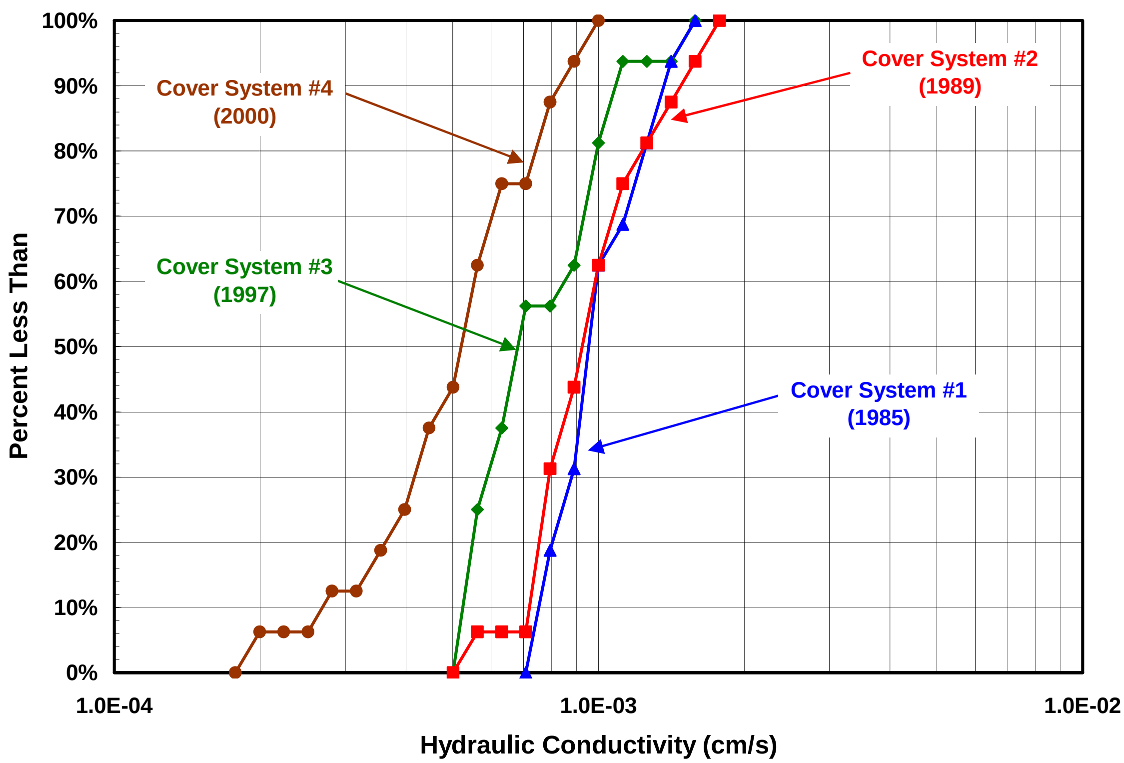

Figure 4.11 Cumulative histogram of the hydraulic conductivity results at the historical site.

The performance of each cover system since construction cannot be determined because no field performance monitoring data is available. However, it is likely that the evolution of the cover materials is a result of both wet-dry cycling and freeze-thaw cycling. It is reasonable to assume these processes would occur considering the general climate conditions at the site.

4.4.4 Summary

The historical site in the western United States provided the opportunity to examine older cover systems. The field *in situ* saturated hydraulic conductivity testing programme examined four cover systems of varying age. The two oldest test plots were constructed of a single layer of coarse textured cover material with low fines content. The newer cover systems, constructed in the late 1990's, incorporated a finer textured material to increase the performance of the cover system. However, field testing showed that at the current time there is less than one-half an order of magnitude between the cover material hydraulic conductivity values. This suggests that the additional expense taken to source, procure and construct a finer-textured cover system has probably not resulted in an increase in cover performance. It should be noted however that this statement is somewhat speculative, given that field performance is not being monitored at the site.

The key lesson learned from field testing at the historical site is the evolution of the two different cover materials to similar hydraulic properties and likely similar field performance. The impact of site specific physical, chemical, and biological processes on long-term performance should be considered when weighing the benefits of improving the as-built cover system design.

5 DISCUSSION

A key point in summarizing the case studies is the relatively short-term monitoring and history of detailed knowledge regarding the application of cover systems for mitigating ARD, in comparison to the long-term environmental liability associated with ARD. This is a result of the short time frame in which ARD has been recognized as one of, if not the major environmental issue facing the mining industry. In general, the issues associated with ARD have only been addressed during the past 20 to 30 years. Soil covers as a method for mitigating ARD have been properly evaluated during the past approximately 20 years. In addition, field case studies with monitoring systems in place to properly evaluate cover system performance have only existed for approximately 10 to 15 years. For example, Equity Silver's till cover system was one of the first full-scale engineered cover systems implemented in Canada for a large surface area waste rock pile, and it occurred in the early 1990's. The consequence of this comparatively short time frame is that it is often difficult to demonstrate the effectiveness of engineered soil cover systems as a long-term closure solution to all interested parties.

The key to addressing this issue is continued monitoring of the sites where appropriate cover system monitoring programs are in place, as well as installation of performance monitoring programmes for newly constructed full-scale cover systems.

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