Design, construction, instrumentation, and monitoring of pilot scale waste rock cover systems: concept review and case studies

Min-North Project, WP2, task 2.3

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1 INTRODUCTION
Min-North project is a trans-national research project, funded by the Interreg V A Nord EU-programme, that focuses on the development, evaluation and optimization of measures to reduce impact on the environment from mining activities in Northern Regions. The project is carried out in cooperation with the Geological Survey of Finland (GTK), University of Oulu, The Arctic University of Norway and Luleå University of Technology, and it involves several SME and mining companies.

The objective of the work package 2 (WP2) of the Min-North project is to study long term behaviour of waste rock piles and performance of cover structures in Nordic climates. Task 2.3 of the WP2 investigates the design, construction, instrumentation and monitoring of experimental waste rock piles. As part of task 2.3, the following report provides a literature-based review of performance monitoring of dry cover system with an emphasis on criteria pertinent to cold climate regions. The report also provides construction details for case study pilot cover systems. Based on the literature review, field scale experimental waste rock piles, with and without covers, will be designed, constructed, instrumented and monitored at the Kevitsa mine site in Northern Finland. Kevitsa mine is producing Ni, Cu, Au, Pt and Pd from a composite ultramafic intrusion of the Central Lapland greenstone belt. Valuable metals occur in the ore deposit as sulphide mineralization. The focus of the report is thus on the cover system pilot test designs for acid-producing waste materials in cold climate regions.

1.1 Introduction to dry cover system design and monitoring
The dry cover systems are used in mining waste disposal areas during mining operations and especially after mine closure to prevent excess environmental impacts of waste areas. A wide variety of different cover structures are nowadays available and the design of the system ultimately depends on the objectives set for the closure of the waste area and the local climatic conditions of the site.

An iterative approach to cold climate cover system design is presented in MEND 1.61.5c (MEND 2012), in which the first step is defining cover system objectives. The objectives of a cover system depend on site specific conditions, but generally include physical and chemical stabilization of waste material, as well as re-establishment of native vegetation (MEND 2012). A systematic approach to defining cover system performance criteria includes site environmental and ecological characterization, soil-plant-atmosphere modelling, and model calibration based on field data (Rykaart et al. 2006, MEND 2012). Performance testing can be conducted and field scale data collection for model calibration can be obtained through the construction and monitoring of pilot scale cover systems. Pilot cover systems also provide a means to evaluate the feasibility and performance of alternative design options prior to full scale construction (MEND 2012).

Monitoring of pilot scale cover systems should provide data necessary to evaluate whether cover system performance meets the design objectives. The primary objective of dry cover systems used to stabilize potentially acid generating (PAG) material is generally to minimize oxygen gas and meteoric water flux to the underlying waste material (O’Kane 2011).
Subsequently, oxygen diffusion rate and net water percolation through a cover are common data objectives of monitoring programs. Monitoring of additional physical and chemical variables, for example, parameters used to further characterise water and energy balances for the waste mass and cover system, can also provide insight to potential failure mechanisms and be used to refine the final cover design. Phillip and O’Kane (2012) suggest that cover performance monitoring should entail site specific climate variable, temperature and moisture profiles throughout the cover, runoff, lateral percolation and net percolation.

The harsh winter conditions and the strong spring flooding in Northern climate set additional requirements on the durability of the cover, as it should be resistant to the freeze-thaw cycles and endure the ample flow of snow melt waters. Common mechanisms for cover system failure specific to regions under significant freeze-thaw influence as described in MEND 1.61.5c (MEND 2012) include:

- Ice entrapment within the cover system or waste material during the construction phase
- Surface water flow control and snow/ice clogging (glaciations)
- Freeze/thaw influence on hydraulic conductivity and structural stability of cover materials
  - Macropore formation and material consolidation
  - Gradual segregation of well graded material
  - Mass wasting (frost creep and gelifluction)

These failure mechanisms illustrate how water and energy balance within the waste mass and cover directly relate to cover performance. The water balance for a waste mass or cover system can be defined through characterization of precipitation (Precip), run off (R), actual evapotranspiration (AET), change in storage (ΔS), net percolation (Perc), and lateral flow (LF), as defined by equation 1 (modified from Tarantino et al. 2008a).

1) Precip = R + AET + ΔS + LF + Perc

Net percolation provides a direct measure of cover system performance in terms of waste stability and as a performance metric is commonly expressed in terms of a percentage of precipitation. Changes in water storage and lateral flow also have direct implications for cover performance, as the degree of pore space saturation influences the layer’s oxygen diffusion coefficient (Aachib et al. 2004, Heinse et al. 2015). Additionally, runoff has a direct influence on the physical stability of the cover system, and is especially relevant in cold regions, where erosion resulting from ice clogging in surface drainage features is recognized as one of the leading mechanisms of failure (MEND 2012). Ongoing monitoring of water balance variables therefore provides insight to numerous aspects of cover system performance in response to site-specific conditions.

The energy balance of a surface cover is of particular importance in cold regions, where ice formation or loss will likely play a role in cover system performance and waste stability. For example, propagation of the freezing front into low permeability cover layers may result in
increased hydraulic conductivity (i.e. K value) through frost heave and subsequent
dewatering, consolidation or macropore expansion (MEND 2012). Alternatively, the
persistence of a frozen cover layer, seasonally frozen cover layer, or frozen basal soil may be
integral to the functionality of the cover or the stability of the waste mass. Such cases
exemplify why exothermic oxidation reactions generating heat within the waste mass may be
of concern (e.g. Smith et al. 2013).

The energy balance of a soil can generally be described by the sum of short and long wave
(net) radiation, the change in latent heat of water through phase changes, and heat
conducted from surrounding soils (Oke 1987). Additionally, heat convection through coarse
material plays an important role specifically in cold regions (MEND 2009, 2012). To evaluate
the energy balance of a soil also requires characterization of the material’s specific heat
(storage) and conduction (flow). These properties can be measured in the field and
laboratory (e.g. Smith et al. 2013) or estimated from more commonly measured material
parameters including particle size distribution, mineralogy, density and water content (Zhang
et al. 2008, MEND 2012). Additional important site-specific variables to consider when
evaluating energy balance include the occurrence and persistence of snow pack during cold
seasons, the presence of a vegetative cover, unfrozen water saturation within the cover soil,
and the occurrence of exothermic oxidative reactions within the underlying waste.

Monitoring chemical parameters from waste material pore waters or discharge waters allows
field verification of contaminant loading useful for verifying that performance objectives are
being met. However, a disadvantage to chemical analyses of field scale discharge is that
reaction rates within the waste may occur too slowly (over 10s to 100s of years), to facilitate
an adequate understanding of acid rock drainage at the scale of a pilot study (O’Kane 2011).

Examples of monitoring approaches for the evaluation of cover system performance are
provided through the summary of seven cold region pilot and full scale cover system case
studies, presented below. Additionally, experimental design considerations and pilot cover
construction details are provided where available. The case studies considered in this review
include:

- Optimizing till compaction techniques at the Boliden Aitik mine, Sweden
- Comparing alternative low permeability barriers at the Inco Whistle mine, Ontario,
  Canada
- Evaluating scale dependence of sulphide weathering at the Diavik mine, Northwest
  Territories, Canada
- Green liquor dregs amended till covers: Luleå University, Sweden
- Oxygen diffusion monitoring techniques: Kristineberg mine, Sweden and undisclosed
  mine site, Quebec, Canada
- Full scale cover performance evaluation at Cluff Lake, northern Saskatchewan
- Lysimeter studies to investigate tailings covers at Pyhäsalmi mine, Finland
2 OPTIMIZING TILL COMPACTION TECHNIQUES AT THE BOLIDEN AITIK MINE, SWEDEN

A dry cover system was designed and constructed in the 1990s to limit acid rock drainage (ARD) formation in waste rock piles at Boliden’s Aitik copper mine site (Lindvall 2005, Lindvall and Eriksson 2005). A recent evaluation of cover system performance suggested oxygen diffusion flux exceeded original design predictions (Sjöblom et al. 2012). Subsequent field and laboratory studies were conducted to evaluate construction options for improving cover system performance (McKeown 2015). During the 2012 field season experimental compaction tests were conducted on field scale test plots. Impacts of a single freeze-thaw season were evaluated for all compaction layers. Additionally, the optimized compaction method was applied in a separate experimental test plot to evaluate freeze-thaw impacts on cover system alternatives, which were evaluated in 2013. (McKeown 2015)

2.1 Introduction and site background

Boliden’s Aitik copper mine is in northern Sweden above the Arctic Circle, where the average annual temperature is 0.6°C, most of the 575 mm of average annual precipitation falls as snow, and potential transpiration is 350 mm (Sjöblom et al. 2012). The mine is located in a boreal forest region of low topographic relief with deep glacial till soils (Lindvall and Eriksson 2005). The mine opened in 1968, is currently one of the Europe’s largest open pit mines, and Europe’s largest copper producing mine, with an annual ore production of 39 Mt (Boliden AB 2015). The primary ore mineral is chalcopyrite (CuFeS2), while other ore minerals include pyrite, pyrrhotite, and in lesser amounts, magnetite, bornite, and molybdenite (Wanhainen et al. 2003). The ore is low grade, with an average of 0.39% Cu, 0.2 ppm Au, and 4 ppm Ag. Mineralization occurs largely in disseminated veins throughout paleoproterozoic muscovite schist and biotite to biotite-amphibole gneisses that have been intruded by quartz monzodiorite pegmatites along a north-south shear zone. The ore zone is approximately 450 m wide, 5,000 m long, and dips to the west at 55°. (Sammelin et al. 2011)

Currently over 500 Mt of waste rock has been disposed of on site, covering an area over 400 ha (Lindvall 2005, McKeown et al. 2015). Waste rock from the footwall contains up to 2% sulphides, while hanging wall waste rock is generally low in sulphides and copper. 35 to 50% of waste rock is estimated to be potentially acid generating (Jönsson 1991, Lindvall et al. 1997, Lindvall 2005). No closure plan was in place when mining began; waste rock was not separated, but was disposed of on low permeability moraine deposits on both the east and west sides of the open pit mine, as determined by convenience. AMD generation from the waste rock piles was identified in the 1970s. AMD was being discharged from the base of the piles and was not in hydrologic connection with the adjacent open mine (Lindvall et al. 1997). As part of later permitting to allow continued mine expansion, decommissioning plans for existing and future waste rock piles were developed (Lindvall et al. 1997, Lindvall and Eriksson 2005).

The discrete distribution of potentially acid generating (PAG) material was exploited through the implementation of a selective waste rock management plan, in which rock containing ≤ 0.1% S, and ≤ 0.03% Cu, with neutralizing potential to acid potential (NP/AP) ratio over 3, was managed separately from PAG waste rock, beginning in 1999 (Lindvall 2005). For
existing PAG waste rock dumps, cover system alternatives were evaluated to determine the most practical, site-specific design (Lindvall et al. 1997). Subsequent to design studies, a full scale dry cover system was implemented on waste rock dump 5 (WRD5) and part of waste rock dump 2 (WRD2) to minimize AMD generation by limiting oxygen diffusion within underlying waste rock piles (McKeown et al. 2015). The original cover system entailed 1 m of compacted till emplaced in two lifts and capped with 0.3 m of organic material as a growing medium (Sjöblom et al. 2012).

Calibrated soil-plant-atmosphere modelling was conducted to evaluate the performance of the cover system. The modelling indicated that annual oxygen diffusion through the compacted cover exceeded original design predictions (Sjöblom et al. 2012). Experimental cover systems were subsequently constructed to evaluate compaction and water retention characteristics of alternative compaction methods with the goal of determining optimum achievable field compaction (McKeown et al. 2015). An additional variable evaluated from the test covers was the influence of a freeze-thaw cycle on cover design performance. In the following sections, the results of the cover system experiments are summarized based on McKeown et al. (2015).

2.2 Design alternatives, construction and monitoring

2.2.1 Compaction test plots

Three compaction alternatives were tested, each on a test plot 60 m x 10 m in dimensions, and each included both level and sloped surfaces. While the original cover system was constructed using a 6-ton smooth roller over ~50 cm lifts, the compaction alternatives were constructed as follows:

- 30 cm thick compacted till layer constructed using a 6 ton smooth roller
- 30 cm thick compacted till layer constructed using a 10 ton smooth roller
- 30 cm thick compacted till layer constructed using a 6 ton pad-foot roller (McKeown et al. 2015).

In the field 86 dry density and water content measurements were collected from the upper 0-20 cm of compacted layers by nuclear densometer following ASTM standard (ASTM 2005). Field water content determinations were compared to laboratory gravimetric water content determinations. An additional 12 dry density measurements were conducted in the original cover layer from 20-40 cm. Field permeability testing was conducted on the cover systems using three separate methods: using the Guelph permeameter (Mohanty et al. 1994), by pressure infiltrometer (Reynolds and Elrik 1990), and by borehole permeameter (ASTM 2011). (McKeown et al. 2015)

Two till samples (approximately 40 kg each) were collected from each test plot for laboratory analysis of particle size distribution, compaction testing, Atterburg limits, and specific gravity. (McKeown et al. 2015)
Upon completion of compaction analysis, geosynthetic fabric and a 0.5 m lift of uncompacted till were placed over the compaction test plots prior to the winter season. (McKeown et al. 2015).

2.2.2 Freeze-thaw test plot

The compaction technique that provided the highest dry density and the lowest hydraulic conductivity was applied in the construction of two experimental cover system alternatives, each constructed in 50 m x 50 m test plots. The preferred cover system alternative entailed a 0.3 m compacted till overlain by 1 m of uncompacted till and 0.3 m of uncompacted till supplemented with organic material as a growth medium. The second, conservative cover alternative was similar, but with a 1.5 m bed of uncompacted till included between the growth medium and compacted layers. Both test plots included plateau and slope (3H:1V) areas. (McKeown et al. 2016)

Instrumentation and laboratory analysis were conducted to assess the degree of saturation throughout the cover profiles, net percolation through the cover systems, and freeze-thaw susceptibility of the two alternatives. Instrumentation included:

- Meteorological station
  - Tipping bucket
  - Net radiometer for assessment of net solar radiation
  - Sonic ranging sensor for continuous snow pack monitoring and,
  - Air temperature sensor
- Automated sensors to measure \textit{in situ} water content, matric suction, temperature, and oxygen gas concentration
- Manual gas sampling ports in both the cover system and underlying waste rock for oxygen gas concentration measurements (McKeown et al. 2016).

2.3 Alternative results and cover performance

Based on particle size analysis and field characterization the construction till materials were approximately 16% by mass >30 mm. The sieved fraction was well graded from 1 to 30 mm, with 30 to 50% gravel, 33 to 52% sand, 15 to 20% silt, and <1% clay. The greatest dry density and lowest water content after compaction were achieved in the 0.3 m till compacted using the 10 ton smooth roller with maximum vibratory action. In the original 0.5 m compacted till design, dry density was found to decrease from 20 to 40 cm, suggesting decreased effectiveness of compaction with depth on the thicker till layer. Further, hydraulic conductivity (K) was lower in the 0.3 m till layers (3 to 5x10^{-6} cm/s) than the 0.5 m layers (6 to 8x10^{-6} cm/s). The 0.3 m till layer compacted with the 10 ton roller was determined to provide optimum compaction to minimize hydraulic conductivity and maximize water retention. (McKeown 2015)

While freeze-thaw did not influence the dry density of the compacted layers, hydraulic conductivity in all three layers increased to > 6x10^{-6} cm/s after one freeze-thaw season. The greatest observed changes in hydraulic conductivity exceeded an order of magnitude in K value. (McKeown 2015) These results are in contrast to previous laboratory studies on the
same material, which suggested that the hydraulic conductivity in non-clayey tills would recover after freeze-thaw, and exhibit no more than a factor of two increase in K value (Viklander 1998). The authors suggest that the greater than expected change in hydraulic conductivity was the result of migration of larger grains through the cover profile during freeze-thaw, which subsequently disrupted the structure of the compacted layer (McKeown 2015). These results illustrate the necessity to prevent the freezing front within a dry cover system from extending into the compacted till layer. (McKeown 2015)

Within the cover system comparison the freezing front did not reach the compacted layer in either the preferred or conservative cover system alternatives. However, the conservative cover design temperature profile clearly showed greater insulation than the thinner, preferred design. Additionally, the authors note that the test winter (2013-2014) exhibited an average temperature (-5.4°C) above the five year average for the site (-6.9°C). Further, consideration should be given to factors that influence the freezing front beyond temperature. The establishment of vegetation, the water content of the overlying sediment, and the presence of snow pack can act to regulate energy flux within the cover system. Accordingly, the greatest risk of a deep penetrating freezing front is likely in the first cold season after construction, especially if freezing occurs prior to moisture accumulation in the unconsolidated overlying layers and the establishment of a vegetation cover. (McKeown et al. 2015)

3 COMPARING ALTERNATIVE LOW PERMEABILITY BARRIERS AT THE INCO WHISTLE MINE, ONTARIO, CANADA

3.1 Introduction and background
The Whistle open pit mine is a Ni-Cu mine in the Sudbury igneous complex of northern Ontario, where average annual precipitation is 870 mm (30% of which falls as snow), potential evaporation in 520 mm, and average annual temperature is 4°C (Ayres et al. 2012, Climatemps 2016). The topography of the mine area is rolling, with up to 50 m hills, low lying poorly drained depressions that form bogs and swamps, and thin, discontinuous till soils (MEND 1997). The crystalline bedrock exhibits little fracturing and has low permeability, which leads to surface water flow dominating the local water balance (MEND 1997). Ore minerals were disseminated to massive Cu, Ni and Co sulphides, and were mined largely from the sublayer norite of the Sudbury igneous complex (Lightfoot et al. 1997). Waste rocks consist of iron sulphides, norite and some carbonates (MEND 1997).

Modern mining operations began at the Whistle mine in 1988 and waste rock was segregated on the basis of sulphide content, resulting in two separate waste rock piles; one which contained primarily granitic non-acid generating (NAG) material, and the other containing potentially PAG norite. The remedial design for the mine upon closure entailed moving 6.4 Mt of waste rock containing on average approximately 3% sulphides into the open pit and constructing a cover system to prevent metals leaching and ARD generation. Cover performance criteria were defined by geochemically modelling waste rock impacts on long term water quality in the open pit. Design criteria entailed limiting oxygen gas influx to the
waste rock, reducing water influx to <5% of annual precipitation, and preventing root penetration into the waste (Ayres et al. 2005).

In order to evaluate construction feasibility and performance of the identified waste rock cover options, a field trial was conducted (Ayres et al. 2002, Adu-Wusu & Yanful 2006, Song & Yanful 2008). The performance of three systems was evaluated with respect to an uncovered control plot. The three test covers and control plot were constructed in 2000 on a waste rock platform at a 20% slope to mimic the final design criteria (as the final waste rock pile would be placed on a slope within the open pit) (Ayres et al. 2002). The cover systems each entailed a different low permeability material, capped by well graded soil and were equipped for monitoring water and oxygen flux through the barriers. The tested barrier materials were:

- Geosynthetic clay liner (GCL)
- Compacted sand-bentonite
- Compacted silt with trace clay (Ayres et al. 2002)

Data from each system were collected for validation and calibration of unsaturated flow and water balance models. Additionally, the field trials provided perspective on site-specific climate impacts on cover performance. (Ayres et al. 2002) Summary of the design, monitoring and performance results of the three cover systems are provided in the following sections based on Ayres et al. (2002), Adu-Wusu & Yanful (2006, 2007) and Song & Yanful (2008).

3.2 Design and construction of cover system test plots
The size of the test cover plots was planned based on steady state two dimensional saturated and unsaturated flow modelling using SEEP/W software by GEO-SLOPE International Ltd (cf. GEO-SLOPE 2016). Test plot dimensions were designed to be large enough that seepage captured in lysimeters was derived from the overlying test cover material, and not influenced by lateral flow from beyond the cover. Additionally, dimensions were planned to minimize flow resulting from liquid or vapour gradients and slope effect at monitoring points. Subsequently, test plot plateaus were 24 m x 12 m, built in piles with 5H:1V (20%) plateau grade (parallel to the waste rock base) and 2H:1V embankment grade. The waste rock platform was constructed to accommodate the experimental cover systems plus the control plot (85 m x 45 m) over a drainage system designed to channel all excess seepage to a down gradient collection pond (Figure 1). (Ayres et al. 2002)

A single lysimeter was constructed beneath each test plot within the waste rock platform. The optimum size and placement of lysimeters for representative seepage collection was defined based on saturated and unsaturated flow modelling. Each lysimeter was 2.4 m in diameter, 2.3 m in height and placed approximately centrally beneath its respective test plot such that the upper edge of the lysimeter was at the base of the interface of waste rock and overlying barrier material. At the bottom of the lysimeter a thin bed of filter sand was used to facilitate flow to the lysimeter basal drain. Above the filter sand the lysimeter was filled with waste rock. The lysimeter basal drain was a 51 mm PVC tubing lain within the waste rock platform.
at a slight grade (1 to 2%) to where it discharged to a data monitoring and sample collection station within a shed adjacent to the platform. Portions of the basal drain line were insulated to prevent seepage from freezing. Additionally, the drain discharged via a one way air trap that prevented oxygen gas ingress into the line, but allowed seepage to discharge from the lysimeter and collection of samples for geochemical analysis directly from the drain line. (Ayres et al. 2002)

Figure 1. Illustration of aerial footprint and profile cross-section of test cover plot design (Modified from Ayres et al. 2002, Adu-Wusu & Yanful 2006).

The surface of the waste rock platform was smoothed to provide a uniform bed for placement of the barrier materials being tested. Each barrier was capped with a 0.9 m protective layer of locally sourced, uncompacted, well graded soil. The cover soil was intended to act as a growth medium and provide store and release moisture control to limit the water influent directly to the barrier. After construction and instrument installation the cover soils were hydro-seeded. (Ayres et al. 2002)
The GCL barrier was a commercially available, Bentomat®St prefabricated barrier which consisted of a <0.1 m layer of Na-bentonite between woven and unwoven geosynthetic textiles. The barrier material came in 4.8 m x 38 m long rolls and was emplaced by unrolling down the grade of the waste rock platform. The upgradient end of the barrier material was buried in a small anchor trench to prevent it from sliding down gradient, and seams between swaths were sealed using small strips of the same barrier material. (Ayres et al. 2002)

The sand-bentonite barrier layer was constructed in two equal sized lifts for a final barrier thickness of 0.45 m. It was composed of 8% by dry weight Na-bentonite. The first lift was constructed directly on top of the waste rock platform by first emplacing sand, and adding granular Na-bentonite (commercially available Envirogel 12, ranging in particle size from fine sand to clay) to the sand. The combined material was blended in situ using a pulvimixer and then moisture conditioned and compacted using a smooth roller drum to 2% wet of optimum moisture content. This moisture content was considered optimum as it provided the lowest hydraulic conductivity. The barrier material for the second lift was blended and moisture conditioned in a flat area adjacent to the waste rock platform out of safety concerns for the equipment operators, and then hauled and emplaced onto the underlying lift. (Ayres et al. 2002)

The third cover system was a silt material with trace clay extracted from a local borrow source. The silt layer was emplaced and compacted using a smooth vibratory roller drum in three 0.2 m lifts to 2% wet of optimum moisture content, for a total thickness of 0.6 m. (Ayres et al. 2002)

3.3 Instrumentation and monitoring

The field monitoring system was designed to characterize the water balance across each test cover system and the control plot for calibration of cover system design numerical models, and to assess cover system performance.

To characterize water balance the following variables were measured:

- Change in moisture storage within cover material
- Lateral drainage within cover
- Net surface infiltration
  - Precipitation
  - Actual evapotranspiration
  - Run-off (Ayres et al. 2002).

In each test plot thermal conductivity sensors (Campbell Scientific 229L) and frequency domain reflectometer sensors (Campbell Scientific CS615-L) were nested in a vertical profile approximately 1.5 m upgradient of the lysimeters (Figure 1). Thermal conductivity sensors provided temperature and matric suction data, while frequency domain reflectometers provided volumetric water content. Measurements from these nested sensors were collected every 6 hours and recorded from data loggers housed in the sample collection station. Surface runoff was routed using a berm at the foot of the test covers and monitored (Ayres et al. 2002, Adu-Wusu & Yanful 2006).
A meteorological station was constructed near the centre of the waste rock platform on the sand bentonite test plot, to measure air temperature, relative humidity, wind speed, wind direction, net radiation, barometric pressure, rainfall and snow fall. (Adu-Wusu & Yanful 2006)

The main parameters of interest to evaluate cover system performance were the net percolation of water and diffusion of oxygen gas through the barriers. Additional data collected for performance assessment were seepage water quality and thermal regime within cover systems. Net percolation through the barriers was monitored directly using a tipping bucket and data acquisition system for discharge from the lysimeter basal drain in the sample collection station adjacent to the waste rock platform. Samples of seepage water were collected from the lysimeter drain system for chemical characterization. Temperature profiles were monitored from thermal conductivity sensors described above. Gas sampling ports were installed above each barrier, at the interface of the barrier and waste rock, and at the base of the waste rock platform beneath each barrier. Oxygen and CO₂ gas concentrations were measured automatically every 12 hours via an in situ gas analysis system. (Ayres et al. 2002, Adu-Wusu & Yanful 2006).

The monitoring array is summarized in Table 1.

Table 1. Instrumentation in test plots (modified from Ayres et al. 2002)

<table>
<thead>
<tr>
<th>Instrument and monitoring</th>
<th>GCL barrier</th>
<th>Sand-Bentonite barrier</th>
<th>Silt with Trace Clay barrier</th>
<th>Control plot (no barrier)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lysimeter (tipping bucket data logger)</td>
<td>1 at barrier-waste rock interface</td>
<td>1 at barrier-waste rock interface</td>
<td>1 at barrier-waste rock interface</td>
<td>1 at surface</td>
</tr>
<tr>
<td>Nested Thermal conductivity and frequency domain reflectometer sensors (6 hour interval automated data collection)</td>
<td>7 in the non-compacted layer 2 in the waste rock</td>
<td>7 in the non-compacted layer 4 in the barrier layer 2 in the waste rock</td>
<td>7 in the non-compacted layer 4 in the barrier layer 2 in the waste rock</td>
<td>4 in the waste rock</td>
</tr>
<tr>
<td>Gas sampling ports (12 hour interval automated data collection)</td>
<td>1 in the non-compacted layer 1 at the barrier-waste rock interface 1 at depth within the waste rock</td>
<td>1 in the non-compacted layer 1 at the barrier-waste rock interface 1 at depth within the waste rock</td>
<td>1 in the non-compacted layer 1 at the barrier-waste rock interface 1 at depth within the waste rock</td>
<td>3 within the waste rock</td>
</tr>
</tbody>
</table>

3.4 Performance monitoring results and final design

Data from each test plot were used to evaluate barrier performance (Adu-Wusu & Yanful 2006, 2007), and to calibrate finite element numerical modelling simulations using VADOSE/W (Krahn 2004) two dimensional modelling software (Song & Yanful 2008).

The GCL barrier was found to have the maximum reduction of net percolation over the three year trial period, followed by the sand bentonite barrier, and then the silt/trace clay mixture. Percolation was reduced to 7%, 20% and 56% of the control plot by these three barriers,
respectively. Infiltration of oxygen gas across the barriers could not be directly assessed due
to the open sides of the coarse waste rock platform, which allowed influx of oxygen. In this
regard, complimentary numerical modelling provided a valuable tool to predict cover
performance with regard to oxygen influx in a full scale scenario (Song & Yanful 2008). Song
and Yanful (2008) noted that while many elements of the test cover water balance were
accurately predicted using the VADOSE/W finite element model, net percolation through the
sand-bentonite layer exceeded model flow predictions.

In all test plots the freezing front progressively increased with cooler winter conditions, and
reached a maximum observed depth of 100 cm. The authors propose that performance of the
GCL and sand-bentonite layers may have been compromised by freeze-thaw. However, at
the scale of the study they determined that the clay amended barriers exhibited the highest
performance with regard to reducing percolation (Adu-Wusu & Yanful 2006). Further,
alumina-silicate dissolution from the sand bentonite layer was observed to buffer the waste
rock seepage, resulting in the lowest dissolved ion concentrations in seepage occurring
beneath that test plot. The lifetime of buffering effects could not be predicted.

Based on field trial observations, model predictions and cost evaluation, the final cover was
constructed from compacted, high clay content barrier material (Ayres et al. 2005).
Performance monitoring of the full scale cover over six years has indicated that the cover has
met design objectives (Ayres et al. 2012).

4 EVALUATING SCALE DEPENDENCE OF SULPHIDE WEATHERING AT THE
DIAVIK MINE, NORTHWEST TERRITORIES, CANADA

4.1 Introduction and site background
The Diavik mine is an operating open pit and underground diamond mine located in an arctic
desert climate in the North West Territories, Canada. The mean annual air temperature is -
8.5 °C, and there is continuous permafrost (Smith et al. 2013). A thawed layer of soil (1.5 m
to 5 m thick) develops above the permafrost in warm months. The site receives an average of
288 mm annual precipitation; 60% of which is snow.

Diamond ore is mined from kimberlite pipes emplaced in Archean granite and pegmatite
granite country rocks. The granite contains also metasedimentary biotite schist xenoliths.
While the granite was determined to be NAG; the biotite schist xenoliths with locally
disseminated pyrrhotite and other sulphides were identified as PAG. The waste rock at the
site is classified into three categories based on the S content. The non-acid generating
granites represent Type I rock (<0.04 wt.%S), which can be used as a construction material.
Type II waste rock (0.04-0.08 wt.%S), mainly composed of granites with accessory biotite schist
and low or no acid generation potential, is produced only in small amounts annually
(<5%). Type III waste rock is the potentially acid generating rock with S content of >0.08
wt.% Type III rocks are composed of granites with larger amounts of biotite schist. The mine
is anticipated to produce up to 120 Mt of waste rock, of which up to 75% could be acid
generating. (Smith et al. 2013)
At the Diavik site three experimental waste rock piles were constructed from 2004 to 2007 to evaluate the scale dependence of mine drainage formation. Specifically, the study objectives were to characterize the physical, chemical and biological characteristics of mine drainage formation at field scale, and to evaluate the accuracy of laboratory scale testing (Smith et al. 2013).

4.2 Pilot scale design and construction
Three waste rock piles were used for comparison of waste rock types and waste rock management. One pile was composed of uncovered non-acid generating (<0.04% sulphides) waste rock, one was uncovered potentially acid generating (>0.08% sulphides) waste rock, and the third was covered, potentially acid generating waste rock. The test waste rock piles were designed based on results from SULFIDOX two-dimensional finite difference reactive transport code (Smith et al. 2013). SULFIDOX (Linklater et al. 2005 and the references therein) was used to evaluate controls on sulphide oxidation and heat balance, and indicated that reducing O$_2$ influx to the waste rock would reduce sulphide oxidation rates. The cover consisted of a low permeability, 1.5 m layer of compacted till topped by 3 meters of non-acid generating waste rock intended to serve as an active freeze-thaw layer. The sides of the cover were contoured and graded to an 18° slope for geotechnical stability and for the safety and accessibility of equipment operators. (Smith et al. 2013)

The dimensions of the waste rock piles were based on SULFIDOX thermal modelling. By modelling gas and water transport, heat transfer and freeze-thaw, it was determined that 15 m high test piles were required to preserve underlying permafrost. Waste pile plateau areas needed to be a minimum of 20 m wide to ensure safe equipment access. The angle of repose of the uncovered test piles was 38°, resulting in final uncovered pile dimensions of 50 m x 60 m. To accommodate the 18° slope defined for optimal cover performance, the final covered pile dimensions were 80 m x 125 m. Test piles were constructed using the techniques that would be applied for full scale construction. Instrumentation was installed throughout the test piles concurrent with construction in order to measure:

- Pore water flow and geochemistry
- Oxygen gas concentration
- Waste rock permeability to air
- Temperature gradients
- Thermal conductivity
- Microbial populations
- To characterize water and energy mass balances. (Smith et al. 2013)

4.3 Instrumentation and monitoring
Seepage flow and chemistry were monitored using basal drain systems beneath each test pile, clustered lysimeters within each pile, and instrumentation placed in vertical and sub-vertical profiles throughout each pile. Additionally, a number of other instruments and sampling ports were placed throughout the interior of the test piles, and in the compacted till and waste rock cover of the covered pile. Instrument placement within the test piles was planned based on SULFIDOX simulations to provide an optimal evaluation of oxygen and
temperature gradients throughout the piles. Instrumentation was placed most densely along four planes that follow the pile’s angle of repose, and which were spaced 5 m apart from the centre toward the edge of each pile’s plateau (Figure 2). In addition to instrumentation along these monitoring planes, gas sampling ports and temperature thermistors were placed throughout the piles. (Smith et al. 2013)

4.3.1 Unsaturated pore water flux and chemical characterization
The experiment was designed to evaluate volume and flow averaged seepage chemistry across three scales: test plot scale seepage was collected from the basal drain system underlying the entirety of each test pile. Lysimeter clusters consisting of 4 m x 4 m x 1 m and 2 m x 2 m x 0.6 lysimeters were installed in each test pile to evaluate progressively smaller flow volumes. In addition, point measurements on water quality and pore volume water content were evaluated from instrumentation clusters installed in a vertical profile above
lysimeter clusters (Figure 2). (Smith et al. 2013) Construction details for each component of this instrumentation scheme are described below. Each of these methods allowed for sample collection, from which laboratory analyses for pH, Eh, EC, TDS, acidity/alkalinity, anions, major ions, and trace metals were conducted.

Beneath each test pile a basal drain system was constructed from high density polyethelyne liner placed on a slightly graded (1.4%) waste pile base. The base of each pile was graded so that seepage collected on the liner was channelled to a schedule 40 PVC drain line and directed to a single discharge point at an adjacent monitoring shed for continuous volume monitoring and chemical characterization. The liner bed was composed of crushed kimberlite for the non-acid generating pile, and medium to course esker sand for the potentially acid generating piles, to facilitate flow to the drain line. The drain lines were traced with heating cables to maintain a temperature between 5 and 10°C. Drain lines were enclosed in 200 mm, insulated PVC to provide additional mechanical protection and to reduce heat loss. (Smith et al. 2013)

Three sets of clustered lysimeters were constructed at the base of each test pile. Two clusters were placed beneath the plateaus of the piles, and one adjacent to the access ramp, where the pile’s vertical profile is lowest. The lysimeters were HDPE lined and their bases were graded 1% toward a corner drain. Additionally, lysimeters were underlain by a heating cable and a layer of Styrofoam insulation to prevent freezing of the seepage water. The lysimeter drain line was attached to a water tight exit port from the lysimeter, where it was capped with a 0.15 m slotted screen to prevent clogging by fines. The drain lines were 38 mm schedule 40 PVC traced with heating cables, and housed within 200 mm insulated PVC pipe. The lines also contain 6 mm outside diameter (OD) low density polythelene or nylon tubing for the purpose of occasional flushing of secondary mineral build-up. Lines were directed at a slight grade (0.5 to 1.5% grade) to the adjacent monitoring sheds. (Smith et al. 2013)

The instrumentation for point measurement collection of pore water quality and volume included Hoskin Scientific model e-127-1920F1L12-B02M2 soil water solution samplers (SWSS) and time domain reflectometer (TDR) probes designed following Nichol et al. (2002, 2003). The SWSS collects pore water via suction from a volume of influence from a few to tens of centimetres for geochemical analysis. The TDR provides volumetric water content across a diameter of a few cm. Data from the co-located TDR and SWSSs can be used to determine matric suction. The combined data provide insight into wetting front and flow pathways. These instruments were nested with a spacing of 0.5 m from each other to prevent interference, and nests were spaced along two monitoring planes within each test pile that follow the pile’s external grade. Because both of these instruments require hydraulic contact with porous media, they were placed in nylon mesh bags filled with crushed waste rock (<25 mm) representative of their respective test piles. The bags for the SWSS were 175 x 325 mm. The bags for the TDR probes were sown to ensure surrounding matrix with a volume greater than the probe’s 50 mm sphere of influence. The SWSS tubing and the TDR cables were routed through protective, heat cable traced 50 mm PVC conduit pipe to the monitoring sheds. (Smith et al. 2013)
4.3.2 O₂ and CO₂ gas concentration
Gas sampling ports were installed throughout each test pile (over 200 sampling ports per pile), including at the base of the test piles and along monitoring planes within the test piles. The ports were spaced 0.5 m from the SWSS and TDR clusters. Gas sample tubing was either nylon tubing (3.1 mm OD with 0.6 mm walls) or low density polyethylene tubing with 0.6 mm inner diameter. Tubing was strung through rigid or flexible PVC pipe and routed to 25 mm holes drilled in the PVC at specified sample intervals. Foam insulation was sprayed into the PVC pipe around the sample port to prevent air flow between sample ports. (Smith et al. 2013)

4.3.3 Temperature gradients and thermal conductivity
Strings of thermistors were installed both vertically and horizontally (10 m into bedrock) beneath the test piles, along monitoring planes within the test piles, and within the compacted till and surficial non-acid generating waste rock of the covered test pile. Thermistor sensors were spaced at approximately 1 m intervals in boundary layers, at 1 to 3 m intervals within waste rock piles and from 1 to 5 m intervals within the cover layer. All thermistors were attached to data loggers for 12 h interval point measurement collection. Similar to gas sampling tubing, thermistors were strung through protective PVC pipe and spray foam insulation was injected into the protective conduit between monitoring ports to prevent air flow along the pipe. 25 mm holes were drilled in the protective PVC above and below thermistor sensors. (Smith et al. 2013)

Additionally, vertical thermal conductivity ports were constructed from 75 mm schedule 40 PVC and were installed on all monitoring faces. At heat source lowered into these ports, paired with rates of temperature increase and decrease measured from surrounding thermistors allows field evaluation of waste rock thermal properties. (Smith et al. 2013)

4.3.4 Waste rock air permeability
Air permeability was measured along monitoring faces near the core of waste rock piles. Air permeability probes consist of a 75 mm diameter perforated plastic ball. A 6.3 mm nylon tube is used to pump N₂ gas into the ball across a range of flow rates and change in pressure is measured from an adjacent 9.5 mm nylon tube within the ball to calculate air permeability within the waste rock. Similar to gas sample lines and thermistors, permeability lines were protected within PVC conduit and air exchange within the conduit was prevented using spray foam insulation between ports. Permeability testing was conducted automatically and recorded by a data loggers accessible in the adjacent monitoring sheds. (Smith et al. 2013)

4.3.5 Microbiology sample ports
To determine whether chemolithotrophic bacteria *Thiobacillus* and *Acidithiobacillus* are active within the waste rock piles microbiology sampling ports were constructed within each test pile. The sampling ports comprised of 0.5 m well screen sections at desired intervals along 50 mm PVC pipe. 4 screened sampling intervals were established in each rock pile, near the central sampling plane of each pile, and ranging from 2 to 11 m depths within the waste rock. Nylon mesh bags were filled with 10 g of crushed pyrite, autoclaved and kept sealed prior to being lowered into sampling ports. To each sample interval 5 autoclaved, pyrite filled bags
were lowered on individual lines to be in contact with the well screen. A single pyrite bag is retrieved from each sample interval annual to evaluate bacteria colony development and assess bacterial influence of waste rock water chemistry. (Smith et al. 2013)

4.4 Summary of experimental design

Experimental waste rock piles constructed at the Diavik mine site included a pile of non-acid generating material, an uncovered pile of potentially acid generating material, and a pile of potentially acid generating material capped with a dry cover. The test pile experiment was designed to collect field data on oxidation processes of mine waste in a region that has persistent permafrost and to use field measurements to evaluate laboratory studies. Waste rock pile dimensions and instrument placement decisions were largely guided by two dimensional finite difference reactive transport modelling using SULFIDOX. The instrumentation and monitoring goals were as follows:

- Basal liner drainage system and clustered lysimeters were constructed to evaluate seepage water volume and quality across multiple scales
- SWSS and TDR probes were installed above lysimeters to correlate point measurement water chemistry and flow to volume averaged measurements
  - TDR probes also allow for internal flow modelling, evaluation of wetting fronts and the development of preferential flow pathways
- Gas sampling ports were installed throughout the test pile to evaluate the progression of sulphide oxidation
- Air permeability probes were installed to evaluate the potential for O₂ transport within waste rock
- Thermistors were strategically installed to monitor temperature gradients and fluctuations throughout the piles, as well as to identify chemical reaction related heat fluxes
- Thermal conductivity ports were also installed to evaluate waste material thermal conductivity (Smith et al. 2013)

Instrument survival rates varied by instrument type. In the uncovered test piles the SWSS and TDR probes had the lowest survival rates, ranging from 40 to 61%. The gas sampling ports, thermistors, thermal conductivity ports, and permeability probes all had >80% survival. For SWSS probes the authors suggest that using epoxy to reinforce instrument connections contributes to greater survival rate. They also note the importance of verifying instrument functionality prior to installation, as some TDR probe loss may have resulted from non-functional probes, as opposed to damage during construction. (Smith et al. 2013)

5 GREEN LIQUOR DREGS AMENDED TILL COVERS: LULEÅ UNIVERSITY, SWEDEN

Mäkitalo (2015) characterized the application of green liquor dregs (GLD), a waste product of paper manufacturing, as an amendment to glacial till barrier layers over PAG waste rock. As part of the performance evaluation, pilot scale test covers were constructed to characterize
aspects of construction feasibility and cover material performance. Additionally, this study documents thorough laboratory characterization of geochemical and geotechnical properties of potential cover materials.

5.1 Site information and materials sources
Pilot scale test covers were constructed at the Ragn-Sells waste management site north of Boden, Sweden in 2014. The site receives 486 mm of average annual precipitation, has an average annual temperature of 1.2°C, and approximately 50% of precipitation in this region is lost to evapotranspiration (Axelsson et al. 1991, Climate-data.org 2016).

Two sets of pilot covers were constructed as part of the progressive evaluation of GLD applications. The first study was conducted to evaluate the compaction properties of a GLD amended till cover against an all-till cover with respect to performance criteria such as hydraulic conductivity and structural stability. In this study GLD was from Smurfit Kappa AB sulphate and paper mill and the till originated from the former Näsliden mine site (Mäkitalo et al. 2015). A second pilot cover study was initiated simultaneously and is ongoing in order to evaluate the long-term performance of a sealing layer composed of a mixture of till and 10% GLD derived from different sources. The pilot test includes measurements of hydraulic conductivity, oxygen ingress, geochemical stability of the cover material, geochemistry of pore water, geochemistry of drainage, and freeze-thaw effects. In this study the till used as a protection layer on top of the sealing layer was derived the Näsliden mine, as was presumably also the till blended with the GLD for the sealing layer. (Note: The source of the till is not described in detail in Mäkitalo 2015). The GLDs were sourced from four different pulp and paper mills located throughout Sweden (Domsjö Fabriker, Smurfit Kappa Kraftliner AB, SCA Obbala AB, and Metsä Board). Six test plots were constructed, each with an 8 m x 12 m footprint. Within the test cover plots a total of four lysimeters placed below the sealing layer were filled with PAG waste rock from the Aitik and Maurliden mines in northern Sweden. (Mäkitalo 2015) PAG waste rock from the Aitik mine is described in section 2.1 of this literature review. Waste rock from the Maurliden mine contains 1 to 10% sulphides, over 30% of which are composed of pyrite, and is considered PAG material (Eriksson et al. 2008, Mäkitalo 2015).

5.2 Material characterization
As part of GLD characterization the material was investigated both in laboratory and field settings. Laboratory testing included characterization of the material’s mineralogical, chemical and physical properties. Mineralogical characterization was carried out with X-ray diffraction (XRD) and chemical analyses included contents of hot HCl-HNO₃ digestible elements (i.e. aqua regia extractable elements) with inductively coupled plasma atomic emission (ICP-AES) and mass spectrometry (ICP-MS) measurements (modified EPA methods 200.7 and 200.8), leaching tests following standard SS-EN 12457-4 (SIS 2003) with some modifications and Steenari et al. (1999), and an assessment of buffering capacity using a batch titration method modified after Wyatt (1984). Further, tailings used in test cells were characterized by acid base accounting following Sobek et al. (1978) and weathering cell leaching tests following Cruz et al. (2001) and Hakkou et al. (2008). (Mäkitalo et al. 2014, Mäkitalo 2015)
Physical characterization of materials conducted in the laboratory included grain size analysis by laser diffraction, as well as material hydrologic and compaction characterisation. Hydraulic conductivity was evaluated in the lab using constant head permeability following Swedish standard (SIS 1989), as well as by constant rate of strain methods following Swedish standard (SIS 1991). Water retention capacity was determined in the laboratory using a Tempe cell pressure plate apparatus (by Soil moisture Corporation) to analyse water content and water tension. Compaction properties (maximum dry density, porosity, and optimum water content) were determined by proctor test following Swedish standard (SIS 1994), using a multivolume helium pycnometer. Uniaxial compressive shear strength was determined to evaluate suitable structural stability. Surface structures of the GLD were further studied with a Scanning Electron Microscope (SEM). (Mäkitalo 2015)

GLD exhibited low hydraulic conductivity ($10^{-8}$ to $10^{-9}$ m/s), and a high water retention capacity, indicating it would provide an effective barrier to water infiltration and oxygen diffusion in waste rock. Leaching of potential contaminants from the GDL was low, though the potential to mobilize As and Mo through an increase in the pH of influent water was recognized. Further, the GLD was found to have low uniaxial compressive shear strength, and therefore was determined not suitable for use as a sealing layer independently. However, when GLD was blended with till, the sealing properties of the till improved. Specifically, for a till comprised of 10 to 30% silt, a 10% GLD addition resulted in a material with a suitable sheer strength for embankment construction, and with increased water retention capacity (WRC) and decreased hydraulic conductivity relative to the unamended till. (Mäkitalo 2015)

5.3 Pilot construction and monitoring
Both sets of pilot covers were constructed in August of 2014. The initial two cells in which GLD amended till was evaluated against a till only cover were approximately 2 m x 2 m (Mäkitalo Pers. Comm. 2016). The primary intent of these cells was to evaluate achievable field scale compaction properties, so instrumentation was not installed, but analyses were conducted immediately after construction. Both pilot sealing layers were constructed in two 25 cm lifts. Each lift was compacted with 6 passes of a 600 kg hydraulic plate compactor (Mäkitalo et al. 2015). Dry density of the compacted sealing layers was measured in the field at 5 cm depth using water volumetry, a Troxler hand-held nuclear density gauge, and a proctor hand hammer. Additionally, dry density was measured at 250 mm with the Troxler nuclear density gauge. (Mäkitalo et al. 2015)

The pilot covers constructed to test GLD from different sources were constructed on a foundation of 0.2 m of till. A total of 5 lysimeters were constructed below the sealing layer in each pilot cell. Four of the basal lysimeters were 400 mm x 300 mm x165 mm, and surrounded a larger central 600 mm x 400 mm x 225 mm lysimeter. While most lysimeters were filled with gravel, a total of four of the basal lysimeters were filled with waste rock, as described above. Lysimeters were covered with a geomembrane and capped with a 5 cm layer of sand to facilitate drainage. The sealing layers, consisting of local till amended with 10% GLD (from different origins), were compacted by 3 to 9 passes, each to a final thickness of 0.5 m. In four of the cells a 400 x 300 x 165 mm lysimeter was also constructed on top of
the sealing layer, at the base of the protective layer. A 1.5 m thick protective layer of till sourced from the Näsliden mine was constructed over the sealing layer with final bank gradients of 2H:1V. Lysimeters all drain to collection ports spaced along the north side of the plot. (Mäkitalo 2015)

Three temperature probes were installed in the protective layer of each test pile at just beneath the till surface, 0.7 m and 1.4 m depth. The completed pilot plots were grass seeded after their first winter to accelerate vegetation growth and minimize erosion (Mäkitalo 2015). For ongoing cover performance monitoring plans have been made to install 4 soil moisture probes (STM by Decagon Devices) and 2 water potential sensors (MPS-6 by Decagon Devices) in the covers to measure dry density and water content. These instruments will report to a RailBox V16 data logger for automatic data collection. (Siren Pers. Comm. 2016).

5.4 Compaction results
Dry density results from proctor tests approximately matched the 250 mm Troxler results at the test plot where a GLD-tailings blend was compared to tailings. Additionally, the water volumetry based density results approximately matched the near surface (50 mm) Troxler results. Based on the laboratory compaction test results, a dry density to 1,800 kg/m³ was required to achieve high compaction for both materials. The in situ density measurements in both cover systems exceeded the high compaction density at 250 mm. The near surface density achieved for the GLD amended till was only about 1,750 kg/m³. However, this was assessed to be an adequate degree of compaction, as additional compaction was anticipated to result from the emplacement of the protective till cover (Mäkitalo et al. 2015).

Similar agreement between compaction assessment methods was found for the comparison of the six pilot plots. In this case laboratory proctor test results aligned well with Troxler density results from 250 mm, and again water volumetry aligned well with Troxler results from 50 mm. While all GLD blends had a dry density of >1,800 kg/m³ at 250 mm, compaction at 50 mm ranged from 1,600 to 1,800 kg/m³. Again, these values were determined to be sufficiently close to the design dry density such that the added weight of the protective layer was expected to result in the desired degree of compaction (Mäkitalo 2015). In addition to the post construction analyses, monitoring of the 6 cell GLD comparison is ongoing to evaluate cover performance in response to site-specific conditions (Mäkitalo 2015).

Monitoring of the performance of the sealing layers will continue in the future studies by Luleå University of Technology.

6  OXYGEN DIFFUSION MONITORING TECHNIQUES: KRISTINEBERG MINE, SWEDEN AND UNDISCLOSED MINE, QUEBEC, CANADA
This section provides a description of techniques for monitoring oxygen diffusion through cover systems based on two different studies. At the Kristineberg mine in northern Sweden six experimental pilot scale cover systems were constructed and monitored to characterize material oxygen diffusion coefficients and oxygen fluxes through the covers (Alakangas et al. 2008). The methods from a second study by Mbonimpa et al. (2008) are also discussed, in
which oxygen concentration gradient was measured in a full scale capillary barrier over mine
tailings at an undisclosed site in the Aibiti-Temiscamingue area of Quebec.

6.1 Kristineberg mine pilot cover system trial

6.1.1 Site background and experimental objectives
The Kristineberg Zn-Cu mine is located within the Skellefte mining district of northern
Sweden, and is approximately 175 km south west of Luleå. The site’s average annual
temperature is approximately 0.7°C, with annual precipitation between 400 and 800 mm, and
snow pack persisting for 6 to 8 months of the year (Axelsson et al. 1986). Soils are
comprised of weathered till and the local vegetation is dominated by coniferous forests, with
some deciduous forest and peatlands (Öhlander et al. 2003 and the references therein). The
primary ore body is within metamorphosed basic volcanic and volcanoclastic rocks (Carlsson
2003 and references there-in). The site was discovered in 1918 and mining by Boliden
Mineral AB began in 1940 (Carlsson 2003). Tailings are held in five different impoundments,
generally with high sulphide and metals contents, and exhibiting varying degrees of oxidation
(Holmström et al. 2001, Öhlander et al. 2003). The primary sulphide minerals in tailings, as
described from impoundment 1, are pyrite, pyrrhotite, sphalerite, chalcopyrite, galena and
covellite (Holmström et al. 2001). The tailings utilized in the experimental cover study were
unoxidized and were classified as sandy-silt, the sulphide component of which was
comprised primarily of pyrite (48%), followed by pyrrhotite (4.8%). Quartz was the dominant
silicate, at 20% (Alakangas et al. 2008).

The study objectives were to evaluate oxygen concentrations within the cover systems,
oxygen diffusion coefficients through different cover material layers, and oxygen flux through
the cover systems. Five experimental cover systems and one control plot of uncovered,
unoxidized mine tailings were constructed in 6 pilot cells at the Kristineberg mine site in 2004.
The following materials were tested in the pilot cells as oxygen barriers:

- Clayey till
- Sewage sludge
- Fine grained apatite concentrate
- Trisoplast (a mixture of bentonite, tailings and sand) (Alakangas et al. 2008).

Clayey till was tested in two cells with varying thickness of protective layer on top of the
sealing layer (Alakangas et al. 2008)

6.1.2 Design, instrumentation and monitoring
The test plots were constructed in concrete cells with dimensions of 5 m x 5 m x 3 m (Figure
3). The concrete was insulated to protect against freezing and lined with HDPE liner to
prevent corrosion from ARD products. Within each cell a 1 m layer of unoxidized sulphide
rich tailings was on top of a 0.3 m basal drainage layer (presumably sand). The tailings were
capped by sealing layers, drainage layers and protective layers. The thickness of the sealing
layers varied and was determined in part by laboratory determination of porosity, saturated
hydraulic conductivity, dry density, and bulk density for each material (with the exception of
sewage sludge, which was not a solid, and therefore was not subject to geotechnical testing). Till and sewage sludge layers were each 0.3 m, apatite concentrate was 0.1 m thick, and the Trisoplast was 0.05 m. An upper 0.3 m thick drainage layer was constructed over all sealing layers. Four of the test cells were capped with a 1.2 m of protective till layer, second cell containing the till sealing layer with only 0.6 m of sealing material, while the control tailings cell had no cap. Instrumentation installed in each test cell included oxygen lysimeters at the base of the tailings and base of the sealing layers. Oxygen sampling ports were installed 0.1 m above the sealing layers, 0.1 m below the sealing layers, and 0.5 m below the sealing layers, and thermistor sensors were placed in each layer throughout the cell profile (Figure 3). (Alakangas et al. 2008)

Figure 3. Pilot cell profiles (modified from Alakangas et al. 2008)

Oxygen lysimeters were 1 m x 1 m x 0.2 m in dimension and were each equipped with a basal drain line to prevent saturation. Sampling lines were run from the lysimeters to the surface of the cells. Lysimeters were filled with quartzite with 54% pore space, their walls were coated with a bentonite seal to prevent oxygen diffusion through the sides and bottom, and they were capped with geotextile to prevent incorporation of material from the overlaying layer. Gas sampling ports were constructed from geotextile balls filled with quartzite, from which gas sampling lines were extended to the surface of cells. (Alakangas et al. 2008)

The effective diffusivity of each non-oxygen consuming layer (therefore excluding sewage sludge, trisoplast and tailings layers) was determined by flushing a lysimeter with N$_2$ gas, so
an initial oxygen concentration within the lysimeter was 0 mg/l, and then measuring change in oxygen concentration across the layer over time according to equation 2.

\[
D_{\text{eff}} = \ln \left[ \frac{c_0}{c_0 - c_{\text{lm}}(t)} \right] \frac{\Delta z}{t} h
\]

Where \(D_{\text{eff}}\) is the diffusion coefficient (m\(^2\) s\(^{-1}\)), \(c_0\) is oxygen concentration at time 0, and \(c_{\text{lm}}\) is oxygen concentration in the lysimeter as a function of time (t). The \(\Delta z\) is the layer thickness, while \(h\) is the height of the lysimeter walls.

The gas sampling ports allowed oxygen concentrations to be measured above and below sealing layers, while atmospheric oxygen concentration from the surface of the pile was also collected to enable concentration gradient to be determined for the entire cover system and waste mass. The harmonic mean of experimentally determined diffusion coefficients for each material layer within a cell was subsequently used to evaluate oxygen flux, following Fick’s 1\(^{\text{st}}\) law (equation 3).

\[
F = -D_{\text{eff}} \left( \frac{\Delta C}{\Delta z} \right)
\]

Where \(F\) is oxygen flux (mole m\(^{-2}\) s\(^{-1}\)), and \(C\) refers to oxygen concentration at a given depth (z).

Gas samples were analysed, presumably on site, using the continuous flow extractive gas analyser, SICK Maihak S710. Sampling was conducted once every two weeks throughout 2004, and monthly in 2005. (Alakangas et al. 2008)

6.1.3 Sampling challenges and conclusions
Challenges encountered during sampling included high water content around sampling ports and within lysimeters during the wettest months, and frozen probe connections during cold months. These issues reduced data points in winter and spring months. (Alakangas et al. 2008)

Oxygen concentration beneath the sealing layers varied seasonally, being lowest in the autumn and highest in the summer. The authors suggest such seasonal variation is likely the result of changing moisture content in the cover. The lowest oxygen concentrations were beneath the sewage cover, while other covers generally exhibited concentrations below 10%, but which varied to as high as atmospheric concentrations. One potential explanation the authors provide for poorer than expected performance in most layers is potential damage from freeze thaw, as the layers froze during the winter season. Additionally, snowmelt water infiltration while the sealing layers were frozen is suspected to have resulted in diminished water saturation within the sealing layers. The authors note that monitoring data from moisture content throughout the cover would have been useful for determining whether undersaturation played a role in the observed rate of oxygen diffusion. (Alakangas et al. 2008)
6.2 Undisclosed capillary barrier system, Quebec, Canada

6.2.1 Site background and experimental objectives
Oxygen gas concentration gradients were measured in a capillary barrier tailings cover from an undisclosed mine site in 2006 and 2007 (Mbonimpa et al. 2008). The study focused on gas sampling and analysis techniques for evaluating performance of full scale cover systems designed to utilize the capillary barrier effect on the basis of oxygen concentration. The mine cover consisted of a 0.5 m drainage layer (sand and gravel) over tailings, covered by a 0.8 m thick moisture retaining layer, and a 0.3 m surface protective drainage layer of sand and gravel.

6.2.2 Monitoring and analysis
Oxygen concentration gradients were measured from sampling probes at different depths and different site locations. Samples were taken from a total of six sites across the barrier, three from approximately level cover plateau areas, and three from cover slopes with 3H:1V grade. At each sample location, samples were collected from at least 5 sample depths (Figure 4). Three samples were collected from within the moisture retention layer, one 15 cm below the surface, one near the middle, and one 15 cm from the base. A sample was collected from the centre of the lower drainage layer, and from 15 cm below the tailings-drainage layer interface. Sampling was conducted as soil moisture allowed for a total of 7 sample events across July, August and October 2006, and June and July 2007. (Mbonimpa et al. 2008)

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Figure 4. Soil vapour probe sampling locations in capillary barrier (from Mbonimpa et al. 2008)
Two different methods were used for oxygen sample collection, and two methods were used for sample analysis. A portion of the samples were collected using soil probes that were installed temporally, on a per sample-event basis, for discrete depth soil vapour collection. These probes were developed by AMS Inc. and were equipped with re-useable sampling tips. The sampling tips included fine screen mesh connected to sample tubing. The screen was protected within a steel casing during installation, after which the casing was retracted to expose the screen and enable soil vapour collection. (Mbonimpa et al. 2008)

A portion of samples were also collected from soil gas probes installed permanently in the cover. These probes utilize a dedicated sampling tip. The sampling tip has gas inlet holes which are protected during installation by a steel casing and which are exposed after sample tip deployment. The sample tip is attached to sample tubing and left in the soil when the probe is extracted. (Mbonimpa et al. 2008)

The probes were installed using a slide hammer or electric hammer drill. Fluoropolymer tubing was used for sample collection for both probe systems. Further sample extraction for both systems can be done using either a manual or peristaltic pump. (Mbonimpa et al. 2008)

Gas sample analysis was also conducted using two different methods. The first method entailed collecting soil vapour samples to nitrogen purged Tedlar bags. The Tedlar bags were then transported to a laboratory and samples were analysed within 24 hours of sampling by gas chromatography using an Agilent MicroGC with O2/N2 and CO2 detection coils. The second method of analysis was initiated in 2007, by which oxygen concentrations were determined in the field using a polymer optical fibre oxygen sensor (the PST3) with OXY-10 reader by PreSens GmbH. The oxygen sensor was determined to have an accuracy of ±0.1% and gas phase readings could be attained in the field in less than ten seconds. (Mbonimpa et al. 2008)

While details on hydraulic studies of the capillary barrier were not provided in this case study, the authors did note instrument installation for this purpose. To measure volumetric water content TDR probes from Soilmoisture Equipment Corp. and echo probes, model EC 5 from Decagon devices, were installed in trenches excavated in the barrier. To measure matric suction, Watermark sensors by Irrometer Co. were also installed. (Mbonimpa et al. 2008)

6.2.3 Lessons learned and conclusions
A number of sampling issues were encountered that led to a reduction in data points. Namely, soil saturation during wet months limited gas sample collection to dryer months only. Further, the authors found that successful sampling generally required 3 days without heavy precipitation prior to sample collection, even during summer months. Additionally, based on suspect oxygen profiles identified in the results, a number of the Tedlar vapour sampling bags used to transport samples were determined to be leaky. Lastly, the 2007 sampling season ended due to the break-down of the Oxy-10 reader of the oxygen sensor. (Mbonimpa et al. 2008)

In general, a decrease in oxygen concentration was observed through the capillary barrier by all methods applied, with the exception of results from leaky bags. Due to the occurrence of
leaky bags, in 2007 all samples were analysed on site. In the plateau areas oxygen concentrations beneath the barrier were between 0 and 1%, indicating good cover performance. Concentrations at embankment crests, however, ranged from 2 to 6%, suggesting slightly lower performance under the slopes of the cover. The lower performance is suspected to result from desaturation of the reduced permeability layer near the top of the embankment, though other factors, such as variability in saturation layer thickness and chemical reactivity of underlying tailings could also play a role. The authors also notes that hydraulic performance data collection is ongoing and will be used to compliment these results. (Mbonimpa et al. 2008)

7 COVER PERFORMANCE EVALUATION AT CLUFF LAKE, NORTHERN SASKATCHEWAN

An experimental waste rock pile with monitoring instruments and lysimeters for discharge collection was constructed in 1997-1998 at the Cluff Lake uranium mine site to study flow routes in the pile and discharge quality and amounts of the acid-producing waste rocks (Wagner 2004). The pile was covered with a low permeability compacted waste rock layer in 2002. In 2001, two additional cover system field trials were built to evaluate construction and performance of the preferred cover design. Based on the trials a full scale cover was established on the Claude waste rock pile at the Cluff Lake mine site in 2006. During the construction, instrumentation to monitor hydrological performance of the cover was installed in the cover structure. (Barber et al. 2015)

Performance monitoring of the full scale dry cover system at the Cluff Lake mine is described by Barber et al. (2015). Data objectives and instrumentation applied for full scale monitoring largely align with those relevant to pilot program monitoring so are described here. Additionally, construction details regarding experimental waste rock pile and the pilot covers used during the design phase are described by Wagner (2004), Wagner et al. (2006; and the references therein) and Barber et al. (2015).

7.1 Site background and monitoring objectives

The Cluff lake mine site is in northern Saskatchewan, approximately 700 km north of Saskatoon, Canada, in a semi-arid, subarctic climate with low topographic relief. The area receives approximately 450 mm of precipitation annually, 30% of which falls as snow, and has an average potential evapotranspiration of 600 mm (Barber et al. 2015). From 1988 to 1999 mean daily summer temperatures ranged from 14.7 to 17.0°C, and mean daily winter temperatures ranged from -17.5 to -20.3 (CNSC 2003).

The Cluff lake mine site is within the Carswell formation on the western side of the Athabasca basin. The Carswell formation is the result of a meteorite impact in which basement rock (Precambrian upper amphibolite to greenshist facies gneisses) are exposed centrally within overturned Athabasca sandstone. Uranium mineralization is sandstone hosted and occurs in association with the unconformity between sandstone and basement rock (Blaise & Koning 1985). Bedrock surrounding the mine area is overlain by 2 to 7 m of glacial till (Wagner 2004).
A waste rock pile from the Claude pit was constructed at the site from 1982 to 1989. The pile is up to 30 m high, covers an area of 26.4 ha, and contains 7.23 million tons of waste (CNSC 2003, Barber et al. 2015). The waste rock is composed primarily of the Peter River aluminous gneiss (containing garnet, cordierite and sillimanite), Earl River feldspathic and mafic gneiss, and small amounts of sandstone (Wagner 2004). Mineralogical characterization conducted by Hollings et al. (2001) showed waste rock is comprised primarily of quartz and Fe rich amphibolites, with chlorite and illite alteration. Small areas within the waste rock also contained biotite, pyrite, chalcopyrite, Th-rich monazite, apatite, zircon and rutile. The sulphide minerals (80% pyrite) within the waste rock were particularly disseminated and comprised a maximum of 1-2% of the mineral composition of any samples (Hollings et al. 2001).

Elevated concentrations of U (200 mg/l) and Ni (43 mg/l) measured from piezometers in the waste rock pile provided indication of acid mine drainage. The identification and characterization of AMD led to the decision that the waste rock pile would be decommissioned through installation of a dry cover system (Barber et al. 2015).

At first, an uncovered experimental waste rock pile was constructed to evaluate geochemical and hydrologic characteristics of the waste material (Wagner 2004). The pile was later covered with a low-permeability compacted waste rock layer to assess the impacts of the cover on the discharge quality (Wagner et al. 2006). Additionally, two pilot cover systems were constructed to evaluate construction feasibility and hydraulic characteristics of the preferred cover design (Barber et al. 2015). Data from pilot cells were also used to develop soil-plant atmosphere model and guided final cover design decisions. (Barber et al. 2015)

The objectives of the final dry cover system were to reduce infiltration to the waste and to decrease discharge from the waste to the surrounding water bodies to levels that did not pose risk to aquatic ecosystems. In addition, the aim of the cover was also to attenuate radiation emissions from the waste and to provide a growth medium that would sustain a vegetation cove over the waste. (Barber et al. 2015)

7.2 Pilot and final cover construction

The experimental, uncovered waste rock pile was 5 m high over an 8 m x 8 m area on top of an existing waste rock pile. The area was divided into sixteen contiguous 2 m x 2 m lysimeters. Impermeable walls were constructed around the waste pile sides to route all drainage to the underlying lysimeters. Lysimeter drain lines were traced with heated cable to prevent freezing and routed to tipping bucket gauges in an adjacent instrumentation building (Wagner 2004, Nichol et al. 2005, Wagner et al. 2006 and the references therein).

Two pilot covers were constructed, one on a nearly level platform, and the second on a 4H:1V grade. The pilot covers were otherwise identical. Pilot covers consisted of a 10 cm thick reduced permeability layer of compacted waste rock, which was overlain by 1 m of locally derived silty sand till. The optimal field compaction technique was defined experimentally prior to pilot cover construction. Pilot covers were monitored for 5 years as described in the following section prior to full scale cover construction. (Barber et al. 2015)
The final cover was constructed following the enhanced store and release principle. A reduced permeability layer (RPL) of at least 20 cm thickness was constructed by compacting the waste rock surface with a Caterpillar CS583 roller to 95% of maximum dry density. The saturated hydraulic conductivity of the compacted layer was estimated in the field to be $10^{-7}$ to $10^{-8}$ m/s. The RPL was capped by 100 cm of uncompacted silty-sand till and seeded with grass and legumes. (Barber et al. 2015)

### 7.3 Instrumentation and performance evaluation

Instrumentation installed in the uncovered experimental waste rock pile included TDR probes to measure volumetric water content, thermal conductivity sensors to measure matric suction, thermistors to measure temperature profile, and suction lysimeters for soil pore water sample collection. Instruments were installed in the experimental pile during construction along 3 vertical profiles. (Wagner 2004, Nichol et al. 2005, Wagner et al. 2006).

Limited details on pilot cover monitoring were provided in the performance monitoring report, but it is noted that *in situ* water content, matric suction and temperature within the cover system and the waste materials were part of monitoring data. These data were used to estimate net percolation and calibrate a numerical soil-plant-atmosphere model to guide final cover design. (Barber et al. 2015)

Net percolation is the primary metric by which full scale cover performance was evaluated. Net percolation was estimated from a daily water balance (Equation 1), defined from automated daily data collection. Data objectives included precipitation, net radiation, runoff, volumetric water content, matric suction and temperature profile. Monitoring was conducted across a range of slope and aspect positions. Information on instrumentation and model used in this study is limited, though it is noted that temperature profiles are measured using thermal conductivity sensors. (Barber et al. 2015)

Net percolation for 8 years of monitoring was on average 22% for plateau areas and 16% for slope areas with large variability between years. The multi-year average meets design criteria. Variation between years is attributed to factors such as the persistence of snow pack and timing of cover freeze-thaw relative to snow melt, and of major precipitation events. Barber et al. (2015) suggest delayed spring thaw within the cover reduces infiltration and improves performance, while high precipitation events during low evaporation, frost free months (September and October), leads to higher infiltration. Further, they suggest performance of the enhanced store and release cover will improve over time as the vegetative cover matures (Barber et al. 2015).

### 8 LYSIMETER STUDIES TO INVESTIGATE SUITABLE TAILINGS COVER STRUCTURES AT PYHÄSALMI MINE, FINLAND

The performance of various different tailings impoundment cover structures utilizing secondary materials is being tested in a lysimeter study at the Pyhäsalmi mine in Finland (Ramboll 2016). The UPACMIC project, which is coordinated by Ramboll Finland Oy, started in July 2013 and will continue until 2019. The field lysimeters were constructed in spring
2016, so no results are yet available. Detailed construction information has also not yet been made available. The overall objectives and approximate structure of the test lysimeters are described here as an example of mine waste lysimeter structures currently being applied in a Nordic environment, though insufficient site information is available to provide a detailed case study at this time.

8.1 Site background and monitoring objectives
The Pyhäsalmi mine is located at the Pyhäsalmi municipality in the south of Oulu province, Finland, approximately 450 km north of Helsinki. The climate is subarctic with yearly average temperature being 2-3°C and the area receives 550-600 mm of average annual precipitation (Finnish Meteorological Institute 2016). The main products of the Pyhäsalmi underground mine are Cu, Zn, Ag, Au and pyrite. The mine was opened in 1962 and it will be closed in 2018. The mine site includes tailings impoundments containing sulphide rich tailings, for which suitable closure options are being investigated.

The objective of the UPACMIC project is to demonstrate the usability of secondary materials in constructing cover layers and basal structures for tailings areas with the primary purpose of preventing contaminants from leaching into groundwater. The main by-products being tested in the project are fly-ash from e.g. power generation, fibre clays from the paper industries, gypsum and foundry sands. (Ramboll 2016)

Due to the unlimited published data on the pilot scale tests carried out at the Pyhäsalmi mine site, the following information is based on the personal communications with Maria Hänninen from the First Quantum Minerals Ltd Pyhäsalmi mine.

8.2 Construction of the lysimeters
Ten lysimeters with pilot cover systems were constructed at the Pyhäsalmi mine site, including one uncovered lysimeter for reference data (Figure 5).

![Figure 5. Ten cylinder shaped lysimeters have been constructed at the Pyhäsalmi mine to test different cover structures for tailings facilities. The lysimeters have been covered with a growth layer (Photo © Teemu Karlsson / GTK)](image)
The lysimeters were constructed using cylinders approximately 1.5 m wide and 1.5 m high. The bottom of the lysimeters consist of a layer of gravel and filter screen, topped by tailings and covered with different kinds of mixed materials and a growth layer. The drainage is conducted to a collection bucket. The lysimeters are enclosed in sand to prevent freezing. The overall design of the lysimeters is presented in Figure 6.

The lysimeters do not contain any instrumentation; only the amount of drainage water is calculated based on the drainage water collection and sampled for chemical analysis. Local precipitation and temperature are being monitored with a weather station.

![Figure 6. The overall design of the field scale lysimeters at the Pyhäselmi mine site (Photo © Teemu Karlsson / GTK)](image-url)
9 SUMMARY OF COLD CLIMATE PILOT SCALE COVER SYSTEMS

Pilot scale cover systems provide an opportunity to verify whether cover design specifications can be attained at a field scale, allow alternate design options to be tested, and provide insight to cover performance under site-specific climate and geochemical settings over time. Additionally, pilot scale monitoring can be used to further characterize the variables that define site-specific energy and water balances. Because these variables ultimately relate to cover performance, they can be used to calibrate model results and optimize design criteria.

The case studies covered in this report provide examples of how the following key data objectives are characterized or monitored for the evaluation of cover system performance:

- Site specific climate conditions
- Runoff
- Cover moisture profile
- Cover temperature profile
- Lateral percolation
- Net percolation
- Oxygen gas diffusion
- Waste mass thermal conductivity
- Cover compaction characteristics
- Pore water or leachate chemistry

Monitoring and characterization approaches for site specific climate data objectives from the case studies are summarized below under section “Site climate characterization”. Laboratory geotechnical and geochemical characterization of cover materials conducted prior to construction, as well as field methods for verifying construction design criteria have been met are summarized in “Pilot cover construction and cover design criteria”. In situ performance monitoring techniques to determine how and why cover performance changes over time in response to site conditions are summarized in “Cover system performance monitoring”. Lastly, some concluding notes are provided on section “General cover construction and monitoring array design considerations”.

9.1 Site climate characterization

Site specific climate monitoring was described in the Aitik, Whistle, and Cluff lake mine case studies (Sections 2, 3 and 7). Site specific climate data are utilized in determining water balance and energy balance, and in unsaturated flow models. These data collected from pilot studies allow for both performance assessment within site-specific conditions, and are important to the iterative cover design process. Weather/climate data type, monitoring approach and data application are described in Table 2.
Table 2. Case study climate monitoring summary

<table>
<thead>
<tr>
<th>Data</th>
<th>Site</th>
<th>Instrument</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitation</td>
<td>Aitik Whistle</td>
<td>Tipping bucket; all season precipitation gauge</td>
<td>Water balance, flow modelling</td>
</tr>
<tr>
<td></td>
<td>Cluff lake</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>Pyhäsalmi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow pack</td>
<td>Aitik</td>
<td>Sonic ranging detector</td>
<td>Water balance, energy balance</td>
</tr>
<tr>
<td></td>
<td>Whistle</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cluff lake</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyhäsalmi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net radiation</td>
<td>Aitik Whistle</td>
<td>Net radiometer</td>
<td>Water balance (potential evapotranspiration), energy balance</td>
</tr>
<tr>
<td></td>
<td>Cluff lake</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyhäsalmi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air temperature</td>
<td>Aitik Whistle</td>
<td>Temperature sensor</td>
<td>Water balance (potential evapotranspiration), energy balance</td>
</tr>
<tr>
<td></td>
<td>Cluff lake</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyhäsalmi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Relative humidity</td>
<td>Whistle</td>
<td>Unspecified</td>
<td>Water balance (potential evapotranspiration)</td>
</tr>
<tr>
<td></td>
<td>Cluff lake</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyhäsalmi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Wind speed and</td>
<td>Whistle</td>
<td>Unspecified</td>
<td>Water balance (potential evapotranspiration), energy balance</td>
</tr>
<tr>
<td>direction</td>
<td>Cluff lake</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyhäsalmi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barometric</td>
<td>Whistle</td>
<td>Unspecified</td>
<td>Water balance (potential evapotranspiration)</td>
</tr>
<tr>
<td>pressure</td>
<td>Cluff lake</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Pyhäsalmi</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface run off</td>
<td>Whistle</td>
<td>Surface water flow controls</td>
<td>Water balance</td>
</tr>
<tr>
<td></td>
<td>Cluff lake</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

9.2 Pilot cover construction and cover design criteria

Cover system design criteria are ideally defined through a combination of material testing, site characterization and modelling, and refined through field testing. Laboratory geotechnical and geochemical material testing methods conducted as part of the evaluation of material suitability were emphasized in the GLD study (Mäkitalo et al. 2014, Mäkitalo 2015, Mäkitalo et al. 2015). Geotechnical testing used to guide design criteria included the following:

- Particle size analysis
- Standard and modified proctor tests to provide maximum dry density, optimum water content, and porosity
- Multivolume helium pycnometer analysis to determine compact density, porosity, and pore number
- Uniaxial compressive shear strength to evaluate material structural stability
- Hydraulic conductivity evaluated by head permeability and constant rate of strain tests
- Water retention capacity evaluated using Tempe cell method
- Particle surface charge determined using electrophoretic measurement
- Particle structure evaluated using SEM

Mineralogical and geochemical characterization performed on cover materials included (Mäkitalo et al. 2014, Mäkitalo 2015):

- Mineralogical characterization by X-ray diffraction
- Content of aqua regia leachable elements by ICP-MS analysis
- Leaching tests at L/S 10 following European standard SS-EN 12457-4 (SIS 2003)
- Buffering capacity using a batch titration method
- Acid base accounting following Sobek et al. (1978) (for tailings only)
- Weathering cell analysis (Cruz et al. 2001, Hakkou et al. 2008)

Pilot scale covers were constructed as part of all the case studies described above, with the possible exception of the undisclosed site in Quebec Canada, for which the design process was not described. Design criteria used to evaluate construction feasibility in the field relative to laboratory defined material characteristics commonly included the dry density and water saturation of compacted cover layers. These parameters may be used to infer water retention capacity, hydraulic conductivity, oxygen diffusion coefficient and therefore the performance of the till cover system (e.g. Ayres et al. 2002, Mäkitalo et. al. 2015). In both the Aitik and GLD case studies pilot cover layer dry densities and water contents were measured in the field with a nuclear densometer (i.e. a Troxler device) (McKeown et al. 2015, Mäkitalo et al. 2015). Water volumetry was also conducted to evaluate water content in covers as part of the GLD studies (Mäkitalo et al. 2015). At the Whistle mine optimum water content (specifically, 2% wet of optimal water content defined by proctor testing) was used as construction design criteria to minimize oxygen diffusion through the barriers (Ayres et al. 2002).

While geotechnical compaction and pore water volume characterization provide metrics for the effectiveness of field scale construction approaches, it should be noted the relationship between these metrics and performance criteria may change over time. As identified by McKeown et al. (2015) in the Aitik case study, while dry density of cover layers did not change after a freeze thaw cycle, hydraulic conductivity increased substantially, indicating the value of assessing hydraulic conductivity in the field in addition to laboratory defined metrics such as dry density.

Table 3. Case study pilot cell construction specifications

<table>
<thead>
<tr>
<th>Site</th>
<th>Footprint</th>
<th>Slope angle</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aitik</td>
<td>50 m x 50 m</td>
<td>3H:1H</td>
<td>By building covers on a waste rock platform with an exposed (uncovered) face, authors noted difficulties evaluating oxygen diffusion through the covers</td>
</tr>
<tr>
<td>Whistle</td>
<td>24 m x 12 m</td>
<td>Plateau at 5H:1V, embankments at 2H:1V</td>
<td></td>
</tr>
<tr>
<td>Diavik</td>
<td>80 m x 125 m</td>
<td>Approx. 5.5H:1V (18° angle)</td>
<td></td>
</tr>
<tr>
<td>GLD</td>
<td>8 mx12 m</td>
<td>2H:1V</td>
<td>The authors note rapid erosion from the embankment attributed to the steep grade, and suggest 3H:1V as a preferable embankment angle.</td>
</tr>
<tr>
<td>Kristineberg</td>
<td>5 mx5 m</td>
<td>3 m high vertical insulated cement wall (this was a cell, not a pile)</td>
<td></td>
</tr>
<tr>
<td>Pyhäsalmi</td>
<td>Approx. 1.5 m diameter</td>
<td>Approx. 1.5 m high vertical cylinder (this was a cell, not a pile)</td>
<td></td>
</tr>
</tbody>
</table>
Pilot cover construction methods were described in detail for the Aitik, Whistle, Diavik, GLD and Kristineberg case studies (Ayres et al. 2002, Alakangas et al. 2008, Smith et al. 2013, McKeown 2015, Mäkitalo 2015). Pilot cell dimensions and embankment angles for these studies are provided in Table 3. It should be noted, that while MEND (2012) suggests minimum pilot cell area of 1 ha (100m x 100m), only the Diavik pilot was this large.

9.3 Cover system performance monitoring

Cover system performance is evaluated from in situ monitoring to some degree within each case study. Data objectives for performance monitoring are dependent on cover performance criteria, and may range in complexity from water balance based estimates of net percolation (e.g. Cluff Lake mine per Barber et al. 2015), to thorough characterization of biogeochemical evolution within the waste mass (e.g. Diavik mine study per Smith et al. 2013). Table 4 summarizes data objectives per case study site, as well as associated instrumentation, instrument placement, data collection intervals and data applications.

Monitoring techniques for oxygen gas concentration are summarized separately in Table 5 to provide space for additional detail. At almost every case study site O2 concentration beneath the cover was a performance metric. Further, for the Kristineberg study, O2 concentration results were used to calculate material oxygen diffusion coefficients.

In addition to the monitoring techniques described here, there exist abundant resources in the literature outlining theory and technique behind physico-chemical monitoring approaches applicable to mine waste cover systems. O’Kane (2011) provides a summary of watershed scale monitoring for cover system performance evaluation, which includes recommendations on data collection approaches for such variables as soil moisture content, soil suction and net percolation. Phillip and O’Kane (2012) provide technical guidance on lysimeter construction to achieve representative net percolation. Tarantino et al. (2008a) provide a review on both field and laboratory methods for evaluating unsaturated flow, a key component of dry cover system functionality.
Table 4. Performance monitoring summary

<table>
<thead>
<tr>
<th>Data</th>
<th>Site</th>
<th>Instrument</th>
<th>Monitoring array</th>
<th>Sample interval</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature gradient</td>
<td>Aitik</td>
<td>Thermal conductivity sensor, Thermistor strings, Temperature probe</td>
<td>Generally sensors placed throughout cover system and waste mass to facilitate measurement of temporal gradient</td>
<td>Every 6 hours at the Aitik and Whistle mines, 12 hours at Diavik, and approx. monthly for the GLD studies</td>
<td>Energy balance/water balance, evaluating freezing front</td>
</tr>
<tr>
<td></td>
<td>Whistle</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td></td>
<td>Diavik</td>
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<tr>
<td></td>
<td>GLD</td>
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</tr>
<tr>
<td></td>
<td>Kristineberg</td>
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</tr>
<tr>
<td></td>
<td>Cluff lake</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soil volumetric water content</td>
<td>Aitik</td>
<td>Aitik unspecified Whistle FDR sensors (Campbell Scientific CS615-L) Diavik TDR GLD: Soil moisture probe 5TM by Decagon Devices Und. Canadian site TDR (Soilmoisture Equipment Corp) and echo probe 8EC 5 by Decagon devices Cluff lake, unspecified</td>
<td>Placed in profile throughout cover/material of interest near to, but out of potential sphere of influence of other monitoring devices (e.g. as part of instrument cluster)</td>
<td>Every 6 hours (specified only for Aitik and Whistle case studies)</td>
<td>Net percolation calculation, other water balance components (e.g. interflow), field based water retention curves, and performance monitoring in general</td>
</tr>
<tr>
<td></td>
<td>Whistle</td>
<td></td>
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<td></td>
<td>Diavik</td>
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<td></td>
<td>GLD</td>
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<tr>
<td></td>
<td>Und.¹ Canadian site</td>
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<td></td>
<td>Cluff lake</td>
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</tr>
<tr>
<td>Matric suction</td>
<td>Aitik</td>
<td>Aitik: unspecified Whistle: Thermal conductivity sensor (Campbell Scientific 229L) Diavik co-location of TDR and SWSS GLD: water potential sensor MPS-6 by Decagon Devices Und. Canadian site: Watermark sensors by Irrometer Co.</td>
<td>Throughout profile of interest, in proximity to other monitoring devices (e.g. within instrument cluster)</td>
<td>Every 6 hours (specified only for Aitik and Whistle case studies)</td>
<td>Water balance, field water retention curve validation, unsaturated flow modelling</td>
</tr>
<tr>
<td></td>
<td>Whistle</td>
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<tr>
<td></td>
<td>Diavik</td>
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<tr>
<td></td>
<td>GLD</td>
<td></td>
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</tr>
<tr>
<td></td>
<td>Und. Canadian site</td>
<td></td>
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<tr>
<td></td>
<td>Cluff lake</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Net percolation</td>
<td>Aitik</td>
<td>Determined either from water balance (including soil water content and matric suction data), lysimeter, and/or using a basal drain of the entire footprint</td>
<td>Discharge from lysimeters and basal drains can be monitored by tipping bucket</td>
<td>Continuous</td>
<td>Cover performance metric, water balance and flow model calibration</td>
</tr>
<tr>
<td></td>
<td>Whistle</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Diavik</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>GLD</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Cluff Lake Pyhäsalmi</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Water quality

<table>
<thead>
<tr>
<th>Site</th>
<th>Instrument</th>
<th>Monitoring array</th>
<th>Sample interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whistle</td>
<td>Automated in situ gas analyser (Nova Analytical Systems) coupled with manual sample ports</td>
<td>7 above, 4 in and 2 below low permeability layer, positioned 1 m upgradient of lysimeter</td>
<td>Every 12 hours</td>
</tr>
<tr>
<td>Diavik</td>
<td>Automated and manual, unspecified</td>
<td>At Diavik sampling locations were extensive, throughout</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Kristineberg</td>
<td>Oxygen lysimeter plus three sampling ports to Maihak S710 gas analyser</td>
<td>Lysimeters below barrier layer and base of tailings, gas sample ports 0.1 m above, 0.1 m below and 0.5 m below barrier layer</td>
<td>Every 2 weeks for year 1 and every month for year 2</td>
</tr>
<tr>
<td>Undisclosed Canadian site</td>
<td>Sample probes to microGC (Agilent) and PSI3 oxygen sensor with OXY10 reader</td>
<td>3 points across water retention layer, one from lower capillary layer, and 15 cm below tailings surface</td>
<td>A total of 7 sample events across two summers when soil moisture permitted</td>
</tr>
</tbody>
</table>

### Waste rock thermal conductivity

<table>
<thead>
<tr>
<th>Site</th>
<th>Instrument</th>
<th>Monitoring array</th>
<th>Sample interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diavik</td>
<td>Heat source port plus temperature sensors</td>
<td>Port on all sample faces; heat source can be lowered to discrete depths in each port</td>
<td>Undefined</td>
</tr>
</tbody>
</table>

### Waste rock air permeability

<table>
<thead>
<tr>
<th>Site</th>
<th>Instrument</th>
<th>Monitoring array</th>
<th>Sample interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diavik</td>
<td>N₂ gas port with pressure transducer</td>
<td>Central to pilot pile, in close proximity of other instrumentation</td>
<td>Undefined</td>
</tr>
</tbody>
</table>

### Waste rock microbial community

<table>
<thead>
<tr>
<th>Site</th>
<th>Instrument</th>
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<th>Sample interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diavik</td>
<td>Retrievable mesh bags of pyrite installed in microbial sampling wells for laboratory analysis</td>
<td>Pyrite bags at different depths across sample faces (e.g. 5, 6, 8.5, and 10.5 m on sample face 2)</td>
<td>One sample annually</td>
</tr>
</tbody>
</table>

1) Undisclosed mine site, Quebec, Canada

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**Table 5. O₂ gas concentration monitoring**

<table>
<thead>
<tr>
<th>Site</th>
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<th>Monitoring array</th>
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</tr>
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<tbody>
<tr>
<td>Aitik</td>
<td>Automated unspecified</td>
<td>Unspecified</td>
<td>Unspecified</td>
</tr>
<tr>
<td>Whistle</td>
<td>Automated unspecified</td>
<td>Unspecified</td>
<td>Every 12 hours</td>
</tr>
<tr>
<td>Kristineberg</td>
<td>Automated unspecified</td>
<td>Unspecified</td>
<td>Every 2 weeks for year 1 and every month for year 2</td>
</tr>
<tr>
<td>Undisclosed Canadian site</td>
<td>Automated unspecified</td>
<td>Unspecified</td>
<td>A total of 7 sample events across two summers when soil moisture permitted</td>
</tr>
</tbody>
</table>

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**Table 5. O₂ gas concentration monitoring**

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</tbody>
</table>
9.4 General cover construction and monitoring array design considerations
To ensure that experimental test cover systems are representative of full scale performance MEND (2012) recommends:

- Test covers be constructed using the same techniques to be employed during full scale construction
- For test covers to include both waste pile plateau and slope areas; and
- For monitored slopes to face different aspects.

MEND (2012) also suggests minimum dimensions of 1 ha to avoid influence from boundary conditions while monitoring water and energy parameters. Additionally, different monitoring devices should be within close proximity to each other so parameters can be correlated (e.g. water volume and matric suction to define water retention), but not so close to be within the sphere of influence of adjacent instruments. For example, for the Diavik study soil solution samplers and TDR probes were placed together throughout the soil profile with 0.5 m between the two probes (Smith et al. 2013).

As described in numerous of the case studies, instrumentation installed within the waste rock is typically placed during pile construction to minimize disturbance to waste material continuity (e.g. Ayres et al. 2002, Alakangas et al. 2008, Smith et al. 2013). Smith et al. (2013) provide details on measures taken to protect instrumentation throughout pile construction, as well as considerations for ensuring hydrologic contact between TDR sensor membranes and the surrounding matrix. Additional considerations regarding selection and placement of instruments for evaluation of hydraulic parameters such as volumetric water content and matric suction are provided by Tarantino (2008b) and O’Kane (2011).
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