

**STORIES FROM A QUARTER CENTURY OF COVER SYSTEM DESIGN
– LEARNINGS TO INFORM THE FUTURE –**

Mike O’Kane¹

¹Okane Consultants
736 6 Ave SW Suite 1900
Calgary, AB T2P 3T7

ABSTRACT

For over twenty-five years, Okane has designed, built, and monitored cover systems for tailings storage facilities and mine rock stockpiles across British Columbia. Typical terminology within the industry refers to “water covers” and “dry covers”. Dry Covers, or cover systems that result in primarily a terrestrial ecosystem, is the focus of this paper. They are the building blocks for achieving future, or returning, land use, and providing a stable, reliable, and sustainable interface between a mine landform and the environment. With, primarily, a warm humid continental and oceanic climate, British Columbia is a unique environment for cover system design. Performance expectation, from a technical perspective, is strongly influenced by the geologic and hydrogeologic system at a mine site. Cover system performance itself is largely dictated by water management, freeze-thaw and wet-dry cycles, and storm events. Each site can also have many microclimates that will impact not just cover system performance but long-term revegetation potential. As new projects explore alternative waste disposal methods, including filtered tailings and co-disposal options, modelling of both saturated and unsaturated zone hydrology will need to consider new land-climate interactions, including land use(s) that are not solely focussed on achieving ecological restoration. Risk-based decisions, informed by geochemical stability will have a greater impact on geotechnical stability; closure criteria requirements for cover systems will evolve. There also remains a need for specific focus on the key aspects influencing cover system functionality to communicate, on a site-specific basis, that cover systems are ‘proven technology’, as defined by the Province’s Technical Readiness Assessment (TRA) guidance, to manage water and water quality risk. This paper highlights key considerations for designing cover systems in British Columbia, historical lessons learned, and factors to consider when designing for future climate change scenarios.

Key words: Land Use, Climate and Climate Change, Cover Systems, Proven Technology, Landforms, Water Balance, Water Quality, Risk-Based Decisions, Adaptive Management

INTRODUCTION

A cover system is a technology in the mining industry, which falls within the broad range of applied sciences aimed at preventing and/or mitigating potential risk arising from mining activity. The need for cover system technology arises because during mining, the target economic mineral extracted, as well as non-economic materials extracted, typically contain sulfide minerals, which can lead to acid mine drainage, or metal leaching and acid rock drainage (AMD/ ML-ARD). ML-ARD risk arises from the presence of these materials at a mine site within tailings storage facilities (TSFs), mine rock stockpiles (MRSs), ore and low-grade ore stockpiles (LGO), heap leach pads (HLPs), exposed pit walls, and underground workings (INAP, 2019). Management of these landforms, and the material within the landforms, is required to manage risk(s) arising from potential degradation of water quality, and limit environmental, social and financial liabilities.

There are two foundational ‘imbalances’ created when a material that was below surface, is placed on the surface within a TSF an MRS, or within an in-pit impoundment during operations and closure; a gravitational imbalance and a thermodynamic imbalance. The thermodynamic imbalance results from material that was in a reducing environment for the most part (*i.e.*, a lack of oxidants, such as oxygen), is placed into an oxidizing environment (*i.e.*, in an MRS, TSF, etc.). The gravitational imbalance results from meteoric water, as well as groundwater and run-on, landing on, and/or coming into the mine landform. The system (the landform) continuously works from a state of higher potential energy to lower potential energy. Hence, a cover system ‘works’ in concert with the landform on which it is placed to manage risk from creation of these two foundational imbalances (*i.e.*, manages ingress of oxygen and limits meteoric water and run-on from entering the landform).

WHAT IS A COVER SYSTEM?

Cover systems are exactly that; systems, because their performance, including performance expectation, is intimately linked to the underlying material, the landform itself, vegetation, and site-specific climate conditions. Hence, while they are frequently labelled as ‘caps’, liners, or ‘covers’, a cover system is much more than the cover material itself. An incorrect thought process, and thus design approach, will often result if a cover system is thought of as the cover material only, because the tendency is then to design each layer in isolation of other factors that influence cover system performance. Cover systems are the building blocks for achieving agreed-upon land uses and support, as a general purpose, surface reclamation of a mine landform, while also providing a stable, reliable, and sustainable interface between the landform and the environment. Purposefully, within the mining industry, this interface is planned as being one that develops into either an aquatic (‘water cover’) or terrestrial ecosystem (‘dry cover’), and either may also include a riparian zone. The latter, ‘dry covers’ is the focus herein.

More simply, cover systems support reclamation of the surface of landforms created from mining activity, and typically are expected to limit net percolation, and/or control oxygen ingress into the landform during operations and in closure, as a means of managing ML-ARD risk.

Learnings to Inform the Future:

Lee Barbour:

“...keep things as simple as possible... but no simpler...”

“...cover system design, is like designing the ‘right-sized flower pot’...”

Application of this learning should focus on the need for developing a conceptual model of cover system performance that is simple to communicate, supported by numerical modelling and field conditions, is coupled to the underlying material, and site-specific climate conditions, and whose benefit to addressing the gravitational and thermodynamic imbalances that result from mining, is simply demonstrated.

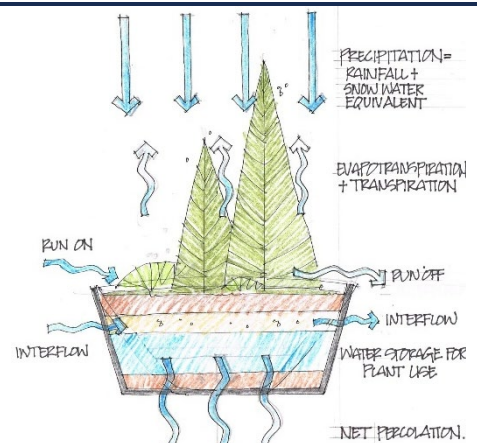


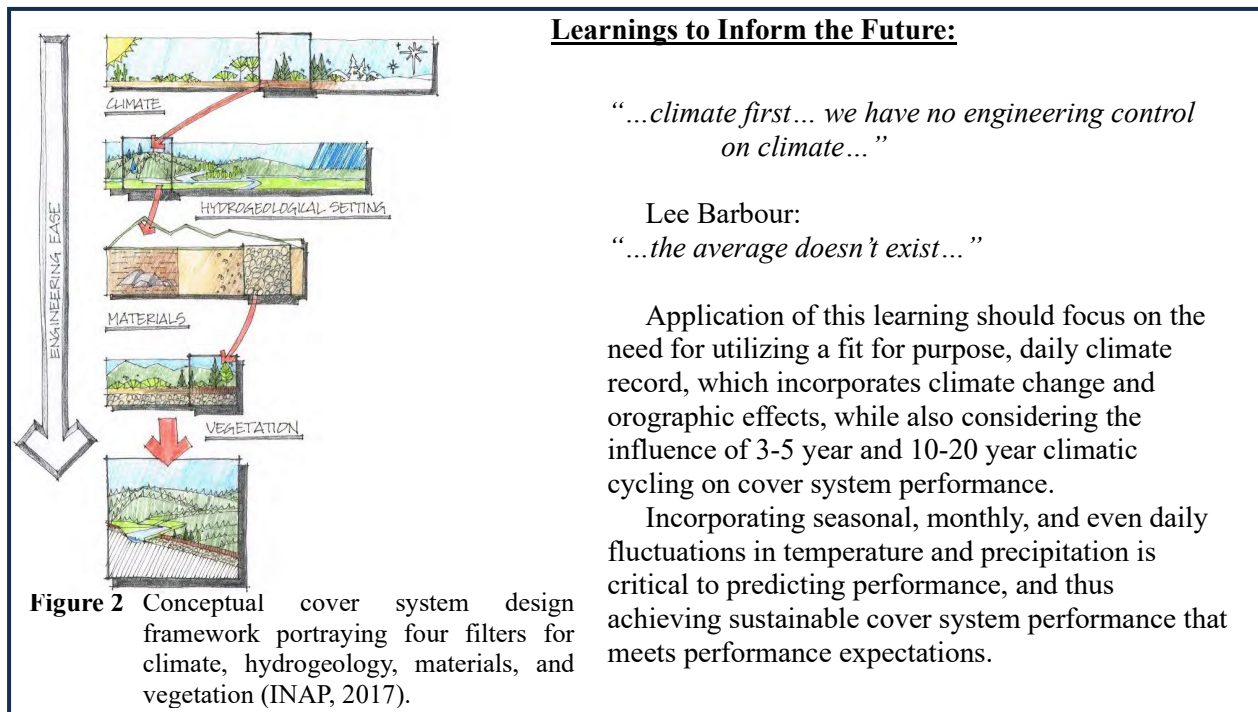
Figure 1 Cover system design is like designing the right-sized flower pot (O’Kane, 2018)

CONCEPTUALIZING COVER SYSTEM PERFORMANCE

The ‘Cold Regions Cover System Design Technical Guidance Document’ (MEND, 2012), and the Global Cover System Design – Technical Guidance Document (INAP, 2017) provide an approach to conceptualize

cover system performance, and therefore design. In the case of the INAP document (2017), a decision-making tool is presented, which advocates use of a hierarchical framework, structured from the basis of ‘engineering ease’ in which to develop a conceptual cover system design. This is depicted in Figure 2, where climate is the first ‘filter’ to look through, because it is the facet of cover system design for which we have no control over. Next, is hydrogeologic setting, which can be ‘engineered’, such as with, foundations, ditches, trenches, cutoff walls, and pumping wells, but is challenging to engineer.

Our capacity to ‘engineer’ materials and vegetation to influence cover system performance is substantially greater as compared to engineering ease with changing hydrogeologic conditions. For example, finer-textured materials retain more water than coarser-textured materials, which will increase a cover system’s capacity for plant available water, and this reduce net percolation. Layering a finer-textured material over a coarser-textured material will further enhance plant available water and reduce net percolation.



Development of a robust site-specific conceptual model for a cover system allows for numerical modelling to be focussed on refining the conceptual model and comparing alternate cover system designs. Very often, numerical modelling to support cover system design is ‘started too early’. There is a focus on undertaking deterministic numerical modelling before a full understanding of what is required from the cover system, which confounds a designer’s capacity to assess uncertainty, and put appropriate controls in place.

Cover system numerical models must have the capacity for coupling heat and mass across the soil-plant-atmosphere interface. Coupling is achieved through modelling actual vapour pressure within the cover material, and the atmosphere, such that the model predicts actual evaporation and transpiration (AE and AT, together AET). This is in contrast to using potential evaporation, and requiring the modeller to limit AE and AT ‘manually’, which ‘de-couples’ the model across the soil-plant-atmosphere. Cover system models require a wide range of inputs, broadly categorized into upper boundary conditions, lower boundary conditions, material properties, and initial conditions. Rarely is there comprehensive data for all of these inputs; however, with a robust conceptual model, assumptions and limitations in numerical modelling can

be communicated in a simple manner, by using the conceptual model of cover system performance as the communication tool, as well as communicating results of sensitivity analyses.

Learnings to Inform the Future:

“...use the conceptual model to communicate expected performance...”

“...complete numerical modelling to enhance understanding of the conceptual model, first, then to compare alternate conceptual designs, and only then, to predict performance...”

Application of this learning should focus on developing, documenting, and communicating the conceptual model, or if preferred, the performance hypothesis, before any numerical modelling commences.

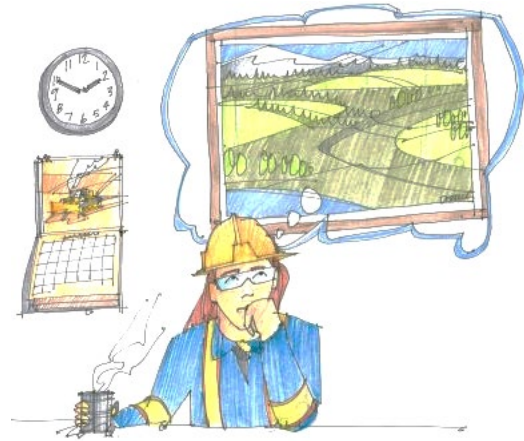


Figure 3 Conceptual model development (O’Kane, 2018).

COVER SYSTEM TYPES, FUNCTIONALITY, AND TERMINOLOGY

MEND (2012), and INAP (2017) summarize cover system types as follows.

1. Simple-protection type cover systems, such as reclamation, re-vegetation, isolation, and erosion protection type cover systems.
2. Store-and-release type cover systems.
3. Enhanced store-and-release cover system type, such as enhanced with a lower permeability layer, a capillary break, and engineered seasonally frozen capillary break diversion type cover systems.
4. Barrier-type cover systems, such as cover systems that include a layer that has a field saturated hydraulic conductivity (k_{fs}) that is 1×10^{-7} cm/s, or less, such as a compacted clay layer (CCL), a compacted sand-bentonite layer, or a permanently frozen layer (permafrost aggradation).
5. Engineered layer type cover systems, which include geomembranes that have a k_{fs} that is 1×10^{-7} cm/s, or less.
6. Saturated soil or rock type cover systems.

Identifying, or labeling, cover system types can appear to enhance communication of design intent. However, it is foundational to focus on cover system functionality, rather than design intent. A particular cover system may fall into more than one cover system type. For example, in respect of net percolation¹, which is different than net surface infiltration², all cover systems have some capacity to ‘store-and-release’ water, as well as ‘shed water’, regardless of cover system type. All cover systems also provide a degree of

¹ ‘Net Percolation’, is in reference to water reporting into the mine landform following placement of a cover system. It is the result of meteoric water (*i.e.*, rainfall and/or snowmelt) infiltrating into the cover system surface, which will either be intercepted by vegetation, runoff, or infiltrate into the surface. Water that infiltrates will be stored in the ‘active zone’ and may then subsequently exfiltrate back to the surface and evaporate, or be removed by transpiration. A percentage of the infiltrating meteoric water will migrate beyond the active zone as a result of gravity overcoming the influence of atmospheric forcing (*i.e.*, evaporation), may report as interflow (water moving laterally within the cover system due to a hydraulic discontinuity), with the result being net percolation to the underlying mine landform.

² ‘Net Surface Infiltration’, is in reference to water reporting into the mine landform for ‘bare surface’ conditions.

erosion protection, and a cover system with a geomembrane may also serve as a store-and-release cover system (INAP, 2017).

A cover system should be evaluated on a continuum of functional performance values. Differing mechanisms will be dominant depending on site-specific controls and on site-specific conditions. Cover system performance is not binary; rather, cover system performance is best communicated as a probability of exceedance, in comparison to design criteria, such that the probability of cover system performance can be communicated in the context of consequence effect. In this manner the benefits from risk mitigation activities can be evaluated against cost.

Learnings to Inform the Future:

“...cover system performance is not binary; every effort should be made to avoid labels for cover systems on the basis of design intent...”

“...rather, cover systems function on a continuum of performance functionality, where different mechanisms are dominant, depending on site-specific conditions...”

Application of this learning should focus on using numerical modelling for sensitivity analysis and understanding probability of meeting design criteria, rather than simply focussing on a binary prediction, such as the ‘average performance’, to make decisions on optimizing cover system design.

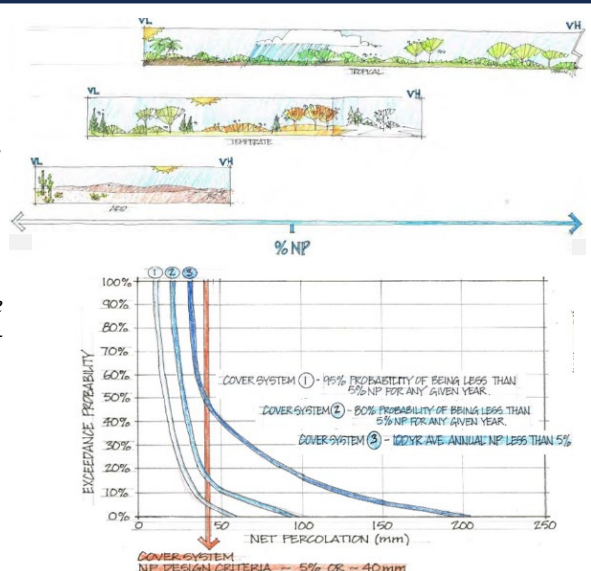


Figure 4 Cover systems function on a continuum (after INAP, 2017).

Learnings to Inform the Future:

“...performance of a geomembrane within a cover system is substantially different than the same geomembrane installed to store or convey water...don't conceptualize or model their performance with the same approach...”

“...in-service holes and tears in geomembranes will happen, embrace this eventuality, and address this risk by ensuring sufficient lateral drainage capacity within the cover system layer above the geomembrane...”

Application of this learning should focus on limiting the time in which positive pore-water pressure exists above the geomembrane; ensure sufficient lateral drainage capacity.

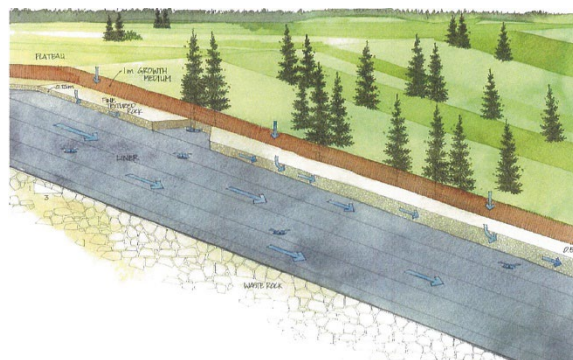


Figure 5 Lateral drainage capacity to de-risk eventuality of development of in-service geomembrane defects

CLIMATE, COVER SYSTEMS, and the BINNING CONCEPT

The Köppen-Geiger climate classification system helps characterize precipitation (PPT) and temperature on a seasonal and annual basis. Both parameters are integral to understanding key physical processes that control a cover system's water balance and consequently influence plant water availability, net percolation and oxygen ingress into a mine landform. The influence of orographic effects and climate change can also be incorporated into a site's Köppen-Geiger climate classification to inform on performance.

The modified Köppen-Geiger system (Peel *et al.*, 2007) divides climate into five major climate types, with each type being divided based on patterns of seasonal precipitation and temperature. The five main groups are Tropical (A), Arid (B), Temperate (C), Continental (D), and Polar (E). To address the dynamic nature of intra-annual climate variability (seasonality), subtypes exist for both PPT and temperature, which further sub-divide tropical, arid, and temperate regions. The amount and timing of water availability are controlled by regional climate. The primary parameters of PPT and temperature are not static, varying on a seasonal, annual, and decadal basis. With a fulsome understanding of the dominant climate at a site, including the highs, lows and cycles of annual, seasonal and decadal variation inherent in all climates, a cover system designer can begin to 'bin' cover system performance on the basis of an appropriate site-specific Köppen-Geiger classification.

Binning, which is a generalization for rounding, is also referred to as discretization, or bucketing. It is a well-known data pre-processing technique, where a set of data that fall into a particular interval, are replaced by a value, or description, representative of the interval.

Understandably, there is a tremendous potential range for cover system performance on a mine landform in BC, given the extent of their location, climatic setting, ore type, etc. Binning allows a cover system designer to focus on the importance of accuracy, versus precision. For a cover system conceptual model, it is foundational to determine 'what bin', or value, a measured facet of cover system functionality is situated. In this context, how close the measurement is to the accepted value (the accuracy) is more important than how close the measurements are to each other (the precision).

Any mine landform can be located, and characterized by its major climate type, and then its sub-type, on the basis of seasonality of temperature and precipitation. Using INAP (2017) a mine landform situated in the Elk Valley in southeastern BC can be used as a relevant example for application of the binning concept. For this example, the landform experiences a Köppen-Geiger climate classification in the Dfb 'bin, based on regional and seasonal temperature, as well as precipitation conditions. This 'bin' helps the designer identify the level control on net percolation or oxygen ingress is most applicable at the site, and for different cover system types. Net percolation rates for a cover system on a mine landform are binned into Very Low (VL), Low (L), Moderate (M), High (H), and Very High (VH) rates. INAP (2017) uses the Köppen-Geiger climate classification system to first bin climate based on regional, and then seasonal temperature and precipitation conditions. Then, INAP (2017) provides the range of the interval for net percolation, depending on texture of the near surface mine landform material, and the cover system type (layering, texture, thickness, vegetation, etc.). The following 'bins' of net percolation performance expectations, and the corresponding cover system type, are determined as per INAP (2017).

- *Very Low (VL):*
in that there is a high probability that net percolation will be <5% of average annual precipitation for any given year
cover system type: Barrier Layer (compacted clay layer; CCL, with k_{fs} of 1×10^{-7} cm/s, or less; sand-bentonite or geomembrane layer, if CCL not available).
- *Low (L):*
in that there is a high probability that net percolation will be 5% to 15% of average annual precipitation for any given year
cover system type: Enhanced Store-and-Release (w/ lower hydraulic conductivity layer).
- *Moderate (M):*
in that there is a high probability that net percolation will be 15% to 25% of average annual precipitation for any given year
cover system type: Enhanced Store-and-Release (w/ capillary break).
- *High (H):*
in that there is a high probability that net percolation will be 25% to 50% of average annual precipitation for any given year
cover system type: Store-and-Release.
- *Very High (H):*
in that there is a high probability that net percolation will be >50% of average annual precipitation for any given year
cover system type: Erosion Protection – Vegetation.

The value is not only in assigning a ‘bin’, but also understanding what the climate information is telling a designer about how a cover system will function annually and seasonally. INAP (2017) also provides binning ranges, from Very Low to Very High, for oxygen ingress, and the same conceptualization can be used for plant available water use, and cover system erosion.

Learnings to Inform the Future:

Mark Logsdon:

“...consider the value in being accurate, before you make effort to be precise...”

Application of this learning should focus on first understanding what range, or bin, a cover system’s functionality will meet performance expectations (*i.e.*, for net percolation, oxygen ingress, plant water use, and erosion), and then on the basis of site-specific climate, determine the most reasonable cover system type that will allow for cover system performance to have a high probability of meeting performance expectations for any given year.

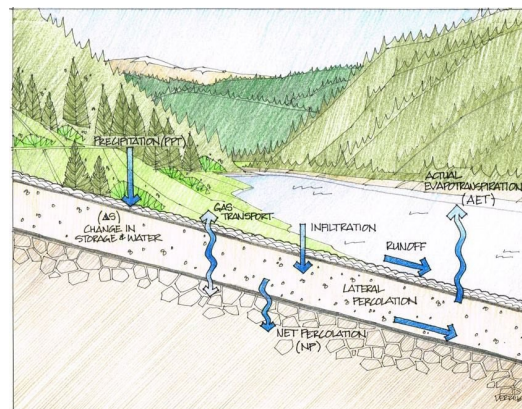
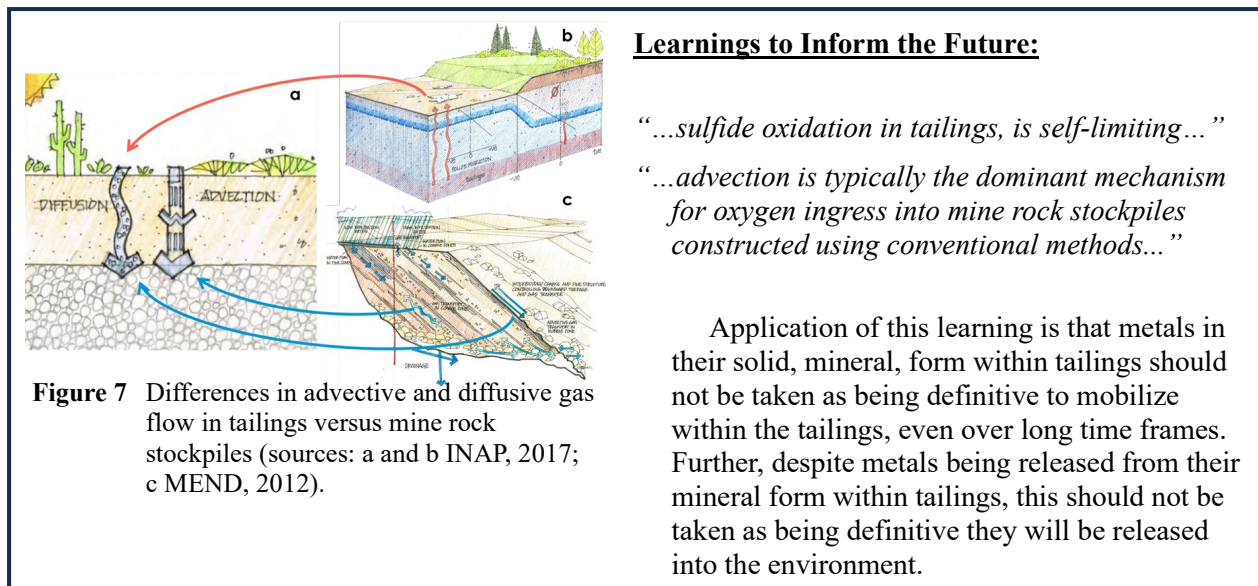


Figure 6 Cover system water balance (O’Kane, 2018).

WHAT LANDFORM?

Sulfides present in mine rock and tailings, when exposed to an oxidant such as atmospheric oxygen, can release metals. While other potentially toxic constituents may be released, sulfide minerals such as pyrite and pyrrhotite also release H^+ ions, which decreases pH, and may result in dissolution of other minerals present that were otherwise stable under more neutral pH conditions. However, even if pH remains neutral (buffered by carbonate minerals or silicates with sufficiently fast weathering rates), so called ‘neutral mine drainage’ may occur and result in elements in toxic quantities if released into the environment. Sulfide oxidation that leads to ML-ARD risk requires three key ‘ingredients’: 1) a ‘source’ of metals, (mainly sulfide minerals containing elements of concern), 2) a ‘fuel’ or an oxidant for sulfide oxidation, and 3) a mechanism to ‘transport’ metals out of the mine landform. Without these ingredients, metals and acidity will not emanate from the landform.

Oxygen is the first oxidant of concern for managing ML-ARD risk, noting that iron will also donate electrons to serve as an oxidant at lower pH ranges. Oxygen can move into and through mine rock and tailings by (1) advection and/or (2) diffusion. In tailings, oxygen ingress is typically limited to diffusion, because the smaller grain size of tailings limits advective airflow into the facilities. Mine rock stockpiles have larger grain sizes (ranging from clay size fractions to car-sized boulders), which allows both advective and diffusive flux of oxygen to enter the pile. This advective flux is partially the reason why such significant acidity and metal is released from mine rock stockpiles; the fuel (*i.e.*, oxygen) for the fire (*i.e.*, metal release from sulfide minerals) is uninhibited to greater depths, creating greater volumes of ‘reactive’ material in terms of sulfide oxidation, relative to tailings. In short, with conventional mine rock stockpiles, there is typically an unlimited re-supply of oxygen for ongoing sulfide oxidation because of the landform’s inherent high internal air flow capacity. In contrast, sulfide oxidation in tailings is self-limiting, as it is limited by the depth of oxidation that can occur from the surface (oxygen transport to a slowly advancing oxidation front). Water will also transport metals through both advective and diffusive processes; however, in the case of metals moving through a typical mine landform, it is assumed that advective flux is much more effective at transporting metals through partially saturated materials.



Mine landforms with tailings or mine rock not only differ in respect of the manner in which gas is transported into, and within these landforms, but also in respect to cover system constructability and water transport and/or storage. Tailings material is typically much finer-textured than mine rock, and while placed at much

higher water content than mine rock, tailings also have much higher water retention capacity than typical mine rock. Hence, cover system construction on tailings can be challenged by the need to create sufficient bearing capacity, as well as settlement due to tailings consolidation following cover system placement. In contrast, mine rock is generally coarser-textured, and thus is often well drained. Cover system construction on mine rock stockpiles can be challenged by steep and long slopes, which is a vastly different condition than a typical mine landform containing tailings.

The differing texture of tailings and mine rock also influences cover system performance as a result of the hydraulic conditions within these materials. Coarser-textured mine rock will typically be drained, so cover system performance will be ‘de-coupled’ hydraulically to any phreatic surface in a mine rock stockpile. In contrast, tailings, as a result of being finer-textured, and placed at relatively high solids content, will often have a phreatic surface that is near to the surface of the landform. Even if tailings are drained, they are often hydraulically ‘coupled’ to the cover system, and thus influence the cover system’s water balance (Shurniak *et al.*, 2008). Meaning, during conditions where evaporative demand is in excess of available water within a tailings landform cover system, water from within the tailings mass (*i.e.* tailings pore-water) will be ‘drawn up’ into the cover system in response to this demand. This can result in supply of more water for plant water use, which may adversely impact intended plant species and groupings and thus land use expectations. Further, if the tailings pore-water contains salinity, or other adverse constituents, there is probability of adversely impacting the rooting zone in a cover system through advective and diffusive transport of the constituents from the tailings, into the cover system. While this can still occur with mine rock material, the probability is substantially higher for tailings, given the finer-textured nature of tailings materials and typically higher water content conditions.

In some cases, where closure of a tailings landform does focus on application of a so called ‘dry cover’, the landform often includes the need for a surface water management pond on the landform, if only ephemeral. In these situations, there will be a high probability of tailings pore-water adversely impacting surface water in ponds and surface runoff.

Learnings to Inform the Future:

“...for tailings landforms, know where your phreatic surface is, and how placement of a cover system will change its depth, or not, during closure...”

A cover system is exactly that, a system, whose performance is influenced by the underlying material’s physical, chemical, and biological characteristics. Don’t exclude the importance of hydraulic characteristics of the underlying materials, when developing your cover system, particularly for tailings

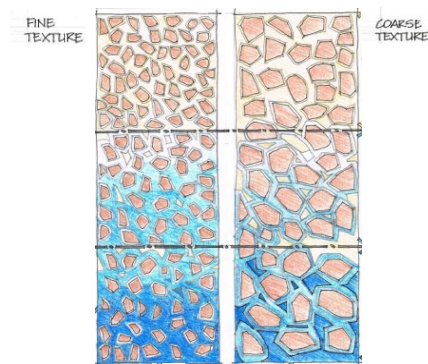


Figure 8 Coarser-textured and finer-textured materials: water retention and drainage differences (O’Kane, 2018)

THE EVENTUALITY OF COVER SYSTEM NUMERICAL MODELLING

Numerical modelling to support and inform on cover system design will eventually be a necessity. Deep conceptualization of cover system design and performance will provide the opportunity to ‘start’ numerical modelling properly. Inputs to cover system numerical modelling include: i) upper boundary conditions, such as climate and vegetation conditions, ii) lower boundary conditions, such as a negative pore-water

condition (*i.e.*, suction) or depth to a phreatic surface (pore-water pressure equal to zero, iii) initial conditions, such as temperature and pore-water pressure conditions of the modelled profile, and iv) material properties, such as thermal and water storage characteristics, thermal and water conductivity characteristics, and vegetation characteristics. However, numerical modelling can be challenging without appropriate thought to modelling inputs because there is as much ‘art and experience’ as there is science and engineering, in choosing cover system numerical modelling inputs. For example, a common challenge for a modeller is choosing / developing initial conditions that do not inadvertently influence model output (results). The same comment can be made in respect of lower boundary conditions; it is common that cover system numerical modelling results are not representative of expected field conditions as a result of an inappropriate assumption for a model’s lower boundary condition, and/or a lower boundary condition that is of insufficient depth from the interface of the base of the cover system and the mine landform.

It is typical for hydraulic material properties for cover system modelling (*i.e.*, the water retention curve (WRC) and the hydraulic conductivity function (k-function)) to be estimated, based on the texture, plasticity, density, and laboratory testing. However, Barbour *et al.* (2004), INAP (2003), and Shurniak (2003) illustrate the importance of incorporating physical, chemical, and biological processes / mechanisms, and site-specific controls on these processes / mechanisms, when considering material property inputs to cover system numerical modelling. The methodology proposed within the INAP Global Acid Rock Drainage (GARD) Guide, as well as documented in MEND (2004) and MEND (2012) and INAP (2017) allows for a cover system numerical modeller to consider evolution of material properties from initial (placed) conditions to longer term *in situ* conditions in response to processes such as, amongst many processes, freeze-thaw and wet-dry cycling, as well as vegetation development.

In INAP (2003) reported on the evolution of a cover system that included a compacted and non-compacted till material using k_{fs} testing of the Equity Silver mine cover system. The Equity Silver cover system consists of 50cm of compacted till, placed in two lifts on the mine rock landform surface, overlain by 30cm of the same till, but non-compacted. The till material is a moderately plastic (plasticity index (PI) ~15-20), well-graded material. Initial k_{fs} for the compacted layer, as reported by O’Kane (1996) was 1×10^{-7} cm/s, or less. Initial k_{fs} for the non-compacted layer, also reported by O’Kane (1996), was $\sim 1 \times 10^{-6}$ cm/s.

Following ten (10) years of in-service performance, k_{fs} was reported by INAP (2003) to be in the range of 1×10^{-4} cm/s to 1×10^{-5} cm/s for the upper 10cm of the compacted layer. The lower 40cm of the compacted layer remained at 1×10^{-7} cm/s, or less (INAP, 2003). The k_{fs} for the non-compacted layer increased following ten (10) years of in-service performance, ranging from 5×10^{-3} cm/s to $\sim 1 \times 10^{-5}$ cm/s (INAP, 2003).

Cover system field performance monitoring data reported in INAP (2003), from instrumentation installed by O’Kane (1996), indicates that increases in k_{fs} in the non-compacted layer was a result of freeze-thaw and wet-dry cycling; vegetation development (roots) likely contributed to the change in k_{fs} . The increase in k_{fs} for the upper 10cm of the compacted layer was a result of wet-dry cycling (INAP, 2003), not freeze-thaw cycling, as atmospheric ‘demand’ for moisture from the cover system during warmer summer conditions was not satisfied by moisture within the non-compacted layer. INAP (2003) reported no change in dry density of the upper 10cm of the compacted till layer.

Shurniak (2003) used *in situ* cover system monitoring data, specifically multiple suction and volumetric water content sensor pairs installed at the same depth across the full depth, and into the underlying mine landform material, as well as k_{fs} measurements of each layer of the cover system, to develop field-based hydraulic material properties. Volumetric water content sensor data was plotted against suction sensor data to develop field-based WRCs and k-functions, the latter using the instantaneous profile method and k_{fs} measurements. Shurniak (2003) demonstrated that the most appropriate method to model cover system performance was to incorporate bi-modal hydraulic material properties into numerical model inputs, because it allowed evolution of the cover material to be modelled numerically.

Learnings to Inform the Future:

“...include the influence of site-specific controls on physical, chemical, and biological processes to address evolution of cover system material properties during modelling...”

“...in-service cover materials that evolve following placement should be modelled using bi-modal hydraulic material properties...”

The most valuable information from cover system field performance monitoring to inform on numerical modelling of a cover system is development of field-based water retention curves and k-functions. Install pairs of suction and water content sensors in any cover system monitoring profile.

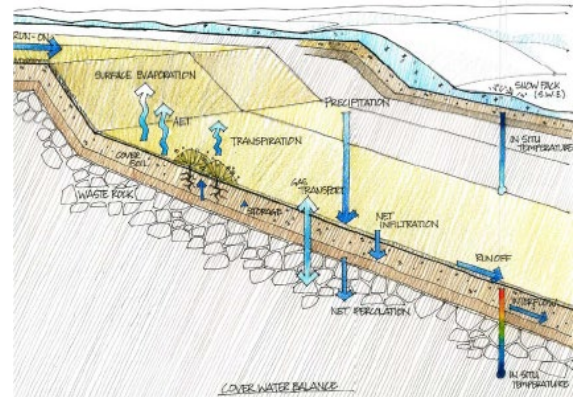


Figure 9 Components of a cover system water balance (MEND, 2012)

THE BEST COVER SYSTEM

The best cover system is challenging to define; however, if ‘what is best’ can be simplified, and alignment on performance expectations is achieved, then the opportunity to meet performance expectations can be vastly increased. INAP (2019), Sawyer *et al.* (2024) and INAP (2024) clearly illustrate the opportunity to decrease reliance on a cover system to manage net percolation and oxygen ingress by constructing mine rock stockpiles that limit internal air flow capacity, thus reducing probability of re-supply of oxygen deep into the landform. This results in a more engineered landform, with reduced uncertainty when predicting performance, as a result of controls put in place during landform construction, which in turns reduces reliance on collection, conveyance, storage, and treatment of effluent from the mine landform.

Hence, cover system expectations can be simplified to managing diffusive gas flux, if required, to the mine rock stockpile, limiting net percolation to manage draindown³, if required, while meeting plant water use requirements and serving to manage erosion on the landform.

Similarly, but perhaps from a different perspective and building from the fact that oxygen ingress into tailings is self-limiting, whether a cover system for a mine landform containing tailings situated in BC needs to manage oxygen, requires consideration. This is not to state that oxygen ingress into tailings is not considered, but rather, that the most pronounced risk in respect of ML-ARD is likely not due to seepage from the tailings mass, but rather as a result of surface runoff from the landform, because net acidity and metals resulting from sulfide oxidation will be focused near the surface of the tailings landform.

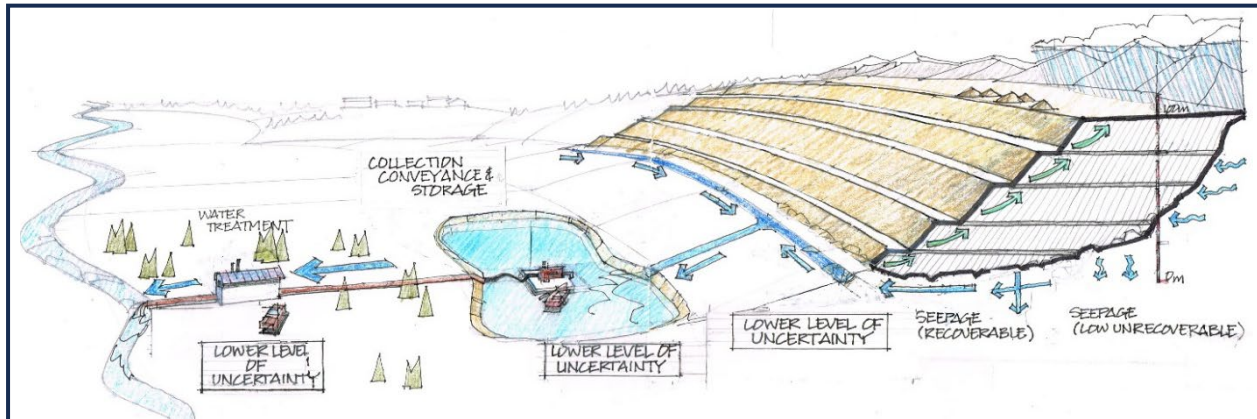


Figure 10 Incorporating source control into mine rock stockpile construction to reduce uncertainty in collection, conveyance, storage, and treatment of ML-ARD (INAP, 2024)

Learnings to Inform the Future:

“...the best cover system, is the one you don't need...”

Application of this learning should focus on recognition that conventional MRS construction can lead to a high level of uncertainty related to design, and challenges with predicting water quantity and quality outcomes. Typical ML-ARD risk management is to collect, convey, store, and treat recoverable surface and seepage water, and construct a cover system to reduce net percolation and oxygen ingress. Generally, challenges in predicting both the volume and quality of recoverable water required for treatment has led to significantly underfunded, and in many cases undesirable, closure outcomes.

³ Draindown: the additional water that drains due to gravity from a porous material if the supply of water at the top of the material is reduced. For example, take a 20 litre bucket and fill it with dry beach sand. Drill holes in the base of the bucket that allow water, but not sand, to drain from the bucket. Apply a relatively higher rate of water to the top of the bucket. Initially, the water will fill up storage capacity within pore-spaces of the dry sand, eventually, water will start to leak out the holes; and will continuously leak as you supply water to the top of the bucket. The leakage rate will be the same as the rate of water supplied to the top of the bucket, provided water is not spilling out over the edges of the bucket. When the water supply at the top of the bucket is reduced, the leakage rate at the bottom does not immediately equate to the reduced application rate at the top; rather, it remains high and then gradually decreases as water in the sand drains down. If the application rate is reduced substantively, or even made zero, the sand will take some time to draindown due to gravity. The water retention characteristics of the sand and the height of the sand will also influence draindown rates and timing (*i.e.*, draindown rates are a function of the volume of pore-space and how finer-, or coarser-, textured the beach sand is).

Learnings to Inform the Future:

“...cover system construction on tailings with low bearing capacity, is always more challenging than anticipated...”

Tailings storage facilities should be considered to be landforms during project initiation, all throughout design, and into closure. All landforms, have a land use, achieving closure land use expectations for a tailings landform must be incorporated into design and operations.

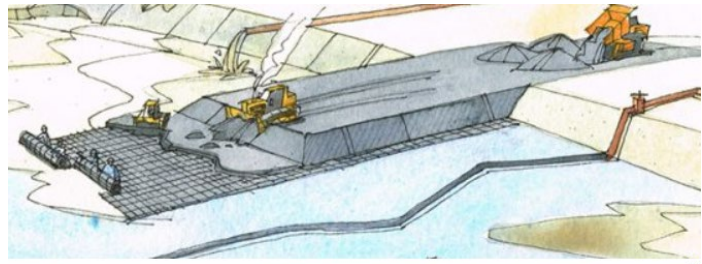


Figure 11 Construction of cover systems on low bearing capacity tailings (from McKenna, 2024)

TECHNOLOGY READINESS ASSESSMENT

British Columbia’s Ministry of Energy, Mines and Low Carbon Innovation (EMLI) and the Ministry of Environment and Climate Change Strategy (ENV), referred to collectively herein as ‘the Province’, released an Interim Technical Guidance document for Technology Readiness Assessment (TRA) in 2022 to provide guidance for assessing Technology Readiness Level (TRL) for source control measures at major mines. TRA is a systemic, evidence-based process, which evaluates readiness of emerging technologies and includes independent peer review, a technology maturation plan, a risk management approach, and a risk register. The BC TRL scale has nine levels to describe different stages of technology development and maturity.

A technology is considered proven, and acceptable to meet regulatory requirements, when it is successfully deployed in the field. Proven technologies are assessed in the Province’s TRL system as either a TRL-8 or a TRL-9 as described below.

- **TRL-8: Actual Technology Completed and Qualified through Test and Demonstrations:**
 - The technology is a first-of-a-kind system complete and proven at full-scale.
 - A risk management approach and risk register have been developed/updated. Identified risks have proposed mitigations through operational and management actions.
 - The technology is transferable and can conceptually be implemented at any site, subject to site-specific conditions.
 - The operational and replacement costs of the technology can be calculated for bonding requirements.
 - Regulatory information requirements for the technology are fully met using an appropriate combination of literature, analogue data, and empirical data for the technology. The technology will likely require site-specific work to collect empirical data to support the regulatory process.
- **TRL-9: Actual Technology Proven through Successful Deployment in Operational Settings:**
 - The technology is a system complete and proven at full-scale in multiple settings.
 - Regulatory information requirements for the technology are met using an appropriate combination of literature and analogue data for the technology. Empirical data may not be required.

On a province wide basis, cover systems are ‘proven technology’ in the mining industry in BC. Cover systems are often included as part of permitting for operations and for closure plans; in both cases, it is common for cover systems to be described in permit conditions. Progressive reclamation is also a ‘proven technology’ in BC. Progressive reclamation is well defined and is tracked in closure plans and annual reclamation reporting, both of which are Conditions for any permitted mine in the Province. The key then, is to work through, on a site-specific basis, the work and research required to bring a cover system to TRL-9 for a particular landform at a site.

Learnings to Inform the Future:

“...TRL enhances risk management and supports decision-making...”

The information to document research and technology development within BC’s TRA system already exists in management plans and documents that describe a project’s approach to developing and implementing technology in BC. TRL is an assessment tool for owners, operators, and stakeholders to understand the transition of technologies, and resource allocation required to mature technologies.

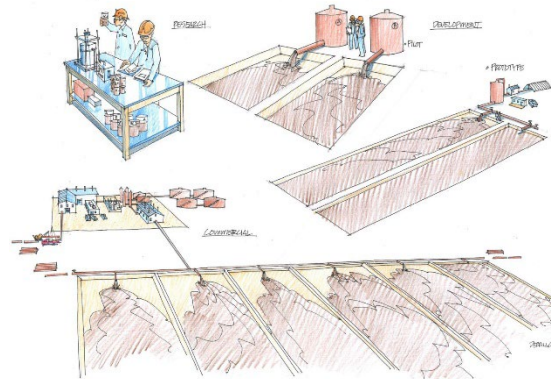


Figure 12 Research and development to commercial application (O’Kane and McKenna, 2014)

EIGHT WAYS TO ENSURE SUCCESS OF YOUR COVER SYSTEM

While not exhaustive, a number of technically focussed ‘lessons learned’ are offered in this paper to support development of a conceptual cover system design. These technical learnings can be coalesced into overarching non-technical lessons learned, the latter of which are supported by the technical lessons learned. These are the ‘eight ways to ensure success of your cover system’ and meet stakeholder and rightsholder expectations (from INAP (2017)).

1. Define and document future, or returning, land use for the mine landform, which considers the landform in the context of the site as a whole.
2. Define and document clear objectives for the cover system, which arise from land use expectations.
3. Ensure appropriate characterization of site-specific conditions (climate, materials, hydrogeology, etc.), such that cover system designs from other sites are not simply ‘transferred’ to the current site, without a full appreciation of the impact of even small differences between sites on cover system design and performance.
4. Consider as a fundamental component of cover systems the concomitant relationship between cover system design, construction, and performance, and mine landform design, construction, and performance.
5. Consider the influence of catchment run-on and lateral groundwater seepage onto and/or into the mine landform to ensure understanding for these conditions are included as part of performance expectations for the cover system.
6. Ensure surface water management onto, within, and/or from the mine landform is considered part of cover system design.

7. Ensure, early in project development, sufficient volume of cover material is available (of the appropriate characteristics, and at the planned unit rate(s)).
8. Ensure the cover system is constructible; meaning, that design complexity does not introduce challenges for implementation, and appropriate quality control and assurance during cover system construction can be achieved.

CONCLUSION

Numerical modelling to support and inform on cover system design is always required; however all too often, the numerical model, and the assumptions within in it, become the tool with which to communicate cover system performance expectations. The result, unfortunately, is a binary perspective on performance (will it ‘fail’, or not). Further, an early focus on numerical modelling can limit opportunity to optimize cover system design during latter stages of development.

This paper advocates for using a conceptual model, which is robustly developed, first on the basis of site-specific climate conditions to define ‘the possible’, and then on the physical, chemical, and biological characteristics of the mine landform on which the cover system is to be placed. The conceptual model then becomes the ‘tool’ for communicating expected performance, as it is refined and enhanced by numerical modelling. In this way, any numerical modelling is started from a stronger place, and is used most appropriately (*i.e.*, to enhance the conceptual model and to compare conceptual designs).

The lessons learned discussed in this paper provide a basis for developing a robust site-specific conceptual cover system design model. The ‘eight ways to ensure success of your cover system’ are the overarching questions a cover system designer should ask, such that a cover system meets performance expectations.

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