Cold Regions Cover System Design Technical Guidance Document

MEND Report 1.61.5c

This work was done on behalf of Aboriginal Affairs and Northern Development Canada (AANDC) and MEND and funded by AANDC

July 2012

COLD REGIONS COVER SYSTEM DESIGN
TECHNICAL GUIDANCE DOCUMENT

MEND 1.61.5c

Prepared for MEND

Funded by AANDC

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EXECUTIVE SUMMARY

The AANDC (Aboriginal Affairs and Northern Development Canada) Northern Contaminated Sites Program (NCSP) is responsible for remediation of contaminated sites on Crown land throughout the Canadian North. A significant percentage of the remediation liabilities faced by AANDC are associated with abandoned mines. Of these mine-related liabilities, a significant number involve the need to construct soil (earthen) covers over reactive tailings and waste rock.

AANDC anticipates that they will implement cover systems at some sites within the next two years. To do so they require additional information on key physical, chemical, and biological processes that affect long-term risk to these cover systems. The appropriate design and long-term effectiveness of earthen covers in cold regions is of central importance to AANDC, as well as to local and regional stakeholders.

The Mine Environment Neutral Drainage program recently completed a Phase 1 review of soil covers on mine wastes in cold regions (MEND 1.61.5a, 2009). Several dozen cold regions processes were identified as potentially important for earthen covers. These effects can develop slowly and may not be immediately evident, but could have significant influence on performance over the operating life of a cover system.

The immediate need of AANDC is for guidance on design of new cover systems at abandoned mine sites in cold regions. To this end, AANDC formed a Technical Advisory Group (TAG) comprised of experts in various fields important to cold region cover system design, to provide advice in the completion of this Guidance Document.

This Guidance Document outlines the current state-of-knowledge of soil cover system design in cold regions, the expectations of AANDC on how a cover system design should be conducted, and a summary of information AANDC expects to receive during the design process so that an informed decision can be made on the preferred design. The information presented in this document is intended to support development of designs associated with closure of abandoned mines, but will also be useful in developing closure plans for operational mines in cold regions.

This is a technical document that fits within the framework of sustainability, including socio-economic and socio-environmental aspects of mine closure. The target audience for this document is AANDC project managers and cover system design practitioners associated with closure and reclamation of mine sites in cold regions (In Canada, cold regions are generally considered those north of 60 degrees, though applicable to any location experiencing significant ground frost). Other groups, such as regulatory agencies, Aboriginal peoples, and non-governmental organizations (NGOs), may find this document of assistance during their review of a proposed design. It is intended to be a resource for guiding cover system designers in evaluating a wide range of possible solutions. AANDC encourages practitioners to consider that when all issues of long-term performance and liability are considered, the lowest cost option for a cold region cover system may not be the 'best' alternative.

This Guidance Document describes key attributes of cold regions and the associated challenges of cover system design in these climates. Cover system design is described beginning with an overview of the philosophy of cover system design, basic theory and fundamental concepts, available cover system design alternatives and their pros and cons, and presents a methodology for applying the tools required to meet cover design objectives. At the end of the document, three case studies are presented to illustrate the practical application of cover system design in cold regions.

SOMMAIRE

Le ministère des Affaires autochtones et Développement du Nord Canada (AADNC) et le Programme des sites contaminés du Nord (PSCN) sont responsables d’assainir les sites contaminés sur les terres publiques dans le Nord canadien. Un pourcentage important des responsabilités du ministère en matière d’assainissement découle de mines abandonnées. Parmi ces responsabilités, un nombre important nécessitent la construction de couvertures de terre pour recouvrir les résidus réactifs et la roche stérile.

Le ministère des AADNC envisage de mettre en place les systèmes de couverture dans certains sites au cours des deux prochaines années. Pour ce faire, il doit obtenir de plus amples renseignements sur les principaux processus physiques, chimiques et biologiques qui influent sur le risque à long terme de ces systèmes de couverture. Les représentants du ministère, de même que les intervenants locaux et régionaux, accordent une grande importance à la conception appropriée et à l’efficacité à long terme des couvertures de terre dans les régions froides.

Les responsables du Programme de neutralisation des eaux de drainage dans l'environnement minier (NEDEM) ont récemment terminé la phase 1 de l’examen des couvertures de terre sur les rejets miniers dans les régions froides (Programme NEDEM, 1.61.5a, 2009). On a identifié des douzaines de processus dans les régions froides comme étant potentiellement importants pour les couvertures de terre. Leurs effets se produiront peut-être lentement et ne seront pas nécessairement évidents à court terme, mais ils pourraient exercer une influence importante sur le rendement d’un système de couverture au cours de sa durée de vie utile.

À l’heure actuelle, le ministère des AADNC a besoin de conseils en matière de conception de nouveaux systèmes de couverture de sites miniers abandonnés dans les régions froides. C’est pourquoi il a formé le Groupe de conseillers techniques (GCT), composé d’experts de différents domaines liés à la conception de systèmes de couverture dans les régions froides. Ces experts doivent formuler des conseils relativement à la mise au point de ce document d'orientation.

Ce document d’orientation présente les connaissances actuelles en matière de conception de systèmes de couverture dans les régions froides, les attentes du ministère quant à la manière de concevoir un système de couverture et un résumé des renseignements que le ministère compte obtenir grâce au processus de conception, afin de prendre une décision éclairée à l’égard de la sélection de la couverture qui lui convient le mieux. Les renseignements présentés dans ce document ont pour but d’appuyer l’élaboration de modèles liés à la fermeture de mines abandonnées, mais ils serviront également à orienter les plans de fermeture de mines en exploitation dans les régions froides.

Ce document technique s’insère dans le cadre de la durabilité, notamment les aspects socioéconomiques et socio-environnementaux de la fermeture des mines. Ce document cible les gestionnaires de projet du ministère des AANDC et les spécialistes de la conception de systèmes de couverture, particulièrement dans le domaine de la fermeture et la réhabilitation des sites miniers dans les régions froides. (Au Canada, on désigne les régions au nord du 60e parallèle comme étant des régions froides, mais cette désignation s’applique à tout lieu qui connaît une gelée du sol importante.) Ce document pourrait être utile pour d’autres groupes, comme les organismes de réglementation, les peuples autochtones et les organisations non gouvernementales (ONG), lorsqu’ils examinent un modèle proposé. L’objectif du document consiste à servir de ressource pour les concepteurs, afin d’orienter leur évaluation d’une gamme de solutions possibles. Le ministère encourage les spécialistes à tenir compte de l’ensemble des facteurs liés au rendement à long terme et à la responsabilité, et leur rappelle que la solution la moins coûteuse en matière de systèmes de couverture dans les régions froides n’est pas nécessairement « la meilleure ».

Ce document d’orientation décrit les principaux attributs des régions froides et les défis liés à la conception de systèmes de couverture dans de tels climats. Le début du document décrit la conception de systèmes de couverture en effectuant un survol de la philosophie de la conception de ces systèmes, de la théorie de base, des concepts fondamentaux, des avantages et des désavantages des différentes solutions en matière de systèmes de couverture et de la méthodologie appliquée aux outils qu’il faut utiliser pour répondre aux objectifs des couvertures. La fin du document présente trois études de cas pour illustrer l’application pratique des modèles de systèmes de couverture dans les régions froides.

DISCLAIMER

The purpose of this report is to provide guidance on the design of new cover systems at mine sites in cold regions. The reader of this report assumes full responsibility for any action taken as a result of the information contained in this report.

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GLOSSARY

Active Layer	The upper portion of a soil profile within a cold region that experiences seasonal freeze/thaw cycles.
Actual Evapotranspiration (AET)	The sum of evaporation and plant transpiration from the surface to the atmosphere.
Air Entry Value (AEV)	The negative pore-water pressure (matric suction) required to initiate drainage of an initially saturated soil.
Available Water Holding Capacity (AWHC)	The difference in volumetric water content between field capacity (FC) and permanent wilting point (PWP).
Cold Region	Geographic locations around the world that experience prolonged cold air temperatures. In the context of mine waste covers, an appropriate definition would include any area where there is a regular occurrence of ground frost sufficient to affect cover performance, often due to frost action.
Field Capacity (FC)	The water content of a soil when drainage under the influence of gravitational forces ceases. Generally measured in the laboratory by measuring the water content of a sample brought into equilibrium in a pressure plate with a suction of 33kPa (fine-textured soils) or 10 kPa (coarse-textured soils).
Frost Action	Soil behaviours that are the result of the freezing and thawing of water within the soil matrix (e.g. frost heave).
Frost Heave	Soil behaviour where water accumulates at the freezing front leading to the creation of ice lenses in the subsurface that cause an annual cycle of heave and settlement.
Infiltration	Vertical movement of water into the soil at the ground surface.
Leaf Area Index (LAI)	Quantifies the amount of potentially active photosynthetic or intercepting foliage are per unit ground surface area; often defined as half the total leaf area per unit ground surface area.
Net Percolation	Movement of water through cover layers into waste—the source of this water may or may not have originated at the ground surface.
Permafrost	Continuous permafrost is defined by the presence of permanent ground freezing throughout the subsurface. Discontinuous

	permafrost is the state of permanent ground freezing that occurs only in some scattered areas beneath the surface.
Permanent Wilting Point (PWP)	The soil water content at a suction of approximately 1,500 kPa and represents the limit of plant-available water.
Potential Evapotranspiration (PET)	The sum of evaporation and plant transpiration that would take place assuming sufficient water was available to meet atmospheric demand. It is influenced by radiation, air temperature, humidity and windspeed.
Slope Aspect	Main compass direction (North, North East, East, South East, South, South West, West, and North West) that a slope faces.
Volumetric Water Content	An expression of water content based on the ratio of the volume of water to the total volume of soil: Vw/Vt. Often expressed as θ.
Water Retention Curve (WRC)	Describes the relationship between the energy state of the pore-water (matric suction or negative pore-water pressure) and the volume of water stored within the soil pores (volumetric water content).

1 INTRODUCTION

1.1 Background

Mining and its associated mineral processing generates large volumes of waste material. Waste rock is produced to access the ore, while tailings are a product of ore milling and processing. Spent ore is the mine waste product from heap leaching. The complexity of waste management practices required to limit potential environmental impacts from mine waste can increase dramatically if the waste material is chemically reactive to air and water. Proper management of reactive waste material is required to control / minimize direct exposure risks, prevent degradation of water quality, and limit environmental and financial liabilities.

The majority of chemically reactive mine waste is associated with sulphide oxidation and the concomitant release of acid rock drainage (ARD) or neutral drainage (ND) with elevated salinity and/or dissolved metals. Acidic effluent from mine waste reporting as groundwater seepage or drainage from mine openings affects both surface runoff and groundwater. Other concerns associated with this effluent include potential contamination of water with chemicals used for processing ore, such as cyanide, petroleum products, oil, solvent, acids, and reagents. Particulate transport due to erosion (by water and wind) and fugitive dust emissions are also a concern.

Deposits of tailings and waste rock need to be reclaimed in an appropriate manner as part of closing or reclaiming a mine site. For acid-generating waste material, the preferred closure option is generally disposal of waste material below the water table to limit further oxidation of sulphidic minerals (e.g. disposal in an abandoned open pit). However, this is usually not a feasible or desirable option at abandoned sites in cold regions, due to prior oxidation and contaminant content in the waste, lack of suitable water bodies, lack of suitable dam construction materials, climate, and/or cost considerations. Therefore, the closure option for most above-grade deposits of tailings or waste rock generally involves construction of a ‘dry’ or soil cover system (i.e. engineered cover system).

1.2 General Purpose of Cover Systems

The purpose of a cover system is restoration of the surface of a waste deposit to a stable, natural condition while minimizing degradation of the surrounding environment following closure of the waste impoundment.

Cover systems over waste material can have numerous objectives, including but not limited to:

- Isolation of waste;
- Limiting influx of atmospheric oxygen;

- Limiting influx of atmospheric water;
- Controlling erosion of waste material;
- Control upward movement of process-water constituents / oxidation products; and
- Providing a medium for establishing sustainable vegetation.

One of the main purposes of placing cover systems over reactive waste material is to protect the downstream receiving environment following closure of the waste storage facility (O’Kane and Wels, 2003). This is achieved by reducing net percolation of meteoric water into the mine waste, which reduces effluent seepage volumes. This reduction in seepage volumes ideally limits peak concentrations of contaminants in receiving waters to levels that can be assimilated without adverse impact to the aquatic ecosystem. In addition to controlling contaminant releases, cover systems can also provide chemical and physical stabilization of waste material and a growth medium for establishment of a sustainable vegetation canopy.

Cover systems can be simple or complex, ranging from a single layer of earthen material to several layers of different material types, including native soils, suitable overburden, non-reactive tailings and/or waste rock, geosynthetic materials, and oxygen-consuming materials (MEND 2.21.4, 2004). The complexity of any given cover system design depends on several factors, which are highlighted in this document.

1.3 Contaminated Sites Program of AANDC

The Contaminated Sites Program of Aboriginal Affairs and Northern Development Canada (AANDC) are responsible for remediation of contaminated sites on Crown land throughout Canada’s North. Approximately 80% of the costs associated with these remediation liabilities are associated with abandoned mines. The need to construct cover systems over tailings and waste rock represents at least one-third of the mine-related liabilities. The appropriate design and long-term effectiveness of cover systems is therefore of central importance to AANDC as well as local and regional stakeholders.

MEND 1.61.5a (2009) identified studies that should be considered to further advance the practice of mine waste cover system design in cold regions. While AANDC supports the undertaking of additional research, the immediate need is for guidance on the design of new cover systems at abandoned mine sites in cold regions. In particular, AANDC requires that critical questions with regard to cold region cover systems be addressed, including:

i) What are the key processes that will affect performance of different types of cover systems within a cold regions context?

ii) How should the design process incorporate these issues?

iii) What are the risks to long-term performance as a result of these cold regions phenomena?

To this end, AANDC formed a Technical Advisory Group (TAG) comprised of experts in various fields relevant to the design of cover systems in cold regions, to facilitate preparation of this Guidance Document.

This document focuses on soil cover systems. Water cover systems can be a feasible part of a mine closure plan; however, they are not addressed in this document. The following MEND reports discuss issues associated with the design and implementation of water covers:

- MEND 2.11.2b, 2009. Literature Review Report: Interactions Between Trace Metals and Aquatic Organisms;
- MEND 2.11.4a, 1995. Geochemical Assessment of Subaqueous Tailings Disposal in Buttle Lake, British Columbia 1993 Study Program;
- MEND 2.11.5ab, 1996. Shallow Water Covers – Equity Silver Base Information Physical Variable;
- MEND 2.11.9, 1998. Design Guide for the Subaqueous Disposal of Reactive Tailings in Constructed Impoundments;
- MEND 2.12.2, 2007. Assessing the Long Term Performance of a Shallow Water Cover to Limit Oxidation of Reactive Tailings at Louvicourt Mine;
- MEND 2.12.2b, 2010. Field Assessment of the Occurrence of Algal Biofilm on Submerged Tailings;
- MEND 2.17.1, 1996. Review of Use of an Elevated Water Table as a Method to Control and Reduce Acidic Drainage from Tailings; and
- MEND 2.18.1, 1997. Review of Water Cover Sites and Research Projects.

1.4 MEND Studies on Cover Systems in Cold Regions

The Mine Environment Neutral Drainage (MEND) program completed a Phase 1 review of soil covers on mine wastes in cold regions (MEND 1.61.5a, 2009). Several dozen cold region processes were identified as potentially significant for soil covers. The most widespread are ground freezing and ground ice formation, ground thawing and associated settlement, and freeze/thaw cycling. Combinations of these processes under specific soil or hydrologic conditions can degrade key soil properties (e.g. compaction and permeability) or result in structural changes such as the development of macroscopic features including solifluction, cracking, mounding or hummocks, or mudboils. These processes may be occurring but develop at a rate at which they are not obvious from field inspections, yet may still have a negative effect on performance over the operating life of a cover system.

The Phase 1 review concluded that designing cold regions cover systems using methods derived largely from experience in temperate zones is not best practice. MEND 2.21.4 (2004) and MEND 2.21.5 (2007) are manuals that include methodologies and case studies for design and performance monitoring of mine waste cover systems, with the latter document focused on the macro- or watershed-scale. Although these manuals discuss such issues as freeze/thaw cycling and snowpack measurements, the majority of the design and monitoring methodologies are based on experiences in more temperate climates.

MEND 1.61.5b (2010) extended the initial work of MEND 1.61.5a (2009) by evaluating the state of cold regions cover system research. This evaluation included the following:

1) Characterization of cold regions phenomena identified in the Phase 1 as ‘observed’, ‘suspected’, ‘expected’ or ‘not expected’ in terms of their potential to affect performance of various types of cover systems;
2) Review of the role of vegetation on cold regions cover systems, including available literature on cold regions evapotranspiration rates and rooting depths;
3) Review of the state-of-the-art for numerical simulation of cold regions cover system performance and related hydrological processes;
4) Evaluation of potential for convective cooling in both flat and sloping cover system designs using a series of bounding calculations;
5) Evaluation of potential for using insulating layers to limit freeze/thaw effects on cover systems that include low-permeability barrier layers; and
6) Identification and summary of information for ongoing cover system field trials or research programs in locations that might experience cold regions effects.

1.5 Report Structure

This report is divided into the following chapters:

- Chapter 2 provides an overview of the geographic extent and key attributes of cold regions, focussing on attributes that have an influence on cover system performance;
- Chapter 3 discusses various aspects pertaining to the philosophy of cover system design for cold region sites including cover system objectives;
- Chapter 4 is an overview of some of the basic theory and fundamental concepts required for cover system design in cold regions;
- Chapter 5 outlines the various cover system design alternatives for cold region sites;
- Chapter 6 describes the methodology for designing cover systems in cold regions; and

- Chapter 7 illustrates the application of the Failure Mode & Effects Analysis (FMEA) for three idealized case studies.

2 GEOGRAPHIC EXTENT AND KEY ATTRIBUTES OF COLD REGIONS

The term ‘cold region’ is used to categorize geographic locations around the world in which trends in air temperatures, snow depth, ice cover on lakes, or the depth of ground freezing are similar (Andersland and Ladanyi, 2004). Cold regions typically experience a variety of extreme climate conditions, with the most obvious condition being prolonged cold air temperatures.

In the context of mine waste covers, an appropriate definition of cold regions would include any area where there is a regular occurrence of ground frost sufficient to affect cover performance. Actual data on ground frost depth is limited (Andersland and Ladanyi 2004). Therefore, frost depth is often estimated from the air freezing index, which uses only meteorological data to assess the combined duration and magnitude of below-freezing air temperatures during a year (Brown and Kupsch 1974). Freezing indices can only be used to approximate ground frost depth as many other factors such as soil mineral and textural composition, snow cover, and vegetation also affect frost depth.

A location that is classified as a cold region can further be subdivided based on freezing conditions in the subsurface (Andersland and Ladanyi, 2004). The subdivisions of a cold region are based on whether the ground is seasonally frozen or whether permafrost exists. Permafrost is a state of permanently frozen ground that occurs when atmospheric temperature is sufficiently low to maintain a ground temperature of less than 0°C for two or more years (Whiteman, 2011). The dividing line between zones of seasonally frozen ground and permafrost is approximated by the -5°C air isotherm. Figure 2.1 shows the general divisions of seasonally frozen ground and permafrost in Canada.

Permafrost exists in either a continuous or discontinuous pattern. Discontinuous permafrost is the state of permanent ground freezing that occurs only in some scattered areas beneath the surface whereas continuous permafrost is defined by the presence of permanent ground freezing throughout the subsurface in all areas (Andersland and Ladanyi, 2004). In discontinuous permafrost zones, factors such as slope aspect, ground cover, and soil conditions affect whether or not a particular area will have permafrost or not. Permanently frozen ground in the discontinuous zone can vary widely, from depths of a few centimetres to depths exceeding 100 m. Permanently frozen ground in the continuous zone can exist to a depth of more than a kilometre and requires an annual freezing index of approximately 3900 degree-days-°C to be sustained (Andersland and Ladanyi, 2004).

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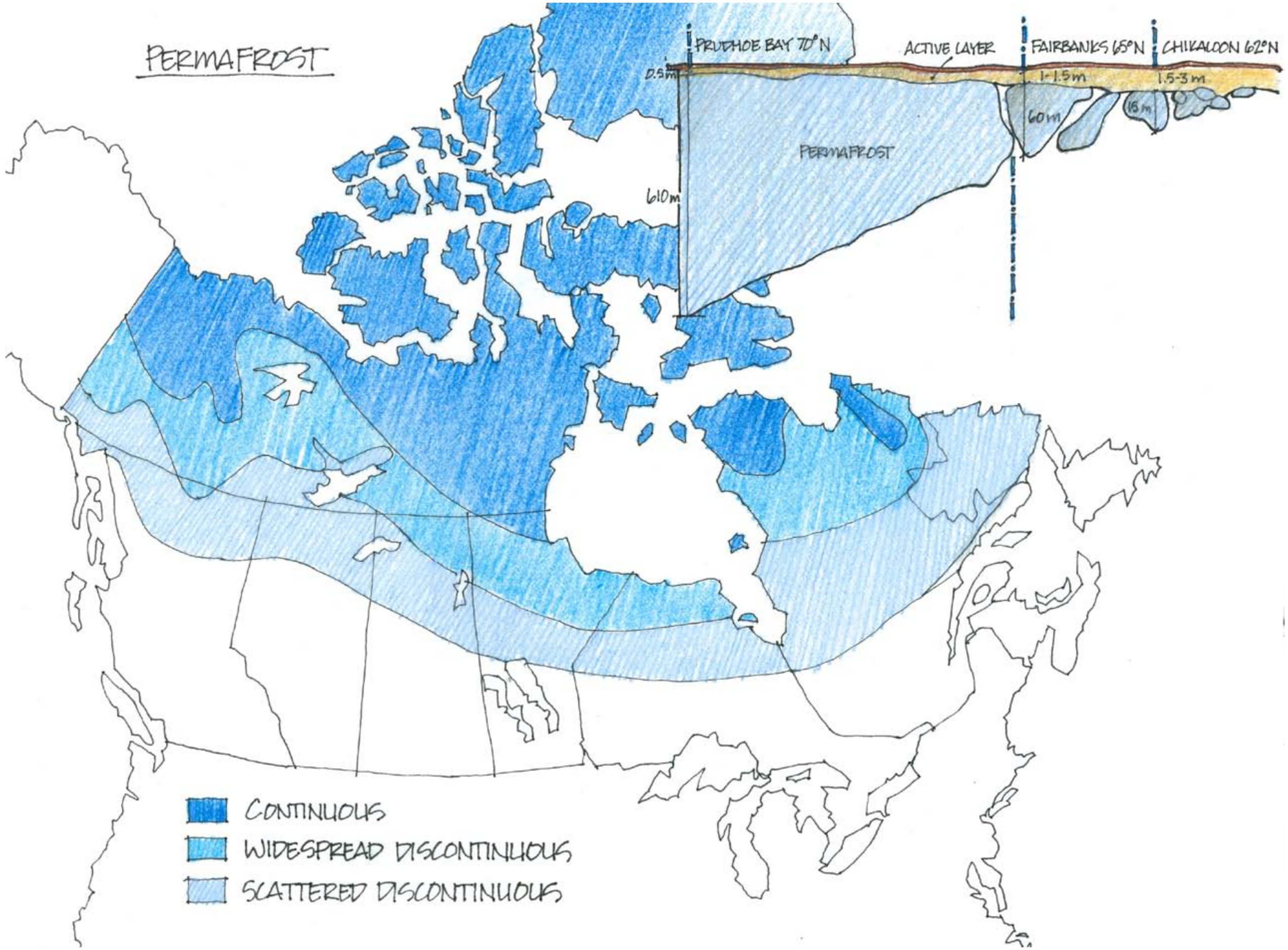


Figure 2.1 Approximate boundaries of discontinuous and continuous permafrost in northern Canada (from Natural Resources Canada, Atlas of Canada Online).

Typical daily evapotranspiration rates in cold regions range from approximately 0.5 – 6 mm with observed annual values ranging from approximately 125 – 475 mm. The growing season in cold regions is typically quite short with low AET rates (~0.5 mm/day) early and late in the growing season. Petrone and Rouse (2000) report that evapotranspiration generally accounts for approximately 50% of precipitation across mainland subarctic and arctic North America (with somewhat lower values among the arctic islands, and higher values during summer in subarctic wetland areas).

2.1 Definition of Active Layer

The upper portion of a soil profile within a cold region that experiences seasonal freeze/thaw cycles is often described as the active layer (see Figure 2.2.). Depending on the geographic location, the active layer can be as shallow as 15 cm in extremely cold climates, to over 1 m in more temperate climates. The thickness of the active layer will vary greatly depending on many influencing factors, including, but not limited to:

- Winter temperatures;
- Summer temperatures;
- Soil and rock type;
- Snow cover;
- Surface vegetation;
- Soil water content and drainage conditions; and
- Aspect to the sun.

In a discontinuous permafrost zone, the active layer may be underlain by either unfrozen or frozen layers (i.e. permafrost) while in the continuous permafrost zone the active layer will typically extend to the top of the permanently frozen layer (the exception to this may be in the vicinity of deep lakes that do not freeze to their entire depth and, consequently, provide a source of heat, which limits the depth of ground frost in the surrounding soil). It is the active layer that is of greatest concern when considering frost action effects. The differences in the active layer and the depth of permafrost profiles moving from continuous to discontinuous permafrost zones are shown in Figure 2.3.

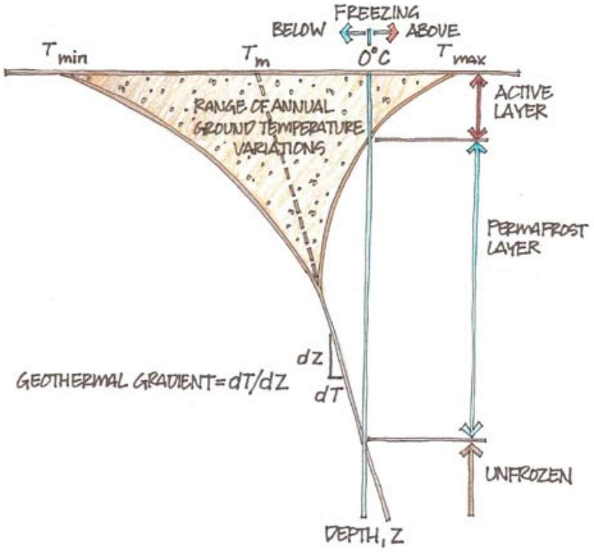


Figure 2.2 Temperature profile and effect on formation of subsurface freezing conditions in perennially frozen soil (from Andersland and Ladanyi, 2004).

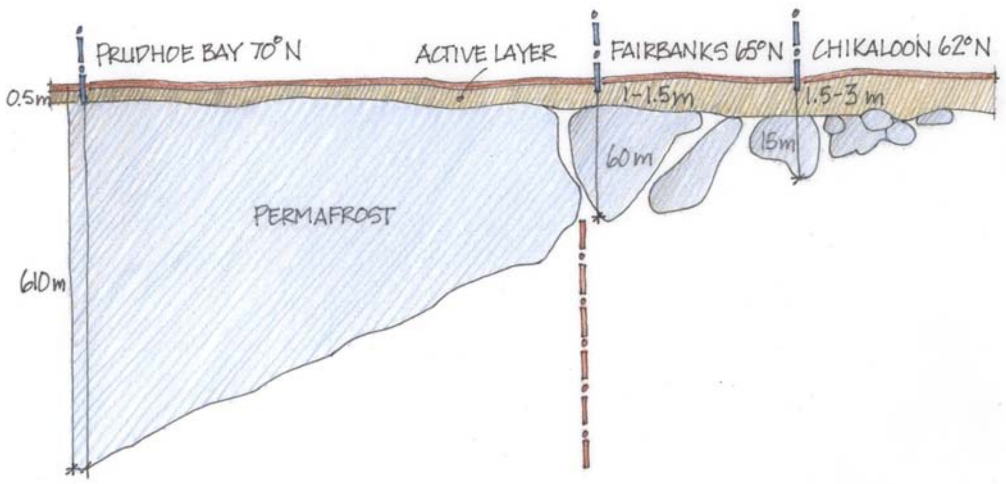


Figure 2.3 Profiles of active layer and permafrost depth moving from continuous to discontinuous permafrost zones.

2.2 Key Attributes of Cold Regions

There is often a surface expression of frozen ground phenomena in cold regions that is not seen in more temperate regions (Washburn, 1973). Common terrain features associated with cold regions include (Figure 2.4):

- Ice wedges,
- Pingos and palsas,
- Thermokarst (see Figure 2.5),
- Patterned ground,
- Boulder fields / pavements,
- Mounds and/or hummocks,
- Mudboils, circles and diapirs, and
- Involutions.

MEND 1.61.5a (2009) includes a description of each of the above terrain features. The significance of frozen ground phenomena for cold regions covers will depend on the time scales under consideration. Unfortunately, much of the periglacial literature focuses on explaining these observed features, with limited reference to their rates of formation. Table 1 in MEND 1.61.5a (2009) outlines the frequency of the periglacial processes occurring in various cold regions, as classified based on altitude and geographic location.

There is a lack of information and research on the topic of how periglacial processes affect various types of engineered cover systems. The potential effect that periglacial processes will have on the design of closure systems for mine waste depends on site-specific conditions such as composition of soil, availability of water, and overall geographic location. The rate at which these effects are generated will vary greatly. The likelihood and potential rates of periglacial processes affecting various types of engineered cover systems is discussed in MEND1.61.5a (2009) and in MEND1.61.5b (2010). Generally, the impacts of periglacial processes on cover systems can be generalized into four categories of impacts, described in the following sections:

1. Frost action / heave;
2. Freeze / thaw effects on hydraulic conductivity;
3. Erosion and slope stability; and
4. Cover material segregation and effects of soil heterogeneity.

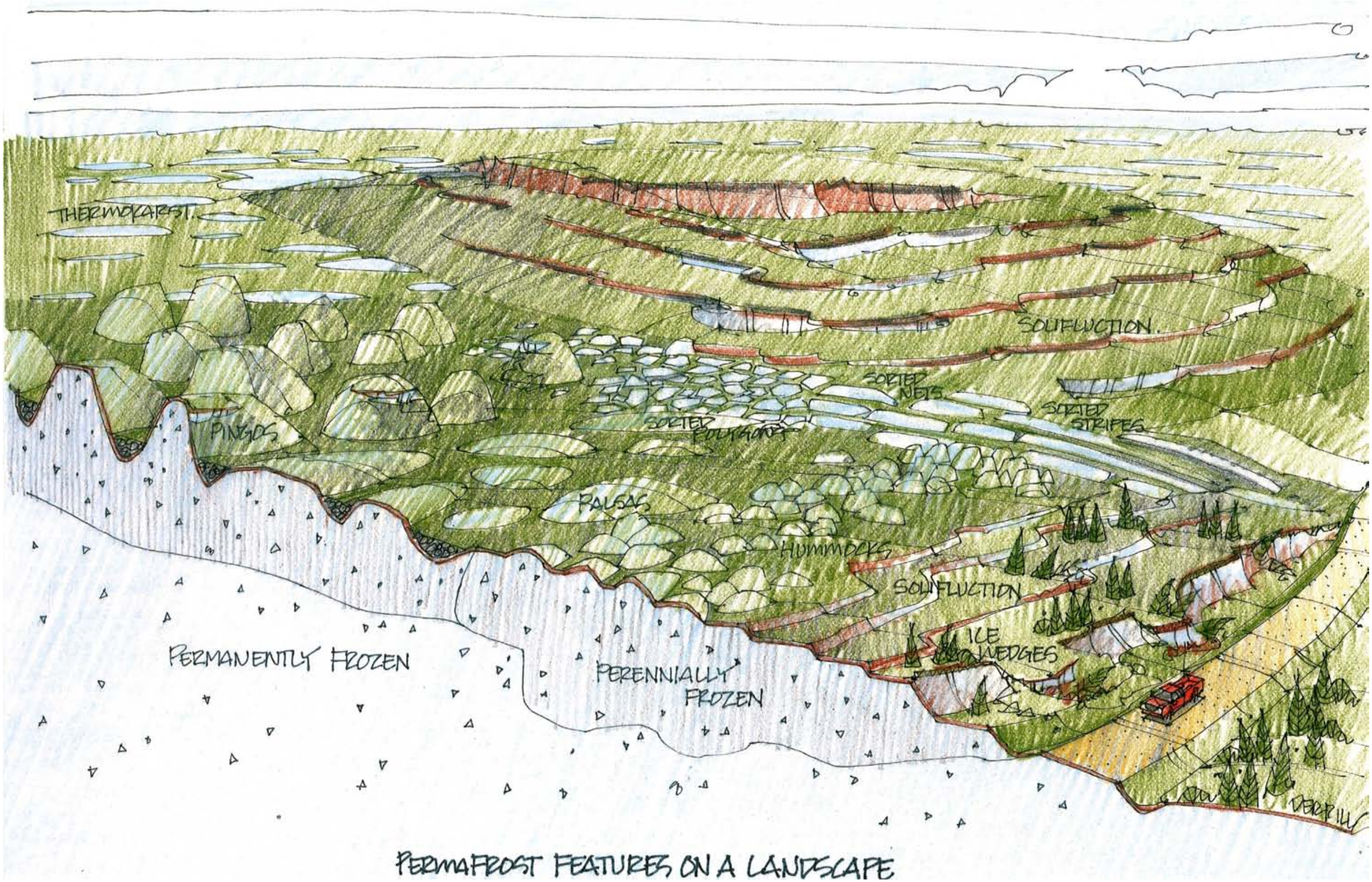


Figure 2.4 Illustration of cold regions phenomena

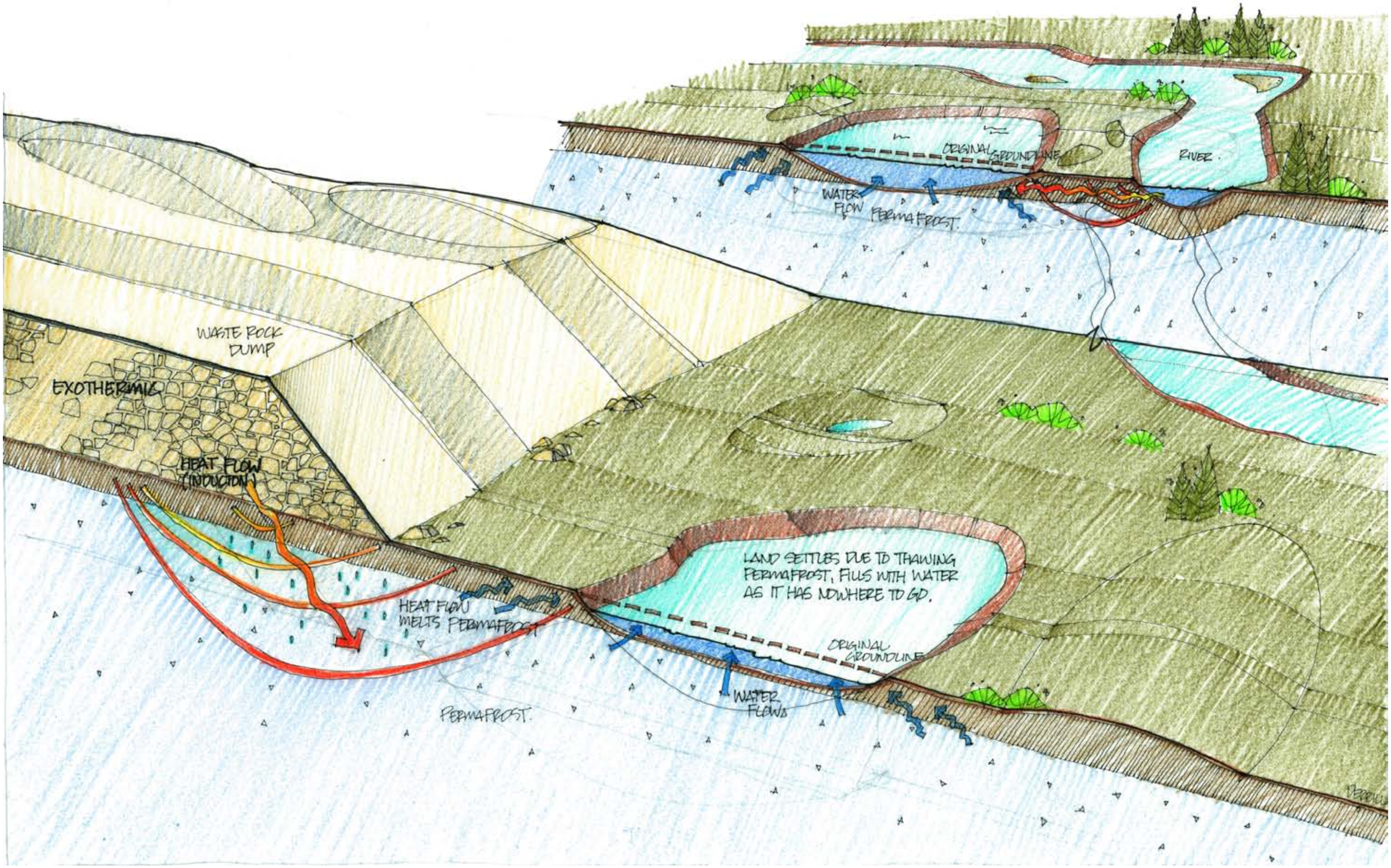


Figure 2.5 Illustration of thermokarst.

2.2.1 Frost Action / Heave

Frost action refers to soil behaviours that are the result of freezing and thawing of water within the soil matrix. One such effect is frost heave, where water accumulates at the freezing front leading to the creation of ice lenses in the subsurface that cause an annual cycle of heave and settlement. Frost heave is experienced to varying degrees at all locations that are considered to be cold regions.

In order to generate frost action, the following conditions need to be present (Bell, 1998):

- Capillary saturation throughout the freezing process;
- A source of water within the subsurface; and
- A soil with high capillarity and moderate permeability (frost susceptible soil).

If these factors are present then the advancing freezing front will slow down as the heat lost to the surface by conduction is balanced by the heat provided by water migration towards the freezing front from below. Negative pore-water pressures are created at the freezing front as water transitions from liquid to solid form and these negative water pressures draw water towards the freezing front. The formation of this stable or slowly advancing freezing front promotes the formation of ice lenses normal to the direction of heat flow in the subsurface resulting in large volume expansion in a soil. The risk for large frost heave is amplified if a water table is located close enough to the freezing front to provide unlimited access to water (i.e. an open system, see below).

The degree to which ice lens formation occurs in a soil is heavily influenced by the availability of unfrozen water beneath the ice lens that is forming. In a freezing soil, the condition by which water migrates to the forming ice lens can be described as either an open or a closed system. In an open system, water can continually migrate to the freezing front from outside the main area of influence, thus creating a larger ice lens. In a closed system, all of the water comes within the area of influence for the freezing front and additional water is not supplied to the ice lens, thereby limiting its growth. An open system creates the largest frost heave in a frost susceptible soil, but can be turned into a closed system by placing a layer of coarse-textured material underneath the soil of concern, thereby limiting the migration of water due to capillarity.

The annual cycle of ice lens formation followed by melting will cause annual cycles of heaving and settlement. Formation of ice lenses can also give rise to what is known as ice wedging in which the ice lenses are formed in a sub-vertical orientation. An ice wedge is a vertical column of pure ice that forms in the soil at the permafrost table, resulting from pore-water freezing in soil cracks and gradually growing larger with time. Formation of large ice wedges can cause surface undulations due to large displacement of soil within the subsurface.

The pressure exerted by a heaving soil varies greatly depending on the freezing processes that occur, and the type of soil under consideration. Estimation of heaving pressures based on empirical relationships is challenging; thus, field studies are typically carried out to determine site-specific heave pressures. Generally, the trends in heaving pressures show a decrease during periods of milder air temperature and an increase during colder periods as larger lenses of ice form (Saetersdal, 1981). Heaving pressures greater than 1,000 kPa can be experienced in regions where deep frost penetration occurs.

Typically, frost heave will only be generated in mine waste or cover systems that are predominantly fine-textured. Frost heave in waste rock piles is generally minimal to nonexistent due to a lack of capillarity and a ready source of water.

If the conditions for formation of ice lenses are not present then the soil will freeze rapidly without formation of ice lenses. In this case, the only volume change that will occur will be that associated with freezing of water within the soil pores. Water will increase in volume by approximately 9% due to freezing. In the case of a saturated soil, this means that total volume change of the soil is only the value of porosity multiplied by 1.09. An exception to this is volume change in tailings. Volume change can occur in tailings due to freeze/thaw cycling that leads to dewatering and consolidation of tailings.

Pingos are an extreme example of frost action. Pingos are created when large mounds of ice form in the subsurface, forcing the ground above the ice to rise above the normal ground surface. The height of pingos can vary greatly depending on freezing conditions, but have been measured to be over 300 m in diameter, 50 m high, and with a soil cover of 3 m overlying pure ice. It has been recorded that in a period of 50 years, a pingo can grow upwards of 10 m in height, at an average volume expansion of 630 m^3/yr (Mackay, 1988).

> ***Frost action affects cover systems by creating cycles of frost heave and settlement (extreme examples are pingos). Fine-textured materials are especially susceptible. Large volume changes to underlying material or cover system material can lead to cover failure.***

2.2.2 Freeze/Thaw Effects on Hydraulic Conductivity

Soil cover systems for mine waste are subject to changes in hydraulic conductivity as a result of freeze/thaw cycling causing changes to soil structure. Even in a soil that is not susceptible to ice lens formation, freezing can lead to formation of macropores created by differential volume change, and soil particle rearrangement/aggregation (Meiers *et al.*, 2011). These macropores create conduits to flow resulting in an increase in hydraulic conductivity. Geosynthetic clay liners (GCLs) may also be susceptible to freeze/thaw cycles—this can occur if they have undergone cation exchange where freeze/thaw may result in changes to the hydraulic conductivity of the clay layer (Adu-Wusu and Yanful, 2006; and Scalia and Benson, 2011).

Studies documented in the literature indicate that a single freeze/thaw cycle can increase the hydraulic conductivity of a soil cover one order of magnitude, creating most of the change that will occur over repeated freeze/thaw cycling (Meiers *et al.*, 2011, MEND 1.61.5a, 2009). Characteristics of the freeze/thaw cycle such as dimensionality of freezing and temperature gradient are factors that influence changes in hydraulic conductivity. The increase in hydraulic conductivity was also found to be inversely proportional to temperature, with the greatest increase in hydraulic conductivity occurring in material subjected to the lowest temperatures. The greatest change was observed over the first few freeze/thaw cycles with subsequent freeze/thaw cycles resulting in relatively little further change in hydraulic conductivity.

Comparison of freeze/thaw test results (Othman and Benson, 1993) shows that an increase in permeability is not consistent in all soil types. Coarser grained materials and those with a higher initial hydraulic conductivity experience minimal effects, whereas clays and materials with low initial hydraulic conductivity experience increases of up to several orders of magnitude.

Placement of a cover system over mine waste that oxidizes and thus generates heat may delay freeze/thaw effects by temporarily reducing the magnitude and depth of the freezing front.

> ***Freeze/thaw cycling affects cover systems by causing changes to soil structure that form macropores and increase hydraulic conductivity. Clays and materials with low initial hydraulic conductivity may experience increases of up to several orders of magnitude, which generally occur over the first few freeze/thaw cycles. GCLs that have undergone cation exchange may also show increases in hydraulic conductivity.***

2.2.3 Erosion and Slope Stability

Additional erosion risks exist in cold regions due to mass wasting. The three main classes of flow-dominated mass wasting are solifluction, skinflows, and bimodal flows (McRoberts and Morgenstern, 1974). Solifluction is the slow movement of non-frozen, saturated soil over the impermeable permafrost layer below. Solifluction includes both frost creep (where particles are lifted by growing ice crystals and then dropped downslope with the ice thaws) and gelifluction (saturated soil flows over a frozen layer). Gelifluction occurs due to the generation of positive pore pressures when the active layer thaws and consolidates. As the active layer thaws, water is released into the soil, and if an underlying layer of permafrost exists, this water will not be able to drain vertically. The presence of high water contents and elevated water pressures within the active layer will increase the potential for slippage/movement of an engineered soil cover system placed on a sloping surface.

Freeze/thaw cycles can cause unpredictable consolidation of material underlying an engineered cover system. As the material thaws and consolidates during periods of warmer temperatures, an increase in pore-water pressures occurs. This increases the risk of slope failure (Bell, 1998). The rate and amount of thaw consolidation has a direct effect on stability of tailings impoundments and development of pore-water pressures. As such, pore-water pressures and rate of consolidation due to freeze/thaw cycles must be monitored.

Placement of mine waste that oxidizes and thus generates heat can also degrade the permafrost layer underlying the impoundment, further increasing consolidation of the soil and most likely leading to negative effects with respect to performance of the impoundment.

> ***The presence of high water contents and elevated water pressures within the active layer will increase the potential for slippage/movement of an engineered soil cover system placed on a sloping surface.***

2.2.4 Cover Material Segregation and Effects of Soil Heterogeneity

Larger diameter particles (i.e. cobbles) can be progressively pushed towards the ground surface as a result of freeze/thaw cycling. This occurs due to the more rapid advance of the freezing front through these larger particles, and the formation of ice lenses below the particles that push them up relative to the surrounding unfrozen soil (MacKay, 1984; French, 2007). This may be of particular concern when using a well-graded till material for a cover system, as the coarser fraction may gradually segregate and move to the surface (Bell, 1998). This effect is most often seen in open freezing systems. The larger diameter materials will form polygons once at the surface due to various forces contributed by the freeze/thaw cycles of the ice. Water can then accumulate in the cracks between the polygons, creating large ice wedges when the water freezes, and thereby increasing crack surface area. This effect is described as patterned ground, in which soil particles of varying sizes are segregated at the surface. Segregation of a cover material has the potential to affect cover performance because of changes to the heterogeneity of the cover and waste material.

Differential frost heave and settlement may occur across a waste storage facility in cold regions. The depth of freezing may vary over the storage facility due to variations in snow cover, water table depth, slope aspect, wind direction, and vegetation growth. Over time, segregation may occur in the materials, which may also affect the freezing depth and lead to differential frost heave and settlement.

> ***Frost action can cause cover material segregation, changing the cover material hydraulic characteristics and potentially resulting in cover failure. Segregation can also enhance differential frost heave and settlement, which can also lead to cover system failure.***

2.3 Considerations for Cover System Design in Cold Regions

There are several overarching factors that dictate how the design objectives of a cover system can be met. These factors include, but are not limited to:

- Climate conditions;
- Cover material characteristics and availability;
- Waste material physical properties and geometry (constructability, settlement, slope stability);
- Waste material chemical properties (toxicity of leachate and cover infiltration criteria);
- Hydrogeologic setting; and
- Site access and constructability.

In addition to these general factors, there are a number of considerations specific for design in cold regions. These may include, but are not limited to:

- The short summer construction season in cold regions will limit the period of access to the site and to construction materials;
- Winter construction will be required due to the short summer construction season. In many cases winter conditions may provide a substantial advantage for construction;
- Cover material availability, particularly fine-textured materials (silts and clays), is often limited in cold regions;
- Locating and reclaiming borrow areas must be considered in light of the challenges associated with processes prevalent in cold regions;
- Short growing seasons in cold regions, as well as substantial runoff during freshet, will result in specific challenges when relying on vegetation to control erosion in the short term;
- Freezing and thawing of cover materials may have an effect on their hydraulic properties resulting in higher infiltration and net percolation rates;
- Design of diversion channels / structures must account for peak flows and ponding caused by glaciation of the channel (i.e. snow and ice within the channel), mound formation, sedimentation, and potential for thermokarst; and
- Freezing of saturated waste (tailings) during placement can lead to locked-in ice or frozen layers and post-cover construction deformation when these degrade.

2.3.1 Key Failure Mechanisms for Cover Systems in Cold Regions

Based on previous experience in dealing with cover systems in cold regions, three key failure mechanisms have been identified by the TAG:

- Shortened construction and vegetative timelines;
- Entrapment of ice layers within deposit; and
- Glaciation of surface water channels.

Due to the shortened growing season in cold regions and resultant effective construction season for earthworks, construction timelines need to be modified from what is typically performed in warmer climates. A shortened field season means less time to move earth or sub-cover material to accommodate the design of the cover system and impoundment as a whole. In addition, the shortened field season correlates to a shorter period to promote vegetative growth, meaning erosion control measures may need to be maintained longer to prevent degradation of the cover and ensure adequate vegetative growth. An illustration of this can be found in Figure 2.6.

Following cover placement, erosion control measures typically include the construction of surface water management swales and channels. During the summer these channels will flow as designed, and in the winter will likely be fully frozen due to sub-zero temperatures. However, in spring and fall, as temperatures fluctuate daily above and below freezing, glaciation of surface water management typically occurs. As temperatures gradually cool in fall, the moving water will freeze in layers, with the slower moving water along the sides of the channel freezing first, while the fast moving water at the centre of the channel continues to flow. As this occurs, the effective channel width will decrease, and may give rise to flow diversion over the top of the channel, causing erosion of the cover material. This effect can also be seen at the point of entry of a fast moving creek into a slow moving portion or a body of water. As the slow moving water will freeze first, the ice can creep up into the fast moving water, forming a wall of ice and blocking the further flow of water. The latter process can result in flow diversion from the fast moving creek. In the spring, similar issues may be observed when slush, ice, and water mixtures flow in the same channel during periods of spring thawing. These mixtures can create blockages in the channels, causing flow diversion and erosion. These processes are illustrated in Figure 2.7.

As tailings are placed in cold regions, a substantial risk exists to entrap ice layers. Due to expansive properties of frozen water, these entrapped frozen materials provide a temporary increase to overall volume of the deposit. As these layers thaw over time, thaw consolidation leads to differential settlement. If reclamation has occurred prior to final thaw settlement, failure of the reclaimed landform can result. This effect is illustrated in Figure 2.8.

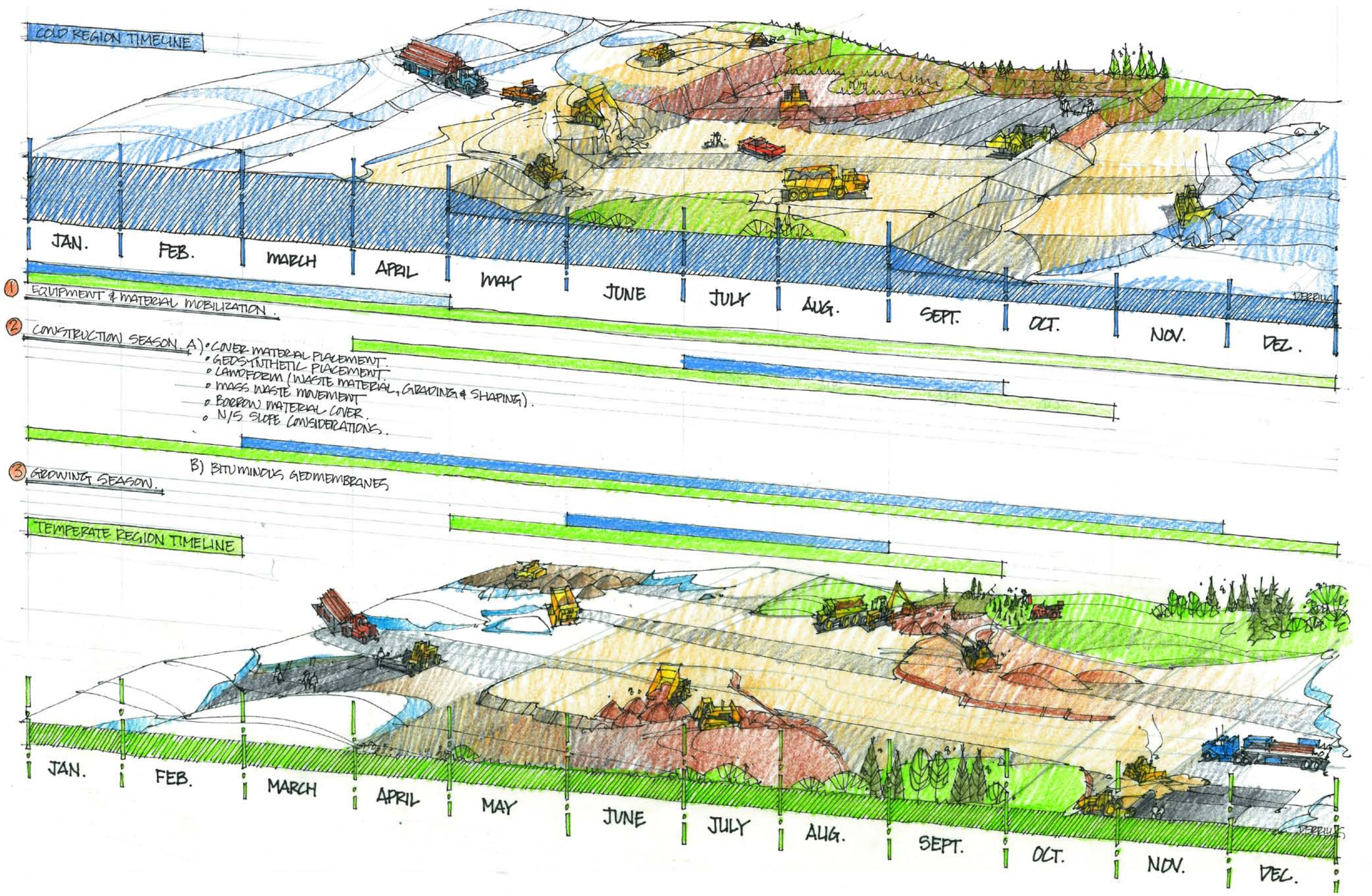


Figure 2.6 Illustration of construction and vegetation timeline for cover systems in cold regions versus that in temperate regions.

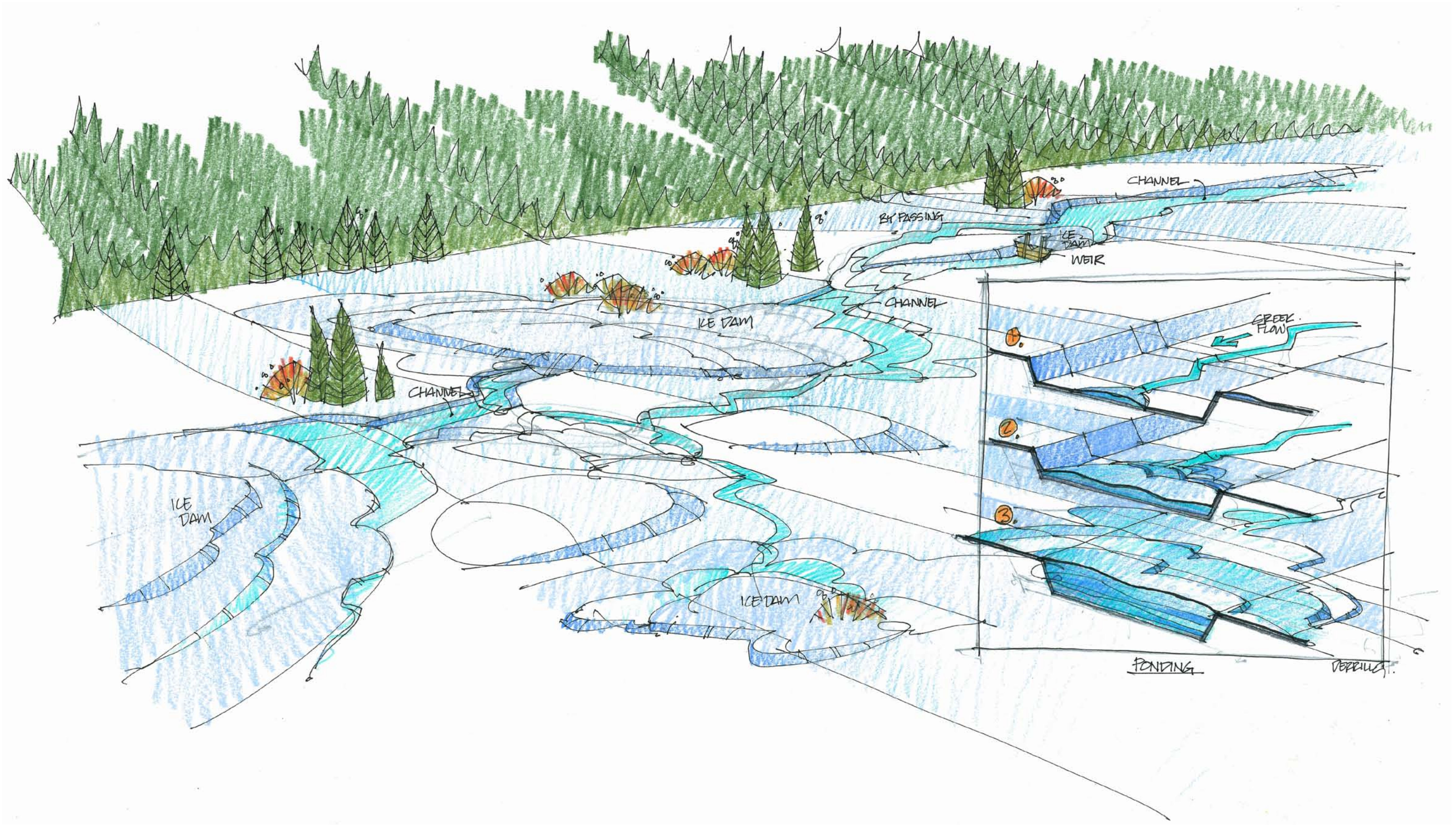


Figure 2.7 Illustration of a key failure mechanism for cover systems in cold regions: glaciation of surface water drainage channels.

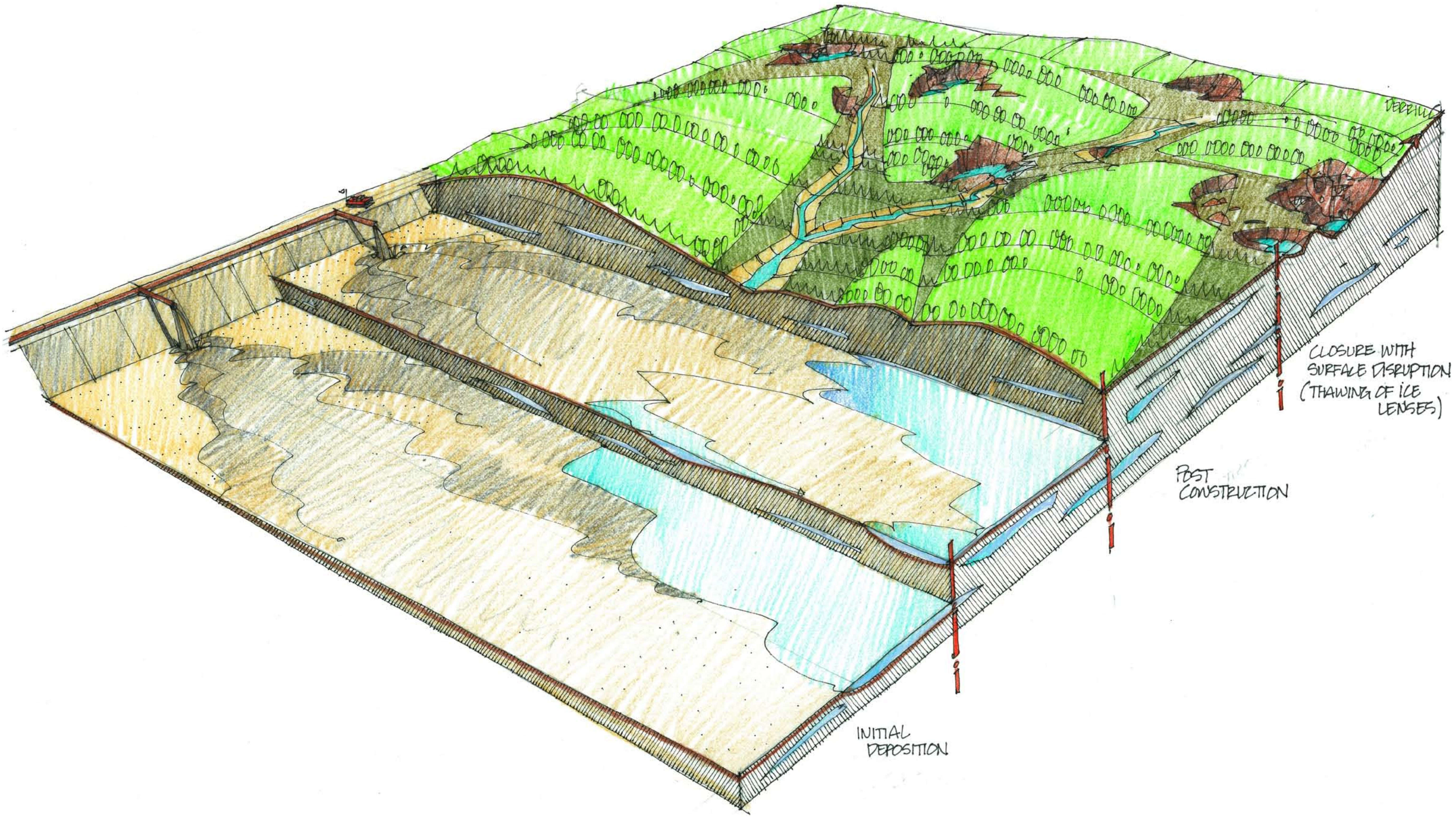


Figure 2.8 Illustration of a key failure mechanism for cover systems in cold regions: locked-in / entrained ice layers leading to failure of final reclaimed landform.

Table 2.1 describes a number of case studies in which freezing processes, and a lack of appreciation for the potential detrimental effects of cold region phenomena, have had an adverse effect on tailings storage facility performance.

Traditionally, the most common soil cover materials utilized as mine waste cover systems have been well-graded, finer textured soils used to create elevated zones of saturation in order to limit oxygen ingress. These conditions are likely to place these covers at risk from frost action under climatic conditions present in cold regions. Mitigation of frost action in a frost-susceptible soil is not feasible in most cases. In order to lower the risk of frost action, the material in question needs to have its frost susceptibility reduced through 'removal' of one of the three key mechanisms contributing to frost action (Section 2.2.1). This might include eliminating potential water sources, lowering the rate of heat loss, or utilization of a non-frost-susceptible soil. These steps might be undertaken independently or in conjunction with each other. However, these methods are not always feasible and may be counter-active to the goals of the cover system for the mine waste.

Table 2.1

Summary of case studies describing failures due to cold region features.

Failure Mechanism	**Result of Failure (MEND 1.61.5a)**
Permafrost degradation beneath reactive waste due to heat generation in waste material	• Subsidence of tailings dam crest (United Keno Hill Mine, YK) • Movement of dump crest and repair requirements post closure (Brewery Creek Mine, Dawson, YK) • Increase in width of talik associated with creek that previously ran through valley (Red Dog Mine, Alaska)
Ice entrainment in mine waste	• Thermokarst topography and differential settlement due to melting of entrained ice (Colomac Mine, Faro Mine, YK) • Reduction in volume available for deposition of tailings due to ice occupying estimated tailings volume (Rabbit Lake Mine, SK)
Convective cooling	• Enhancement of other frozen ground processes which could contribute to detrimental performance (anecdotal evidence at Key Lake Mine, SK) • Cryocentration and explusion of tailings pore fluids is expected at Snap and Diavik
Migration of fines through cover	• Fine tailings covered with a shallow rock layer—boils containing fines formed on surface after 5 years. Required new engineered cover 10 years following deposition, but boils continued to form on surface. A second new cover was placed following another 10-year cycle (Beaverlodge Mine, SK). It was later determined the main cause was high pore pressures combined with freeze/thaw cycles. • 0.3 m silty clay overlain by 0.3 m crushed rock cover had boils form 7 years following deposition, consisting of fine textured material being forced through pore space in crushed rock (Discovery Mine, NT).

3 COVER SYSTEM DESIGN PHILOSOPHY FOR COLD REGIONS

The key closure objectives for most sites are based on the final land-use plan for each area of the mine site and on water quality criteria for receiving environments, where these criteria exist. Key stakeholders, including local communities, should be consulted to determine the preferred use for the various components of a mine site (e.g. open pits, tailings impoundments, waste rock piles, etc.) and any criteria that must be met through closure. The land-use plan must take into account the desired land capability of the rehabilitated area and determine whether this requires waste isolation or waste stabilization to maintain this capability. The cover system design for a mine waste storage facility must also be consistent with the closure objectives for the entire mine site.

Closure criteria specific to each waste storage facility or deposit must be developed once stakeholders agree to the final mine-closure objectives. Key closure criteria may include limits on contaminant loading to surface and groundwater receptors for constituents of concern, design earthquake event for long-term geotechnical stability, acceptable rates of soil erosion, design storm event for the surface water management system, and desired revegetation outcomes. Once these criteria have been defined, a final landform and cover system can be designed to ensure the rehabilitated waste storage facility meets these criteria.

This section discusses the following topics related to cover design philosophy for cold regions:

- Mine closure planning and progressive reclamation;
- Cover system design objectives;
- Utilizing attributes of cold regions;
- Designing for sustainability;
- Importance of final landform design; and
- Design life and assessment period.

3.1 Mine Closure Planning and Progressive Reclamation

Although the focus of this document is abandoned mines, it is important to discuss two important elements that should be implemented for operational mines: mine closure planning and progressive reclamation.

Mine closure planning is a process that involves determining site closure objectives, such as planned final land use, and implementing the processes and steps required to meet those objectives. The closure objectives can be integrated into the mine plan to a much greater extent, more efficiently, and more cost-effectively when closure planning is developed as part of feasibility studies for the potential mine, but at the very least prior to closure (or abandonment) of the mine. This integration may include considerations of segregation of waste streams, stockpiling topsoil and non-reactive overburden, and progressive reclamation.

Progressive reclamation, or reclaiming completed mining landforms during mine operations, allows the operator to amortize closure costs over the life of the mine and allows short-term reclamation performance monitoring during operations. This creates an iterative process by which performance of reclaimed areas is monitored and evaluated while the mine is still operational, so that the final cover system design can be validated and improved. The results of performance monitoring are then integrated into the closure plan and modifications made to optimize design of subsequent reclamation plans. This approach is much more cost-effective than monitoring and re-evaluation of performance solely in the post-closure period.

3.2 Cover System Design Objectives

A cover system is often an integral component of the design required to meet mine closure objectives. The objectives of a cover system may vary from site to site but generally include:

1) Physical stabilization:
    - Provide dust and erosion control, particularly wind and water erosion of waste materials; and
    - Act as a barrier to prevent direct contact of the waste by flora and fauna;
2) Chemical stabilization:
    - Chemical stabilization of mine waste through control of oxygen or water ingress; and
    - Contaminant release control through control of infiltration;
3) Meeting land-use objectives and other societal values:
    - Provide a growth medium for establishment of sustainable vegetation; and
    - Reclaim the area for desired post-closure land uses.

Two key processes are fundamental to both defining and meeting these objectives. These processes are the surface water balance and surface energy balance. The surface water balance is a function of many factors such as climate, soil type, and hydrogeologic setting. Of these factors, the hydrogeologic setting of a waste storage facility exerts a predominant control on the cover system requirements. For example, the location of the final water table has a large influence on predicted amount of net percolation, leaching processes, and oxygen ingress into a waste storage facility. In a setting where the water table interacts with stored waste, leaching (by water and any remnant acidity) will take place regardless of the ability of the cover system to control water infiltration. Therefore, the design of a cover system is highly dependent on the conceptual and detailed understanding of hydrogeologic conditions at the site, leading to an understanding of the surface water balance of the cover system.

In cold regions, the surface water balance and surface energy balance (characterized by the thermal regime) are tightly coupled. Soil-atmosphere water transfers during unfrozen conditions continue to be important (as in the case of temperate climate zones); however, formation and distribution of ground frost has a dominant influence on cover system hydrology in cold regions. As a consequence, it is fundamental to characterize the energy (heat) transfer between the soil (cover materials and underlying waste) and the atmosphere.

Other cold regions climate factors affecting the surface water and energy balances (and thus cover performance) include snow cover, surface radiation, convective heat flow, and evaporation and condensation. The large temperature variability experienced in cold region soils over the short term (seasonal freeze/thaw cycle, thermal regime of active layer) and long term (permafrost, climate change) make understanding the surface energy balance of equal importance to understanding the water balance for effective engineering designs of cover systems in cold regions. Additionally, the spatial variability of engineered landforms in cold regions, including aspect and slope, can substantially enhance climate factors affecting cover system performance (e.g. north- versus south-facing slopes), and highlights the need for accurate understanding of water and energy balances.

The following sections describe in greater detail how each of the three categories of objectives is typically met when designing a cover system.

3.2.1 Physical Stabilization

Dust and erosion of waste materials are minimized by placement of an erosion-resistant material, and/or placement of a layer of material suitable for surface soil stabilization through vegetation establishment. Mulch can be used to temporarily stabilize the surface, especially before vegetation becomes well developed. Alternative controls include placement of gravel to resist wind erosion and coarse rock riprap to resist water erosion. Erosion can also be controlled by selective shaping of the landform or cover surface; for example, hummocks are often used in wet climates to minimize erosion during rainfall events (note that these surface shaping treatments may act in opposition to other cover objectives such as control of infiltration).

3.2.2 Chemical Stabilization

The level of reactivity and buffering capacity of the waste are critical in determining design objectives of the cover system. In general, reactive waste usually dictates that the cover system meets a ‘higher performance expectation’ in order to reduce contaminant releases to acceptable levels (MEND, 2004). In most cases, a ‘higher performance expectation’ implies a low net infiltration rate to the underlying reactive waste material (e.g. less than 5% of annual average precipitation), and/or control of oxygen ingress.

3.2.2.1 Control of Gas Transport

The principal mechanisms contributing to airflow and gas transport in waste piles include diffusion, convection due to thermal gradients, and advection due to wind gradients or barometric pumping. A detailed discussion of gas transport mechanisms is available in GARD (2011) and Wels *et al.* (2003). Figure 3.1 illustrates how interbedded layers of coarse- and fine-textured materials in a waste rock dump can create an environment leading to advective gas transport.

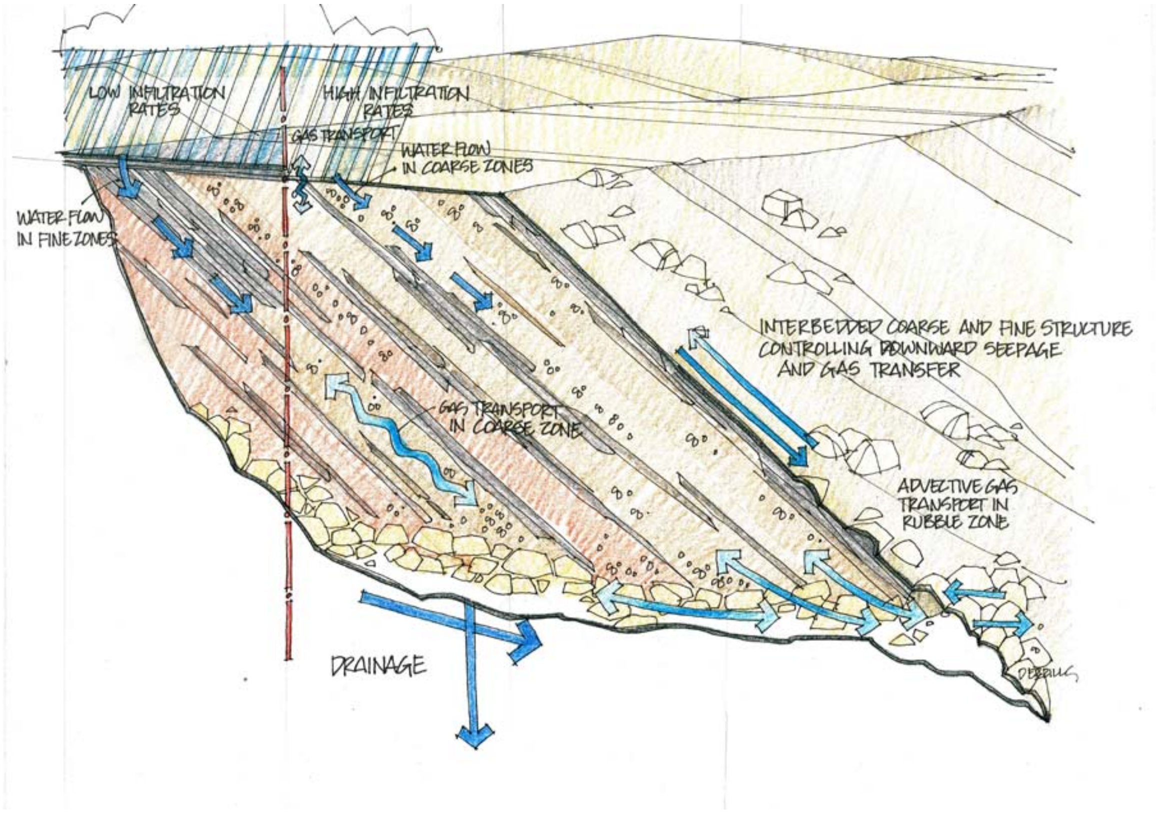


Figure 3.1 Illustration of gas transport within a waste rock pile.

Diffusion

Diffusion typically occurs from concentration gradients created in the waste due to chemical or biological reactions that lead to changes in the concentration of a gas inside the waste material. For example, oxygen concentration gradients are created between the gas phase within the waste and atmospheric air surrounding the waste due to oxygen depletion within the waste. These gradients drive oxygen from the surface to the interior of the waste. The active area for diffusion is usually limited to within a few metres of the air-cover or air-waste interface, whereas convection and barometric pumping can move gas to much greater depths. In waste rock, both diffusive and advective gas flows are typical, whereas diffusion is the predominant mechanism for oxygen flux in tailings because the waste is more reactive and saturation levels limit bulk gas transport (Wels *et al.*, 2003).

The principal mechanism utilized to inhibit oxygen ingress by diffusion is to utilize the low rate of oxygen diffusion through water. This can be obtained through development of saturated conditions within a cover system or use of a surface water cover. In the case of a soil cover, a tension-saturated layer of cover material limits the oxygen diffusion rate into the waste to the rate at which oxygen can diffuse through water; in essence, providing a ‘water’ cover, or a ‘blanket of water’, without the requirement for standing water at surface.

Convection

The differences between the internal temperature of a waste rock pile and that of the surrounding air can lead to thermal convection. The phenomenon is well established for reactive mine rock, where the reactions generate heat. However, it can occur whenever there are temperature differences between the air within the waste and the atmosphere and there is a sloping surface. Recent work has shown that it can also be caused by significant diurnal or seasonal temperature cycles. Water vapour can also be transported by thermal convection.

In many cases, even a simple soil cover can significantly reduce convective transport. This is due to the fact that the cover soil is often finer and at a higher water content than the waste rock, which gives it a substantially lower air permeability.

Sulphide oxidation is a temperature-dependant process. Both chemical and biological oxidation rates decrease with decreasing temperature (MEND 1.61.1., 1997). At freezing temperatures, microbial activity is nearly absent, and chemical oxidation rates are less than 15% of their value at 25 °C. However, it should be noted that biological and chemical reaction rates associated with sulphide oxidation are merely reduced in cold regions, they are not necessarily absent. It should also be noted that the heat of these oxidation reactions can generate and maintain temperatures internal to reactive waste deposits that greatly exceed atmospheric temperatures, even in winter months.

Advection

Advective gas transport can occur as a result of ‘barometric pumping’ or due to pressure gradients caused by wind. Barometric pumping is the movement of air in and out of the ground in response to cycles of atmospheric pressure. Barometric pumping is the movement of air in and out of the ground in response to cycles of atmospheric pressure as the volume of air within the waste rock compresses and then expands during cycles of increasing and then decreasing atmospheric pressure. However, recent work on reactive waste rock has suggested that thermal convection is the more predominant mechanism of gas movement (Hockley *et al.*, 2009; Phillip *et al.*, 2009).

3.2.2.2 Control of Net Percolation

Limiting net percolation of water into waste is generally achieved by one of three methods:

1) **Barrier layer –** a layer of the cover system may be constructed from materials with a sufficiently low hydraulic conductivity so as to limit downward percolation of rainfall or snowmelt. This water is then stored in the growth medium layer for subsequent removal via evapotranspiration or is 'released' as surface runoff or interflow.
2) **Frozen barrier –** a variation of the barrier type of cover system available in cold climates is to permanently freeze waste so that it creates a low hydraulic conductivity barrier to water flow. Alternatively, a layered cover system could be engineered such that a seasonally frozen lower layer of elevated saturation is maintained during the spring freshet so that waters infiltrating into a thawed active layer are diverted away from the underlying waste as interflow and/or runoff. This was described by Barbour (2011) as a seasonally frozen capillary break diversion (SFCBD) cover system.
3) **Store-and-release –** infiltrating water is stored within the rooting zone of the cover so that it can be subsequently released via evapotranspiration. In these types of covers, the objective is to minimize deep percolation by returning most of the infiltrating waters to the atmosphere.

For all three methods of controlling infiltration, local climatic conditions play a major role in what type of cover system is feasible.

3.2.3 Meeting Land-Use Objectives and Societal Values

Aside from physical and chemical stabilization of the waste, the cover system must also meet the final land-use objectives and satisfy other societal values. Land-use objectives for reclaimed areas in cold regions are typically re-establishing the pre-mining ecosystems and land-uses. These may be forests, grasslands, tundra, wetlands etc., with associated uses of wildlife habitat, traditional use by Aboriginal communities, and/or commercial forest harvest in some areas. Another land-use objective may be to establish recreational areas or parks.

3.3 Utilizing Attributes of Cold Regions

Historically, some cold region cover systems have been designed based on experience and technologies developed for temperate regions, without a thorough evaluation of the effect that cold region climatic conditions may have on performance. These effects can often be detrimental; however, there is also potential to utilize the unique climatic and geologic setting inherent to cold regions to advantage. Key attributes of the cold regions pertinent to the design of a mine waste cover system include:

- Low precipitation relative to most other parts of Canada, with a large fraction of water delivery supplied as melt during a few short weeks in spring;

- High actual evapotranspiration (AET) rates (relative to precipitation) during the summer months due to warm temperatures and long daylight hours;
- Prolonged, cooler temperatures during the winter months, which can result in deeper frost penetration;
- Relatively coarse-textured soils, which are less susceptible to frost action and may be suitable for capillary break layers, and a corresponding frequent scarcity of fine-textured materials for construction of durable barrier layers;
- High runoff coefficients in the spring when only the upper surface has thawed and deeper infiltration is impeded by frozen ground; and
- Surfaces covered by snow and ice most of the year, thus limiting exposure.

Designers need to consider both opportunities that these attributes offer as well as constraints they place on design, by incorporating elements such as the following into a cold region cover system design.

1) Divert snowmelt waters to the greatest extent possible by incorporating topographic relief, naturally frozen ground, and/or an engineered SFCBD cover system in the final landform design.
2) Maximize AET rates during the summer months by establishing vigorous vegetation cover systems, and by supporting this vegetation with sufficient soil water storage. Vegetation establishment and subsequent water removal can be enhanced by:
    - incorporating organics or fine-textured mineral materials, where available, in the upper cover profile;
    - designing sufficient depth of the upper profile to store water and appreciably reduce seasonal moisture deficits (reduce the difference between potential and actual evapotranspiration); and
    - incorporating textural discontinuities (multiple layers) in the upper profile, where possible, to retard vertical drainage of soil water, thereby increasing effective storage during the growing season.
3) Take advantage of the increased role slope and aspect can play in the energy and water balances. For example, slopes with different aspects have large differences in energy balances, which may encourage different reclamation techniques for the same closure landform.
4) Encourage deep freezing of the waste material where possible to minimize percolation of meteoric waters through the waste material.

3.4 Designing for Longevity

Ideally, closure of a mine waste storage facility should generate a 'walk-away' (permanent) solution. However, as with all engineering, and in particular with mine waste management, elements of a closure plan are subject to failure and consequently have a fixed lifespan. To design a cover system to maximize longevity means incorporating an 'engineered' structure into the landscape in a way that is sustainable over the long term.

It is also important to understand that mining results in disturbance of the land. The two most important disturbances associated with the closure of a mine site are those associated with water balance (hydrological disturbance) and energy balance (thermal disturbance). The mining activity, as well as the construction of the mine closure design, creates landforms that are no longer in equilibrium with the surrounding environment. This creates a state of both hydrological and thermal disequilibrium. The designer must address the implications that re-establishment of equilibrium conditions may have on the performance of closure landforms, a process which, in permafrost regions, may take hundreds of years.

3.4.1 Landform Design

Evaluating a structure within the landscape is often called landform design. Landform design is a fundamental consideration when designing cover systems for waste storage facilities located in cold regions. Poor surface water management and landform instability are common factors leading to failure of cover systems around the world (MEND 2.21.4, 2004). Many potential failure modes result from a design approach that attempts to build engineered structures to oppose natural processes rather than developing engineered systems based on natural analogues that integrate rapidly with the hydrology and ecosystem of the surrounding setting (Ayres *et al.*, 2006).

The final landform design (including the cover system) depends greatly on the mine closure objectives established by the stakeholders. Generally, the reclaimed landscape must be returned to a productive land use. Examples include wildlife habitat, traditional uses by aboriginal communities, and commercial forestry. Successful reclamation will not 'restore' a landscape but rather provide conditions for a landscape to 'develop' towards a capability equivalent to that existing prior to mining (MEND 2.21.5, 2007). The priorities of general landform design are to create a stable landform, and have the landform meet slope and shape criteria determined by the land-capability requirement. After these criteria are met, additional details can be incorporated, such as the cover system and drainage channels.

Landscape design is dependent on numerous factors, including climate, geology, soils, local hydrogeologic patterns, topography and final land use (MEND 2.21.5, 2007). A large challenge concerning landform design is the objective of long term sustainability; design timeframes may be in the order of hundreds of years. The changes that will occur during this period are difficult to predict and quantify, yet will affect the system. Processes that affect the evolution of a system can be grouped into physical, chemical, and biological categories, and each will affect the landform differently over time (see Figure 3.2). MEND 2.21.5 (2007) describes a design methodology for developing a sustainable final landform.

The longevity of a landform (including the cover system) should be evaluated in relation to site-specific physical (including thermal), biological, and chemical processes that will alter as-built performance and determine long-term performance (INAP, 2003). It is noted, however, that in many respects the effect of biological and chemical processes specific to a site on long-term cover system performance can only be evaluated from a qualitative perspective. In contrast, many of the physical processes affecting long-term performance are quantifiable using state-of-the-art technology, provided that adequate materials characterization data are available. Recent reviews based on 10 to 15 years of cover system performance data indicate that cover systems may limit, but do not stop, infiltration and sulphide oxidation (Wilson, 2008; Wilson *et al.*, 2003; and Taylor *et al.*, 2003). However, the achieved reduction in oxidation (and attendant ARD and metal/element leaching) may be sufficient to meet design goals and at a minimum would reduce water treatment requirements.

One of the most common failure modes of cover systems in general, and for cover systems in cold regions in particular, is the failure of the surface water management system to safely convey runoff off of the landform. Settlement of the cover surface resulting from consolidation of the underlying waste, usually tailings, is a key factor influencing sustainable performance of the surface water management system.

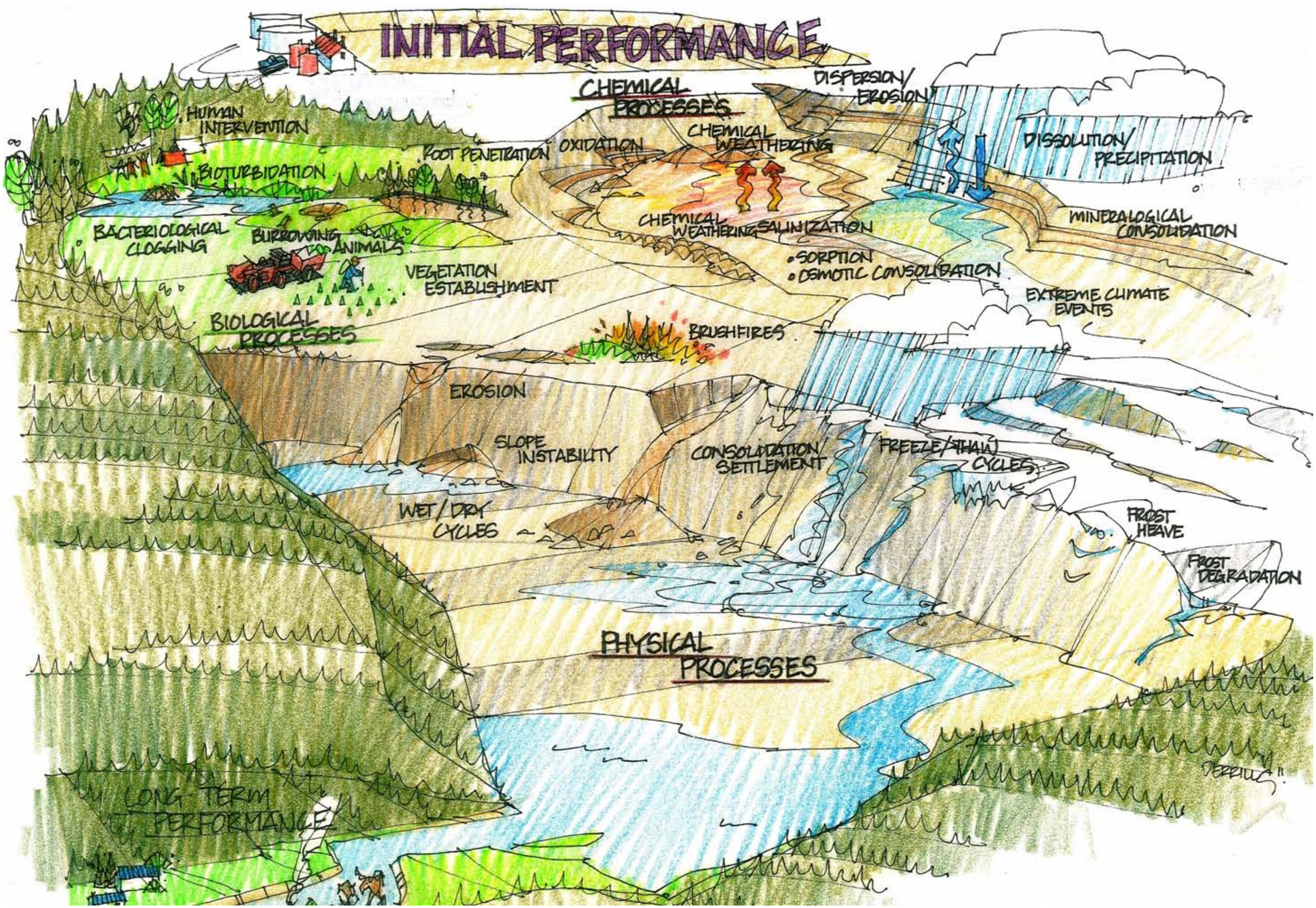


Figure 3.2 Conceptual illustration of processes affecting long-term performance of cover systems in cold regions.

3.4.2 Assessment Period and Design Life

Cover system design practitioners, through consultation with AANDC and regulatory agencies, must determine an appropriate lifespan for the cover system design alternatives for each site. Cold regions, in general, have a lower human population density, thus making most mine sites more remote from human centres than in warmer climates. Therefore, the opportunity to perform long-term monitoring is limited and long-term risks are more difficult to manage. Much of the cost of reclamation in remote areas (25 – 40%) can be mobilization of equipment and materials; thus, any repair required due to reclamation failure is of significant economic consequence. For this reason alone, the design life for a cold region site should be longer than that typically used for sites in temperate regions.

The design life of a product or structure is the period of time during which the item is expected by its designers to work within its specified parameters; in other words, the life expectancy of the item. For example, man-made products such as HDPE geomembrane liners and reinforced concrete spillways have a specified design life. To the extent possible, components of a closure plan for a mine waste storage facility should have a design life that exceeds the design life of the closure plan. This should not preclude use of man-made products to meet design goals for timeframes less than the design life.

It is recommended that cover systems be designed using a minimum 100-year design life. However, the design itself must be evaluated on a site-specific basis using a risk-based approach, which in this document is the Failure Modes and Effects Analysis (see Section 6.6.1).

Examples of developing a design for an operating life of 100 years include, but are not limited to:

- Utilizing a site-specific 100-year climate database (if available) for predicting cover system performance (annual net percolation rates, cumulative erosion, etc.);
- Understanding the potential for change in cover material properties on a 100-year basis;
- Understanding evolution of the waste material and/or contaminant source(s) (e.g. tailings pore-water and by-products of ARD in waste rock) on a 100-year basis;
- Evaluating performance of man-made materials (e.g. concrete, geosynthetic liners) on a 100-year basis;
- Specifying a thickness of the cover system that accounts for erosion over a 100-year period;
- Evaluating the potential effect of climate changes over 100 years; and
- Incorporating expected evolution of the vegetation community and its effect on performance over a 100-year basis.

3.4.3 Climate Change

Climate change refers to a change in the state of the climate that can be identified (e.g. by using statistical tests) by changes in the mean and/or variability of its properties and that persists for an extended period, typically decades or longer (IPCC, 2007). Climate change excludes fluctuations in climate over periods shorter than a few decades (e.g. El Niño).

Climate change could potentially have large impacts on cover system performance and longevity (see Figure 3.3). However, climate change (especially with respect to precipitation) is difficult to predict with certainty, due to the large number of factors affecting climate, referred to as 'forcing mechanisms'. Forcing mechanisms include natural internal processes and external forcings, but the largest and most variable of these mechanisms are anthropogenic factors (i.e. human activities which affect the climate).

MEND 1.61.7 (2011) describes the potential impacts that climate change may have on Canadian mine sites—specifically those related to ARD. These impacts include those related to the activities and infrastructure used to minimize ARD processes or the release of contaminants to the environment, such as cover systems. According to MEND 1.61.7 (2011), the temperature increases in Canada over the past century were approximately double the global average and Canada as a whole is expected to continue warming at 1.5 times the global average. The arctic is expected to warm at a rate of up to 3 times the global average, which is a trend described as polar amplification.

The Intergovernmental Panel on Climate Change (IPCC) prepared the 'Special Report on Emissions Scenarios' (SRES) in 2000 (IPCC, 2000). The SRES report defines 40 different emissions scenarios, each making different assumptions for future greenhouse gas pollution, land-use and other driving forces. These scenarios are commonly referred to as the SRES scenarios and are used as inputs in climate models predicting future climate changes.

There are numerous climate models worldwide that implement the SRES scenarios for predicting future climate change. For Canada, the Canadian Centre for Climate Modelling and Analysis (CCCMA) provides regional climate change predictions based on the SRES scenarios on its website (Environment Canada, 2011). These predicted changes in climate can then be used to adjust an historic climate database prepared for a given site so that it accounts for various SRES scenarios. A cover system can then be simulated with the application of various climate databases, adjusted using different SRES scenarios, to model how climate change will affect long-term performance of the cover system.

Global warming over a 100-year period should be addressed in each cover system design developed for cold regions.

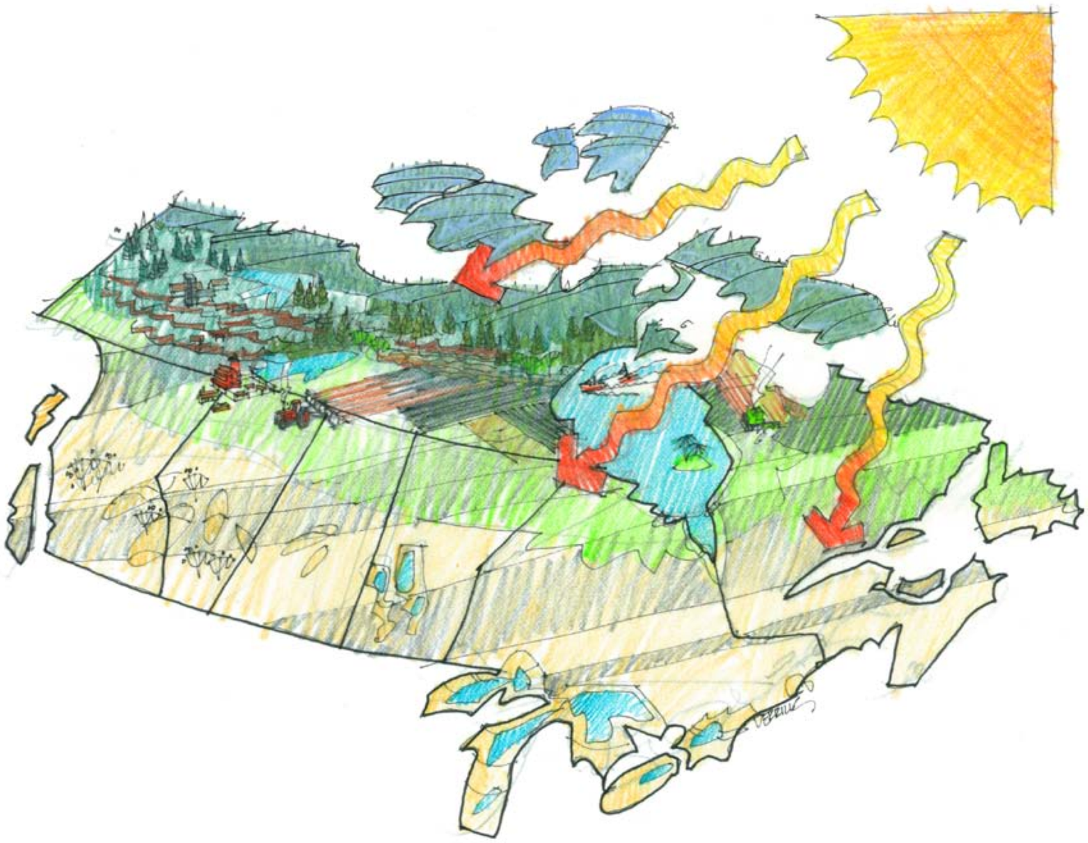


Figure 3.3 Potential influence of climate change on future cold regions climates.

3.5 Revegetation in Cold Regions

Establishment of vegetation is often included as a criterion for closure. The purpose of the vegetative cover system may include erosion control, enhancement of evapotranspiration as part of a store-and-release cover system, re-establishment of sustainable ecosystems, satisfaction of requirements for post-closure land use, including regulatory requirements, and visual appeal. The overall performance of a vegetation cover in meeting these objectives is dependent on the vegetation cover density, the species composition, and the depth and quality of available rooting-zone materials.

Generally, a diverse vegetation community that mimics or replicates the existing native communities in the surrounding area will provide the best long-term cover performance. More specifically, a cover system revegetation plan should provide for establishment of initial plant communities using available species that are tolerant of drought, extreme (low or high) soil pH, and low nutrient availability (under conditions of limited cover organic matter content). In some cases, plant selection will also have to include species tolerant to the presence of elevated salts, metals, or other constituents within the rooting zone (MEND 2.21.4, 2004). Reclamation revegetation plans should include a diversity of plant species to increase the probability of successful revegetation (even if some of the included species do not thrive), to provide resilience against pests and climatic extremes, and should allow for the evolution of a mature vegetation community similar to those found in adjacent ecosystems (Peters, 1988).

Establishment of vegetation is generally more challenging on reclaimed sites in cold climates than in warmer regions, as short frost-free periods restrict the window for revegetation activities, the rate of vegetation establishment, and the range of plant species capable of colonizing and persisting on a site. Primary challenges in cold region revegetation include:

1) *Species selection and availability*—historically, agronomic grass/legume mixes have been used extensively in mine reclamation in broadcast seeding applications due to the rapid establishment and growth of these species, to their widespread availability and low cost, and to the resulting cost-efficacy of large-scale reclamation with this technique. However, in many cold region reclamation projects, this agronomic-based approach may not be viable, as:
    a) short growing seasons prevent successful seed-set (reproduction) of these temperate-adapted species and thus limit their long-term persistence and sustainability on site; and
    b) their use may not be desired by stakeholders, due to biodiversity (the desire to prevent colonization by non-native species) and/or habitat and end land-use considerations. Many jurisdictions encourage or require the use of local or native species to ensure ecological continuity with surrounding areas and to minimize care and maintenance.

    As a result, vegetation species selection for reclamation in cold regions is often restricted to those species native to the local area or region. Use of these cold region species for reclamation programs is not well developed, and technology and capacity for their seed increase (for generating supply for broadcast seed applications) or propagation (for production of container-seedling stock for planting programs) is limited or non-existent. In addition, experience indicates that many revegetation techniques that can be successful in temperate climates, such as planting of non-rooted cuttings, may be less successful in cold regions. This means that reclamation practitioners are often forced to develop project-specific capacity for revegetation, which can limit the rate at which reclamation revegetation programs can be conducted, can increase costs of revegetation, and can reduce overall success in comparison to temperate-region projects.

    Generally, propagation techniques for large woody species (coniferous and deciduous trees and common shrub species such as willow, birch, and alder) are well known. Rapid and large-scale nursery production of container seedlings of these species should be feasible and successful, and can be conducted at off-site facilities with more developed infrastructure. Incorporation of less common native woody species and herbaceous plants (grasses and forbs) into a revegetation program would involve more investment and development to bring to operational-scale feasibility.

Because of these considerations, cold region revegetation projects require more lead time from design to implementation. Planning for revegetation and sourcing of vegetation materials should begin at project commencement, rather than assuming that these activities can be delayed until the project nears readiness for revegetation. If revegetation planning includes use of local species (either as seed or container seedlings), work should commence to ensure their availability for reclamation, including collaborative or project-specific seed and stock development programs. Where possible, and where more unconventional revegetation treatments are planned / desired, field trials and progressive reclamation should be incorporated into the reclamation program to allow time for development and adjustment of revegetation techniques.

2) *Rate of vegetation establishment*—in addition to climatic factors that reduce growing-season length and thus the period of active establishment and growth of vegetation, many native species that may be used in cold region revegetation projects are not adapted for rapid establishment. Even native species that may be commercially available as seed, and thus potentially incorporated into broadcast seed treatments (e.g. native grasses such as wheatgrass, hairgrass, fescue, etc.), are slower to establish than agronomic grasses and legumes, and establishment of substantial vegetation cover through seeding of non-commercial species or planting of container seedlings will be slower still. Thus, the contribution of vegetation to meeting primary cover objectives (e.g. reducing net percolation through transpiration, erosion control) will be delayed and may take years to fully manifest. Depending on vegetation type and surficial materials in the cover, establishment can take from one to five or more growing seasons. Use of plant species that have rapid establishment and that form continuous ground covers (e.g. sod-forming grasses) or dense vegetation establishment (e.g. planting densities of over 5,000 stems per hectare) will generally reduce the timeframe over which vegetation effects become operative, while use of slower-growing vegetation will provide less initial benefit. This is particularly an issue on sites or areas of sites where surface erosion is a concern. Although one objective of revegetation may be erosion control, the bulk of erosion may occur prior to vegetation becoming an effective control mechanism. This could be a failure mode for the cover system if the longer revegetation times in cold regions are not explicitly incorporated into cover system design. It should be noted that treatments designed to ensure rapid vegetation establishment for erosion control, particularly the use of sod-forming grasses, can delay or prevent ingress of native species and vegetation succession, due to competitive exclusion. Thus their use should be carefully balanced with other site objectives.

3) *Material availability*—in cold regions, where soil development processes both occur slowly and may have been occurring over only a limited time, there may be restricted (or negligible) availability of suitable materials for the surface growth medium layer of a cover system. This restriction may be exacerbated in reclamation of historic operations, where retention of growth medium materials may not have been an operational priority, and where these materials may now be buried under and/or incorporated into waste deposits. Available overburden, soil, and/or borrow materials for potential use in reclamation in cold regions are frequently coarse-textured (with high coarse fragment contents and/or sandy fine fraction textures)—although local vegetation is adapted to these substrates, reduced soil water and nutrient retention may contribute to slow vegetation establishment and growth and accentuate the challenges discussed in item 2, above. In addition, sourcing of materials for construction of a growth medium layer may require new disturbance, and the benefits and liabilities of this disturbance need to be carefully evaluated, particularly in light of slow recovery/revegetation processes in cold regions (for further discussion of availability of cover materials, see Section 6.8.1).

   If reclamation suitable material volumes are limited, this may mean that growth medium layers are not possible on some covers, that materials in these layers will be of less-than-ideal quality, and/or that growth medium layers will be thinner than would be specified if material-availability limitations were removed. These modifications can produce further limitations in water and nutrient availability for revegetation and, where a root-impermeable layer is not used to separate the growth medium layer of the cover from underlying waste, can expose vegetation to waste constituents such as salts and/or metals. This may further limit success of revegetation programs, necessitate the use of species adapted to very specialized niches (e.g. saline substrates), and may expose other environmental receptors (i.e. wildlife consuming vegetation) to waste constituents.

   These considerations of growth medium availability emphasize the importance of integrating growth medium requirements into the overall cover system design and associated material balance, rather than assuming that growth medium layers can be constructed out of remaining local material once volumes for geotechnical requirements have been met. The revegetation design is likely to involve iteration between site closure / cover system design objectives and material availability to produce a final design that meets objectives while incorporating material constraints.

The above three challenges are additive and interactive and must all be addressed by the cover system design team.

Vegetation can interact with other aspects / components of cover systems in a number of ways. For instance, dense vegetation with well established root systems can substantially change cover water balances through transpiration but can also create soil macropores that enhance infiltration.

Dense, above-ground plant biomass can act to reduce the velocity of surface runoff and wind, decreasing surface erosion, but may also eventually contribute to cover perturbation through senescence, burning, toppling, etc.

One factor that arises in some mine closure projects is the objective of limiting or prohibiting revegetation of covers. This objective is usually discussed for two reasons:

1) Vegetation, or some types of vegetation, is not desired for engineering reasons—due to the desire to maintain an easily inspected cover system and/or to prevent cover system degradation through rooting, windfall, etc.; and/or
2) Vegetation is not desired for stakeholder reasons—due to concerns that vegetation growing on reclaimed sites will take up contaminants and transfer these contaminants to wildlife.

There may be some cases of mine closure in cold regions where revegetation is simply not likely or not appropriate (e.g. when surrounding ecosystems are restricted to crustose lichens growing on blockfields). In these cases, vegetation will not contribute to cover system function, and what revegetation will occur can be left to natural processes of recolonization, perhaps over hundreds of years. However, in many cases, vegetation *will* recolonize sites unless actively and perpetually prevented from doing so. In these cases, it may be preferable to incorporate revegetation treatments as an active component of closure planning, rather than expecting that recolonization can be prevented in perpetuity. As a specific example, shallow-rooting plant communities are often thought to be preferable for cover systems that include some sort of ‘barrier’ layer, so that rooting will not disrupt the integrity of the cover system. Hence, grasses and shrubs are often used to vegetate the surface of a cover system. However, consideration should be given to expected vegetation dynamics over time on a reclaimed site (‘succession’), and whether desired plant communities can be maintained without excessive maintenance over the cover design life.

Rooting depth is dependent on a number of edaphic factors, such as material texture, nutrient and moisture availability, the presence of root restricting layers (e.g. impermeable mineral layers, ice, water tables), as well as on vegetation type. A comparison of maximum rooting depths for northern ecosystems indicates that in tundra ecosystems, the mean maximum rooting depth is ~0.5 m (likely often restricted by permafrost), with maximum observed values of approximately 1 m. In contrast, for tree species characteristic of boreal forest ecosystems, the mean maximum reported rooting depth is ~2 m, with a maximum value of over 3 m. Agronomic forbs can achieve rooting depths similar to those of trees, with maximum values typically between 1 and 3 m. Note that even when deep rooting is observed, the majority of plant roots remain in the upper 0.5 m or less of the soil profile. However, in most cases, even where cover depths exist to meet average plant moisture demands, roots may extend deeper during anomalous drought periods. Thus, designing a cover system to prohibit, rather than reduce, root presence at the cover-waste interface is difficult and may require volumes of material in excess of those locally available. The most effective way to reduce rooting at this interface is through the presence of a drier (coarser) or permanently frozen underlying layer.

Where stakeholder concern over contaminated vegetation / wildlife is an issue, this issue should be evaluated in the context of other cover system design objectives such as water removal through transpiration. When designed properly, vegetation established on covered waste deposits will have low contaminant uptake, and in many cases will have concentrations of elements of concern indistinguishable from or lower than surrounding ecosystems. This is due to the presence of naturally mineralized surficial materials in these ecosystems, or, in the case of many abandoned mine sites, to a history of fugitive dust emissions during and following mine operations.

3.6 Critical Factors Affecting Cover System Performance in Cold Regions

There are five critical factors that affect cover system performance in cold regions:

- Frost action,
- Slope / aspect,
- Water availability (precipitation vs. potential evaporation/evapotranspiration),
- Vegetation, and
- Available cover material.

All of the factors noted above are interrelated. For instance, slope / aspect, water availability, vegetation, and cover material all affect frost depth at a particular location. Similarly, vegetation at a given location is affected by frost depth, slope / aspect, water availability, and the cover material. Despite these factors being interrelated, they must be considered individually when evaluating cover system performance.

Frost action is discussed in Section 2.2.1, while revegetation pertaining to cold regions is reviewed in Section 3.5. The following sections give background information on the additional issues of slope / aspect, water availability, and cover material, which are factors that affect cover performance in all climates, but need specific consideration in cold regions.

3.6.1 Slope / Aspect

As part of designing a cover system on a landform, consideration must be made for the resulting slope angles and slope aspects. The surface water balance changes substantially when slopes are introduced—runoff, run-on, interflow, seepage, evapotranspiration, and net percolation rates are all directly or indirectly influenced by the slope of the cover system. The surface energy balance is also affected by slope because it affects micro-climatic conditions (e.g. wind speed and direction, snow accumulation, and net radiation).

Slope aspect (the orientation of a slope in relation to the angle of the sun—see Figure 3.4) has a direct effect on net radiation at a particular location on a cover system. In cold (high-latitude) regions, the effect of slope aspect is magnified compared to warmer (lower-latitude) climates; the sun angle is lower resulting in greater variation in both seasonal and spatial variation in net radiation.

Slope aspect affects snow accumulation, frost penetration, and results in delayed snowmelt. In discontinuous permafrost zones, permafrost may occur in areas with a north-facing aspect and not occur in areas with a more southerly aspect. Vegetation growth is affected by slope aspect partly as a direct function of the variation in available solar radiation, and partly as a function of how slope / aspect effects soil temperature and frost, snow retention, and moisture availability.

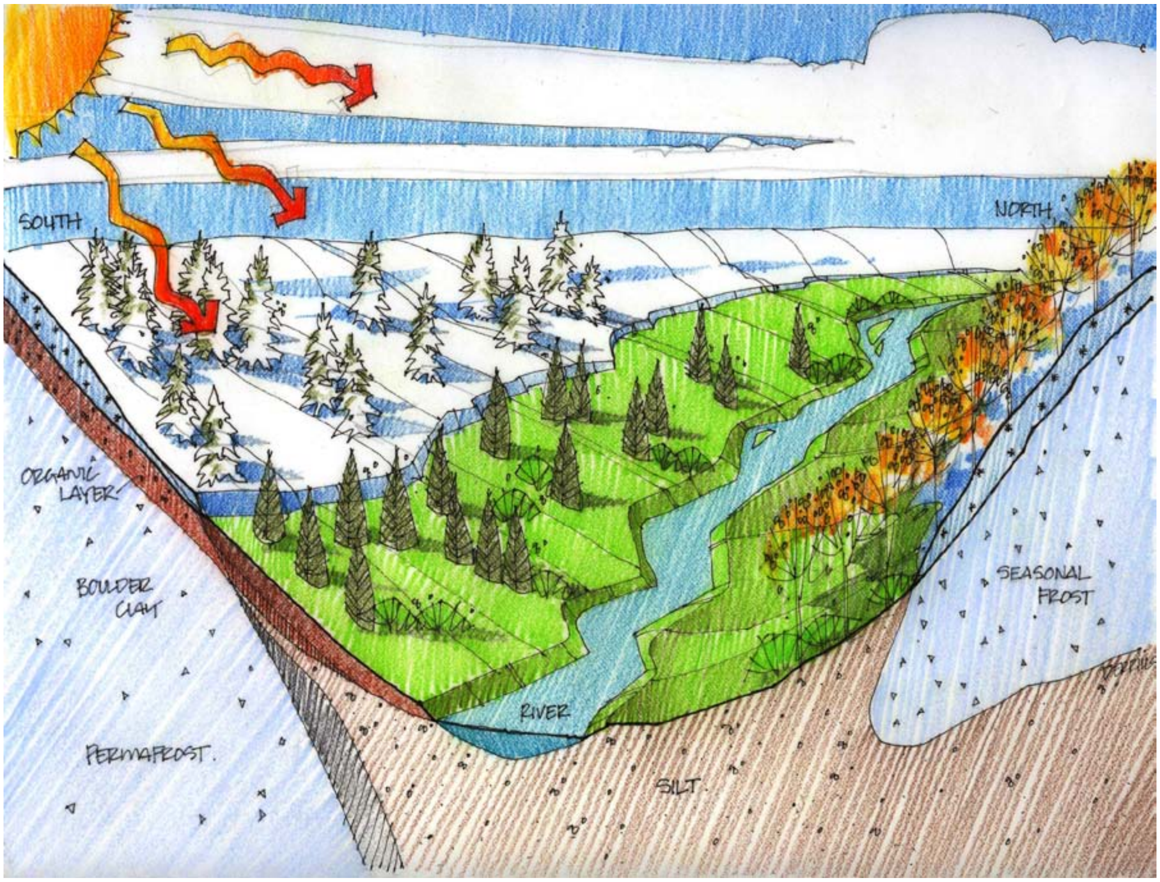


Figure 3.4 Illustration of sun angle and slope aspect effects in northern latitudes.

3.6.2 Water Availability

Water availability is a key cover system design consideration in cold regions, as it is in temperate climates. The water balance of the cover system (and the associated landform) must be considered to evaluate performance of the cover system. Two factors that affect the water balance for a given location are precipitation and potential evapotranspiration. Precipitation in cold regions is a combination of rainfall and snowfall. It is important to consider precipitation and evaporation on at least a seasonal (monthly) basis, rather than simply on an annual basis. The growing season in cold regions is typically quite short with low AET rates (~0.5 mm/day) early and late in the growing season, which means excess moisture can be generated from smaller precipitation events.

Snowfall contributes to the water balance of the cover system predominantly during spring melt. In cold regions, snowmelt may occur for a shorter, more intense, duration than in more temperate climates as peak melt occurs during periods of warm temperatures and high net radiation. Depending on ground temperatures, frozen / unfrozen water contents, and topography, much of the snowmelt water may run off rather than infiltrate into the cover system.

Snow drifts and snow redistribution also need to be accounted for in the water balance of the cover system as understanding how snow is distributed is important in estimating infiltration rates during snowmelt. Snow normally crests at the top of leeward slopes and where there are reductions in wind speed. It is not uncommon to find large differences in snow accumulation over short distances (e.g. tens of metres—Pomeroy and Gray, 1995).

Sublimation of snow constitutes a significant portion of the water balance in several seasonally snow-covered areas of the Canadian North (Pomeroy and Gray, 1995, Essery *et al.*, 2003). Snow interception and sublimation are important hydrological processes that occur as a result of complex mass and energy exchanges. Sublimation of snow intercepted in the vegetation canopy can be as high as 25 – 45% of annual snowfall (Pomeroy and Gray, 1995).

3.6.3 Available Cover Material

The texture and chemistry of available borrow materials at the site will have a considerable influence on the final design of a cover system. Finer textured soils have higher moisture storage capacity compared to coarser textured soils, which is beneficial for plant growth and reducing net percolation rates. However, some finer textured soils are more prone to soil erosion and frost heave compared to coarser textured soils.

The chemistry of candidate cover materials must also be considered during the design of a mine waste cover system. Cover materials with elevated levels of metals, other elements, and/or salts may produce unacceptable water quality in the receiving environment. Also, these same materials may be detrimental to the development of a sustainable vegetation cover. However, it should be recognized that naturally mineralized materials exist in many surficial materials in zones hosting ore bodies, and may well be present in the pre-disturbance environment. Thus, some elevated element levels in candidate cover materials may not necessarily be cause for excluding these materials from the cover system design.

4 BASIC THEORY AND FUNDAMENTAL CONCEPTS

The key theoretical and fundamental concepts pertaining to a cover system situated in a cold region are as follows:

- Unsaturated zone hydrology;
- Surface energy balance / frozen ground;
- Convective cooling of cover layers;
- Freeze/thaw effects on permeability; and
- Evapotranspiration in cold regions.

4.1 Unsaturated Zone Hydrology

One of the principal phenomena of interest in cover system design is the transient flow of water within the unsaturated zone. For the design of earthen covers, the primary issues of concern are the mechanisms responsible for the storage and movement of water in unsaturated soil, also referred to as the vadose zone. This section briefly defines the water retention curve and hydraulic conductivity function to introduce storage and movement of water in the unsaturated zone. This is followed by a brief description of the capillary barrier concept, which can be utilized in cover system design. MEND 2.21.4 (2004) provides detailed information on the theory of unsaturated flow and its application to cover system design.

There are two fundamental relationships that define the storage and movement of water in the vadose zone: the water retention curve (WRC) and the hydraulic conductivity function. The WRC is central to the design of any unsaturated system, such as a cover system, because it describes the relationship between the energy state of the pore-water (matric suction or negative pore-water pressure) and the volume of water stored within the soil pores (volumetric water content) (Barbour 1998).

Figure 4.1 presents typical WRCs for fine- and coarse-textured materials. The negative pore-water pressure required to initiate drainage of an initially saturated soil is called the air entry value (AEV). The WRC can be obtained from a laboratory test in which the volumetric water content of a soil sample is measured at different applied suctions or from an interpretation of field monitoring of suction and water content.

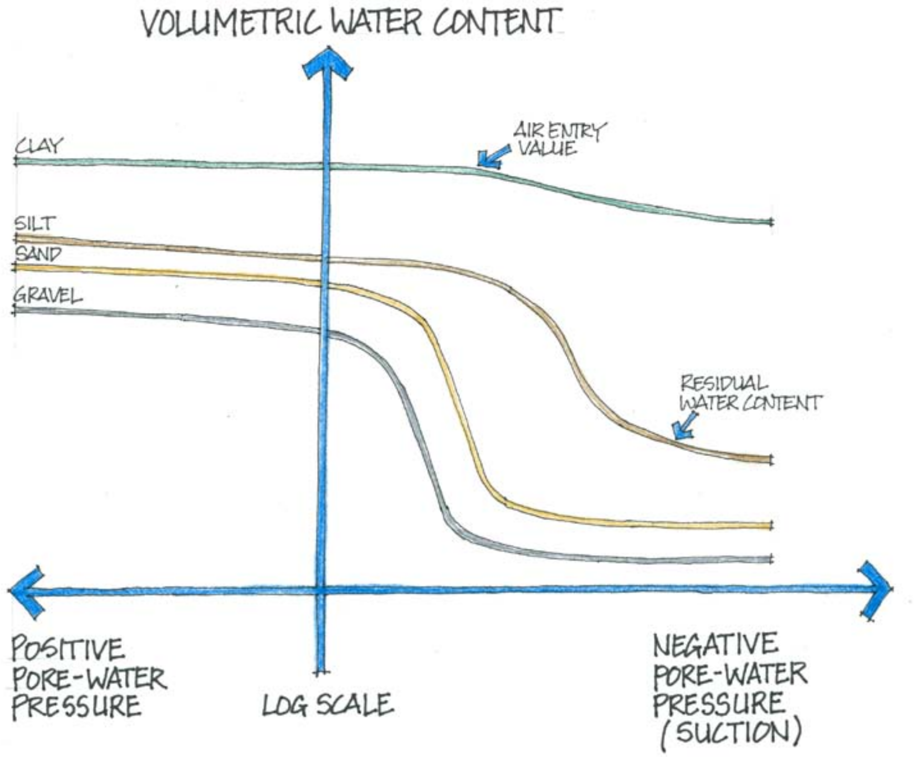


Figure 4.1 Water retention curves (WRCs) for different soil types (after Freeze and Cherry, 1979).

A finer textured material has the ability to retain water under higher suction values as compared to coarser material because of smaller pore sizes. Hence, the coarser textured material starts to drain first (low AEV) as suction is increased from saturated conditions, while the finer textured material remains saturated until much higher suction conditions are reached (high AEV). The slope of the WRC is primarily related to pore-size distribution and soil structure of the material. The latter factor in fine-textured soils is strongly influenced by factors such as compaction conditions, as well as the effects of freeze/thaw and/or wet/dry cycles. The high AEV of clays tend to decrease following freeze/thaw cycles or dessication due to structural changes. A material with a uniform particle size will tend to drain 'rapidly' over a small range of suction values because pore sizes are generally the same size. Well-graded materials will have a moderate slope to the WRC once drainage conditions are initiated because they possess a wide range of pore sizes.

As suction increases past the AEV (due to drainage and/or evapotranspiration), the soil drains until the residual water content is reached. The residual water content is characterized by the relatively flat portion of the WRC at high suctions where large increases in suction result in very small changes in water content. At water contents greater than the residual water content, water movement in soils is primarily through liquid water flow. At water contents less than the residual water content, water movement is dominated by vapour flow because the remaining water is bound more tightly to the soil particles.

The ability of vegetation to draw water from a soil is commonly related to two ranges of negative pore-water pressures: field capacity and permanent wilting point. The field capacity (FC) is defined as the water content of a soil when drainage under the influence of gravitational forces ceases. Field capacity is generally measured in the laboratory by measuring the water content of a sample brought into equilibrium in a pressure plate with a suction of 33 kPa (fine-textured soils) or 10 kPa (coarse-textured soils). The permanent wilting point (PWP) is typically considered to be the water content at a suction of approximately 1,500 kPa and represents the limit of plant-available water. These values vary depending on soil texture and vegetation type. The difference in volumetric water content between FC and PWP is defined as the available water holding capacity (AWHC) and when integrated over the rooting depth represents the total volume of water available to plants.

Hydraulic conductivity is the soil property that characterizes the ability of the soil to transmit fluid. Water will move through soil in response to energy gradients. These gradients are commonly due to mechanical energy gradients (e.g. total head comprised of pressure head and elevation head), but may also be due to thermal, electrical, or chemical energy gradients (Mitchell, 1976).

The flow of liquid water flow in response to a mechanical energy gradient is defined by the relationship between a unit flux of water and the energy gradient and is commonly referred to as Darcy's Law:

$$q = -ki \qquad [4.1];$$

where q = unit flux of water ($m^3/\cdot s\cdot m^2$), k = hydraulic conductivity (m/s) and i = energy gradient represented by change in total head with position (dh/dx; unitless). Both h and x are expressed in units of length; however, hydraulic head represents the energy per unit weight of water.

Darcy's Law is applicable to both saturated and unsaturated soil. The key difference, however, is that the hydraulic conductivity of a saturated soil is often taken as a constant (for a given density or void ratio), whereas the hydraulic conductivity of an unsaturated soil will change with the degree of saturation or volumetric water content (see Figure 4.2). This function can also be described by a relationship between hydraulic conductivity and suction, as shown in Figure 4.2, because volumetric water content is related to suction through the WRC. Detailed descriptions of the theory of water flow in unsaturated soils are well defined by Freeze and Cherry (1979), Fredlund and Rahardjo (1993), and Guymon (1994).

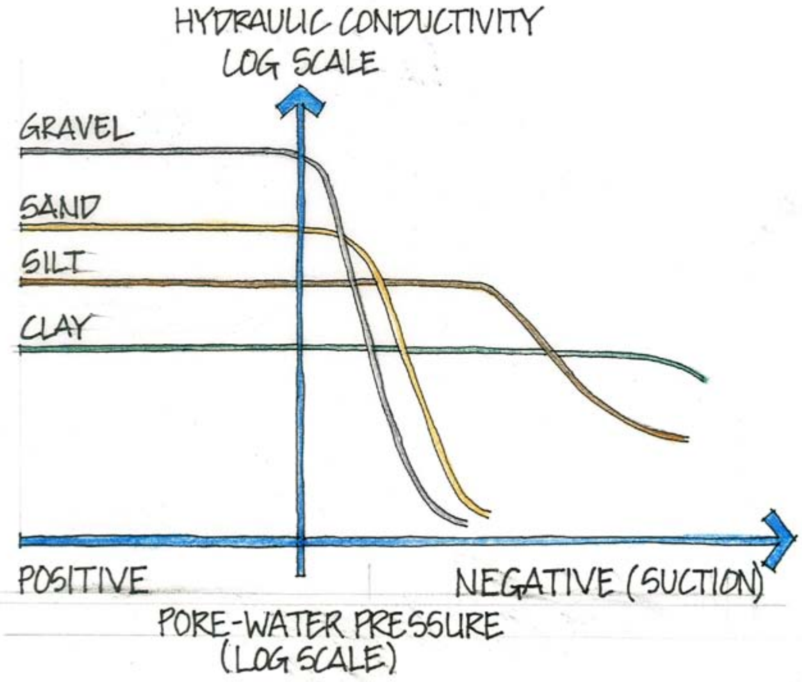


Figure 4.2 Hydraulic conductivity functions (versus suction) for different soil types (after Freeze and Cherry, 1979).

4.1.1 Capillary Barrier Concept

The capillary barrier concept is commonly used in the design of cover systems and more specifically, the design of multi-layer cover systems. Rasmusson and Erikson (1986), Nicholson *et al.* (1989), Morel-Seytoux (1992), MEND 2.22.2a (1996), Aubertin *et al.* (1996), Bussière and Aubertin (1999), and others describe the capillary barrier concept in detail.

A capillary barrier results when a finer textured material overlays a coarser textured material, as illustrated in Figure 4.3. The lower, coarser textured material will drain to a residual water content following an infiltration event; however, the suction in the coarser soil at this water content is relatively low. The overlying finer-textured material will not drain at this low suction and as a result, it remains in a tension-saturated condition. This ‘capillary break’ will occur during drainage whenever the residual suction of the lower coarser textured material is less than the AEV of the upper finer textured material.

The design of a capillary barrier is dependent on the contrast between the hydraulic properties of the coarser and finer textured materials. Capillary barriers, unlike compacted barriers, do not rely solely on low hydraulic conductivity to restrict movement into underlying material. Processes that increase hydraulic conductivity, such as desiccation and freeze/thaw, do not necessarily decrease the effectiveness of a capillary barrier over time.

A coarser textured layer overlying a finer textured layer may also be included in the design of a capillary barrier system, but the role of this coarser layer is simply to prevent evaporation from the finer textured layer. The upper, coarser textured layer may also reduce runoff by increasing the available storage of water during infiltration. Capillary barriers also act to restrict the upward capillary rise of salts and/or oxidation products from underlying waste material into the finer textured cover material, which in turn could have a detrimental effect on vegetation.

Caution is required when using the phrase ‘capillary break’, as it can be misleading. There are true ‘breaks’ in continuous liquid phase when a very coarse material is used and any liquid flow must occur first as discontinuous liquid flow (i.e. drops). Many ‘capillary break’ layers still maintain a continuous liquid phase, but due to the differences in capillarity the maximum suction that can be generated under drainage in the coarser material is insufficient to drain the finer overlying material to levels less than tension-saturated conditions.

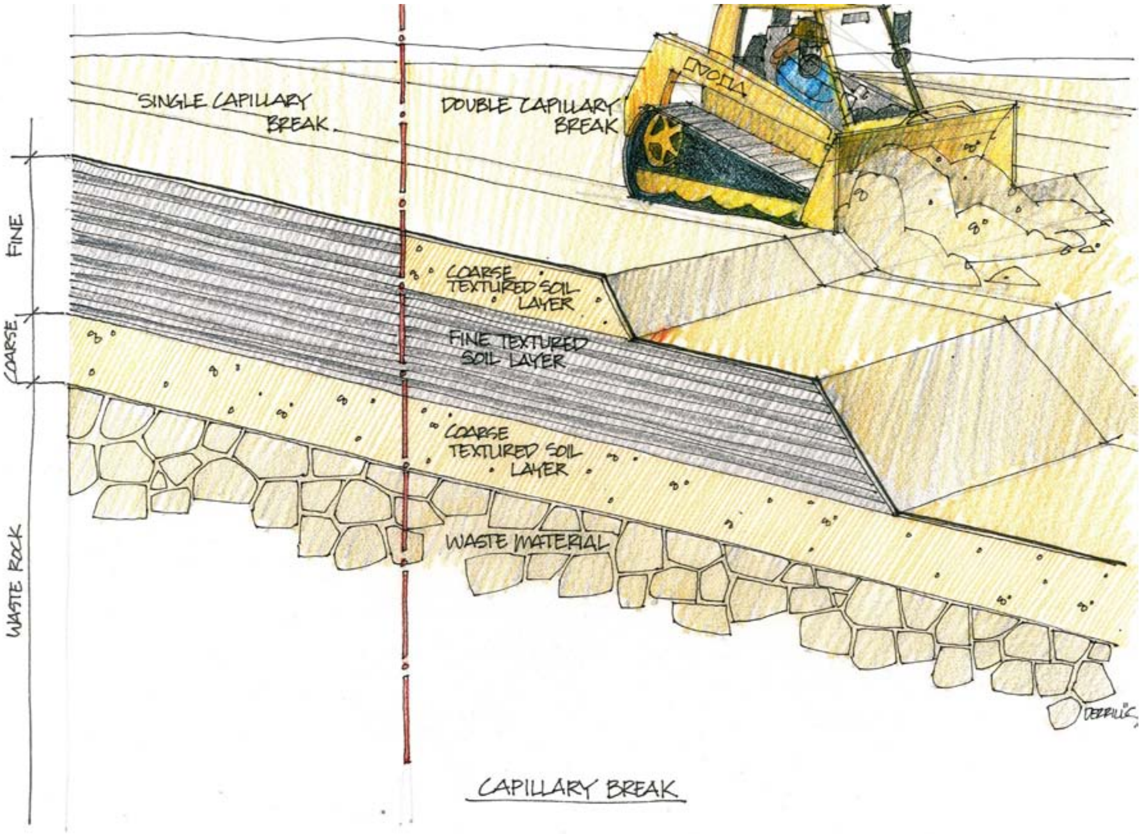


Figure 4.3 Capillary break cover system over waste material.

4.2 Surface Energy Balance

Cover system design in temperate climates has tended to focus on the hydrology (water balance) associated with the portion of the year in which air and ground temperatures are above zero. Under these conditions the thermal regime of the cover system has little influence on water balance, unless the site is not vegetated and evaporation rather than transpiration dominates water losses to the atmosphere.

However, the hydrology of soils in cold climates is strongly controlled by the presence, distribution and timing of ground frost relative to snowmelt. These, in turn, are strongly influenced by slope and aspect (radiation), snowpack accumulation and melt, material type, and antecedent moisture conditions prior to freeze-up. In all cover system designs, the hydrological response of the cover system to snowmelt is a critical component of the water balance. In addition, the designer will need to evaluate the potential development of frost phenomena that might have a detrimental effect on cover performance. These phenomena may be the result of changes in energy balance (freeze or thaw) caused by disturbance of the thermal regime during cover placement or landform development and the resulting thermal disequilibrium. In some cases, the cover system design may rely on seasonal or permanent development of ground frost to control water and/or gas movement.

The surface energy balance describes the net change in energy at the surface over a given time period. Energy is contributed to the surface largely from incoming short- and long-wave radiation, heat from the phase change of water, and conduction of heat from the surrounding soil. Energy is removed from the surface due to outgoing radiation, heat removed from the phase change of water, and conduction of heat to the surrounding soil.

The basic energy balance equation is described as (Oke, 1996):

$$Q^{*} = Q_{H} + Q_{E} + Q_{C} \qquad [4.2];$$

where Q^{*} is net all-wave radiation, Q_H is sensible heat, Q_E is latent heat, and Q_C is conduction to or from the underlying soil (all units in W/m^2).

The two key mechanisms controlling the energy balance of soils (or earthen materials) are those governing the flow and storage properties: the specific heat (storage) and conduction (flow). Conduction can be described by the following equation for steady-state heat flux through soil:

$$q = -k\frac{\partial T}{\partial x} \qquad [4.3];$$

where q is heat flux (J/s·m^2), k is thermal conductivity of the soil (J/s·m·°C), T is temperature (°C), and x is distance (m).

The critical parameters that must be known for a given soil material are thermal conductivity (*k*), volumetric heat capacity (*c*) and unfrozen water content function (ω_u(T)). These are typically estimated based from more fundamental soil properties (e.g. particle size distribution, mineralogy, density, volumetric water content, etc) using a variety of methods proposed in the literature. Zhang *et al.* (2008) describe the various parameterization techniques for determining these variables and evaluate their influence on evaluations of ground freezing and thawing.

The energy balance and heat transfer estimations provided above all assume that convective heat transfer in soil is negligible. In most climates this is a valid assumption as the topsoil, litter layer, and vegetation all act to slow air movement. However, in cold regions, or other regions with limited vegetation and coarse surface materials, convective heat transfer in the soil must be considered (see Kane *et al.* (2001) for more details). The concept of convective cooling is discussed in detail in the following section.

4.3 Convective Cooling of Cover Layers

Heat transport in porous media generally occurs either by convection or conduction where convection involves the bulk movement of air or water and conduction occurs by heat transfer through water or solid particles. MEND 1.61.5a (2009) and MEND 1.61.5b (2010) provide a detailed summary of the process of convective cooling as it relates to mine waste cover systems in cold regions. The following is a synopsis of information contained in the above-referenced literature.

Convective flow of cold winter air through coarse rock materials can cause significant cooling. Convection is driven primarily by the difference in temperature between the air and the rock, which retains some of the heat it gains during summer, geometry of the pile (i.e. height and slope), and material properties at the pile surface. Air within the rock pore-space is slightly warmed by contact with the rock, which causes it to rise. The rising air pulls colder air into the rock pore-space. The resulting convective cycle continues until the rock is cooled to the same temperature as the surrounding air; or, more commonly, until summer conditions cause the air temperature to rise above that of the rock. In summer, a change to the cycle can occur where the cooler air inside the rock sinks and draws in warmer air from above, which in turn warms the rock. This process is illustrated in Figure 4.4.

The degree to which permafrost is maintained through convective cooling is greatly influenced by the presence of a cover or lack thereof. The presence of a cover can block convective cooling currents, meaning the sole method of cooling the rock is through conduction. The cover can be in the form of a barrier component of the cover system, or a layer of insulating snow. By reducing the rate of cooling, the interior of the pile supplies heat over a longer timeframe, thereby increasing the amount of permafrost degradation. This process is illustrated in Figure 4.5.

The convective process has been studied as a means to prevent permafrost degradation. Convection within embankments of coarse rockfill has been proposed in designs of road and railways to control settlement caused by thawing of permafrost. Field tests have confirmed (e.g. Goering and Kumar, 1996) that convective flow through a porous embankment results in cooling in winter, and that convection stopped during the summer months, limiting heat gain to the much slower process of conduction. The combined effects resulted in preservation of basal permafrost layers.

The simplest approach to assess the potential for convective cooling is to calculate the ratio of convective factors to conductive factors. This is most commonly done through reference to a dimensionless number known as the Rayleigh-Darcy number (refer to MEND 1.61.5b (2010) for a detailed description of this number). The importance of the Rayleigh-Darcy number is that many studies have shown that natural convection will occur only when the Rayleigh-Darcy number is above a critical threshold. In the case of a flat-lying layer with an open top surface, the minimum critical Rayleigh-Darcy number is equal to 27.10 (Nield and Bejan, 1999), which is higher than that for the same layer on a slope. Any combination of geometry, temperature differences, material properties and gas properties can be expressed as a Rayleigh-Darcy number and compared to this value to determine whether convective cooling is possible.

Calculations presented in MEND 1.61.5b (2010) indicate that convective cooling could be of interest to designers of cover systems in cold regions. Where high permeability rock is available for cover construction, which is often the case at mine sites, the resulting heat removal could be sufficient to cause the underlying waste material to freeze. An ongoing research project at the Diavik mine in NWT is evaluating convective heat transfer through both covered and un-covered waste rock (Pham *et al.*, 2009).

Wind flow over a waste rock pile can induce pressure gradients around the pile, which can result in air flow through the pile (Amos *et al*., 2009) and result in cooling. The mass of air (wind) moves across the surface and contacts the porous material in the pile, but does not penetrate deep enough to change internal temperatures. The high pressure air naturally flows to the lower pressure zone, pulling more atmospheric air through the porous media as it leaves the system. When the atmospheric air replacing the air leaving the system is at a lower temperature than internal dump temperature, an induced cooling effect is generated. This addition of colder air into the system can help maintain permafrost beneath the cover system.

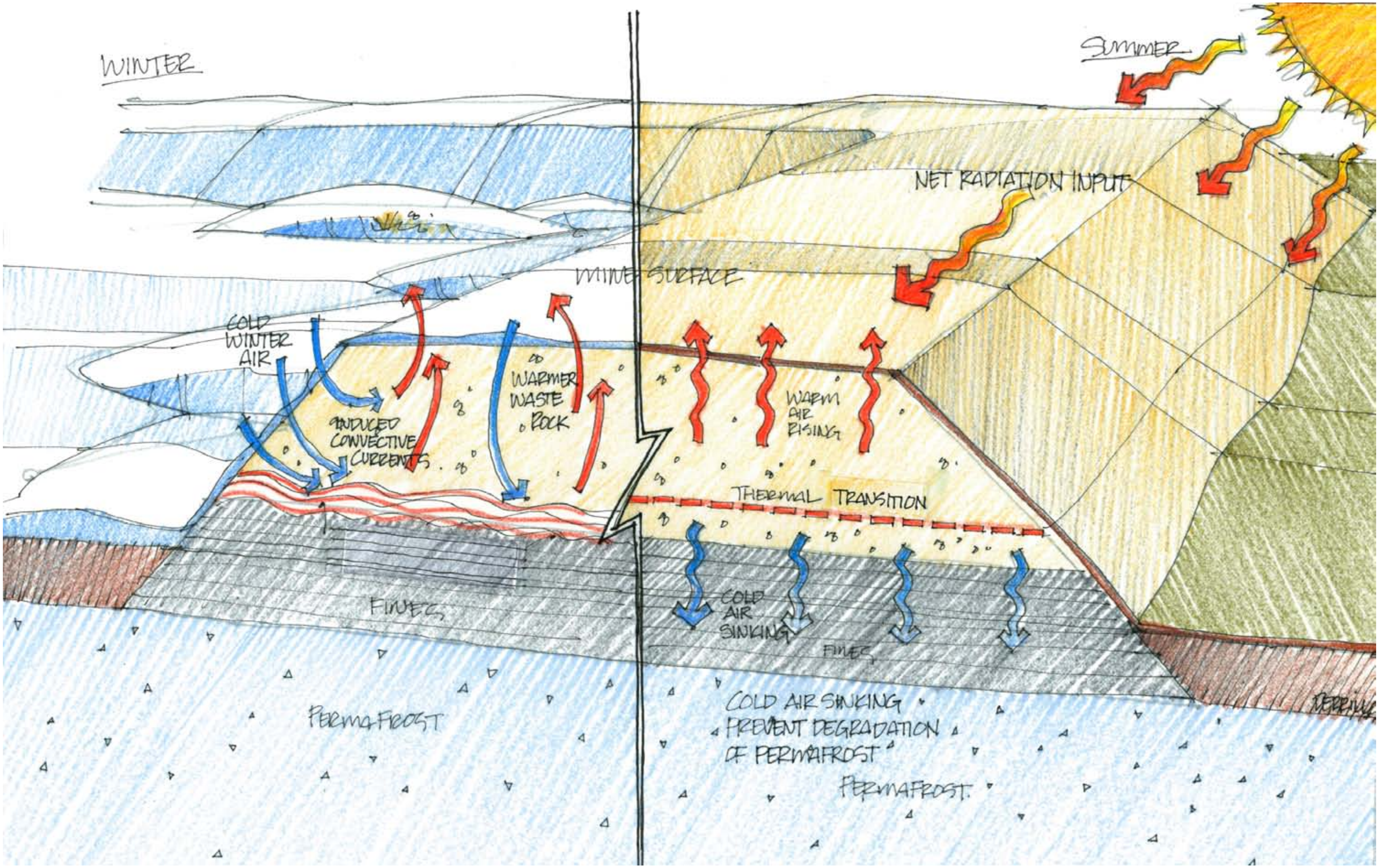


Figure 4.4 Illustration of convective cooling within a granular material with no cover.

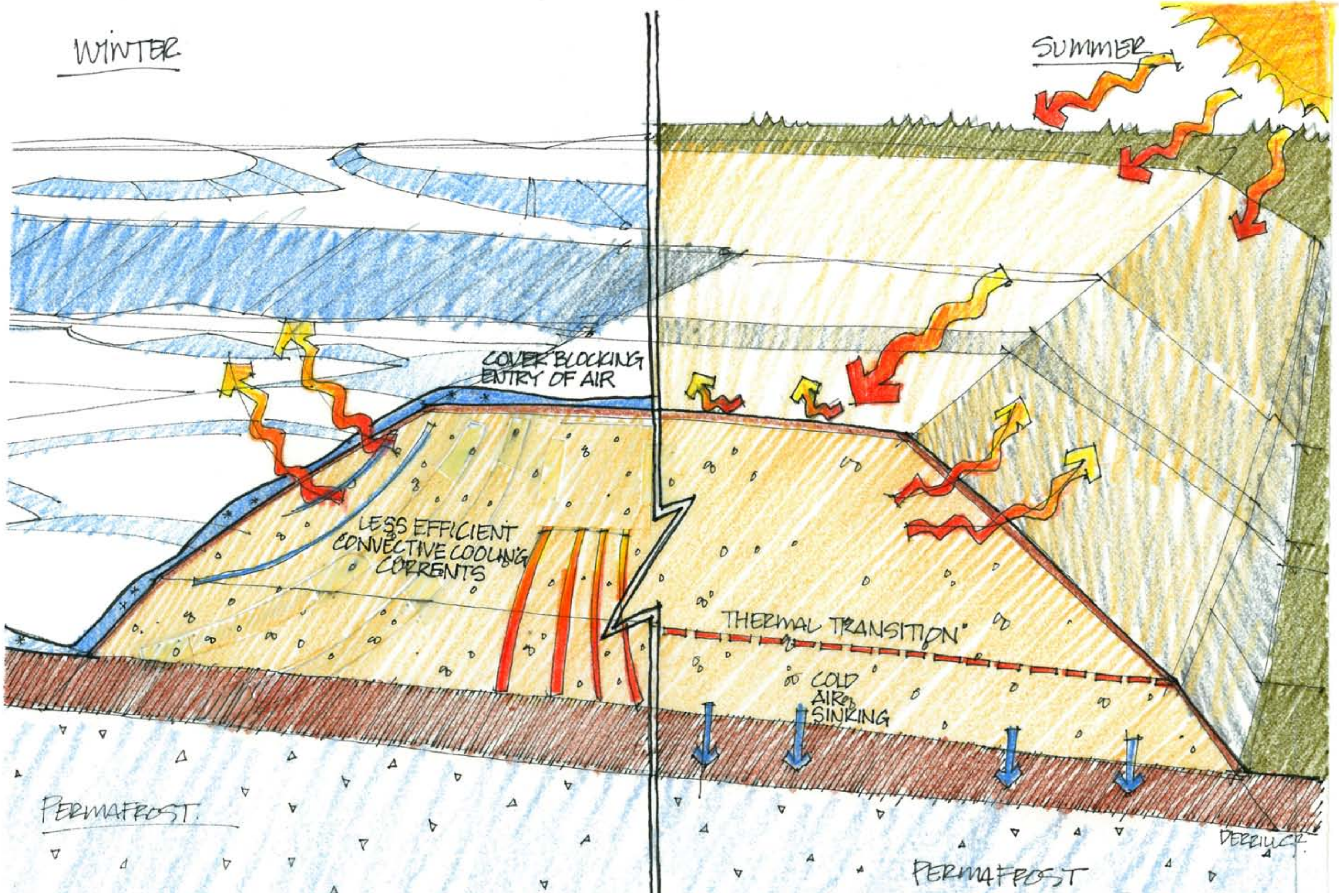


Figure 4.5 Illustration of a finer textured cover layer acting as a barrier to convective cooling within a granular material.

4.4 Evapotranspiration in Cold Regions

Evapotranspiration (ET) is a process of moisture and heat exchange between the earth surface and the atmosphere, which occurs through evaporation of water from the soil surface and through transpiration of water by vegetation. The potential evaporation (PE) is, theoretically, the maximum rate at which water can evaporate from a soil surface. PE can be estimated using evaporation pans (Maidment, 1993), or calculated based on air temperature, relative humidity, wind speed, and solar radiation (net radiation) (Penman, 1948). Additional methods to estimate PE include the Thornthwaite (1948) method, the Priestley Taylor (1972) Model, and the Complimentary Relationship (Bouchet, 1963). All of these methods vary in their estimates of PE; thus, it is important to research which estimation method is most suitable for a given site and available dataset. Caution is required when using pan evaporation to characterize evaporation at a site, which may overestimate the cumulative PE (Gray, 1970) (see Figure 4.6).

Evaporation from the soil surface is influenced by the soil's ability to store and transmit water (e.g. surface roughness, soil structure, texture, organic matter content, presence of non-permeable layer such as rock, ice or clay, and soil water content), while transpiration is regulated by plant morphology and physiology (e.g. plant structure and size, leaf anatomy, rooting depth, water use efficiency, photosynthetic capacity, age). While in a non-vegetated soil only the moisture from upper soil horizons is available for evaporation, vegetation facilitates movement of water from deeper soil horizons through water uptake by plant roots (MEND 1.61.5a, 2009).

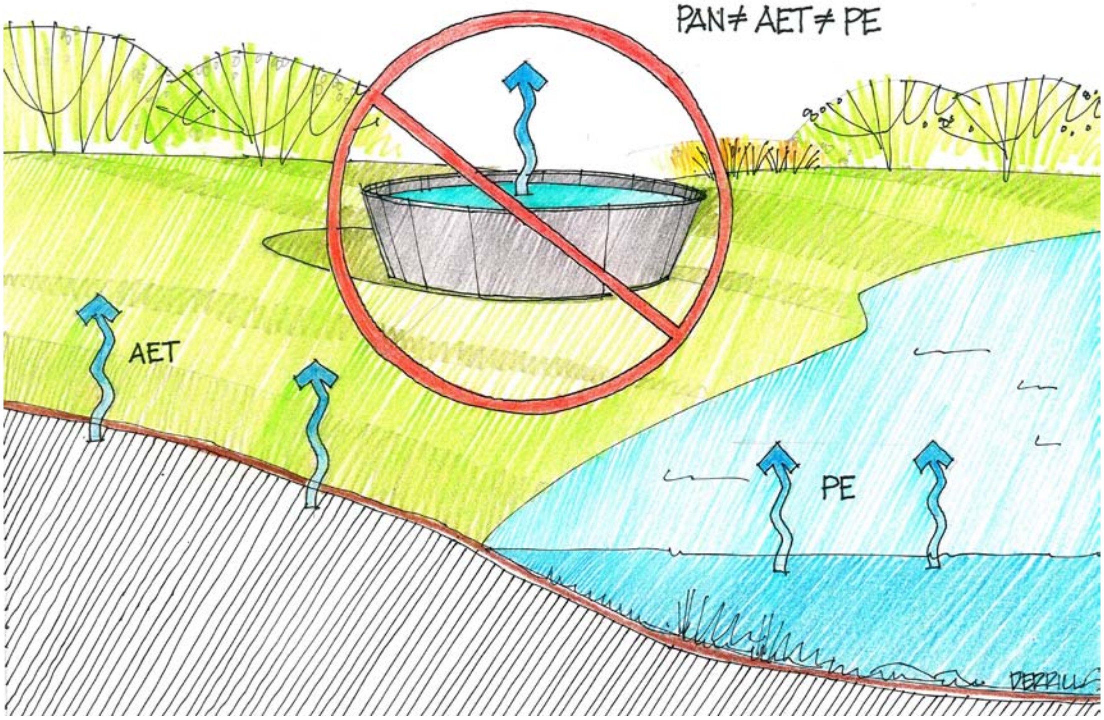


Figure 4.6 Illustration showing differences between AET, PE, and pan evaporation.

Actual evapotranspiration (AET) will rarely, if ever, equal PE. There are numerous mining operations where rainfall is significantly less than PE. These sites are broadly classified as 'dry sites', which is often useful when comparing relative seepage from a waste storage facility to a site where rainfall exceeds PE on an annual basis (i.e. a 'wet site'). However, these broad classifications cannot be used to estimate the water balance for sites as a means of estimating net percolation rates for a given cover system. For example, if mean annual rainfall at a dry site is 500 mm per year and mean annual PE is 1,500 mm, one cannot conclude that the net loss will be 1,000 mm of water, nor can it be assumed that net percolation from the cover system to the underlying waste will be zero. This is because AET is always less than PE and precipitation and evaporation events may not occur at the same time.

Site-specific values are likely to vary from typical or regional values as influenced by the following.

1) *Month / stage of growing season* – Evapotranspiration rates change substantially throughout the year, peaking in July, with lowest values in the winter. Lower daily values of ~0.5 mm are associated with the beginning and end of the growing season (typically May / June and August / September, respectively, depending on latitude and altitude). Higher values are associated with vigorous communities (e.g. boreal aspen) at the peak of the growing season, in the absence of substantial soil moisture deficits.

2) *Climatic controls* – Growing-season precipitation and antecedent soil moisture conditions will strongly influence evapotranspiration.

3) *Leaf area index (vegetation cover)* – Leaf area index (LAI) is influenced both by vegetation type (see 4 below) and vegetation community age. ET values are strongly correlated with LAI, and so will be maximized when LAI is highest. LAI trajectories for forest stands developing on reclaimed mine sites may occur over decades, with these stands typically reaching maximum LAI at the time of crown closure, which may be at age 30-50 years after stand initiation, depending on the species and location. LAI trajectories for forb- and/or shrub-dominated communities are generally much shorter, with maximum LAI being achieved within five years of establishment in many forb-dominated communities.

4) *Vegetation type* – Daily peak growing-season ET values in arctic (non-forested) North America may be as low as 1.3 mm for sparsely vegetated tundra, to as high as 2.7 mm for wet sedge / grass meadows. Intermediate daily ET values (1.5 – 2.3 mm) are associated with sparse to dense covers of common shrubs such as dwarf birch and willow, grasses, and *Sphagnum* mosses. In the context of reclamation (in similar zones), lower cited values will be typical of mid-growing-season ET for establishing (young) vegetation on mine waste covers, or established vegetation on very coarse or thin covers, while intermediate values will be typical of mid-growing-season ET for established vegetation on better cover materials. Reduced values (0.5 – 1.5 mm) would be expected before reclamation vegetation reaches

maturity, and for the early and late periods of the growing season. In forested areas, mean (not peak) daily observed ET values are ~1.3 mm for conifer stands, and ~2.3 mm for deciduous stands, and similar values can be expected for established forest tree species on reclaimed covers. Typical annual ET values for non-forest vegetation types in cold regions would range from approximately 150 to 300 mm, depending on stand density, vigour, species, and stage of development. Lower values (less than 150 mm) would be applicable to juvenile communities developed on newly-reclaimed covers. Even in the lower-biomass, higher-latitude vegetation communities, contribution of ET to the surface hydrological balance is substantial, and has implications for design of mine waste cover systems in cold regions, particularly cover systems that utilize the moisture store-and-release concept.

5 COVER SYSTEM DESIGN ALTERNATIVES FOR COLD REGIONS

In order to meet the chemical, physical and land-use objectives described in Chapter 3, various cover system designs may be employed. This section outlines these alternatives and describes their benefits and applicability for use in cold regions.

Many of the cover system designs that are used in temperate or tropical climates are not suitable in cold regions. Wet covers and water covers are difficult to maintain in climates where a large portion of the year has freezing conditions. For the purposes of describing the appropriate cover system designs for cold regions, the designs have been divided into the following six categories:

1) Erosion-protection cover systems;
2) Store-and-release cover systems;
3) Enhanced store-and-release cover systems (e.g. enhanced with a lower permeability layer, a capillary break, and/or an engineered seasonally frozen capillary break diversion (SFCBD));
4) Barrier-type cover systems (e.g. compacted soil or permanently frozen layer);
5) Cover systems with engineered layers (e.g. geosynthetic layers); and
6) Saturated soil or rock cover systems.

It should be noted that a particular cover system may fall into more than one category. For example, all cover systems will provide a degree of erosion protection, and a cover system with a geomembrane can also serve as a store-and-release cover system.

These cover systems include various design components to help meet specified objectives for each site. Chapter 6 will discuss how to design the cover systems in order to meet these objectives; this chapter simply outlines the cover types and their applicability in cold climates.

5.1 Erosion-Protection Cover Systems

The key closure objectives at some sites may be solely dust control and erosion protection. In these cases, the waste material itself is not reactive and the goal is to develop a stable landform. Generally, there are two types of erosion-protection covers applicable to cold regions:

1) Vegetated, and
2) Surface layer of coarse gravel or riprap.

An erosion-protection cover system refers to the erosion of the waste, not the erosion of drainage channels, etc., which is discussed in Section 6.9.3. An example of an erosion-protection cover system is shown in Figure 5.1.

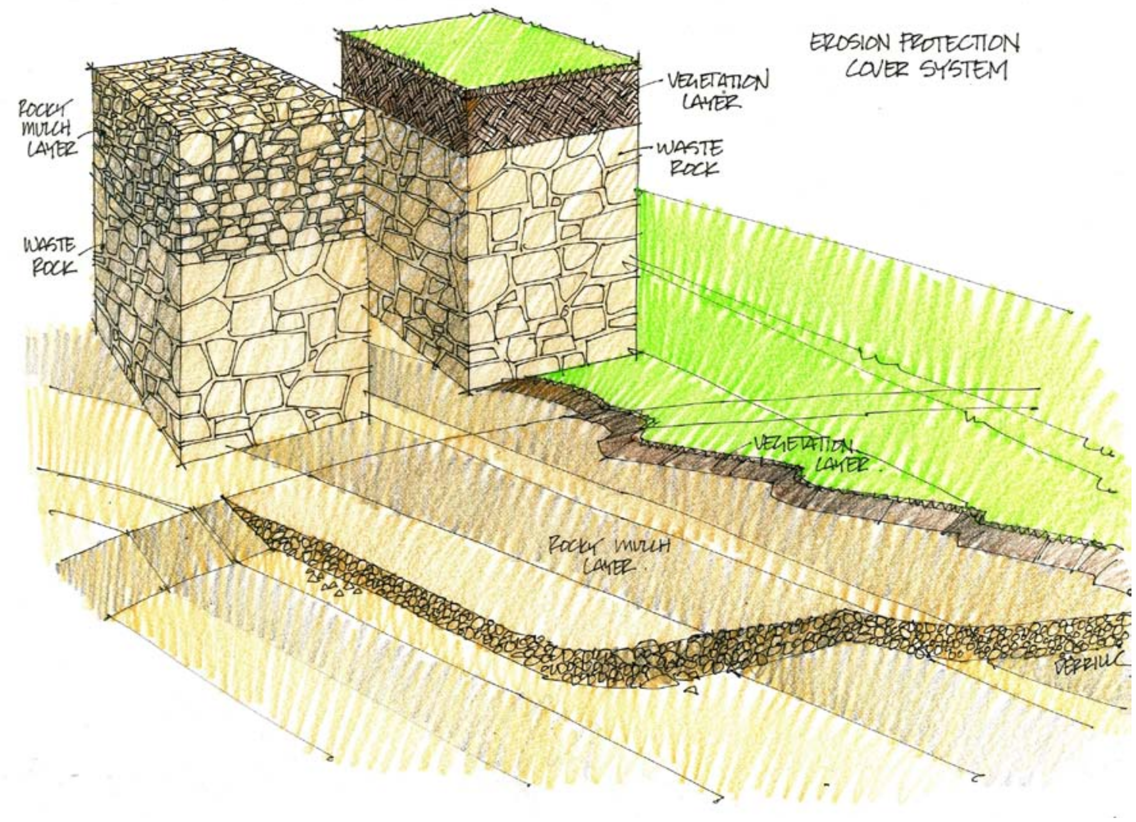


Figure 5.1 Erosion-protection cover system.

The vegetation approach to erosion protection involves rapid establishment of a vegetation cover over the waste as a means of minimizing erosion. The waste must be non-reactive and the contaminant uptake by vegetation should be minimal. The waste (with or without a surface soil amendment) must also have sufficient water-holding capacity to support vegetation growth. Site preparation and vegetation treatments must be conducted to ensure rapid vegetation establishment in order to minimize erosion during the establishment period.

In cold regions, the time required to establish sufficient vegetation to provide erosion protection may be excessive (many years), leading to unacceptable erosion rates prior to full establishment, particularly for highly erodible waste materials. In other cases, the waste material may not have sufficient water holding capacity for direct revegetation. In these instances, there are several options: add an appropriate thickness of soil to provide a rooting zone for vegetation; blend (harrow) an appropriate soil into the waste to facilitate water retention; use landform design features (e.g. micro-topography) and/or mulch materials to reduce erosion until vegetation can be fully established; or place an erosion-protection gravel or riprap layer over the waste. In the latter case, the material must be sufficiently coarse that is not susceptible to erosion. Ideally, this layer should also support vegetation, if vegetation establishment is desired, although it is likely to support only species adapted to establishment and growth on coarse-grained substrates.

In some cases, a lack of vegetation establishment may be an explicit cover or closure objective (due to technical and/or stakeholder concerns). As with revegetation, the goal of no vegetation establishment brings its own challenges (see Section 3.5).

5.2 Store-and-Release Cover Systems

The suitability of cover systems that rely on the water store-and-release concept to control net percolation will depend on site-specific climate conditions, material availability, and the required performance criteria. Figure 5.2 illustrates a generic store-and-release cover system. Water infiltrates during periods of high precipitation or spring melt. The infiltrated water is stored within the cover until atmospheric and biotic demands are able to remove the water through evaporation and transpiration.

Caution must be used when selecting a store-and-release cover system design based on annual average climatic data. Sites that experience highly variable climatic conditions (e.g. high-intensity precipitation over short periods of time) may have low average precipitation and high potential evapotranspiration; yet, due to the timing of precipitation, the storage may be overwhelmed during periods of low potential evapotranspiration. For example, in many cold regions climates it would not be unusual for the net infiltration from snowmelt to exceed the storage capacity of the cover material such that net percolation will occur (MEND 2.21.4, 2004). Similarly, there are many sites in which precipitation exceeds potential evapotranspiration on an annual basis, but during the dry growing seasons these sites have moisture deficits due to potential evapotranspiration exceeding precipitation and soil water storage. Store-and-release cover systems must be designed and monitored to evaluate the design against a longer term, site-specific climatic record (e.g. tens of years) rather than an average ‘design’ year, and to monitor performance over the longer term (i.e. within individual years, net percolation may exceed design specifications, but the long-term average value may be acceptable) (O’Kane and Barbour, 2006; MEND 2.21.4, 2004).

In cold regions, material availability is a significant factor when designing any type of cover system, but is of particular importance for a store-and-release cover system that relies entirely on hydraulic characteristics of the materials. The materials that are typically available in these regions are tills (often sandy and with high coarse-fragment contents), esker or other glaciofluvial material, waste rock, colluvium, and alluvium. There is potential to mix tailings into available coarser cover materials to increase the fines content; however, the potential for increased contaminant loading from the cover material must be carefully considered.

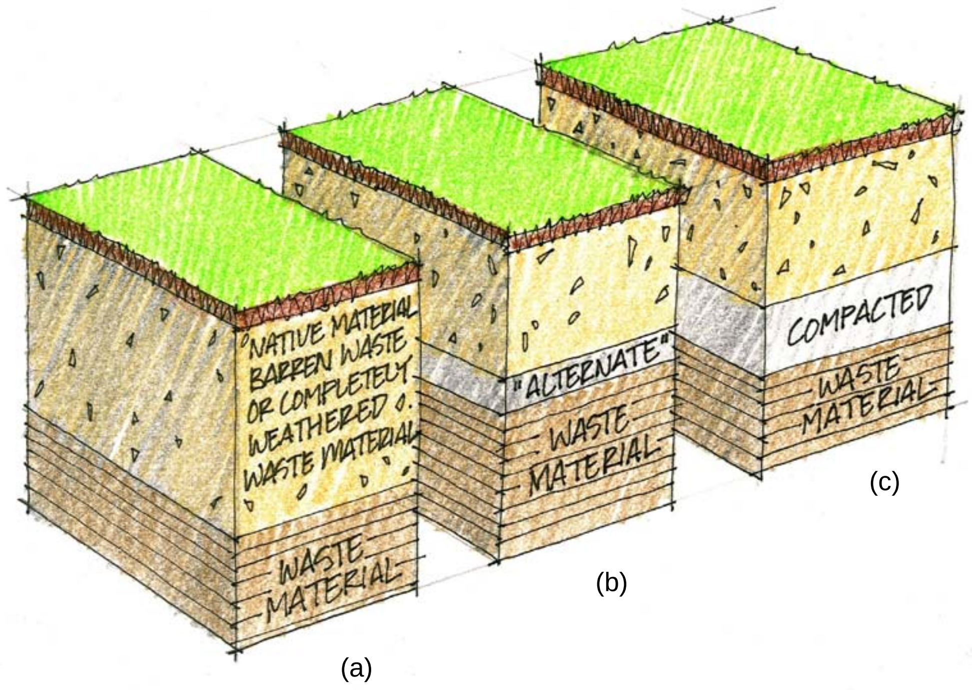


Figure 5.2 Store-and-release cover systems: (a) basic store-and-release cover system, (b) and (c) enhanced store-and-release cover systems showing additional lower hydraulic conductivity layers below the storage layer.

5.3 Enhanced Store-and-Release Cover Systems

The term ‘enhanced store-and-release’ is used to describe a cover system that utilizes the store-and-release concept to meet most of the cover objectives, but includes additional layers designed to limit net percolation during relatively short-duration seasonal events in which the storage capacity of a store-and-release cover system might be exceeded. This differentiates these covers from barrier-type cover systems (Section 5.4) in that the permeability of these layers only needs to be lower than the average flux rate during these short-duration seasonal events, rather than functioning as a barrier to water flow throughout the year. If the low permeability barrier used in an enhanced store-and-release cover system is susceptible to processes such as freeze/thaw cycling, root penetration, etc., then sufficient cover soil must be provided to protect the barrier layer from these effects.

In some cases the enhanced water diversion provided by this type of cover is not required over the entire life of the cover. The enhancement may be required to limit net percolation only until mature vegetation can be established and the full evapotranspirative capacity of the store-and-release layer can be realized.

5.3.1 Lower Permeability Layer

An enhanced store-and-release cover system may include an additional low hydraulic conductivity layer below a non-compacted layer. The purpose of this lower hydraulic conductivity layer is to ‘delay’ downward percolation. This layer could be weathered surficial waste rock compacted as a result of haul truck traffic on top of a dump lift or compacted locally available silt/clay (i.e. from local till or lacustrine materials). Inclusion of this reduced hydraulic conductivity layer at the base of the store-and-release cover system was shown to reduce the average annual net percolation (as a percentage of annual precipitation) by as much as 7% for a 0.5 m cover system and slightly less for thicker store-and-release cover systems (Christensen and O’Kane, 2005). The restricted infiltration layer can lead to increased interflow within the non-compacted layer and increased surface runoff, which increases the risk of surface erosion. An example of a store-and-release cover system with a low permeability layer is shown in Figure 5.2.

In cold regions, it may not be prudent as part of a cover system design to include a layer in the thermal active zone with a hydraulic conductivity less than 1 $\times 10^{-7}$ cm/s, as freeze/thaw cycling is likely to increase this hydraulic conductivity over time (see Section 2.2.3). However, note that net percolation through a material with a hydraulic conductivity of 1 $\times 10^{-6}$ cm/s and a unit gradient is less than 1 mm/day. Any infiltration that is greater than this rate will either be stored or diverted laterally within the cover layer. Consequently, even a material experiencing freeze/thaw cycles may provide sufficiently low values of hydraulic conductivity to meet design objectives. Evolution of the low permeability layer into a store-and-release layer (until vegetation becomes fully established) should be assessed to see if the cover system still meets performance objectives at the end of the design life.

5.3.2 Capillary Break Layer

Capillary break layers are discussed in detail in Section 4.1.1. To summarize, the presence of a coarse-textured layer within an otherwise homogeneous finer-textured profile will produce a sharp drop in suction (an increase in negative pore-water pressure) within the coarser layer. The presence of these lower suctions allows the overlying finer textured soil layer to maintain higher water contents than would be expected for a homogeneous soil profile (e.g. > field capacity). The development of a ‘capillary break’ depends on the contrast between the hydraulic properties of both the coarser- and finer-textured materials, so their use in cold region climates will be limited by the availability of appropriate material.

5.3.3 Seasonally Frozen Capillary Break Diversion (SFCBD)

It is well established through observations of natural sites in cold regions that snowmelt waters can be diverted downslope as lateral flow within a shallow active layer overlying a deeper frozen soil zone (Hayashi *et al.*, 2003, and Carey and Woo, 2001). The underlying frozen zone may eventually thaw but not until after snowmelt is over. This often occurs when the upper layer is relatively coarse-textured and at low water contents; consequently, the upper layer thaws relatively rapidly each spring, while the lower soil zone is at a higher water content and takes much longer to thaw. Work by Stähli (2006) shows that the infiltration capacity of a frozen soil is 3 to 5 orders of magnitude less than in unfrozen conditions. The reduction in vertical water infiltration is primarily a function of soil moisture prior to freezing and the heat transfer between infiltration water and the frozen soil.

This natural process suggests that it is possible to create an engineered layered system in which a surficial, well drained, active layer is formed over a lower, higher water content layer that remains frozen for a longer period than the layer above. This lower layer may have elevated water contents because it is finer and/or it is overlying relatively coarse waste rock or other coarse-textured soil. This layered system will result in an increased storage capacity in the upper soil that may be removed from the system laterally as interflow, on the surface by runoff, or by vegetation. Once the deeper frozen layer eventually thaws, the increased vegetation and seasonal climate conditions allow the layers to act as a store-and-release cover system for the remainder of the summer. This cover system design for cold regions was first proposed by Barbour *et al.* (2011).

5.4 Barrier-Type Cover Systems

Barrier-type cover systems incorporate a low hydraulic conductivity layer to control the ingress of atmospheric water and in some cases, atmospheric oxygen. Three barrier layers that fall under this category are compacted clay, compacted sand-bentonite, and permanently frozen layer. A cover system incorporating a geosynthetic material or geomembrane is also a barrier-type cover system; these cover systems are reviewed in Section 5.5. Figure 5.3 illustrates barrier-type covers.

5.4.1 Compacted Clay Layer (CCL)

A compacted clay layer (CCL) in a mine waste cover system is generally between 30 and 50 cm thick. CCLs are typically constructed in lifts ranging in thickness from 15 to 25 cm. The actual lift thickness is dependent on soil characteristics, compaction equipment, and strength of the underlying materials. In general, thinner lifts are preferred due to more energy being delivered per unit volume of soil; thin lifts allow compactive energy to reach the base of the lift. A sheepsfoot roller is able to ‘knead’ adjacent lifts together to eliminate preferential flow paths, provided the height of the roller’s feet is greater than the lift thickness (Holtz and Kovacs, 1981). MEND 2.21.4 (2004) provides further details related to construction of a CCL; however, key aspects are reviewed below.

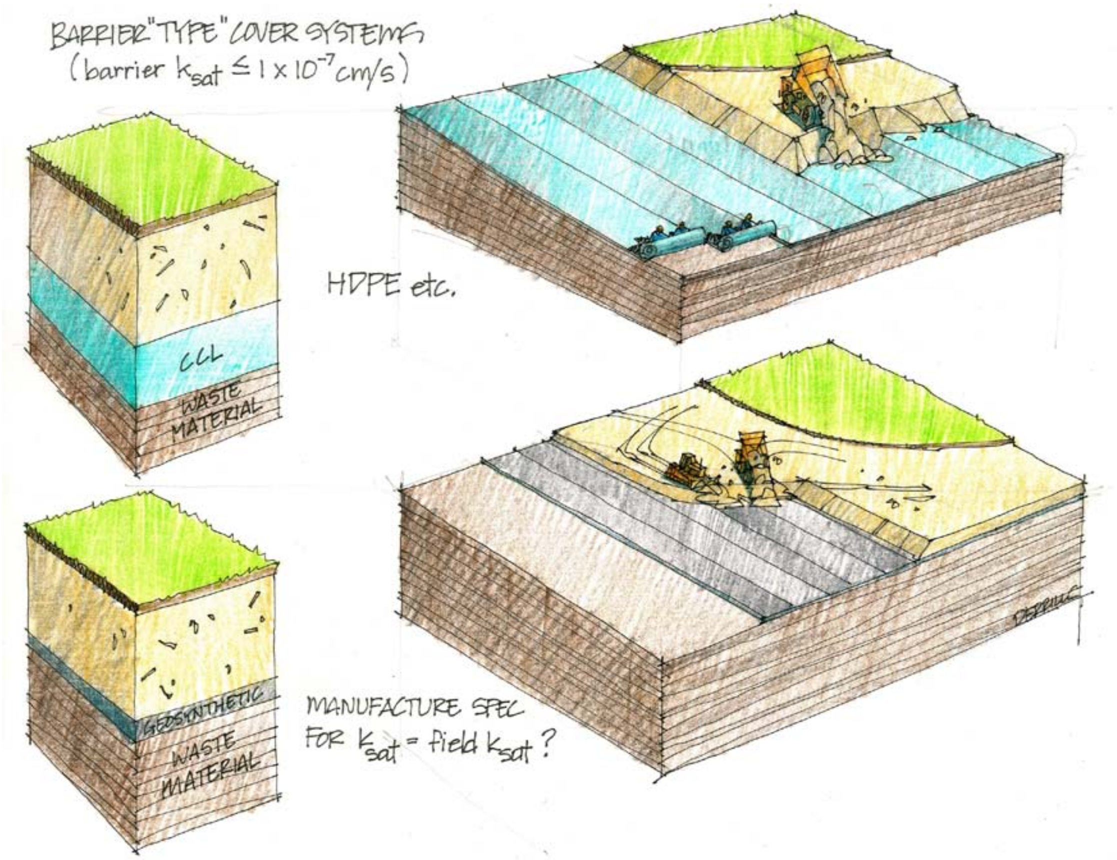


Figure 5.3 Barrier-type cover systems.

Moulding water content and dry density are the two key parameters that must be controlled during material placement and compaction, assuming that the required material is being used for construction and the underlying surface has been prepared properly. A compaction (or Proctor) test is conducted in the laboratory to develop a compaction curve for a given material, which is a plot of dry density versus water content. Moulding water content is the water content at which the soil matrix is compacted, and is referred to as the optimum water content (OWC) at the maximum level of density. In general, it is preferable to compact clay materials at one to two percent wet of OWC in order to achieve a minimum saturated hydraulic conductivity as reported in Lambe (1958) and Mitchell *et al.* (1965).

Field compaction trials are recommended prior to commencing full-scale construction of a CCL. Compaction trials are primarily done to ensure that the two important elements -- density and water content -- are obtainable throughout construction. The trials are also helpful to optimize equipment selected for construction and to identify unforeseen construction issues. If applicable, field trials should be constructed on both a horizontal and sloping area. This is important to evaluate variations in density obtained with compaction equipment when operating on a level or sloping surface. Finally, compaction field trials also provide an opportunity to evaluate and calibrate quality control testing equipment (e.g. a nuclear densometer) prior to the start of CCL construction.

Cover systems that include a barrier layer (such as a CCL) have a number of issues that affect their suitability in cold climates. Clay materials suitable for low hydraulic conductivity barriers (or materials with clay) may be locally limited or not available. If used, consideration must be given to protecting the layer from damage due to freeze/thaw cycling and/or root penetration. To keep the CCL from freezing (in areas without permafrost), a certain thickness of material above the barrier layer is required. An added benefit of the protective layer above the CCL is that it can be designed to act as a store-and-release layer where appropriate. CCL barriers must only be considered at sites where the depth of freezing has been evaluated.

5.4.2 Compacted Sand-Bentonite (CSB)

In circumstances where a cover system requires a water infiltration barrier but no appropriate fine-textured materials are available, a barrier can be constructed by combining available sand (or sandy material) with bentonite (Chapuis, 2002; Chapuis, 1990). Most bentonites are either sodium or calcium bentonite, and are characterized by the type of external cation (i.e. sodium or calcium) that is adsorbed onto the surface of the clay particle during mineral formation (Gleason *et al.*, 1997). Sodium bentonite is generally preferred over calcium bentonite because of its superior swelling capacity and lower hydraulic conductivity to water (Alther, 1987). The bentonite content in CSB layers is commonly in the 5-15% range of the host mineral material on a dry mass basis.

The hydraulic conductivity of CSB depends on several factors, including the quality of bentonite, bentonite content, particle size distribution of the host material, degree of blending bentonite into the host material, and level of compaction. A barrier layer that is made of CSB has similar issues to a CCL and is generally not recommended for cold climates. However, this material is less susceptible to freeze/thaw processes compared to a CCL. Wong and Haug (1991) found that there were no significant increases in hydraulic conductivity in unconfined sodium bentonite soil cover material after repeated freeze/thaw cycles. Chemical compatibility with the overlying cover soil, the underlying waste material, and infiltrating water must be confirmed to prevent cation exchange with the bentonite (Haug *et al.*, 1988).

It is common practice to specify a range of moulding water contents between optimum and plus 2% of optimum for compacted layers comprised of natural clay or silty materials. However, moulding water content does not appear to be a critical design factor in the construction of CSB layers based on the work of Haug and Wong (1992). Constructing CSB layers at somewhat lower moulding water contents is beneficial as wet sand-bentonite tends to stick to compaction equipment and has lower bearing capacity compared to drier sand-bentonite.

Proper blending or mixing of bentonite into the host material is essential in order to achieve the lowest possible hydraulic conductivity for a CSB layer. The bentonite product should be powdered (not granular) and air-dried to aid in blending. In addition, the material should be thoroughly mixed using one of two methods. The first method is to use a pug-mill, which generally results in better blending but costs more due to double-handling of the host material. The second method is to use a pulvi-mixer to blend bentonite applied to the surface of a lift of host material in the construction zone.

5.4.3 Permanent Frozen Layer (or Permafrost Aggradation Layer)

As described for the seasonally frozen capillary break diversion (Section 5.3.3), the infiltration capacity is 3 to 5 orders of magnitude less for a frozen material than for the same material in an unfrozen state. It is possible to take advantage of this phenomenon in permafrost zones to use the frozen material as a barrier layer. The cover material would contain the entire active layer, and a zone of permanently frozen ground (permafrost) would develop at the base of the seasonally frozen cover and progress downward. If the frozen material stays at a sufficiently high water content, it could be used as a barrier (see Figure 5.4). However, it should be noted that wetter materials take much longer to freeze than dry ones, so any saturated layer at depth will considerably slow the descent of the freezing front on an annual basis.

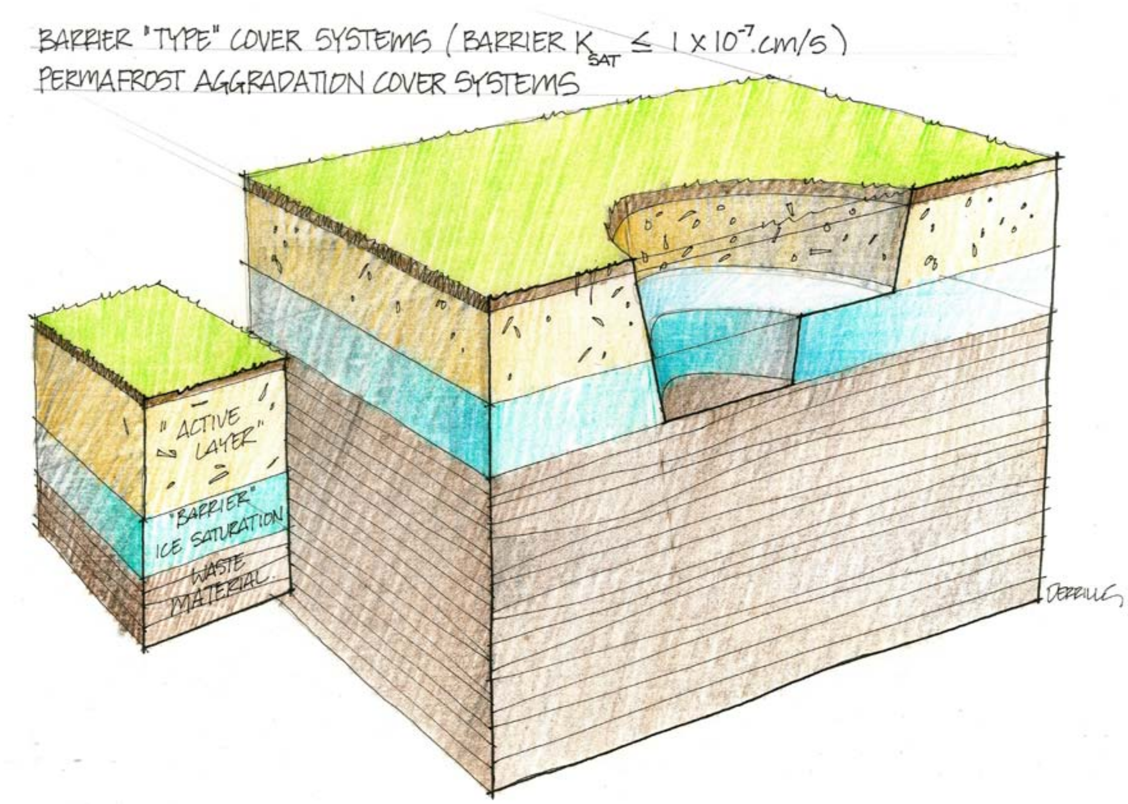


Figure 5.4 Permanently frozen barrier layer cover system.

The creation of a permanently frozen barrier layer within the waste itself requires that steps be taken to ensure that frozen conditions can be established and maintained, and that the waste is at a sufficiently high degree of saturation to ensure a low hydraulic conductivity. This barrier layer must remain below the active zone to maintain the reduced infiltration capacity for the required operating life of the cover system. The time required to develop permanent ground frost in deep thawed waste may be significant and alternative means of control may be required in the interim.

5.5 Cover Systems with Geosynthetic Materials

The use of geosynthetic materials within cover systems can dramatically reduce water infiltration and oxygen ingress. Inclusion of a geosynthetic material or geomembrane as part of a cover system design is often required if the performance objective of a cover system includes achieving low net percolation rates (e.g. <5% of precipitation). These materials include polypropylene (PP), chlorinated polyethylene (CPE), polyvinyl chloride (PVC), linear low-density polyethylene (LLDPE), high-density polyethylene (HDPE), geosynthetic clay liners (GCLs), and bituminous geomembranes (BGMs). Benson (2000) provides a general review of various geomembranes in the application of liners and cover systems for waste containment systems. Relevant physical properties (i.e. strength, durability, and permeability) are summarized and reviewed along with a discussion of advantages and disadvantages associated with each liner. Numerical relationships to assess the effective hydraulic conductivity of these liner materials are also presented.

Most geosynthetics are subject to degradation by sunlight, physical penetration, or damage (including vandalism) and must be protected with an earthen cover material. If one of the cover system objectives is to establish vegetation, then an overlying earthen layer suitable to this purpose must be included. A protective or growth medium layer above a geomembrane is at additional risk of solifluction due to the relatively impervious nature of the liner (hence increased water contents and pore-water pressures within the cover above the liner) and the potentially lower friction angle of the geosynthetic material (solifluction described in Section 2.2.4). Before placement of any geosynthetic liner, the surface of the underlying material must be carefully and uniformly compacted and must be free from sharp edges that may damage the geomembrane. An example of a cover system with engineered layers is shown in Figure 5.5.

Additional details are provided below on the three most common geosynthetic liners used in cover system applications; namely, HDPE / LLDPE, BGMs and GCLs.

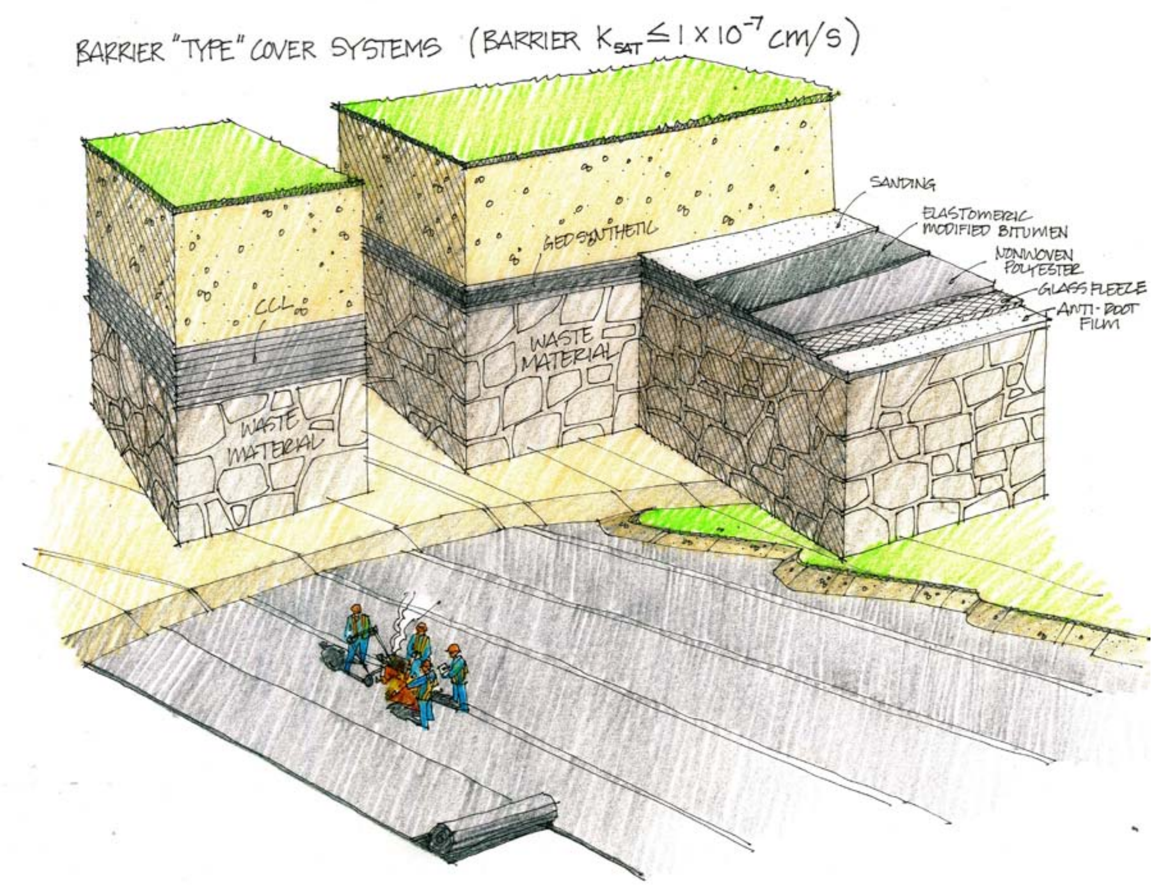


Figure 5.5 Barrier-type cover system with a CCL or BGM.

5.5.1 Polyethylene Geomembranes (HDPE / LLDPE)

Polyethylene geomembranes are thin polymeric sheets having a thickness between 1 and 3 mm. Research in the 1980s showed that HDPE is highly resistant to degradation by nearly all chemicals and as such, have been used extensively for landfill liner applications (August and Tatzky, 1984; Rowe, 2001). LLDPE is a more flexible material compared to HDPE, and is generally used in applications where additional puncture resistance is required or colder temperatures exist during installation (Lupo and Morrison, 2007). LLDPE can undergo much greater strain before failure than HDPE and as such, is often used in cover applications where distortion is more likely to exist (Benson, 2000). HDPE and LLDPE geomembrane panels are generally welded together in the field using specialized equipment.

Some of the factors that must be considered when designing with HDPE or LLDPE in cold climates include the following.

1) *Foundation preparation:* The performance of these layers is predicated on the presence of a smooth, well-compacted, foundation layer that limits the development of imperfections. Careful sloping of the foundation layer can also minimize a funnel effect in which lateral flow

along the liner is directed towards an imperfection within the liner by the topography of the foundation layer.

2) *Construction in cold climates:* These materials become brittle at cold temperatures and are difficult to place at low air temperatures (generally less than 5°C, although this varies for different products). This limits the construction season at cold region sites to relatively short periods of time. Welding geomembrane layers that are less than 40 mil thick is also difficult under cold temperatures. Minimum thicknesses of 60 or 80 mil should be considered for cold climates. Another significant problem is the extreme daily temperature range that black liners may experience, especially in late summer and early fall. These cause thermal expansion / contraction and can make it difficult to deploy, weld, and cover the liner. Trampolines and fold-over wrinkles may develop.
3) *Performance under freezing conditions:* Freezing can draw water upwards towards the base of the geomembrane liner, where it can form an ice layer directly under the liner. Thaw of this ice can in turn create positive pore-water pressures along the base of the liner, which leads to cover system instability when placed on a slope (i.e. plastic sitting on a layer of water). Modelling is recommended when considering this type of layer to evaluate coupled thermal and moisture regimes to evaluate the potential for this type of moisture migration.
4) *Drainage layer above the liner:* A drainage medium such as a coarse-textured soil layer or geo-composite drainage net (GDN) may be required to alleviate the build-up of positive pore-water pressures above the liner during wet conditions; if not addressed properly, a piping failure or shallow instability of the overlying cover soil can occur. To be effective, drainage layers must have adequate capacity and a freely flowing outlet; inadequate capacity or a poor outlet can result in stability problems more significant than those caused by not incorporating a drainage layer (Benson, 2000).
5) *Proper keying in along the perimeter:* In many cases, key-in trenches are specified for the sole purpose of securing edges of the geomembrane liner to the ground. However, in a cover system designed to minimize the entry of meteoric water and atmospheric oxygen, proper keying in of the geomembrane liner along the cover perimeter is critical to minimizing preferential flowpaths to the mine waste material.

Giroud (2000) found that 25% of localized defects in geomembranes are due to installation problems, with the most common installation defect being seaming faults. This accounts for up to 80% of flaws identified during installation of geomembrane liners. Giroud (2000) also found that 70% of detected leaks were due to mechanical damage caused during the placement of the overlying soil cover layer. Material should be spread in a continuous push with minimal turning to reduce heavy equipment puncture and equipment-driven stone puncture.

A well-designed and installed intact geomembrane liner may be expected to experience some degradation or aging with time (Rowe and Sangam, 2002). The key factors that lead to aging of geosynthetics are exposure to UV radiation, high temperatures, high oxygen concentrations, and various hazardous chemicals (Reddy and Butul, 1999). Koerner *et al.* (2005) present predictions of the lifetime of HDPE geomembranes, predicting lifetimes of 700 years or more when covered and at temperatures of 20°C or less.

5.5.2 Bituminous Geomembranes (BGM)

BGMs are a composite of several different materials that combine to provide a low permeability membrane. The layers include a geotextile, glass fibre fleece, bitumen, sand surfacing and an anti-root film. The geotextile provides the primary strength and puncture resistance. The glass fibre fleece provides additional strength and puncture resistance, but also provides ‘stiffness’ to the product. The primary function of the bitumen is to provide a low permeability for the geomembrane. The bitumen also acts as a coating to the core of the product (geotextile impregnated with bitumen); damage such as scratches or small indentations to the coating does not impair the performance of the geomembrane. The sand surfacing improves the engineering frictional resistance of the geomembrane and provides a non-slip surface to improve the health and safety of workers during installation. Finally, a Terphane film on the underside of the geomembrane provides an anti-root penetration barrier.

BGMs are manufactured in ~5 mm thick sheets that are delivered to the site on rolls. The mass per unit area for some BGM products is in the range of 6,400 g/m^2, about four times that of a 60-mil HDPE geomembrane. Seams are made by welding adjacent panels together using a propane torch. A BGM has a low coefficient of thermal expansion making it insensitive to temperature variations during installation and service. It also remains ductile at low temperature (given the appropriate specification of BGM is utilized), making it suitable for cold weather installation (Brodie *et al.*, 2010). An appropriate thickness of cover soil is required to protect the liner from UV radiation, as well as to provide a rooting zone for vegetation. Similar to polyethylene geomembranes, caution must be used when placing cover soils on top of BGMs and the potential need for a drainage layer above the BGM must be assessed.

A BGM will flow over time, leading to some degree of liner thinning. However, most BGM products have a high friction angle and do not become brittle at cold temperatures. This is highly advantageous in cold climates as these liners can be placed at temperatures as cold as -20°C. If winter construction is unavoidable, the cost premium for BGMs may become justified based on the ease of constructability. These liners are practical for cold regions applications. However, a similar issue as described above for geomembrane liners can occur (i.e. movement of moisture to the underside of the liner). Hence, it is recommended that evaluations be made of coupled thermal and moisture migration when considering this type of cover system design.

5.5.3 Geosynthetic Clay Liners (GCL)

GCLs are geo-composites consisting of a thin layer of sodium bentonite (~7 to 10 mm) sandwiched between two geotextiles or glued to a geomembrane (Estornell and Daniel, 1992). GCLs are manufactured in large sheets that are delivered to the site on rolls. Once unrolled, seams are made by overlapping adjacent GCLs and a strip of powdered bentonite is added in the seam. Angular rocks or other sharp objects should not be present in the foundation or overlying growth medium material to avoid puncturing the GCL; however, unlike a polyethylene or bituminous geomembrane, the bentonite in the GCL, when hydrated with adequate confining pressure (i.e. >0.3 m cover soil), has the ability to swell around the object puncturing the GCL. An appropriate thickness of cover soil is required to prevent dehydration of the bentonite over time; otherwise, desiccation cracks that develop in the thin bentonite layer may not swell shut during rewetting (Lin and Benson, 2000).

The saturated hydraulic conductivity (k_{sat}) of GCLs can vary depending on the product and manufacturer, but in general, specified maximum k_{sat} values are below 1 x 10^{-9} cm/s (Daniel *et al.*, 1997). An effective k_{sat} of 5 x 10^{-9} cm/s is generally recommended for GCLs to account for some leakage that occurs through the seams. The performance of a GCL can be enhanced by laminating a geomembrane (GM; e.g. polyethylene) to one side of the GCL. A GCL including a laminated GM is typically abbreviated as GCL-L. The GM included in a GCL-L decreases leakage rates through the liner by providing an additional hydraulic barrier, and can provide some protection from pore-water with chemistry that may negatively affect the bentonite performance in a GCL (see below).

Multi-valent cations (e.g. Ca and Mg) in pore-waters can replace the inter-layer sodium ions within the bentonite layer and decrease the swelling potential of a GCL (Benson and Meer, 2009). Meer and Benson (2007) exhumed and tested GCL samples from final covers at four different landfills in the USA. Exchange of Ca and Mg for Na occurred in all of the exhumed GCLs, and the bentonite had a swell index similar to that for Ca or Mg bentonite. Hydraulic conductivities of the GCLs varied over 5 orders of magnitude regardless of cover soil thickness or presence of a geomembrane liner. Comparison of these data with other data from the United States and Europe indicates that exchange of Ca and/or Mg for Na is likely to occur in the field unless the overlying cover soil is sodic (sodium rich). Meer and Benson (2007) further state that k_{sat} values in the range of 10^{-6} to 10^{-4} cm/s should be expected if cation exchange occurs coincidently with dehydration; the effects of dehydration are permanent once the water content of the GCL drops below ~100%. The investigators also found that the most common test method used to assess compatibility between bentonite and cover soils (i.e. ASTM D6141) is unable to discriminate between conditions that cause long-term alterations in the exchange complex and k_{sat} of GCLs. Meer and Benson (2007) concluded that more research is needed regarding installation methods that ensure rapid hydration of GCLs, protective measures that will prevent dehydration, and test methods that can be used to diagnose whether a GCL is likely to undergo large increases in ksat when used in a cover system. Osicki *et al.* (2004) describe an alternative compatibility test method for materials comprising bentonite, which is based on viscosity as opposed to swelling potential.

The long-term increases in hydraulic conductivity as a result of repeated freeze/thaw cycling are minimal for GCLs (Kraus *et al.*, 1997). Podgorney and Bennett (2006) subjected three GCLs to 150 freeze/thaw cycles at effective stresses of 20 kPa and 60 kPa, and found no appreciable changes in the GCLs' hydraulic conductivity (~1 x 10^{-9} cm/s). This is attributed to the fact that the hydrated bentonite in a GCL is very soft and compressible such that after the ice lenses thaw any micro-cracks that have developed are closed under only minimal overburden pressure. Adu-Wusu and Yanful (2006) found that freeze/thaw may have compromised the integrity of a GCL cover; however, it is possible that cation exchange had affected the ability of the GCL to self-heal. This, again, stresses the importance of determining chemical compatibility between the GCL and the environment.

Similar to polyethylene and bituminous geomembranes, caution must be used when placing cover soils on top of GCLs and the potential need for a drainage layer above the GCL must be assessed. A slope stability analysis is recommended when a geosynthetic layer is incorporated in a multi-layer earthen cover placed on relatively steep slopes.

GCLs are popular geosynthetic barriers in temperate climates. However, this product is generally not recommended for cover system designs in cold climates due to the following concerns.

1) The fibres are small in these layers, which will lead to an increased rate of deterioration. The lifespan of these layers are approximately 20 years—a relatively short life span for a cover system.
2) There can be considerable internal movement from freeze/thaw of the waste and cover materials so the layer is susceptible to damage in cold climates.
3) In cold climates, any holes that are present are susceptible to piping of the bentonite layer.
4) The friction angle of the bentonite layer is low; hence, when placed on a slope, the GCL must rely on the friction characteristics of the fibres (and as noted above, the fibres are susceptible to deterioration over time).
5) The bentonite may not stay hydrated under cold climate conditions.

5.6 Saturated Soil or Rock Cover Systems

Disposal of waste below a water cover (Figure 5.6) is one of the most effective methods for limiting sulphide oxidation (and thus ARD) due to the significant limitation of oxygen transport. As discussed previously, this document addresses only soil cover design, not water covers. It is possible however, with the proper conditions and careful design, to create saturated waste deposits that are effectively 'water covered' without open water. This type of approach has the potential to have greater longevity than other closure solutions.

The objective of a saturated cover is to cover the waste with a layer of water to restrict oxidation and acid generation. The key design consideration is to raise the water table above the contaminated waste by placing an inert material, usually a coarse gravel, as a cover and maintain the water table within this layer. The water table can fluctuate within the gravel cover, but the cover must be designed so that the water table does not fall below the surface of the waste, nor breach the surface and express as standing water. The water table is often controlled within the inert layer through the use of a spillway, with input provided from groundwater and/or surface water.

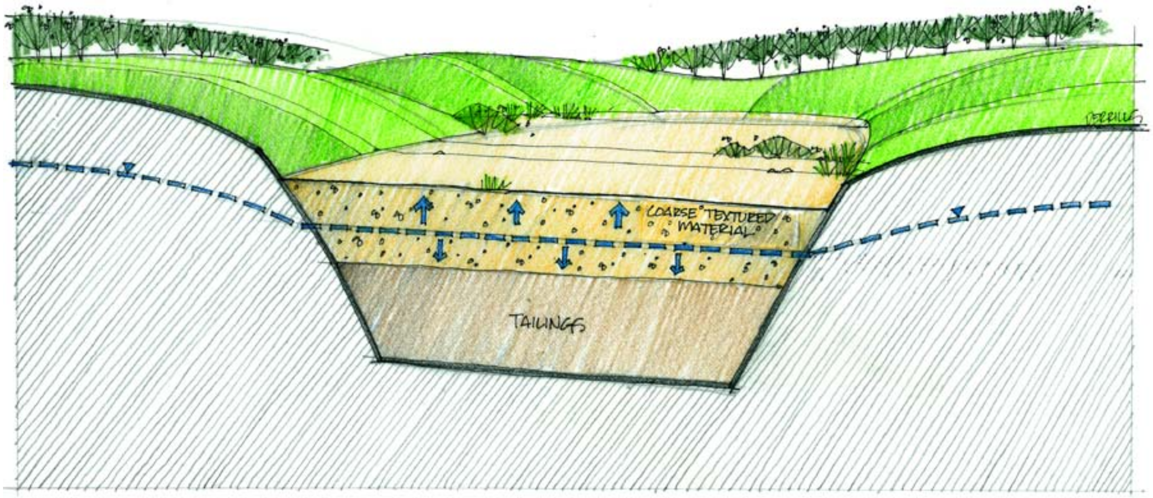


Figure 5.6 Saturated soil or rock cover system.

Use of a saturated cover must consider climate, topography, hydrology and hydrogeology, and the hydraulic properties of the waste and cover material. The GARD Guide (GARD, 2011) has a brief discussion on controlling the water table above the waste to limit ARD (referred to as a Partial Water Cover in the GARD Guide). Special considerations in cold regions include the potential for thawing of permafrost in the ground surrounding a saturated cover, and the potential for freeze/thaw of fine-textured waste material (e.g. tailings) heaving and mixing with the inert layer above.

Depending on the climate, the saturated cover would likely require water to be fed from either surface water diversion or groundwater to maintain saturation. The water table would be at a maximum after each spring's freshet. By using gravel, evapotranspiration is minimized, thereby limiting drying of the cover and maintaining sufficient water volume to cover the waste.

5.7 Summary of Cover System Design Alternatives for Cold Regions

A summary of the information presented in the previous sections is shown in Table 5.1.

Table 5.1

Summary of cover types, cover objectives, and adaptations for cold regions applications.

Cover Type	Primary Cover Objectives	Performance Expectations	Requirements	Cold Regions Issues	Cold Regions Adaptations/Mitigation
Erosion Protection	• Stabilize landform by reducing erosion of waste.	• Reduce waste exposure and erosion.	• Requires non-reactive waste. • Requires no potential for contaminant uptake by vegetation.	• Failure of surface water drainage system. • Long time frame to establish vegetation.	• More robust landform design to prevent erosion. • Use of mulch, gravel, or rip rap to control erosion in the short to long term.
Store-and-Release	• Reduce net percolation. • Enhance vegetation development.	• Net percolation of 10 – 40% of precipitation.	• Requires appropriate material. • Requires appropriate climate conditions.	• Availability of suitable material. • Failure of surface water drainage system.	• Possible use of tailings to increase fines. • More robust landform design to prevent erosion.
Enhanced Store-and-Release	• Reduce net percolation. • Enhance storage for high infiltration events. • Enhance vegetation development.	• Net percolation of 10 – 15% of precipitation.	• Requires appropriate materials, including a lower k material. • Requires appropriate climate conditions.	• Availability of suitable materials. • Freeze/thaw cycles increasing k of lower-k layer. • Failure of capillary break due to fines migration to underlying coarse textured layer. • Failure of surface water drainage system.	• Use of seasonally-frozen, capillary-break diversion layer. • More robust landform design to prevent erosion.
Barrier-Type (CCL, CCB, PAL)	• Low net percolation.	• Net percolation of 5 – 10% precipitation.	• Requires suitable materials, typically not locally available. • Requires stable and trafficable surface.	• Prohibitive cost. • Implementation issues such as mob/demob of specialized equipment, QA/QC requirements, short installation season. • Frost action leading to consolidation, frost heave, increased k, leading to failure of barrier layer. • Failure of surface water drainage system.	• Use of permanently frozen layer. • More robust landform design to prevent erosion.
Barrier-Type (Geo-Synthetics)	• Very low net percolation.	• Net percolation of <5% of precipitation.	• Requires geo-synthetics transported to site. • Requires stable and trafficable surface.	• Prohibitive cost. • Implementation issues such as mob/demob of specialized equipment, QA/QC requirements, short installation season. • Failure of barrier layer due to frost action (consolidation / frost heave) or cation exchange (increased k). • Failure of surface water drainage system.	• Use of synthetics better suited to cold climates (e.g. BGM). • More robust landform design to prevent erosion.
Saturated Soil or Rock	• Maintain saturated conditions in waste material.	• Limit oxygen transport to waste.	• Requires specific location (e.g. pit) where waste is below natural water table.	• Thawing of permafrost surrounding waste. • Heave of saturated fine-textured materials (e.g. tailings). • Failure of surface water drainage system.	• More robust landform design to prevent erosion.

6 COVER SYSTEM DESIGN METHODOLOGY FOR COLD REGIONS

The objective when designing a cover system is to meet the defined performance criteria. The level of control required by the cover system (e.g. oxygen ingress, net percolation, erosion control) defines these performance criteria. Figure 6.1 puts forward a methodology for developing site-specific performance criteria for a cover system designed to control ARD / metal leaching and/or gas fluxes. The methodology links the predicted performance of a cover system to groundwater, surface water, and air quality impacts.

The iterative process presented here for cover system design allows for the development of a cover design that meets all the site closure objectives, including objectives such as water quality, aesthetics, stakeholder needs, and cost. Historically, cover design has often focused solely on downstream impacts, such as water quality. A single cover design with given thicknesses of various layers would be designed to reduce impacts to downstream receptors, often by reducing downward net percolation. The actual translation of this cover design to a two-dimensional landform would often come much later in the design process, typically long after the cover design had been finalized. In cold regions especially, failure of the surface water drainage over the two-dimensional landform is one of the most critical and likely failure modes of a cover system (described in Section 2.3.1). The process for cover design described here integrates landform design early on in the design process, so that a stable landform is one of the cover design objectives, and landform failure is integrated into risk analyses of potential cover alternatives. By integrating landform design into the cover design phase, the likelihood of landform failure is greatly reduced.

The following sections discuss in more detail the various steps of the cover system design methodology illustrated in Figure 6.1.

6.1 Define Cover System Design Objectives

The objectives of the cover system must be developed in concert with the site-wide closure plan, as depicted by the dashed line connecting these two topics in Figure 6.1. This is the first step of any cover system design process. For example, the cover system design objective may be dust and erosion control to minimize contamination of air, plants, and water from arsenic-laden tailings. In the case of reactive material, the cover system design objective may be to reduce net percolation into the waste to less than 1% of precipitation to reduce contaminant loading to surrounding water bodies to an acceptable level. With clearly defined objectives, the cover designer has a more defined scope to proceed with site and material characterization and subsequent development of feasible cover system design alternatives. Unfortunately, all too often cover system designs are developed with no consideration of impacts to the receiving environment.

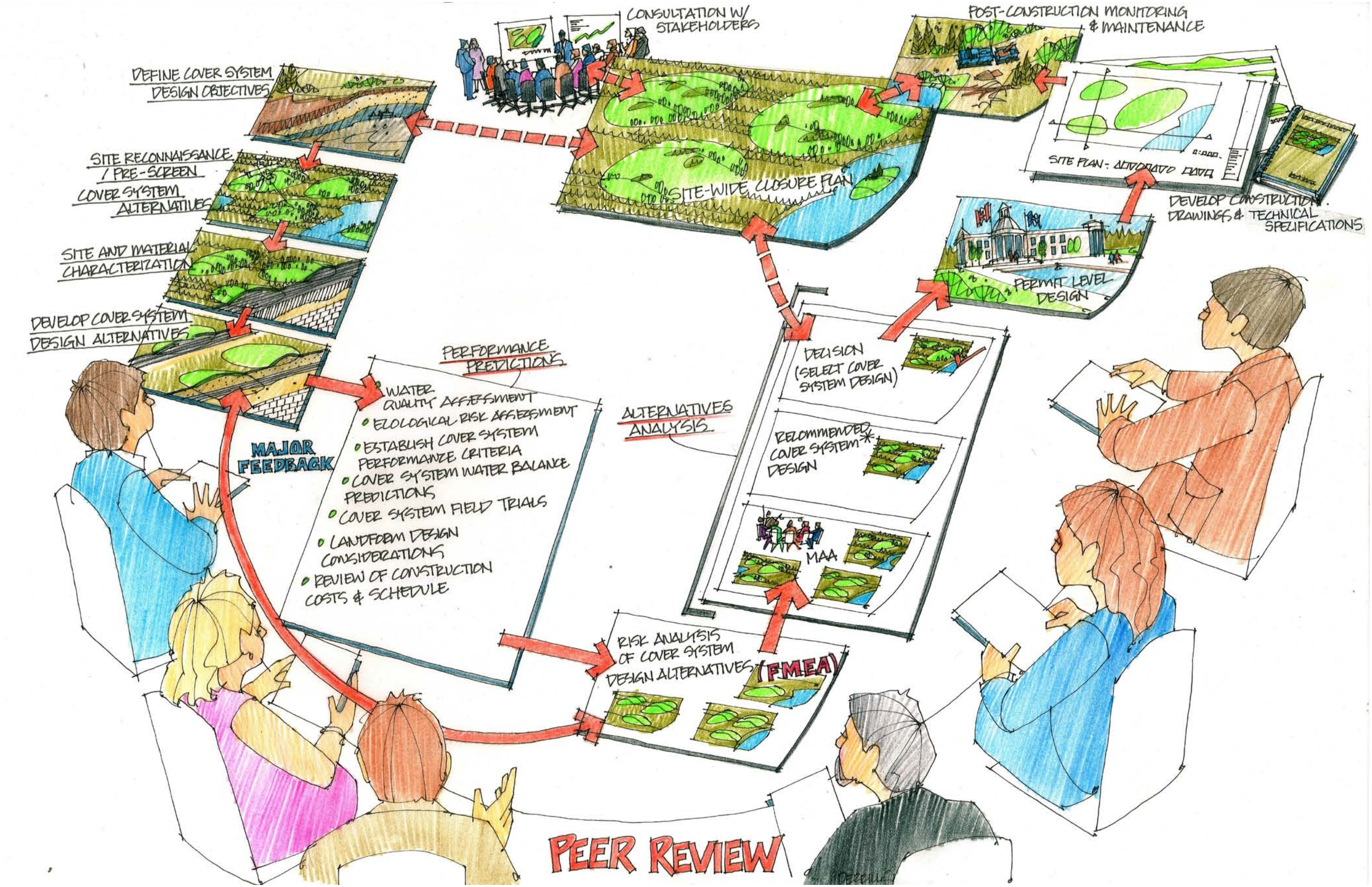


Figure 6.1 Flow chart for the cover system design process.

The cover system design objectives must be site-specific. Site-specific objectives allow the needs of all the stakeholders to be included in the design process from the beginning. These objectives may need to be revised once further field investigations and an impacts analysis (e.g. water quality or ecological risk assessment) are completed.

6.2 Site Reconnaissance / Pre-Screening of Cover System Alternatives

Site reconnaissance is a fundamental step for cover system design projects in order to develop an appropriately scoped site and material investigation program. Based on initial observations of the reactivity of the waste material(s) and available borrow materials for cover construction, possible cover system designs noted in Chapter 5 can be pre-screened to develop design alternatives that should be considered for further analysis. Tasks that are typically completed during site reconnaissance include, but are certainly not limited to:

- Air photo interpretation to search for potential borrow sources, cold region terrain features, natural landforms as analogues for landform design, and native vegetation;
- Search of site and company archives (if they exist) for historical investigations on such topics as geochemistry, available borrow materials, hydrogeology, hydrology, etc.; and
- Collection of digital photos of pertinent objects including the waste storage facility, potential borrow areas, cold region features, seepage faces, native vegetation, etc.

6.3 Site and Material Characterization

Proper site characterization is paramount for the design of an appropriate, sustainable mine waste cover system, particularly for sites situated in cold regions. The following elements should be characterized when a soil cover system is being designed in a cold region:

- Frozen ground conditions;
    - Spatial and temporal (both short-term [seasonal] and long-term [design life]) variability in active layer depths, as well as permafrost conditions;
- Climatic conditions;
    - Development of long-term climatic data set for design;
    - Consideration of possible / probable changes in long-term climatic data due to climate change;
- Geochemical and geotechnical characteristics of the waste material;
- Hydrogeological setting of the waste storage facility;
- Availability of potential cover materials;
- Impact of removal of cover material from borrow area(s),

- Availability and characteristics of materials suitable as growth media, where revegetation is desired, and
- Surrounding vegetation, both to guide revegetation planning, where desired, to provide information on probable mature plant communities to assist in development of long-term water balances for the cover, and to provide information on probable ingress of volunteer vegetation where revegetation is not desired.

6.4 Development of Cover System Alternatives

Cover system design alternatives for a waste storage facility must be selected based on climatic conditions, available cover materials, and the specified design objectives of the cover system. It is critical that the design alternatives are tailored to the characteristics of the specific site and not chosen based solely on the design having ‘worked at another site’. Consideration of the chemical, physical, and biological processes that could alter the properties of the cover material (e.g. saturated hydraulic conductivity), and thus influence long-term performance of the cover system, must be included in this design stage (INAP, 2003). This aspect is fundamental in ensuring that a potentially fatal flaw in the design is not introduced.

It is also important to realize that more than one cover system design might be the best option for closure of a single waste storage facility. For example, consider a reactive tailings impoundment with coarse-textured tailings at a higher elevation (i.e. the beach area) and fine-textured tailings or slimes at a lower elevation. In many cases, given the topography and hydrogeological setting, the slimes area supports ponded water; draining this area to construct a soil cover might not be practical. A barrier-type cover system might be warranted for closure of the beach area, while a saturated soil or rock cover might be the best option for the slimes area. Runoff waters from the reclaimed beach area could be directed to the slimes area, thereby maintaining saturated conditions and limiting the ingress of atmospheric oxygen.

The conceptual design stage must also include cover system design variations that account for the final landform, which will encompass different aspects, slopes, and therefore varying thermal regimes. Spatial variability is an important factor to investigate with respect to frost heave, settlement, ponding, etc.

Finally, consideration for construction issues (e.g. constructability, complexity, difficulty with quality assurance / control) must also be included in the conceptual cover system design stage. In cold regions, it is important to consider construction issues early in the design stage due to considerable limitations in borrow material availability, high construction costs, and short construction seasons.

6.5 Performance Predictions

Performance predictions of the selected closure scenarios for a waste storage facility are required in order to determine the preferred cover system design. A water quality and, in some cases, ecological risk assessment, often referred to as an impacts analysis, is needed to determine the required control on water infiltration and oxygen ingress for closure of the waste storage facility (O’Kane and Wels, 2003). The goal is to select a closure scenario that will attenuate peak concentrations for contaminants of concern in the receiving environment to levels that can be assimilated without adverse impact over the long term. Additional analyses that might be necessary to support the preferred cover system design(s) include predictions of:

- Water balance fluxes (soil-plant-atmosphere modelling);
- Thermal regime (frost heave, freeze/thaw cycling, convective cooling and permafrost thawing);
- Tailings consolidation; and
- Potential uptake of salts and/or metals into the rooting zone.

If time and budget constraints are not an issue for the project, then constructing and monitoring performance of cover system field trials are recommended to gain site-specific data for refining numerical or analytical model predictions. Additional information is provided below on cover system field trials as well as other key aspects of performance predictions.

6.5.1 Impacts Analysis

An impacts analysis quantifies the relationship between cover performance criteria and environmental impacts. The specific environmental impacts to be evaluated depend on the objective(s) of the proposed cover system design in conjunction with the site closure plan and local regulations. Environmental impacts most commonly evaluated during cover system design include:

- Impacts on surface water quality;
- Impacts on groundwater quality;
- Impacts on air quality;
- Impacts on vegetation; and
- Impacts on wildlife.

Solute transport predictions using a 2-D or 3-D groundwater flow model are often warranted to determine the required control on water infiltration and/or oxygen ingress for closure of a waste storage facility. A key element for solute transport modelling is to develop representative source terms for contaminants of concern, which considers water and oxygen infiltration rates specific to each closure scenario. A geochemical speciation model such as PHREEQC is often used to help interpret available geochemical characterization data and develop a range of realistic *in situ* pore-water source concentrations. Changes in the source terms with time are approximated based on available geochemical data and evolution of the geochemical regime within the waste material. The groundwater flow model is then used to evaluate the effect of varying levels of cover performance on downstream receptors and where applicable, the anticipated length of time for operating a site water treatment plant. For example, the effect of 20% net percolation through the cover system and resulting seepage over the long term can be compared against the results of 5% net percolation. The flow models also provide estimates of the length of time required for the phreatic surface in the waste storage facility to equilibrate with local hydrogeologic conditions.

If the impact analyses indicate that none of the proposed cover system designs are likely to result in compliance, have acceptable risk, or be economically viable, then the proposed cover system designs must be modified and the analyses must be repeated (Figure 6.1). If these analyses indicate required modifications to the cover system design that are deemed too expensive or not achievable, then this would constitute a ‘fatal flaw’ and other cover system design alternatives must be considered.

6.5.2 Soil-Plant-Atmosphere Numerical Modelling

Numerical analyses may be carried out to develop quantitative relationships between cover system properties (material type and layering, cover thickness, slope angle, vegetation density / mix, etc.) and cover system performance criteria (e.g. net percolation, oxygen ingress, erosion, available water holding capacity). These quantitative relationships are generally developed by constructing numerical models that simulate cover system performance (e.g. a soil-plant-atmosphere numerical model). The cover system properties are then systematically varied within a plausible range and the corresponding cover system performance is simulated. The scope and extent of such sensitivity analyses will depend on the complexity of the cover system design, the range of materials and material properties available for cover construction, and site-specific climatic conditions.

The cover system performance criteria for which a sensitivity analysis is usually performed include net percolation, surface runoff, sediment loss, oxygen ingress, vegetation density, vegetation diversity, or some other site-specific criteria. Additional site-specific cover system design parameters may include slope angle, slope length, level of compaction effort, natural variability in soil properties, compaction moulding water content, layering of the cover system, etc. The quantitative relationships between cover system design parameters and cover system performance criteria provide a framework for evaluating the range of environmental impacts for different cover scenarios, and ultimately, to select the most cost effective cover system design.

The general purpose for conducting soil-plant-atmosphere numerical modelling is to gain an understanding of the key processes and characteristics that will control performance. The physics describing soil-plant-atmosphere interactions are highly non-linear; consequently, iterative numerical techniques are required in simulations. An important aspect of soil-plant-atmosphere numerical modelling is the ability to predict actual evapotranspiration based on potential evaporation and predicted soil suction.

MEND 2.21.4 (2004) outlines the approach and methodologies for modelling mine waste cover systems in general. Several commercial soil-plant-atmosphere, or surface flux boundary, numerical models are available to predict performance of cover systems. These models have limited ability to simulate ground freezing and thawing and they use empirical relationships to simulate the complex effects of snowmelt, snow redistribution and interception, infiltration into frozen soils, hillslope water movement over permafrost, actual evaporation and runoff from frozen surfaces, and radiation exchange from complex surfaces. Soil-plant-atmosphere modelling is usually limited to simulating only summer seasons, and artificial hydrographs are developed to simulate available moisture contributing to snowmelt infiltration after the ground has thawed. Sensitivity analyses are then used to examine the effects of soil-structure changes arising from freeze/thaw effects (MEND 1.61.5b, 2010).

6.5.3 Thermal Modelling Predictions

Ground thawing and freezing strongly influence the energy balance and hydrology in cold region climates, as well as the physical integrity of many cover systems. Methods to simulate this vary in algorithm type, soil parameterization, representation of unfrozen water content, and latent heat (Zhang *et al.*, 2008). Using these methods, frost heave, freeze/thaw depths, convective cooling, or permafrost thawing may be predicted.

6.5.3.1 Numerical Modelling

Numerical algorithms are able to simulate heat transfer through porous media simultaneously including soil, water, ice, and air, in order to determine ground freezing depths and convective cooling. Thermal numerical modelling can be used to simulate permafrost thawing and convective cooling of tailings and waste rock.

Inputs to thermal numerical models include unfrozen water content, thermal conductivity, and volumetric heat capacity. Boundary conditions required are temperature or heat flux.

Thermal numerical modelling can be used in conjunction with seepage modelling to simulate the effect of moving water on heat transfer; however, in general typical thermal numerical models are not capable of modelling the very complex physical coupling between water, ice, air and soil that occurs during ice lens formation and freezing.

Soil-plant-atmosphere modelling methods of water balance are well established for non-frozen conditions, and thermal modelling is well established for geotechnical problems associated with pipelines or construction in cold regions. However, there has been limited water / energy balance modelling completed to simulate the fully coupled process over a continuous cycle of frozen and non-frozen conditions (i.e. an entire year). Current practice is to simulate thermal regimes using conventional geothermal modelling followed by conventional soil-plant-atmosphere modelling that takes into account unique controls of the underlying thermal regime on hydrologic processes.

6.5.3.2 Analytical Methods

Soil freezing rates, freezing and thawing depths, and frost heave can be modelled with numerical methods, but are typically modelled using analytical solutions. MEND 1.61.5b (2010) describes a methodology for calculating soil freezing rates as well as freeze/thaw depths. The following describes an overview of frost heave prediction methods.

Frost heave (defined in Section 2.2.1) estimation is used to determine the potential for detrimental effects on cover systems in cold regions. For example, the estimation of frost heave in tailings may be desired to determine the potential for damage to a geomembrane layer within the overlying cover system.

The most practical methods of estimating frost heave are based on segregation potential (SP) theory—Konrad’s method and Saarelainen’s method. These methods are described in detail in Doré and Zubeck (2009).

Konrad’s method is:

$$h = 1.09 \cdot SP \cdot T_G \cdot t_{fs} \tag{6.1}$$

where:

SP = segregation potential (m^2/ °C day),
T_G = thermal gradient (°C/ m), and
t_{fs} = duration of the freezing period in the subgrade soil.

SP describes the ratio of velocity of pore-water entering the unfrozen soil to the temperature gradient in the soil (Konrad, 2005). SP is a function of soil porosity, soil type, overconsolidation ratio, pore-fluid chemistry as well as pressure at the freezing front, overburden pressure and number of freeze/thaw cycles. SP may be measured in the laboratory by subjecting a soil sample to a freezing test and controlling the above variables to conditions as estimated in the field (Konrad, 2005). When laboratory testing is not feasible, SP may be estimated. Konrad (2005) describes an empirical estimation method based on the fines fraction of the soil (d_{50}(FF)), overburden pressure (P_e), specific surface area (S_S), and ratio of the material’s water content to its liquid limit (w/w_L). If the soil pore-fluid is saline then salinity also affects SP. Konrad (1990) describes a method to estimate SP to account for salinity.

Saarelainen's method uses similar information as Konrad's method, but assumes that the thickness of the frozen soil remains as a constant, and is proportional to the SP of the soil in question (Doré and Zubeck, 2009). Heave can be predicted using Equation 6.2:

$$h = \frac{2 \cdot SP \cdot (x - d)}{\left(\frac{x}{\sqrt{FI_s}}\right)^2} \qquad [6.2]$$

where:

h = average frost heave,
SP = segregation potential (m^2/ °C day),
x = depth of active layer (m),
d = depth of cover material (m), and
FI_s = surface freezing index.

6.5.4 Tailings Consolidation Analysis

The objectives of a tailings consolidation analysis are to assess the magnitude of future deformation (settlement) of tailings during and following cover placement, and to estimate the amount of contaminated pore-water that may be released during this process. Consolidation of tailings and resultant differential settlement may affect the integrity of a cover system, particularly ones that include a soil or geomembrane barrier layer. Consolidation in cold regions is caused by various processes, including thaw consolidation due to thawing of ice lenses, self-weight consolidation due to drain-down of the phreatic surface, and loading consolidation following cover placement and dissipation of excess pore-water pressures. Desiccation due to atmospheric drying can also cause consolidation of the upper tailing profile.

Thaw consolidation depends on consolidation and soil structural changes that occurred during the previous freezing cycle. In fine-textured soils (silts and clays), slow freezing permits local ice segregation that, upon thawing, generates more water than can be absorbed by the soil skeleton and results in settlement (Andersland and Ladanyi, 2004). A simple procedure for estimating thaw settlement involves placing about 0.03 m^3 of frozen soil in a container and allowing it to thaw. The amount of water collected, in excess of that absorbed by the soil, corresponds to the thaw settlement. See Figure 6.2 for thaw settlement measurements of natural soils in cold regions.

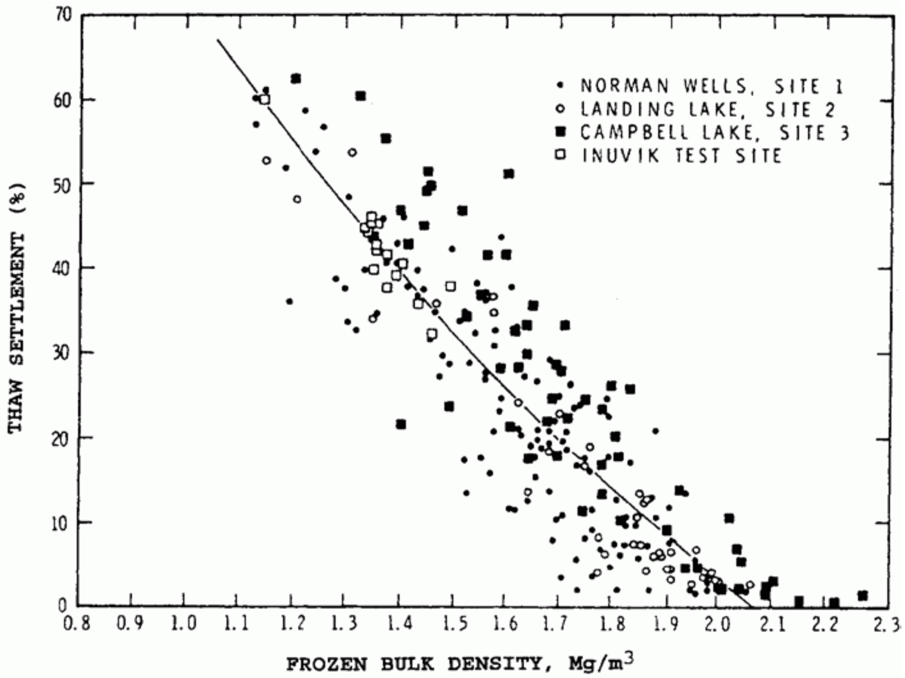


Figure 6.2 Thaw settlement measurements of Mackenzie Valley soils (Reprinted with permission from *North America Contribution: Permafrost Second International Conference*, 1973, by the National Academy of Sciences, Courtesy of the National Academies Press, Washington, D.C.).

Thaw settlement may also be estimated. For a given layer of frozen tailings of thickness H_f, thaw settlement (ΔH) may be calculated as follows as a function of the frozen (ρ_{df}) and thawed ($\rho_{d,th}$) dry densities (Andersland and Ladanyi, 2004):

$$\Delta H = H_f \left[1 - \frac{\rho_{df}}{\rho_{d,th}} \right] \tag{6.3}$$

The presence of a surface layer can influence thaw settlement of an underlying soil layer with different thermal and geotechnical properties. Cold regions natural soil profiles are often characterized by a surface layer of organic soil that overlies and protects a frozen mineral soil. Cover systems in cold regions will consist of layers of materials with different thermal and geotechnical properties, which will lead to complications in thaw settlement estimates.

Self-weight or loading consolidation may be estimated using large-scale strain analysis software packages such as: CONDES0 (Yao and Znidarcic, 1997) and FSConsol (Thode and Fredlund, 2009). CONDES0 is public domain software, while FSCosol is commercial software. These software packages do not directly output strength in tailings but output void ratio with time, which can be used to get effective stress in tailings. An empirical relationship between effective stress and shear strength can then be used to calculate strength. Seepage velocities may also be obtained from modelling to predict release of pore-waters, but they are a boundary condition and not a direct output of the model; thus, seepage velocities can only be determined by a method of trial and error to match other conditions or requirements.

Key material properties for large-strain consolidation analyses include void ratio vs. effective stress, hydraulic conductivity vs. void ratio, and specific gravity of tailings material.

Various stages of tailings consolidation should be simulated to account for construction of the cover system. These include:

- Period of filling (with self-weight consolidation only);
- Period of desaturation (prior to cover placement); and
- Period after cover placement until full consolidation.

6.5.5 Solute Uptake Assessment

The primary objective of a solute transport analysis is to assess whether transport of solutes from the waste material into the overlying cover system would be great enough to limit vegetation growth. Plant growth may be negatively affected for pore-water EC greater than 4,000 μS/cm (Larcher, 1995), or when pore-waters become slightly saline.

Solutes may be transported into a vegetated cover layer by diffusion and advection. Advective solute transport requires bulk water flow from the waste into the cover profile. The seepage flow velocities within the cover profile must be known to calculate advective solute transport. Typically, a soil-plant-atmosphere model or a seepage model is first used to calculate flow velocities, which are then used as input for solute transport modelling.

The material properties required for solute transport modelling are the bulk diffusion coefficient for the solute and the material (using a function like that described by Olesen *et al.* (1996)), the relationship between diffusion coefficient and moisture content of the soil (using an empirical relationship like Millington and Quirk (1961)), and longitudinal and transverse dispersivity coefficients. Boundary conditions such as source concentrations and initial solute concentrations in the pore fluid are required.

Solute transport modelling, especially when coupled with soil-plant-atmosphere modelling, has limitations:

- Preferential seepage pathways may not be accounted for in the model. Preferential seepage would result in less efficient flushing of salts and greater salinity levels in the vegetation layer;

- Transport phenomena that can lead to increased transport rates of contaminants such as anion exclusion and diffuse double layer interactions may not be accounted for in the model;
- Site-specific data are rarely available for inputs such as diffusion and dispersivity coefficients, requiring these coefficients to be estimated. Temperature correction is important for cold regions, as most empirical estimations assume temperatures of approximately 20°C;
- Adsorption of solutes may not be considered in some models. This is a reasonable assumption for relatively conservative solutes (e.g. SO_4). For other solutes that have stronger interactions with soil particles, adsorption would delay the upward solute diffusion when net percolation is low and delay the downward advective flushing of solutes when net percolation is high; and
- Other solute retention mechanisms related to the degree of saturation, soil organic matter content, immobile water content, and other factors may be beyond the scope and capability of many modelling programs.

6.5.6 Cover System Field Trials

Where time and budgets permit, field trials of the most promising cover system design alternatives should be established at the project site. The purpose of cover system field trials is to:

1) Evaluate construction methodologies and equipment in support finalizing the full-scale cover system design;
2) Obtain performance monitoring data for calibration of numerical models, which will result in improved confidence in the predicted long-term performance of the final cover system design;
3) Develop an understanding of key characteristics and processes that control cover system performance; and
4) Track evolution of the trialed cover systems in response to various site-specific physical, chemical, and biological processes.

Design of a cover system trial program needs to consider the following factors: a) size of the cover trials; b) location of the cover trials; c) scope of performance monitoring; and d) length of monitoring period. Cover trials need to be large enough to properly evaluate construction methodologies and equipment that would be used for full-scale construction. In addition, cover trials need to be large enough to minimize edge effects on instruments installed to monitor performance. A ‘watershed’ approach as opposed to a ‘test plot’ approach is preferred in order to gain a better understanding of cover system performance under site-specific conditions. At a minimum, cover trials should be 1 ha in size (e.g. 100 m by 100 m), but preferably in the 2-3 ha size range. Stakeholders will also gain more confidence in the cover system design process if trial areas cover a larger portion of the final reclaimed landscape.

Cover system field trials should be located on final re-contoured slopes of the waste storage facility. For a waste rock dump, consideration should be given to locating trials on both plateau and sloping areas; for larger stockpiles, consideration should also be given to establishing trial areas on different slope aspects (e.g. north and south). It might be simpler to construct cover trials at the toe of a long slope; however, the cover trial water balance could be influenced by surface run-on waters from upslope areas and laterally flowing seepage waters. For a tailings impoundment, cover system performance is influenced by the texture of the underlying tailings and depth to the water table; in some cases, it would be warranted to establish cover trials in both the beach and slimes area.

Cover trial performance monitoring systems should be designed to measure most components of the surface water and energy balances, as well as oxygen ingress rates, as shown schematically in Figure 6.3. This includes meteorological monitoring, monitoring of moisture and heat storage changes, and monitoring of net percolation, surface runoff, erosion, and vegetation (MEND 2.21.4, 2004). The majority of the instruments should be located in a single location, typically near the centre of the trial area (primary monitoring site). Secondary monitoring locations should also be established to quantify potential differences in spatial performance, not only due to slope position and aspect, but also due to textural variability in the cover materials. Finally, it is recommended that field permeability testing be conducted on an annual basis to track evolution of the cover materials in response to wet/dry cycling, freeze/thaw cycling and vegetation developments (see Meiers *et al.*, 2011).

Performance of cover system field trials should be monitored for a minimum of 2-3 years prior to proceeding with final design of the full-scale cover system, and ideally up to 5 years to capture climatic variability from one year to the next. Monitoring over a shorter period does not provide sufficient variability in thermal and hydraulic field responses to adequately calibrate a soil-plant-atmosphere model. It is hoped that vegetation will have established and the upper cover layer will have come into equilibrium with local climatic conditions by Year 3 of the monitoring program. Two examples of cover system field trial projects are detailed in Aubertin *et al.* (1997) and Adu-Wusu and Yanful (2006).

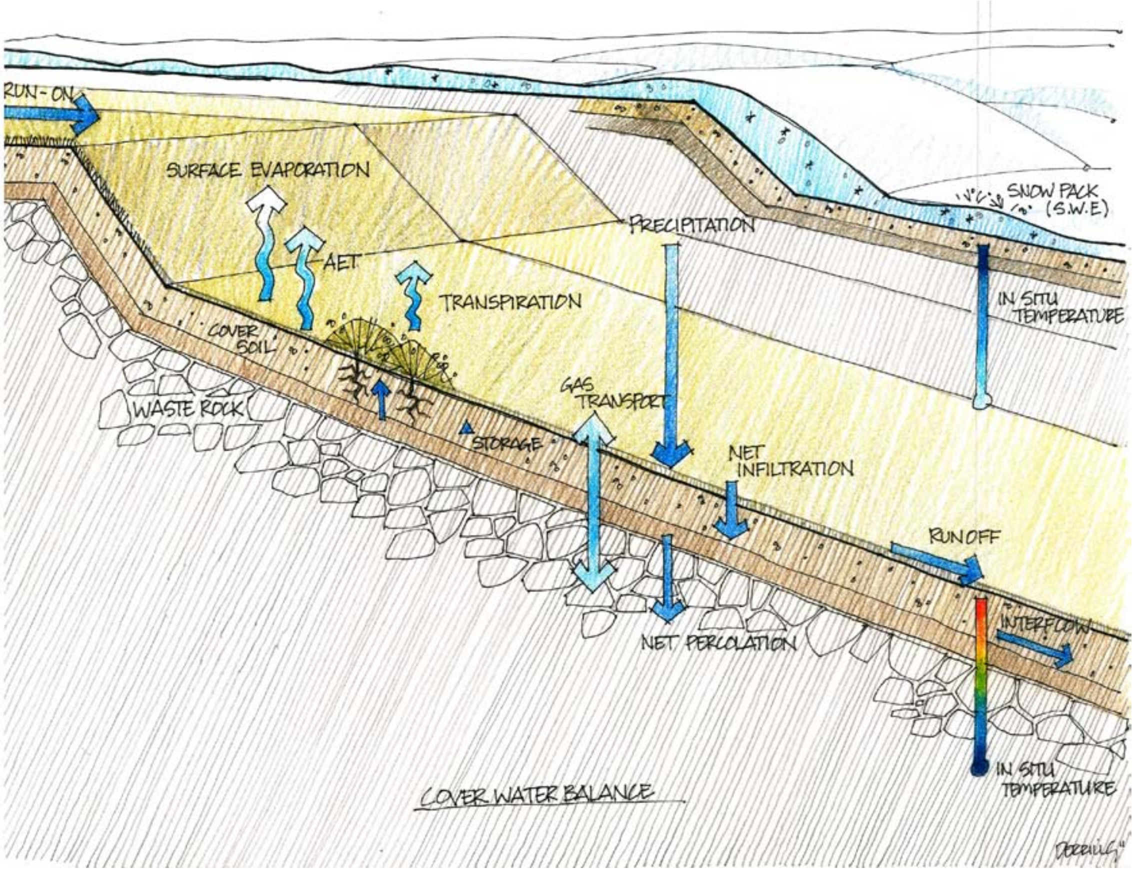


Figure 6.3 Conceptual schematic of the components of a field performance monitoring system.

6.6 Risk Analysis of Cover System Design Alternatives

Appropriate methods need to be used to weigh the advantages and disadvantages of various alternatives selected for reclamation of a mine waste storage facility. For selecting the preferred design for a cold region cover system, a Failure Modes and Effects Analysis (FMEA) is recommended. Robertson and Shaw (2006) describe the FMEA approach in detail. A summary of the FMEA method and case studies are presented in Section 7 of this document.

An FMEA is a methodology for assessment of 'risk', which is a combination of likelihood and consequences of failure. Its value and effectiveness depends on having experts with the appropriate knowledge and experience participate in the evaluation during which failure modes are identified, risks estimated, and appropriate mitigation measures proposed. An FMEA provides evaluators with the ability to perform a systematic and comprehensive evaluation of potential failure modes of the design / plan in order to identify potential hazards. Once the failure modes and measures with the highest risk have been identified, it is possible to consider mitigation or alternative designs to reduce risks. FMEAs are therefore an essential part of any risk- and liability-reduction program.

The term 'risk' encompasses both the concepts of likelihood of failure, or 'expected' frequency of failures, and 'severity of the expected consequences' if such events were to occur. It is an imprecise art because predictive risk assessment involves foreseeing the future. There is a difference between risk of a failure and uncertainty in the estimate of that risk. There are also separate uncertainties associated with both expected frequency and expected consequences.

6.7 Multiple Accounts Analysis (MAA)

A multiple accounts analysis (MAA) is a multi-stakeholder, multi-disciplinary tool that provides the means by which evaluators can select the most suitable, or advantageous, alternative from a list of options, by weighing the relative benefits and costs (or losses) of each. This method is described in detail in Robertson and Shaw (2004). The method involves three basic steps:

1) Identify the impacts (benefits and costs) to be included in the evaluation;
2) Quantify the impacts (benefits and costs); and
3) Assess the combined or accumulated impacts for each alternative, and compare these with other alternatives to develop a preference list (ranking, scaling and weighting) of the alternatives.

In mining, the diversity of impacts that must be considered makes integrated (combined and cumulative) impacts assessment difficult. How does one compare the 'apples and oranges' in one fruit basket with the 'plums and bananas' in another to decide which is preferable? To a large extent, any comparison is subjective and depends on the flavour preference (value basis) of the analyst. It is not possible, and probably not desirable, to remove this subjectivity as each analyst seeks to have his/her value basis applied in the analysis. It is therefore an advantage if the evaluation methodology is systemized and transparent, allowing the various analysts to clearly indicate their value basis and results. If the results of analyses from two analysts are similar, despite differences in value basis, then there is likely to be consensus on the alternative selected. If results are materially different, then the root cause of the difference can be identified and discussions and/or additional studies can be focused on the material, value basis, and/or issues to determine if a consensus resolution can be reached.

The MAA process has been utilized for a number of purposes in practical applications, including:

- Identifying information gaps and data needs from which studies can be developed;
- Providing a framework in which all stakeholders can identify and discuss the issues of importance to them;
- Providing an objective and simplified basis on which sensitive issues can be discussed;
- Providing a defensible and transparent tool with which decision makers can evaluate the positive and negative impacts of available alternatives; and

- Providing a framework for describing alternatives considered, evaluation basis and conclusions for inclusion in other documents (e.g. EIS, EA, permit applications etc.).

6.8 Design and Implementation Issues Applicable to all Cover System Designs

The intent of this section is to discuss design issues applicable to most cover system designs and practical implementation / construction issues for cover systems in cold regions.

6.8.1 Availability of Cover Materials

The availability of potential cover materials and the distance to borrow sources is a key factor when developing a cover system design, with transport and placement costs evaluated against the benefits of using greater volumes and/or more suitable materials. Ideal cover materials for the project location, climate, and waste may not be readily available in the immediate area, while other materials in the area may be less than ideal but more feasible to use due to cost and/or logistical considerations. Material scarcity can be an important factor in decision making. Licensing may also be required to access/use borrow materials, which can add substantial, perhaps prohibitive, time to the process. Additionally, third parties may interfere with access to borrow material sources.

Scarcity of natural materials often goes hand-in-hand with increasing variability of material properties within a given deposit. Adequate characterization of borrow material sources is especially important as material variability increases. This variability must be fully characterized and accounted for in the prediction of cover system performance.

The environmental impact of material borrows and transportation should also be evaluated to ensure that the use of the material provides a net benefit to the project. This is particularly important in cold regions as areas sensitive to disturbance of permafrost and vegetation communities may not recover from disturbance, or have a long recovery process.

6.8.2 Need for a Robust Growth Medium / Protective Layer

Growth medium layers will be subject to numerous wet/dry and freeze/thaw cycles in cold regions. Certain materials may not hold up as well as others when subjected to the stress of climatic cycles and must be tested before use. Soil-plant-atmosphere field response simulations can be used to develop models calibrated to field data from cover system field trials.

The required thickness and characteristics of the growth medium will strongly influence the ability of the cover system to meet expectations over the design life. For example, if layers are not thick enough, tailings pore-water has been shown to be ‘pulled’ up into the rooting zone. This occurs in late fall / early winter, implying a freezing-front process.

Compaction of growth medium layers that develops due to repeated equipment traffic must be addressed through ripping or scarified at the end of construction. These compacted areas, if left intact, will hamper the ability to achieve successful revegetation, and may lead to other issues, such as increased erosion downslope of the compacted area.

6.8.3 Revegetation

Rapid establishment of vegetation following cover material placement is important both to:

- limit erosion of and sediment transport from the cover materials, particularly where:
    - topsoil has been used as the surface cover layer, as significant nutrients and vegetation propagules can be lost due to surface erosion; and/or
    - where receiving environments are intolerant of sediment delivery; and
- to take advantage of conditions most favourable to vegetation establishment through seeding or planting, as many cover materials composed of unweathered tills will exhibit drying and/or cementation following placement, which can reduce revegetation success.

Topsoil, where available, can be used as a source of nutrients and vegetation propagules, but, as above, must be protected from surface erosion (through surface preparations to control surface drainage), and is often available in limited volumes, such that its use must be carefully matched to cover system design and overall site objectives. Initial fertilizer treatments may be necessary for successful vegetation establishment, but continued fertilizer applications may be detrimental to native species establishment (as most cold region native species are adapted to low-nutrient conditions). Treatments that increase the creation of micro-topography (e.g. surface landforming, placement of woody debris and/or large rocks) can be effective in increasing establishment and diversity of vegetation on reclamation covers, provided that they are consistent with other cover system design objectives.

6.8.4 Need for Proper Management of Surface Water Drainage

As discussed in Section 3.4.1, one of the most common failure modes of cover systems in general, and for cover systems in the cold regions in particular, is the failure of the surface water management system to safely convey runoff off of the landform. Surface water management systems must be robust, as any failure is visible to stakeholders. Even if the failure does not result in increased contaminant loading or other critical failures, the surface drainage system is visible and even small glimpses of erosion give the impression of poor design and management.

A surface water management system will be successful if it manages to convey all the required surface water and does not suffer greatly from erosion, sedimentation and turbidity. This success is largely based on choosing a reasonable design storm event during planning. In cold regions, care must be taken to consider spring snowmelt in conjunction with the design rainfall event, as well as glaciation of surface water conveyance channels. Glaciation of surface water channels and ditches, particularly near the 'outlet' area of the landform, is a very common failure mechanism of cover systems in cold regions.

Erosion can result in stream water with high turbidity and large sediment loads. If sediment gets into surface water onsite, it may become an environmental contaminant requiring treatment. The best approach is to reduce or eliminate suspended fines rather than removal and treatment which can be difficult and costly. Key factors are to prevent raindrop erosion and slow surface water velocity in bare areas. This can be done through establishing adequate vegetation, proper grading of contours, berms, and swales, diversion ditches, and rock armouring (Norman *et al.*, 1997). Design of armoured drainage channels is discussed in Section 6.9.3.

Reclamation of large waste storage facilities should include the construction of small catchment areas and wetlands upstream of final surface water discharge points when compatible. This will attenuate surface runoff to reduce peak flows and increase sedimentation prior to reaching receiving streams. In some cases, products such as silt fences or straw wattles are recommended to provide temporary sediment control until the cover surface stabilizes.

6.8.5 Placement of Cover Material on Soft Tailings

The use of construction equipment to re-grade tailings surfaces and place cover material requires sufficient dewatering of the upper tailings profile to provide adequate shear strength and improve trafficability conditions. Drain-down of tailings can be achieved by collecting and treating supernatant and seepage waters over a period of time. A staged advancement of several thin layers of cover material may be required with provision to allow consolidation and strength gain at each stage, to avoid a rotational failure (slumping) or a bearing capacity failure near the advancing edge of the cover material (Wels *et al.*, 2000). Use of geosynthetic products, such as a geogrid or geotextile, and wick drains, are often required to improve strength conditions and accelerate consolidation of tailings, respectively.

Placement of the initial cover layer during winter when the upper tailings are frozen is another option, particularly where tailings are finer textured (see Ricard *et al.* (1997) or MEND 2.22.4a (1999) for case study of winter tailings cover construction). However, it is fundamental that an understanding of the potential for settlement, and differential settlement, following thaw of the tailings is developed. Sustainability of any surface water management system on top of the cover system of a tailings storage facility is intimately linked to settlement characteristics of the tailings.

6.8.6 Logistics, Project Management, and Contract Administration

Project management must deal with the transition from design drawings and specifications to implementation of the work that meets the overall objectives of the cover system. It is inevitable that problems will arise. In addition to the typical problems of any construction project, cover system construction will be affected by some issues that are somewhat unique to cover systems: variability in mine waste materials, construction sequences for sloping surfaces, and borrow area management.

In the case of cover systems in cold regions, the construction season is short. This limits the extent of construction that can be practically completed in a single season. It is very important to recognize that the timing and duration of the construction season can be seriously affected by delays in the tendering process (a common problem particularly with government contracts).

Cover systems on tailings in cold regions may be influenced by post-construction deformation associated with consolidation of the tailings mass (see Section 6.5.4). Ideally, these factors will be addressed during the design stage. However, they can affect the timing, duration, and sequence of cover construction, and should be considered in preparation of tender documents.

6.8.6.1 Variability in Mine Waste Materials

These issues arise from the variability in the supply of earthen materials used in cover system construction, especially if using material recovered from mine waste and overburden stockpiles. This is due to the inherent variability of mine waste materials and the mining method / material handling processes used in the construction of the stockpiles.

Cover systems on waste rock will have to deal with boulders and rocks up to run-of-mine size (~1 m diameter), which complicate construction. These issues can be reduced by avoiding geometries with fine tolerances for performance, for example:

- A flat ditch gradient of less than 1% may end up with blockage and/or pools unless considerable construction effort is expended; and
- Subgrade finishing for placement of geosynthetic liners will have to accommodate depressions and bumps, which are impossible to avoid. Infilling and fillets will be required. The grain size and durability of the waste rock should be considered when planning for the bedding soil for the geosynthetic liner.

Problems associated with construction on mine waste materials (waste rock or tailings) and when using mine waste materials for cover construction make it difficult to meet construction specifications and, more importantly, to meet design objectives of the cover system. Construction specifications should be prepared in consideration of how cover performance may be affected if significant areas of the cover system are constructed at the limit (upper or lower) of the specifications.

The designer and construction manager should recognize that the variability in supply of earthen materials will lead to problems, for which two options exist:

1) Undertake a comprehensive characterization of all construction materials, with emphasis on those materials to be sourced from mine waste stockpiles; and
2) Prepare tender documents and approach to construction management with the intent to identify problems in material supply and resolve them during the construction process.

Some of Option 1 is necessary; however, it is probable that even if Option 1 is done very well, it will not preclude the need for Option 2. Determination of the balance of these two options should be undertaken:

- Early in the planning process, with greater site characterization for situations where a high standard of cover system performance is needed; and
- After the design is complete and tender documents are being prepared.

6.8.6.2 Construction Sequence on Sloped Surfaces

Although it is a basic tenet of contracting to avoid telling the contractor how to do the work, consideration should be given to encouraging cover construction starting from the bottom and moving upwards. There are several reasons for this:

- Top-down cover construction followed by initial establishment of vegetation (for erosion control) has significant potential to result in late and inadequate vegetation for the freshet of the next year. Bottom-up construction gives the lowest area of the cover system (greatest catchment and therefore greatest erosion risk) the longest growing opportunity for initial vegetation in the year of construction activity. This is especially critical in cold regions where vegetation establishment is slow.
- Top-down construction should be expressly prohibited in the tender specifications if the cover system incorporates a geosynthetic liner.
- If top-down construction is not practical, two options might be considered:
    - Include in the tender specifications that initial vegetation must follow closely behind the advance of cover construction (such as ‘maximum X ha of un-vegetated area at any time’);
    - Modify the design to include features to limit concentrated downslope runoff, such as:
        - Riprap swales where downslope runoff cannot be avoided;
        - Aggressive use of soil tackifier and/or erosion control matting (in addition to hydroseed effort).

  - A settling pond for clarification of runoff; and
  - Provision for maintenance & repair (by the contractor) for a specified period after the construction is complete.

It should be noted that bottom-up construction may result in a slightly higher cost of construction compared to top-down construction; however, the additional upfront cost might offset future costs arising from maintenance and repair work.

6.8.6.3 Borrow Area Management

Borrow area management must be fully addressed in the design and tender documents. This should include: access, slope stability and water management (operation and post-closure), management of reject materials, and reclamation.

Reject quantities may be significant if using mine waste materials. Compared to natural deposits, mine waste stockpiles may have:

- greater variability in grain size distribution;
- variable density and moisture content;
- irregular ice formation;
- contamination with mineralized rock; and
- presence of deleterious material (especially organic matter from pit stripping and buried organic matter in the dump foundation).

These factors should be addressed in the design of the borrow area and the contract specifications for handling reject materials.

6.9 Permit-Level Design

The permit-level or detailed design stage typically includes additional numerical modelling, design of the final landform, design of surface water management systems, calculation of estimated material volumes, design of the revegetation plan, and producing technical specifications and drawings for construction.

6.9.1 Additional Numerical Modelling

Ideally, field trials are conducted prior to the final design such that the final cover system design can be verified and/or modified to ensure that it meets all the required performance criteria. Utilizing field performance monitoring to finalize the design allows a timeframe over which the cover design objectives can be reviewed and the actual performance of the cover system can be observed. This is a valuable tool that can often give additional insight into the feasibility and desirability of various cover system design performance objectives.

If field trial performance data are available, then the permit-level design phase may include development of a numerical model calibrated to these data. Once calibrated, the model can be used to complete predictive modelling to develop further understanding for long-term performance of the cover system. Availability of better quality field data will enhance confidence in long-term predictions.

Additional numerical modelling that should be undertaken to support final design of the cover system includes slope stability analyses, consolidation analyses, and solute uptake analyses. Slope stability modelling may be required depending on the slopes of the final landform, materials chosen for the cover system, and potential for cold regions phenomena such as moisture migration or frost heave to impact the stability of materials. Consolidation analyses are required to ensure that the self-weight consolidation of tailings material, as well as tailings consolidation following placement of any cover material, is understood. From a closure perspective, the primary influence on cover system performance with respect to consolidation is the surface water management system. Other possible effects are cracking of compacted soil barrier layers or tearing of a geosynthetic layer.

Solute uptake analysis may be required when there is concern about the potential for vegetation uptake of contaminants.

6.9.2 Final Landform Design

Final landform design is a fundamental consideration when designing cover systems for waste storage facilities located in cold regions. Careful consideration must be given to a planned final landform to ensure that performance of a given cover system can be sustainable over the long term.

Stakeholder expectations for rehabilitation of mine waste landforms are becoming increasingly high. Traditional methods of establishing functioning ecosystems on drastically disturbed lands are no longer adequate to meet stated goals and objectives. Historically, rehabilitated mine landforms possessed uniform slopes conforming to neat lines and grades. This lends itself to uniformity of design and construction, but does not necessarily achieve the mine closure objectives of minimum erosion and long-term sustainability.

Uniform landforms represent immature topography, and are poised to evolve to lower energy states by shallow slope failures or accelerated erosion. In contrast, the development of a sustainable landscape for mine closure involves the development of landforms that replicate natural landscapes. The replication of mature and relatively stable natural systems reduces the rate and risk of accelerated erosion.

6.9.2.1 Landform Design Philosophy

Landform design involves a multidisciplinary approach; it draws heavily on practical mine reclamation experience but also involves expertise in geotechnical engineering, surface water, groundwater, soils, vegetation, and wildlife.

Following a tour of 57 abandoned and partially reclaimed operating mines, McKenna and Dawson (1997) created an inventory of mine closure practices, physical performance of reclaimed areas, and environmental impacts of reclaimed and abandoned mines. The inventory shows that the greatest physical risk to the landscapes is associated with gully erosion and re-established surface water drainage courses. Poor surface water management and landform instability are common factors leading to failure of mine waste cover systems around the world (MEND, 2004). These factors are much more prevalent at sites situated in cold regions where processes such as frost heave and snowmelt can substantially diminish the integrity and performance of a reclaimed mine landform.

The consideration of geomorphic principles is fundamental when designing a stable landform. Reclamation failure can usually be traced to violation of geomorphic principles, most fundamentally having too great a disparity between force and resistance (Toy and Hadley, 1987). Basic geomorphic principles dictate slope angles, drainage density, and size of drainage basins, but many different landscape designs can satisfy these criteria.

Surface water management systems must be robust as any failure is visible to stakeholders. Even if the failure does not result in increased contaminant loading or other critical failures, small glimpses of erosion give the impression of poor design and management. In cold regions, glaciation or ‘icing’ of surface water channels and ditches, particularly near the outlet area of the landform, is a very common failure mechanism of reclaimed mine landforms. Reclamation of large waste storage facilities should include the construction of small catchment areas and wetlands to reduce peak flows and increase sedimentation prior to reaching receiving streams. Finally, the design and implementation of a sound revegetation plan including rapid establishment of vegetation following construction can significantly limit erosion and sediment transport.

A landform design philosophy for mine waste stockpiles can be summarized as follows:

- Design of a final landform should take place prior to construction of the initial landform;
- Geotechnical stability is paramount, but aesthetics and natural appearance should be considered in the design of mine landforms;
- Geomorphic principles must be considered in order to design landforms that will be stable over the long term; and
- Surface water management systems must be robust.

6.9.2.2 Incorporating Landform Design into Mine Planning

Landform design for mine rehabilitation requires a holistic view of mining operations, where each operational stage and each component of the mine is part of a plan that considers the end-use of the site as much as the immediate need. This plan, which needs to be flexible to accommodate changes in methods and/or technology, is about optimizing post-mining land capability, minimizing the costs in achieving optimal land use, and limiting long-term maintenance liabilities.

Traditionally, landform design and implementation is conducted during the operational and/or closure phases of a mine's life. This is often true even in cases where the closure plan was initially developed as part of mine feasibility. This approach leads to significant challenges for rehabilitation and closure due to, among several factors (Howard *et al*., 2011):

- Failure to source and store sufficient quantities of suitable cover materials;
- Failure to segregate these suitable cover materials from unsuitable materials;
- A requirement to double-handle materials that otherwise could have been handled once with some additional haulage distance had the mine closure plan been integrated early with the mine plan; and
- Increasing the cost of re-shaping the landform to achieve a suitable post-mining landform.

A key component of integrating the landform design into the mine planning is characterization of materials early in a mine's life. Detailed characterization can provide a strong basis for planning for eventual closure, so that costs of final closure works are substantially minimized, the quality of the outcome is maximized, and the risk of failure (and costly remediation works) is reduced. Mine planning must be closely integrated with mine closure planning in order to achieve the required rehabilitation objectives as cost effectively as possible.

AANDC is primarily concerned with mines in the closure or post-closure stages and thus, this type of recommendation does not directly apply. However, incorporating mine closure planning into mine planning is applicable to all new and operating mines in cold regions and was included for reference.

6.9.2.3 Landform Design Methodologies

Design methodologies for developing a sustainable final landform are described in MEND 2.21.5 (2007) and by McKenna (2011). McKenna (2011) puts forward a 12-step program for landform design, which includes:

1) Work within goals and objectives of site-wide closure plan;
2) Review depositional or construction history of the waste storage facility;
3) Collect data:

    a) Surface Investigation,
    b) Sub-surface Investigation,
4) Analyze data:
    a) Geotechnical characterization,
    b) Hydrogeology characterization,
5) Specify final outlet location and elevation:
    a) Governs rest of landform design,
    b) Needs to merge with larger picture drainage plan,
    c) Design against beavers damming the outlet,
6) Assess tailings stabilization and capping (if required);
7) Design preliminary topography and drainage;
8) Perform hydrologic modelling and water balance;
9) Conduct monitoring and maintenance of settlement;
10) Construct cover system and revegetate;
11) Perform ongoing operation of landscape (monitoring, maintenance); and
12) Attain certification and bond release.

An important factor in final landform design is aesthetics. Building landforms that have a more natural appearance typically have the same cost as traditional reclamation landforms, can be done with medium to large equipment, are usually simpler than traditional reclamation, and the resulting landforms are always appealing to stakeholders and regulators, staff and management (McKenna, 2009).

The use of natural analogs is an important design tool to achieve an aesthetically pleasing landform. Mine plateaus, slopes, and streams are designed to mimic natural features in the region based on the theory that the shape of the natural landforms are stable products of the conditions of the local climate and processes over thousands of years (McKenna, 2009). Generally, by incorporating surface water management features into the landform, along with the use of local revegetation species planted in patterns similar to the local native vegetation, the resulting landscape will be natural looking.

Table 6.1 provides a list of design elements that can be used for the design of landforms with natural appearance (adapted from McKenna (2009)). All elements need design by qualified individuals and signoff that regulations will be met, geotechnical stability is assured, and that the elements will work well together to provide the promised landscape performance.

Table 6.1
List of landform design elements for natural appearance
(adapted from McKenna (2009)).

Item	Example
Meandering creek	• Irregular 100-300 m wavelength, minimum amplitude = 1 to 2 creek widths.
Connect swales with natural watercourses	• Drain swales into adjacent watercourses. Carry vegetation patterns from natural gullies up onto the dyke or dump slopes.
Watershed berm at crest	• Push up dump material and round the downstream crest as a final design feature. • Horizontal wavelength 200 to 400 m, zigzag 0 to 20 m, vertical height 2 to 4 m, 2.5 to 4H:1V side-slopes with 3 to 5 m crest width. • Can be built using large mining trucks and later shaping the resulting line of spoil piles.
Irregular ridge mounds	• To add diversity to skyline profile, add irregularly shaped mounds at the downstream crest. • Mounds can be 3 to 5 m high, 3H:1V side-slopes or flatter, 20 – 30 m wide, 30 – 80 m long (2000 to 10,000 m^3 each). • Consider planting schemes to enhance appearance. • Mound heights should be designed to be 5-15% of the landform height to break up sightlines. • Mounds can be placed near the crest—act like false storefronts in a Western town.
Reslope benches	• When finished with benches, reslope by regrading substrate or adding additional reclamation material. • Ensure access is maintained in order to place reclamation material.
Wetlands at toes	• Enlarge toe ditch (toe creeks) to create shallow wetland, 2 m deeper than toe ditch invert (where ditch invert is shallow). • Consider 10 – 20 m wide, 30 to 60 m long (1000-5000 m^3). • Use irregular shoreline, very shallow slopes, create mounds with spoil.
Tailored planting	• Follow ecosite planting schemes—tailor the planting to fit conditions. • Consider planting swaths of trees for visual patterns on slopes. • Use this scheme to mimic natural vegetation elsewhere.
Swales on slopes	• Construct swales and ridges of slopes to carry runoff safely to the toes of dumps. • Use diagonal, elbow, and curvilinear shapes. • Hydrologic design required above threshold watershed areas and slope gradients
Reclaim erosional fans and gullies in place	• Once gullies are stabilized instead of 'erasing' them, simply repair them in places. • Allows increased diversity, reduced cost. • Need to remove the 'cause' of the gully prior to repair in most cases.
Irregular shoreline	• Irregular shoreline should be integrated with construction for lakes, wetlands, marshes, and fens.
Littoral zone	• Build large littoral zones (typically less than 2 m deep) into the design of lakes.

Table 6.1 (cont.)
List of landform design elements for natural appearance
(adapted from McKenna (2009)).

Item	**Example**
Add additional fill at toe	• Adding fill at toe to break up straight lines and add topographic diversity may be desired. • Similar effect achieved by reclaiming erosion fans in place. • Expensive if not a short haul/ short overhaul.
Mounds on plateaus, benches, slopes	• Small mounds on berms and slopes add topographic diversity. • Can be pushed up or placed or cut/filled from other projects. • Typically 10 – 30 m diameter, 3 – 5 m high (300 – 4000 m^3). • Field fit where practical.
Brushpiles / snags	• Temporary habitat improvements can be made by having small brush piles for small animals or standing snags for raptors.
Rockpiles	• Build rock piles from siltstone for animal habitat (6 to 15 m diameter, 2 to 4 m high).
LFH placement	• Place forest floor salvage in islands to promote early biodiversity. • Slash (coarse woody debris) also enhances diversity and habitat.
Micro-topography	• Roughen slope to create micro-topography to enhance soil moisture and diversity.
Cover soil diversity	• Use different prescriptions in different areas to enhance diversity.
Access controls	• Establish a plan for long-term access to the area. • Provide good access, but restrict number of roads and type. • Use aesthetic design principles from trail guides to guide designs.
Viewing platforms / photo locations	• Install viewing platforms for tours and future recreational opportunities.

Landform evolution modelling can be a tool used in the design of mine closure landscapes. Geomorphic landform evolution models estimate erosion and sediment loss over a three-dimensional landscape by linking the hydrological response of the landform to precipitation (rainfall). The potential application of these models to cold regions is not well understood as the primary runoff events in cold regions are associated with snowmelt runoff and the thickness of the active layer rather than rainfall events. In addition, these models have not been calibrated to any existing cold region sites, natural or engineered.

Once the final landform design is complete, the required volumes of various materials can be calculated. Often the available material volumes will be assessed during the initial design stage as a cover system will not be feasible if there is not sufficient available volume (see Section 6.8.1). A borrow investigation is required, including test pitting, to determine available material volumes. Samples are collected for various laboratory tests including grain size distribution, Atterberg limits, compaction and other tests deemed relevant. Based on the testing results, volumes of suitable materials available can be calculated. Processing of materials can be undertaken depending on requirements and available resources.

Construction of final landforms includes earth work and vegetation seeding. Construction issues have a large bearing on the eventual success of a landform. Construction issues that can impact on eventual landform success include (Howard *et al.*, 2011):

- Placement of incorrect material (e.g. placement of saline material on surface);
- Failure to place correct material (e.g. failure to place topsoil over rocky substrate);
- Poorly designed/constructed rock drains (e.g. lack of freeboard, inappropriate rock grading, failure to consider underlying materials);
- Poor cross-slope ripping;
- Failure to control water flows (e.g. uncontrolled discharge of water from landform top onto the side-slopes);
- Poor management of vegetation;
- Poor and/or inadequate project management, including the ability to facilitate change orders with the contractor (if utilized); and
- Inadequate QA/QC for earthworks and/or inexperienced construction supervision personnel.

6.9.2.4 Landform Design Considerations for Cold Regions

Many of the potential failures of cover systems in cold regions are due to failures of the landform due to frost action. In fact, many of the natural analogues surrounding a potential landform may show impacts of frost action, despite being relatively ‘stable’ landforms. Thus, in cold regions it is important to design a robust landform with the understanding that the landform will undergo evolution and to understand what frost action processes may lead to landform failure and inevitably to cover failure.

In cold regions, landform morphology will play an important role in snowpack accumulation and aspect ratios, which in turn may control the depth of ground freezing, timing and rate of snowmelt, etc. For example, it would be ideal to limit snowpack development on a waste storage facility from an environmental loading and erosion perspective; however, this results in the cover profile being more susceptible to freeze/thaw cycling, which could have detrimental impacts on long-term performance. This may be managed by encouraging snow drifts in certain areas and not in others. Alternatively, substantial snowpack may limit the development of a permafrost aggradation barrier layer within a cover system.

6.9.3 Design of Surface Water Drainage Channels

Surface water drainage channels are typically designed using the tractive force method as described in Smith (1995). In principle, the method is used to evaluate the adequacy of a designed channel from comparison of the shear stress generated by the flow to the shear resistance of the channel lining material. That is, the shear resistance of the lining material (grass, gravel, riprap, etc.) must be greater than the shear stress generated by the flow to produce a stable channel. In the case of a steep channel, it is necessary to modify the basic tractive force theory concept to also include the destabilizing influence of gravity on the stone material. Inclusion of the effect of gravity on stone stability was addressed using a procedure for the design of steep channels as outlined in Smith (1995).

A graded riprap material is preferred as a result of greater interlocking effect between particles (giving increased shear strength) and decreased porosity (giving a better filter effect between the flowing water and the base material under the stone) (Smith, 1995). The thickness of a riprap layer should be a minimum of 1.5 times the median stone size but not less than 150 mm from a quality control and construction perspective (Smith, 1995). Typically, filter layers are required beneath coarse riprap to prevent foundation material from being washed out or sucked through the voids in the riprap layer. A properly graded soil filter medium is recommended over a geotextile product in a mine waste cover system application given the relatively short service life of geosynthetics. Finally, aprons of riprap should be included for additional erosion protection where surface waters on plateau areas converge prior to entering steeper channels on slopes of the reclaimed facility.

A high level of quality control and assurance during construction of armoured drainage channels is critical to the long-term integrity of the cover system and outer slopes if present. The selected cobble or stone for riprap should be hard and of such quality that it will not disintegrate on exposure to water or weathering and be chemically stable. Angular rocks are preferred for armoured drainage courses over smooth stones typically found in till deposits due to their interlocking capabilities. If an economically viable source of angular rock is not available at the site, then a local till deposit can be processed to produce riprap meeting the required gradation specifications. The channel floors require grading that meets design specifications and nominal compaction to provide adequate strength for the armoured layer. Quality control testing must be implemented to ensure that the riprap material and thickness of the armoured layer meets specifications.

6.9.4 Revegetation Plan

Permit-level revegetation design includes both the designs for growth medium cover layers and paired revegetation treatments. At this stage of the design process, the plan should provide detail on:

- species selection and mixes to be used per revegetation treatment unit;
- planned seeding rates and planting densities;
- establishment techniques (broadcast seeding, hydroseeding, etc.) to be used;
- vegetation material sources; and

- sequencing and timing of revegetation activities, linked to the cover placement schedule.

Results from prior operational reclamation and/or field trials should be discussed and incorporated, where available.

As discussed previously, some revegetation treatments in cold regions may not be effective at reducing surface erosion in the short term, due to slow vegetation establishment. One approach to address this issue in permit-level design is to categorize areas for revegetation planning based on erosion risk. For areas where control of surface erosion is a primary revegetation objective (e.g. longer / steeper slopes), revegetation can be designed for rapid establishment and growth; additional objectives, such as water removal through transpiration and provision of wildlife habitat, may become secondary, long term goals. On sites where surface erosion is a lesser or minimal concern, revegetation can be designed to emphasize other objectives such as diversity, native species establishment, and habitat creation.

6.10 Post-Construction Monitoring and Maintenance

Long-term performance monitoring is critical for evaluating performance of cover systems. It is impossible to develop a single rule for how long monitoring should occur that would apply to every cover system. Instead, each system must develop a monitoring strategy integrated within the design of the cover system, regulatory requirements, the needs of the mine operation and the stakeholders, and most importantly be conducted within the context of the mine closure plan.

Historically, cover system performance was evaluated by water quality analyses of seepage discharged from the waste storage facility. This approach empirically describes a waste storage facility through monitoring of its cumulative effect at the base (Morin and Hutt, 1994). In addition, for sites actively generating ARD, monitoring gaseous oxygen and temperature profiles can also serve as a tool for evaluation of cover system performance, because the profiles indicate the internal behaviour of the waste storage facility (Harries and Ritchie, 1987). Although these monitoring techniques have their merits and are fundamental components of a cover system monitoring program, they should not be used as the sole means of measuring cover system performance. It may take tens of years before a considerable change is measured inside or downstream of the waste storage facility due to the drain-down effect and complete oxidation of sulphide minerals within the waste storage facility.

Including direct measurement of field performance as part of a cover system monitoring program is the state-of-practice methodology for measuring performance of a cover system. Field performance monitoring can be implemented during the design stage with cover system field trials (see Section 6.5.6), or following construction of the full-scale cover (e.g. Ayres *et al.*, 2007). Direct measurement of field performance of a cover system is the best method for demonstrating that the cover system will perform as designed. The main objectives of field performance monitoring (adapted from MEND 2.21.4, 2004) are to:

- Obtain a heat and mass (water) balance for the site;
- Develop a set of field data to calibrate a numerical model (which can be used to predict cover system performance in the future);
- Develop confidence with all stakeholders with respect to cover system performance; and
- Develop or enhance understanding for key characteristics and processes that control performance.

A recommended minimum level of monitoring for full-scale cover systems includes meteorological monitoring (i.e. determination of potential evaporation rates), site-specific precipitation, cover material moisture storage and temperature changes, watershed or catchment area surface runoff, vegetation, and erosion (MEND 2.21.4, 2004). Performance monitoring must also allow ‘feedback’ depending on the needs of the stakeholders, but also in response to the performance being monitored. For example, if the hydraulic conductivity of the cover material is found to be changing with time, a greater frequency of field hydraulic conductivity measurements should be taken to better quantify and understand the changes.

All cover systems will need some repairs and maintenance at some point. It is the goal that all maintenance is required in the short term and that in the long term, the cover system be designed to be maintenance-free. Common short-term maintenance activities include repair of erosional features, re-establishment of surface water drainage channels and ditches, application of additional revegetation and/or fertilization treatments, and repair and maintenance of performance monitoring equipment.

In general, post-closure maintenance should include cleaning out drainage channels of sediment and vegetation and repairing erosion damage until the landform reaches equilibrium. Geotechnical stability audits should be completed on a regular basis. Water sampling should be completed for both surface and ground water on a regular basis.

7 APPLICATION OF FMEA TO COLD REGION COVER SYSTEM DESIGN

The TAG believes that an FMEA is a key component of the cover design process. As part of the cover system design methodology outlined in Section 6 (and illustrated in Figure 6.1), the FMEA allows for a risk analysis, at an early stage in the design process, that highlights potential failure modes. Cover systems with high potential failure rates can be omitted from consideration and/or modifications can be made to cover system designs to mitigate these failure modes. For example, if long-term maintenance is not desired in the final cover design, the FMEA can show long-term maintenance requirements as a failure mode, highlighting which cover designs result in long-term maintenance.

This section first summarizes the FMEA methodology followed by presentation of three FMEA case studies generically representative of different sites and climatic conditions encountered in cold regions. The case studies are presented to demonstrate the application of the FMEA process to cover system design in cold regions. Though they are based on actual sites and data, they have been simplified and only a brief selection of data is presented. The purpose of presenting these idealized case studies is to highlight the FMEA process rather than the outcomes. The outcomes of an FMEA from one site cannot be applied directly to another site; each site not only has unique climate and materials, but also have unique stakeholder needs that change the relative consequences of failure.

Background for each case study is presented, followed by the cover system design performance criteria and a description of the cover system design and materials. The results of the FMEA conducted by the TAG are summarized in tabular format, with key discussion points included that provide examples of typical interpretations of the FMEA results.

7.1 Failure Modes and Effects Analysis (FMEA)

An FMEA is a methodology for assessment of 'risk', which is a combination of likelihood and consequences of failure. The goal is to provide a useful analysis technique that can be used to assess the potential for, or likelihood of, failure of structures, equipment or processes and the effects, including human health and safety, of such failures on the larger systems of which they form a part, and on the surrounding ecosystems. For the purposes of this document, failure is defined as the cover system no longer meeting the design expectation and/or criteria. Some failures will be repairable and others will require a critical assessment of whether a new or reconstructed cover system is required.

The environmental community often uses this type of process for conducting environmental risk assessments and engineers use this type of method to assess the risk of engineered systems. Mining companies can use this assessment method to evaluate the risk that their Closure Plans impose on the surrounding environment, workers and the public. This analysis methodology has been adapted for many applications over numerous industries including 'systems' approach and 'criticality' analysis.

An FMEA is a top-down / expert-system approach to risk identification and quantification, and mitigation measure identification and prioritization. Its value and effectiveness depends on having experts with the appropriate knowledge and experience participate in the evaluation during which failure modes are identified, risks estimated, and appropriate mitigation measures proposed. It is therefore essential that the evaluation team include representatives who understand the geotechnique, hydrology, environmental impacts and regulatory requirements applicable to the engineered and natural systems and their surroundings, as well as the past history of the mine's design, construction, operation and performance.

An FMEA provides evaluators with the ability to perform a systematic and comprehensive evaluation of potential failure modes of the design / plan in order to identify potential hazards. The technique is not limited to this, but is applied as such in this instance. An FMEA can be used to evaluate potential for failures in the Closure Plan that could result in environmental impacts, legal and other obligations, effects to reputation with stakeholders, and human health and safety concerns. A risk profile can be developed for each of these concern areas. Once the failure modes and measures with the highest risk have been identified, it is possible to consider mitigation or alternative designs to reduce risks. FMEAs are therefore an essential part of any risk- and liability-reduction program.

The term 'risk' encompasses both the concepts of likelihood of failure, or 'expected’ frequency of failures, and ‘severity of the expected consequences' if such events were to occur. It is an imprecise art because predictive risk assessment involves foreseeing the future. There is a difference between risk of a failure and uncertainty in the estimate of that risk. There are also separate uncertainties associated with both expected frequency and expected consequences.

Table 7.1 shows recommended classifications to be used to identify likelihood of risk and Table 7.2 shows recommended consequence classifications to describe the severity of effects.

The level of confidence the evaluators have with their ratings will vary based on the knowns and unknowns of each site and failure mechanism. The level of confidence felt by the evaluators for each evaluation should be identified using the designations described in Table 7.3.

The first step in an FMEA is for the various evaluators to determine a list of potential failure modes for the site and identify the effects and pathways for each. A failure mode can be naturally initiated (e.g. an 'act of God' such as an earthquake, which is greater than the design event), or it can be initiated by the failure of one of the engineered subsystems (e.g. instability of a dam), or result from operational failure (e.g. failure to close a valve releasing contaminating fluids). It is often necessary to confine evaluations to those that represent a significant risk because of the large number of potential failure modes that could be included in an FMEA. Failure modes can also be combinations of events where a small trigger event sets off a chain of events resulting in substantial or large consequences.

Appendix A provides a list of possible failure modes identified by the TAG for cover systems in cold regions. The list provided is extensive, and is recommended as a 'pre-list' of failure modes for cover systems in cold regions. It is recommended that modes be screened out should they not apply to the situation. In general, it is common that approximately 25 to 30 failure modes remaining that merit at least some additional consideration. Once the failure modes and effects and pathways are identified for the site, the FMEA worksheet can be completed (see Appendix B).

The list of failure modes is meant to be comprehensive, but a key message is that no list can be absolutely comprehensive; there are always additional unknown hazards, and the combination of hazards increases the complexity.

The assessment of the severity of effects (or consequences) of specific failure modes should be based on evaluations or analyses of expected responses following failure. Adverse effects may have physical, biological, and/or health and safety consequences. The estimate of consequences is based on a professional judgement of the anticipated impact of that failure.

A risk matrix used to evaluate the failure modes is shown in Table 7.4. This matrix combines the likelihood of occurrence with the severity of effects for each of the failure modes and assigns a risk level (ranging from low to critical) to it. The 'High' and 'Critical' risk levels should be viewed as unacceptable and steps taken to reduce these risk. The 'Moderate' and 'Moderately High' levels are acceptable if they are 'As Low as Reasonably Practical' (ALARP). For a risk to be ALARP it must be possible to demonstrate that the cost involved in reducing the risk further would be grossly disproportionate to the benefit gained. The 'Low' risk designation is broadly acceptable.

Table 7.1

Recommended risk likelihood classes for FMEAs conducted in cold regions.

Likelihood Class	Likelihood of Occurrence for Environmental and Public Concern Consequences over the assessment period
Not Likely (NL)	< 0.1% chance of occurrence
Low (L)	0.1 - 1% chance of occurrence
Moderate (M)	1 - 10% chance of occurrence
High (H)	10 - 50% chance of occurrence
Expected (E)	> 50% chance of occurrence

Table 7.2

Recommended severity of effects for FMEAs conducted in cold regions.

Consequence Categories	Low	Minor	Moderate	Major	Critical
Environmental Impact	No impact.	Minor localized or short-term impacts.	Significant impact on valued ecosystem component.	Significant impact on valued ecosystem component and medium-term impairment of ecosystem function.	Serious long-term impairment of ecosystem function.
Special Considerations	Some disturbance but no impact to traditional land use.	Minor or perceived impact to traditional land use.	Some mitigatable impact to traditional land use.	Significant temporary impact to traditional land use.	Significant permanent impact on traditional land use.
Legal and Other Obligations	No non-compliance but lack of conformance with departmental policy requirement.	Technical/ Administrative non-compliance with permit, approval or regulatory requirement.	Breach of regulations, permits, or approvals (e.g. 1 day violation of discharge limits).	Substantive breach of regulations, permits, or approvals (e.g. multi-day violation of discharge limits).	Major breach of regulation—wilful violation.
	Informal advice from a regulatory agency.	Warning letter issued.	Order or direction issued.	Prosecution.	Court order issued.
	No land claim or other agreement.	Land claim or other agreement requires the Crown to satisfy administrative obligations (e.g. notification).	Land claim or other agreement requires the Crown to respond, but no time frame is specified.	Land claim or other agreement requires the Crown to exercise its obligations within a specified time frame (i.e. 2-5 years).	Land claim or other agreement requires the Crown to exercise its obligations within a specified short time frame (i.e. 1-2 years).
Consequence Costs	<$100,000	$100,000 - $500,000	$500,000 - $2.5 million	$2.5 - $10 million	>$10 million
Community/ Media/ Reputation	Local concerns, but no local complaints or adverse press coverage.	Public concern restricted to local complaints or local adverse press coverage.	Heightened concern by local community, criticism by NGOs or adverse local/ regional media attention.	Significant adverse national public, NGO, or media attention.	Serious public outcry/ demonstrations or adverse international NGO attention or media coverage.
Human Health and Safety	Low-level short-term subjective symptoms. No measurable physical effect. No medical treatment.	Objective but reversible disability/impairment and/or medical treatment. Injuries requiring hospitalization.	Moderate irreversible disability or impairment to one or more people.	Single fatality and/or severe irreversible disability or impairment to one or more people.	Multiple fatalities.

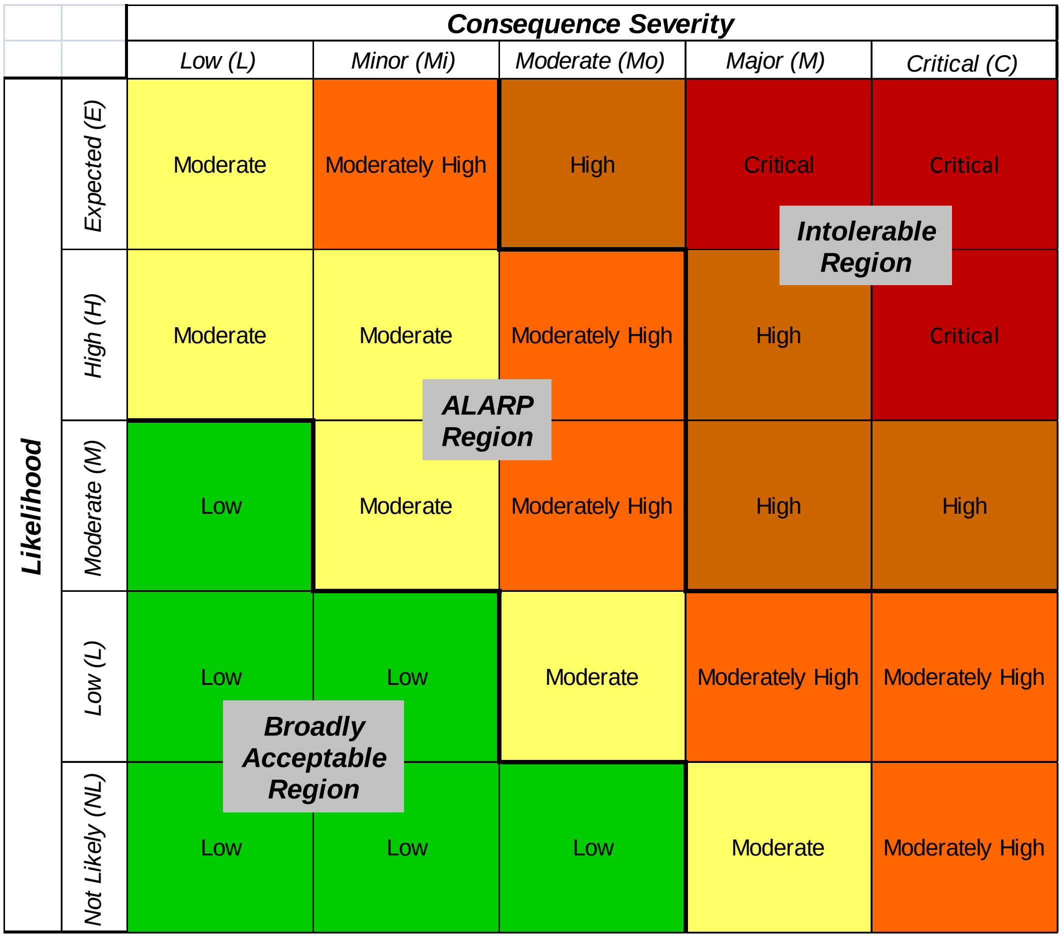
Table 7.3

Recommended level-of-confidence scale for FMEAs conducted in cold regions.

Confidence	Description
Low (L)	Do not have confidence in the estimate or ability to control during implementation
Medium (M)	Have some confidence in the estimate or ability to control during implementation, conceptual level analyses
High (H)	Have lots of confidence in the estimate or ability to control during implementation, detailed analyses following a high standard of care

Table 7.4

Risk Matrix for FMEA.



		Consequence Severity				
		Low (L)	*Minor (Mi)*	*Moderate (Mo)*	*Major (M)*	*Critical (C)*
Likelihood	*Expected (E)*	Moderate	Moderately High	High	Critical	Critical
	High (H)	Moderate	Moderate	Moderately High	High	Critical
	Moderate (M)	Low	Moderate	Moderately High	High	High
	Low (L)	Low	Low	Moderate	Moderately High	Moderately High
	Not Likely (NL)	Low	Low	Low	Moderate	Moderately High

Intolerable Region

ALARP Region

Broadly Acceptable Region

7.2 Case Study #1—Discontinuous / Seasonal Permafrost Region

7.2.1 Background

Case Study #1 (CS1) comprises waste rock dumps (WRDs) at an abandoned zinc and lead mine in the discontinuous / seasonal permafrost zone of northern Canada. Over 32 Mt of sulphidic waste rock capable of producing acidic drainage exists at the site. The WRDs possess both north- and south-facing slopes at ~3H:1V gradients. The surrounding landforms include morainal till veneers and till blankets along with glaciofluvial and glaciolacustrine deposits. The WRDs are composed of coarse waste rock that is free draining; therefore, the potential exists for convective gas transport.

The site is semi-arid and has an annual average air temperature of -2°C, with daily averages ranging from -20°C to 15°C. Mean annual precipitation at the site is 300 mm with approximately one-third falling as snow. Actual evapotranspiration varies from 75 mm/year for a north-facing slope to 200 mm/year for areas with large amounts of available moisture and incoming radiation. Spring thaw takes an average of 15 days to thaw to a depth of about 0.75 m and an additional 20 days to thaw to a depth of approximately 2 m.

Infiltration through the WRD is currently leading to groundwater contamination in the area, which results in surface water contamination. The pit area was flooded and the waste rock was deposited in a series of dumps surrounding the pit. A creek initially flowed directly over the pit area but the water is currently diverted around the pit. Studies have shown that it is not stable to maintain this diversion over the long term.

Cover material suitable for use as a low-permeability cover layer is available in the surrounding area, as is granular cover material. Coarse rock fill is not readily available and must be obtained by processing granular deposits or geochemically suitable waste rock, or by quarrying bedrock. A limited volume of organic soil is available, but requires significant effort to develop road access and would require new disturbance.

7.2.2 Cover System Performance Criteria

The cover system design for CS1 is based on its ability to achieve certain levels of performance. Vegetation establishment is an important factor over the long term as forests will increase ET rates, decrease freezing depth, and create wildlife habitat. The following are the cover system design performance criteria for the WRDs at CS1:

- Low net percolation (5% – 15% of precipitation);
- Dust control;
- Erosion control;

- Geotechnical stability;
- Vegetation establishment; and
- Control / reduce convective gas transport.

7.2.3 Cover System Design

The cover system design chosen for closure of the CS1 WRDs consists of 0.5 m of compacted till placed directly on the prepared waste rock surface, overlain by a minimum of 0.5 m of non-compacted till, as shown in Figure 7.1.

The till cover material has a tendency to become dense and hard packed following placement, which can result in rill and sheet erosion, and presents challenges for establishing vegetation. The surface of the cover system becomes slick and often non-trafficable when wet.

7.2.4 FMEA Results

The failure modes identified by the TAG for CS1 are listed below in Table 7.5 along with the effects and pathways, and high concern issues. The full FMEA worksheet, which includes mitigation recommendations for all the failure modes for CS1, is shown in Appendix B.

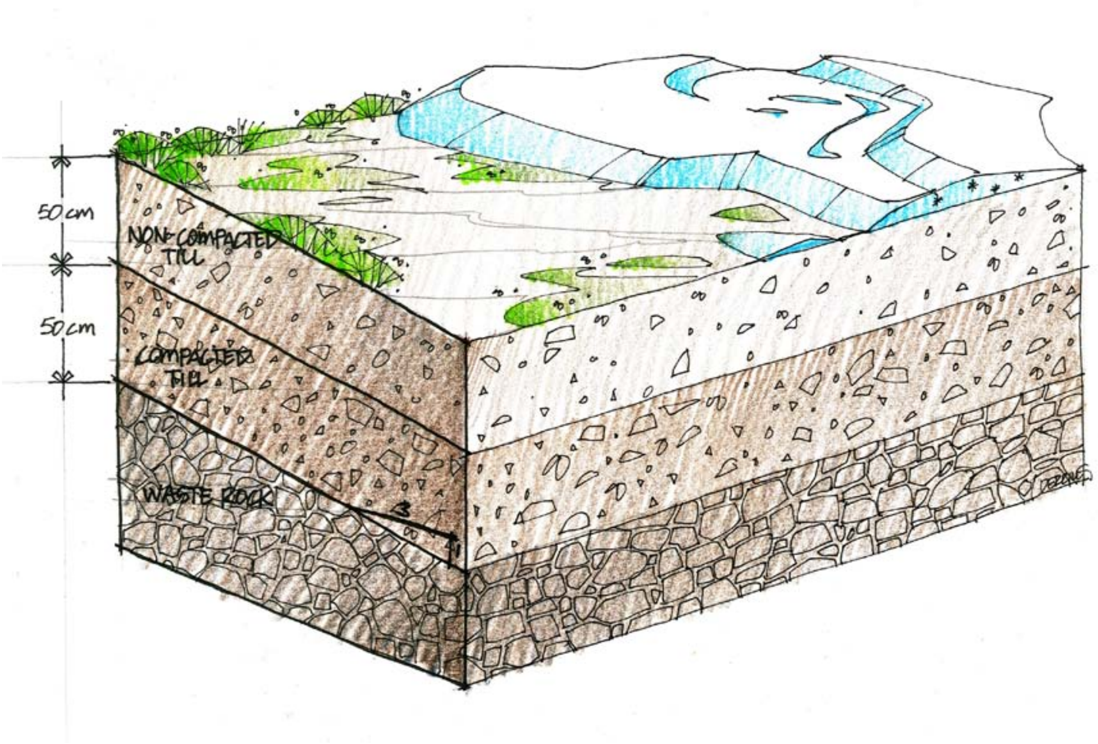


Figure 7.1 Cover system design for Case Study #1.

Table 7.5

FMEA key findings for Case Study #1.

Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***High Concern Issue***
1	Erosion due to rainfall and snowmelt to the extent that cover profile is breached	Exposure of waste material and loss of isolation. Results in exposure of salts / oxidation products and potential for contamination of surface water, and possible sediment delivery to receiving environments. Also results in decrease of cover effectiveness and higher net percolation rates, leading to increased volumes and/or contaminant loading in waste-dump seepage water.	high
2	Erosion due to rainfall and snowmelt to the extent that cover performance does not meet design criteria	Increased net percolation results in increased contaminant loading to the aquatic receptors and possible sediment delivery to receiving water bodies.	moderately high
3	Erosion due to extreme event to the extent that the cover profile is breached	Exposure of waste material and loss of isolation. Results in exposure of salts / oxidation products and potential for contamination of surface water, and possible sediment delivery to receiving water bodies. Also results in decrease of cover effectiveness and higher net percolation rates, leading to increased volumes and/or contaminant loading in WRD seepage waters.	moderately high
4	Erosion to the extent that spillway performance is degraded and ponding and bypass occurs	Results in erosion extending back up into / onto the cover system and breach of the cover system, loss of isolation of waste rock and transport of waste into environment.	critical
5	Freeze/thaw, wet/dry settlement, hummocks leading to cracking	Expect deterioration leading to two-orders of magnitude higher permeability of compacted layer. Increased net percolation results in increased volumes and/or contaminant loading in WRD seepage waters.	critical
6	Blockage of surface water drainage swales and/or channels due to sedimentation	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderate
7	Blockage of surface water drainage swales and/or channels due to vegetation	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderate
8	Blockage of surface water drainage swales and/or channels due to snow / ice	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderately high
9	Alteration of surface water drainage swales and/or channels due to disruption (frost heave, settlement, including thermokarsts, etc.)	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	low
10	Limitations in cover system constructability	Additional cost to overcome difficult access for material removal and replacement, requires additional rockfill for access, geotextile for support.	low
11	Inappropriate / incorrect quality-assurance program for construction conditions and inadequate and/or inexperienced quality control during construction	Some increase in seepage for the period of repair until repair occurs. Failure to establish vegetation results in increased net percolation and/or erosion. Use of contaminated cover materials.	low
12	Fire	Fire burns large sections of vegetation on the cover surface. Potential change to permafrost regime and slope stability / deformation. Potential for erosion increases if vegetation is relied on for erosion control. Increase in sediment release off of cover surface. Potential decrease in cover system performance (net percolation), if vegetation is relied on to limit net percolation.	moderate
13	Cover detachment, slippage, sloughing, due to thaw-induced pore-water pressures and weakening at interfaces, and piping (assume underlying structure is stable)	Exposure of the waste material and/or degradation of cover system performance.	moderate
14	Reduction in geotechnical stability due to cold regions phenomena such as ice lenses or water layers	Potential for slope failure leading to exposure of the waste material and/or degradation of cover performance. Potential for human harm.	low
15	Consolidation / settlement / hummocks causing ponding as a result of chemical weathering of waste rock and loss of shear strength	Weathering and water entry causes differential settlement, which causes ponding, and this leads to further water entry and weathering.	moderately high
16	Material mixing due to cold regions phenomena such as mudboils and cryoturbation	May result in exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water.	low
17	Surface disturbances due to cold regions phenomena such as solifluction, boulder movement, and frost mounding/hummock formation	Solifluction may lead to the development of micro-topography, which may decrease runoff and increase infiltration rates. Boulder movement and frost mounding may lead to changes in macro-scale topography which may also affect runoff and infiltration rates and potentially vegetation growth.	moderate
18	Change in active layer depth due to climate change causing degradation of cover performance.	Increased permeability and thus contaminant discharge.	low
19	Dispersion / cementing / crusting (or clay sizes causing clogging of surface pores) of cover material leading to a change in cover performance	Change in surface infiltration characteristics, enhanced erosion, and lack of moisture for vegetation.	moderately high
20	Burrowing animals	Focused infiltration and potential for increases in net percolation rates.	low
21	Vegetation effects (root penetration, blow down, etc.)	Degradation of engineered cover layer and/or compacted layer hydraulic characteristics (k_{sat}, WRC, gas transport).	critical
22	Poor vegetation establishment due to cover material physical (lack of moisture) and/or chemical (lack of nutrients, salt ingress) properties	Results in higher erosion rates (breach of cover profile, or cover system performance does not meet design criteria).	high
23	Poor vegetation establishment due to cover-material physical (lack of moisture) and/or chemical (lack of nutrients, salt ingress) properties	Results in higher net percolation rates such that cover system performance does not meet design criteria.	high
24	Cracking of top of dump cover leading to venting of lethal gas and accumulation in enclosures on top of dump	A space with lethal gas conditions leading to potential harm of wildlife or humans.	critical
25	Egress of lethal gas from waste storage facility	A space with lethal gas conditions leading to potential harm of wildlife or humans.	critical
26	Unplanned anthropogenic activity which aids the formation of MOST of the above failure modes	Results in higher net percolation rates such that cover system performance does not meet design criteria.	

The results of the FMEA showed five failure modes that fall under the critical risk category, three high risk failure modes, and five moderately high risk failure modes (see risk matrix in Table 7.4). Both the critical and high risk categories are considered an intolerable risk, whereas the moderately high risk categories are considered risks that should be minimized to As Low As Reasonably Practical (ALARP). Each of the critical risk failure modes will be discussed below along with the mitigation recommendations made by the TAG.

The first critical failure mode is 'e*rosion to the extent that spillway performance is degraded and ponding and bypass occurs'.* This failure mode would result in erosion extending back up into or onto the cover system and would result in a breach of the cover system. The cover system breach would result in loss of isolation of waste rock and transport of waste materials into the environment. This failure mode had critical severity in almost all consequence categories (environmental impact, legal and other obligations, consequence costs, community/media/reputation, and human health and safety consequences) and, combined with a high likelihood of occurrence (10-50%), this failure mode became a critical risk failure mode. To mitigate this failure mode, the TAG recommends the following:

- Construct erosion resistant channels leading into the spillway;
- Observe / measure cover performance under site climatic conditions;
- Inspect cover following storm events; and
- Perform routine maintenance to repair rills and gullies.

From a design perspective, this failure mode could be mitigated by increasing the thickness of cover (growth medium), increasing design storm event criteria, evaluating if vegetation is capable of controlling erosion in the long-term, including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is established, and re-designing the landform and/or surface water management system. To re-design the landform and/or surface water management system, greater understanding would be required on the surface water flow patterns, the requirements of storm water channels, and potential landform evolution.

The second critical risk failure mode is '*freeze / thaw cycles, wet / dry settlement, and development of hummocks leading to cracking of the cover*'. This failure mode would result in deterioration of the cover leading to an increase in permeability of the compacted layer by approximately two orders of magnitude. This failure mode had critical severity in the consequence costs category and, combined with an expected likelihood of occurrence (>50%), this failure mode became a critical risk failure mode. To mitigate this failure mode, the TAG recommends the following:

- Inspect landform at regular intervals; and
- Perform routine maintenance to repair cracks.

From a design perspective, this failure mode could be mitigated by ensuring that a change in hydraulic characteristics of cover materials due to frost action is incorporated into the design (i.e. accounted for), rather than result in a reduction in performance relative to expectations.

The third critical risk failure mode is '*vegetation effects on cover performance due to root penetration, blow down, etc.'*. This failure mode would result in degradation of the compacted layer hydraulic characteristics (e.g. increased permeability, changes to moisture retention characteristics, or increased gas transport). This failure mode had critical severity in the consequence costs category and, combined with a high likelihood of occurrence (10-50%), this failure mode became a critical risk failure mode. To mitigate this failure mode, the TAG recommends increasing the thickness of the growth medium layer.

The fourth critical risk failure mode is '*cracking of top of dump cover leading to venting of lethal gas and accumulation in enclosures on top of dump*'. This failure mode would result in a space with lethal gas conditions. This failure mode had critical severity in most of the consequence categories (legal and other obligations, consequence costs, community/media/reputation, and human health and safety consequences) and, combined with a high likelihood of occurrence (10-50%), this failure mode became a critical risk failure mode. To mitigate this failure mode, the TAG recommends the following:

- Implement institutional controls (e.g. fencing);
- Prevent camping;
- Prevent placement of structures on WRDs; and
- Install warning signs that dangerous conditions may exist.

The fifth critical risk failure mode was '*egress of lethal gas from waste storage facility'*. This failure mode could result in a space with lethal gas conditions. This failure mode had critical severity in most of the consequence categories (legal and other obligations, consequence costs, community/media/reputation, and human health and safety consequences) and, combined with a high likelihood of occurrence (10-50%), this failure mode became a critical risk failure mode. This failure mode differs from the above failure mode in that there is still potential for an egress of lethal gas even if the cover system has not cracked—other factors may contribute. To mitigate this failure mode, the TAG recommends that the factors that may contribute to lethal gas accumulation, such as poor air circulation and mixing, need to be evaluated.

7.3 Case Study #2—Discontinuous Permafrost Region

7.3.1 Background

Case Study #2 (CS2) is a tailings storage facility (TSF) at a mine in a discontinuous permafrost zone of northern Canada. The site is underlain by fractured bedrock characterized as possessing high hydraulic conductivity. The tailings are not expected to be acid generating.

The site is semi-arid with a mean annual air temperature of -5 °C. Average annual precipitation at this site is 275 mm with an approximate 65/35 split between rainfall and snowfall. Mean annual potential evaporation is approximately 425 mm.

Significant arsenic dust exists in the atmosphere at the CS2 site, which is extremely hazardous to human health and safety as well as the environment. The arsenic present in the dust is also very soluble, posing a significant risk to local groundwater resources.

A creek has been heavily altered in order to accommodate mining activities in the area and flows through the site. The creek is heavily contaminated with arsenic, both soluble and in the form of sediments. Pumping water from the mine has lowered the natural groundwater table, resulting in a groundwater flow condition towards the mine workings.

Materials suitable for a cover system are available within the vicinity of the CS2 site. Potential sand and gravel borrow materials are relatively near to the TSF, as are finer textured materials (a silty clay).

7.3.2 Cover System Performance Criteria

The cover system design for the CS2 TSF is based and evaluated on its ability to achieve certain levels of performance. The following are the cover system design performance criteria for CS2:

- Moderate net percolation (10% – 40% of precipitation);
- Dust control;
- Erosion control;
- Vegetation establishment; and
- Isolation of contaminants.

7.3.3 Cover System Design

The cover system design for the TSF at CS2 consists of a 50 cm layer of coarse-textured cover material placed directly on the tailings material, overlain by a 50 cm layer of fine-textured soil, as shown in Figure 7.2. The coarse-textured layer is intended to prevent upwards migration of contaminants from the tailings into the cover system, and reduce the downward penetration of plant roots. The cover system will also act as a protective barrier against the removal of tailings by erosion and will provide a growth medium layer for vegetation establishment.

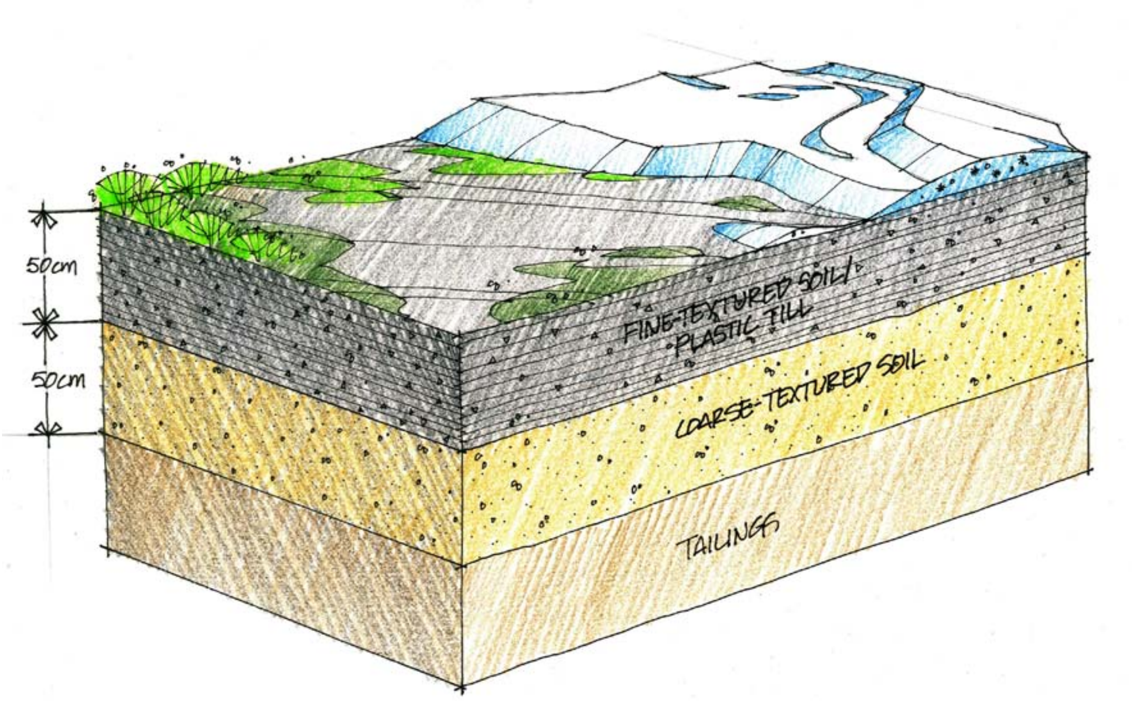


Figure 7.2 Cover system design for Case Study #2.

7.3.4 FMEA

The failure modes identified by the TAG for CS2 are listed below in Table 7.6 along with the effects and pathways, and high concern issues. The full FMEA worksheet, which includes mitigation recommendations for all the failure modes for CS2 is shown in Appendix B.

Table 7.6
FMEA key findings for Case Study #2.

Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***High Concern Issue***
1	Erosion due to rainfall and snowmelt to the extent that cover profile is breached	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	low
2	Erosion due to rainfall and snowmelt to the extent that cover performance does not meet design criteria	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	moderate
3	Erosion due to an extreme event to the extent that the cover profile is breached	Storm event causes erosion of cover and exposure of waste material. Loss of isolation and material (but this should not necessarily be considered to be an instantaneous event (first extreme event may cause the weakness and then a subsequent event results in the actual failure). Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	moderately high
4	Erosion to the extent that spillway performance is degraded that ponding and bypass occurs (spillway may be other than the dam spillway, it is simply a location where water is focused from the cover surface to transport water of the cover surface)	Results in erosion extending back up into / onto the cover system and breach of the cover profile, loss of isolation of tailings and transport of tailings into environment.	high
5	Freeze/thaw, wet/dry settlement, hummocks leading to cracking of cover profile	Results in higher net percolation rates such that cover system performance does not meet design criteria.	moderate
6	Blockage of surface water drainage swales and/or channels due to sedimentation	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderate
7	Blockage of surface water drainage swales and/or channels due to vegetation	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	Moderate
8	Blockage of surface water drainage swales and/or channels due to snow / ice	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderately high
9	Blockage of surface water drainage swales and/or channels due to animals (beavers)	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	low
10	Alteration of surface water drainage swales and/or channels due to disruption (frost heave, settlement, including thermokarsts, etc.)	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderately high
11	Cover system constructability	Additional cost to overcome difficult access for material removal and replacement, requires additional rockfill for access, geotextile for support.	moderately high
12	Inappropriate / incorrect quality assurance program for construction conditions and inadequate and/or inexperienced quality control during construction	Some increased seepage for the period of repair until repair occurs or could have chronic adverse effects on performance, latter being less likely. Failure to establish vegetation results in increased net percolation and/or erosion rates. Use of contaminated cover materials.	moderately high
13	Fire	Fire burns large sections of vegetation on the cover surface. Potential change to permafrost regime and slope stability / deformation. Potential for erosion increases if vegetation is relied on for erosion control. Increase in sediment release off of cover surface. Potential decrease in cover performance (net percolation), if vegetation is relied on to limit net percolation.	moderate
14	Cover detachment, slippage, sloughing, thaw-induced pore-water pressures and weakening at interfaces, and piping (assume underlying structure is stable)	Exposure of the waste material and/or degradation of cover system performance.	low
15	Reduction in geotechnical stability due to cold regions phenomena such as ice lenses or water layers	Potential for slope failure leading to exposure of the waste material and/or degradation of cover system performance. Potential for human harm.	low
16	Consolidation / settlement causing ponding	Potential for adverse effect on surface water management system(s) and ponding of water. Ponding where cracks form is a concern (and if ponding occurs, it will more than likely lead to cracking). Might enhance thaw consolidation. Challenges with cover material placement (soft tailings).	moderately high
17	Material mixing due to cold regions phenomena such as mudboils and cryoturbation	May result in exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water.	low
18	Surface disturbances due to cold regions phenomena such as solifluction, boulder movement, and frost mounding / hummock formation	Solifluction may lead to the development of micro-topography, which would decrease runoff and increase infiltration rates. Boulder movement and frost mounding may lead to changes in macro-scale topography which may also affect runoff and infiltration rates and potentially vegetation growth.	low
19	Change in active layer depth due to climate change	Degradation of cover system performance.	moderate
20	Dispersion / erosion	Change in surface infiltration characteristics and enhanced erosion (lack of moisture for vegetation).	low
21	Burrowing animals	Focused infiltration and potential for increases in net percolation rates.	low
22	Vegetation effects (root penetration, blow down, etc.)	Focused infiltration and potential for increases in net percolation rates.	low
23	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher erosion rates (breach of cover profile, or cover system performance does not meet design criteria).	low
24	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher net percolation rates such that cover system performance does not meet design criteria.	low
25	Anthropogenic activity which aids the formation of MOST of the above failure modes	Results in higher net percolation rates such that cover system performance does not meet design criteria.	moderate
26	Excess element uptake in vegetation	Risk to human health and/or wildlife.	
27	Loss of isolation or use of contaminated soils	Ingestion by humans and/or wildlife.	

The results of the FMEA showed no failure modes that fell under the critical risk category, one high risk failure mode, and six moderately high risk failure modes (see risk matrix in Table 7.4). The high risk category is considered an intolerable risk, whereas the moderately high risk category is considered risks that should minimized to As Low As Reasonably Practical (ALARP). The high risk and a few of the moderately high risk failure modes will be discussed below along with the mitigation recommendations made by the TAG.

The results of the FMEA showed that only one failure mode should be considered to have an intolerable risk; namely, '*erosion to the extent that spillway performance is degraded such that ponding and bypass occurs*'. This failure mode would result in erosion extending back up into or onto the cover system and breach of the cover system, loss of isolation of tailings, and transport of tailings into the environment. This failure mode had major consequence severity in the categories of environmental impact and consequence costs and had moderate severity in the category of legal and other obligations. Combined with a high likelihood of occurrence (10-50%), this failure mode became a high risk failure mode. To mitigate this failure mode, the TAG recommends the following:

- Construct erosion resistant channels leading into the spillway;
- Observe / measure cover performance under site climatic conditions;
- Inspect cover following storm events; and
- Perform routine maintenance to repair rills and gullies.

From a design perspective, this failure mode could be mitigated by increasing the thickness of cover (growth medium), increasing design storm event criteria, evaluating if vegetation is capable of controlling erosion in the long-term, including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is established, and re-designing the landform and/or surface water management system. To re-design the landform and/or surface water management system, greater understanding would be required on the surface water flow patterns, the requirements of storm water channels, and potential landform evolution.

One of the moderately high risk failure modes was '*consolidation / settlement causing ponding*'. This failure mode would result in adverse effects on surface water management system(s) and ponding of water. Settlement can cause low areas or cracks in the cover surface that encourage ponding, which then leads to more cracking and can enhance thaw consolidation. Cracks in the cover material reduce the performance of the cover system by exposing the waste, allowing increased net percolation and increased gas transport. This failure mode creates challenges with cover material placement over soft tailings.

This failure mode had moderate consequence severity in almost all consequence categories (environmental impact, legal and other obligations, consequence costs, and community/media/reputation) and was combined with a moderate likelihood of occurrence (1-

10%). The TAG had a low level of confidence for this failure mode, indicating that they had low confidence in their estimates. To mitigate this failure mode, the TAG recommends the following:

- Place waste rock in areas with softer tailings as soft tailings are more prone to this failure mode;
- Conduct appropriate levels of analyses to evaluate the potential for consolidation / settlement; and
- Conduct field trials to determine optimum material placement techniques and timing and amend construction methodology accordingly.

Another one of the moderately high risk failure modes was '*blockage of surface water drainage swales and/or channels due to snow or ice build-up (glaciation)'*. This failure mode would limit drainage of the cover system during spring melt and/or extreme rainfall events, which could lead to erosion as a result of focused water and could also result in higher net percolation rates due to ponding. This failure mode is more likely to occur with drainage swales and/or channels that are north facing as these swales and/or channels melt later in the spring. This failure mode had moderate consequence severity in the consequence categories of environmental impact, legal and other obligations, and consequence costs and was combined with a high likelihood of occurrence (10-50%). For this failure mode, the TAG assumed that the surface water management system would be designed adequately, but that the design would not have accounted for glaciation. To mitigate this failure mode, the TAG recommends the following:

- Design wider channels and include erosion protection in swales;
- Construct erosion resistant channels leading into the spillway;
- Observe / measure cover performance under site climatic conditions;
- Inspect cover following storm events; and
- Perform routine maintenance to repair rills and gullies.

From a design perspective, this failure mode could be mitigated by increasing design storm event criteria and re-designing the landform and/or surface water management system. To re-design the landform and/or surface water management system, greater understanding would be required on the surface water flow patterns, the requirements of storm water channels, and potential landform evolution.

Another one of the moderately high risk failure modes was '*alteration of surface water drainage swales and/or channels due to disruption (frost heave, settlement, including thermokarsts, etc.)'*. This failure mode would limit drainage of the cover system during spring melt and/or extreme rainfall events, which could lead to erosion as a result of focused water and could also result in higher net percolation rates due to ponding. This failure mode is more likely to occur with drainage swales and/or channels that are north facing as these swales and/or channels melt later in the spring. This failure mode had moderate consequence severity in the consequence categories of environmental impact, legal and other obligations, and consequence costs and was combined with a moderate likelihood of occurrence (1-10%). To mitigate this failure mode, the TAG recommends the following:

- Observe / measure cover performance under site climatic conditions;
- Inspect cover following storm events; and
- Perform routine maintenance to repair rills and gullies.

From a design perspective, this failure mode could be mitigated by increasing design storm event criteria and re-designing the landform and/or surface water management system. To re-design the landform and/or surface water management system, greater understanding would be required on the surface water flow patterns, the requirements of storm water channels, and potential landform evolution.

7.4 Case Study #3—Continuous Permafrost Region

7.4.1 Background

Case Study #3 (CS3) consists of both tailings and waste rock in a surface impoundment situated in a continuous permafrost zone of northern Canada. The tailings are located within a lake basin and are comprised mostly of sandy silt. The waste rock is potentially acid generating, and high concentrations of arsenic are present in both the tailings and waste rock. The active layer in the area varies between 1.5 m and 3.8 m deep.

The mean annual temperature is approximately -10°C. The average annual precipitation is 250 mm, with an approximate 60/40 split between rainfall and snowfall. The open-water period is approximately 100 days. Potential evaporation ranges from 225 to 350 mm per year.

Numerous lakes fill the lowlands, with tailings surface runoff directed through a discharge channel to a nearby lake. Elevated levels of arsenic and slightly acidic pH are present in groundwater below and down-gradient of the impoundment.

Potential cover materials within the mine site area include a sand and gravel esker material. Bedrock outcrops are common throughout the area with a discontinuous veneer of till.

7.4.2 Cover System Performance Criteria

The CS3 cover system design performance criteria include:

- Very low net percolation (1% – 5% of precipitation);
- Dust control;
- Vegetation establishment; and
- Isolation of contaminants.

7.4.3 Cover System Design

The site closure plan recommends relocating waste rock material to the tailings pond to minimize the surface area of waste to be covered. The closure plan also calls for landfill waste (e.g. barrels, scrap metal, etc.) to be placed within the tailings impoundment.

The cover system design for the waste material includes a bituminous geomembrane (BGM) overlain by 75 cm of well-graded, sandy gravelly esker material (see Figure 7.3). The BGM is intended to ensure a very low annual net percolation rate such that dissolution and migration of arsenic is minimized, and migration of oxidation products is controlled. The till layer provides a growth medium layer for any vegetation that naturally invades the covered tailings.

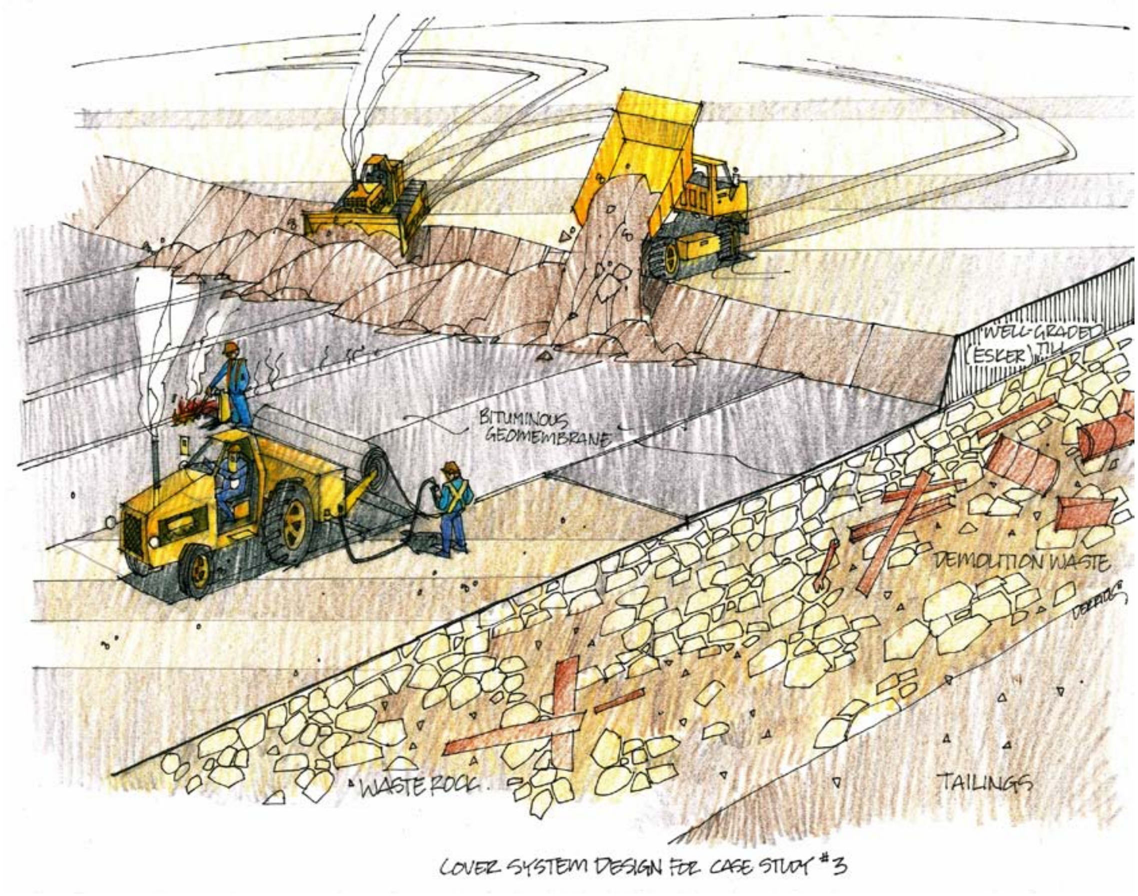


Figure 7.3 Cover system design for Case Study #3.

7.4.4 FMEA Results

The failure modes identified by the TAG for CS3 are listed below in Table 7.7 along with the effects and pathways, and high concern issues. The full FMEA worksheet, which includes mitigation recommendations for all the failure modes for CS3 is shown in Appendix B.

Table 7.7
FMEA key findings for Case Study #3.

Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***High Concern Issue***
1	Erosion due to rainfall and snowmelt to the extent that cover profile is breached	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	low
2	Erosion due to rainfall and snowmelt to the extent that cover performance does not meet design criteria	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	moderate
3	Erosion due to an extreme event to the extent that the cover profile is breached	Storm event causes erosion of cover and exposure of waste material. Loss of isolation and material (BUT THIS SHOULD not necessarily be CONSIDERED TO BE AN INSTANEOUS EVENT (first extreme event may cause the weakness and then a subsequent event results in the actual failure). Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	moderate
4	Erosion to the extent that spillway performance is degraded such that ponding and bypass occurs (spillway may be other than the dam spillway; it is simply a location where water is focused on the cover system to transport water off the cover surface)	Results in erosion extending back up into / onto the cover system and breach of the cover system, loss of isolation of tailings and transport of tailings into environment.	moderately high
5	Freeze/thaw, wet/dry settlement, hummocks leading to cracking	Expect deterioration leading to one-order magnitude higher NP than expected from intact (uncracked) BGM liner.	moderately high
6	Blockage of surface water drainage swales and/or channels due to sedimentation	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderate
7	Blockage of surface water drainage swales and/or channels due to vegetation	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderate
8	Blockage of surface water drainage swales and/or channels due to snow / ice	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	high
8a	Blockage of surface water drainage swales and/or channels due to animals (beavers)	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	low
9	Alteration of surface water drainage swales and/or channels due to disruption (frost heave, settlement, including thermokarsts, etc.)	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north-facing as these swales and/or channels will melt last.	moderately high
10	Cover system constructability	Additional cost to overcome difficult access for material removal and replacement, requires additional rockfill for access, geotextile for support.	high
11	Inappropriate / incorrect quality assurance program for construction conditions and inadequate and/or inexperienced quality control during construction	Some increased seepage for the period of repair until repair occurs or could have chronic adverse impacts on performance latter being less likely.	moderately high
12	Fire	Fire burns large sections of vegetation on the cover surface. Potential change to permafrost regime and slope stability / deformation. Potential for erosion increases if vegetation is relied on for erosion control. Increase in sediment release off of cover surface. Potential decrease in cover performance (net percolation), if vegetation is relied on to limit net percolation.	moderate
13	Cover detachment, slippage, sloughing and piping (assume underlying structure is stable)	Exposure of the waste material and/or degradation of cover system performance.	low
14	Reduction in geotechnical stability due to cold regions phenomena such as ice lenses or water layers	Potential for slope failure leading to exposure of the waste material and/or degradation of cover system performance. Potential for human harm.	low
15	Consolidation / settlement causing ponding	Potential for adverse effect on surface water management system(s) and ponding of water. Can enhance thaw consolidation. Challenges with cover material placement (soft tailings).	moderately high
16	Material mixing due to cold regions phenomena such as mudboils and cryoturbation	May result in exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water.	low
17	Surface disturbances due to cold regions phenomena such as solifluction, boulder movement, and frost mounding / hummock formation	Solifluction may lead to the development of micro-topography, which would decrease runoff and increase infiltration rates. Boulder movement and frost mounding may lead to changes in macro-scale topography which may also affect runoff and infiltration rates and potentially vegetation growth.	moderate
18	Change in active layer depth due to climate change	Degradation of cover system performance.	moderate
19	Dispersion / erosion	Change in surface infiltration characteristics and enhanced erosion (lack of moisture for vegetation).	low
20	Burrowing animals	Focused infiltration and potential for increases in net percolation rates.	low
21	Vegetation effects (root penetration, blow down, etc.)	Focused infiltration and potential for increases in net percolation rates.	low
22	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher erosion rates, leading to breach of cover profile.	low
23	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher net percolation rates such that cover performance does not meet design criteria.	moderately high
24	Anthropogenic activity which leads to aids the formation of any of the above failure modes	Results in higher net percolation rates such that cover performance does not meet design criteria.	moderately high
25	Inappropriate inclusion of demolition waste in tailings impoundment	Results in damage to the BGM such as tearing, puncturing, etc.	

The results of the FMEA showed no failure modes that fell under the critical risk category, two high risk failure modes, and seven moderately high risk failure modes (see risk matrix in Table 7.4). The high risk category is considered an intolerable risk, whereas the moderately high risk category is considered risks that should minimized to As Low As Reasonably Practical (ALARP). The high risk and a few of the moderately high risk failure modes will be discussed below along with the mitigation recommendations made by the TAG.

The first high risk failure mode was '*cover system constructability'*. This failure mode would result in additional cost required to overcome difficult access for material removal and replacement, additional rockfill required for access, and the addition of a geotextile for support. This failure mode had moderate severity in the consequence cost category (low in all the others) and was combined with an expected likelihood of occurrence (>50% chance of occurrence). As there is no way to reduce these expected costs, the TAG's recommendation for mitigation is limited to a change in cover design to avoid these constructability issues.

The second high risk failure mode was '*blockage of surface water drainage swales and/or channels due to snow or ice formation (glaciation)*'. This failure mode would limit drainage of the cover system during spring melt and/or extreme rainfall events, which could lead to erosion as a result of focused water and could also result in higher net percolation rates due to ponding. This failure mode is more likely to occur with drainage swales and/or channels that are north facing as these swales and/or channels melt later in the spring. This failure mode had moderate consequence severity in the consequence categories of environmental impact, legal and other obligations, and consequence costs and was combined with an expected likelihood of occurrence (>50%). For this failure mode, the TAG assumed that the surface water management system would be designed adequately but that the design would not have accounted for glaciation. To mitigate this failure mode, the TAG recommends the following:

- Design wider channels and include erosion protection in swales;
- Construct erosion resistant channels leading into the spillway;
- Observe / measure cover performance under site climatic conditions;
- Inspect cover following storm events; and
- Perform routine maintenance to repair rills and gullies.

From a design perspective, this failure mode could be mitigated by increasing design storm event criteria and re-designing the landform and/or surface water management system. To re-design the landform and/or surface water management system, greater understanding would be required on the surface water flow patterns, the requirements of storm water channels, and potential landform evolution.

Of the seven moderately high failure modes, four are the same as those discussed in the previous case studies, with similar mitigation recommendations:

- *Erosion to the extent that spillway performance is degraded such that ponding and bypass occurs (spillway may be other than the dam spillway, it can be a location where water is focussed from the cover surface to transport water off the cover surface);*
- *Freeze/thaw, wet/dry settlement, hummocks leading to cracking—in this case deterioration would result in an expected one order-of-magnitude increase in net percolation compared to intact liner;*
- *Alteration of surface water drainage swales and/or channels due to disruption (frost heave, settlement, including thermokarsts, etc.); and*
- *Consolidation / settlement causing ponding.*

A moderately high risk failure mode, not previously discussed, was '*inappropriate / incorrect quality assurance program for construction conditions and inadequate and/or inexperienced quality control during construction'.* This failure mode would result in some increases in seepage for the period of repair until repair occurs and it could have chronic adverse impacts on performance. The TAG believes that there is a high likelihood for a scenario of chronic adverse impacts on performance for this failure mode at CS3. This failure mode had moderate severity for the consequence categories of environmental impact and consequence costs combined with moderate likelihood of occurrence (1-10%). The TAG assumed that standard QA/QC protocols for cover construction would be followed and their estimation of the likelihood of failure was based on experience and observations. Thus, mitigations would require enhancing QA/QC protocols.

Another moderately high risk failure mode, not previously discussed, was '*poor vegetation establishment due to lack of moisture, nutrients, salt ingress, and physical properties of the cover material'.* This failure mode would result in higher net percolation rates such that cover performance does not meet criteria. This failure mode had critical severity in the consequence category of special considerations and had a high likelihood of occurrence (10-50%). In this case, the consequences of failure would be significant or permanent impact on traditional land use. To mitigate this failure mode, the TAG recommends an increase in thickness of the growth medium layer and to create a capillary break as part of the cover system design.

The last moderately high risk failure mode, also not previously discussed, was *'anthropogenic activity that leads to or aids in the formation of any of the above failure modes'*. This failure mode was considered low severity in all the consequence categories except special considerations and had a high likelihood of occurrence (10-50%). To mitigate this failure mode, the TAG recommends a greater buffer between potential human activities at the surface by increasing the thickness of the growth medium layer and adding a capillary break as part of the cover system design.

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Appendix A

Cover System Performance Risk Assessment Checklist

Table A-1 presents a list of failure modes, triggers, activities, and risks that can be used to develop a list of hazards and failure modes for a failure modes and effects analysis (FMEA).

Many of these items are mechanisms of natural landscape evolution and may not represent 'failure' of the cover system (many may be considered beneficial change). A cover system or landform design should consider each of these, at least at a cursory level. It is recommended that the list be pre-screened, and that items in the resulting 'short list' be rated according to likelihood and consequence and mitigated where necessary through design or maintenance. Residual risks can then be described.

It is important to note that the list is incomplete (it will likely never be complete) and that many of the failure modes will be linked spatially or temporally.

Use of this table has been successfully tested and proven useful for several landforms at the Syncrude Mildred Lake Operation, a large oil sands mine.

Table A-1 Hazards, triggers, activities and concerns for cover systems in cold regions.

Hazard, trigger, activity, or concern	Explanation
Physical	
Anthropogenic activity: land use	Alteration of cover system performance due to agricultural, industrial or residential activity.
Anthropogenic activity: resource exploitation	Removal of cover material and/or waste for construction materials, earth/rock fills, or artisanal mining.
Anthropogenic activity: recreation	Alteration of cover system performance due to recreational use (e.g. ATV trails resulting in erosion and permafrost regime changes).
Animal-induced erosion	Physically, animals can significantly affect the landscape in many ways. Perhaps the most common is beavers causing flooding and outburst flooding. Wildlife causing wallows, trails, and burrows.
Avulsion and flooding	Overtopping of stream channels by rivers at a high stage or due to blockage can cause flooding. Avulsion occurs where the floodwaters create a new channel and the old channel is abandoned or reduced in flow.
Bank erosion	Erosion of the sides of channels or streams by flowing water, typically along the outer bends of channels.
Blockage: Beaver dam	Blockage of a waterway by a beaver dam. Dams may be three to four metres and several hundred meters long. They can create or enlarge ponds to many square kilometres in size.

Hazard, trigger, activity, or concern	Explanation
Blockage: Ice jam	Partial or complete blockage of a river or lake outlet by pieces of ice.
Blockage: Log jam	Partial or complete blockage of a river or lake outlet by a jumble of logs, sticks, and other woody debris.
Breaching	Loss of containment of a water or fluid tailings containment structure. Typically results in a large initial outburst flood followed by a much slower gradual or sporadic loss of contents. May be triggered by overtopping, piping, vandalism or sabotage, or a downstream or upstream failure.
Catastrophic outflow	Sudden flow of water, fluid or fluid tailings due to breaching, loss of blockage, or liquefaction of a slope.
Channel deposition	Deposition of material on channel floors or banks, often referred to as silting up but may be clay, sand or rock.
Creep (solifluction or gelifluction)	Downslope movement due to gravity and affected by solifluction, freeze-thaw, freeze-induced and thaw-induced pore-water pressures, etc.
Debris flows	Very rapid flow of mud, rock, and vegetative debris along channels.
Deep-seated landslides	Downslope movement of materials along a weak plane or zone at depth resulting in disruption to the cover.
Desiccation	Cracking of cover material due to evaporation resulting in increases in net percolation and convective gas transport.
Drought	Prolonged periods with little or no rain resulting in desiccation and/or cover vegetation failure (e.g. leading to increased erosion and reduction of AET).
Earthquake / tectonism	Natural shaking or trembling of the ground due to tectonic seismic or volcanic forces, or uplift or down-drop of blocks.
Fan deposition	Fan-shaped sediment deposit at an abrupt break in slope due to a reduced gradient of a stream or channel (often an alluvial fan).
Flowslide / liquefaction	Large, long-runout failure of slopes due to liquefaction of sediments (static or dynamic).
Freeze-induced cracking	Resulting in disruption to cover system performance, and potentially desiccation of cover material, and formation of ice wedges.
Glacial advance	Advance of local or continental ice sheet.
Gullying	Water erosion of slopes forming ephemeral distinct narrow channels.
Ice mounds (pingos)	Mounding of ice caused by retardation of artesian seepage pressures, typically 20 metres in diameter and 1.5 metres high.
Ice push	The lateral pressure exerted by the expansion or wind shear on shoreward moving ice, particularly on lakes and reservoirs.
Icing (aufeis or glaciation)	Freezing of channelized water forming deposits of ice that can fill a channel cross-section. Groundwater discharge and freezing.
Migrating dunes	Migrating wind deposits of sand or silt.
Permafrost aggradation	Changes in substrates, vegetative cover, or microclimate which cause

Hazard, trigger, activity, or concern	Explanation
	creation of permafrost.
Permafrost degradation and thermokarst	Changes in substrates, vegetative covers, fills, or microclimate which cause degradation of landscape due to ground ice melt (e.g. failure of stream and pond banks, enlargement of flow channels and ponds).
Phreatic surface (water table) fluctuations	Unexpected lowering or rising of the phreatic surface resulting in slope instability problems, potential contamination of the cover profile, or increases in gas transport across the cover system.
Piping	Increasing loss of sediment due to high groundwater gradients causing internal or tunnel erosion. Particularly problematic for tailings sand, silt, and dispersive clays.
Raindrop erosion	Erosion of material by raindrops due to direct impact or leaf drip.
Settlement induced cracking	Differential settlement caused by consolidation of waste resulting in disruption of cover system performance (e.g. cracking, tearing of geomembranes, disruption in surface water drainage system, increased convective gas transport).
Settlement induced ponding	Differential settlement caused by consolidation of waste resulting in depressions causing increased net percolation.
Sheet erosion	Erosion of slopes by sheet flow. Also called slope wash.
Shoreline erosion	Erosion of shorelines by ice push, waves, long-shore currents.
Silting up of wetlands/lakes	Infilling of wetlands, lakes, reservoirs due to sediments.
Slipoff failures	Shallow slope failures in top centimetres to few metres of substrates.
Slumps	The downward slipping of a mass of rock or unconsolidated material moving as a unit, usually with backward rotation on a more or less horizontal axis parallel to the cliff or slope form which it descents
Snow avalanche	A large mass of snow or ice falling, sliding or flowing very rapidly under the force of gravity, typically on a steep slope in alpine areas.
Stream avulsion	Change in stream course due to overtopping of channel banks.
Stream flooding	Flooding of land due to high stream water levels or downstream blockage. Catastrophic outflows from upstream (natural landslide or ice dams) or artificial dam breaks, beaver dam breaks, etc.
Subsidence /consolidation	Settlement of fills due to densification or loss of material at depth.
Undermining	Collapse of surface features or facilities due to collapse into underground workings.
Vandalism or sabotage	Wilful degradation of landscape of facilities by others including staff, delinquents, or terrorists.
Volcanism	Deposition of lava or ash, landslides, sediment loading either from offsite or onsite.
Wind erosion and deposition	Wind erosion of sand and silt particles (particularly tailings) and subsequent deposition in sheets or dunes.

Hazard, trigger, activity, or concern	Explanation
Biological	
Blight / disease	A disease or injury of plants resulting in withering, cessation of growth and death of parts.
Blowdown / tornado	Loss or damage to vegetation due to storms or high winds.
Browsing / grazing	Removal of vegetation and reduction of AET rates.
Browsing / grazing	Ingestion of toxic elements via soil and/or plants.
Climate change	Fluctuations in temperature, rainfall, snowfall, sunlight.
Failure to set up nutrient cycle	Soils may fail to set up nutrient cycle in reasonably short time frames due to poor components or poor vegetation.
Fertilizing	Application of fertilization to reclaimed areas.
Fire	Loss of vegetation resulting in reduced AET and potentially higher rates of soil erosion.
Groundwater contaminating plants	Plant growth or viability affected by contaminated groundwater.
Groundwater contaminating animals	Animal health affected by contaminated groundwater.
Logging	Removal of trees for lumber or pulp. Involves logging roads, trunk roads and sorting areas.
Loss of diversity	Over time, the landscape becomes less diverse, either through loss of species or age diversification in an area.
Micro-climate change	Changes to the climate by the construction of hills or lakes or the draining of large areas.
Non-native invasion onsite	Invasion of non-native plants from offsite (from nearby agricultural, forestry, or reclamation sites).
Not self-sustaining	Plants wither or die without ongoing human intervention.
Nutrient accumulation	Accumulation of nutrients causing excessive plant growth.
Over-fishing	Removal of too many fish of a certain species by fishing.
Over-hunting	Removal of too many animals of a certain species by hunting.
Over-grazing	Drastic reduction in vegetation through grazing pressure.
Over-trapping	Removal of too many animals of certain species by trapping.
Pseudo-climax	Planted reclamation species form stable community for decades or hundreds of years not allowing natural invasion of native species.
Root penetration	Root penetration of low permeability cover layers resulting in degradation of cover system performance (e.g. increased net percolation and convective gas transport).
Salt accumulation / salt pan	Accumulation of salts in terrestrial areas through groundwater evaporation.

Hazard, trigger, activity, or concern	Explanation
Chemical	
Acid rock drainage (ARD)	Acid rock drainage is produced by the oxidation of sulphides exposed during mining, which produces sulphuric acid and sulphate salts. The acid dissolves minerals in the rocks, further degrading the quality of the drainage water.
Cementation	Precipitation of a mineral cement along the grains of the sediment.
Decementation	Leaching of precipitation of mineral cements in a granular material.
Gas evolution	Generation and release of gas from wastes or underground mines.
Leachates	Chemically contaminated groundwater from leaching of minerals in fills.
Piping in dispersive clays	Freshwater migration through sodic clays resulting in surface and tunnel erosion and, in the case of dam cores, potential failure.
Radioactivity	The property possessed by some elements (like uranium) of spontaneously emitting alpha, beta or, sometimes, gamma rays by the disintegration of the nuclei of atoms.
Spontaneous combustion	Self-ignition of combustible materials through chemical action (like oxidation) of its constituents.
Human health and safety	
Bioaccumulation / food chain	Increase in toxicity up the food chain which ultimately presents hazards to humans at the end of the food chain.
Boreholes / wells	Cylindrical vertical voids left by drilling or well activity.
Breach / flooding	Loss of reservoir on stream contents causing danger to humans.
Dust	Wind-borne material from disturbed areas.
Gas emissions	Lethal gases or lack of oxygen emanating from waste storage facility potentially resulting in risk to humans and wildlife.
Groundwater contamination	Potential of human ingestion of contaminated groundwater.
Ingestion	Consumption of contaminated soils.
Pits and water bodies	Danger to people drowning in old pits or water bodies.
Radioactivity	Exposure of people or animals to unacceptably high levels of radioactivity or radon.
Sinkholes	A circular hole in the ground caused by exposure of underground voids left by dissolution, piping, or undermining.
Failure to perform intended function	
Act as aquifer	Some substrates may be designed to transmit water.
Aesthetics	Landscape is not aesthetically pleasing to public – based on visual, olfactory, or other criteria.
Barrier: Sight	A strip of trees or a long berm designed to limit visual access from roadways or rivers.
Barrier: Sound	A solid fence or windrow that blocks direct sound transmission, usually

Hazard, trigger, activity, or concern	Explanation
	to residential areas.
Contain / isolate fluids	Reservoirs and dams contain fluids.
Contain / isolate solids	Containment or isolation of solids – usually covered dumps and pits.
Corridor: Industrial	Landforms may be designed to provide corridors for a variety of uses.
Corridor: Road	
Corridor: Wildlife	
Corridor: Transportation	
Corridor: Wildlife	
End land use	Landscapes are usually designed to permit certain land uses.
Firewall	Some landscape elements may be designed to resist transmitting of failure modes – for example rocky areas to minimize risk of spread of wildlife, armouring of lake outlets to prevent downcutting and downstream damage.
Foundation soils	Areas may be designed to provide suitable foundations for buildings, roads, or other facilities.
Groundwater barrier	Fills or slurry walls may be designed to reduce fluxes of groundwater.
Littoral zone	Shallow areas of lakes may be designed to provide productive littoral zones
Meet corporate objectives	There may be mining company landscape performance objectives or agreements to meet.
Meet design or code	There may be specific design elements or codes to meet
Regulate water discharge	The discharge of water to the environment may be regulated with a dam or weir.
Regulatory: Receive regulatory approval	A landform or landscape will be designed to meet regulatory approval. It may also be designed to meet expected future regulatory conditions.
Regulatory: Continue to meet future regulatory approval	
Support infrastructure	Landscape may be designed to support mine operations, maintenance or other infrastructure.
Support vegetation	Most landscapes are designed to promote vegetation and there may be agreements for certain productivity levels.
Trafficable	Landscape is usually designed to provide trafficability to people, animals, and certain equipment.
Trap sediments	Some areas of the landscape may be designed to improve water quality by trapping sediment.
Water: Attenuate	Lakes and wetlands may be designed to attenuate water flows.
Water: Gather	Some hydrologic elements (lakes, wetlands, creeks) are designed to gather water usually for release via a river or pipe.

Hazard, trigger, activity, or concern	Explanation
Water: Release	Elements designed to release surface water to the receiving environment.
Water: Store	Some elements, such as lakes and wetlands, are designed to store water.
Water: Transmit	Rivers and creeks are designed to transmit water safely.
Water: Cleaning/ treatment	Active (water treatment plants) and passive (wetlands and lakes) may be designed to improve water quality.
Waves: Attenuate / block	Some elements, such as breakwaters, may be designed to attenuate or block waves.

Appendix B

FMEA Worksheets for Case Studies

Appendix B presents the results of a failure modes and effects analysis (FMEA) completed on the three case study sites by the members of the TAG. Tables B-1 through B-4 describe the relative rankings of likelihood of risk, level of confidence, severity of effects, and the risk matrix. The FMEA tables for each case study are presented in Tables B-5, B-6, and B-7. In the FMEA tables, each failure mode was given a failure mode ID (column 1), a description (column 2), a description of the effects and pathways (column 3), and a likelihood of occurrence (column 4, based on Table B-1). Each consequence was then evaluated based on the severity of effects (columns 5 –10, based on Table B-3). The ***letters*** assigned to each column correspond to the severity of effects described in Table B-3 (low (L), minor (Mi), moderate (mo), major (Ma), and critical (C)). The ***colour*** in each of the columns (columns 5 – 10) represents the risk rating that is determined using Table B-4 based on the combination of the likelihood (column 4) and the consequence severity (letters in columns 5 – 10). Column 11 describes the level of confidence the TAG had in their estimates for each failure mode, based on Table B-2. Column 12 shows the highest risk rating in each row of consequences (highest risk rating in columns 5 – 10 shown by the cell colour). Lastly, mitigation measured suggested by the TAG are described in column 13.

Table B-1 Likelihood of occurrence of failure mode.

Likelihood Class	Likelihood of Occurrence for Environmental and Public Concern Consequences over the assessment period
Not Likely (NL)	< 0.1% chance of occurrence
Low (L)	0.1 - 1% chance of occurrence
Moderate (M)	1 - 10% chance of occurrence
High (H)	10 - 50% chance of occurrence
Expected (E)	> 50% chance of occurrence

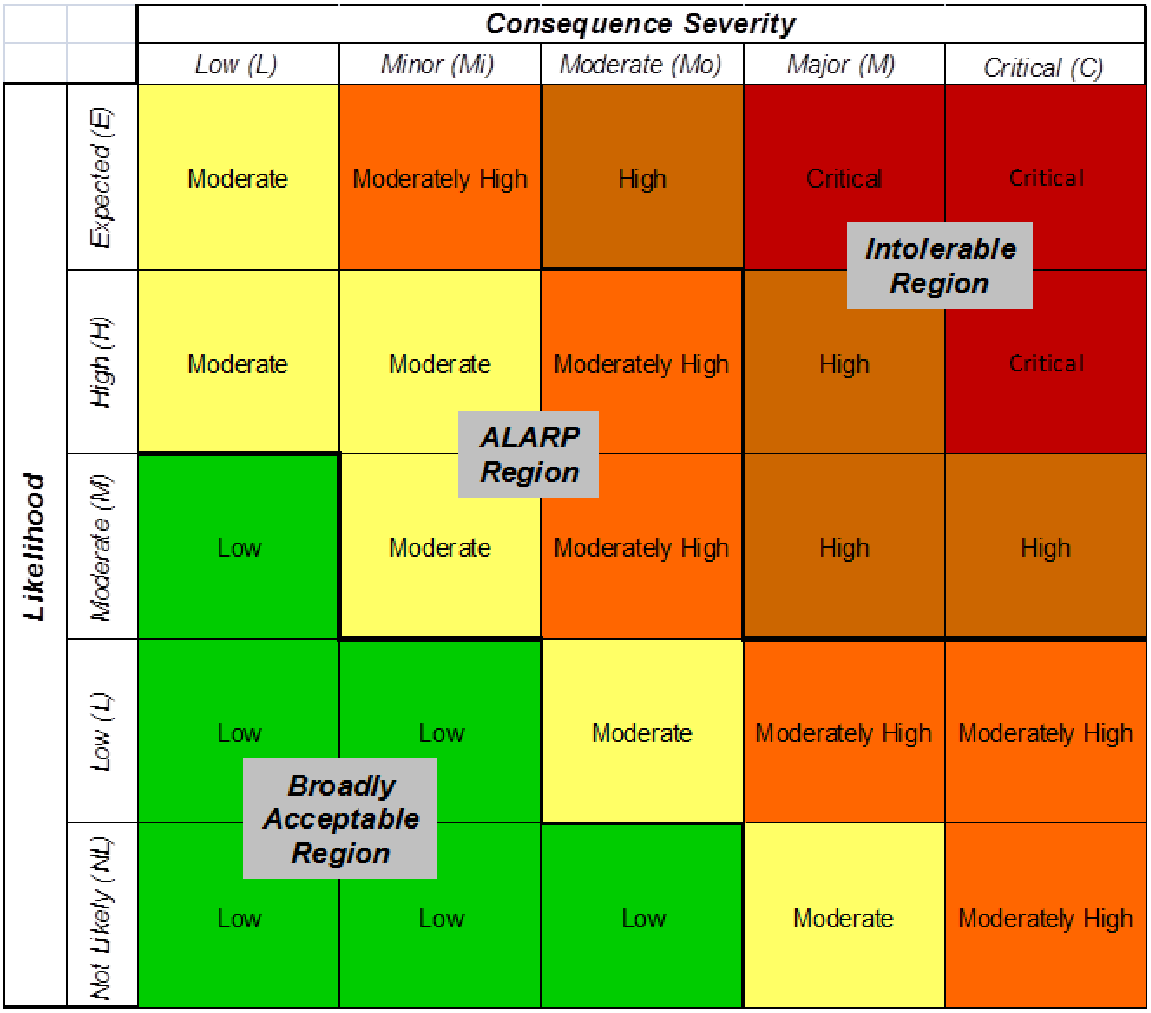
Table B-2 Level-of-confidence scale for cold regions.

Confidence	Description
Low (L)	Do not have confidence in the estimate or ability to control during implementation
Medium (M)	Have some confidence in the estimate or ability to control during implementation, conceptual level analyses
High (H)	Have lots of confidence in the estimate or ability to control during implementation, detailed analyses following a high standard of care

Table B-3 Severity of effects.

Consequence Categories	Low	Minor	Moderate	Major	Critical
Environmental Impact	No impact.	Minor localized or short-term impacts	Significant impact on valued ecosystem component.	Significant impact on valued ecosystem component and medium-term impairment of ecosystem function.	Serious long-term impairment of ecosystem function.
Special Considerations	Some disturbance but no impact to traditional land use.	Minor or perceived impact to traditional land use.	Some mitigatable impact to traditional land use.	Significant temporary impact to traditional land use.	Significant permanent impact on traditional land use.
Legal and Other Obligations	No non-compliance but lack of conformance with departmental policy requirement.	Technical/ Administrative non-compliance with permit, approval or regulatory requirement.	Breach of regulations, permits, or approvals (e.g. 1 day violation of discharge limits).	Substantive breach of regulations, permits, or approvals (e.g. multi-day violation of discharge limits).	Major breach of regulation—wilful violation.
	Informal advice from a regulatory agency	Warning letter issued.	Order or direction issued.	Prosecution.	Court order issued.
	No land claim or other agreement	Land claim or other agreement requires the Crown to satisfy administrative obligations (e.g. notification)	Land claim or other agreement requires the Crown to respond, but no time frame is specified.	Land claim or other agreement requires the Crown to exercise its obligations within a specified time frame (i.e. 2-5 years).	Land claim or other agreement requires the Crown to exercise its obligations within a specified short time frame (i.e. 1-2 years).
Consequence Costs	<$100,000	$100,000 - $500,000	$500,000 - $2.5 million	$2.5 - $10 million	>$10 million
Community/ Media/ Reputation	Local concerns, but no local complaints or adverse press coverage.	Public concern restricted to local complaints or local adverse press coverage.	Heightened concern by local community, criticism by NGOs or adverse local/ regional media attention	Significant adverse national public, NGO, or media attention.	Serious public outcry/ demonstrations or adverse international NGO attention or media coverage.
Human Health and Safety	Low-level short-term subjective symptoms. No measurable physical effect. No medical treatment.	Objective but reversible disability/impairment and/or medical treatment. Injuries requiring hospitalization.	Moderate irreversible disability or impairment to one or more people.	Single fatality and/or severe irreversible disability or impairment to one or more people.	Multiple fatalities.

Table B-4 Risk matrix. Low risks (green) are considered broadly acceptable, moderate (yellow) and moderately high (orange) risks should be controlled to As Low As Reasonably Practical (ALARP), and high (dark orange) and critical (red) risks are considered intolerable and must be avoided.



		Consequence Severity				
		Low (L)	Minor (Mi)	Moderate (Mo)	Major (M)	Critical (C)
Likelihood	Expected (E)	Moderate	Moderately High	High	Critical	Critical
	High (H)	Moderate	Moderate	Moderately High	High	Critical
	Moderate (M)	Low	Moderate	Moderately High	High	High
	Low (L)	Low	Low	Moderate	Moderately High	Moderately High
	Not Likely (NL)	Low	Low	Low	Moderate	Moderately High

Table B-5 FMEA Worksheet—Case Study #1

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
1	Erosion to the extent that cover is breached due to rainfall and snow melt	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	E	L		L	Mo	L	L	H	high	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
2	Erosion to the extent that cover performance does not meet design criteria due to rainfall and snow melt	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	L	L		L	C	Mo	L	H	moderately high	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
3	Erosion to the extent that the cover is breached due to extreme event	Storm event causes erosion of cover and exposure of waste material. **Loss of isolation and material.** Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	H	Mo		Mo	Mo	Mo	L	H	moderately high	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)

Table B-5 FMEA Worksheet—Case Study #1 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
4	Erosion to the extent that spillway performance is degraded that ponding and bypass occurs	Results in erosion extending back up into / onto the cover system and breach of the cover system, loss of isolation of tailings and transport of tailings into environment.		C		C	C	C	C		critical	Erosion resistant channels leading into the spillway. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
5	Freeze/thaw, wet/dry settlement, hummocks leading to cracking	Expect deteriation leading to two-orders of magnitudehigher permeability of compacted layer.	E	L		L	C	L	L		critical	Inspection at regular intervals. Maintenance of cracks. FROM A DESIGN PERSPECTIVE: Ensure that change in hydraulic characteristics of cover materials is incorporated into design (i.e. accounted for), rather than result in a reduction in performance relative to expectations.
6	Blockage of surface water drainage swales and/or channels due to ***sedimentation***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	L	Mo		Mo	Mo	Mo	L	H	moderate	Maintenance will occur, so that while it would be expected to occur, it will be cleaned out. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
7	Blockage of surface water drainage swales and/or channels due to ***vegetation***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	L	Mo		Mo	Mo	Mo	L	H	moderate	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)

Table B-5 FMEA Worksheet—Case Study #1 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
8	Blockage of surface water drainage swales and/or channels due to **snow / ice**	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	M	Mo		Mo	Mo	Mo	L	H	moderately high	FMEA rankings from TAG assumes adequate design for no glaciation, but inadequate if glaciation occurs. Lack of understanding in the design itself. We expect this to occur; hence, allow for (provide for) wide channels and erosion protection in swales. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
9	Alteration of surface water drainage swales and/or channels due to **disruption (frost heave, settlement, including thermokarsts, etc.)**	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	L	L		L	Mi	Mi	L	H	low	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
10	Cover system constructability	Additional cost to overcome difficult access for material removal and replacement, requires additional rockfill for access, geotextile for support	NL	L		L	Mo	L	L	H	low	
11	Inappropriate / incorrect quality assurance program for construction conditions and inadequate and/or inexperienced quality control during construction	Some increases seepage for the period of repair until repair occurs. Failure to establish vegetation results in increased net percolation and/or erosion. Use of contaminated cover materials.	L	L		L	L	L	L	H	low	Assumes that the issue is identified and fixed and this affects the costs
12	Fire	Fire burns large sections of vegetation on the cover surface. Potential change to permafrost regime and slope stability / deformation. Potential for erosion increases if vegetation is relied on for erosion control. Increase in sediment release off of cover surface. Potential decrease in cover performance (net percolation), if vegetation is relied on to limit net percolation.	H	Mi		L	L	L	L	H	moderate	Consider predictions of performance for cover system without the benefit of vegetation. Direct impact of a fire will change over time. Careful monitoring of the cover will be required after a fire is known to have occurred in the area.

Table B-5 FMEA Worksheet—Case Study #1 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
13	Cover detachment, slippage, sloughing, thaw-induced pore-water pressures and weakening at interfaces, and piping (assume underlying structure is stable)	Exposure of the waste material and/or degradation of cover performance.	M	Mi		L	Mi	L	L	M	moderate	
14	Reduction in geotechnical stability due to cold regions phenomena such as ice lenses or water layers	Potential for slope failure leading to exposure of the waste material and/or degradation of cover performance. Potential for human harm.	NL	Mi		L	Mi	L	L	H	low	
15	Consolidation / settlement / hummocks causing ponding as a result of chemical weathering of waste rock and loss of shear strength	Weathering and water entry causes differential settlement, which causes ponding, and this leads to further water entry and werathering	H	Mo		Mo	Mo	Mo	L	M	moderately high	If the crack forms in a ponded area, it should be expected to result in a large volume of seepage.Will occur much more in the softer tailings (place WR in that area) Ensure appropriate level of analyses conducted to evaluate potential consolidation / settlement. Amend surface slopes and construction (material placement) methodology (undertake field trials for material placement and timing of material placement).
16	Material mixing due to cold regions phenomena such as mudboils and cryoturbation	May result in exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water.	NL	L		L	L	L	L	H	low	
17	Surface disturbances due to cold regions phenomena such as solifluction, boulder movement, and frost mounding/hummock formation	Solifluction may lead to the development of microtopography, which would decrease runoff and increase infiltration rates. Boulder movement and frost mounding may lead to changes in macro-scale topography which may also impact runoff and infiltration rates and potentially impact vegetation.	M	Mi		L	Mi	L	L	M	moderate	
18	Change in active layer depth due to climate change causing degradation of cover performance.	Increased permeability and thus contaminant discharge	NL	L		L	L	L	L	H	low	Active layer deeper than liner, therefore should not be an issue, unless it causes thermokarsts in the underlying tailings. But it is laready thaw strained

Table B-5 FMEA Worksheet—Case Study #1 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
19	Dispersion / cementing / crusting (or clay sizes causing clogging of surface pores) of cover material leading to a change in cover performance	Change in surface infiltration characteristics and enhanced erosion and also leading to a lack of moisture for vegetation	L	L		L	C	Mo	L	L	moderately high	Re-vegetate immediately after material placement and/or other site prep to assist germination (e.g scarifying) Non-dispersive cover materials. Adequately characterize cover material, and do not use inappropriate materials and/or amend (Ca) as necessary.
20	Burrowing animals	Focused infiltration and potential for increases in net percolation	L	L		L	L	L	L	H	low	Increase thickness of growth medium, add capillary break layer
21	Vegetation effects (root penetration, blow down, etc.)	Degradation of engineered cover layer and/or compacted layer hydraulic characteristics (k_{sat}, MRC, gas transport)	H	L		L	C	L	L	H	critical	Increase thickness of growth medium.
22	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher erosion rates (breach of cover, or cover performance does not meet criteria)	M	L		L	C	L	L	H	high	Increase thickness of growth medium, create capillary break as part of cover system design
23	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher net percolation rates such that cover performance does not meet criteria	M	L		L	C	L	L	H	high	Increase thickness of growth medium, create capillary break as part of cover system design
24	Cracking of top of dump cover leading to venting of lethal gas accumulation into enclosures on top of dump	A space with lethal conditions	E	L		C	C	C	C	H	critical	Implement institutional controls (e.g. fencing), prevent camping, and placement of structures on WR dumps, not ethat conditions here may not exists but serve as an indicator (flag) of potential conditions
25	Egress of lethal gas from waste storage facility	A space with lethal conditions	E	L		C	C	C	C	H	critical	Physical setting for lethal gas accumulation can occur needs to be evaluated (poor ciculation and mixing etc.)

Table B-6 FMEA Worksheet—Case Study #2

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
1	Erosion to the extent that cover is breached due to rainfall and snow melt	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	NL	Mo		Mo	Mi	Mi	L	M	low	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
2	Erosion to the extent that cover performance does not meet design criteria due to rainfall and snow melt	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	L	Mo		Mo	Mo	Mi	L	M	moderate	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
3	Erosion to the extent that the cover is breached due to extreme event	Storm event causes erosion of cover and exposure of waste material. Loss of isolation and material (but this should not necessarily be considered to be an instantaneous event (first extreme event may cause the weakness and then a subsequent event results in the actual failure). Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	L	M		Mo	Mo	Mi	L	M	moderately high	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)

Table B-6 FMEA Worksheet—Case Study #2 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
4	Erosion to the extent that spillway performance is degraded that ponding and bypass occurs (spillway may be other than the dam spillway, it is simply a location where water is focussed from the cover surface to transport water of the cover surface)	Results in erosion extending back up into / onto the cover system and breach of the cover system, loss of isolation of tailings and transport of tailings into environment.	H	M		Mo	M	Mi	L	M	high	Erosion resistant channels leading into the spillway. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
5	Freeze/thaw, wet/dry settlement, hummocks leading to cracking	Expect deteriation leading to one-order magnitudehigher NP than expected from intact (uncracked) liner.	H	Mi		L	L	L	L	L	moderate	Inspection at regular intervals. Maintenance of cracks. FROM A DESIGN PERSPECTIVE: Ensure that change in hydraulic characteristics of cover materials is incorporated into design (i.e. accounted for), rather than result in a reduction in performance relative to expectations.
6	Blockage of surface water drainage swales and/or channels due to ***sedimentation***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	L	Mo		Mo	Mo	Mi	L	M	moderate	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
7	Blockage of surface water drainage swales and/or channels due to ***vegetation***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	L	Mo		Mo	Mo	Mi	L	M	moderate	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)

Table B-6 FMEA Worksheet—Case Study #2 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
8	Blockage of surface water drainage swales and/or channels due to ***<u>snow / ice</u>***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	H	Mo		Mo	Mo	Mi	L	M	moderately high	FMEA rankings from TAG assumes adequate design for no glaciation, but inadequate if glaciation occurs. Lack of understanding in the design itself. We expect this to occur; hence, allow for (provide for) wide channels and erosion protection in swales. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
9	Blockage of surface water drainage swales and/or channels due to ***<u>animals (beavers)</u>***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	NL	Mi		Mo	Mo	Mi	L	M	low	FMEA rankings from TAG assumes adequate design for no glaciation, but inadequate if glaciation occurs. Lack of understanding in the design itself. We expect this to occur; hence, allow for (provide for) wide channels and erosion protection in swales. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
10	Alteration of surface water drainage swales and/or channels due to ***<u>disruption (frost heave, settlement, including thermokarsts, etc.)</u>***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	M	Mo		Mo	Mo	Mi	L	M	moderately high	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
11	Cover system constructability	Additional cost to overcome difficult access for material removal and replacement, requires additional rockfill for access, geotextile for support	H	L		L	Mo	L	L	H	moderately high	

Table B-6 FMEA Worksheet—Case Study #2 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
12	Inappropriate / incorrect quality assurance program for construction conditions and inadequate and/or inexperienced quality control during construction	Some increases seepage for the period of repair until repair occurs ***or could have chronic adverse impacts on performance*** latter being less likely. Failure to establish vegetation results in increased net percolation and/or erosion. Use of contaminated cover materials.	M	Mo		L	Mo	L	L	M	moderately high	Assumes that the issue is identified and fixed and this affects the costs (this is for the more common scenario)
13	Fire	Fire burns large sections of vegetation on the cover surface. Potential change to permafrost regime and slope stability / deformation. Potential for erosion increases if vegetation is relied on for erosion control. Increase in sediment release off of cover surface. Potential decrease in cover performance (net percolation), if vegetation is relied on to limit net percolation.	E	L		L	L	L	L	H	moderate	Consider predictions of performance for cover system without the benefit of vegetation. Direct impact of a fire will change over time. Careful monitoring of the cover will be required after a fire is known to have occurred in the area.
14	Cover detachment, slippage, sloughing, thaw-induced pore-water pressures and weakening at interfaces, and piping	Exposure of the waste material and/or degradation of cover performance.	NL	L		L	L	L	L	H	low	
15	Reduction in geotechnical stability due to cold regions phenomena such as ice lenses or water layers	Potential for slope failure leading to exposure of the waste material and/or degradation of cover performance. Potential for human harm.	NL	L		L	L	L	L	H	low	
16	Consolidation / settlement causing ponding	Potential for adverse effect on surface water management system(s) and ponding of water. It is the crack where you have the ponding is the issue (and if you have the ponding, it will more than likely lead to crack). Can enhance thaw consildation. Challenges with cover material placement (soft tailings).	M	Mo		Mo	Mo	Mo	L	L	moderately high	If the crack forms in a ponded area, it should be expected to result in a large volume of seepage.Will occur much more in the softer tailings (place WR in that area) Ensure appropriate level of analyses conducted to evaluate potential consolidation / settlement. Amend surface slopes and construction (material placement) methodology (undertake field trials for material placement and timing of material placement).
17	Material mixing due to cold regions phenomena such as mudboils and cryoturbation	May result in exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water.	NL	Mi		Mi	Mi	L	L	L	low	Not likely because of impermeable membrane

Table B-6 FMEA Worksheet—Case Study #2 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
18	Surface disturbances due to cold regions phenomena such as solifluction, boulder movement, and frost mounding/hummock formation	Solifluction may lead to the development of microtopography, which would decrease runoff and increase infiltration rates. Boulder movement and frost mounding may lead to changes in macro-scale topography which may also impact runoff and infiltration rates and potentially impact vegetation.	NL	Mi		Mi	Mi	L	L	L	low	
19	Change in active layer depth due to climate change	Degradation of cover performance.	E	L		L	L	L	L	H	moderate	Active layer deeper than liner, therefore should not be an issue, unless it causes thermokarsts in the underlying tailings. But it is laready thaw strained
20	Dispersion / erosion	Change in surface infiltration characteristics and enhanced erosion (lack of moisture for vegetation)	NL	L		L	L	L	L	H	low	Non-dispersive cover materials. Adequately characterize cover material, and do not use inappropriate materials and/or amend (Ca) as necessary.
21	Burrowing animals	Focused infiltration and potential for increases in net percolation	M	L		L	L	L	L	H	low	Increase thickness of growth medium, add capillary break layer
22	Vegetation effects (root penetration, blow down, etc.)	Degradation of engineered cover layer and/or compacted layer hydraulic characteristics (k_{sat}, MRC, gas transport)	NL	L		L	L	L	L	H	low	Increase thickness of growth medium.
23	Poor vegetation establisment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher erosion rates (breach of cover, or cover performance does not meet criteria)	NL	Mo		Mo	Mo	Mi	L	H	low	Increase thickness of growth medium, create capillary break as part of cover system design
24	Poor vegetation establisment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher net percolation rates such that cover performance does not meet criteria	NL	L		L	L	L	L	H	low	Increase thickness of growth medium, create capillary break as part of cover system design
25	Anthropogenic activity which leads to aids the formation of ***MOST*** of the above failure modes	Results in higher net percolation rates such that cover performance does not meet criteria	E	L		L	L	L	L	H	moderate	Increase thickness of growth medium, institutional controls

Table B-7 FMEA Worksheet—Case Study #3

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
1	Erosion to the extent that cover is breached due to rainfall and snow melt	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	NL	Mo	Mi	Mo	Mi	Mi	L	M	low	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
2	Erosion to the extent that cover performance does not meet design criteria due to rainfall and snow melt	Exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	L	Mo		Mo	Mo	Mi	L	M	moderate	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
3	Erosion to the extent that the cover is breached due to extreme event	Storm event causes erosion of cover and exposure of waste material. **Loss of isolation and material (BUT THIS SHOUDL not necessarily be CONSIDERED TO BE AN INSTANEOUS EVENT (first extreme event may cause the weakness and then a subsequent event results in the actual failure).** Results in exposure of salts / oxidation products and potential for contamination of surface water. Also results in decrease of cover effectiveness and higher net percolation rates.	L	M		Mo	Mo	Mi	L	M	moderate	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)

Table B-7 FMEA Worksheet—Case Study #3 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
4	Erosion to the extent that spillway performance is degraded that ponding and bypass occurs (spillway may be other than the dam spillway, it is simply a location where water is focussed from the cover surface to transport water of the cover surface)	Results in erosion extending back up into / onto the cover system and breach of the cover system, loss of isolation of tailings and transport of tailings into environment.	H	M		Mo	M	Mi	L	M	moderately high	Erosion resistant channels leading into the spillway. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: Increase thickness of cover (growth medium), increase design storm event criteria, is vegetation capable of controlling erosion in the long-term, consider including surface erosion control measures (e.g. rock mulch) to control erosion until vegetation is able to, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
5	Freeze/thaw, wet/dry settlement, hummocks leading to cracking	Expect deteriation leading to one-order magnitudehigher NP than expected from intact (uncracked) liner.	E	Mi		L	L	L	L	L	moderately high	Inspection at regular intervals. Maintenance of cracks. FROM A DESIGN PERSPECTIVE: Ensure that change in hydraulic characteristics of cover materials is incorporated into design (i.e. accounted for), rather than result in a reduction in performance relative to expectations.
6	Blockage of surface water drainage swales and/or channels due to ***<u>sedimentation</u>***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	L	Mo		Mo	Mo	Mi	L	M	moderate	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
7	Blockage of surface water drainage swales and/or channels due to ***<u>vegetation</u>***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	L	Mo		Mo	Mo	Mi	L	M	moderate	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)

Table B-7 FMEA Worksheet—Case Study #3 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
8	Blockage of surface water drainage swales and/or channels due to ***snow / ice***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	E	Mo		Mo	Mo	Mi	L	L	high	FMEA rankings from TAG assumes adequate design for no glaciation, but inadequate if glaciation occurs. Lack of understanding in the design itself. We expect this to occur; hence, allow for (provide for) wide channels and erosion protection in swales. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
8a	Blockage of surface water drainage swales and/or channels due to ***animals (beavers)***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	nl	Mi		Mo	Mo	Mi	L	L	low	FMEA rankings from TAG assumes adequate design for no glaciation, but inadequate if glaciation occurs. Lack of understanding in the design itself. We expect this to occur; hence, allow for (provide for) wide channels and erosion protection in swales. Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
9	Alteration of surface water drainage swales and/or channels due to ***disruption (frost heave, settlement, including thermokarsts, etc.)***	Limits drainage of cover system during spring melt and/or extreme rainfall events, which can lead to erosion as a result of focused water. May also result in higher net percolation rates due to ponding. Failure mode 'enhanced' with drainage swales and/or channels that are north facing as these swales and/or channels will melt last.	M	Mo		Mo	Mo	#REF!	L	L	moderately high	Observe / measure cover performance under site climatic conditions. Inspection of cover following a storm event. Maintenance of rills/gullies FROM A DESIGN PERSPECTIVE: increase design storm event criteria, re-design landform and/or surface water management system (focus of surface water? storm water channels sufficient? landform evolution?)
10	Cover system constructability	Additional cost to overcome difficult access for material removal and replacement, requires additional rockfill for access, geotextile for support	E	L		L	Mo	L	L	H	high	

Table B-7 FMEA Worksheet—Case Study #3 (cont.)

				Consequences								
Failure Mode ID	***Failure Mode Description***	***Effects and Pathways***	***Likelihood***	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	***Level of Confidence***	***Highest Risk Rating***	***Mitigation / Comments***
11	Inappropriate / incorrect quality assurance program for construction conditions and inadequate and/or inexperienced quality control during construction	Some increases seepage for the period of repair until repair occurs ***or could have chronic adverse impacts on performance*** latter being less likely	m	Mo		L	Mo	L	L	M	moderately high	Assumes that the issue is identified and fixed and this affects the costs (this is for the more common scenario)
12	Fire	Fire burns large sections of vegetation on the cover surface. Potential change to permafrost regime and slope stability / deformation. Potential for erosion increases if vegetation is relied on for erosion control. Increase in sediment release off of cover surface. Potential decrease in cover performance (net percolation), if vegetation is relied on to limit net percolation.	E	L		L	L	L	L	H	moderate	Consider predictions of performance for cover system without the benefit of vegetation. Direct impact of a fire will change over time. Careful monitoring of the cover will be required after a fire is known to have occurred in the area.
13	Cover detachment, slippage, sloughing and piping (assume underlying structure is stable)	Exposure of the waste material and/or degradation of cover performance.	NL	L		L	L	L	L	H	low	
14	Reduction in geotechnical stability due to cold regions phenomena such as ice lenses or water layers	Potential for slope failure leading to exposure of the waste material and/or degradation of cover performance. Potential for human harm.	NL	L		L	L	L	L	H	low	
15	Consolidation / settlement causing ponding	Potential for adverse effect on surface water management system(s) and ponding of water. It is the crack where you have the ponding is the issue (and if you have the ponding, it will more than likely lead to crack). Can enhance thaw consildation. Challenges with cover material placement (soft tailings).	H	Mo		Mo	Mo	Mo	L	L	moderately high	If the crack forms in a ponded area, it should be expected to result in a large volume of seepage.Will occur much more in the softer tailings (place WR in that area) Ensure appropriate level of analyses conducted to evaluate potential consolidation / settlement. Amend surface slopes and construction (material placement) methodology (undertake field trials for material placement and timing of material placement).
16	Material mixing due to cold regions phenomena such as mudboils and cryoturbation	May result in exposure of waste material. Results in exposure of salts / oxidation products and potential for contamination of surface water.	NL	Mi		Mi	Mi	L	L	L	low	Not likely because of impermeable membrane

Table B-7 FMEA Worksheet—Case Study #3 (cont.)

				Consequences								
Failure Mode ID	**Failure Mode Description**	**Effects and Pathways**	**Likelihood**	*Evironmental Impact*	*Special Considerations*	*Legal and Other Obligations*	*Consequnce Costs*	*Community / Media / Reputation*	*Human Health and Safety*	**Level of Confidence**	**Highest Risk Rating**	**Mitigation / Comments**
17	Surface disturbances due to cold regions phenomena such as solifluction, boulder movement, and frost mounding/hummock formation	Solifluction may lead to the development of microtopography, which would decrease runoff and increase infiltration rates. Boulder movement and frost mounding may lead to changes in macro-scale topography which may also impact runoff and infiltration rates and potentially impact vegetation.									moderate	
18	Change in active layer depth due to climate change	Degradation of cover performance.	E	L		L	L	L	L	H	moderate	Active layer deeper than liner, therefore should not be an issue, unless it causes thermokarsts in the underlying tailings. But it is laready thaw strained
19	Dispersion / erosion	Change in surface infiltration characteristics and enhanced erosion (lack of moisture for vegetation)	NL	L		L	L	L	L	H	low	Non-dispersive cover materials. Adequately characterize cover material, and do not use inappropriate materials and/or amend (Ca) as necessary.
20	Burrowing animals	Focused infiltration and potential for increases in net percolation	M	L		L	L	L	L	H	low	Increase thickness of growth medium, add capillary break layer
21	Vegetation effects (root penetration, blow down, etc.)	Degradation of engineered cover layer and/or compacted layer hydraulic characteristics (k_{sat}, MRC, gas transport)	NL	L		L	L	L	L	H	low	Increase thickness of growth medium.
22	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher erosion rates (breach of cover, or cover performance does not meet criteria)	NL	Mo		Mo	Mo	Mi	L	H	low	Increase thickness of growth medium, create capillary break as part of cover system design
23	Poor vegetation establishment due to lack of moisture, nutrients, salt ingress, physical properties of cover material	Results in higher net percolation rates such that cover performance does not meet criteria	NL	L	C	L	L	L	L	H	moderately high	Increase thickness of growth medium, create capillary break as part of cover system design
24	Anthropogenic activity which leads to aids the formation of any of the above failure modes	Results in higher net percolation rates such that cover performance does not meet criteria	NL	L	C	L	L	L	L	H	moderately high	Increase thickness of growth medium, create capillary break as part of cover system design