Thermal Cover Design for Mine Waste Facilities in Cold Regions

Christopher W. Stevens
SRK Consulting (U.S.) Inc., Anchorage, Alaska, USA

Tia Shapka-Fels
SRK Consulting (Canada) Inc., Vancouver, British Columbia, Canada

Maritz Rykaart
SRK Consulting (Canada) Inc., Vancouver, British Columbia, Canada

ABSTRACT: Thermal covers have been widely adopted in northern Canada for freeze encapsulation of potentially reactive mine waste to limit acid rock drainage. A better understanding of the predicted and observed thermal performance of these cover systems is needed to improve design and gain regulatory and public acceptance of the strategy for long-term closure. This paper describes the design and dominant heat transfer mechanisms that impact thermal performance of thermal conduction, latent heat, and air convection covers. Thermal model results for each cover type is compared to demonstrate major differences in short and long-term thermal performance. Review of Canadian mining projects that have adopted the freeze encapsulation strategy indicate that the most common design is the thermal conduction cover which is generally performing as expected under contemporary climates. Thermal covers for freeze encapsulation of mine waste remain a viable approach for closure of some mine waste facilities located in cold regions.

1 INTRODUCTION

Thermal covers have been widely adopted for freeze encapsulation of potentially reactive mine waste rock and tailings. The covers are constructed over potentially acid-generating (PAG) waste to limit the depth of seasonal thaw to non-acid-generating (NAG) cover material, and to promote ground cooling that sustains a perennially frozen condition of the waste. Freezeback of the PAG waste can limit geochemical and biochemical oxidation of sulfides by reducing surface water infiltration and availability of in situ pore water within the waste material. It has also been argued that freezeback may limit oxygen supply and biological activity that contribute to the sulfide oxidation (MEND 1996).

Thermal covers have been previously referred to as an “insulating cover” (MEND 1993, MEND 1996, Pham 2013), however, this nomenclature is misleading as few covers are specifically designed to restrict heat transfer using a material of high thermal resistance. The term “thermal cover” is more appropriate to describe cover function and its dependency on the thermal regime.

This paper describes the three main thermal cover designs and the dominant mechanisms of heat transfer for each. Numerical thermal modeling results are provided to compare thermal performance of the different covers based on an equivalent cover thickness and surface climate. A review of Canadian projects and mines that have adopted thermal covers as part of the closure strategy are also summarized, followed by a description of guiding principles for cover design.

2 THERMAL COVER FUNCTION AND DESIGN

Mine waste cover systems are designed to perform specific functions that allow for the management of acid rock drainage (ARD) to the extent that the site closure objectives can be met. The primary function of a thermal cover is to limit seasonal thaw (i.e. the active layer) to the depth of the NAG cover material and to decrease the gain and/or increase the loss of heat from the underlying PAG waste. The net annual loss of heat results in perennially frozen PAG waste and establishment of the top of permafrost into the cover (Figure 1a).

Figure 1b shows near surface ground temperature and the corresponding active layer depth; i.e. the uppermost portion of the thermal cover that seasonally thaws. The active layer begins to thaw in the spring as ambient air and ground surface temperature warm above 0°C. Freezeback is typically in early winter depending on the site climate and heat in the ground. Year-to-year variability in active layer thickness caused by annual difference in heat transfer with the atmosphere and the ground can be expected.

There are three basic thermal cover designs; thermal conduction covers constructed of geochemically suitable run-of-mine (ROM)/run-of-quarry (ROQ) rock or overburden (typically sand and gravel), latent heat covers that incorporate a material of relatively high moisture content, and air convection covers that consist of poorly graded ROM/ROQ rock to achieve a high air permeability of the material (Figure 1c). A fourth cover type is based on the use of passive thermosyphons installed below a layer of insulation to cool the ground. However, this design has limited application for large mine waste facilities due to the relatively small effective freeze radius around a thermosyphon evaporator pipe and the related cost of these systems.

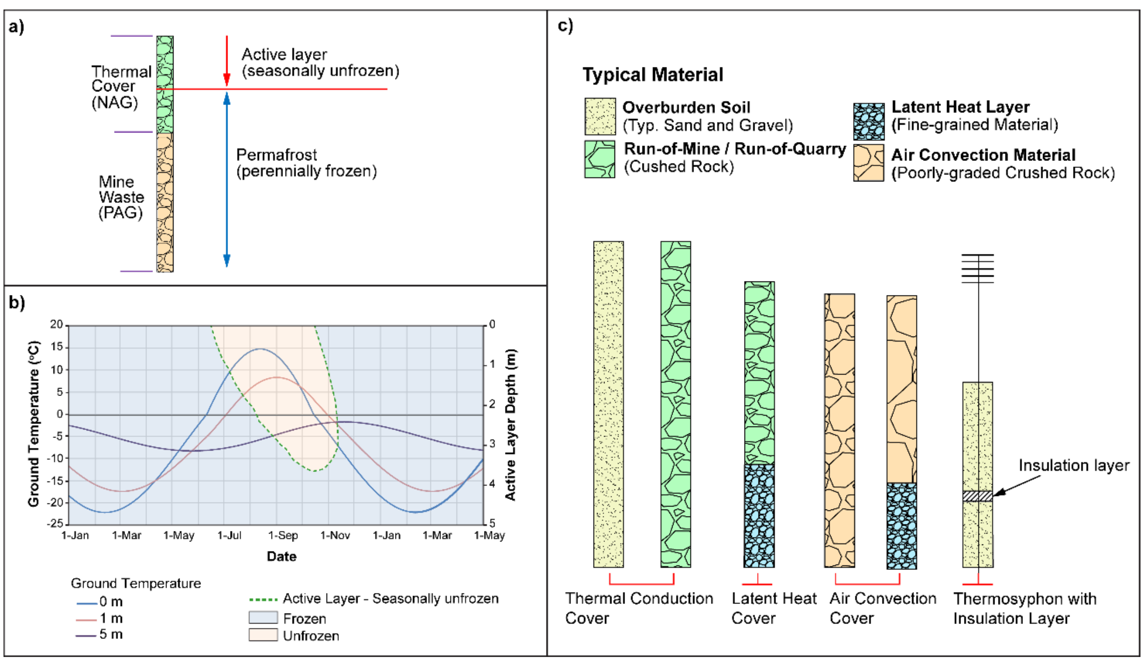

Figure 1. a) Schematic diagram of a thermal cover, b) typical progression of active layer and near surface ground temperatures for one year, and c) basic types of thermal covers.

3 DOMINANT MECHANSIM OF HEAT TRANSFER

The dominant mechanism(s) of heat transfer for each cover is a function of the thermophysical properties of the cover material and the applied thermal boundaries. There are three heat transfer mechanisms that impact cover design and performance: thermal conduction through solids and liquids, convection in fluids (liquid or air), and radiation from the particles.

Johansen (1975) evaluated heat transfer mechanisms for various granular material as a function of the d_{10} particle size and the degree of saturation. Figure 2 shows the theoretical and experimental limits of the mechanisms for heat transfer. At a low saturation for silt and clay, the moisture content gradient may allow for vapor diffusion due to the differences in relative humidity of the air within the soil pores, with thermally redistributed moisture at higher material saturation. Thermal conduction dominates the heat transfer through the material as a material becomes progressively coarser or saturated, until reaching a high saturation and grain size that thermal convection can effectively occur within the pore space. Convection in sand and gravel at relatively high saturation is caused by thermally related gradients in the water density that allow for natural convection within the pore space or the advection of heat from the movement of water through the material (Figure 2). Gravel or larger material with a relatively high air-saturation (low moisture) may allow for differences in air density that result in natural air convection or cross-pore radiation through air-filled pores due to the transfer of electromagnetic energy from a warmer to colder particle.

Thermal conduction is often regarded as the most common means of heat transfer; however, other mechanisms exist and should be considered depending on the physical properties and expected thermal boundary conditions applied to the cover material.

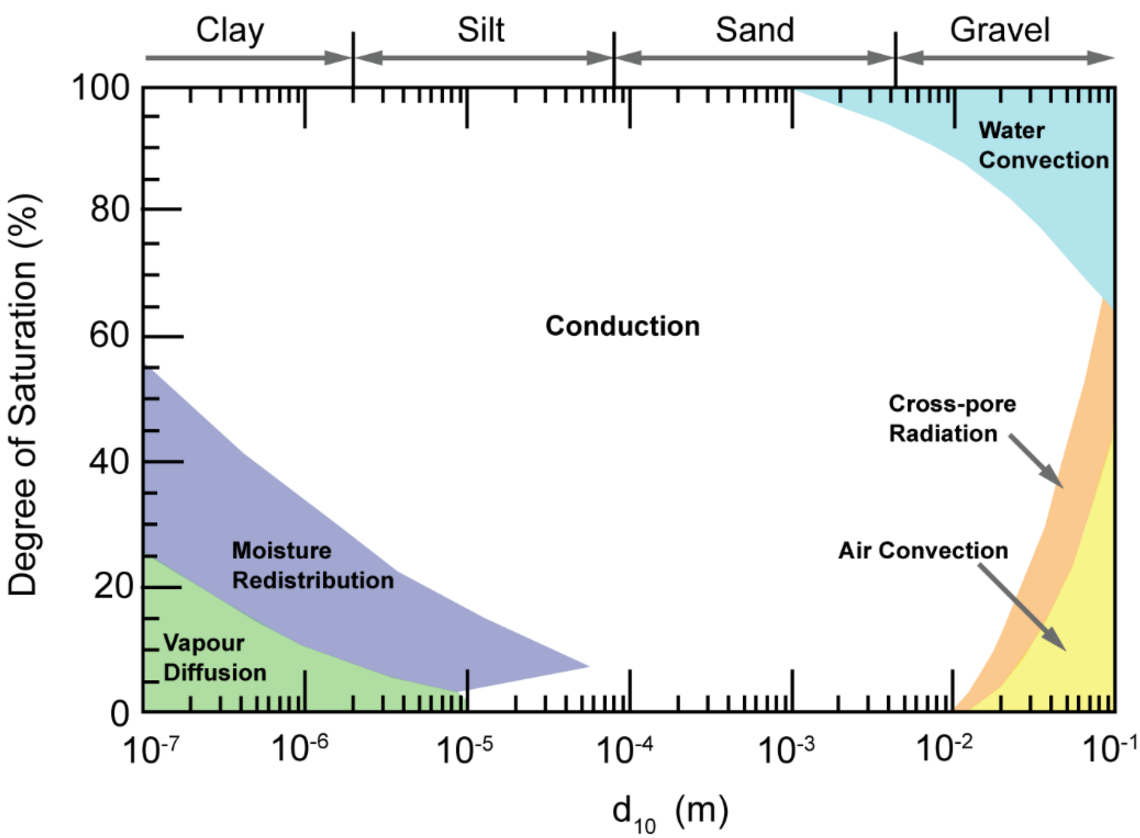

Figure 2. Heat transfer mechanisms for soils based on d_{10} particle size and degree of saturation (modified from Johansen 1975).

3.1 *Thermal Conduction Cover*

Thermal conduction covers are constructed of a single layer of geochemically suitable ROM/ROQ rock or coarse-grained overburden sand and gravel (Figure 1c). The material is typically well-drained, poorly to moderately graded crushed or blasted rock, but natural overburden may also be suitable. The degree of saturation of the ROM/ROQ rock is typically less than 30% depending on the physical properties of the material and site conditions.

Thermal conduction is the dominant mechanism for heat transfer through thermal conduction covers, i.e. most of the transfer of thermal energy by molecular vibration between particles. Air convection may still occur with the thermal conduction cover due to the coarse nature of some types of rock fill material due to the low fines content. The low moisture content of the cover material reduces the heat capacity and less energy is required to raise the temperature of the material. The low moisture content also results in a low latent heat requirement, and therefore less energy is required for phase change of liquid water or ice within the cover material.

3.2 *Latent Heat Cover*

A latent heat cover commonly consists of a double-layer cover constructed of ROM/ROQ material with an underlying soil of relatively high moisture content, referred to as the latent heat layer (Figure 1c). The dominant mechanism of heat transfer for a latent heat cover is thermal conduction. However, heat transfer and the advancement of the thawing front is greatly controlled by the moisture content within the latent heat layer. A significantly greater amount of latent heat energy (334 kJ kg^{-1} of water) is required to change phase of the pore ice to liquid water within this layer. The latent heat energy requirement consequently delays advancement of thaw into the cover. The elevated heat capacity of the high moisture layer also increases the energy requirement to raise the sensible heat component of the material. These effects reduce active layer depth and warming of the underlying waste.

3.3 *Air Convection Cover*

An air convection cover is constructed of highly porous, poorly graded material with a low fines content (Figure 1c) to allow for density-driven instability of the air column within the cover material that results in air displacement; i.e. the temperature gradient causes an air density difference that allows for the circulation of the air in the pore space and mass transfer of heat.

During the thawing season (summer), the cool air remains at the base of the cover and reversal in the air density gradient halts the natural air convection process. Thermal conduction becomes the dominant mechanism for heat transfer during this period. The active layer depth for a natural air convection system is dependent upon the low thermal conductivity resulting from the very low moisture content of the well-drained porous ROM/ROQ rock. During the freezing season (winter), the heat transfer by natural convection is more efficient than thermal conduction taking place in summer. The imbalance in heat transfer between freezing and thawing season results in more rapid freezeback and colder waste temperatures than would be achieved from conductive heat transfer alone. Pham (2013) previously evaluated natural air convection for design of thermal covers.

4 THERMAL PERFORMANCE MODELING

Thermal cover performance is routinely evaluated using numerical thermal modeling which considers site-specific factors including: contemporary and long-term climate, waste and cover material thermal and geochemical properties, and operational placement/management of waste material. Where exothermal reactions from the oxidation of sulfides are expected, heat generation should be considered to fully evaluate performance of the thermal cover. The objectives of the models and basis for evaluating thermal performance include the timing of waste freezeback, cover active layer depth, and the short- and long-term thermal regime.

4.1 *Model Setup*

SVHeat and SVAir finite element models with FlexPDE version 6.35 solver was used to show major differences in thermal performance of each cover type and sensitivity to key input parameters for some of the covers. The hypothetical model cases are based on site-specific information to provide credibility to the model results, yet were not completed for a specific mine project.

The model domain consisted of a one-dimensional model based on an 80-m section of waste covered with a 5.0-m-thick cover. The model results were evaluated on the basis of active layer depth, although additional evaluation criteria are often used during design (see Section 6.1). For simplicity, heat generation from the mine waste and geometric effects of the waste facility were not considered in the models.

4.1.1 *Boundary Conditions*

The thermal boundary applied to the uppermost surface of the model was defined by a sinusoidal air temperature wave corrected to ground surface temperature using average thawing and freezing n-factors for exposed crushed rock and gravel. The n-factors act as a constant offset to summarize heat transfer between the cover surface and the atmosphere. The surface boundary was defined as:

$$T = \max\left(nf * \left[MAAT + (C_A * t) + Amp * \sin\left(\frac{2\pi+(t+P)}{365}\right)\right], nt * \left[MAAT + (C_A * t) + Amp * \sin\left(\frac{2\pi+(t+P)}{365}\right)\right]\right) \quad (1)$$

where T is the surface ground temperature (°C), $MAAT$ is the mean annual air temperature (°C), Amp is the air temperature amplitude (°C), C_A is the air climate change factor (°C d^{-1}), t is time (days), P is the phase of the sine wave (°), and nf and nt are the respective surface freezing and thawing n-factors. Climate change is considered in Equation 1 using the air climate change factor which allows for a daily increase in the model. Table 1 summarizes input values applied to Equation 1.

Table 1. Surface boundary conditions.

Model Parameter	Value
Mean annual air temperature *(MAAT)*	-10.7°C
Air temperature amplitude *(Amp)*	21.0°C
Climate change factor (C_A)	0.000203
Surface, Thawing n-factor *(nt)*	1.52
Surface, Freezing n-factor *(nf)*	0.86

A geothermal heat flux of 2.11 kJ/(m·day·°C) is applied to the lower boundary of the model which was calculated from the average geothermal gradient (0.018°C m^{-1}) and the thermal conductivity of the mine waste rock. The initial conditions were defined by each material region in the model and assumed to be -1°C to represent an average material temperature for waste placed during operation. The average waste rock temperature applied to the model is conservative when compared to the colder waste rock temperature measured at the Diavik Mine North Country Waste Rock Facility. The cover material was specified as a constant initial temperature of 0°C. Initial conditions used in cover design should agree with site-specific conditions.

4.1.2 *Thermal Properties*

Table 2 provides a summary of the thermal properties applied to the models. The thermal conductivity and heat capacity were calculated in accordance with Cote & Konrad (2005) and make use of typical index properties of the material based on laboratory measurements and experience. Thermal properties for mine cover design should be based on the physical and thermal properties of materials intended to be used for construction of the cover system, as discussed in Section 6.

The waste rock and ROQ material used for the rock fill of thermal covers were assumed to have the same thermal properties. The tailings thermal properties were based on physical samples of tailings. Tailings process water was assumed to not have an appreciable level of dissolved ions which contribute to a freezing point depression, and no allowance was made in the model. In some cases, the inclusion of a freezing point depression in the model may be warranted by the mine waste and pore water chemistry. The latent heat material was based on a fine-grained material with 40, 60, and 80% saturation (Table 2). The tailings and latent heat material included an unfrozen water content curve based on published values for similar material. Crushed rock for the air convection material was assumed to be selected material with a d_{10} of 75 mm. Intrinsic air permeability was calculated to be of 5.6E-07 using the Chapuis equation modified version of the Kozeny-Carman equation (Chapuis 2004).

Table 2. Material thermal properties applied to thermal models.

Material	Degree of Saturation (%)	Porosity	Thermal Conductivity kJ/(m·day·°C)		Volumetric Heat Capacity kJ/(m^3·°C)	
			Unfrozen	Frozen	Unfrozen	Frozen
ROQ / Waste Rock Material	30	0.30	104	117	1697	1509
Tailings	100	0.55	123	232	3502	2350
Latent Heat Material 1	40	0.40	81	92	2109	1942
Latent Heat Material 2	60	0.40	100	131	2445	2109
Latent Heat Material 3	80	0.40	115	172	2779	2277
Air Convection Material	5	0.43	59	54	1367	1367

4.2 *Model Results*

Figure 3 shows the estimated active layer depth for thermal conduction, latent heat, and air convection covers of an equivalent thickness and applied surface boundary condition. The active layer depth is observed in the models to decrease over the first five to six years following cover construction due to cooling (heat loss) that occurs as a new thermal equilibrium within the cover and underlying waste is established. Over the long term, the active layer depth increases in response to the climate warming applied to the upper surface of the model.

A large difference in short- and long-term performance of the covers exists when comparing active layer depth for a thermal conduction cover placed over waste rock versus tailings due to the difference in heat transfer through the waste material (Figure 3a). The results demonstrate the importance of completing thermal modeling that is specific to the mine site and material type. The difference in active layer depth between the conduction covers placed over waste rock and tailings is 0.9 m for model year 10 and 2.6 m for year 75. The active layer is shown to be maintained long-term for the thermal conduction cover placed over tailings due to the combined effects of thermal properties and latent heat requirements in the higher moisture content tailings. Greater heat transfer that contributes to ground warming takes place in the low moisture content rock fill used in the thermal conduction cover and underlying waste rock, resulting in a more rapid advancement of the thawing front (Figure 3a).

Figure 3b shows the impact of changes in active layer depth for a thermal conduction cover constructed over waste rock as a function of variation in the applied n-factor which changes the ground surface temperature applied to the uppermost surface of the model. As expected, warmer ground surface temperatures result in greater active layer depth over time.

Figure 3c shows the active layer depth for a latent heat cover modeled with 3.0 m of ROQ rock underlain by a 2.0 m thick latent heat layer. The active layer depth and rate of change over time due to increasing air temperature is less for the latent heat cover (Figure 3c) when compared to a thermal conduction cover (Figure 3b). The results show the effectiveness of the latent heat requirements to reduce seasonal advancement of the thawing front into the relatively high moisture content layer located at the base of the cover. Figure 3c shows sensitivity of active layer depth to change in volumetric water content for a soil porosity of 0.4 and an initial saturation of 40%, 60%, and 80%. Seasonal thaw depth is estimated to increase as the water content and latent heat requirements decrease. The change in water content also modifies the frozen and unfrozen thermal conductivity and heat capacity of the materials.

The predicted performance of an air convection cover with and without a basal latent heat layer is shown in Figure 3d. The air convection cover generally performs better over the first 50 years when compared to the thermal conduction cover (Figure 3b) and latent heat cover (Figure 3c). The addition of a 2.0-m-thick latent heat layer below the poorly graded air convection material results in a 0.4-m decrease in thaw depth by model year 75. However, the active layer depth increases at a relatively high rate over time once the thaw penetrates the underlying latent heat layer located below the air convection cover material. This behavior is shown in the model results for an air convection cover with a 2.5-m-thick basal latent heat layer (Figure 3d), and represents an important attribute of cover performance to consider.

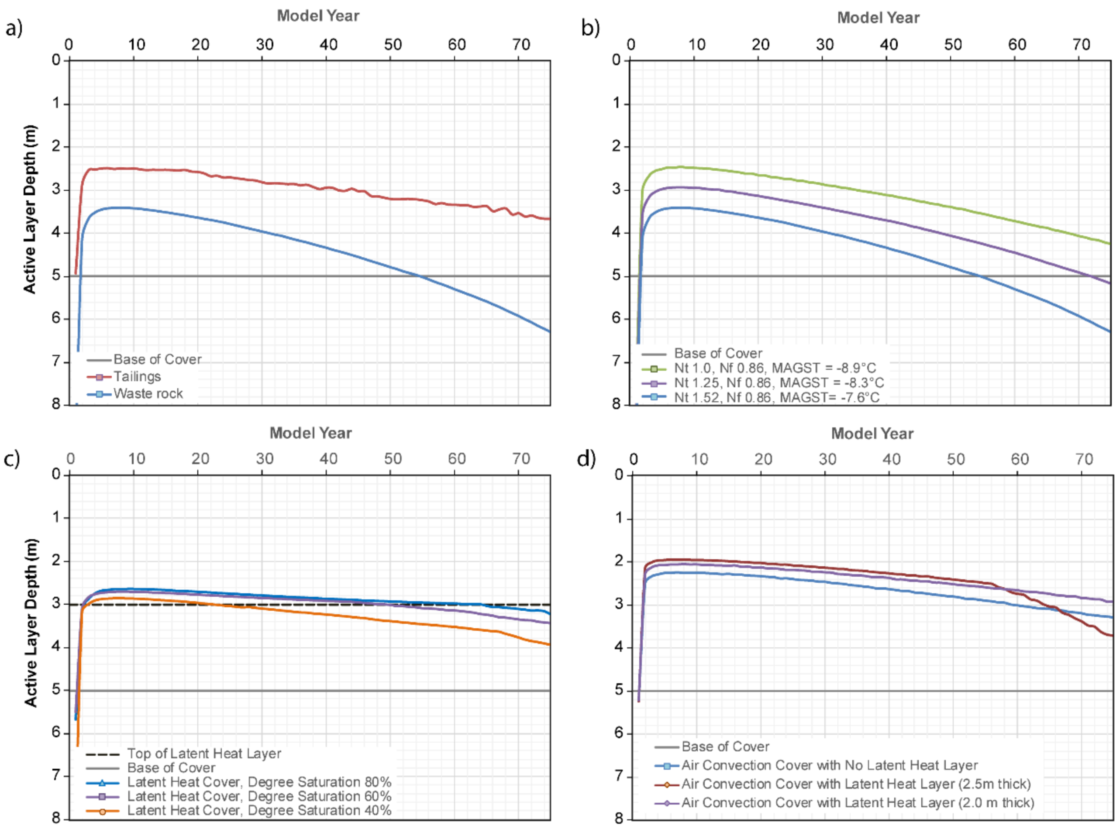

Figure 3. Estimated active layer depth for a) thermal conduction covers underlain by waste rock and tailings, b) thermal conduction covers with varying ground surface temperature, c) latent heat covers with varying material saturation, and d) air convection covers with and without a latent heat layer.

5 REVIEW OF THERMAL COVERS IN CANADA

Canadian mining projects that use thermal covers for closure of mine waste rock facilities were reviewed to compare differences in general climate and geographic applicability, design procedure and specifications. The covers were reviewed using the most recent publicly available information.

5.1 *Review Summary*

Thermal covers have been constructed, or are proposed to be implemented, at a minimum of eight mines in Nunavut and Northwest Territories for the closure of waste rock facilities (Figure 4). Climate change was considered in the design process in varying degrees for each of the covers reviewed. The geographic coverage ranges from high latitude sites in the Canadian Arctic (i.e. Nanisivik) to lower latitude sites located along the southern margin of the continuous zone of permafrost (i.e. Snap Lake), covering a MAAT range of approximately -8 to -15°C. While continuous permafrost is not a limiting factor for thermal covers, continuous permafrost is presently within regions that maintain colder air temperatures.

Each cover has been designed to consider site-specific factors, which include, but are not limited to: waste material properties and reactivity, availability of construction material, material placement history, facility design, and stage of project. Thermal cover thickness is also dependent on cover type and design, which is specific to the individual mine waste facilities. Care must be taken to consider these factors when directly comparing cover thicknesses between projects.

The reviewed thermal covers for waste rock storage areas (WRSAs) ranged from 2.2 m to 5.0 m in thickness. Figure 5 demonstrates the trend and variability of cover thickness, compared to MAAT, latitude, and cover type. Cover thickness is generally greater at southerly sites which exhibit warmer MAAT and longer periods of seasonal thaw. Northerly sites located at higher latitudes generally exhibit colder MAAT, and shorter periods of thaw, thus requiring less cover material to maintain the active layer within the cover. At some sites, the current active layer depth for the WRSAs were found to exceed the cover thickness due to ongoing placement of material and ground thermal conditions, which are currently in thermal disequilibrium with the surface conditions. Over time and with limited heat generation from the waste rock, the net heat loss from the waste rock is expected to lead to decreased active layer depth as the thermal regime shift to colder conditions. This decrease has been observed at several of the Canadian sites and is consistent with numerical modeling results shown in Section 4.2.

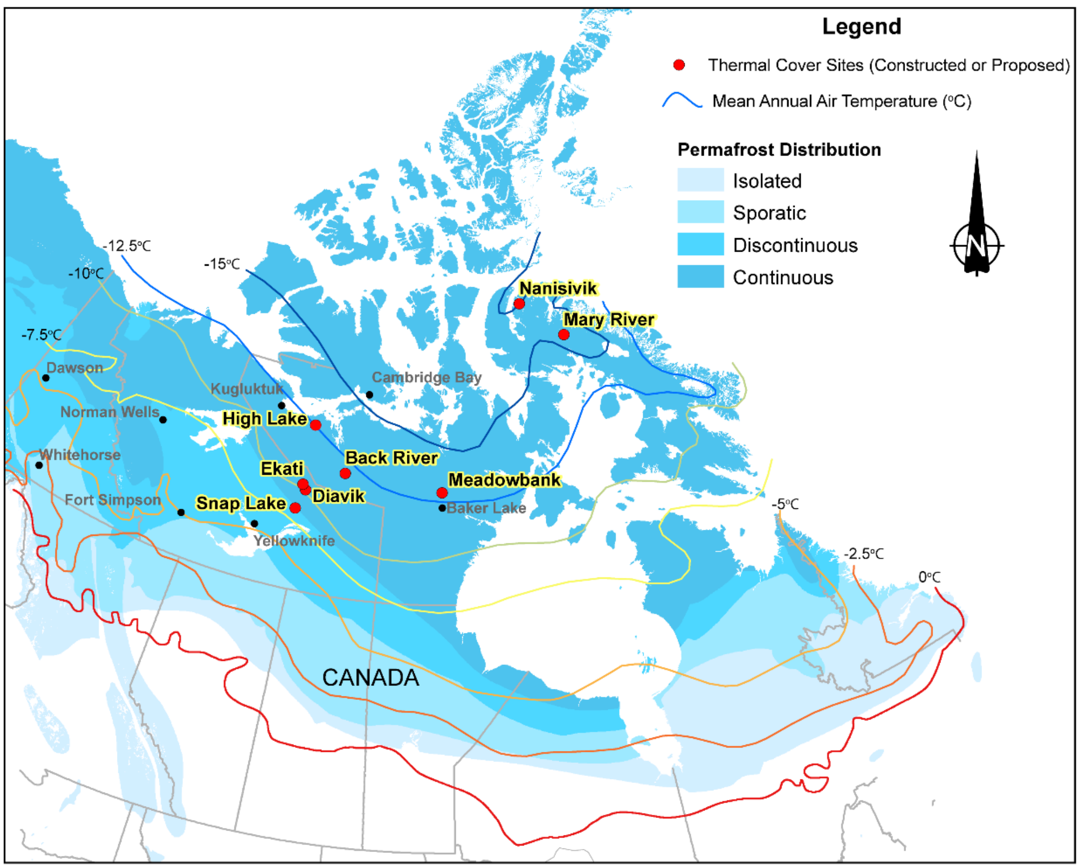

Figure 4. Thermal covers constructed or proposed for closure of waste rock facilities in Canada.

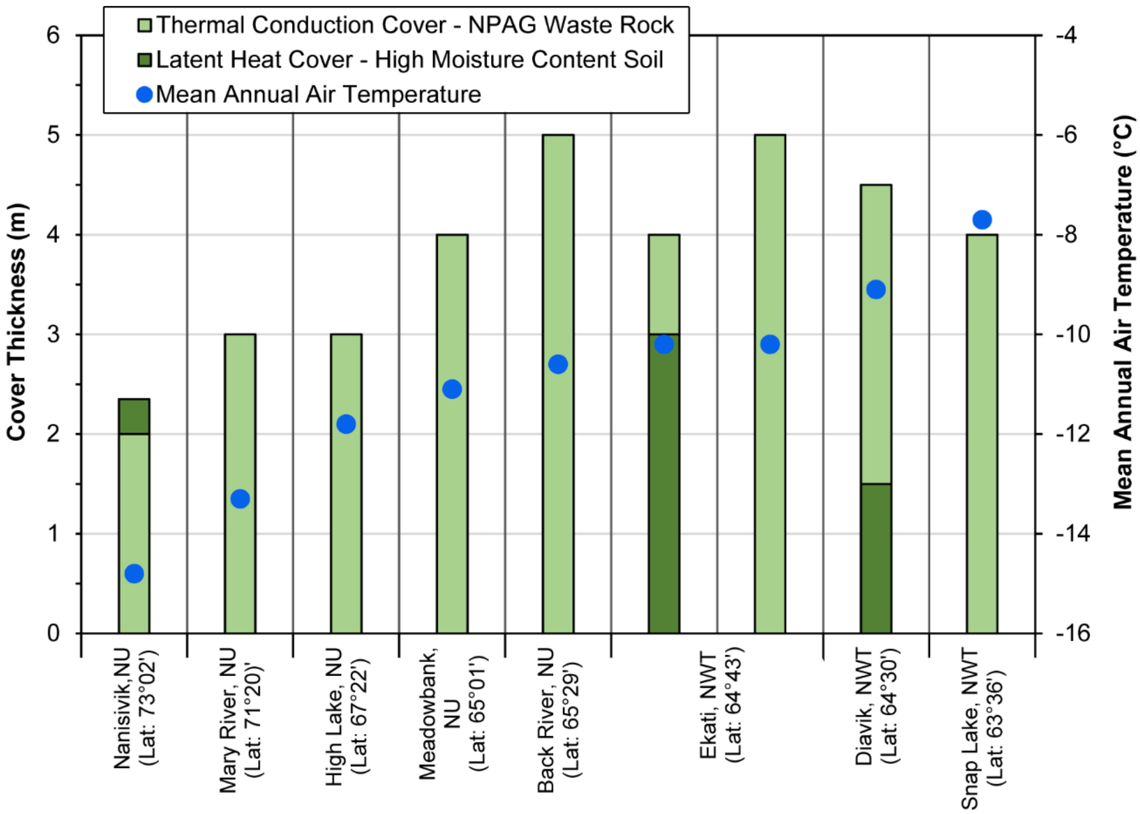

Figure 5. Summary of thermal conduction covers and latent heat covers for waste rock facilities in Canada.

Figure 6 shows maximum annual ground temperature and active layer depth measured at the Nanisivik Mine West Open Pit Waste rock cover, and clearly illustrates establishment of the active layer following cover construction. The Nanisivik zinc-lead mine, located in Nunavut on Baffin Island operated between 1976 and 2002, with full-scale mine reclamation beginning in 2004. As part of site closure, test and full-scale thermal covers were constructed (BGC 2004). MAAT at the site is -14.9°C (BGC 2018).

The West Open Pit Waste rock cover, constructed in 2006, consists of a minimum thickness of 2.0 m of granular shale overlain by 0.35 m of armor material consisting of sand, gravel, and cobbles. The waste rock used to backfill the pit has frozen back and the permafrost table has vertically aggraded into the cover (Figure 6). Net annual loss of heat from the underlying permafrost has resulting in the decrease in active layer depth between 2009 and 2014.

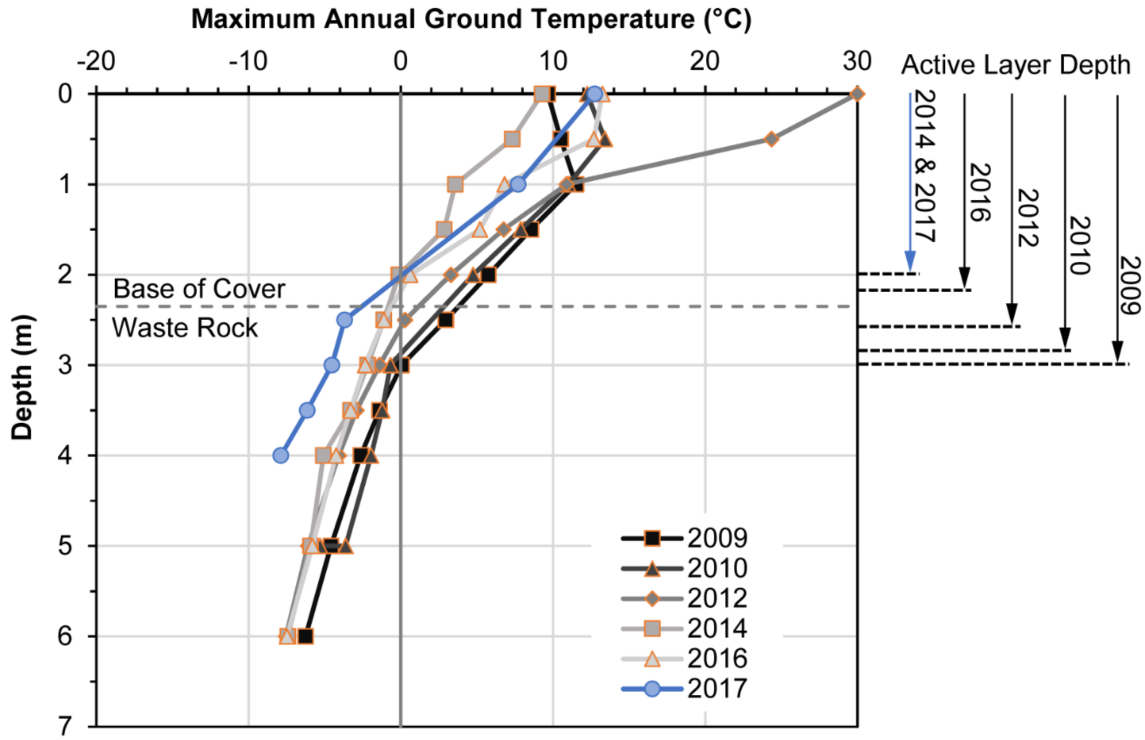

Figure 6. Measured ground temperature from mid-August and estimated active layer depth for the Nanisivik West Open Pit Waste Rock Thermal Cover. Ground temperature data reproduced from BGC (2018).

6 GUIDING PRINCIPLES FOR COVER DESIGN

6.1 *Suitability*

Adequate long-term performance of thermal covers is largely dependent on site climatic conditions. Selection of this as the preferred closure strategy will require an appropriately conservative and rigorous design and monitoring approach to demonstrate that the required design criteria can be met, considering relevant climate change predictions. The authors are of the opinion that thermal covers are best suited for areas well within the continuous permafrost regions of Canada.

6.2 *Thermal Modeling*

The current accepted practice for evaluating the thermal performance of a thermal cover is based on numerical modeling. The models are typically based on a finite element approach and account for present-day and future climate. Future climate should be assessed using best practice approaches which represents a clear understanding of the uncertainty and bias of the information (Rykaart et al. 2016). The authors view is that prediction of thermal cover performance should be modeled to the year 2100, given the current uncertainty and variability in climate change model outputs beyond this point. This limitation in the analysis tools should however be carefully considered when evaluating the long-term performance.

Performance criteria for evaluating the model results in the context of the closure objectives should be developed and consider:

- Evolution of the thermal regime, such as the aggradation of permafrost
- Short- and long-term active layer depth
- Sensitivity of cover performance to key inputs to model

One-dimensional numerical models may not be appropriate in all cases to estimate cover performance due to the complex geometry of the waste facility. For example, greater active layer depth may occur beneath side slopes where greater accumulation of snow occurs or within south-facing slopes that receive greater solar insolation from incoming shortwave radiation. Two-dimensional models should be used to account for geometric effects and where possible boundary conditions modified to meet surface conditions. Thermal models should be calibrated with site-specific ground temperature measurements.

Thermal properties and freezing characteristics for the waste and cover materials can be reasonably estimated using laboratory measurements of the physical index properties, and should be measured where possible to verify estimates and define heterogeneity from material placement. For air convection covers, the intrinsic air permeability and thermal conductivity of the material exert the greatest control on the estimated heat transfer whereas the predicted heat transfer for a latent heat layer is sensitive to differences in moisture content of the material. Sensitivity analysis for key model inputs and boundary conditions should be performed to understand the potential variability in thermal conditions over time. Thermal covers designed for tailings verses waste rock facilities should be independently evaluated due to the significant different thermal properties and heat transfer through the underlying waste, as shown in Figure 3a. Engineering judgement must also be used to evaluate the model results in the context of the model assumptions and the closure objectives.

6.3 *Trial Covers*

Trial covers have been constructed to confirm performance of the cover system at the project site. The contemporary conditions observed from trial covers does not unequivocally equate to the long-term performance as time is necessary for the ground thermal regime to adjust to a new equilibrium following waste placement and cover construction. Additionally, inherent differences that exist for trial cover construction when compared to full-scale covers may materially affect the inferred performance. Therefore, although trial covers can offer useful insight, the authors do not believe that trial covers should be a prerequisite, and if a trial cover is proposed it should be intentionally designed to verify:

- Construction methods and materials
- In situ physical and thermal properties of the cover material
- Thermal surface boundary conditions
- Seasonal thaw depth
- Time-dependent changes to the cover which impact thermal performance

6.4 *Construction Quality Assurance and Quality Control*

Construction quality assurance (QA) and quality control (QC) should be clearly defined to ensure cover construction meets the design specifications and conditions used in thermal modeling to predict long-term performance. If field conditions are found to not be within the allowable limits of the design, additional thermal modeling may be warranted to verify acceptable performance will be achieved.

The type and level of construction QA/QC that is required largely depends on the cover type, method of construction, and site-specific constraints, such as timing of material placement and construction materials. At a minimum, the QA/QC program should verify that key parameters controlling heat flow, as specified by the design are met. For example, a performance latent heat cover is controlled by the amount of latent heat required to change phase of the pore ice to liquid water. The performance of this type of thermal cover relies on the ability to achieve and retain the required moisture content. A design specification should therefore ensure physical moisture conditions will be met, maintained, and confirmed during construction.

6.5 Monitoring

A suitable monitoring program should be developed to adequately characterize conditions within the cover and underlying mine waste. The monitoring frequency and period are determined by the design and closure objectives for the site. At a minimum, ground temperature cables should be installed to monitor the ground thermal regime and active layer depth, with site locations selected to capture the expected variability in ground thermal conditions. For covers that include a latent heat layer, continuous moisture content profile monitoring may be necessary. Long-term site-specific climate measurements are also required to confirm climate change predictions.

The monitoring period will be site-specific, but is likely to be in the decadal scale. The period should focus on establishing two key elements: agreement with the modeling progression independent of the climate change predictions, and confirmation that the climate change predictions are reasonable.

7 DISCUSSION AND CONCLUSIONS

Thermal covers for freeze encapsulation of mine waste remain a viable approach for closure of some mine waste facilities located in cold regions. The primary function of a thermal cover is to limit geochemical and biochemical oxidation of sulfides by reducing surface water infiltration and availability of in situ pore water. To achieve these conditions, the cover system is designed to maintain seasonal thaw within the NAG cover material and contribute to the frozen condition of the underlying PAG waste.

The dominant heat transfer mechanism(s) for each cover is a function of the thermophysical properties of the cover material and the applied thermal boundaries. Numerical thermal modeling is the currently accepted approach to demonstrate adequate thermal performance of the design for the current and long-term climate conditions. Thermal analyses were carried out in this paper to show relative differences in active layer depth based on typical cover materials under an equivalent cover thickness and climate. The results show reduced active layer depth and improved performance are achieved with a latent heat and air convection cover design when compared to thermal conduction covers. Thermal conduction covers remain a suitable design, but require greater cover thickness to achieve the same performance. Thermal covers are sensitive to key physical parameters that should be considered during cover design and construction to ensure adequate performance.

A comprehensive understanding of the geochemical properties of the waste is required to determine if sulfide oxidation is expected to significantly contribute to heat generation and impact freezeback. For simplicity, heat generation was not addressed in this paper. Freeze encapsulation and performance of the thermal cover is dependent upon proper waste management during operation. It is imperative that the waste be managed on site through an effective plan which aims to limit sulfide oxidation during placement, as heat generation during operation could exclude the future use of the freeze strategy for closure. Waste management plans may specify segregation or blending, a maximum annual lift thickness for placement of waste to achieve annual freezeback, and other mitigation to limit heat generation prior to cover placement.

A review of thermal covers for waste rock facilities in Canada has indicated that thermal conduction covers are the most common. Where constructed, these covers are described to be adequately performing under the contemporary climate. The continuation of thermal cover monitoring will improve prediction of long-term performance through better definition of the physical and thermal conditions over time. Climate change presents unique challenges for cover function and public acceptance, but are no more or less vulnerable to poor performance when compared to alternative types of covers, as suitability of the cover system must be assessed individually for each site.

REFERENCES

BGC Engineering Inc. (BGC). 2004. Nanisivik mine closure studies engineering design of surface reclamation covers (Water License Part G, Item 4). Report submitted to Canzinco Ltd.

BGC Engineering Inc. (BGC). 2018. Nanisivik Mine, Nunavut 2017 annual geotechnical inspection. Report submitted to NYRSTAR.

Chapuis, R.P. 2004. Predicting the saturated hydraulic conductivity of sand and gravel using effective diameter and void ratio. Canadian Geotechnical Journal. 41: 787–795.

Cote, J. & Konrad, J.-M. 2005. A Generalized thermal conductivity model for soils and construction materials. Canadian Geotechnical Journal. 42: 443–458.

Johansen, O. 1975. Thermal conductivity of soils. Ph.D. thesis, University of Trondheim, Trondheim, Norway. CRREL Draft English Translation 637, US Army Corps of Engineers, Cold Regions Research and Engineering Laboratory, Hanover, N.H. p. 291.

MEND. 1993. Preventing AMD by disposing of reactive tailings in permafrost, MEND Project 6.1. Technical report.

MEND. 1996. Acid mine drainage in permafrost regions: Issues, control strategies and research requirements, MEND Project 1.61.2. Technical report submitted to Department of Indian and Northern Affairs Canada.

Pham, H.N. 2013. Heat transfer in waste-rock piles constructed in a continuous permafrost region. PhD Dissertation. Department of Civil and Environmental Engineering. University of Alberta. 376 p.

Rykaart, M., Munoz, V., & Stevens, C.W. 2016. Climate change for the engineer: standardized procedure for climate change integration into engineering design. Saskatchewan Mining Association Environmental Forum. October 18–20. p. 10.