Covers For Reactive Tailings Located in Permafrost Regions Review

MEND Report 1.61.4

This work was done on behalf of MEND and sponsored by:
The Mining Association of Canada
MEND

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Prepared by

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EXECUTIVE SUMMARY

Detrimental effects of acidic drainage on the environment are well recognized in areas not encompassed in permafrost in Canada. There are numerous abandoned, operating and proposed mines in Canadian permafrost regions. These northern mines have an additional tool to combat acid generation by freezing and keeping the wastes in a frozen state. This tool requires careful evaluation to determine where and how it may be used economically by the mining industry for the closure of tailings impoundments and waste rock piles.

Covers placed over reactive tailings and waste rock in non-permafrost regions have been studied and field-tested for many years. Many operating mines in the Canadian permafrost region have adopted, or are considering, encapsulating reactive tailings in permafrost. This can be accomplished in permafrost areas with suitable cold air temperatures and incorporating a suitable design for the active layer. This layer located at the ground surface, thaws every summer, and thereby develops a potential condition for tailings or rock waste to oxidize during the summer. To achieve encapsulation of tailings or rock waste in permafrost it is necessary to place material (e.g. a cover) over the tailings or waste rock that will contain the seasonally annual thawed zone, or the active layer, within it. This will prevent thawing of the tailings or rock waste near the surface.

Encapsulating in permafrost appears to be a good option for reactive tailings in continuous permafrost because it does not require either, 1) a dry cover such as a clayey till material, a material that is generally lacking in continuous permafrost, or 2) a water cover that is difficult to maintain because of high evaporation rates observed in most of the Canadian permafrost region. In addition, water covers are costly for remote Arctic sites because of higher construction, inspection and maintenance costs.

Four recent case histories from cover test pads constructed over reactive tailings in continuous permafrost provide information on parameters that govern the design of a cover to maintain the tailings in a frozen state. Case histories from Nanisivik, Raglan, Lupin and Rankin Inlet represent different tailings operations; cover design approaches, and physical and climate conditions.

Naturally, the first condition for encapsulating tailings in permafrost is to have sufficiently low air temperatures that create continuous permafrost. While permafrost is defined as a ground that remains at or below 0°C for two consecutive years, it is suggested that for permafrost encapsulation the ground temperature at a depth of zero annual amplitude be at, or at least, -2°C. This ground temperature translates to a mean annual air temperature (MAAT) of about -8°C when short-term annual air temperature fluctuations of about 1.5°C and the difference between MAAT and the mean annual ground surface temperature (MAGST) of about 4.5°C are applied.

The above criterion does not consider global warming which may have important implications for permafrost. Early documentation of global warming was done by Nichols (1975) who showed through radioactive carbon dating of peat that the earth experienced a little Ice Age about 300 years ago and has been warming ever since. Three progressively increasing warming trends have been recorded since.

Observations indicate that about 50% of the glaciers in the Swiss Alps have melted between 1850 and 1985 and an additional 25% have melted since 1985 (2003 Permafrost Conference address). Anisimov and Fitzharris (2001) have reported a warming trend in air temperatures of 2 to 4ºC worldwide and up to 5ºC/100years since the beginning of the 20^{th} century at selected locations in northern Siberia and Alaska. An increase in the warming trend has been observed in both Alaska (Esch 1990) and Canada since 1980 (Dyke and Brooks 2000). MAAT records for selected Canadian sites are given in this report.

Under present conditions, encapsulation of tailings is generally feasible northwest of the Mackenzie River in the Northwest Territories, all of Nunavut and the most northern region of Quebec. However, with the present global warming trend, permafrost encapsulation in some of the northern regions of the Northwest Territories and Quebec may not be sustainable in 100 to 200 years. Mines considering encapsulating tailings in permafrost will need to determine what impact global warming will have on their design.

The design concept for encapsulating reactive tailings in permafrost is to provide a sufficiently thick cover material that will maintain the active layer (annual thaw) within the cover. The thickness of the active layer is determined by site air temperature, moisture content in the soil/rock stratigraphy, surface vegetation, slope orientation, colour of the surface material (albedo), snow depth that varies with local topography, and other factors. Because these factors vary greatly from site to site, and even sometimes across a given site, the thickness of the active layer may vary from 0.5m to 5m. Site-specific factors are important considerations for the design of covers.

The dominant factors that govern the thickness of the active layer in the four case histories presented are air temperature and water content. The other factors are of less importance for the following reasons:

- Surface vegetation – Establishing a vegetative cover in permafrost regions is a slow process. It can be assumed that there will be no vegetation on top of the tailings or waste rock surface for some time.
- Slope orientation – Most of the tailings are deposited at near horizontal slope.
- Colour – Most of the soil cover materials have similar colours. However, colour could be a factor as discussed in the Nanisivik case history.

After establishing the air temperature distribution for the site, the moisture content of the cover material is the most important parameter governing the maximum thaw depth or the required cover thickness.

The effect of the moisture content within the cover material on the thickness is illustrated by the four case histories discussed in this report and the Diavik proposed cover design:

Raglan — A cover design of 2.4m was selected. It consists of a 1.2m layer of mine rock underlain by 1.2m of crushed sand and gravel esker. The measured active layer base is at a 1.9m depth (based on 0ºC freezing temperature). The thaw depth is 1.9m.

Nanisivik — Constructed five test pads with a 2m thick cover with varied stratigraphies. The active layer in the five test pads varied depending on the moisture content. It ranged from initial moisture content of about 34% at 1m to about 7% at 1.5m. The average thaw depth at the five test pads varied from 1.0 to 1.4m. The smallest thaw depth corresponding to the cover with the highest moisture content.

Lupin — The cover ranges from 0.6 to 1.6m of sand and gravel esker material. The active layer was observed to be a function of the location of the groundwater surface. It varied from 1.3m for no cover and fully saturated tailings to a depth of 1.8m when groundwater surface was likely at the base of the 1.6m thick cover.

Rankin Inlet — A 1m sand and gravel esker material was used for a cover. The freezing point was depressed to about -4ºC due to seawater infiltration and oxidized sulphides being dissolved. The active zone is estimated to be at about 5m based on the depressed freezing point and visible ice. At 0°C the thaw depth would be estimated at 2.7m.

The four case histories demonstrate that to minimize the active layer thickness within a cover, the moisture content within the cover has to be maximized. Naturally, the highest moisture content that can be reached within the cover is complete saturation. However, partial or complete saturation of the cover could result in the establishment of a stagnant water layer within the cover that prevents oxidation without the need for freezing (Li et al 1997). It has been demonstrated in previous MEND studies (MEND 2.22.2) that an effective barrier to oxygen diffusion will result if the degree of saturation of a soil layer can be maintained greater than 85 to 90%.

Based on a design concept given in MEND 6.1, work done on a stagnant water cover by Li et al (1997) and column testing by CANMET (MEND 2.12.1e), Lupin selected for its closure of their filled tailings cells, a saturated zone cover design. (Holubec 2002). The tailings will be covered with 1m of esker sand and gravel that will maintain a saturation zone at the base of the cover. Monitoring of the thermal conditions and groundwater level within the cells covered in 1995 and 1998 has supported this concept.

RÉSUMÉ

Les répercussions du drainage acide sur l'environnement sont nettement reconnues dans les régions du Canada dépourvues de pergélisol. Au Canada, les mines abandonnées, en exploitation et à l'état de projets sont nombreuses dans les régions à pergélisol. Ces mines nordiques disposent d'un outil supplémentaire pour lutter contre la production d'acide, soit le gel des rejets et leur conservation dans cet état. Cet outil doit faire l'objet d'une évaluation approfondie afin qu'il soit possible de déterminer où et comment il peut être utilisé économiquement par l'industrie minière en vue de la fermeture des parcs à résidus et des haldes de stériles.

Les couvertures placées sur les résidus et les stériles réactifs dans les régions dépourvues de pergélisol ont été étudiées et soumises à des essais sur le terrain durant de nombreuses années. Un bon nombre de mines en exploitation situées dans la zone de pergélisol canadienne encapsulent, ou envisagent d'encapsuler, les résidus réactifs dans le pergélisol. Cette technique peut être appliquée dans les régions à pergélisol où la température de l'air est suffisamment froide et à condition de prévoir pour la couche active. Située à la surface du sol, cette couche dégèle chaque été, ce qui peut potentiellement entraîner l'oxydation des résidus ou des stériles pendant l'été. Pour encapsuler des résidus ou des stériles dans du pergélisol, il faut placer sur ces résidus ou ces stériles un matériau (p. ex., une couverture) qui emprisonnera la zone de dégel saisonnier annuel, ou couche active, et préviendra ainsi le dégel des résidus ou des stériles près de la surface.

L'encapsulation dans le pergélisol semble être une bonne option pour les résidus réactifs lorsqu'il s'agit de pergélisol continu, parce qu'elle ne nécessite pas de 1) couverture sèche comme une formation morainique argileuse, un matériau qui est généralement absent dans la région du pergélisol continu ou de 2) couverture aqueuse, qui est difficile à maintenir en raison des taux d'évaporation élevés dans la plus grande partie de la région à pergélisol du Canada. De plus, les couvertures aqueuses coûtent cher dans les régions arctiques éloignées parce que les coûts de construction, d'inspection et d'entretien y sont plus élevés qu'ailleurs.

La mise à l'essai récente de quatre couvertures construites sur des résidus réactifs dans du pergélisol continu fournit de l'information sur les paramètres qui régissent la conception d'une couverture destinée à maintenir les résidus dans un état de gel. Ces études de cas exécutées à Nanisivik, Raglan, Lupin et Rankin Inlet correspondent à diverses opérations de gestion des résidus; approches en matière de conception de la couverture; et conditions climatiques et physiques.

Évidemment, il n'est pas question d'encapsuler des résidus dans du pergélisol lorsque les températures de l'air ne sont pas suffisamment basses pour créer un pergélisol continu.

Le pergélisol se définit comme étant un terrain dont la température demeure à 0 °C ou sous 0 °C durant deux années consécutives mais, aux fins de l'encapsulation dans le pergélisol, il est préférable que la température de ce dernier à la profondeur d'amplitude annuelle zéro soit de – 2 °C ou moins élevée. Cette température du sol se traduit par une température annuelle moyenne de l'air (TAMA) d'environ – 8 °C lorsque les fluctuations à court terme de la température annuelle de l'air sont d'environ 1,5 °C et que la différence entre la TAMA et la température annuelle moyenne de la surface du sol est de quelque 4,5 °C.

Le critère ci-dessus ne tient pas compte du réchauffement de la planète, lequel peut avoir d'importantes répercussions sur le pergélisol. Nichols a documenté le réchauffement de la planète dès 1975. Au moyen de la datation de la tourbe par le carbone 14, il a démontré que la Terre a connu une courte période glaciaire il y a environ 300 ans et qu'elle se réchauffe depuis. Trois tendances à un réchauffement progressivement plus élevé ont été enregistrées depuis.

Les observations indiquent que près de 50 % des glaciers des Alpes suisses ont fondu entre 1850 et 1985 et qu'une proportion supplémentaire de 25 % a fondu depuis 1985 (allocution prononcée à 2003 Permafrost Conference). Anisimov et Fitzharris (2001) ont signalé que les températures de l'air ont augmenté en général de 2 à 4 º C partout dans le monde et qu'elles se sont accrues de 5 ºC/100 ans depuis le début du 20^{e} siècle en certains endroits du nord de la Sibérie et de l'Alaska. Une hausse de la tendance au réchauffement a été observée en Alaska (Esch, 1990) et au Canada depuis 1980 (Dyke et Brooks, 2000). Les données sur la TAMA à certains sites canadiens sont fournis dans ce rapport.

À l'heure actuelle, l'encapsulation des résidus est en général faisable au nord-ouest du fleuve Mackenzie dans les Territoires du Nord-Ouest, dans tout le Nunavut et dans l'extrême-nord du Québec. Cependant, en raison de la tendance au réchauffement de la planète, l'encapsulation dans le pergélisol dans certaines régions nordiques des Territoires du Nord-Ouest et du Québec pourrait ne pas être durable dans 100 à 200 ans. Les mines qui envisagent l'encapsulation des résidus dans le pergélisol devront déterminer quel impact le réchauffement de la planète aura sur leur design.

Le concept du design dans le cas de l'encapsulation des résidus réactifs dans le pergélisol consiste à fournir un matériau de couverture suffisamment épais pour que la couche active (dégel annuel) soit maintenue dans la couverture. L'épaisseur de la couche active est fonction de la température de l'air au site, de la teneur en eau des diverses couches de sol/roche, de la couverture végétale, de l'orientation de la pente, de la couleur du matériau de surface (albédo), de l'épaisseur de la neige (qui varie selon la topographie locale) et d'autres facteurs. Comme ces facteurs varient grandement d'un site à l'autre et même quelquefois au sein d'un même site, l'épaisseur de la couche active peut se situer entre 0,5 m et 5 m. Il est important de tenir compte des facteurs particuliers au site dans la conception des couvertures.

Les facteurs dominants de l'épaisseur de la couche active dans les quatre cas présentés sont la température de l'air et la teneur en eau. Les autres facteurs sont moins importants pour ces raisons :

- couverture végétale – établir une couverture végétale dans les régions à pergélisol prend beaucoup de temps; on peut raisonnablement supposer qu'aucune végétation ne couvrira les résidus ou les stériles durant une bonne période;
- orientation de la pente – la majeure partie des résidus n'ont presque pas de pente;
- couleur – la plupart des matériaux pour les couvertures ont des couleurs similaires; cependant, la couleur pourrait être un facteur, comme le montrent les essais réalisés à Nanisivik.

Après l'établissement de la répartition de la température de l'air au site, la teneur en eau du matériau de la couverture est le plus important paramètre pour gouverner la profondeur maximale du dégel ou de l'épaisseur à donner à la couverture.

L'effet de la teneur en eau du matériau de la couverture sur l'épaisseur de la couche active est illustré par les quatres études de cas présentés dans ce rapport et par la conception proposée pour la couverture à Diavik.

Raglan - Une couverture de 2,4 m d'épaisseur a été choisie. Elle consiste en une couche de stériles concassés qui a une épaisseur de 1,2 m et qui repose sur un esker de sable et de gravier concassés d'une épaisseur de 1,2 m. Selon les mesures effectuées, la base de la couche active se trouve à 1,9 m de profondeur (pour une température de congélation de 0º C). Le sol dégèle sur 1,9 m.

Nanisivik - Cinq cellules expérimentales ont été construites. La couverture a 2 m d'épaisseur et la stratigraphie est hétérogène. Aux cinq sites, l'épaisseur de la couche active varie selon la teneur en eau de la couverture, allant de 1 m pour une teneur de 34 % à près de 1,5 m pour une teneur de 7 %. La profondeur moyenne du gel aux cinq sites varie de 1,0 à 1,4 m. La pénétration du dégel la moins élevée correspond à la teneur en eau de la couverture la plus élevée.

Lupin - La couverture a une épaisseur de 0,6 à 1,6 m et est composée de sable et de gravier d'esker. L'épaisseur de la couche active est fonction de la nappe phréatique. Elle varie de 1,3 m lorsqu'il n'y a pas de couverture et que les résidus sont entièrement saturés jusqu'à 1,8 m lorsque la nappe phréatique se trouve à la base de la couverture d'une épaisseur de 1,6 m.

Rankin Inlet - La couverture est constituée de 1 m de sable et de gravier d'esker. Le point de congélation est abaissé jusqu'à environ -4º C en raison d'une infiltration d'eau de mer et de la dissolution des sulfures oxydés. L'on estime que la couche active a une épaisseur de près de 5 m, compte tenu du rabaissement du point de congélation et de la glace visible. L'on estime que le sol dégèle jusqu'à 2,7 m de profondeur à 0° C.

Les quatre études de cas démontrent que, pour réduire le plus possible l'épaisseur de la couche active située dans une couverture, la teneur en eau de la couverture doit être la plus élevée possible. Évidemment, la teneur en eau la plus élevée que peut avoir une couverture est la saturation complète. Cependant, la saturation partielle ou totale de la couverture pourrait déboucher sur la formation, dans la couverture, d'une couche d'eau stagnante qui prévient l'oxydation sans qu'il soit nécessaire d'avoir recours au gel (Li et coll., 1997). Le NEDEM a déjà montré dans certaines de ses études (NEDEM 2.22.2) qu'on obtient une barrière efficace contre la diffusion de l'oxygène si l'on maintient le degré de saturation d'une couche du sol à un niveau plus élevé que 85 à 90 %.

D'après un concept de design fourni dans NEDEM 6.1, les travaux effectués sur une couverture d'eau stagnante par Li et coll. (1997) et des essais sur colonne réalisés par CANMET (NEDEM 2.12.1e), Lupin a choisi une couverture avec zone saturée en vue de la fermeture de ses cellules situées dans le parcs à résidus (Holubec, 2002). Les résidus seront recouverts d'une couche de sable et de gravier d'esker d'une épaisseur de 1 m qui maintiendra une zone de saturation à la base de la couverture. Les résultats du suivi des conditions thermiques et de la nappe phréatique dans les cellules recouverts en 1995 et en 1998 confirment la validité de ce concept.

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Much of the information on ground temperatures, permafrost and tailings facilities reported herein has been gathered during the author's preparation of a Monograph on Dams in Canadian Permafrost to be published in early 2005. The Monograph sponsors made possible several of the site visits and gathering of information that was used for the preparation of this report.

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GLOSSARY OF PERMAFROST AND RELATED GROUND-ICE TERMS

Selected terms were obtained from the glossary published by the International Permafrost Association Standing Committee on Data Information and Communication (Everdingen 2002).

active-layer

The layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.

active-layer thickness

The thickness of the layer of the ground that is subject to annual thawing and freezing in areas underlain by permafrost

COMMENT:
The thickness of the active-layer depends on factors such as the ambient air temperature, vegetation, drainage, soil or rock type and total water content, snow cover and the degree and orientation of the slope. The thickness can vary from year to year, primarily due to variation in the mean annual air temperature, distribution of soil moisture, and snow cover.

albedo

A measure of the reflective power of a surface, expressed as the fraction of the incoming solar radiation reflected by the surface.

COMMENT:
The albedo of natural land surfaces varies over a wide range, and it changes with the season, primarily due to changes in vegetation and snow cover.

approximate thawing index

The cumulative number of *degree-days* above 0ºC for a given time period, calculated from the mean monthly temperatures for specific stations without making corrections for negative *degree-days* in spring and fall.

closed talik

A layer or body of unfrozen ground occupying a depression in the *permafrost table* below a lake or river.

continuous permafrost

Permafrost occurring everywhere beneath the exposed land surface throughout a geographic region. The existence of small taliks within continuous permafrost has to be recognized.

creep strength

The failure strength of a material at a given strain rate or after a given period under deviatoric stress.

degree-days (C or F)

A derived unit of measurement used to express the departure of the mean temperature for a day from a given reference (or base) temperature.

COMMENT:

The *freezing index* and the *thawing index* are expressed in degree-days with respect to a reference temperature of 0ºC (32ºF); units: degree-day C or F.

depth of thaw

The minimum distance between the ground surface and *frozen ground* at any time during the thawing season in an area subject to seasonal freezing and thawing.

depth of zero annual amplitude

The distance from the ground surface downward to the level beneath which there is practically no annual fluctuation in ground temperature

COMMENT:

The temperature at the depth of zero annual amplitude ranges from about -0.1ºC at the southern limit of permafrost to about -15ºC in the extreme polar reaches of *continuous permafrost*.

design thawing index

The cumulative number of *degree-days* above 0ºC, calculated by taking the average of the *seasonal thawing indices* for the three warmest summers in the most recent 30 years of record.

COMMENT:

If data for 30 years are not available, then the index is based on the warmest summer in the latest 10-year period of record.

discontinuous permafrost

The major subdivision of a permafrost region in which permafrost occurs in some areas beneath the exposed land surface, whereas the other areas are free of permafrost.

COMMENT:

The zone of discontinuous permafrost lies between the *continuous permafrost* zone and the southern *latitudinal limit of permafrost* in lowlands. Near its northern boundary, *discontinuous permafrost* is extensive, whereas near its southern boundary it occurs as *isolated patches of permafrost,* and *sporadic permafrost.* There is no sharp distinction or boundary between the continuous and discontinuous permafrost zones.

freezing (of ground)

The changing of phase from water to ice in soil or rock.

COMMENT:

The temperature at which ground starts to freeze may be lower than 0ºC as a result of *freezing-point depression.*

frozen ground

Soil or rock in which part or all of the *pore water* has turned to ice.

geothermal gradient

The rate of temperature increase with depth in the subsurface.

COMMENT:

Commonly expressed as ºC per metre depth

ground ice

A general term referring to all types of ice contained in freezing and *frozen ground.*

ice-rich permafrost

Permafrost containing excess ice.

COMMENT:

A qualitative term. Ice-rich permafrost is *thaw-sensitive.*

isotherm

A line on a map connecting points on the earth's surface having the same mean temperature or the same temperature at a given time.

mean annual air temperature (MAAT)

The mean annual air temperature is obtained by averaging the 12 monthly values.

COMMENT:

1) Air temperatures are measured in a louvered, wooden shelter mounted 1.5m above ground, which is usually a level, grassy surface, with the nearest obstacle being at least four times its height away.

2) The 'daily' temperature is the average of the mean daily maximum and minimum temperatures.

mean annual ground temperature (MAGT)

Mean annual temperature of the ground at a particular depth.

COMMENT:

The mean annual temperature of the ground usually increases with depth below the surface. The mean annual ground temperature at the *depth of zero annual amplitude* is often used to assess the *thermal regime of the ground* at various locations.

mean annual ground-surface temperature (MAGST)

Mean annual temperature of the surface of the ground.

COMMENT:

Permafrost exists if the mean annual ground-surface temperature is perennially below 0ºC. Although the mean annual surface temperature may be below 0ºC, the surface temperature will fluctuate during the year, causing a layer of the ground immediately beneath the surface to thaw in the summer and freeze in the winter (the *active layer*).

mean annual ground design temperature (MAGAT)

The mean annual ground temperature at the *depth of zero annual amplitude.*

COMMENT:

Designation proposed herein for assessing the thermal regime of a site.

n-factor

The ratio of the *surface freezing* or *thawing index* to the *air freezing* or *thawing index.*

COMMENT:

At any site, (standard) air temperatures are seldom the same as surface (air/substrate boundary) temperatures. Because air temperatures (measured at weather stations) are usually available and surface temperatures are not, then n-factor (an empirically determined coefficient) is used to relate air temperatures to surface temperatures in order to establish the thermal boundary conditions at the surface, particularly for engineering purposes.

Also, known as "mean annual near-surface ground temperature.

The difference between air and surface temperatures at any specific time and location is greatly influenced by climatic, surface and subsurface conditions (e.g, latitude, cloud cover, time of day or year, relative humidity, wind speed, type of surface – wet, dry, moss, snow, natural vegetated terrain, mineral soil, pavements and *thermal properties of the ground*).

Values of freezing and thawing n-factors have been determined for a large number of sites and surfaces and are widely used for predicting surface temperatures and the *thermal regime of the ground.*

open talik

A body of unfrozen ground that penetrates the permafrost completely, connecting suprapermafrost and subpermafrost water.

COMMENT:
Open taliks can be found below large rivers (*river taliks*) and lakes (*lake taliks*).

peat

A deposit consisting of decaying or partially decayed humidified plant remains.

COMMENT:
Peat is commonly formed by slow decay of successive layers of aquatic and semi-aquatic plants in swampy or water-logged areas, where oxygen is absent.

permafrost

Ground (soil or rock, including ice and organic material, that remain at or below 0ºC for at least two consecutive years.

COMMENT:
Permafrost is synonymous with perennially *cryotic ground*: it is defined on the basis of temperature. It is not necessarily frozen, because the freezing point of the included water may be depressed several degrees below 0ºC; moisture in the form of water or ice may or may not be present.

permafrost base

The lower boundary surface of permafrost, above which temperatures are perennially below 0ºC and below which temperatures are perennially above 0ºC.

saline permafrost

Permafrost in which part or all of the *total water content* is unfrozen because of *freezing-point* depression due to the dissolved-solids content of the *pore water.*

salinity

1. A general property of aqueous solutions cause by the alkali, alkaline earth, and metal salts of strong acids (CI, SO_4 and NO_3) that are not hydrolyzed.
2. In soil science, it is the ratio of the weight of salt in a soil sample to the total weight of the sample.

COMMENT:
Often used, inappropriately, as a synonym for the dissolved-solids content of aqueous solutions.

talik

A layer or body of *unfrozen ground* occurring in a permafrost area due to a local anomaly in thermal, hydrological, hydrogeological, or hydrochemical conditions.

temperature profile

The graphic or analytical expression of the variation in ground temperature with depth.

thawed ground

Previously *frozen ground* in which all ice has melted.
Unfrozen ground is thawed ground only if it was previously frozen.

thawing index

The cumulative number of degree-days above 0ºC for a given time period.

COMMENT:
Four main types of air thawing indices have been used.

1) *Approximate thawing index* – calculated from the mean monthly air temperatures for a specific station without making corrections for negative *degree-days* in spring and fall.
2) *Total annual thawing index* – calculated by adding all the positive mean daily temperatures for a specific station during a calendar year.
3) *Seasonal thawing index* – calculated as the arithmetic sum of all the positive and negative mean daily air temperatures for a specific station during the time period between the lowest point in the spring and the highest point the next fall on the cumulative *degree-day* time curve.
4) *Design thawing index* – calculated by taking the average of the seasonal thawing indices for the three warmest summers in the most recent 30 years of record. If data for 30 years are not available, then the index is based on the warmest summer in the last 10 year period of record.

The *design thawing index* is commonly used in engineering design to estimate the maximum *depth of thaw* in *frozen ground*.

tundra

Treeless terrain, with a continuous cover of vegetation, found at both high latitudes and high altitudes.

upward freezing

The advance of a *freezing front* upwards from the *permafrost table* during annual freezing of the *active layer*.

1.0 INTRODUCTION

1.1 Background

The Canadian permafrost region provides different challenges in the design of covers for reactive tailings because of cold temperatures, availability of cover materials and remoteness of the mining sites. While presently there are not many mines operating in the Canadian permafrost regions, there is a need to further the knowledge for the design of covers for both reactive and non-reactive tailings because of the large number of abandoned and closed mines that still have to be reclaimed, and for the design of new mines. The Canadian north has experienced recent growth in mining with the discovery of diamonds. Most of these mines are located in permafrost.

A prevailing closure plan for reactive tailings in continuous permafrost is to provide a sufficiently thick cover on top of the tailings to permanently encapsulate the tailings in permafrost. Recent construction of field test pads, with various cover designs over reactive tailings and monitoring of their performance at four sites in continuous permafrost, has provided an opportunity to monitor key parameters that control the design of covers to encapsulate the tailings in permafrost.

The Mine Environment Neutral Drainage (MEND) program realized the uniqueness of permafrost and sponsored several studies that are listed in Table 1-1.

Table 1-1. MEND projects on permafrost

MEND Project	Title	Year
6.1	Preventing AMD by Disposing of Reactive Tailings in Permafrost	1993
1.61.1	Roles of Ice, in the Water Cover Option, and Permafrost in Controlling Acid Generation from Sulphide Tailings	1996
1.61.2	Acid Mine Drainage in Permafrost Regions, Issues, Control Strategies and Research Requirements	1996
1.61.3	Column Leaching Characteristics of Cullaton Lake B and Shear (S) – Zones Tailings Phase 2: Cold Temperature Leaching	1997
1.62.2	Acid Mine Drainage Behaviour in Low Temperature Regimes – Thermal Properties of Tailings	1998
W.014	Managing Mine Wastes in Permafrost Zones. Summary Notes MEND Workshop	1997
5.4.2d	MEND MANUAL, Volume 4 – Prevention and Control, Chapter 4.8 Permafrost and Freezing	2001

Some key information derived from the above reports is summarized below:

MEND Report 6.1

This report reviewed the key elements of permafrost regions and summarized the information available on how cold temperatures affect oxidation of reactive tailings and thereby the production of acidic drainage. In general, it was known that there was considerable reduction in the rate of oxidation when the temperature dropped from 20ºC to 2ºC, but little was known about the reaction at temperatures below 0ºC. It provided the ground/tailings information measured at four mines; three mines in 'warm' or discontinuous permafrost (Giant, Faro and Rabbit Lake) and one mine (Lupin) in 'cold' or continuous permafrost. Finally, it reviewed various cover options to completely encapsulate the tailings within permafrost and suggested a novel cover design option. This consisted of covering the tailings with a sufficiently thick granular cover that would maintain a water level within the cover during the summer by means of frozen perimeter dykes.

MEND Report 1.61.1

This report stated that a water cover can significantly reduce the effective diffusion rate of oxygen into tailings and is considered both an economical and effective technique for the control of sulphide oxidation in the long-term. The impacts of cold temperature conditions on the water cover are relatively small. It recommended that future work be done to quantify the impact of below freezing temperatures on the rates of acid generation and the longer-term performance of various cover scenarios.

MEND Report 1.61.2

This report provided perspectives on issues, strategies, and research requirements for disposing of potentially acid generating mine tailings and waste rock in a permafrost environment. It noted the importance of distinguishing between the continuous and the discontinuous permafrost environment. Within the discontinuous permafrost regions, the 'warm' permafrost conditions may be susceptible to thaw degradation.

A control strategy that takes advantage of permafrost conditions is freeze control. This approach may be a viable strategy for tailings in 'warm' permafrost; however, there is a need for more cost effective insulating cover designs and a more thorough understanding of frozen tailings thermal properties.

MEND Report 1.61.3

Cold temperature column leaching tests at 2ºC and 10ºC were conducted for Cullaton tailings to evaluate oxidation and leaching characteristics at temperatures that are expected during the thaw period. The tests showed that the rate of acid generation was low and the occurrence of acidic drainage was delayed at the lower test temperatures as compared to those observed at 25ºC in a previous study by Davé (1992). Tests carried out at 2ºC showed that the acidic drainage occurred at the end of a two-year leaching period and that the overall impact in terms of total acidity and effluent metal loading was low.

MEND Workshop W.014

Open discussion of current practice and priorities for future research on the issues of permafrost to manage mine waste concluded that although engineered structures incorporating permafrost have been used successfully for mine waste control, there is a lack of fundamental knowledge pertaining to the geochemical aspects of the behaviour of mine wastes in northern environments. Technical issues yet to be resolved (in 1997) included:

1. Oxidation kinetics at low temperatures;
2. Unfrozen water in tailings;
3. Freezing point depression by process chemicals;
4. Thermal effects of oxidation at low temperatures; and
5. Effective covers in permafrost zones.

MEND MANUAL, Volume 4 (5.4.2d).

The MEND Manual summarizes the research and technologies developed since the inception of the MEND program in 1989. Issues related to permafrost are presented in Chapter 4.8 Permafrost and Freezing. Projects related to permafrost have investigated:

- Effects of freezing on the sulphide oxidation process;
- Effects of heat from sulphide oxidation on permafrost and freeze-back;
- Effects of freezing on metal leaching;
- Acid control strategies that could potentially take advantage of permafrost; and
- Use of water and dry covers in permafrost regions.

Since the preparation of the above MEND research documents, a better understanding of permafrost has been obtained from the design and construction of several mines in permafrost and valuable information has been collected from field test pads and design analyses. This information should advance the selection and design options of tailings covers in permafrost regions.

1.2 Permafrost

Permafrost is defined as a "thermal condition in soil or rock having temperatures below 0ºC persisting over at least two consecutive winters and the intervening summer" (Brown and Kupsh 1974, Everdingen 2002). It underlies almost half of Canada's land surface (Figure 1-1). The occurrence and the ground temperatures of permafrost are affected by various climatic and terrain factors. Therefore, its distribution is not only a function of the latitude but also of continental climate, local vegetation, characteristics of surficial materials, orientation of slopes and altitude in mountainous areas.

The southern limit of permafrost coincides roughly with the -1ºC MAAT (mean annual air temperature) isotherm where the permafrost is restricted mainly to drier portions of peatland, some north-facing slopes and local shaded areas. Sporadic and discontinuous (warm) permafrost is found between about -1ºC and -7.5ºC MAAT isotherm. About 50 to 90% of the discontinuous permafrost area is underlain by permafrost. Continuous (cold) permafrost is located north of the -7.5ºC MAAT isotherm. The effect on permafrost equilibrium as a result of construction and mining is different within the warm and cold permafrost regions. This information has to be considered in the selection of tailings cover design.

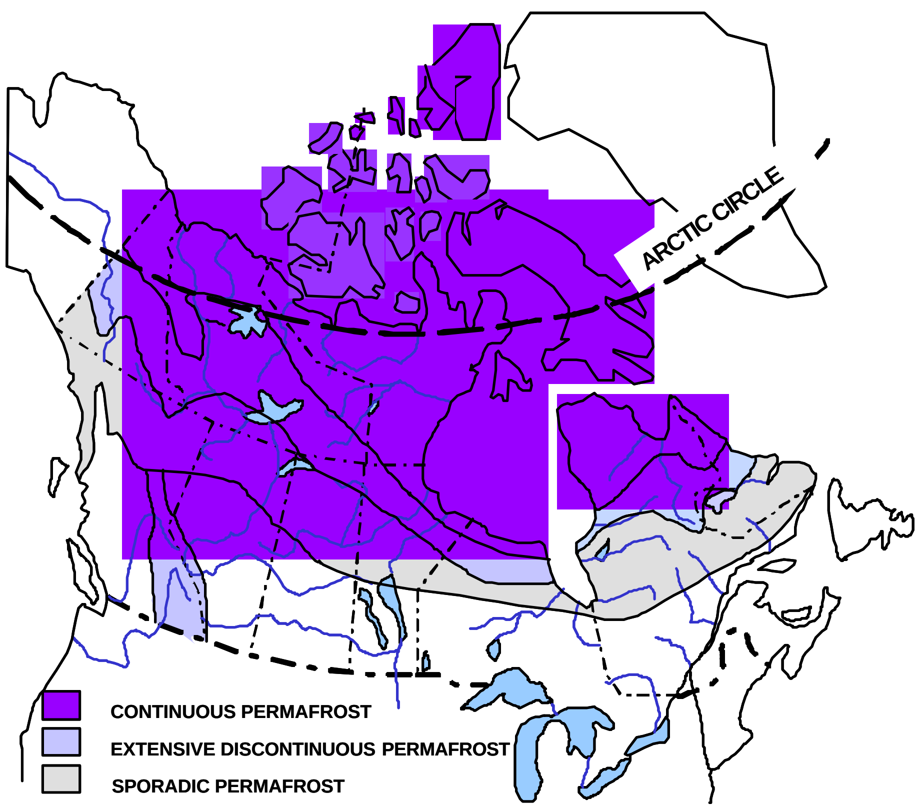


Figure 1-1. Permafrost distribution in Canada, (National Atlas of Canada 1995)

The boundary between the warm and cold permafrost is poorly defined because of a lack of climatic data and the influence of local terrain factors. Climatic data that is available only from sparsely located weather stations, normally hundreds of kilometers from a mining site. Therefore it is important to install a weather station at the site and correlate the data with the closest station with long-term climatic information for a period of at least 2 years. Use of long-term climatic permafrost information to extend the local station data for many years is important because of the large variation observed between years.

1.3 Cover Practice

In temperate and tropical climates the common methods for reclaiming reactive tailings use water and earth covers. Water covers, with a depth of about 1.0m, have been found to be the most effective means to combat acid generation. However, these covers require an adequate water supply during dry years and a program of continuous dyke maintenance. Earth or dry covers are an alternative where flooding is not feasible. These covers do not provide complete protection against oxidation and seepage and they are costly to construct in many areas of Canada.

The general intent in the Canadian permafrost region has been to encapsulate reactive tailings or waste rock within permafrost. This requires placing a sufficiently thick cover over the reactive material so that the annual thaw depth (base of the active layer) remains within the cover material. Normally, this requires thick covers with high placement costs.

This report presents the following information:

a) An overview on permafrost and its distribution across Canada.
b) Addresses global warming, and its effect on the distribution and temperatures of permafrost.
c) Identifies the factors that determine annual thaw depth (active zone) from four tailings cover field trials and tailings reclamation sites. The case histories are from Nanisivik, Raglan, Lupin and Rankin Inlet mines.
d) Presents an alternative cover design for active tailings in permafrost that requires considerably smaller cover thickness resulting in decreased cost.

The alternative cover design was introduced in MEND 6.1 and its benefits have been demonstrated at Lupin since 1995 (Holubec et al 1982).

2.0 PERMAFROST

2.1 Permafrost Glossary

A permafrost glossary defining permafrost and related ground-ice terminology used in this report is included. The definitions were obtained from a glossary of terms published by the International Permafrost Association Standing Committee on Data Information and Communication (Everdingen 2002).

2.2 Background

Permafrost is defined as a thermal condition in soil or rock with a temperature below 0ºC that persists over at least two consecutive winters and the intervening summer; moisture in the form of water or ground ice may or may not be present. The definition does not include the location of the frozen soil or rock within the stratigraphy, or its temperature, or water/ice content that may determine physical and chemical properties. Nor does it consider the depression of the freezing point that may be relevant to the oxidation of reactive tailings.

For the design of engineered structures, be they: roads, dams, foundations or tailings/rockfill covers, a broader understanding of ground temperature distribution and changes and definition of material properties in both the thawed and frozen state, including ice content, are required.

One of the complexities of permafrost is illustrated by the effect of a vegetation cover on ground temperature and the presence of permafrost. In sporadic and discontinuous permafrost regions, disturbance of vegetation by construction will frequently result in ground warming and thawing of the permafrost. An example of degradation of permafrost caused by removal of vegetation and organic cover in discontinuous permafrost was provided by Linell (1973) and is illustrated in Figure 2-1. This example shows permafrost degradation as a result of two progressive degrees of vegetation removal; namely; a removal of trees and subsequent removal of moss and peat cover. Other examples of permafrost degradation can be found in ROW clearance along NW pipeline (Burgess and Lawrence 1997, and Burgess and Smith 2003).

The reverse occurs in continuous permafrost regions. While summer construction in cold permafrost region may temporarily deepen the summer thaw, this degradation will heal itself during the following winter to re-establish a new temperature equilibrium for the new conditions. Some settlement may occur during the initial thaw period. New earth embankments will freeze and become permanently frozen with the exception of the surface-active layer. The feasibility of constructing frozen earth structures is illustrated by the construction of several dams at the Lupin mine (Holubec 1982). In this case, a sand fill embankment constructed during the summer froze the following winter to form a frozen dam.

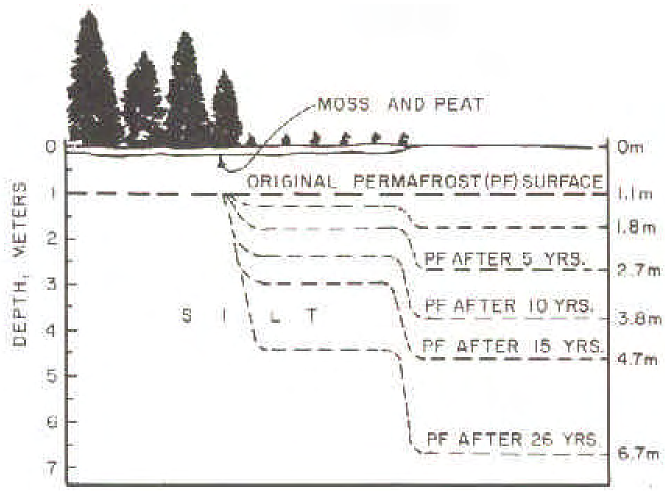


Figure 2-1. Vegetation removal effect in discontinuous permafrost (Linell 1973)

Existence of permafrost, the temperature of the frozen ground and the ease of disturbance or development of permafrost are a function of many parameters with the air temperature being the fundamental factor. The other factors are vegetation cover, soil and rock type and their moisture content, snow-cover, hydrology and local topography. The combination of these factors creates a ground temperature profile shown on Figure 2-2.

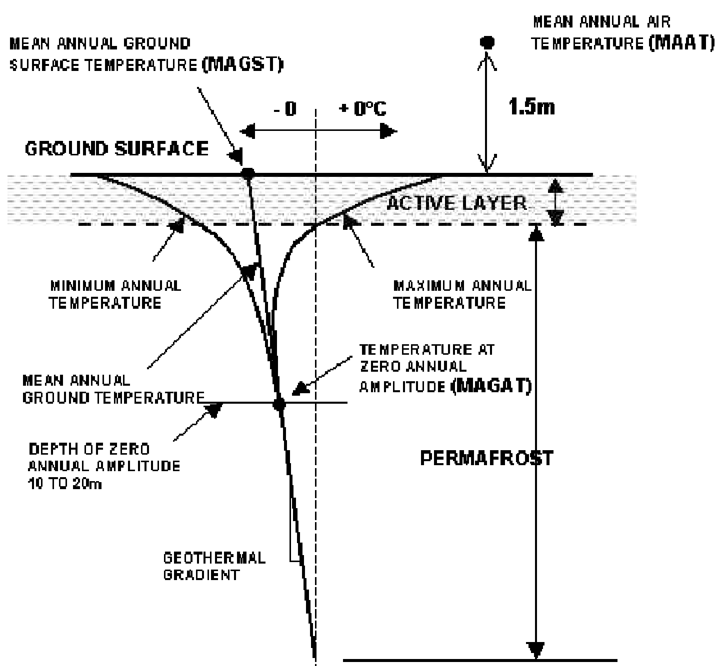


Figure 2-2. Ground temperature regime in permafrost

Parameters identified in Figure 2-2 are given in summary form below, with the formal definitions given in the Glossary.

- Mean Annual Air Temperature (MAAT) is measured within a louvered wooden shelter mounted 1.5m above the ground.
- Mean Annual Ground Temperature (MAGT) is depth specific. It increases with depth (generally) with the increase defined by the geothermal gradient.
- Geothermal Gradient ranges from about 0.6 to 5ºC/100m. An average value of 1.85ºC/100m can be used for initial purposes until site specific information is obtained. (Johnston 1981).
- Mean Annual Ground Surface Temperature (MAGST) occurs at the ground surface and is normally estimated from the mean annual ground temperature profile.
- Mean Annual Ground Design Temperature (MAGAT) is *the mean annual ground temperature* at the *depth of zero annual amplitude.* It occurs at a depth of about 10 to 20m and shows only small changes over a number of years depending on global temperature changes.
- Active Layer represents the layer of ground that is subject to seasonal thawing and freezing in areas underlain by permafrost. The thickness of the active-layer (thaw depth) depends on parameters, such as: the ambient air temperature, vegetation, drainage, soil or rock type and total water content, snow cover and the degree and orientation of the slope. The thickness at any given location can vary from year to year, primarily due to variation in the mean annual air temperature, distribution of soil moisture, and snow cover.

The four areas that will be further addressed are: air temperature, ground temperature, active layer and global warming. Global warming is an important topic because the recent information indicates that global air temperatures have increased considerably during a very short time, in terms of geological time, and that glaciers and permafrost are disappearing.

2.3 Air Temperature

The Canadian permafrost region extends from near 53º Latitude N in Quebec, where isolated patches of permafrost are observed, to the most northerly tip of Ellesmere Island in the Arctic at about 83º latitude. It is influenced by a wide range of air temperatures and continental air mass movements. Mean annual air temperature (MAAT), the main parameter that determines the presence of permafrost, and air temperature changes through the year, used to predict the ground temperatures, are estimated from either published correlations or by conducting thermal analyses. Air temperatures are measured at weather station across Canada by Environment Canada and are available from:

www.climate.weatheroffice ec.gc.ca/climate_normals

from which the following up to date information can be obtained:

- Climate Data Online
- Climate Normals and Averages
- Climate Data CD-ROM

The most detailed climatic data information is collected for southern Canada where the greatest population concentration and largest number of cities and towns are located. The number of climate stations decrease towards the north.

Limited climatic records are available for northern Canada areas that are underlain by permafrost. The number of meteorological stations and the mean annual air temperature of two areas with discontinuous permafrost and two areas of continuous permafrost are given in Table 2-1.

Generally a fair amount of climate information is available for the Yukon, southwestern Northwest Territories, and generally west of the Mackenzie River. These areas are underlain by discontinuous or 'warm' permafrost. However, in the remaining northern part of Canada that is representative of cold permafrost, climatic records are scarce and are obtained from sparse settlements or radar stations. Table 2-1 provides the number of meteorological stations and the mean MAAT in the three territories, with the Northwest Territories region subdivided to represent warm and cold permafrost regions.

Table 2-1. Number of meteorological stations and mean annual air temperatures

Region	Number of meteorological stations	Mean annual air temperature, °C [a]	Permafrost type[b]
Yukon Territory [c]	14	-3.5	Discontinuous
Southwestern Northwest Territories	8	-4.0	Discontinuous
Northeastern Northwest Territories	6	-12.3	Continuous
Nunavut	23	-13.2	Continuous

Notes: a) Average annual mean air temperature based on 1971 – 2000 Climatic Normals from Environment Canada.
b) As related to the available meteorological station locations.
c) Number does not include 2 stations at or near Arctic Ocean coast.

The list of stations with their average annual mean daily temperatures and average annual total precipitation are given in the Appendix.

The MAAT's shown in Table 2-1 illustrate that the Yukon and southwestern Northwest Territories, with the exception of the most northerly areas, have an average MAAT of -3.5 and -4.0ºC respectively. This range of temperatures is common to sporadic and discontinuous permafrost. Northeastern Northwest Territories and Nunavut have an average MAAT of -12.3 and -13.2ºC respectively. As will be discussed later, the design of tailings covers in areas with MAAT warmer than -7.5ºC would normally follow the southern design approach while in areas with MAAT colder than -7.5ºC, permafrost encapsulation may be considered as long as the effect of global warming is included.

The distribution of the mean annual air temperatures across Canada is illustrated by isotherms in Figure 2-3 (Smith et al. 2001). The map in this figure also provides mean annual near-surface ground temperatures (MAGST) distribution. Figure 2-3 illustrates that the -2ºC MAGST corresponds approximately to -7.5ºC isotherm. The significance of the -2ºC is discussed in subsequent sections.

2.4 Ground Temperature

It is recommended that for the selection of permafrost encapsulation design a ground temperature at the *depth of zero annual amplitude* (MAGAT) should be -2ºC for the cover design criterion. Ground temperature data has been published by the Geological Survey of Canada (GSC) in the National Atlas of Canada (Natural Resources of Canada 1995) and more recently by Smith and Burgess (GSC Open File Rpt 3954, 2000). In both these publications the ground temperatures represent the *mean annual ground-surface temperatures* (MAGST). It should be noted that since there is only a small difference of about 0.3ºC between the MAGAT and MAGST due to the small thermal gradient, these two temperatures can be considered to be the same. This difference is small when it is compared to MAGAT variation of about 4ºC that may exist at any given site due to variation of local ground conditions, in particular variation in organic cover and snow. The variation of ground temperature at several sites at Fort Simpson and along the Mackenzie delta was shown by Burgess and Smith (2000).

Because of the small difference between the MAGST and MAGAT, the published MAGST data can be used for the selection of a cover design for reactive tailings in permafrost. A good indicator if permafrost encapsulation is feasible at a site is the mean annual ground temperature near the ground surface (MAGST). Isotherms of the MAGST prepared by Smith et al (2001) is shown on Figure 2-3.

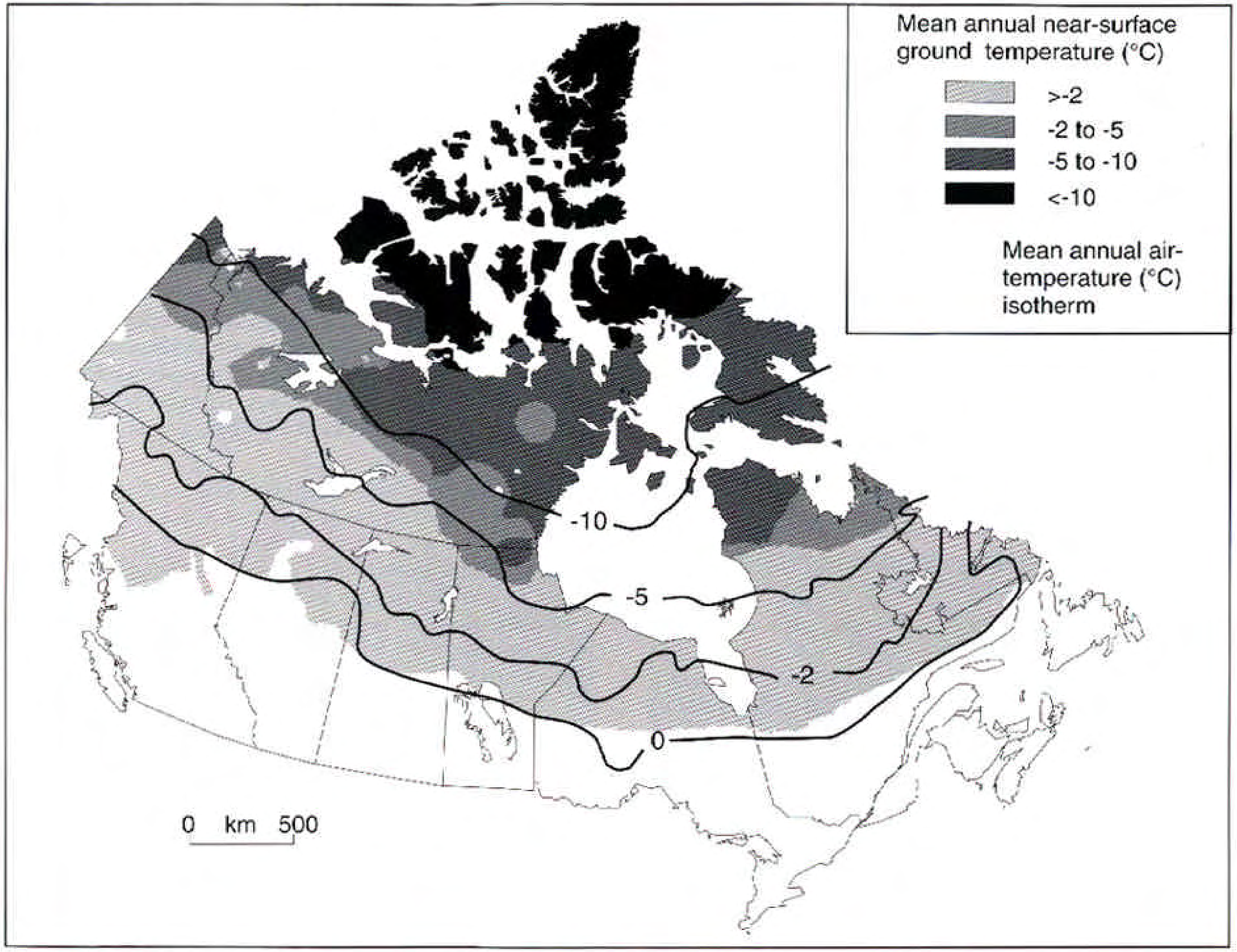


Figure 2-3. Mean annual air temperatures and near-surface ground temperatures (Smith et al. 2001)

More detailed MAGST data is given in the open file GSC report (File Rpt 3954, 2000) prepared by Smith and Burgess. This report provides a statistical relationship between the mean annual air temperature (MAAT) and the mean annual near-surface ground temperature (MAGST) shown on Figure 2-4. The relationship is linear but with considerable spread. Based on a trend line, the zero mean annual surface ground temperature occurs at a mean annual air temperature of about -4.35ºC. However, there is considerable spread along the trend line, indicating that the 0ºC MAGST can occur between MAAT of -2 and -7.5ºC.

The author's experience at several mines in permafrost shows that a variation of the MAGST at a site can be 2ºC to 4.5ºC. For the design of the tailings rehabilitation cover option, it is necessary to measure the MAGAT at a representative location because of this large possible variation of MAGAT at a site. It is recommended that the MAGAT should be established at a high ground location and without trees or shrubs if below the tree line.

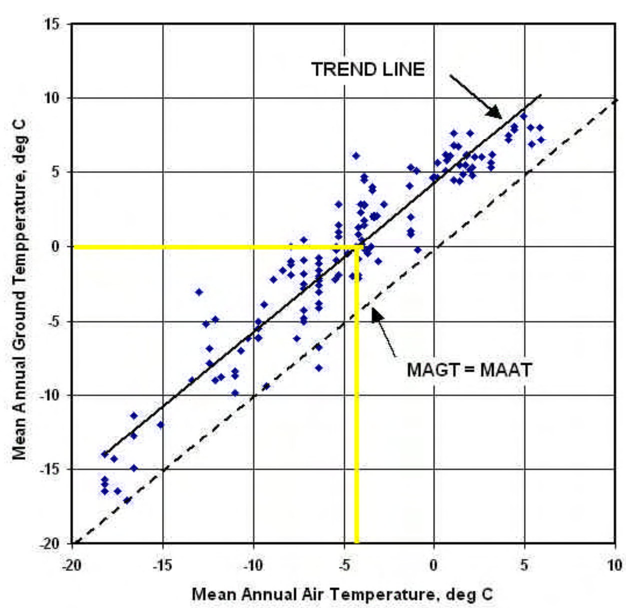


Figure 2-4. Relationship between mean annual air temperature and mean annual near surface ground temperature

2.5 Active Layer

Encapsulating reactive tailings within permafrost is based on the concepts that the annual thaw occurring during the summer, the *active layer*, will remain within the cover layer and the cover consists of non-reactive material.

The thickness of the *active layer* is dependent on numerous parameters and therefore can vary greatly at a given site depending on the surface and near surface conditions. Parameters include: local air temperature, type and thickness of vegetation cover, depth of snow, orientation of the terrain, soil/rock stratigraphy, moisture within surface layers, colour of the surface, etc. In this section historic data from the GSC (Smith and Burgess 2000) and some examples from the author's experience are provided to illustrate the variability of the thickness of the active layer. More information for the design of the *active layer* can be obtained from the four case histories presented in subsequent sections.

The GSC "Ground Temperature Database for Northern Canada" (Smith and Burgess 2000) provides information on the thickness of the active layer and the environment for a number of locations. This information was obtained from many sources that established the active layer depth. The GSC data is plotted against the reported MAAT in Figure 2-5. The graph provides only the most general information since soil/rock stratigraphy is not described in detail and the moisture content within the upper zone is not given for the data.

The data in Figure 2-5 is differentiated only by the presence of an organic cover and if the stratigraphy consists of coarse granular material or bedrock. The trend line for the data with organic cover shows the thickness of the active layer to vary from about 1.1m at the southern boundary of the discontinuous permafrost to about 0.7m in the Arctic islands. However, for locations with granular or bedrock at the surface, the thickness of the active layer in cold permafrost region with a MAAT colder than -10ºC varies between 1.5 and 4.5m.

Active layer thickness (thaw depth) can be determined by either frost gauges or by the analysis of the changing temperature profiles obtained by vertical thermistor cables. Thaw depths measured by means of thermistor cable at five mine sites are given on Table 2-2. A comparison of the thaw depths in Figure 2-5 and Table 2-2 show that the depths in granular or bedrock are consistent. Thaw depths with organic cover provide a different range of values. It should be noted that it takes many years for the establishment of vegetation on rehabilitated tailings surfaces.

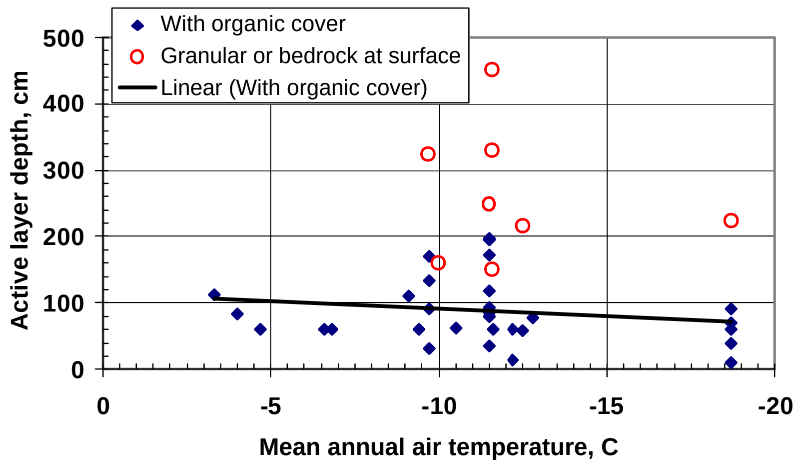


Figure 2-5. Relationship between active layer depth and mean annual air temperature

Table 2-2. Range of active layer depth measured at several mines in cold permafrost

Colomac Mine	Estimated MAAT -7.8ºC
64º 25'N, 115º 115 06'W	
In valley with thick peat Abutment with little organic/soil cover	1.8m 3.5m
Lupin Mine	Estimated MAAT -11ºC
65º 46'N, 111º 14'W	
0.3m organic over silty sand till Tailings covered with 0.5m sand Below dam crest, silty sand fill Bedrock with thin organic/soil cover	1m 2.5m 3.2m 3.8m
Ekati Mine	Estimated MAAT -10.3ºC
64º 40'N, 110º 40'W	
East Dam, organic over sand till Spillway Dam, Panda Dam	2.3m 1.9m 2.7m
Diavik Mine	Estimated MAAT -10ºC
64º 31'N, 110º 20'W	
Till with organic cover Drained esker Bedrock at surface	1.5 to 2m 2 to 3m 5
Raglan Mine	Estimated MAAT -10.5ºC
61º 41'N, 73º 41'W	
River flood plain Abutments Uplands with organic and granular till	4 to 4.5m 3 to 3.3m 1.6m

Information in Figure 2-5 and Table 2-2 illustrate that the presence of an organic cover has a great impact on the thaw depth or thickness of the active layer.

The *thawing index* is commonly used to estimate the thaw depth or the thickness of the active layer (Everdingen 2002). The thawing index is based on the cumulative number of degree-days above 0ºC for the summer period. Four definitions of thawing indices have been used. They are: approximate thawing index; total annual thawing index; seasonal thawing index; and design thawing index. The difference between the four definitions is explained in the Glossary. In engineering designs either the approximate or the total annual thawing index is commonly used.

A general relationship between the thickness of the active layer and the thawing index for unsaturated waste rock and saturated tailings is illustrated in Figure 2-6 (MEND 1.61.2 1996).

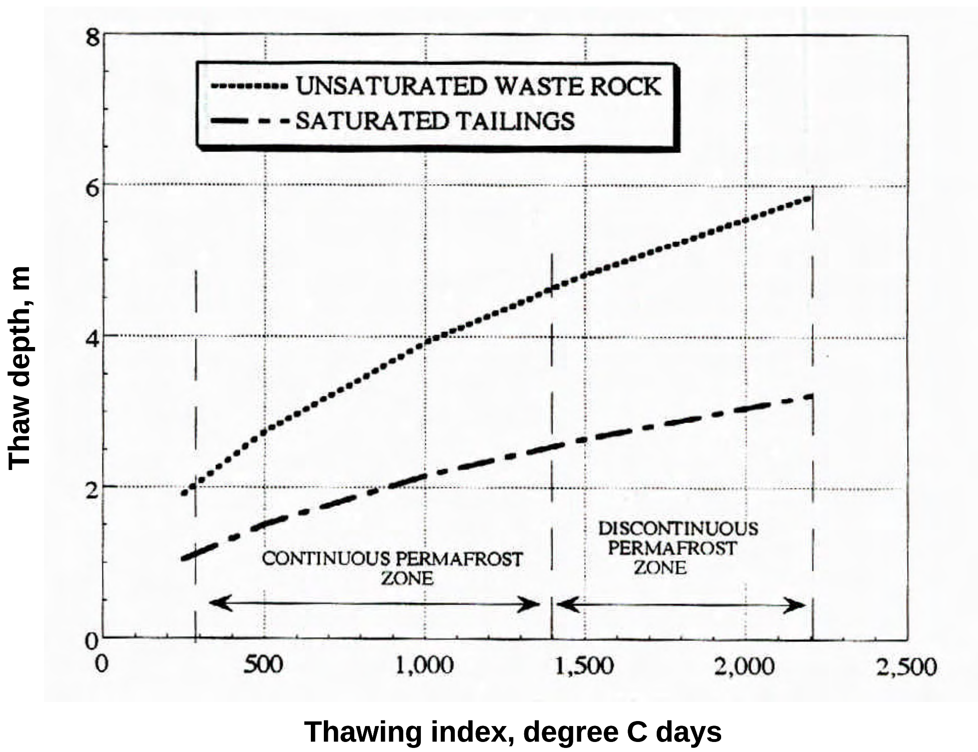


Figure 2-6. Estimated thaw depth based on the thawing index

Figure 2-6 illustrates the significant difference in the thaw depth for unsaturated waste rock and saturated tailings. The dry waste rock represents a medium with large thaw depth, massive rock having even greater thaw depth, and saturated tailings with a high pore volume, and therefore water content, that reduces the thaw depth because of the latent heat of water.

2.6 Freezing Point Depression

2.6.1 General

Permafrost is defined by the ground temperature being at or below 0ºC for at least two consecutive years. However, soils or tailings are a three phase system when at or above 0ºC, consisting in solids, gases and water. At temperatures below 0ºC, a four phase system is created consisting of solids, ice crystals, gases and unfrozen water. The unfrozen water influences the strength of soils or tailings and also effects the immobilization of the pore fluid that may be impacted by the mill chemistry or sulphide oxidation.

Unfrozen water may be free water (within pores) and/or bonded water that surrounds the solid particles. The bonded water is less significant in seepage of oxidation products because it is attached to the tailings particles. The volume of bonded water is governed mainly by temperature, specific surface area of the soil/tailings matrix and the activity of the soil/tailings minerals (Johnston 1981). This means that the tailings located distant from the discharge points consisting of smaller particles will have larger volume of bonded water at a given temperature below 0ºC.

The freezing point of the free water (pore water) is a function of the amount of solute that is present in the water. Pure water will freeze completely when the temperature falls below 0ºC. Once solute is introduced into the water, some of the pore water within the tailings will freeze to form ice and the remaining solution will become more concentrated. The ratio of ice to the unfrozen solution increases as the temperature falls below 0ºC. The solute known to depress the freezing point can either be salt water infiltration, as experienced at Rankin Inlet (Section 8.0) or the assumed depression produced by chemistry mill water at Raglan (Section 6.0). However, it is likely that the by-products of sulphide will also depress the freezing point.

2.6.2 Rankin Inlet experimental work

Laboratory work was undertaken to expand the knowledge of sulphide oxidation rates at temperatures below 0ºC to evaluate if permafrost encapsulation is a satisfactory concept for reclamation of the Rankin Inlet tailings (Meldrum et al 2001). Four 40cm high by 10cm diameter columns were filled with different materials and pore fluids (Table 2-3) and then placed in a low temperature incubator to measure temperature, volumetric water content and oxygen concentration. Four different incubator temperatures were used and testing durations were as follows: 30ºC for 5 days followed by 30 days each at 0, -2 and -10ºC.

Test results in Table 2-3 show that at -2ºC some oxidation occurs. However, at -10ºC all oxidation had ceased. Table 2-4 shows that there was a considerable volume of unfrozen pore water in all the samples tested at -2ºC. This would be expected for the three materials with seawater. Dissolving of the sulphide oxidation products caused depression of the freezing point for the columns with the distilled water. At -10ºC practically all sea pore water was frozen in the silty sand but in the case of the tailings, intact and cuttings, still had a significant volume of unfrozen water.

Table 2-3. Average oxygen flux
(± 5mol O_2/(m^2-year)

		Temperature (ºC)			
Material	Pore fluid	+30	0	-2	-10
Silty sand	Sea water	14	2	0	0
Intact tailings	In situ pore water	148	19	7	0
Cuttings	Sea water	68	3	0.5	0
Cuttings	Distilled water	89	2	2	0

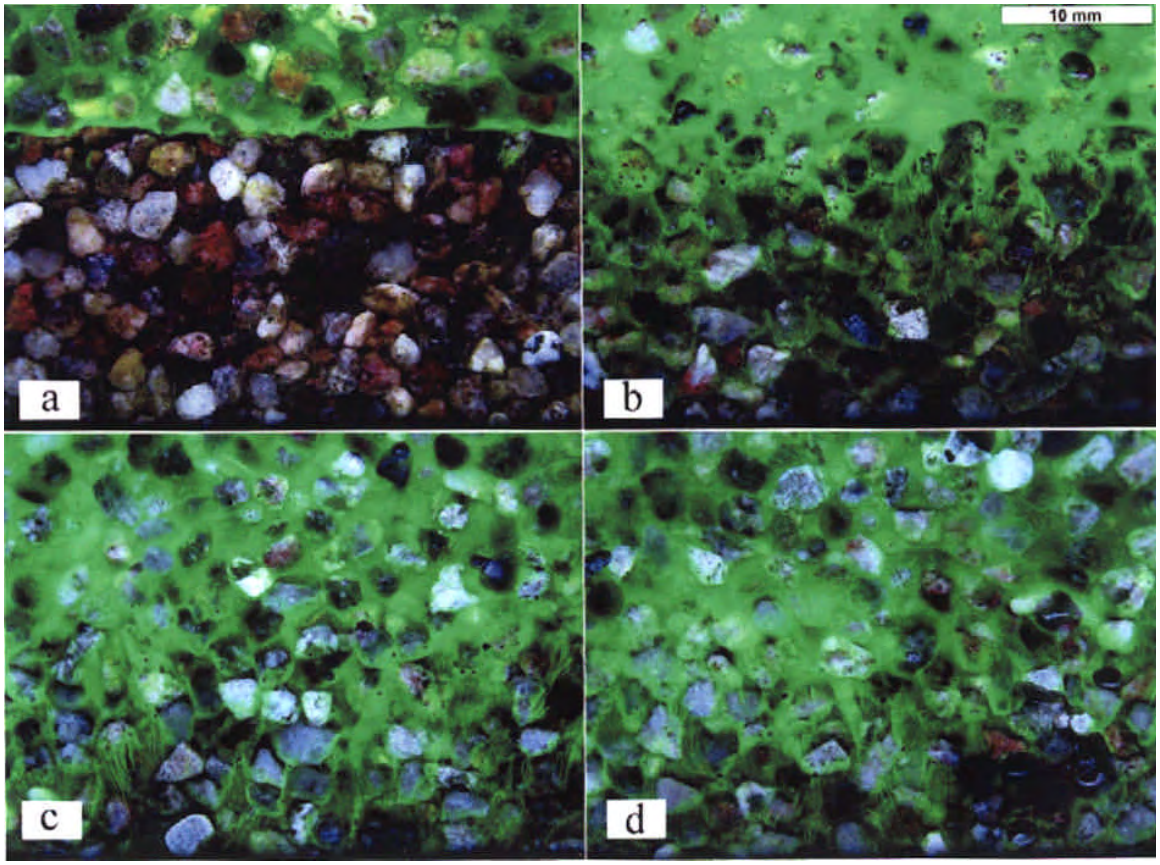
Table 2-4. Average unfrozen volumetric water content

		Temperature (ºC)			
Material	Pore fluid	+30	0	-2	-10
Silty sand	Sea water	23	16	11	1
Intact tailings	In situ pore water	32	20	15	9
Cuttings	Sea water	24	18	14	5
Cuttings	Distilled water	21	16	13	4

2.6.3 Freezing advance

Arenson and Sego (2004) set up a simple experiment to photograph the freezing front advance in a poorly graded medium sand. This experiment would be used to assess the boundaries of solid particles, ice, unfrozen water and gases under controlled freezing gradients and using pore water with several salinities. In this experiment the freeze front advance and ice formation were followed optically by introducing fluorerscein into the pore water. The fluorerscein caused the unfrozen water to have a greenish colour and became colourless (dark in the photographs) when frozen. The results are shown by four photographs in Figure 2-7.

These tests illustrated the effect of the freezing point depression. Test ‘a’ in Figure 2-7, in which the sample was saturated with distilled water, shows the freeze front advancing in a horizontal line. There is a clear distinction between the frozen and unfrozen zones. The frozen front in Test ‘a’ advanced the greatest distance of the 4 tests with different salinities. Tests ‘b’ to ‘d’ with salinities of 5, 10 and 30 ppm respectively showed smaller freezing front advances and the frozen boundary to be blurred. The lack of a clear boundary at the frozen zone is caused by the presence of increasing unfrozen water as the salinity increases. The freezing front advances in stages leaving behind unfrozen water channels with higher salinity concentrations. Eventually these channels close under decreasing temperatures to form pockets.



Note: Frozen sand after 1.5 hours in coolant at -12ºC. Salinity concentrations:
a – 0 ppt; b – 5 ppt, c – 10 ppt and d – 30 ppt.

Figure 2-7. Ice advance in sand with pore water at different salinities.

This experiment illustrates that while salinity or any other solute introduced to the pore water will lower the freezing temperature, it will also creates zones where pore water will not be frozen. This is supported by the Rankin Inlet tests (Table 2-4) that show decreasing unfrozen water content with a decrease of temperature for the tailings pore water.

The conclusions from these two case histories show that salinity, solute from mill water and tailings oxidation may depress the freezing point and produce a zone at the surface of the frozen tailings that may have a considerable volume of unfrozen water at temperatures below 0º C.

2.7 Global Warming

Climate, and therefore air temperature, is not constant but experiences changes both on a short (10 to 50 year) and long (200 and over) term basis. The short-term change can be seen from the Canadian Climatic Normals that have been collected for 50 years or more and the long-term has been deduced from botanical studies of past vegetation. These studies have found that during the last 10,000 years the climate has experienced three warm climate periods (Figure 2-8) and is currently in the process of warming. This is aside from the current affect of human activity (Nichols, H. as reported by Dredge 2001).

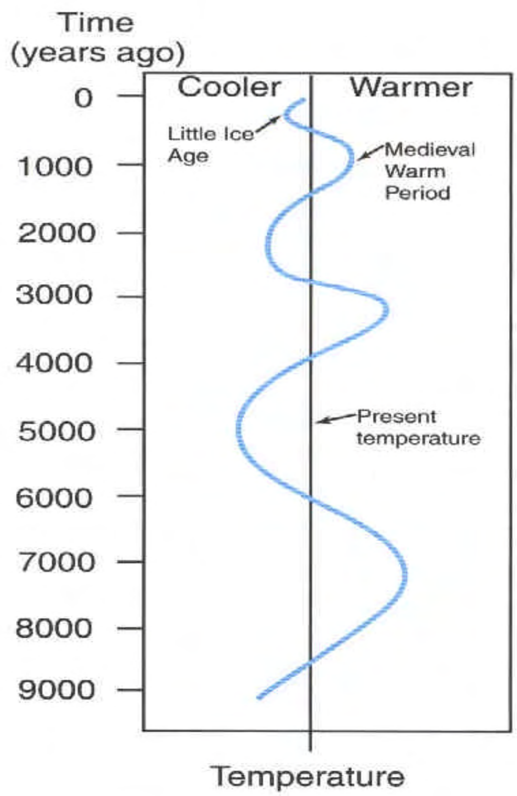


Figure 2-8. Climate change at Kugluktuk (after Nichols 1975)

Climate change is the most discussed topic on the global environmental agenda (Burn 2003). It has been found that the warming coincides with increasing concentration of carbon dioxide and other gases in the atmosphere. Global Climate Models (GCM's) predict that the air temperatures will continue to increase for some time. GCM shows that the MAAT along the Mackenzie delta will increase 1.0 to 2.5°C during 2010-2039 period and similarly precipitation is projected to increase 6-10%.

During the 8th International Conference on Permafrost (Zurich 2003), it was reported that 50 percent of glaciers in the Alps have melted between 1850 and 1985 and since 1985 another 25 percent of the glaciers have melted. In the 1980's it was recognized that a warming trend was occurring (Esch 1990). Available data show a warming trend from the 1800's to 1940, a short cooling from 1940 to 1976 and subsequent warming from 1976 to the present time. A review of MAAT data from climatic stations near four mines located in continuous permafrost in Canada show that at three of the four mine sites, a warming trend is occurring. One station in the Eastern Arctic indicates a slight cooling until about 1990 and then changes to warming trend.

The temperature changes at these four locations are summarized on Table 2-5 and Figure 2-9 and Figure 2-9 as obtained from Environment Canada (2002). The 30 year normal MAAT for 1971 to 2000 is given in Table 2-5

Table 2-5. Mean annual air temperatures (MAAT) and change MAAT

Location	MAAT Avg. 1971 - 2000	MAAT in 2000 Based on trend line	Estimated Change in MAAT 1950 to 2000
Yellowknife	-4.6	-4.0	+1.7
Lupin	-11.1	-10.6	+1.2
Resolute (Nanisivik)	-16.4	-16	+0.6
Iqaluit	-9.8	-9.6	-0.4

This information shows that a warming trend is occurring across the Canadian permafrost region with the exception of the Eastern Arctic. The trend line for Eastern Arctic in Figure 2-10 shows a decrease in the MAAT for the full 1950 to 2000 period. On closer observation it can be seen that while the temperatures decreased to about 1990, the trend has reversed from 1990 onward. This trend is similar to the one observed in Alaska (Esch 1990).

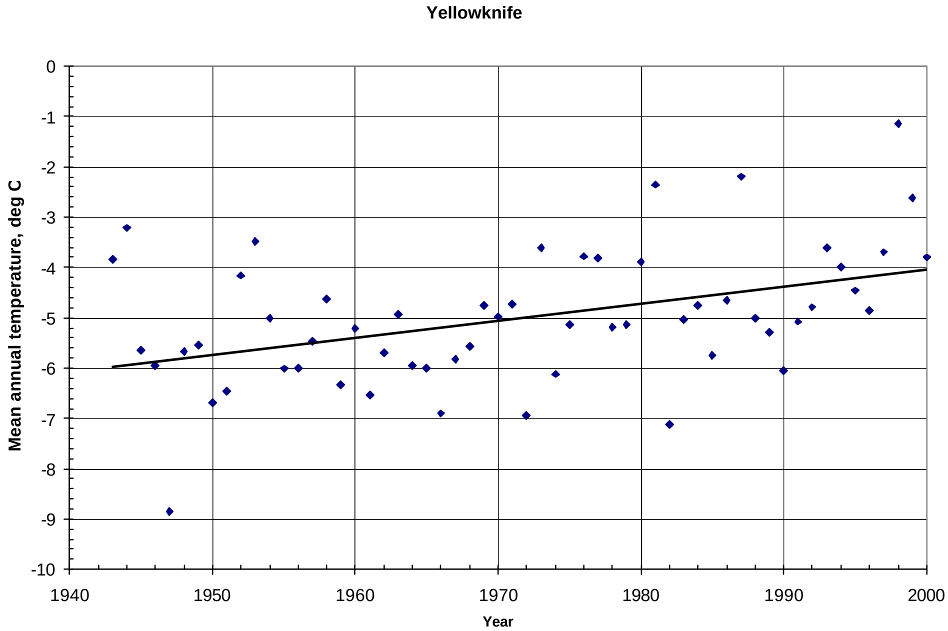
The warming trend is also demonstrated by a review of the Canadian Climate Normals published by Environment Canada. This trend is confirmed for the four locations when the MAAT's are compared for periods from 1951-1980 and 1971-2001 from station where both values are available. The overall change of the MAAT of three Canadian regions with permafrost, namely, Yukon, Northwest Territories and Nunavut are given in Table 2-6.

Table 2-6. Mean change of MAAT between two periods (1951 to 1980 and 1971 to 2000) for three Canadian Regions with permafrost.
(Based on Environment Canada Climatic Normals).

Territory	Change between 1951 to 1980 and 1971 to 2000	Estimated Change for 100 years	Comments
Yukon	0.8	4.0	All stations warming
Northwest	0.7	3.5	All stations warming
Nunavut	0.2	1.0	12 stations out of 16 warming

Note: Climatic Normals of the two periods for all the stations of the above territories are given in the Appendix.

Table 2-6 supports the warming trend shown in Table 2-5 and demonstrates that there has been warming in northern Canada which has to be considered in all designs that may be affected by changes in the permafrost.



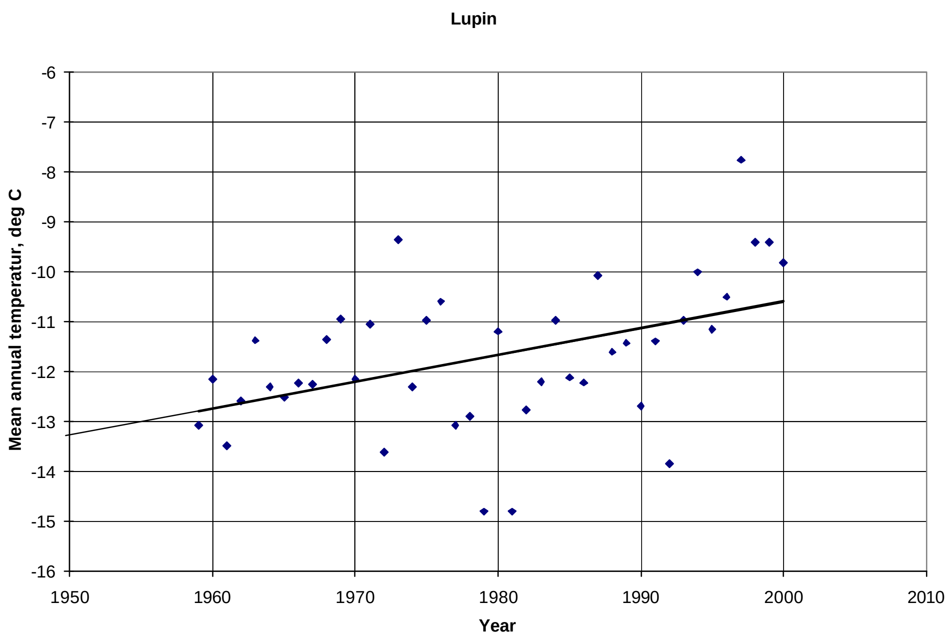
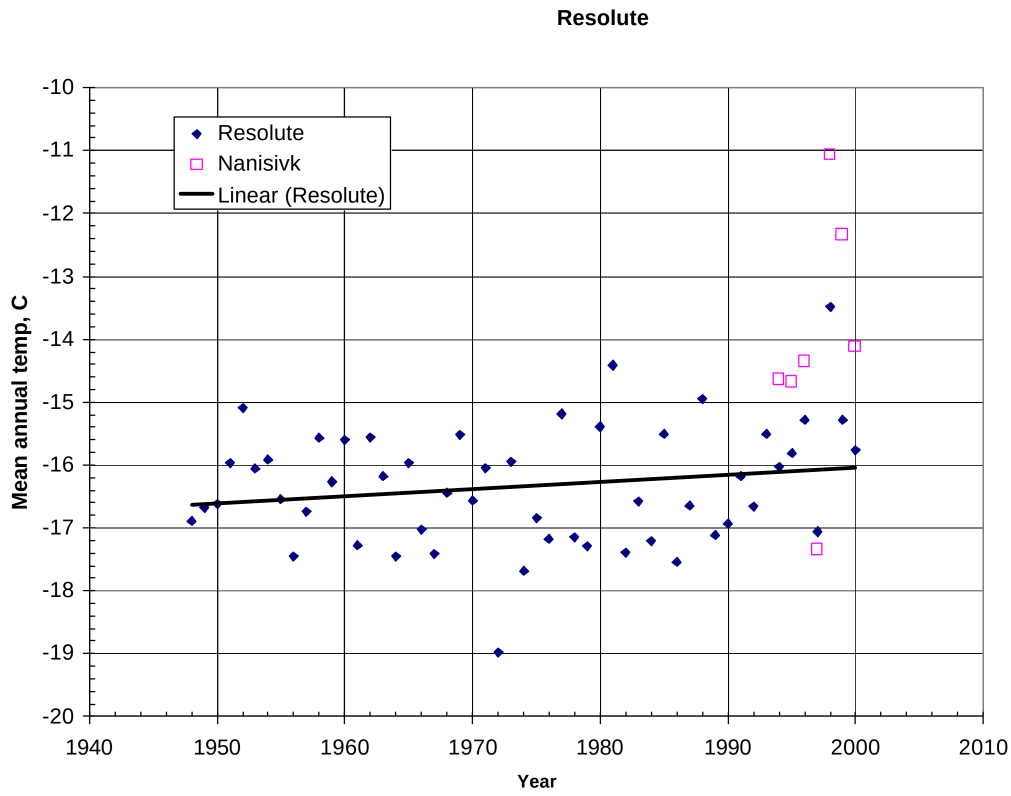


Figure 2-9. Mean annual air temperatures for Yellowknife and Lupin



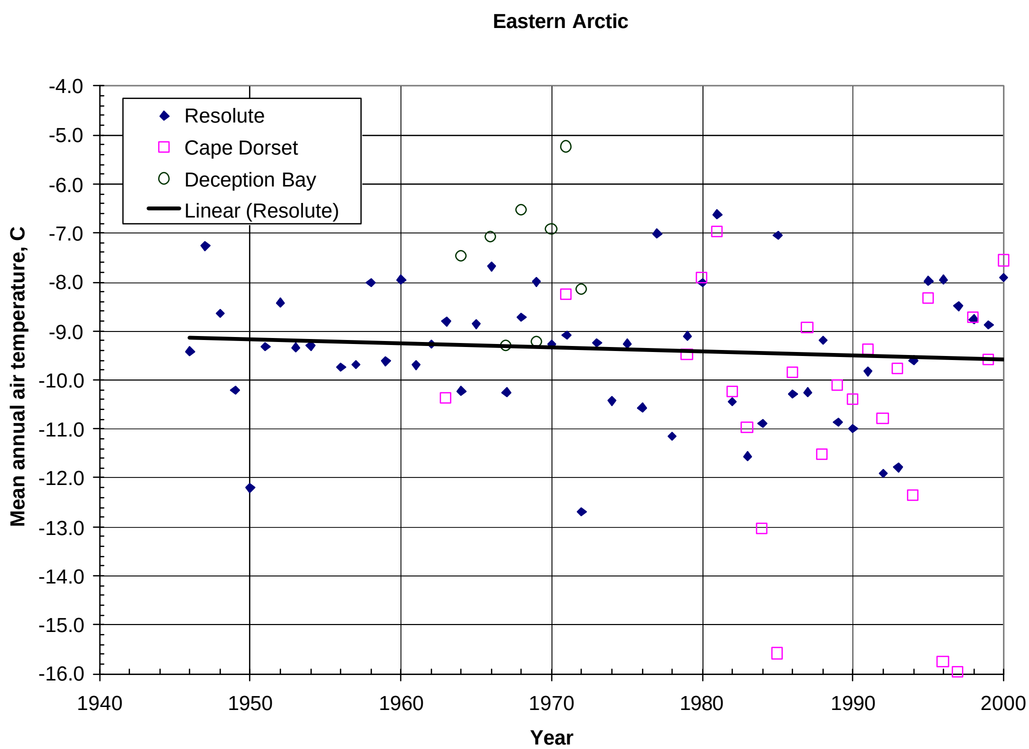


Figure 2-10. Mean annual temperatures for Resolute and Eastern Arctic

3.0 COVERS FOR REACTIVE TAILINGS

3.1 Introduction

Covers placed over reactive tailings located in non-permafrost regions to prevent or reduce the oxidation have been studied and field-tested for many years. This work has been documented by several MEND reports and is summarized in Volume 4 of the MEND Manual (MEND 5.4.2d).

In warm climates, as opposed to climates promoting permafrost, the main prevention and control technologies consists of dry and water covers. Water covers are subdivided into two categories, namely water covers constructed over oxidized tailings and subaqueous disposal of fresh tailings in a constructed pond.

In permafrost regions the concept of encapsulating potentially reactive tailings, and mine rock, in permafrost has been widely studied. Permafrost encapsulation requires an adequately cold temperature climate to maintain the reactive tailings in a frozen state and a sufficiently thick cover that will contain the annual thawing (active layer) within the non-reactive cover material. Material thickness required to maintain the active layer within the cover is dependent on many factors and may range from 1.5 to 5m. The main parameter controlling the cover thickness is the moisture content of the cover material. Global warming is also an important parameter that needs to be considered when designing covers for tailings facilities in permafrost areas.

An alternative cover for permafrost, that is also applicable to non-permafrost regions, is a cover with a saturated zone at its base (saturated zone cover). This cover was first proposed in MEND 6.1 (December 1993). It is based on a stagnant water cover that has been studied for warmer climate (Li et al 1997). Since this time, reactive tailings at the Lupin Mine were covered with gravelly sand as proposed in MEND 6.1. Monitoring of ground temperature, water levels in the cover and water quality at Lupin since 1995 support this saturated zone cover concept (Section 7.0).

3.2 Tailings Covers in Non-Permafrost Regions

3.2.1 Dry covers

Dry covers have been widely used for the management and decommissioning of waste rock and tailings around the world. The objectives of dry covers are to minimize the influx of water and provide an oxygen diffusion barrier to minimize the influx of oxygen. Aside from these functions, dry covers are expected to provide erosion protection and support vegetation.

Dry covers can be simple or complex, ranging from a single layer of earth material to several layers of different materials, including native soils, non-reactive tailings and/or waste rock, geosynthetic materials and oxygen consuming organic materials. Multi-layer cover systems utilize the capillary barrier concept to keep one (or more) of its layers near saturation under all climatic conditions. This creates a "blanket" of water over the reactive waste material, which reduces the influx of atmospheric oxygen and subsequent production of acid drainage (MEND 5.4.2d, 2001). Extensive research into dry cover designs has been sponsored by MEND. Cover designs varied from a two-layer 0.8 m thick clay cover used at Equity Silver Mine (Aziz 1997) to reduce seepage, to a more complex multi-layer cover designs studied at Waite Amulet (MEND 2.21.1, 1992) and Les Terrain Auriferes (MEND 2.22.4, 2000).

Laboratory studies to identify material properties that minimize oxygen influx (MEND 2.22.2a, 2.22.2b) have shown that an increase of saturation within a cover significantly decreases oxygen flux within this cover. The studies have shown that if high saturation ($\geq$90%) can be maintained in the cover through capillary barrier effects, then a layer of fine material (i.e. tailings) sandwiched between two sand layers will effectively reduce the oxygen flux to the reactive tailings by a factor of 1,000 times. These laboratory findings are supported by experimental field cells using clean tailings, silty soil and bentonite tailings mixture (MEND 2.22.2c). Test results from these installations showed that the fine material in a capillary barrier cover will maintain a degree of saturation above 85%.

The main observation from these laboratory and field studies relevant to tailings cover design in non-permafrost areas is that an increase of water saturation, corresponding to an increase of moisture level, is beneficial in reducing or eliminating acid drainage. In permafrost, the increase of moisture content will also decrease the active layer and thereby reduce the required thickness of the cover to maintain permafrost within the cover.

3.2.2 Water covers and underwater disposal

Research has demonstrated that oxidation of sulphides in mine tailings and waste rock is inhibited by placing mine wastes under a water cover (MEND 5.4.2d). The suitability of this method is subject to site-specific factors, and as such is not universally applicable. However, where a water cover can be used, this method offers one of the best solutions for preventing sulphide oxidation and acid generation over the long-term.

A critical concern for this design has been the potential for trace metals, contained in the tailings pore water, to leach into the overlying water column. Extensive studies on lakes where tailings had been disposed of in the past have demonstrated that the tailings are geochemically stable.

A water cover can be provided either by disposing the tailings below water or by flooding the existing tailings by means of a water retention structure. These two are differentiated as follows:

- **Subaqueous disposal** refers to placement of fresh tailings under water within either constructed pond or an existing impoundment formed by a lake or ocean.
- **Flooding** refers to submerging oxidized tailings by water that is contained by engineered water retention structures.

An important finding for the proposed saturated zone cover for permafrost regions is the research done at Noranda Technology Centre that assessed the depth of water required to prevent oxidation of sulphide tailings under various conditions (Li et al 1997). They found that in sub-aqueous disposal in a constructed pond, 0.3m depth of ‘stagnant’ water was sufficient to inhibit tailings oxidation. This depth is supported by the results of two test-cells constructed adjacent to Louvicourt tailings pond (MEND 2.12.1c, 1992). However, this work does not consider wave action that may re-suspend the tailings.

Research (MEND 5.4.2d, 2001) and actual mine site case histories (Davé and Vivyurka 1994) have demonstrated that water covers inhibit AMD. The depth of water over tailings is not only governed by the criterion to create an oxygen barrier, but also the prevention of mobilizing tailings by wave action and ice scour (Atkins et al 1997).

From theoretical studies that were also confirmed by field observations at Equity Silver, it was determined that a water depth of 1.3 to 1.4m is required to combat wave and ice scour action (Atkins et al 1997). The required water depth for a particular site is site specific. A water depth of 1.0m is commonly used in practice.

It is difficult to maintain a water cover in most of the Canadian permafrost regions because evaporation of water at the pond water surface is greater than normal precipitation (Latham 1988). Also it is very costly to monitor and maintain the structural components of a water retention system in remote areas after mine closure.

3.3 Tailings Covers in Permafrost Regions

The main cover strategy for tailings in continuous permafrost has been encapsulation. This is based on the assumption that permafrost will develop within the tailings and the annual thaw is prevented from encroaching into the frozen tailings by a non-reactive granular cover over the tailings. This strategy has been adopted in many mine closure plans.

Field data for the design of cover over reactive tailings to result in permafrost encapsulation has been lacking until the most recent field tests became available from four field programs: Nanisivik (Elberling 2001), Raglan (AMEC 2001), Lupin (Holubec 2003) and Rankin (Meldrum et al 2001).

All presently proposed permafrost encapsulation rehabilitation options assume that permafrost will remain permanently. Considering that temperature records over the last 50 years show a warming trend, and that there is evidence that global warming has occurred over a much longer period, the effect of global warming on encapsulation has to be addressed.

Cover designs that have been proposed or are in various stages of application are summarized below. These are discussed in greater detail in subsequent sections.

Ekati – A layered cover consisting of fine grain soils to retain moisture overlain by granitic waste rock. Anticipated thickness of 1.5 to 2.0m.

Diavik – A composite cover of 0.5m of silty sand till overlain by 3m of clean mine rock. It is predicted that the active layer will extend partly into the silty sand. Oxidation of the tailings will be prevented firstly by the upper zone of the silty sand being fully saturated and secondly by the fact that the lower part of the silty sand and the tailings will be in permafrost. Total cover thickness of 3.5m.

Nanisivik – One meter of shale (sandy gravel sizes) covered with 0.25m of esker sand and gravel. Permafrost is anticipated to stay within the cover. Total cover thickness of 1.25m

Raglan – Filter pressed tailings compacted in a mound will be covered with 1.2m of crushed sandy esker material that is expected to retain some moisture and followed by a 1.2m mine rock surface zone for erosion protection. Total cover thickness of 2.4m.

Lupin – Tailings to be contained within cells and covered with about 1m of esker sand. Covers will be designed so that at least 0.3m of the esker cover will remain saturated and thereby provide an oxygen barrier. Total cover thickness of 1.0m. Not a permafrost encapsulation design.

Rankin – One meter of esker sand and gravel over tailings with saline pore water. Active layer penetrates the tailings because of freezing point depression.

Three basic design concepts considered for tailings in permafrost are illustrated in Figure 3-1.

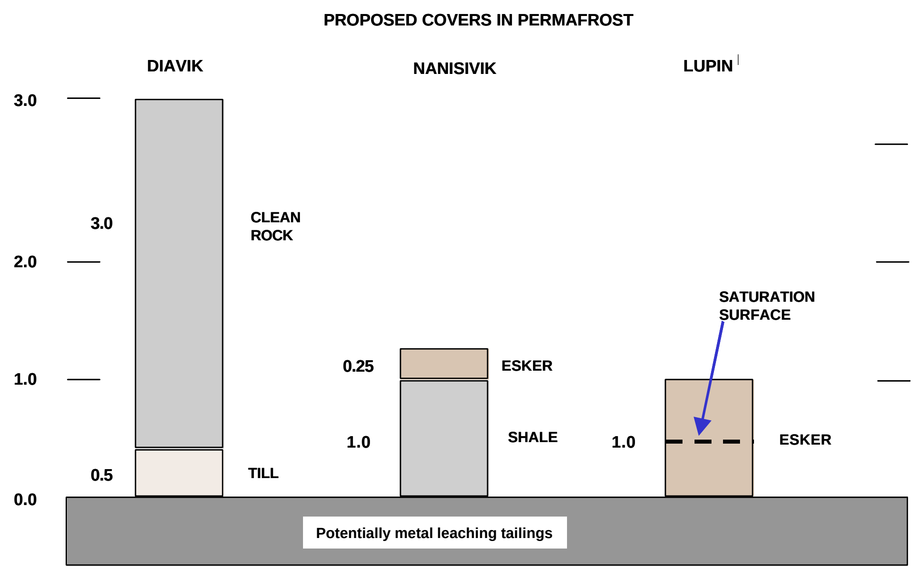


Figure 3-1. Cover design concepts for reactive tailings in permafrost.

<u>Concepts:</u>

Diavik	Permafrost encapsulation by active zone predominantly in clean mine rock.
Nanisivik	Ice rich permafrost zone developed at the base of the shale cover.
Lupin	Saturated zone in base of esker prevents oxidation of tailings.

4.0 CASE HISTORIES

Four informative case histories of cover performance in continuous permafrost are available. They differ in the climatic conditions, design of their tailings storage facility and the design of the covers. In all four cases the cover design was evaluated using test pads or cells with covers over reactive tailings. The monitoring method varied among the sites and therefore different information was collected at each. The different locations, type of tailings facility, and cover design used provide a wealth of information for future designs of covers over reactive tailings.

The case histories described are: Nanisivik, Raglan, Lupin and Rankin Inlet. Their general location is superimposed on the Mean Annual Ground Temperature map shown on Figure 4-1.

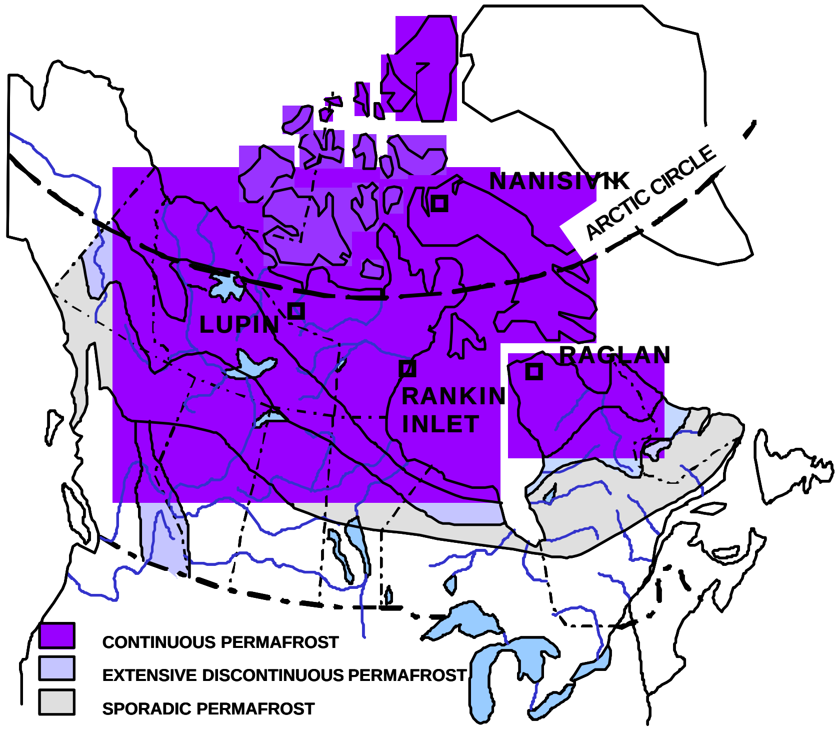


Figure 4-1. Location of four case histories

The tailings storage method used for these four mines are illustrated schematically in Figure 4-2 to Figure 4-5. In all four cases, the main interest is to document the temperature or thaw depth performance of their test pads. To understand how the proposed cover designs were selected and the performance of these test pads, background for each mine is provided. It consists of a brief history of the mine, the local topography and permafrost regime, including air temperature and its changes over the monitoring period.

Brief introductory summaries of the four sites are as follows:

Nanisivik. Nanisivik initially discharged the tailings under water within an existing lake. After the lake was filled, tailings were discharged in a surface cell constructed above the original lake by means of progressive upstream dyke construction. To select a cover design with the smallest thaw depth for the surface tailings, five test pads were constructed. The effect of cover layering, compaction, saturation and colour of the surface layer was studied. The thaw depth was monitored for a period of 8 years by means of thaw depth gauges and thermocouples.

Raglan. Raglan decided to filter press the tailings and compact the filter cake within a mound. Raglan conducted a parametric thermal analysis to develop a cover design to retain the active layer within the cover. A test pad was constructed and two years of temperature data is available that show the temperature distribution and changes within the cover.

Lupin. Lupin discharged the tailings within cells and covered the filled cells with a sandy esker material. To develop the final cover design, Lupin instrumented the two covered cells in 1996 and monitored the temperatures, water levels within the cover and water quality of the pore water. Results showed that the best approach was a saturated zone cover.

Rankin Inlet. Oxidized tailings located on the ground surface were placed within a pumped out deep pond and covered with 1m of esker sand and gravel. Seawater and the presence of sulphide minerals within the oxidized tailings caused a freezing point depression of at least 4ºC and the active layer penetrated to a much greater depth than the cover thickness.

The case histories of the three test pad installations or one final cover are presented in greater detail in the following Chapters 5 to 8.

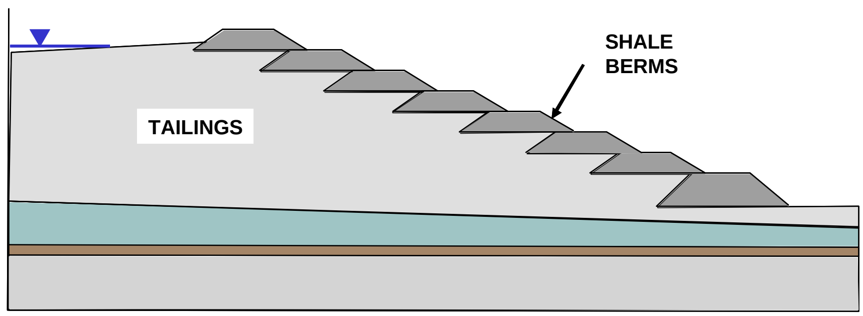


Figure 4-2. Nanisivik; upstream tailings embankment

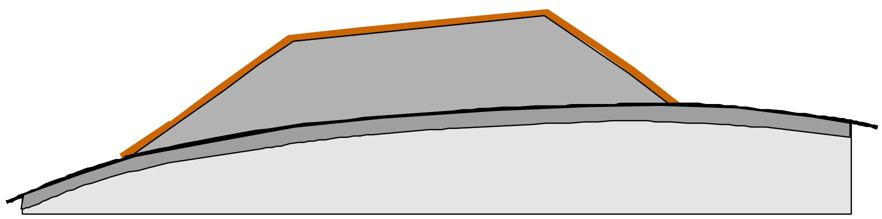


Figure 4-3. Raglan, tailings filter cake mound

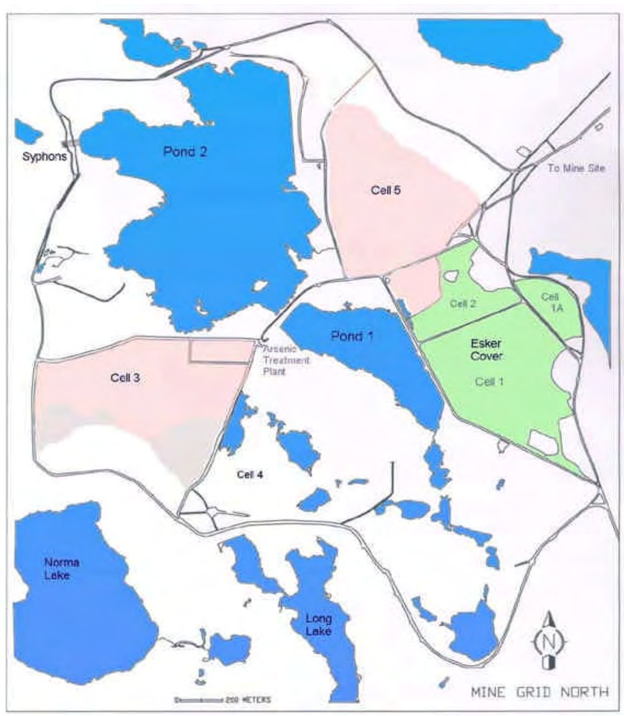


Figure 4-4. Lupin, tailings slurry within cells

Legend: **A -** Deep Pond, **B** – Shallow Pond and **C** – Tailings Pond (Erickson 1995).

Figure 4-5. Rankin Inlet with ponds prior to reclamation.

5.0 NANISIVIK

5.1 Background

The Nanisivik Mine is located adjacent to the Strathcona Sound on the northern tip of Baffin Island, Nunavut, at latitude 73º 02'N and longitude 84º 31W. The community of Arctic Bay is located approximately 25 km west of Nanisivik. The site is considered as high Arctic with cold permafrost with MAAT being -15.2ºC and MAGT between -9.4º to -11.7ºC observed during subsurface rock exploration (Watts et al 1973). Mean annual precipitation is 240mm (Cassie and LeDrew 2001).

The mine was developed to produce zinc and lead mineral concentrates that are shipped during the ice-free season. It was put into production in 1976 with an initial proposed mine life of 12 years. Additional ore reserves extended the life of the mine to September 2002 when the mine closed due to sustained depression of the metal market.

5.2 Tailings Disposal

All tailings from ore processing were stored in West Twin Lake, part of a two lake system located about 3 km southeast of the mill and 5 km south of Strathcona Sound. East Twin Lake was selected to supply potable water to the project since its water level was higher than West Twin Lake and therefore would not be contaminated by discharge water from West Twin Lake. Another reason is that West Twin Lake had more storage capacity for the tailings. A plan of the two lakes is shown in Figure 5-1 and in an aerial photo of West Twin Lake in Figure 5-2 (Nanisivik 1997).

The initial plan was to dispose all tailings underwater within West Twin Lake. This was carried out successfully until 1991, about 3 years past the 12-year initial mine life. Alternative deposition had to be developed to prevent raising the water level in West Twin Lake to or above East Twin Lake. It was decided to construct a dyke across West Twin Lake on top of the tailings and provide additional tailings storage west of the dam (Figure 5-1). This area is called the Surface Cell. The east portion of West Twin Lake, the Reservoir, would retain its original lake level with an existing deep area being used for emergency tailings deposition during mid-winter conditions.

The dyke was constructed on top of an existing north-south causeway underlain by deposited tailings. During subsurface investigation along the proposed dyke, it was observed that the stratigraphy below the causeway was frozen to a depth of at least 11m (Golder 1999). The stratigraphy below the causeway varied from about 7m of tailings underlain by 1m of sandy till before bedrock, to 3m of tailings underlain by 3m of sandy till before bedrock.

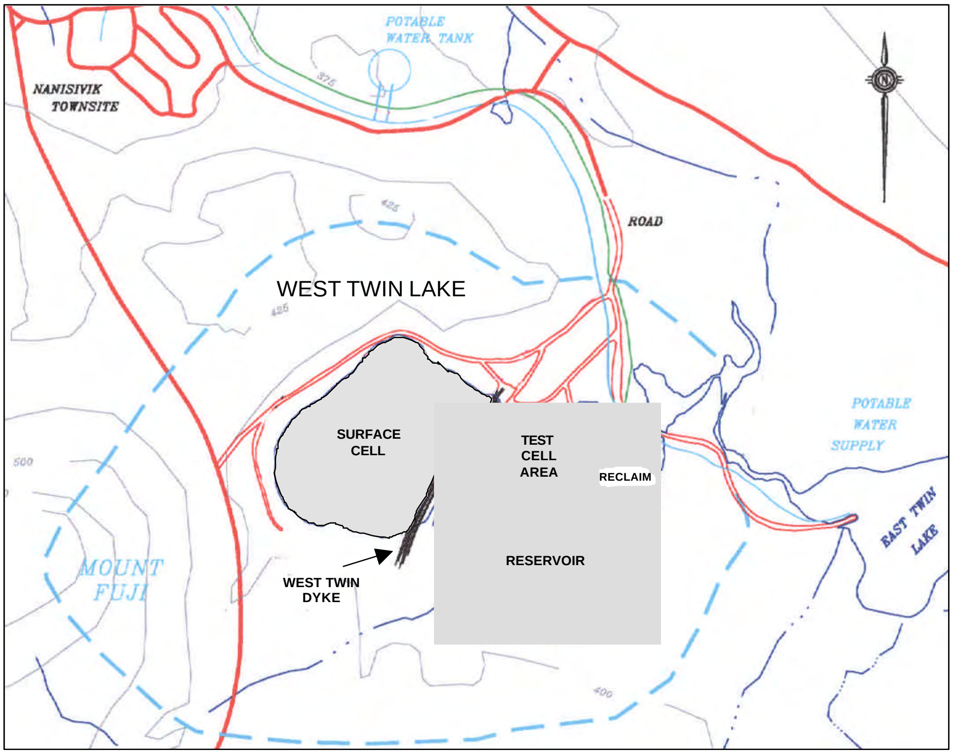


Figure 5-1. Tailings disposal plan

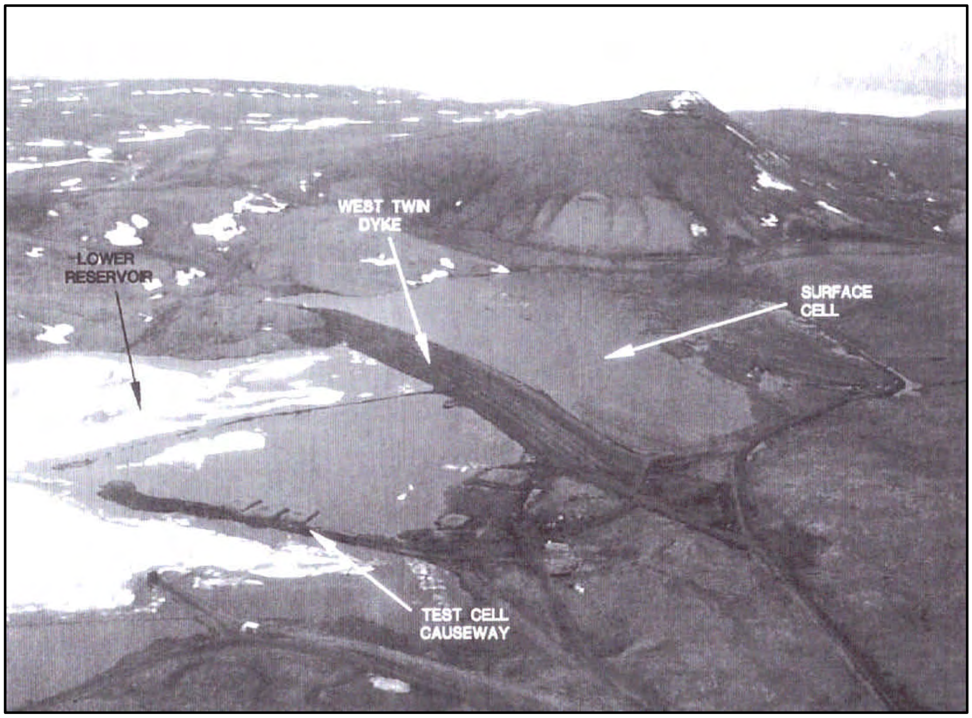


Figure 5-2. Airphoto of West Twin Lake tailings area

The dyke design consists of upstream construction of about a 4 m wide zone of sand and gravel sized shale material obtained by ripping exposed shale bedrock. With the exception of the first lift, which was 3m high, the dyke was raised in 2m lifts until it reached the final elevation of 388m. The shale fill was placed in 0.3 to 0.4m layers and then compacted by construction traffic. The dyke base on tailings was at El 371m. By setting back each subsequent berm, a downstream slope of about 3.7 horizontal to 1 vertical was achieved (Golder 1999).

The dyke was constructed on top of a shale causeway fill, underlain by tailings, overburden consisting of silt sediments and sandy till and finally, dolomite and shale bedrock. Two thermocouples installed through the causeway showed the underlying stratigraphy was frozen to at least 11m. Cross sections of the dyke and foundation stratigraphy below the dyke are shown in Figure 5-3.

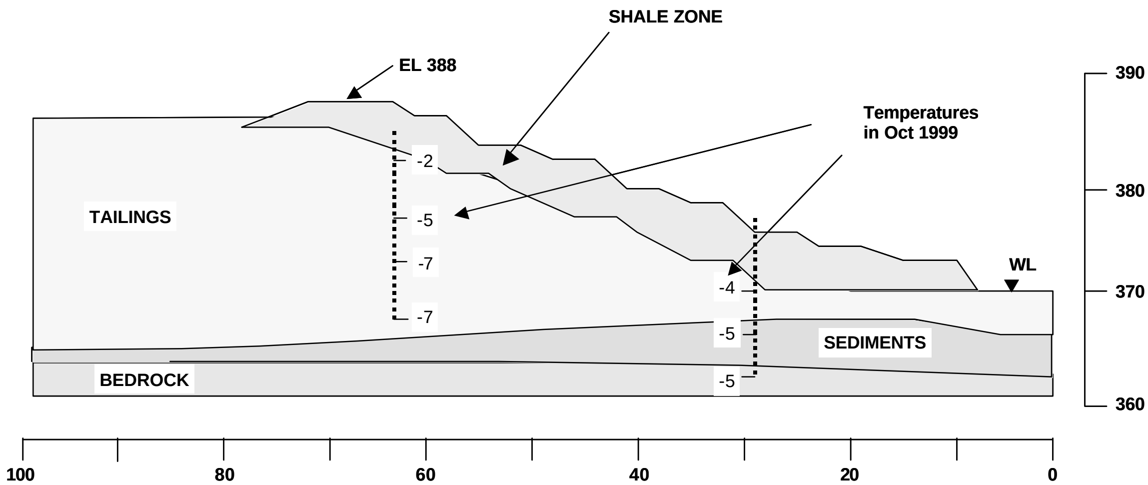


Figure 5-3. Typical cross section through West Twin Dyke

The cold temperatures measured within the tailings illustrate the relatively rapid cooling of the tailings. The upstream thermistor cable shown in Figure 5-3 were likely placed between 1991 and 1996. The temperature readings show that in about 4 to 5 years of tailings placement, the tailings temperature at greater depths were between -5ºC to -7ºC. The relatively quick cooling and development of permafrost in tailings not covered with water was also demonstrated at several other West Twin Dyke locations.

5.3 Tailings Cover Test Pads

In 1991 Nanisivik Mines Inc. decided that they would develop a cover design for tailings that would be exposed to air in the surface cell. The tailings were determined to be potentially acid generating (Terratech 1993). Terratech recommended a cover that would prevent oxidation of the tailings by encapsulating them in permafrost and ensuring that the tailings would remain frozen by containing the active layer within an inert cover. The active layer would be underlain by an ice saturated zone within the cover that would prevent air and water from contacting the tailings.

Terratech report suggested that there were three techniques that could be used to minimize the active zone and thereby the cover thickness, namely:

1) Use of fine grained soils to raise the base of the active layer;
2) Use of light coloured surface material that absorbs less heat (has a higher albedo); and
3) Accelerate the creation of a saturated base by constructing and saturating the base during freezing temperatures.

To assess the impact of the above parameters on the active layer depth, an instrumented test cell program was implemented for several years before closure.

5.4 Test Cell Program

5.4.1 Materials

The potential materials for the cover identified at or near the site were:

- Shale consisting of sand and gravel material sizes that could be obtained by ripping a local shale deposit;
- Sandy till, local overburden;
- Twin Lake sand and gravel, and
- Airport Road sand

Shale was considered a desirable cover material because it could be ripped during frozen condition and because it contained some carbonate to neutralize any potential acid seepage. Ripping of the shale resulted in a granular material with about equal amounts of sand and gravel with about 5% fines. It was deemed necessary to cover the shale with a lighter coloured material to decrease the formation of a deep active layer.

Sandy till is a local overburden that consists of a heterogeneous mixture of silt and clay, sand, gravel, cobbles and boulders. It was not considered as an ideal cover material because it could only be exploited during the warm summer months when it was thawed.

Twin Lakes sand and gravel is derived from a delta fan that was indurated and thereby produced a cemented rust or reddish coloured material. It was considered as a material to be used for wind erosion protection but was rejected because of its dark colour that would encourage a deeper active layer.

Airport Road sand; is a light coloured sand from the surface decomposition of a local sandstone bedrock.

5.4.2 Test pad program

Five test pads were constructed to assess the influence of several parameters, namely:

- Compaction of cover material;
- Covering the dark shale with the lighter Airport Road sand to reduce radiation heating;
- Use a layered cover with compacted zones at various depths; and
- Saturation of the shale during winter placement to create a frozen ice rich base in the cover.

The test pads were constructed downstream of the West Twin Lake dyke against and on the west and north shores of West Twin Lake as shown on Figure 5-4. The location of the test cell area is also shown on Figure 5-1 (Nanisivik 2001).

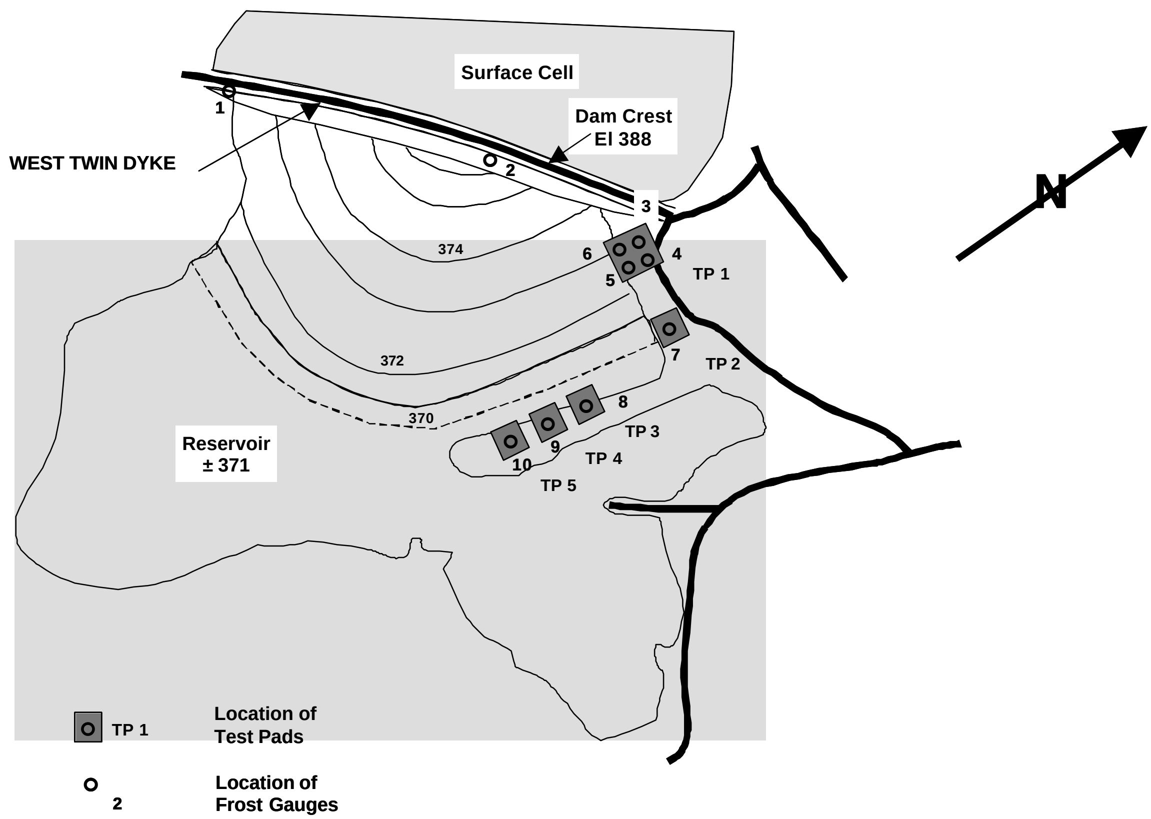


Figure 5-4. Test pad locations

Test Pad 1 was constructed in the fall of 1991 using non-compacted shale with a 10cm cover layer of light Airport Road sand. The cover was about 2m thick. The test pad is about 30m by 30m in size. It was instrumented with 4 frost gauges and one thermocouple was placed in the centre of the cell.

Test Pad 2 was constructed using shale that was saturated and compacted during placement and than covered with 0.3m of Twin Lake sand and gravel. It was constructed in May 1992.

Test Pad 3 was first constructed in the spring of 1993 with 1m of shale and a second metre of shale was added in 1995.

Test Pads 4 and 5 consisted of multi-material zones with varied thicknesses and compactions. A 0.4m compacted shale zone in Test Pad 4 was about 0.3 m below the surface and Test Pad 5 had a compacted Twin Lake sand and gravel zone about 0.7m below the surface.

Test Pads 2 to 5 are 16m by 16m in size and all are instrumented with one frost gauge and one thermocouple.

The stratigraphy of the 5 test pads and the average thaw depths are shown in Figure 5-5.

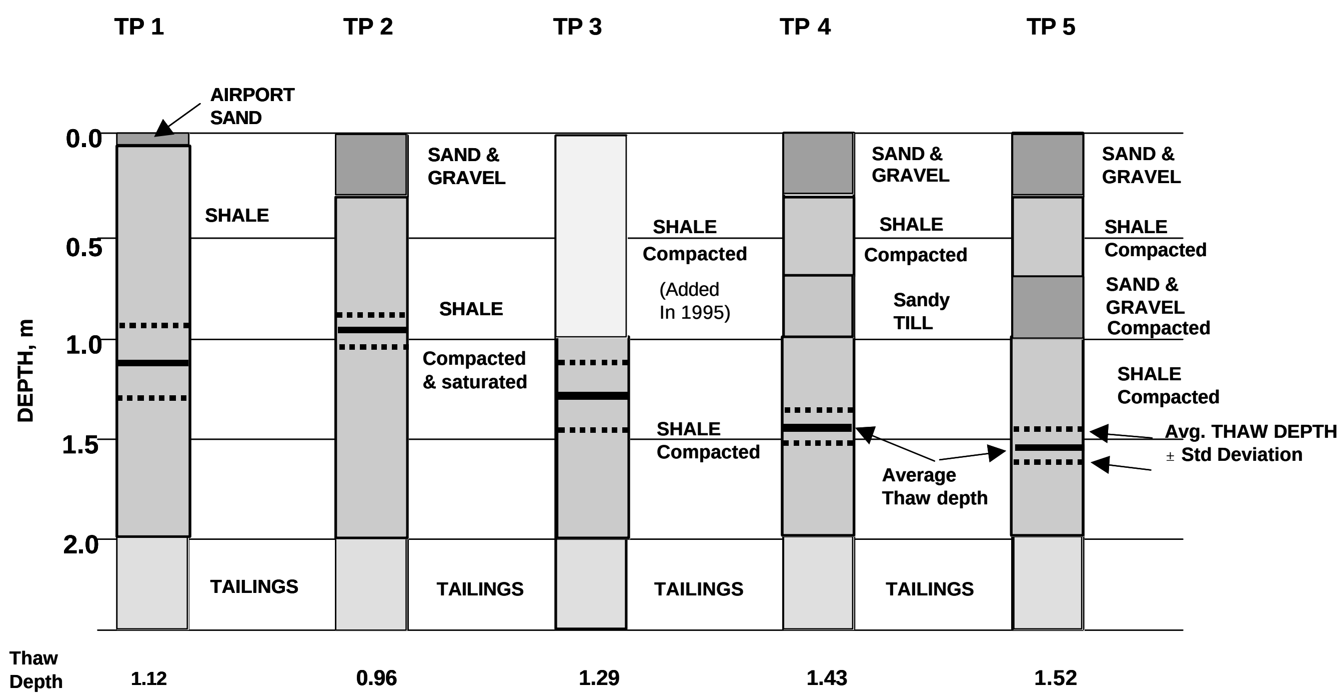


Figure 5-5. Test pad stratigraphies

Water contents of the cover materials were measured in Test Pads 2, 3, 4 and 5 during the construction of the pads. The values given in Table 5-1 represent the initial water content values measured during construction. The water content was measured on minus 20mm fraction of the shale.

Table 5-1. Water contents measured in June 1992

Test Pad	Water Content Values, %	Avg. Water Content, %
Test Pad 2	43.3, 30.1, 27.2	33.5
Test Pad 3	6.9	6.9
Test Pad 4	8.2, 7.7, 9.1	8.3
Test Pad 5	5.9, 6.7	6.3

Wetting the shale during construction produced the high water content in Test Pad 2.

5.4.3 Monitoring

The thaw depths were measured by means of frost gauges that showed the difference between thawed and frozen fluid by colour changes. The gauges consist of a 2200mm long clear tubing with an outside diameter of 20mm that were filled with water and methylene blue dye mixture and sealed at both ends. The water/methylene blue mixture becomes colourless upon freezing. These gauges were inserted in 25mm diameter plastic casings that were placed in drill holes. Pulling out the frost gauges and measuring the length of the clear frozen mixture at the base of the tube established the advance of depth of thaw during the summer.

In addition to the frost gauges in the test pads, two frost gauges were installed in the West Twin Dyke. Frost gauges F1 and F2 were installed within the shale outer zone at about mid-height of the dam. These are shown on Figure 5-4.

The changes in the thermal condition within and below the test pads were also monitored by means of vertical thermocouple cables installed in the centre of each cell.

The thermocouples and frost tubes were read/measured on a monthly basis. The thaw depths in this report are based on the frost tube results because detailed thermocouple data was not available.

5.5 Cover Performance

5.5.1 General

Thaw depths measured from 1993 to 2000 are given in Table 5-2 (Nanisivik 2001). While the mean thaw depth is about 1.20m for the 8 years of record (Table 5-3), there is a considerable variation in the data, from a minimum depth of 0.73m to a maximum of 2.09m. The large range of the thaw depths is due to different test pad designs, moisture contents and changes of the air temperature during the test period. To compensate for the variable air temperatures during the 8 year period, the mean, minimum and maximum range of values are provided for each frost gauge for the period in Table 5-3.

The factors that affect the thaw depth are discussed in the next sections.

Table 5-2. Maximum annual thaw depth measured by frost gauges, in metres

	Frost Gauge Number	1993	1994	1995	1996	1997	1998	1999	2000
Dyke	F1	1.43	1.18	1.11	1.06	1.02	1.14	1.03	0.65
	F2	1.42	1.26	1.29	1.18	1.19	1.50	1.20	0.76
Test P1	F3	0.99	0.85	0.73	0.73	0.73	1.30	1.10	0.88
	F4	1.26	1.09	0.93	0.90	0.95	1.30	1.10	1.30
	F5	2.09	1.86	1.38	1.24	1.05	1.05	1.05	1.15
	F6	1.66	1.29	1.08	1.03	0.97	1.02	0.95	1.15
Test P 2	F7	0.95	0.90	0.94	0.98	0.87	1.03	0.95	1.11
Test P 3	F8	1.00	1.03		1.27	1.24	1.48	1.25	1.43
Test P 4	F9	1.55	1.45	1.46	1.35	1.33	1.46	1.34	1.49
Test P 5	F10	1.63	1.63	1.59	1.50	1.40	1.55	1.40	1.49
	Avg	1.40	1.25	1.17	1.12	1.08	1.28	1.14	1.14

Table 5-3. Statistical analyses of thaw depth data

Location	Frost Gauge Number	Thaw depth, m			
		Mean	Min'm	Max'm	Range
Dyke	F1		0.65	1.43	0.78
	F2	1.15	0.76	1.50	0.74
Test P1	F3		0.73	1.30	0.57
	F4		0.90	1.30	0.40
	F5		1.05	2.09	1.04
	F6	1.13	0.95	1.29	0.34
Test P 2	F7	0.97	0.87	1.11	0.24
Test P 3	F8 (a)	1.02	1.00	1.03	0.03
	F8 (b)	1.33	1.24	1.48	0.24
Test P 4	F9	1.43	1.33	1.49	0.16
Test P 5	F10	1.52	1.40	1.63	0.23
	Avg	1.20	0.99	1.42	0.43
	Minimum of all	0.97	0.65		0.16
	Maximum of all	1.52		1.86	0.81

Note: Frost Gauge 8 – (a) refers to the first 2 years when the cover was only 1m thick and (b) to the last 5 years when the cover was 2m thick.

5.5.2 Air temperature

The key parameter that governs the thaw depth is air temperature and its variation over the year; especially the air temperatures above zero that occur during the summer period. The air temperature over a specific year is portrayed in general terms by the MAAT which changes from year to year and may exhibit a long-term trend. The MAAT has varied considerably during the 1994 to 2000 monitoring period as demonstrated by the MAAT measured at the Nanisivik Airport (Figure 5-6). Data in this figure show that the MAAT has varied from a high of -11.1ºC to a low of -17.3ºC from 1993 to 2000.

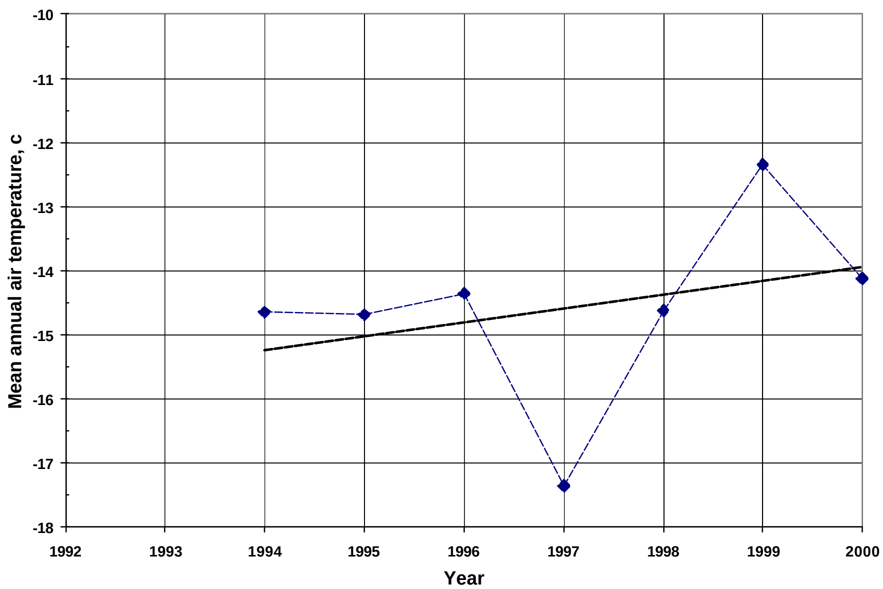


Figure 5-6. Mean annual air temperature at Nanisivik airport (Environment Canada)

The thaw depth can be correlated to the MAAT. However, it is more correct to relate the thaw depth to the thawing index since it represents more accurately the above zero degree temperatures that cause the thaw.

Average thaw depths (for the combined frost gauge measurements), are plotted against the MAAT and thawing index in Figure 5-7 and Figure 5-8 respectively. The values used in these figures are given in Table 5-4.

Table 5-4. Active layer depth related to MAAT and Thaw Index at Nanisivik

	1993	1994	1995	1996	1997	1998	1999	2000	Avg
Thaw depth, m	1.40	1.25	1.17	1.12	1.08	1.28	1.14	1.14	1.20
MAAT, deg C	-15.6	-16.1	-15.9	-15.3	-17.1	-13.5	-15.3	-15.8	-15.6
Thawing index, deg-days	282	235	267	159	166	410	324	241	261

Note: Thaw depth represents the mean thaw from 10 frost gauges.

The MAAT and thaw depth curves in Figure 5-7 show a reasonable correlation between the thaw depth and the MAAT. These curves demonstrate that in general terms the thaw depth decreased to 1.08m when MAAT decreased to -17.1ºC in 1997 and increased to 1.28m when the MAAT increased to -13.5ºC in 1998.

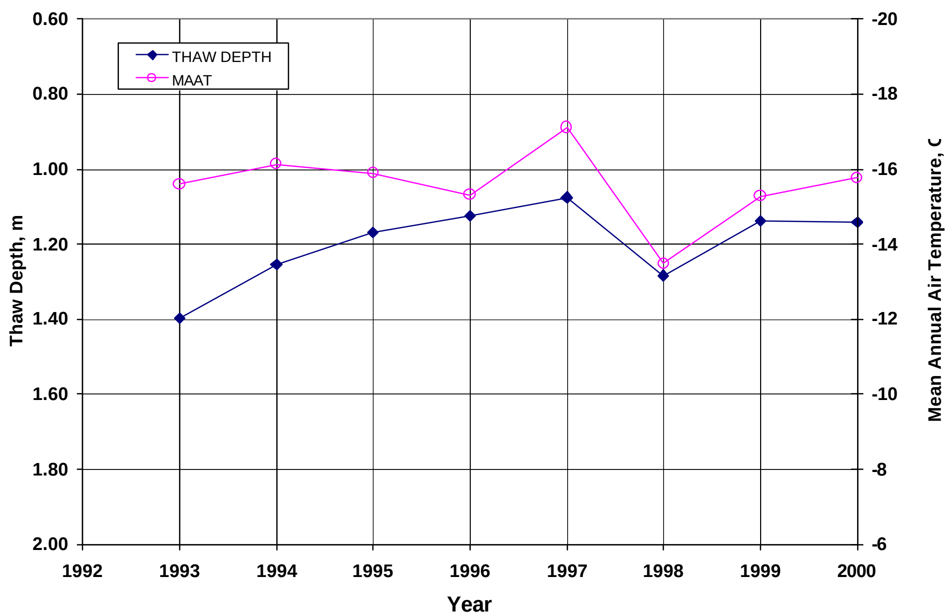


Figure 5-7. Average thaw depth for all test pads related to MAAT, Nanisivik test pads

However, the thaw depth is more a function of the temperatures occurring through the summer than the mean of the whole year temperatures (MAAT) because the thawing is a near surface phenomenon. A better temperature parameter for assessing thaw depth is the thawing index. The relationship between thaw depth and thawing index for the Nanisivik test pads is shown in Figure 5-8.

In Figure 5-8 the trend line is drawn through the thaw depths from 1995 to 2000. Thaw data from 1993 and 1994 was not considered in development of the trend line because it was assumed that during the first two years the moisture content within the covers was developing towards an equilibrium. This is supported by the fact that the thaw depth from the first year (1993) after pad construction is further from the trend line than the thaw depth from the second year (1994). The good correlation of the thaw depth to the thawing index in Figure 5-8 shows that the thawing index is a good parameter for evaluating the thaw depth within a cover, assuming that the moisture content or groundwater level within the cover are relatively constant.

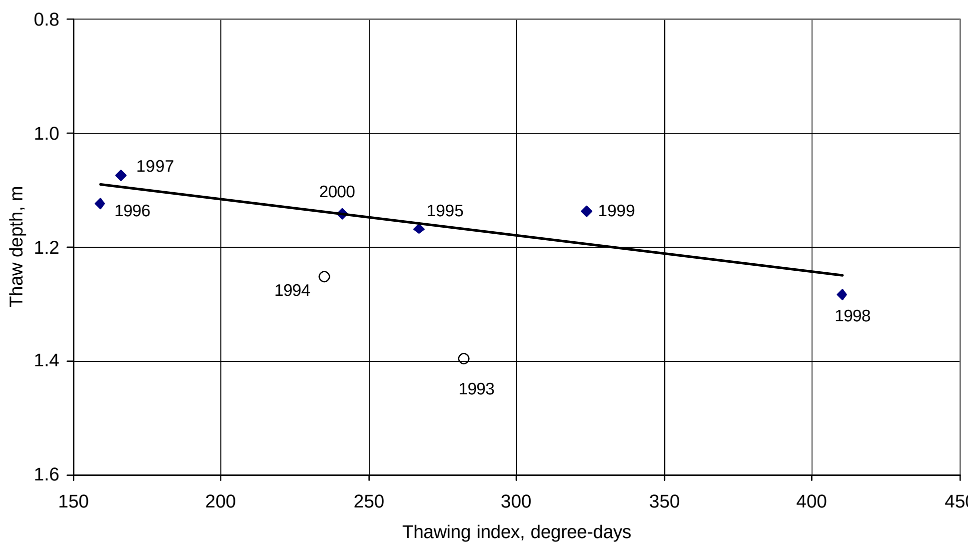


Figure 5-8. Average thaw depth for all test pads related to thawing index, Nanisivik

5.5.3 Effect of moisture content

The effect of moisture on reducing the thaw depth is demonstrated when comparing the thaw depths of Test Pad 2 and the initial two years of Test Pad 3, when the cover was only 1m thick, to the thaw depths of the remaining test pads. Test Pad 2 was constructed using shale that was saturated, compacted, and covered with 0.3m of Twin Lake sand and gravel. The initial water content measured in May 1992 was 33.5%. Moisture contents within the covers were not measured after the initial measurements in May and June 1992. It could be assumed that the Test Pad 2 maintained a high moisture content, because 1) it likely had high clay content (being a weathered shale), 2) it was saturated during placement and 3) it would likely not drain because of low permeability produced by compaction during construction. It can be observed that Test Pad 2, with the high moisture content had the smallest thaw depth: with an average of 0.97m, ranging from 0.87m to 1.11m over the eight years of monitoring.

During the first two years Test Pad 3 with 1m shale cover experienced a shallow thaw depth of 1.00m and 1.03m. It is believed that this small thaw depth was the result of the weight of the pad compressing the underlying saturated tailings, with the excess water migrating into the shale. An additional 1m of shale on the previously shale cover did not have the same effective compressive weight to push water into the new overlying shale layer. The lower saturation of the upper 1m of the shale resulted in the thaw depth increasing to an average of 1.33m for the years 1996 to 2000.

Test Pads 4 and 5 with initial moisture contents of 8.3% and 6.3% respectively, showed the deepest thaw depths of 1.43m and 1.52m.

5.5.4 Effect of colour (albedo) of surface material

The benefits of colour of the surface materials on the thaw depth have been studied through experimental road sections in Alaska. Eight road test sections in Fairbanks, Alaska have shown that road surface painted white or yellow reduced the surface temperatures (Berg and Esch 1983). Esch (1988) reported painted surfaces decreased the mean annual pavement surface temperature by as much as 1.7ºC. Naturally, the lower surface ground temperature would also decrease the thaw depth.

It is difficult to evaluate accurately the influence of the colour of the surface material of the test pads at Nanisivik because of additional variables within the covers. The most dominant parameters are the moisture content of the near surface unsaturated zone and the location of the groundwater level. Making a simplified assumption that the other parameters are constant, the effect of the colour of the thaw depth was assessed by grouping the test pad cells by the colour of the surface zone (Table 5-5).

Neglecting the results from Test Pad 2 that had a much greater degree of saturation, the smallest thaw depth of 1.13m was observed in Test Pad 1. It is covered with light Airport Road sand.

Test Pads 4 and 5 covered with a darker reddish sand and gravel, and Test Pad 3, covered with a dark grey shale, experienced average thaw depths of 1.48m and 1.33m respectively. The three test pads with darker surface colours did exhibit greater thaw depths than was measured at Test Pad 1, with a light Airport Road sand. The results from Test Pad 2 make it hard to make any definite conclusions.

Table 5-5. Effect of colour of cover surface on the thaw depth

Surface colour	Material	Test Pad	Mean thaw depth, m
Light	Airport Road sand	1	1.13
Reddish [a]	Twin Lake sand & gravel	2	0.97
Reddish	Twin Lake sand & gravel	4 & 5	1.48
Dark grey	Shale	3	1.33

Note [a] - Can be neglected because of known high water saturation

5.5.5 Effect of cover layer system design.

As mentioned in Section 5.3, one of the objectives for the construction of the test pads was to assess if a multi-layer cover would reduce the active layer (thaw depth). In this program five test pads were constructed with single and multiple layers with different material properties. This approach is similar to the studies made for dry covers in temperate regions (MEND 5.4.2d). The layer system varied from a single layer to a four-layer system shown in Figure 5-5.

The earlier observations showed that the key factor that controls the thaw depth is moisture level within the cover. Ignoring minor factors that also affect the thaw depth, such as colour of surface material, sequence of layers and changes of hydraulic conductivity by compaction etc., the following observations can be made:

1) Single layer covers consisting of sandy gravel shale with minor quantity of fines experienced the smallest thaw depths. Test Pad 2 with compacted and saturated shale experienced an average of 0.97m thaw and Test Pad 1 with compaction by construction equipment had an average thaw depth of 1.02m. The small thaw depth was a function of the higher moisture level in the shale.

2) Test Pad 3 was constructed from shale but in two 1m lifts in 1993 and 1995 respectively. It showed an intermediate thaw depth of 1.33m after 1995.

3) Test Pads 4 and 5, that had other granular material zones interjected within the shale material, showed the greatest thaw depths of 1.43m and 1.52m respectively. It is likely that the covers with granular layers did not hold as much moisture as those constructed predominantly from shale.

5.6 Thermocouple Results

One thermistor cable with multiple sensors was installed in the centre of each test pad. The thermocouples in Test Pads 1 to 4 extended only to a depth between 3.5m and 5m and therefore the results provide only the average annual ground temperatures (Nanisivik, 2001). The thermocouple results from Test Pad 5 where the thermistor cable extended through the tailings and into the bedrock for a depth of 13.5m are of greater interest (Figure 5-9). This thermocouple shows that one year after in stallion (in 1993), the tailings were frozen and permafrost extended to about 10m below the test pad surface. It is likely that this trend of the permafrost base getting progressively deeper and the tailings getting cooler will continue until the local mean annual ground temperature is reached.

5.7 Conclusions

The cover test pad program undertaken by Nanisivik Mine provides valuable information for the design of encapsulating tailings by permafrost and maintaining the tailings permanently frozen by limiting the annual thaw depth within the inert cover. The thaw depth observed in several cover materials are summarized in Table 5-6-and the variation of these depths were given earlier in Table 5-2 and Table 5-3.

Table 5-6. Active layer depth summary

Location	Thaw depth, m								Avg
	1993	1994	1995	1996	1997	1998	1999	2000	
Shale zone in dyke	1.43	1.22	1.20	1.12	1.11	1.32	1.12	0.71	1.15
Shale with light surface, TP 1	1.50	1.27	1.03	0.98	0.93	1.17	1.05	1.12	1.13
Saturated shale, TP 2	0.95	0.90	0.94	0.98	0.87	1.03	0.95	1.11	0.97
Zoned covers, TP 3 to 5	1.39	1.37	1.53	1.37	1.32	1.50	1.33	1.47	1.41

Some key observations from this case study are:

1) Nanisivik Mine is located in cold permafrost with mean annual air temperature (MAAT) of -15.2ºC and the mean annual ground temperature (MAGAT) of about -11ºC.

2) Tailings deposited subaqueously up to about 1991 were frozen to a depth of 11m in 2000. The temperature at the base of the tailings was about -4ºC and it is still cooling.

3) The major factor influencing the thickness of the active layer (thaw depth) is the saturation level of the cover material. The shale cover that was initially saturated to a high level, and likely remained so, showed the smallest thaw depth over the 8 years of monitoring.

4) For given moisture content, the thaw depth measured over 8 years of monitoring is governed by the thawing index.
5) There is an indication that a lighter material covering the shale may reduce the thaw depth.
6) No conclusion can be made on the benefits of using a multi layer cover.
7) The selected tailings cover design consists of 1m of shale overlain by 0.25m of sand and gravel; for a total thickness of 1.25m (Nanisivik 2002).

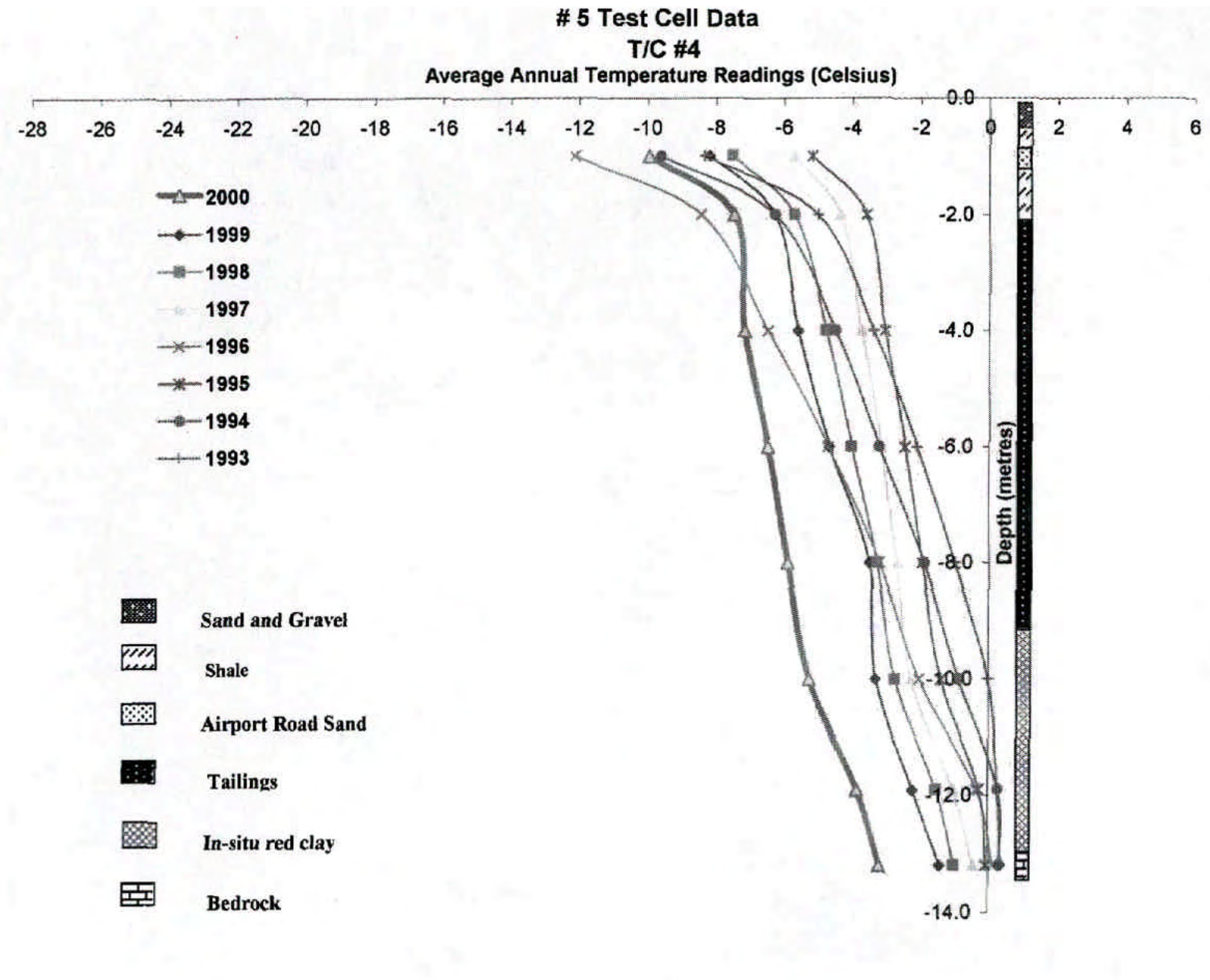


Figure 5-9. Mean annual temperatures measured below Test Pad 5 (Nanisivik 2001)

6.0 RAGLAN MINE

6.1 Background

Raglan Mine is a nickel-copper operation that started production in 1997. It is located in northern Quebec, about 80 km southeast of Hudson Strait, at latitude 61°41N and longitude 73°41W (Figure 6-1). It is a division of Falconbridge Ltd.

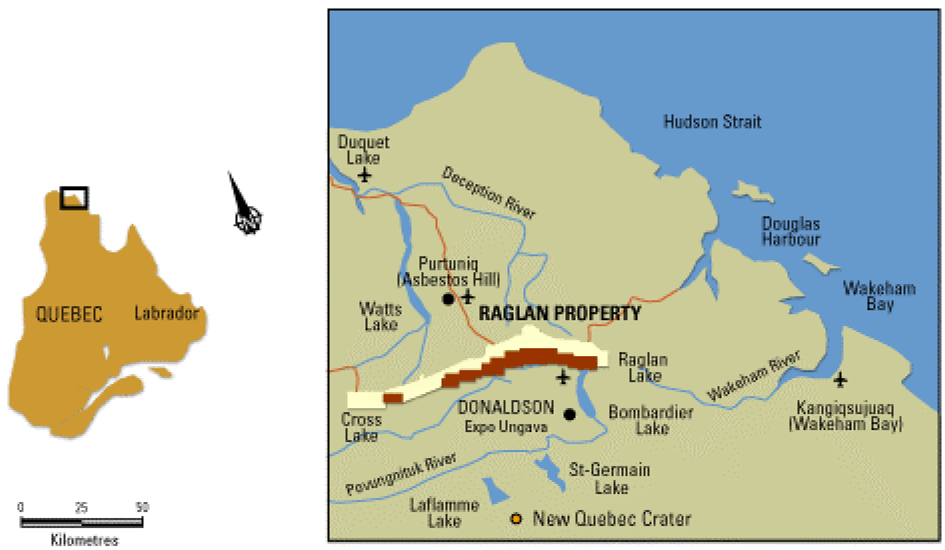


Figure 6-1. Raglan Mine location

The mine is located above the tree line in the continuous permafrost region. It has a barren landscape that is influenced by being at a relatively high elevation (600m). The region is characterized by a landscape of mounds of broken rock and shallow valleys with modest slopes. Encapsulation of the tailings in permafrost was selected as the best site closure option as the tailings can generate net acidity and runoff enriched in metals in above freezing temperatures if exposed to air and moisture (AMEC 2002). The preparation and storage of the tailings is unique because it involves filter pressing of the tailings to a filter cake consistency to allow the tailings to be placed and compacted in the shape of a mound. At closure the tailings will be covered with two layers of granular material with a total thickness of 2.4m. This is expected to maintain the tailings permanently encapsulated in permafrost. Raglan has extended considerable effort in establishing the site-specific conditions, conducting thermal analyses of several combinations of cover thicknesses and constructing a test pad based on the selected cover design (Nixon 2000, AMEC 2002). As of December 2003, Raglan had two years of temperature data from this test pad. Being inland and at a relatively high elevation at 600m results in a colder climate than the nearby communities with climatic stations at the coast.

6.2 Site Description and Tailings Placement

The tailings site was chosen to be on a small plateau to prevent surface water flowing towards the tailings stack and to avoid eliminating a potential mineral source. The final tailings stack will occupy an area of about 76 ha. It is about 2 km from the process plant. The location of the tailings stack with respect to the process plant and the topography at the Raglan project are shown in Figure 6-2.

Figure 6-2. Process plant and tailings stack location

The topography at the tailings stack by means of contours and the final geometry are illustrated on Figure 6-3. A perimeter ditch surrounds the stack and collects all surface drainage during the stack operation and directs it to a collection pond from which it is pumped to a water treatment plant. Overburden at the stack consists of relatively thin layers, of about 1m, of either ablation or lodgement till. The tills consist of a bony matrix of boulders, cobbles and gravel with a silty sand matrix. Underlying the overburden is a combination of volcanic rocks and mafic to ultramafic intrusives.

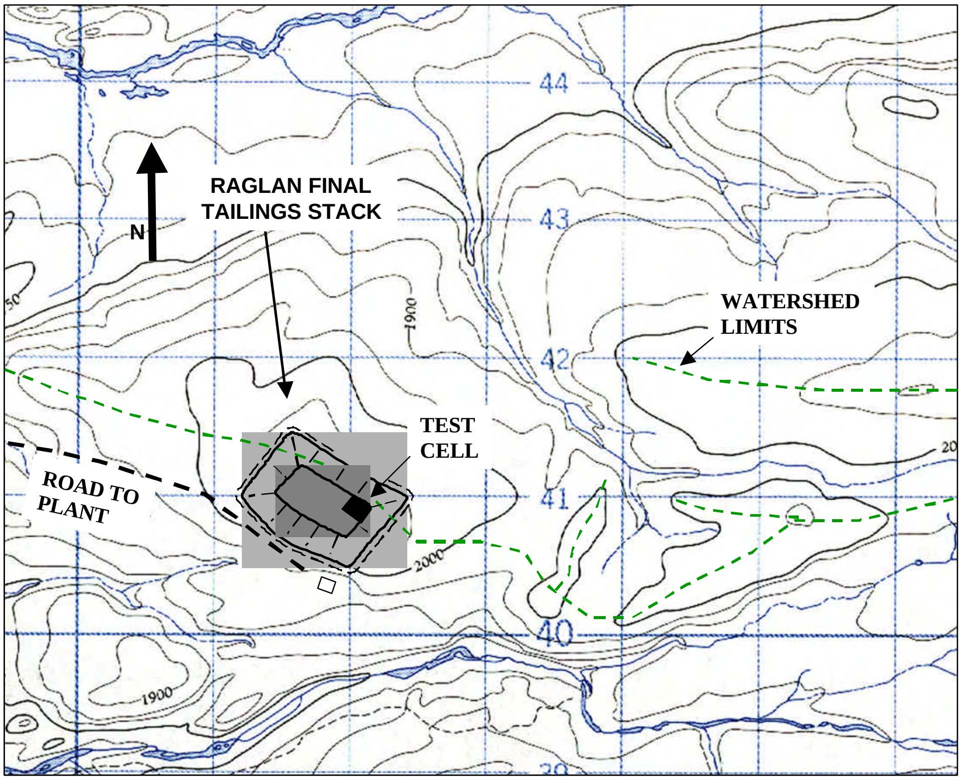


Figure 6-3. Raglan tailings stack location

The process plant produces tailings consisting of sandy silt particle sizes. They are pumped into plate filter presses where excess water is removed to produce a filter cake with a consistency of 'dry' earth type material. It has a moisture content between 18 and 20% (Raglan 2003). The tailings are trucked to the stack where they are dumped, spread and compacted to form a mound. A cross-section of the ultimate stack is illustrated on Figure 6-4. This cross section also shows the location of the test cell that forms the Raglan case history. A photo illustrating winter spreading and compaction on the stack is shown in Figure 6-5.

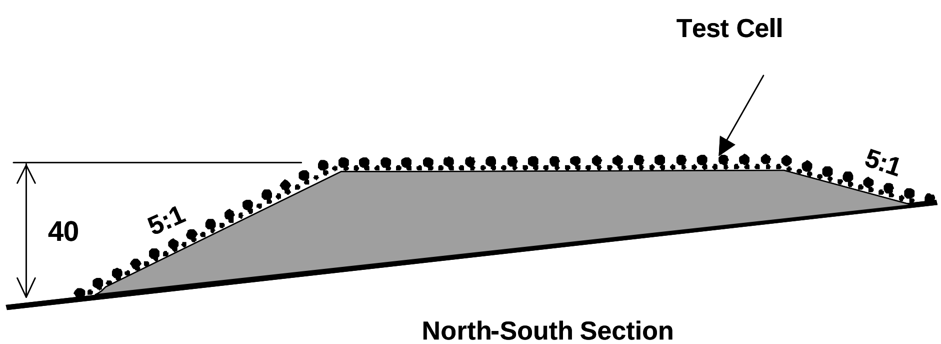


Figure 6-4. Cross section of ultimate stack

Figure 6-5. Tailings being spread and compacted on stack

6.3 Climate and Permafrost

Raglan is located in continuous permafrost above the tree line. During the design of the cover there was limited long-term or recent air temperature records available. Considerable reliance was placed on adjacent sites for long-term averages and trends. The closest site, Asbestos Hill, had records for only 3 years during the 1960's. Other sites that have long-term records, such as Iqaluit, Cape Hope Advance and Kuujjuak are all coastal communities that normally have warmer air temperatures. A climate station was established at the Donaldson airport, located about 20 km east of Raglan. However, at the time of the thermal analyses to assess permafrost development in the proposed tailings stack, it had only one-year, 1998/99 of data.

Analyses of all available temperature data by Nixon (2000) resulted in the mean annual air temperature (MAAT) being estimated to be -8.8ºC. This MAAT was considered to be appropriate for a reactive tailings storage based on permafrost encapsulation. The mean monthly air temperatures and precipitation are given in Table 6-1.

Table 6-1. Mean monthly climatic data assumed for Raglan site.

(Nixon 2000 and Roche 1994)

Month	Temperature ºC (Nixon)	Total Precipitation mm	Precipitation As snow, mm Water equivalent	Temperature ºC (Roche)
January	-28	12.6	12.6	-27.6
February	-25	10.1	10.1	-30.0
March	-22	12.4	12.4	-24.7
April	-13	19.2	16.6	-16.3
May	-4	23.2	13.7	-7.0
June	3	36.1	4.3	2.4
July	9	55.1	0.7	8.0
August	8	62.4	0.0	7.0
September	3	64.6	6.4	0
October	-6	52.4	26.5	-7.0
November	-12	44.9	44.9	-16.0
December	-18	25.2	25.8	-24.8
Mean or total	-8.8	418.2	174.0	-11.2

Two other temperature studies, conducted by Roche in 1992 and 1994 (Roche 1994) for the design of the Raglan fresh water reservoir (Katinniapik Reservoir), estimated colder air temperatures. In the 1992 “Base Line Study” Roche recommended to use the Iqaluit mean annual air temperature of minus 1ºC, which suggests a MAAT of -10.5ºC for Raglan. In the final design of the Katinniapik dam, it was found that the -10.5ºC did not correspond to the mean annual ground temperatures (MAGT) of -6.5ºC measured in the abutments of the dam. Through subsequent thermal calibration, a new monthly temperature distribution was obtained (Table 6-1). This new distribution provided a MAAT of -11.2ºC. This is in better agreement with the relationship between MAGT and MAAT published by Smith and Burgess (2000). The Raglan case history provides an example of the difficulties associated in establishing design climatic conditions for a site in the remote Arctic regions.

The design of the composition and thickness of the cover for the Raglan tailings is based on a mean annual air temperature of -8.8ºC, a thawing index of 707 degree-days and the probability of an extreme warm year occurrence being one in 100 years (AMEC 2002). Prediction of the thaw depth was based on the thawing index. The thawing index for the extreme warm year was obtained by increasing the mean thawing index by a factor of 1.38, resulting in a value of 976 degree-days. The 1.38 factor was obtained from a frequency analysis of thawing indices from adjacent climatic stations.

Difficulty in selecting design air temperatures and thawing indices due to annual changes is illustrated by the mean annual air temperatures records and the thawing indices from Cape Dorset, located on the coast about 250 km north of Raglan. This information is plotted on Figure 6-6.

The MAAT and thawing index at Cape Dorset show a significant fluctuation of values in the 20 years of records and a rise in trend lines for both the MAAT and thawing index. These values varied between -7 and -13ºC and about 400 and 680 degree-days respectively. These variations and rise in the values illustrate the difficulty in selecting the design criteria for the long-term and extreme climatic conditions.

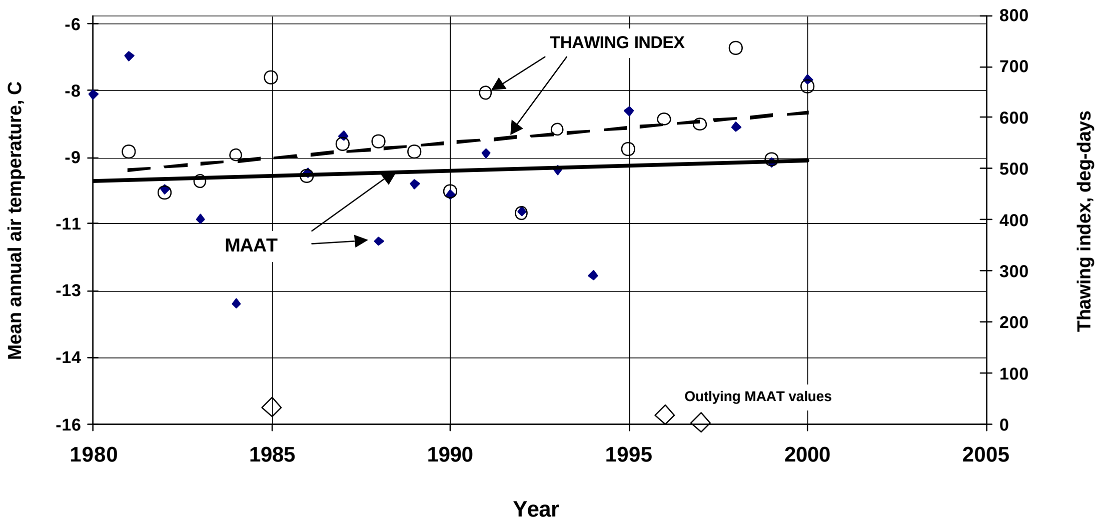


Figure 6-6. MAAT and thawing index for Cape Dorset (1980 - 2000)

6.4 Design of Tailings Cover

6.4.1 General

The proposed reclamation of the tailings stack is to encapsulate the tailings in permafrost by covering the tailings with a cover thick enough to contain the active layer within the cover (AMEC 2002). Two main construction materials to be used for this cover are:

- Crushed esker (primary insulation layer); and
- Rockfill (erosion protection/insulation layer).

It was determined that the crushed esker material should be a silty-gravelly sand containing a minimum 10 percent of fines (passing #200 sieve). The purpose of the fines is to hold moisture that increases its latent heat and retards the thawing process. The maximum size for the rockfill was selected to prevent water erosion under a probable maximum precipitation (PMP) event. The gradation limits for these two materials are show on Figure 6-7. The rockfill was selected to mimic the natural landform and to integrate with the surroundings.

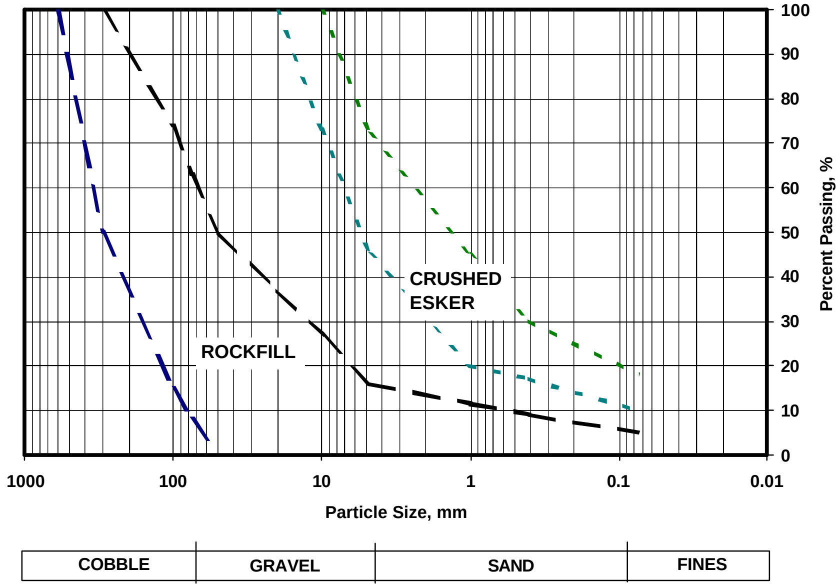


Figure 6-7. Gradation limits for crushed esker and rockfill

The selection of the optimum thickness of the proposed two-layer cover was based on the results of two thermal analyses. Nixon's thermal analyses (2000) assumed two moisture levels for the transition layer (esker layer) and concluded that a two-layer cover with a moisture content of 6% in the esker would produce a thaw depth of 2.2m. The thaw depth would be reduced to 1.7m if the moisture content in the esker could be increased to 12%. An updated thermal analyses conducted by AMEC (2002) was used to select the proposed cover design of 1.2m of crushed esker overlain by 1.2m rockfill for a total cover thickness of 2.4m. This is discussed in the following section.

6.4.2 Thermal analysis

Parametric thermal analyses were conducted to evaluate the maximum thaw for different combinations of layer thicknesses to derive the optimum design. It was assumed that the tailings have a freezing point depression of -0.5ºC. The analyses were conducted with a temperature distribution represented by a) mean annual air temperature and b) 1:100 warm year event. The boundary temperatures for the 1:100 warm year event were obtained by increasing the mean monthly temperatures during the months with above zero temperatures by a factor of 1.38 (Nixon 2000). Thermal modelling was carried out by AMEC using a 1D version of AMEC's geothermal simulator SIMTEMP (AMEC 2002).

The physical and thermal properties of materials used in the analyses are given in Table 6-2 and the results in terms of thaw depth in Table 6-3.

Table 6-2. Physical and thermal properties of materials

Material	Dry Density	Moisture Content	Latent Heat	Freezing Point	Thermal Conductivity, W/m/h		Heat Capacity MJ/m³	
	Kg/m³	%	MJ/m³	ºC	Frozen	Unfrozen	Frozen	Unfrozen
Rockfill	1700	2	6.03	0	2.50	2.00	1.88	2.03
Esker	2200	7	36.84	0	3.43	2.99	2.26	2.68
Tailings	1700	18	91.11	-0.5	1.47	1.43	2.14	2.80
Bedrock	2650	0.5	4.19	0	3.49	3.49	1.88	1.88

Table 6-3. Depths of thaw from geothermal analyses
(Based on -0.5ºC freezing point depression for tailings)

Case	Layer Thickness, m		Total	Maximum Thaw, m	
	Esker	Rockfill	Cover, m	Avg. year	1:100 year
S-1	0.3	1.0	1.3	1.65	1.93
S-2	0.6	1.0	1.6	1.79	2.01
S-3	0.9	1.0	1.9	1.95	2.13
S-4	0.9	1.5	2.4	2.20	2.39
S-5	1.2	1.0	2.2	2.05	2.29
S-6	1.5	1.0	2.5	2.17	2.40
S-7	1.2	1.5	2.7	2.32	2.55
S-8	1.5	1.5	3.0	2.40	2.70

AMEC thermal analyses demonstrated that the proposed cover design with a total thickness of 2.4m would meet the design requirements of keeping the thaw within the cover even during a 1:100 warm year event.

6.5 Tailings Stack and Test Pad

As stated earlier, the tailings stack consists of ‘dry’ tailings that are spread and compacted on a mound located east of the process plant. The final perimeter of the tailings storage area (stack) will be about 1,000m by 700m with a maximum height of about 40m on the southwestern edge. The stack will have side slopes of 5 horizontal to 1 vertical that will be protected against erosion by a cover. The top of the stack will be sloped at about 3 percent to allow runoff (Figure 6-3).

The proposed cover design is as follows:

- 1.2m thick crushed minus 20mm esker material and/or thermally equivalent screened lodgement till, placed in 0.4m lifts and compacted with a minimum 4 passes of a 10-tonne vibratory roller.
- 1.2m thick minus 600mm sound rockfill (not acid generating), such as the local gabbro or from "harvesting" the local ablation till. The rockfill will be placed in 0.6m lifts and compacted by 6 passes of a 10-tonne vibratory roller.

The cover will be constructed on top of a minimum 3m thick layer of fresh tailings that will be compacted to a minimum 95% standard Proctor maximum dry density. The fresh tailings layer would be placed and the cover constructed during the winter to prevent any oxidation before cover placement. A cross section of the tailings stack with the cover is illustrated in Figure 6-8.

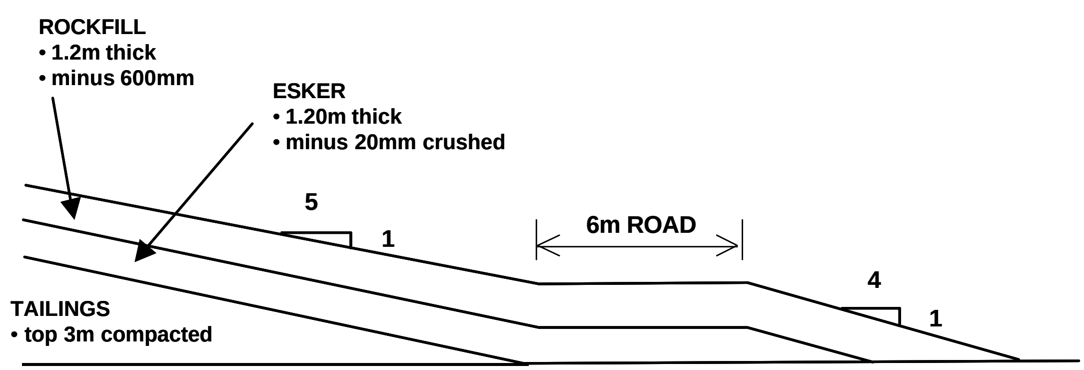


Figure 6-8. Tailings stack slope with cover

Tailings disposal started in 1997 at the east boundary of the tailings disposal area (Figure 6-3). To confirm, and if necessary optimize, the cover design, a test pad (cell) measuring approximately 40m by 40m was constructed on a completed northeast corner of the stack in October and November 2001. The test pad was instrumented with two (2) multi-bead thermistor cables at about the centre (T3 and T4) and four single bead thermistors in the four corners. The beads of the latter thermistors are located in the upper, middle and lower zones of the cover and one within the tailings. The multi-bead thermistor cables T3 and T4 extended to a depth of about 5.5m. The location of the test pad and the thermistors are shown on Figure 6-9. In addition to these thermistors, single point thermistors were installed in the pad (T5 to T8). Two reference thermistors, T1148 measuring the ground temperature changes within the natural ground and BH1 showing the ground temperatures changes of natural ground covered with a granular road fill, provide the reference ground temperatures for the tailings mound. These are also shown in Figure 6-9.

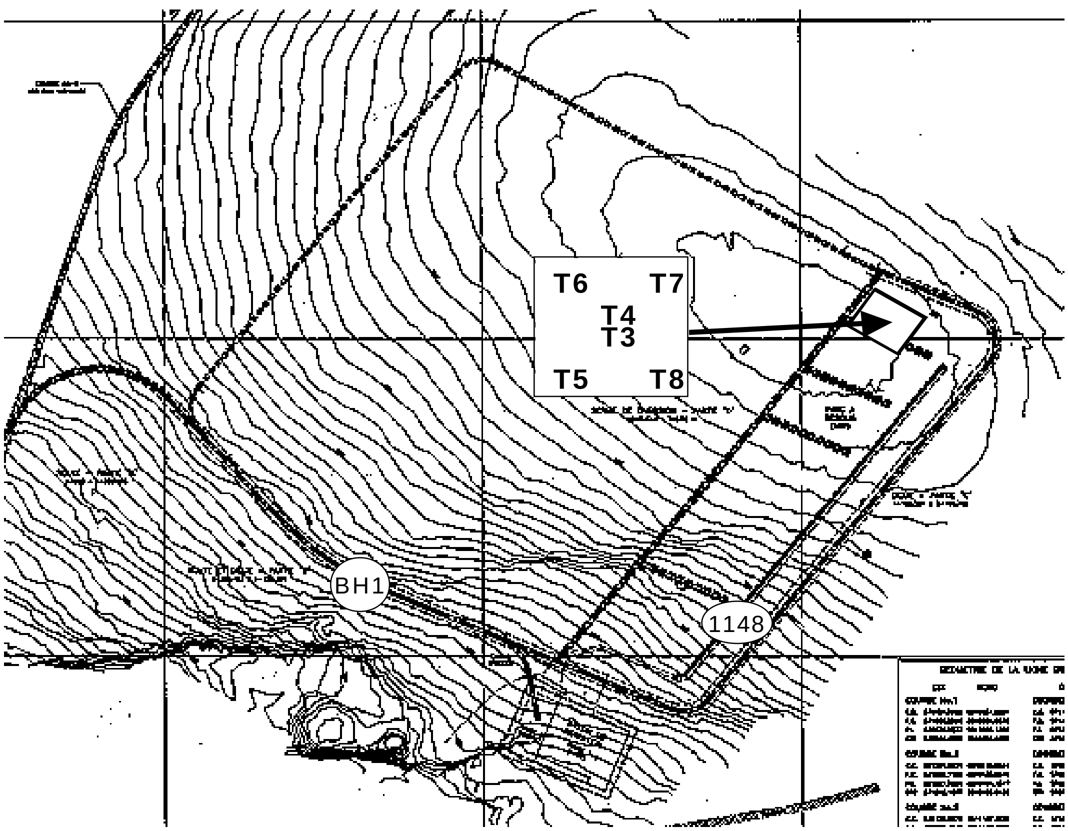


Figure 6-9. Test pad and instrumentation location

6.6 Test Pad Performance

Performance monitoring of the test pad has been ongoing since the winter of 2001/2002. Monitoring consists of weekly temperature readings during the warmer part of the year and less frequent readings during the winter when the cover and underlying tailings are completely frozen and when the near surface temperatures are very cold. The fluctuations of the temperatures within the cover and the underlying tailings are illustrated using the results from thermistor string T3 readings from winter 2002 in Figure 6-10. The progress of the thaw zone through the summer is illustrated in Figure 6-11. It shows that the pad surface starts to thaw in early June. The active layer progresses deeper during June and July, reaching its maximum depth in about September. The freezing starts from both the surface and the base of the active layer during October.

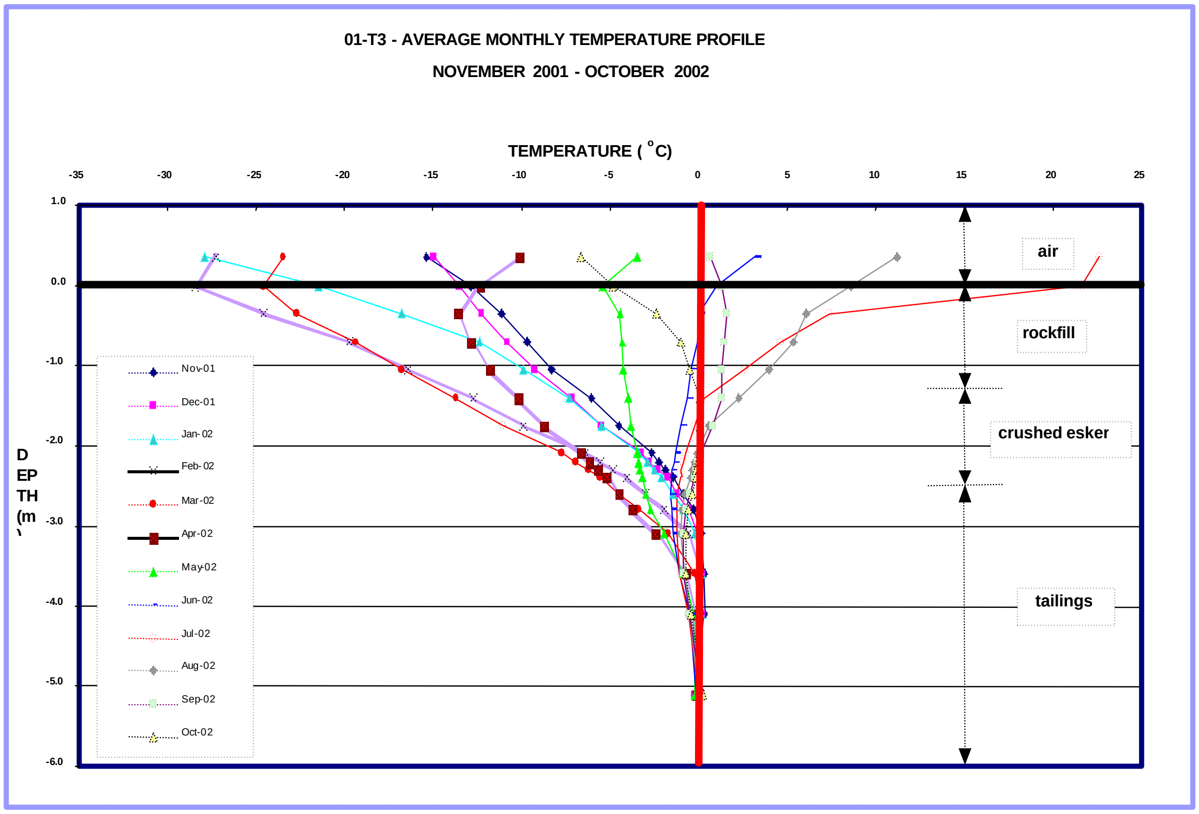


Figure 6-10. Ground temperature fluctuation in test pad, measured by T3

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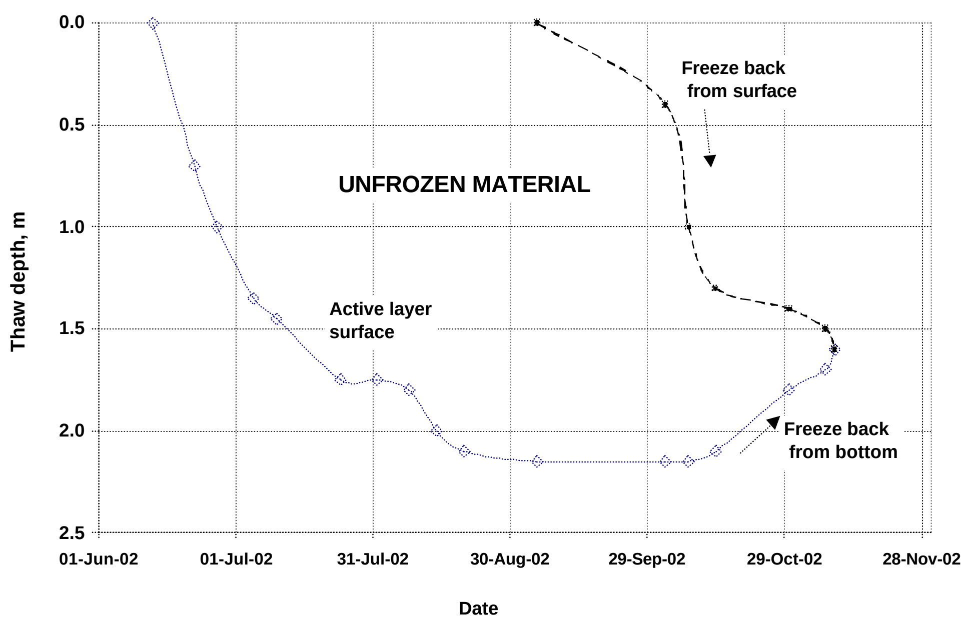

Figure 6-11. Advancement and regression of thaw zone, from T3 year 2002

Figure 6-12 presents the continuous temperature changes within the test pad as measured in the centre of the test pad. This plot shows that during the summer of 2002 the temperature in the tailings 2.6m and 2.8m below the surface just reached or was slightly higher than the freezing point based on a 0.5ºC freezing point depression. The temperature at the base of the esker at 2.4m and within the esker at a depth of 2.3m reached a high of about -0.2ºC. This means that for about 3 months in 2002, the very surface zone of the tailings was not frozen based on the minus 0.5ºC freezing point depression.

The maximum thaw depths for years 2002 and 2003 estimated from thermistor cables T3 and T4 readings using the zero degree temperature criterion for the esker layer are given in Table 6-4. Thawing index for these two years is also given in this table.

Table 6-4. Depth of thaw in test pad

Year	T3 m	T4 m	Avg. m	Thawing index, Degree-days
2002	2.10	1.78	1.94	509
2003	1.90	1.90	1.90	565

The above thaw depths show that the active layer remained within the esker material and the tailings surface was covered by more than 0.4m of frozen esker during these two years. Furthermore, the data shows that the depth of thaw has decreased slightly from 2002 to 2003 even though 2003 appears to have been a warmer summer based on the thawing index. It is believed that, even though the thawing index increased, the active layer decreased because runoff water infiltrated the cover and changed the cover's thermal properties sufficiently to decrease the thaw depth in spite of the warmer summer.

The thaw depth in Table 6-4 is based on a zero degree representing the freezing point. If the thaw depth is interpreted on a minus 0.5ºC freezing depression in the tailings, the thaw front has penetrated the tailings based on thaw depths shown in Table 6-5

It is anticipated that the thaw depth, or active layer, will decrease further over the years assuming normal summer temperatures with a similar thawing index. This decrease should continue with time due to additional snow runoff and rain infiltration. The majority of the infiltrated water should stay within the cover because it cannot drain downwards into the tailings since they are frozen, and the lateral drainage is very slow because of the small gradient and the high fines content in the crushed esker layer. It is likely that, in time, a saturated/frozen zone will develop at the base of the cover.

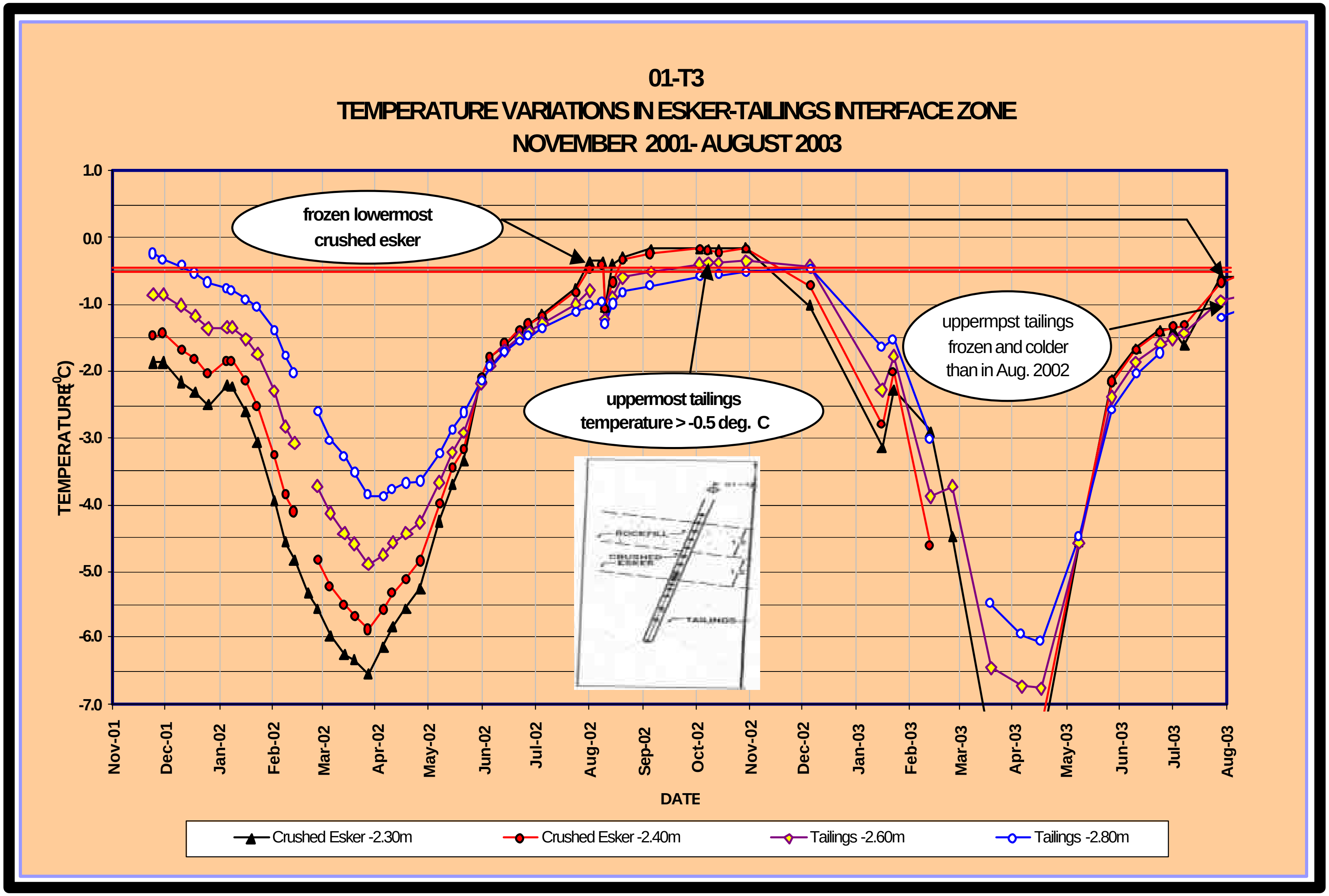

Figure 6-12. Raglan cover design field verification

Table 6-5. Thaw depth based on minus 0.5ºC isotherm in test pad

Year	T3 m	T4 m	Avg. m	Thawing index, Degree-days
2002	2.80	2.70	2.75	509
2003	2.50	2.60	2.55	565

If the thaw depth is interpreted from the single bead thermistors T5, T6, T7 and T8, smaller values for thaw depths are obtained (T5 at 1.30m, T6 at 1.80m, T7 at 2.3m and T8 at 2.50m). Table 6-6 shows the average thaw depths for the four thermistors based on 0ºC and -0.5ºC freezing points

Table 6-6. Average thaw depth interpreted from single thermistors T5 to T8

Year	T5 to T8, m 0ºC Freezing point	T5 to T8, m -0.5ºC Freezing point	Thawing index, Degree-days
2002	2.20	2.30	509
2003	1.60	2.10	565

Different active layer depths may be measured at one site because of the many other variables, such as; vegetation cover, moisture content, surface orientation and colour. This is illustrated from other thermistor cables around the stack in natural ground (thermistor 1148) and in the granular road pad (BH1). These thermistor readings showed the thaw depth in the natural ground with some minor organic layer and likely higher saturation to be 1.2m while the thermistor through the granular relatively 'dry' road pad had a thaw depth of about 2.5m. The measured or estimated thaw depths discussed herein and the thaw depth versus cover thickness obtained from the thermal analyses (zero temperature freezing point) are summarized in Figure 6-13.

6.7 Climate

Raglan site had limited and short term air temperature records at the time of this report preparation. To analyze the thaw depth measurements at Raglan temperature data was related to longer established meteorological stations, namely Iqaluit and Cape Dorset. In addition, since the air temperatures were missing for some of the months at Raglan, the

MAAT and thawing index were estimated by using the average temperatures from the previous 2000 to 2002 years.

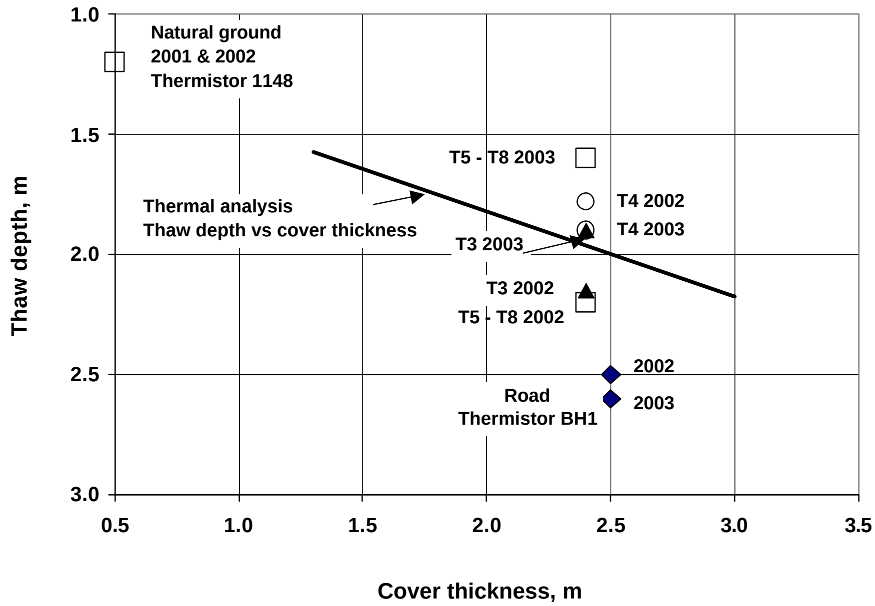

Figure 6-13. Simplified thaw depth versus cover thickness observed at Raglan

Available MAAT for Iqaluit, Cape Dorset and Raglan from 2000 to 2003 are shown in Table 6-7.

Table 6-7. MAAT for Iqaluit, Cape Dorset & Raglan from 2000 to 2003, ºC

Location	2000	2001	2002	2003	Avg.
Iqaluit	-8.3	-8.0	-9.3	-7.8[a]	-8.4
Cape Dorset	-7.8	-7.4	-8.1	-7.7[a]	-7.7
Raglan	-9.4	-	-11.5	-10.0[a]	-10.3

Note (a) Estimate values by using the average temperatures of previous years for the last two or three months of 2003.

Table 6-7 shows that the MAAT at Raglan has varied by 2.1ºC over the last three years for which records are available and that Raglan is about 1.9ºC and 2.6ºC colder than at Iqaluit and Cape Dorset respectively. Colder MAAT is anticipated because Raglan is inland, not warmed by coastal conditions, and is at a higher elevation.

The important climatic parameter to assess the annual thickness of the active layer is the thawing index. Thaw indices for the three locations were calculated from the mean monthly temperatures above zero and the number of days in the respective months. For the years 2001 to 2003, only the mean monthly temperatures were available for Iqaluit and Cape Dorset. The results are given in Table 6-8.

Table 6-8. Thaw indices for Iqaluit, Cape Dorset and Raglan from 2000 to 2003. Degree-days.

Location	2000	2001	2002	2003	Avg.
Iqaluit	714	725	715	764	729
Cape Dorset	648	665	685	634	658
Raglan	527	-	509	565	534

Thaw indices shown in Table 6-8 again demonstrate that Raglan has the coolest summers of the three locations. 2003 was the warmest summer for Iqaluit and Raglan in the four years in which records for Raglan are available. It is expected that the greatest depth of thaw should have occurred during the summer of 2003.

7.0 LUPIN MINE

7.1 Background

Lupin Mine is located on the west shore of Contwoyto Lake, approximately 285 km southeast of Kugluktuk, Nunavut and approximately 400 km northeast of Yellowknife, N.W.T. It is about 80 km south of the Arctic Circle at 65°46'N latitude and 111°14'W longitude. Echo Bay Mines Ltd. developed the gold property by underground mining. The mine opened in 1982 with a design production rate of 950 tons per day was increased to 2,300 tons per day in 1993. It suspended operation for two years in 1998, and again in September 2003 and restarted its operation in early 2004. The ore contains minor quantities of pyrite or traces of chalcopyrite minerals that resulted in some tailings oxidation and metal leaching (Echo Bay Mines 2001).

Lupin started its operation by depositing the tailings in a large surface containment area developed about 5 km south of the plant. A paste backfill plant was constructed in December 1994 to pump some of the tailings underground and provide additional safety for underground mining. This also reduced the volume of tailings deposited on the surface (Echo Bay Mines 2001a).

Lupin is located north of the tree line in an area with a rolling topography in continuous permafrost. It has tundra vegetation consisting of grass, sedges, moss, etc. The tailings area was located in an area with numerous shallow lakes whose drainage is sometimes difficult to define. An aerial view of the tailings area during its early years of operation is shown on Figure 7-1.

Figure 7-1. Aerial view of Lupin's tailings area on startup 1982

The MAAT temperature at Lupin obtained from the Canadian Climate Normals (Environment Canada 1982) for the period of 1951-1980 is -12.0ºC. Since that time the MAAT has been warming as can be seen by MAAT values from 1980 to 2002 shown in Figure 7-2.

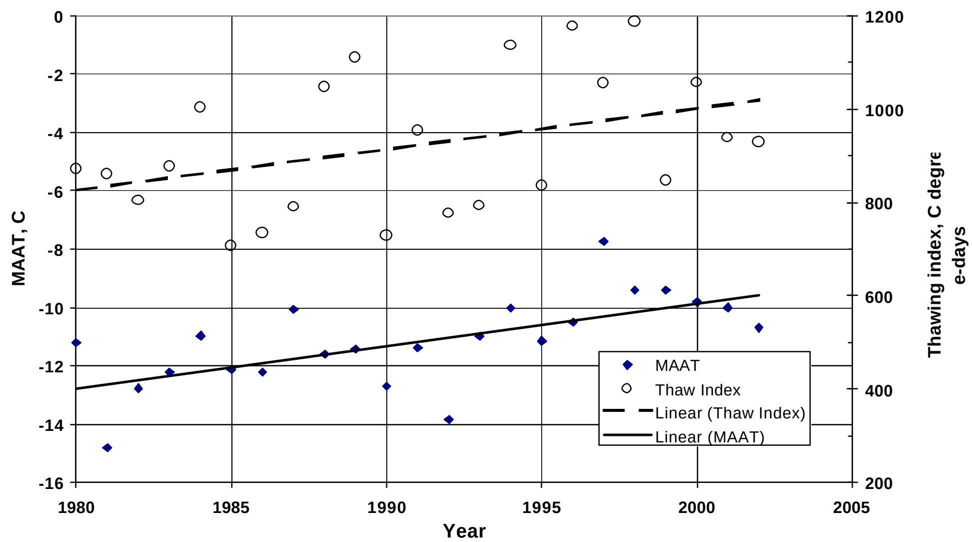

Figure 7-2. MAAT and thawing index for Lupin, 1980 to 2002

Based on the trend line of Climate Normals (Figure 7-2), the MAAT at Lupin has increased from about -13ºC in 1980 to -10ºC in 2000. A similar increase was observed for the thawing index. These data illustrates a warming trend and a large variation of these two parameters from year to year at the Lupin site.

7.2 General Description

Lupin is located in a rolling topography with a small relief containing numerous small lakes. The most advantageous site for the tailings disposal was a watershed with an area of 614 ha that contained 15 small lakes. It was decided to store the tailings and all water within this Tailings Containment Area (TCA) for the initial years of operation until the water quality could be determined and its treatment by either plant process adjustments or treatment at the TCA could be decided upon. The small relief of the site resulted in the need to construct numerous small dams with one dam placed across the original watershed discharge stream and the remaining dams placed across small drainage divides to contain the water/tailings from impacting adjacent watersheds as the tailings area filled.

The TCA was created in 1981 by the construction of four small dams (Dams 1a, 2, 3 and 4) and two divider dykes (Dams 1b and 1c). Dam 1a was constructed across the original discharge stream (Geocon 1980, Holubec et al 1986). Photograph in (Figure 7-1) shows the TCA in 1982 before the construction of Dams 3 and 4.

The TCA was operated as one large containment water area until 1985. Increased production of ore and deteriorating water quality within the pond led to the adoption of a tailings management strategy to deposit the tailings within cells created in the TCA (Wilson 1989). Excess water from these cells is directed into two ponds within the TCA to improve the water quality before the water is discharged (Figure 7-3). Since 1985, water was discharged from the downstream polishing Pond 2 to control the water level within the ponds.

The TCA consists of 5 cells where tailings have been, or are proposed to be, deposited. During start-up, tailings were initially discharged into an area identified as Cell 5. The tailings deposition strategy of using cells started in 1985 with the construction of J Dam and several internal dykes to create Cells 1a and 1. After 1985 the tailings were deposited in Cells 1a and 1 that were filled to capacity and covered in 1988 and 1995 respectively.

Since about 1990, tailings were discharged into Cell 3 for 10 months of the year and Cell 2 for the two summer months. In the last few years Cell 5 was partitioned with the construction of internal dams to allow the old tailings to be covered. During 2003, the tailings were discharged into Cells 2, 3 and 5. Some tailings that were discharged in the early 1990's into the area represented by Cell 4 are covered with water.

Water collected within the TCA is derived from excess tailings slurry water that is not contained within the settled tailings pores, and precipitation. Water from Cells 3 and 4 decants naturally into Pond 1 while water from Cell 5 is pumped into Cell 4. Water from these cells is stored in Pond 1 for a period of 11 months to allow water quality to improve; which was mainly cyanide destruction by natural degradation. At the end of summer, water is siphoned out of Pond 1 into Pond 2 for a further eleven months of natural treatment before this water is siphoned over Dam 1a and released to the outside environment.

7.3 Reclamation of TCA

Progressive reclamation was started in 1995 with the placement of an esker sand cover over the tailings. Cell 1a and 1 were completely covered and the cover for cells 2 and 3 was started. The tailings deposition arrangement, superimposed on an aerial photo of the TCA, is shown on Figure 7-3.

In 2002 Echo Bay Mines Ltd. proposed a partially saturated esker cover (saturated zone cover) as a closure plan for the reactive tailings at Lupin (Holubec 2002, Holubec and

Hohnstein 2003). This design evolved from a concept proposed by Holubec (MEND 6.1) and after extensive monitoring of ground temperatures within the existing covered cells (Geocon 1990, Klohn-Crippen 1997, BGC 2000 and Lupin 2002).

Figure 7-3. Tailings containment area in 2001

7.4 Covered Cells 1a and 1.

Cells 1a and 1 were covered with a sandy material in 1988 and 1995. This material was obtained from a large esker deposit, Fingers Lake Esker, which is located about 5 km south of the TCA. The cover thickness varies from about 0.6 to 1.5 m. In 1988 Lupin started a monitoring program to increase their understanding of: a) development of permafrost within the covered tailings; b) effect of cover thickness on the active layer, and c) water quality within the cover system and ponded water within the cell.

Since 1988, five monitoring programs were instituted on the covered cells to confirm the final cover design. The instrumentation used to monitor the cells consisted of the following:

a) Three thermistors installed in Cell 1a in 1988.
b) After the main Cell 1 was covered during the winter of 1995, three thermistor strings were installed in Cells 1a and 1 in the summer of 1995.
c) In 1998 two water-sampling pipes were installed within the esker material in Cell 1 to monitor the water quality within the pores. Water quality has been monitored annually in these pipes since.
d) In the summer of 2002 nine additional pipes were installed in the esker cover material in Cell 1 to monitor the water level and water quality within esker cover of Cell 1.
e) At the end of spring 2003, one test pad was constructed in existing Cell 1 to monitor the water balance within the esker cover under more controlled conditions.

7.5 Saturated Zone Cover – Lupin Mine

The saturated zone cover concept consists of two layers; a) a surface layer that lowers the rate of evaporation of the saturated base esker material, and b) a lower saturated layer that prevents oxidation of the tailings. It is based on a *stagnant water cover* design concept investigated by Li et al (1997) and column testing by CANMET (MEND 2.12.1e) that demonstrated that in absence of water movement, even a small depth of water greatly inhibits oxidation. CANMET column testing demonstrated that 300mm is sufficient to provide an oxygen barrier.

It should be noted that 300mm of saturated sand or gravel provides a greater barrier than 300mm of water because the cross section of the esker saturated zone is occupied by both water and solid particles that are practically impermeable. In a typical granular, the water in the pores of the saturated material would represent only about 35 percent of the volume while the solids would occupy the remaining 65 percent of the volume.

The thickness of the saturation surface within the cover will fluctuate during the summer when the top of cover is thawed. The top of the saturation zone may vary between the cover surface to a depth governed by evaporation. It is assumed that the rate of evaporation of the pore water will decrease with the depth of the water level within a sand and gravel cover and thereby the drop in the water level, due to evaporation, will be smaller than in water alone.

Lupin has an annual open water evaporation of about 300mm. Therefore, assuming that at the start of the thaw season the cover is completely saturated and a 300mm of permanently saturated zone is desired, a theoretical sand gravel thickness of 600mm would be required to provide for evaporation and maintain a 300mm saturation zone at the cover base. This is based on the assumption that annual precipitation will raise the water level within the cover to its surface.

7.6 Lupin Monitoring Experience

7.6.1 Cell 1a cover

Three thermistor strings were installed in Cell 1a in 1988 to determine how rapidly permafrost developed within the tailings, and the thickness of the active layer. Cell 1a is a small 1ha cell that was developed against Dam 3 (Figure 7-4). It was filled and covered early to provide a buffer between the TCA and adjacent Boomerang Lake. Being adjacent to the TCA watershed divide, the tailings depth is relatively shallow, averaging about 3m. The tailings were covered with about 0.6m of sand esker material in 1988. An additional 0.5m of esker material was added in 1995 to bring the total cover thickness to 1.1m.

Three thermistor strings were installed within Cell 1a as shown on Figure 7-4. Monitoring of the temperatures showed that the tailings completely froze during the first winter after the cover was placed in 1988 with the ground temperatures at a depth of 5m being -5.2ºC in September 1989.

7.6.2 Cell 1 cover

In October 1995 six thermistor strings were installed in Cells 1 and 2 to monitor the seasonal fluctuation of the active layer in areas where the tailings were covered with esker sand (Klohn-Crippen 1997). The location of these strings is shown on Figure 7-5. The operational life of these thermistors varied from 1 to 5 ½ years, with one still in operation. Thermistor identification, location, and the last monthly reading, are given in Table 7-1. All thermistor strings were installed to a depth of 13m.

Table 7-1. 1995 Thermistor string installation summary

Thermistor	Location	Cover Thickness, m	Tailings Thickness, m	Stopped Operating
TC1-1	Cell 1a	0.9	+13	Oct 2000
TC1-2	Cell 1a	1.2	+13	Dec 1997
TC1-3	Cell 1	1.2	4.6	Operating
TC1-4	Cell 1	0.6	10.6	Dec 1999
TC1-5	Cell 1	1.6	11.7	Dec 1997
TC2-1	Cell 2	0.9	5.3	Dec 1999

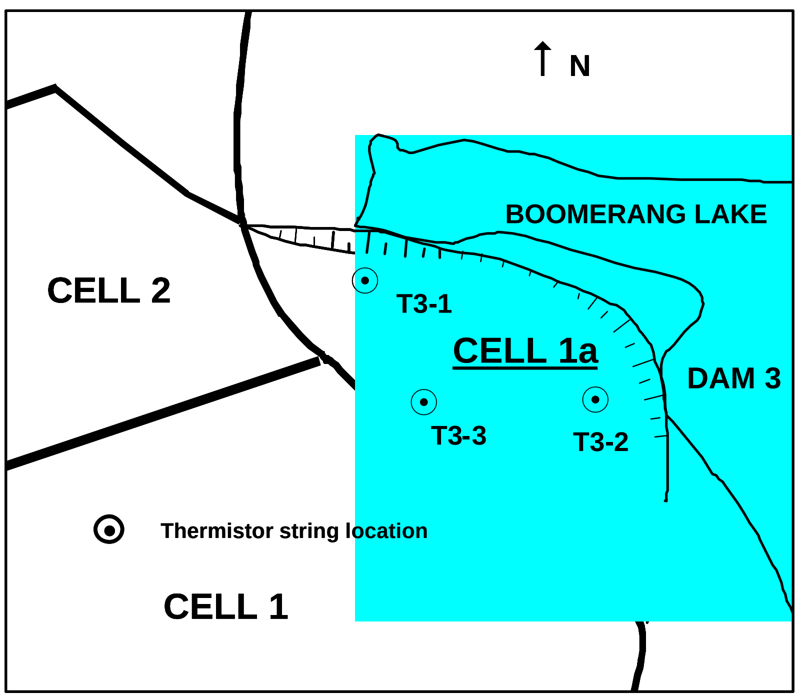

Figure 7-4. Thermistor installation in Cell 1a

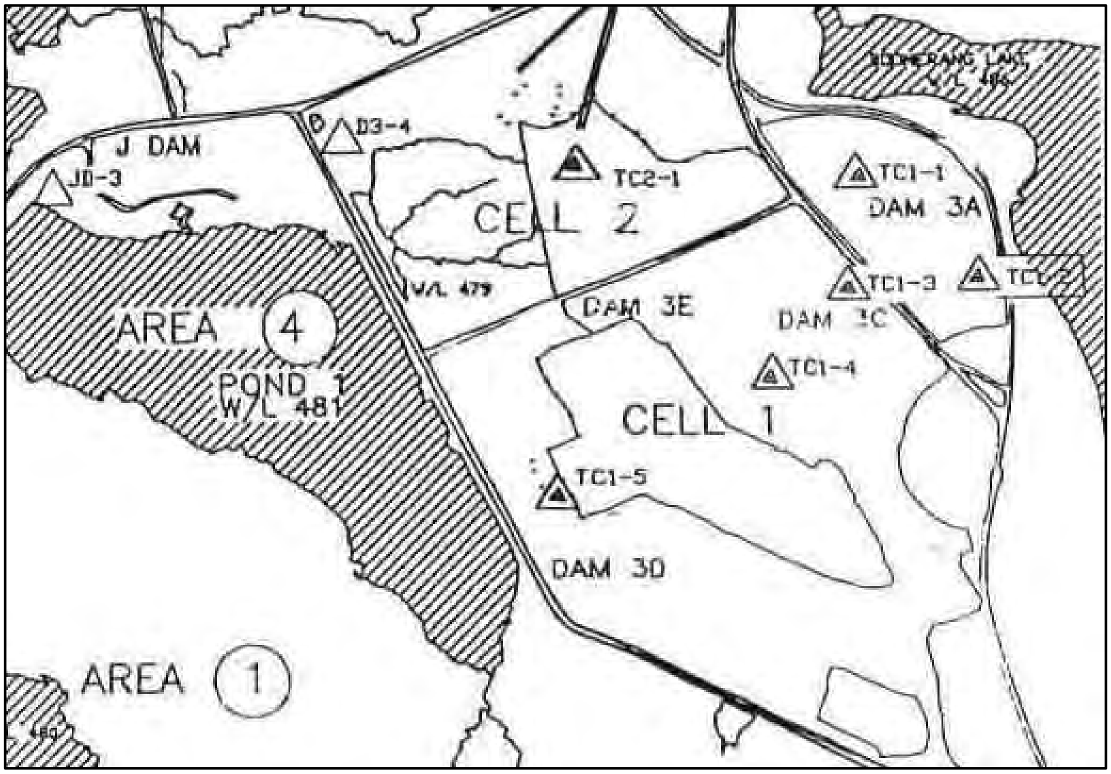

Figure 7-5. 1995 Thermistor installation in Cells 1a and 1

The maximum thickness of the active layer and the 'steady' ground temperature observed in 1996 are summarized in Table 7-2. It should be noted that the location of the groundwater surface at these locations is not known.

Table 7-2. Permafrost performance at 6 locations observed in 1996

Thermistor	Cover Thickness, m	Active layer Thickness, m	Temperature at 13 m, ºC
TC1-1	0.9	1.5	-5
TC1-2	1.2	1.7	-6
TC1-3	0.6	1.2	-7
TC1-4	0.6	1.7	-3
TC1-5	1.6	1.8	-4.5
TC2-1	0.9	1.8	-6

Relating the active layer (thaw depth) to the thickness of esker cover in Figure 7-6 shows that by increasing the cover thickness, the active layer or depth thaw becomes greater.

In the absence of knowing the groundwater depth at each of these thermistors, water content of the saturated zone and the moisture content of the surface unsaturated zone, it is difficult to make definite comments on the Figure 7-6 relationship. Generalized conclusions that can be made are from the observations that: 1) the groundwater surface was at or is near the bottom of the esker cover and 2) tailings beneath the cover are completely or nearly fully saturated. Based on these assumptions, the relationship in Figure 7-6 indicates the following for the Lupin site:

a) Saturated tailings without a cover would experience a thaw depth of 1.3m.
b) To encapsulate the tailings completely with sand and gravel would require a minimum 2m cover plus additional thickness for warm years and other uncertainties.

It should be noted that a higher water table observed at the covered cells impacted the thickness of the cover.

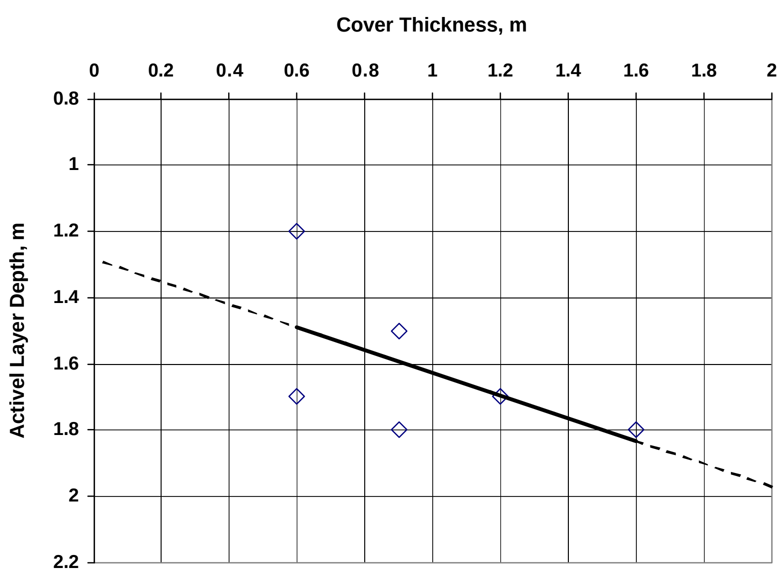

Figure 7-6. Thaw depth related to Lupin esker cover thickness

The progression of the active layer in and out of the cover and its changes over the years can be seen in the data of thermistor string TC1-3 which has operated for 7 years. The thaw depth progression for each of the 7 years is shown on Figure 7-7. At this location the thaw depth varied from 1.15 to 1.35 m during the 7 years of monitoring. The cover at this location is 1.2m.

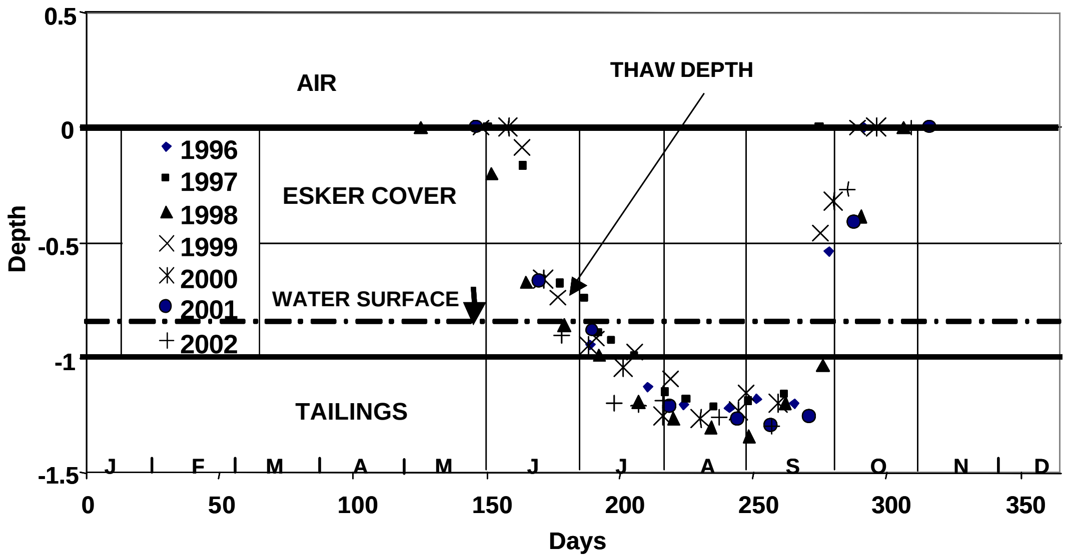

Figure 7-7. Thaw depth changes in esker covered tailings over a 7 year period, TC1-3

Figure 7-7 also illustrates that: a) thaw depth penetrated into the tailings by about 0.4m, b) unfrozen conditions lasted for less than 3 months and c) during this period the temperature within the thawed tailings reached a maximum of 5ºC. This temperature was interpreted from individual thermistor bead locations and likely due to the variation of snow cover.

The thaw depth for the seven years (1996 to 2002) was plotted against the thawing index at Lupin for the same years respectively (Figure 7-8). This shows a good relationship between thaw depth and thawing index. The fluctuation of the data near the trend line can likely be attributed to the changes observed for the saturation of the esker material.

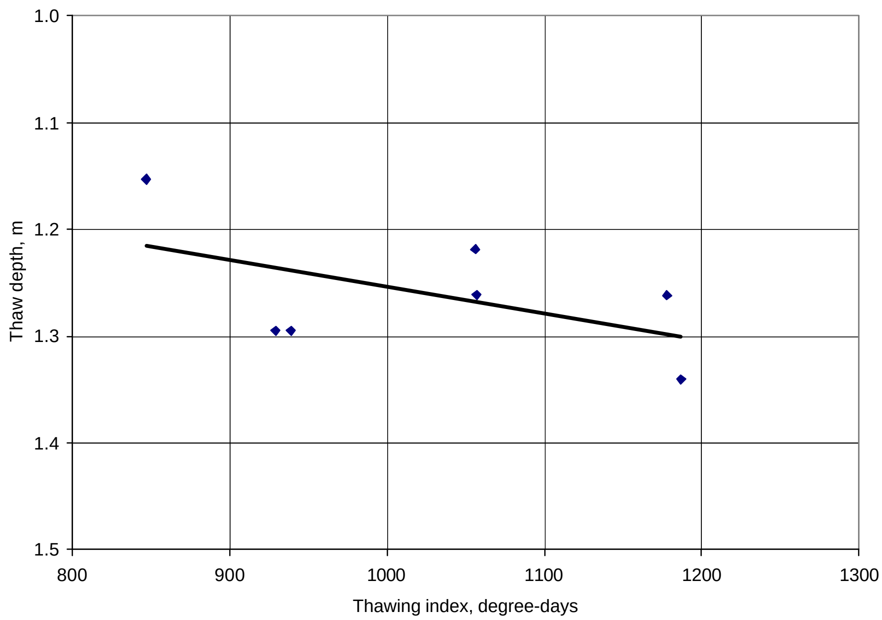

Figure 7-8. Thaw depth as a function of thawing index

Monitoring of the esker covered tailings in Cell 1a and Cell 1 shows the following:

- Thickness of the esker varied from 0.6 to 1.6m.
- Active layer (thaw) depth varied from 1.2 to 1.8 m.
- Thaw depth was greatly influenced by the thickness of the saturated zone within the esker material.
- Good correlation between thaw depth and the thawing index.
- Thaw depth will fluctuate because of the variation of summer temperatures (thawing index) from year to year.
- Below the active layer, the tailings were completely frozen with ground temperatures ranging from -3ºC to -7ºC at a depth of about 13m.

7.7 Cell Groundwater Monitoring (1998).

In 1998 water-monitoring pipes were installed at three existing thermistor string locations to measure the water level in the esker cover. Their purpose was to evaluate the water quality within the esker cover material. These wells were installed at thermistor locations TC1-1 (Cell 1a), TC1-5 (Cell 1) and TC2-1 (Cell 2) as shown on Figure 7-5. The results of the annual water quality are discussed in Section 7.8.

7.8 2002 Site Assessment of Covered Cells

A visit by Holubec to the covered Cell 1 in June and August 2002 and a review of the monitoring data, supported the saturated zone cover concept proposed by Holubec in 1993 (MEND 6.1). In addition, it demonstrated that to propagate vegetation on the cover, it is necessary to have the groundwater level near the ground surface. This observation was made earlier during a review of the effect of drill and road pads on permafrost in the Alaska National Petroleum Reserve (Holubec 1994). These studies found that the areas with thinner pads retain sufficient moisture to enable grasses to establish and as a result the pads blend in more quickly with the surrounding landscape. Oil exploration companies adopted a practice of using thin (0.5m thick) gravel pads for winter exploration to minimize impact on the ground and foster quicker re-vegetation (Brewer 1983).

Inspection of Cell 1 showed that in areas with less than 1m of esker cover, vegetation grew on top of the cover without any seeding or fertilizing (Photo 1) while areas covered with about 1.5m esker showed only sparse vegetation. The vegetation likely originated from within the esker deposit from borrow area. Subsequent observations of the groundwater level within the cover showed the groundwater level was much closer to the surface in areas with thinner cover. Revegetation of disturbed areas with a thin granular cover was also observed at an abandoned airstrip at the Lupin site. The airstrip was constructed with a variable thickness of esker material. A section with a thin esker pad developed more vegetation than a thicker granular pad (Photo 2). This again supports Brewer's observation that thinner gravel pads foster quicker revegetation.

A method to enhance the development of vegetation on the tailings cover was also demonstrated at Cell 1a. Six vegetation islands were created on top of Cell 1a by dumping organic material stripped from the esker borrow area (Photo 3). These islands are thriving and should in time spread naturally over the remaining cell area.

Photo 1. Vegetation on Cell 1.

Photo 2. Vegetation developed on abandoned rehabilitated airstrip.

Photo 3. Vegetation islands developed on Cell 1a.

7.9 Recent Monitoring

In support of the saturated zone cover at Cells 1a and 1, a more extensive monitoring program was started (Holubec 2002). This included the installation of nine additional pipes within Cell 1 (Figure 7-9) in the summer of 2002 to:

1) Determine more accurately the thickness of the esker cover at Cell 1.
2) Monitor the saturation level within the esker.
3) Obtain water samples from the saturated esker zone.

To ensure that water samples were collected from within the esker pores, the pipes bases were installed about 150mm above the tailings surface. The thickness of the esker cover and the thickness of the saturation surface within the esker cover at the pipe locations are given in Table 7-3.

Table 7-3. Esker thickness and saturation level in Cell 1 pipes. (Measured in August 2002)

Pipe	Esker Thickness, m	Thickness of Saturation zone, m
1	1.2	BP
2	1.1	0.2
3	1.0	BP
4	1.3	0.3
5	1.2	0.8
6	1.0	0.4
7	1.2	BP
8	1.1	0.4
9	1.0	BP
Average	1.1	0.3

Note BP - At these locations the water level was below the bases of the pipes and therefore could not be measured or sampled. The base of the pipes was located approximately 0.15 m above the tailings.

Table 7-3 shows the esker thickness at the nine pipe locations varied between 1.0 to 1.3m and the saturation thickness of the esker zone varied from 0.1m (estimated) to 0.3m along the north and west perimeter of the cell and 0.5m or more in the centre of the cell. Locations where water was not observed within the pipes are located near the tailings cell perimeter where the slope of the tailings surface likely drains the esker sand that has a low percentage of fines. This indicates that at these areas it may necessary to raise the water level by constructing internal baffles within the cover material.

7.10 Water Quality

In addition to the regulatory requirements, water quality within the tailings pond was investigated for the purpose of evaluating the effectiveness of the esker cover at Cells 1a and 1. It should be noted that the tailings remained exposed prior to cover placement and that some oxidation may have occurred. This has likely affected the water quality in the esker-saturated zone. A summary of the water quality results of the covered tailings cells is presented. Water quality discharge criteria are given in Table 7-4.

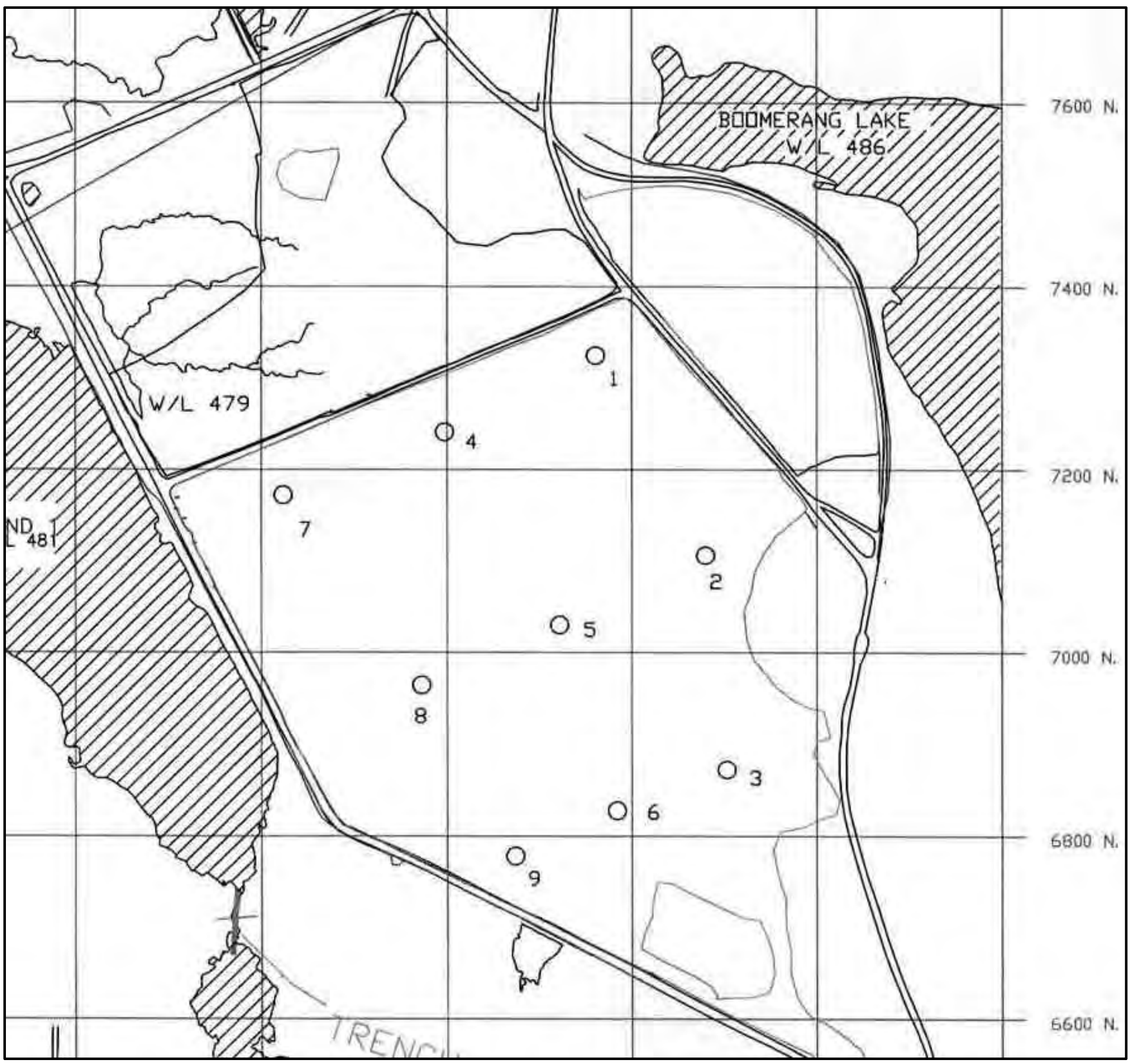

Figure 7-9. Location of pipes installed in 2002

Table 7-4. Water License discharge water quality criteria

Parameter	Maximum Avg., ppm
Total arsenic	0.50
Total copper	0.15
Total cyanide	0.80
Total lead	0.10
Total nickel	0.20
Total zinc	0.40
TSS	15
pH range	6 to 9.5

7.10.1 Pipes installed in 1998

Water samples have been collected from pipes TC1-1 and TC1-5 since 1998. Results given in Table 7-5 show that water quality results exceed the Water License limits in nickel, zinc and pH. It is likely that water quality improvement of the esker pore water is slow because of the very slow migration of water through the esker saturated zone. This may be due to the small gradient within the cover and the low permeability of the esker material. While a somewhat elevated concentration of nickel and zinc in the pore water was observed at two locations in Cells 1a and 1, these concentrations do not impact the tailings pond water quality because of its very slow release.

Table 7-5. Pore water quality (ppm) in esker cover pores (Measured in pipes in 1998)

Water License Parameter	Max'm Avg. ppm	Average Values for TC1-1 & TC1-5				
		1998	1999	2000	2001[a]	2002[a]
Total Arsenic	0.5	0.41	0.01	0.01	0.02	0.012
Total Copper	0.15	0.80	0.77	0.04	0.05	0.21
Total Cyanide	0.8	<.002	<.002	<.002	<.002	<.002
Total Lead	0.1	NA	NA	NA	0.01	0.01
Total Nickel	0.2	3.99	3.15	1.14	2.20	3.06
Total Zinc	0.4	1.06	0.96	0.23	0.60	0.69
TSS	15					
pH	6 to 9.5	5.1	4.8	4.7	4.7	5.1

Note a): For Year 2001 only TC1-1 was available; for Year 2002 only TC1-5 was available.

Extensive sampling and testing of the esker pore water was started in August 2002 to increase the information on the water quality in the esker pores. The results from five water samples from the pipes installed in 2002 (Table 7-6) show that the total nickel exceedence is much smaller than measured in 1998 (TC1-1 and TC1-5) and the total zinc met the discharge limits. It is likely that the lower metal concentrations were obtained because the more recently installed pipes were about 0.15m above the tailings surface. The earlier pipes penetrated into the tailings and the tailings pore water may have affected the water quality of the samples. Samples could not be obtained in some of the pipes because of insufficient water within these pipes.

Table 7-6. Pore water quality (ppm) in esker pores (Measured in pipes in 2002)

Water License Parameter	Max'm Avg.	Max'm Grab	TC1-2	TC1-4	TC1-5	TC1-6	TC1-8	Avg
Total Arsenic	0.50	1.00	0.005	0.004	0.02	0.004	0.019	0.009
Total Copper	0.15	0.30	0.31	0.19	0.25	0.006	0.042	0.160
Total Cyanide	0.80	1.60	0.002	0.06	0.004	0.002	0.002	0.014
Total Lead	0.10	0.20	0.025	0.01	0.02	0.002	0.003	0.010
Total Nickel	0.20	0.40	1.32	0.85	3.51	0.015	1.11	1.361[a]
Total Zinc	0.40	0.80	0.62	0.32	0.91	0.035	0.300	0.437
TSS	15	30						
pH	6 to 9.5		3.96	5.7	5.0	5.9	4.9	5.09

Note a) Marginally above limits, L5x

The 2002 test results show that the water quality of the esker pore water is just marginally above the license limit for nickel only. The impact of the pore water on the surface water was studied by taking water samples at various points along the flow path of the water towards the release point as follows: 1) saturated esker material just beside the ponded cell water located in the centre of the Pond (Saturated Esker); 2) from ponded water in the lower part of the cell; 3) Pond 1 that receives excess water from Cell 1, and 4) Pond 2 that receives the water from Pond 1. Water quality measurements made in August 2002 are given in Table 7-7.

Table 7-7. Water quality (ppm) at locations receiving esker pore water

Water License Parameter	**Max'm Avg,**	**Saturated Esker, Cell 1**	**Cell 1 Ponded water**	**Pond 1**	**Pond 2**
Total Arsenic	0.50	0.01	0.01	0.01	0.09
Total Copper	0.15	0.01	0.02	0.01	0.03
Total Cyanide	0.80	BL[a]	BL	BL	BL
Total Lead	0.10	0.00	0.00	0.00	0.00
Total Nickel	0.20	0.08	0.01	0.08	0.07
Total Zinc	0.40	0.02	0.17	0.20	0.05
TSS [a]	15				
pH	6 to 9.5	7.3	6.1	7.0	7.5

Note a) BL – Below detection limit

Evaluation of the migration of the esker pore water shown in Table 7-7 shows that cover pore water does not impact the surface (pond) water within Cell 1. This water meets the discharge limits. This water remains within the discharge limits as it is transferred from Pond 1 to the final polishing Pond 2 before being discharged into the environment.

In summary, water quality measurements from the saturated portion of the esker cover show that even though the pore water marginally exceeds discharge limits, it does not significantly impact the quality of surface water because of its small loading. Furthermore, the loadings to the environment have been decreasing over the years.

7.11 Conclusions Reached from Lupin Covered Cells

Monitoring of Lupin's covered cells demonstrates the potential validity of the saturated zone cover for the rehabilitation of potentially oxidizing tailings. The key points for using this cover are:

1) Research and field tests carried out in southern climates demonstrate that a 0.3m stagnant water cover is sufficient to prevent oxidation of sulphide containing tailings. A 0.3m of saturated esker zone may be more effective than stand alone water because more than two thirds of the saturated zone consists of inert solid sand particles.
2) Even though permafrost encapsulation is not required with this saturated zone cover, temperature monitoring of the covered tailings at Lupin show that permafrost develops within the tailings that have a 1m thick esker cover with a saturated zone. The active layer penetrated about 0.4m into the tailings. This active layer exists for less than 3 months of the year and the maximum temperature within this zone did not exceed 5ºC during the warmest part of the thaw cycle. Within this short period and a relatively cool temperature, oxidation of the tailings even if not saturated would proceed at a very slow rate even if a water cover did not protect the tailings.
3) Since durability of a saturated cover is not based on permafrost, global warming is not an issue.
4) Gravel pad performance research has shown that pads 1m or less are preferred in permafrost regions because they provide moisture to support vegetation.
5) Minimizing the use of esker for covers reduces the excavation of existing esker deposits. This is preferable since they provide a preferred habitat for animals.

8.0 RANKIN INLET

8.1 General

The Rankin Inlet mine was a nickel-copper mine that operated between 1957 and 1962 (Meldrum et al 2001). This operation produced 297,000 t of tailings that were discharged into three tailings ponds and scattered on the surface in an area between the Rankin Inlet community and Hudson Bay, illustrated in Figure 8-1. Because of low ground elevation and the proximity to Hudson Bay, the tailings were periodically flooded by seawater. This resulted in the tailings pore water becoming saline with a maximum salinity of 52 ppm. The ore contained a Ni-Cu-platinum group of elements bearing sulphide mineralization. Petrographic examination showed the tailings contained 5-20% pyrrhotite that would make the tailings highly reactive. The pyrrhotite and minor amounts of pyrite, chalcopyrite and pentlandite caused the tailings to be classified as reactive sulphide tailings.

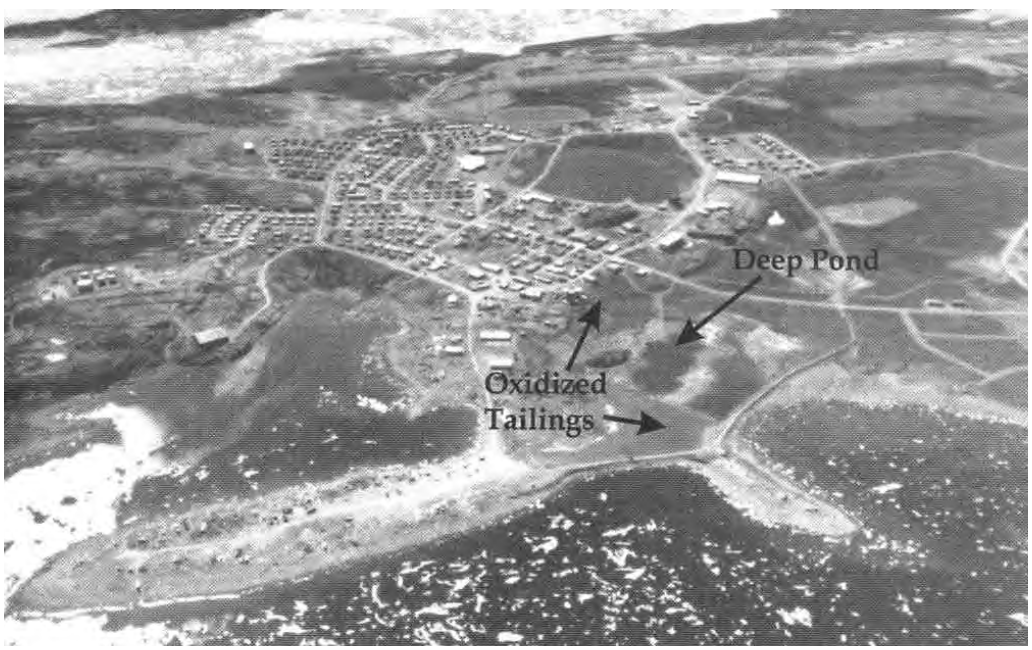

Figure 8-1. Aerial photograph of Rankin Inlet with tailings deposits

The existing tailings were a concern to the community for over 30 years after closure because tailings deposited above the high-tide dried and were spread across the vicinity through wind erosion and surface waters draining from the ponds. Surface tailings deposits caused metals to be introduced into the sea. The concentration of soluble Ni in the water of the three ponds varied between 170 and 2500 ppb, well above the maximum acceptable value for the protection of aquatic life (Environment Canada 1991). Due to environmental concerns, reclamation work was done between 1992 and 1994.

The reclamation consisted of treating the contaminated water in the three tailings ponds and pumping out the water from the Deep Pond. A temporary dyke with a crest elevation of 5m was constructed to protect the tailings from high tides. The maximum high tide at Rankin Inlet is about 4m. About 48,000m^3 of surface tailings were removed from high ground and deposited within the drained Deep Pond to a maximum depth of about 16m. These tailings were covered with 1m of sand and gravel esker to encapsulate the tailings in permafrost (Erickson 1995). The elevation of the top of the cover varies between 4.2 and 4.8m above sea level. It was assumed that the active layer would stay within. The plan for the Deep Pond tailings storage area is shown in Figure 8-2.

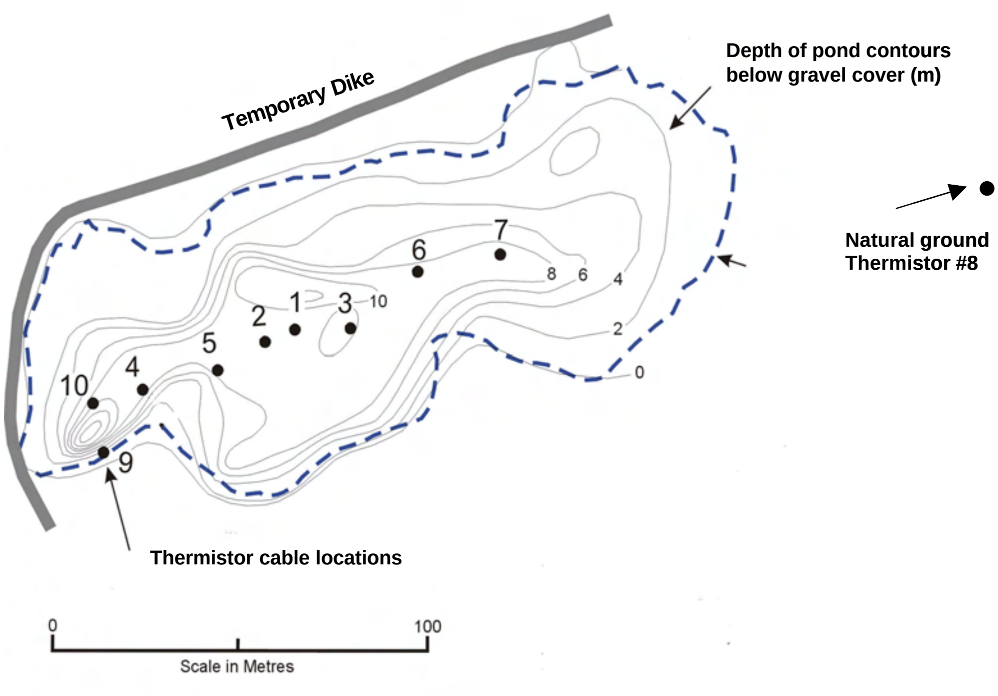

Figure 8-2. Rankin Inlet Deep Pond tailings storage area

Rankin Inlet is located in the continuous permafrost region with a MAAT between -7 and -8ºC and an average active layer thickness of 1.5m in till and gravel (Brown 1978). There was a concern about the effectiveness of the permafrost encapsulation concept because of unfrozen pore water caused by the salinity of the pore water and the potential for heat generation through sulphide oxidation. Field and laboratory-testing programs were started in 1997 to determine the effect of the salinity and sulphide oxidation on the effectiveness of permafrost encapsulation (Meldrum 1998 and Meldrum et al 2001).

8.2 Ground Temperatures in Tailings

Several boreholes were drilled to assess the permafrost condition, obtain tailings samples and install thermistors in March 1997. Locations of the thermistors are shown on Figure 8-2. During drilling by means of an air-rotary method it was observed that the tailings were ice-bonded to a depth of about 4m below where the tailings were thawed. Ground temperatures measured in the tailings on March 31, 1997 show the ground temperature at a depth of 4m to be about -7ºC shown on Figure 8-3.

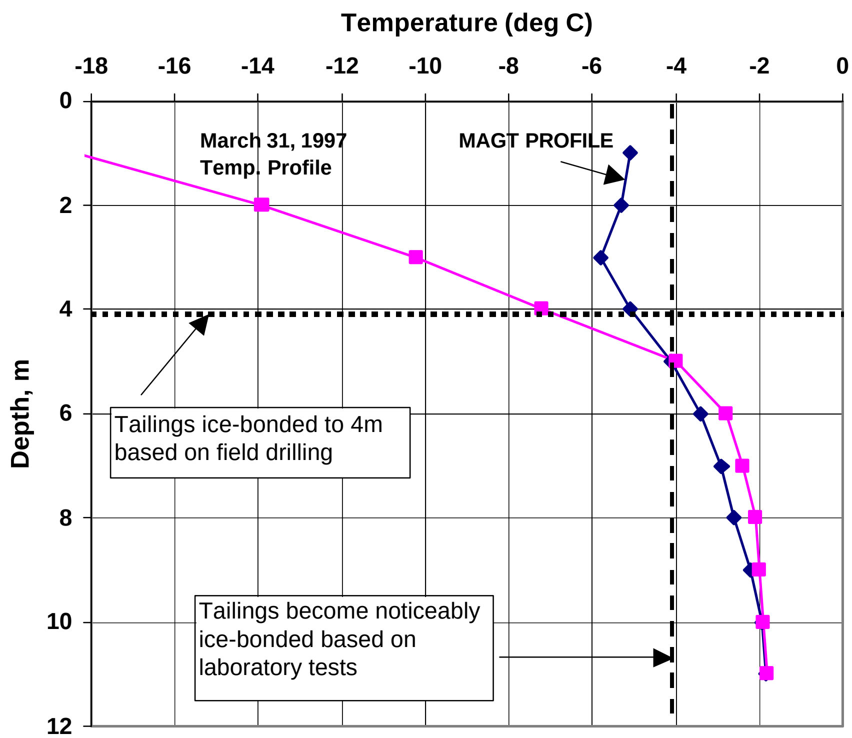

Figure 8-3. Ground temperature profiles and boundaries for ice bonded tailings at Thermistor 6, Rankin Inlet

Laboratory testing to determine the temperature for ice bonding formation showed that noticeable ice bonding occurred at -4ºC. This boundary is also indicated on Figure 8-3. The difference of the temperature at which ice bonding occurs obtained from the field and laboratory observations is due to the fact that ice bonding occurs over a range of temperatures in soils/tailings with freezing point depressed pore water (Arenson and Sego 2004). Freezing point depression is discussed in Section 2.6.

Changes of ground temperatures in natural ground adjacent to Deep Pond and in the Deep Pond filled with tailings between March 29, 1997 and February 1998 are shown on Figure 8-4 and Figure 8-5 respectively.

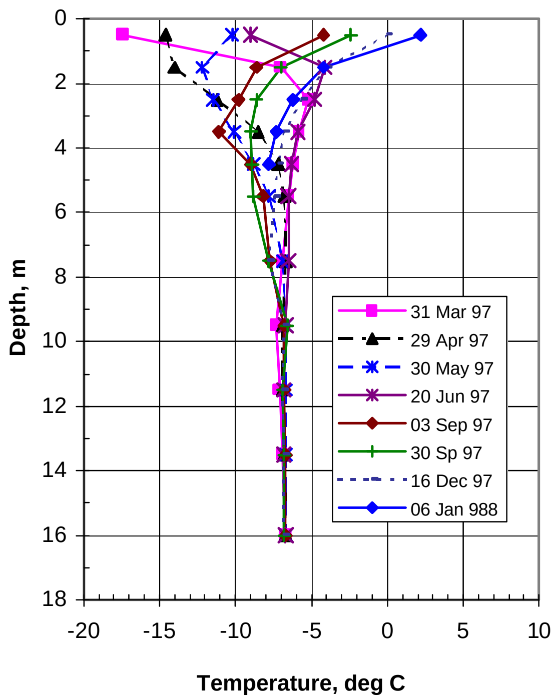

Figure 8-4. Temperature profiles within natural ground at thermistor cable 8

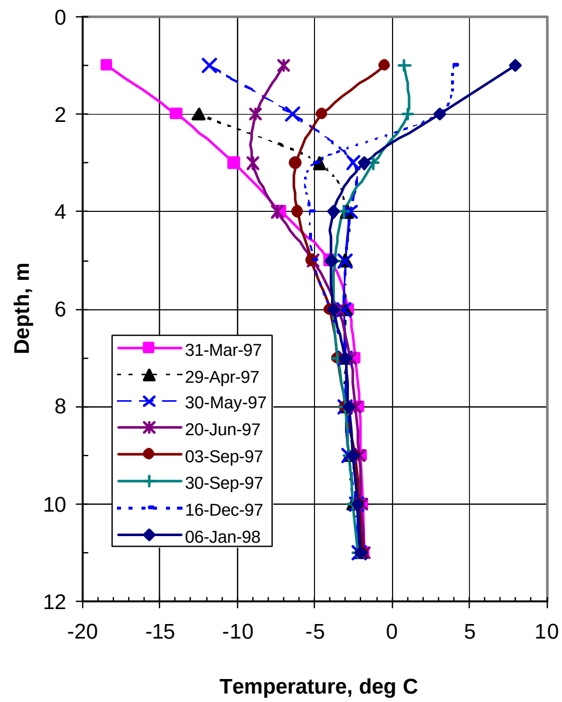

Figure 8-5. Temperature profiles within tailings at thermistor cable 6

Temperature profiles in natural ground adjacent to Deep Pond (Figure 8-4) show an active layer depth of about 1m and the MAGAT at a depth of about 15m being -6.7ºC. Figure 8-5 shows temperature profiles within the reclaimed tailings about 4 years after cover installation. The temperature profile interpretation were be done based on the following three temperature criteria:

1) 0ºC – representing the freezing point of normal ground water.
2) Minus 2ºC – a temperature at which very low reactivity and oxidation is expected (Meldrum 2001).
3) Minus 4ºC – temperature at which noticeable ice bonding appears.

The following observations are made;

1) The 0ºC criterion shows that the active layer depth was lowered from 1m in the natural ground to about 2.7m within the covered tailings.

2) The deeper active zone depth based on 0ºC can be explained by the location of the groundwater surface. It was located at 2.3m below the cover surface (Dyke 2004).
3) Assuming that -2ºC represents the depth at which appreciable oxidation stops, the profiles show that after four years of cover placement, the mean annual ground temperature at 11m depth, at about -1.7ºC has not reached this criterion. It has to be noted that at this depth the tailings are saturated.

Meldrum et al (2201) predict that the temperature will fall below -2ºC at the deepest part of Deep Pond in 7 years after the relocation of the tailings and the placement of a cover. Also that ice bonding throughout the entire tailings will occur after more than 15 years.

8.3 Pore Water

Water chemistry was determined for samples obtained from three sources; a) pore water obtained through the drilling and sampling program b) two streams not in contact with the tailings and c) seawater. Average values for selected parameters are given in Table 8-1.

Table 8-1. Selected average parameters of tailings pore , stream and sea water

	Tailings pore water	Stream water	Seawater
Dissolved oxygen (mg/L)	<0.1	10.2	nd
pH	6.8	7.4	7.8
Alkalinity (mg/L $CaCO_3$)	385	56	169
Chloride (ppm)	15,059	34	16,100
Sodium (ppm)	11,115	7	15,400
Sulphate (ppm)	5,757	66	2,840
Nickel (ppm)	6,613	666	35
Zinc (ppm)	145	220	10

Note: Results for Cu were not available and ‘nd’ means not detectable.

The comparison of the tailings pore water to thee stream and sea waters show that the pore water in Deep Pond tailings are the result of seawater intrusion and sulphide oxidation. The high alkalinity was the result of the addition of lime during neutralization of Deep Pond and the extremely low oxygen in the tailings pore is the result of sulphide oxidation that consumes the oxygen.

8.4 Observations

1) Establishing the ground temperature at which sulphide oxidation stops in permafrost region is difficult for tailings with pore water having a depressed freezing point. Freezing point depression can be the result of a) infiltration of seawater, b) mill water chemistry or c) sulphide oxidation.
2) When drilling through tailings at Rankin Inlet that were infiltrated by seawater, ice bonding was observed at a depth of 4m. This was followed by unfrozen tailings. Ground temperature measured few days after drilling showed a ground temperature of about -7ºC at a depth of 4m.
3) Laboratory program showed significant reduction of oxidation at -2ºC and no measurable oxidation at -10ºC (See Section 2.6.1).
4) Based on the laboratory work, Meldrum et al (2001) assumed that freezing of tailings with a salinity of 35 ppt begins at -4ºC.

8.5 Conclusions

1) Establishing the temperatures at which freezing occurs, or oxidation effectively stops, is difficult when the pore water in the tailings has a depressed freezing point.
2) Arkenson and Sego (2004) determined the reason for this difficulty in their experimental work. Their results, summarized in Section 2.6.3, shows that at the depressed freezing point of pore water, the transition between unfrozen and frozen water is a zone, not a point, that expands as the freezing point increases.

9.0 OBSERVATIONS

9.1 General

Encapsulating reactive tailings in permafrost to prevent oxidation and metal leaching requires a site that has a mean annual air temperature (MAAT) that will develop and maintain the tailings in a frozen state. The tailings cover needs to be designed so that it contains the active layer and thereby prevents the annual thaw from reaching the reactive tailings. Permafrost can be developed and maintained in tailings in a continuous permafrost region as long as global warming does not change the local climate significantly. The design of an economical cover in permafrost is greatly dependent on moisture content of the cover material and the thawing index of the site.

It has been shown that increased moisture content will decrease the cover thickness and therefore the ideal cover will either: a) use a material with fine particles that inherently maintain a high moisture content or b) design the cover geometry to maintain a saturated zone at the base of the cover. If saturation is maintained at the base of the cover, then preventing the active layer from penetrating underlying reactive tailings is not required since the saturated zone at the base of the cover will act as a water barrier to prevent oxidation.

The following summarizes the information previously discussed.

9.2 Global Warming

Warming of the air temperature is occurring as documented by the melting of glaciers on all continents. In Switzerland it has been observed that about 50% of the glaciers have melted between 1850 and 1985 and an additional 25% have melted from 1985 to 2000 as was presented at the ICOP (2003). A similar trend is observed in Canada as shown by the melting glaciers and long-term air temperature records (Environment Canada, CRYSYS 2003), although the temperature increases are not the same for all regions.

The largest temperature increase in Canadian permafrost region occurred in the Yukon and the Northwest Territories. The temperature rise from 1950 to 2000 in these regions has been estimated to be 3 to 4ºC in 100 years. Nunavut has experienced smaller temperature increases over most of its area. It is projected to be about 1ºC in the next 100 years. The rate of temperature rise appears to have increased from 1980 onwards in Western Arctic. This is consistent with observations reported from Alaska. Global warming has not been demonstrated as clearly in Eastern Arctic. The mean annual air temperature has been near constant or slightly decreasing up to about 1985. However since 1985, a warming trend has been observed there also.

9.3 Continuous Permafrost

Only continuous permafrost regions should be considered for encapsulation of reactive tailings in permafrost. These conditions are generally found northeast of the Mackenzie River in Northwest Territories, Nunavut and the most northerly area of Quebec.

Most of the Yukon and southwest of the Mackenzie River of Northwest Territories are not conducive for permafrost encapsulation by natural means because of warmer permafrost temperatures. These areas are within discontinuous permafrost that tends to thaw upon physical disturbance.

Continuous permafrost boundary follows approximately the -7.5ºC MAAT isotherm that lies just south of the tree line. Smith and Burgess (2000) have shown a relationship between MAAT and MAGST (mean annual ground surface temperature) where the MAGST is about 4.4ºC warmer than MAAT. This provides a means of estimating the MAGST from MAAT or vice versa.

A permafrost glossary provides two mean annual ground temperature definitions and the author suggests a third definition as follows:

- MAGT – is the mean annual ground temperature with no depth specified.
- MAGST – is the mean annual ground temperature at the ground surface.
- MAGAT – the author suggests to define the mean annual ground temperature at a *depth of zero annual amplitude.*

To obtain the ground temperature at a *depth of zero annual amplitude*, an additional 0.3ºC has to be applied to the MAGST to compensate for the effect of the thermal gradient existing between the ground surface and the depth of zero ground fluctuation. Theoretically, a -7.5ºC MAAT would produce a -2.8ºC at the *depth of zero annual amplitude.* This is an approximation since other factors, i.e. vegetation, snow, etc. impact the magnitude of the ground temperature.

The rise in MAAT due to global warming needs to be considered when planning to encapsulate reactive tailings in permafrost. Sites, such as Lupin with an MAAT of about -10ºC in 2000, may experience a rise in the MAAT greater than 4ºC in the next 100 to 200 years. This could change its state into a discontinuous permafrost condition with the potential of thawing of the frozen tailings.

9.4 Site Temperature Regime

Encapsulating reactive tailings in permafrost requires the site to have a low MAAT that will maintain the tailings permanently frozen; measured by the mean annual ground temperature (MAGAT). MAGAT is related to the MAAT but its value is also a function of other parameters, with vegetation cover and moisture content being the dominant ones.

MAGT generally increases with depth, due to the thermal gradient, and above the *depth of zero annual amplitude*, the ground temperature changes during the year. Because of the thermal gradient, it has to be defined by a given depth. The author suggests that the mean annual ground temperature *at depth of zero annual amplitude* be used as a datum ground temperature (MAGAT). The advantage of this datum ground temperature is that it can be measured by a one-determination of a vertical thermistor cable installed to a depth of 15m.

The main function of the cover is to maintain the active layer within inert material above the frozen tailings. Other functions of the cover are to provide protection against wind and surface water erosion. The thickness of the active layer is determined by the air temperature, as measured by the daily mean air temperature, energy balance at the cover surface and thermal properties of the cover material. For calculating or analyzing the depth of thaw, the daily mean air temperatures are given in terms of the *thawing index* which is calculated either from the daily or monthly mean air temperatures.

In summary, for establishing if a suitable climate for encapsulating tailings in permafrost exists at a site and designing a cover to maintain the active layer above the frozen tailings, the following climatic data is required:

- MAGAT (estimate can be obtained from MAAT).
- Mean daily air temperatures for the year.
- Thawing index (derived from mean daily temperatures).

Climatic data is sparse in the Canadian permafrost region. To establish reliable mean monthly air temperatures and MAAT at a new site requires operating a meteorological station at the site for several years. These short-term data measurements need to be calibrated with the nearest adjacent station with long-term climatic data. An alternate method in obtaining this information is by drilling a 15 to 20m deep hole at the site in question and installing a thermistor string. This would allow measurement of the MAGAT. It is important to select the location of the drill hole so that the MAGAT will replicate the terrain of the proposed facility. Uplands are suitable for the determination of the MAGAT.

The mean monthly air temperatures for the year can be obtained by using the air temperatures records from the nearest climatic station and calibrating the temperatures by means of thermal analysis until the site temperatures corresponds to the measured MAGAT. For a preliminary design, the mean monthly air temperatures should be sufficient.

9.5 Active Layer

The thickness of the active layer or thaw depth is dependent on many factors that make it difficult to obtain a relationship between the MAAT or the thawing index; the thawing index being the more representative parameter. Factors other than temperature include: organic cover, snow thickness, moisture content within the cover, colour of the surface and orientation of the slope. In case of covers over tailings, the organic layer and the orientation of the cover slope can be neglected. Vegetation is not an issue for tailings surfaces because of the time it takes to develop vegetation in a permafrost region. The slope of the tailings cover can be neglected because tailings surface are practically horizontal.

9.5.1 Thawing index

The thawing index is commonly used in engineering designs to estimate the maximum depth of thaw in frozen ground. It is defined as the number of degrees above freezing integrated over the time during which the surface is above freezing and is expressed in degree-days.

For inert material covers the thawing index is a good parameter to evaluate changes of the thaw depth over a number of years if the other major parameters influencing the thaw depth, namely the moisture content within the thawing stratigraphy, remain constant. The thaw depth of covers of the first three case histories was related to the thawing index. For simplicity and lack of information, other parameters, such as snow depth, surface colour etc. were assumed to be the same in these case histories.

Carreau et al (2003) noted that the maximum thaw depth at the Nanisivik test pads decreased with time from 1993 to 1997. It is believed that during the first 2 years the decrease of the thaw depth was predominantly due to an increase of moisture within the cover. Furthermore, the MAAT was practically constant (at -15.6ºC and -16.1ºC) and the thawing index increased from 1993 to 1994. From 1995 to 2000 the thaw depth did follow to some degree the MAAT as shown on Figure 5-7.

A better relationship of thaw depth to air temperatures is obtained with the thawing index observed in Figure 5-8, with the exception of the first two years for the reason noted earlier.

A similar conclusion is obtained from the Lupin field tests when the mean thaw depths measured between 1996 and 2002 are plotted against the thawing index (Figure 7-8).

The Raglan case study shows that there was a decrease of the thaw depth even though the thawing index had increased from 509mm to 565mm from year 2002 to year 2003.

Strictly based on the thaw index, the thawing depth should have increased. One likely explanation for the decrease is that the moisture content within the cover increased due to water infiltration during the summer.

To evaluate how the thaw depth corresponds to the thawing index based on the three field studies, the information from the three sites was plotted on one chart shown on Figure 9-1.

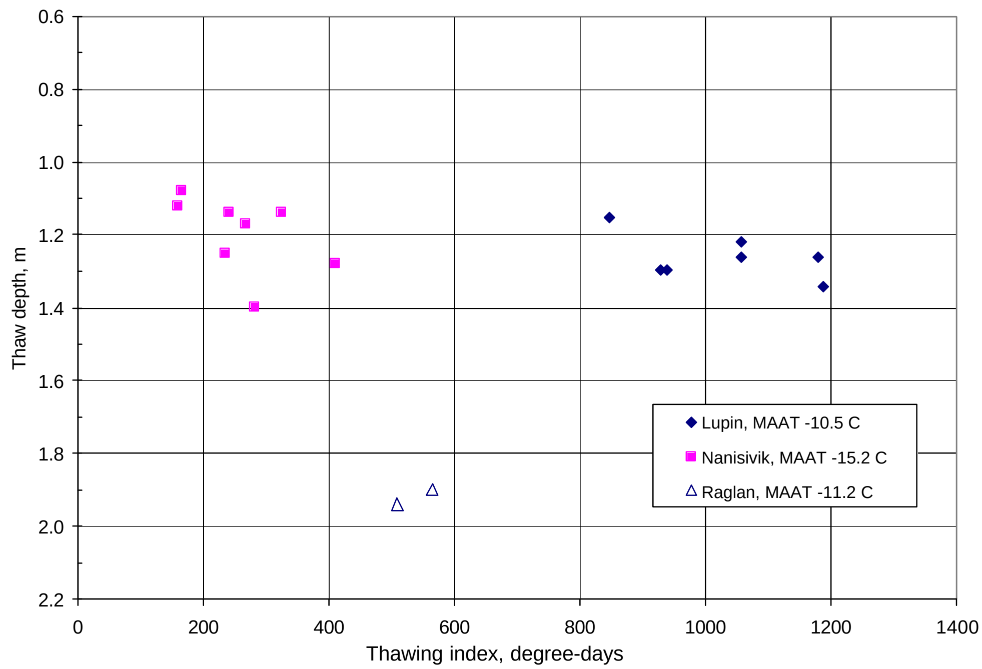

Figure 9-1. Combined thaw depth versus thawing index chart

Figure 9-1 shows that there is a poor correlation between thaw depth and thawing index when data from three different locations are used. The reason is that the thaw depth is a function of one additional important parameter, namely, moisture content. The three sites have different cover materials and designs which results in different moisture content within the unsaturated zone and likely different depths to the groundwater surface. Locations of the groundwater surface at the Nanisivik and Raglan sites are not known. It is believed that moisture content within the cover at Raglan was low because of the coarse nature of the cover materials.

The Lupin cells have an average cover thickness of 1.1m and the bottom 0.3m of the cover was observed to be fully saturated. Therefore, only the upper 0.8m of the cover was unsaturated. Water content of the upper 0.8m has not been determined.

The comparison of the thaw depth versus the thawing index for the three sites demonstrates that the moisture content within the cover plays a large role in determining the thaw depth. Measurements of the moisture content within the cover and the location of the groundwater surface need to be done in the field to determine how these parameters control the thaw depth within covers.

9.5.2 Moisture content

Review of the basic soil thermal properties and the magnitudes of these properties in a typical cover show the impact of the moisture content on the thaw depth. Basic soil thermal properties include: thermal conductivity, heat capacity and latent heat. They vary with phase composition, and hence temperature, and the index properties of the soil or rock. The Raglan parametric thermal analysis (AMEC 2002) in Table 9-1 provides physical and thermal properties of common materials that may be used in a typical tailings cover design. The geotechnical index properties, dry density and moisture content, are the key geotechnical parameters for tailings cover design.

Table 9-1 illustrates that in practical terms only the latent heat is impacted by changes of moisture content and this impact is large. Bedrock and rockfill, that may have moisture content from 0.5 to 2%, have a latent heat in the range of 4 to 6 MJ/m^3. Esker, that consists of sand and gravel with a moisture of 7%, has a latent heat of 36.8 MJ/m^3 and tailings at a moisture content of 18% have latent heat of 91.1 MJ/m^3.

The typical values in Table 9-1 illustrate that of the three soil thermal properties, the total (volumetric) latent heat, which is directly related to the moisture content, is the most important parameter.

Table 9-1. Physical and thermal properties of materials. (AMEC 2002)

Material	Dry Density	Moisture Content	Latent Heat	Freezing Point	Thermal Conductivity W/m/h		Heat Capacity MJ/m^3	
	Kg/m^3	%	MJ/m^3	ºC	Frozen	Unfrozen	Frozen	Unfrozen
Rockfill	1700	2	6.0	0	2.50	2.00	1.88	2.03
Esker	2200	7	36.8	0	3.43	2.99	2.26	2.68
Tailings	1700	18	91.1	-0.5	1.47	1.43	2.14	2.80
Bedrock	2650	0.5	4.2	0	3.49	3.49	1.88	1.88

The Raglan cover design demonstrates the major impact of the moisture content through its influence of the latent heat, on the thaw depth (Table 9-1). The surface rockfill zone that represents half of the cover material (1.2m thickness of the total 2.4m cover) has a moisture content of 2% and latent heat of 6 MJ/m^3. Because of the low latent heat, this zone thaws rapidly. In the Raglan thermal analyses the esker was assumed to be unsaturated with 7% moisture content. Even with this moisture content the latent heat is about six times larger than the rockfill. This means that if the thaw front reaches the esker its advance would be greatly reduced. Should the esker zone become fully saturated by a rise of the groundwater level, the latent heat will increase to a value close to the tailings value and the thaw depth advance rate would decrease even further.

To illustrate the impact of moisture content on the latent heat, and thereby the thaw depth, the latent heat values of the Raglan fully saturated materials were estimated and the results along with the design latent heat values are given in Table 9-2. The comparison of latent heat for the design and saturated conditions in Table 9-2 demonstrate the benefit of increasing the moisture content to decrease the thickness of a cover.

Table 9-2. Estimated moisture content and latent heat of rockfill and esker materials.

		Design Conditions		Saturated Conditions	
Material	Dry Density	Moisture Content	Latent Heat	Moisture Content	Latent Heat
	$Kg.m^3$	%	MJ/m^3	%	MJ/m^3
Rockfill	1700	2	6.0	8	24.0
Esker	2200	7	36.8	14	73.7
Tailings	1700	18	91.1	22	111
Bedrock	2650	0.5	4.2	2	16.8

At Raglan the moisture content within the esker zone will increase with time because of the medium permeability of the esker layer and the shallow of the slope of the top of the large tailings pile.

9.5.3 Freezing point depression

Encapsulating reactive tailings in permafrost depends on the practically impermeable condition of the frozen material. The Institute of Permafrostology of the Siberian Division, former USSR Academy of Science conducted freezing experiments to gather information for the construction of frozen core dams (reported by Biynov 1975). They constructed nine test pads from frozen soil at different compactions and poured water on each layer to ‘saturate’ the fill material. The experiment showed that in all nine-field plots the frozen material did not permit any seepage.

However, a frozen condition with ice bonding may not develop at 0ºC temperature if freezing point depression is present. It has to be noted that a temperature below 0ºC defines permafrost. It does not address freezing point depression or the state of the ground, i.e. if a solid frozen structure with ice crystals is present. The temperature at which ice crystals form will also be lower because of the freezing point depression. In addition, the solute may depress the freezing point and could create a zone with both frozen and unfrozen water (Arenson and Sego 2004).

In the Raglan case history it was assumed that the mill water chemistry could depress the freezing point. Raglan assumed that the freezing point would be depressed by 0.5ºC.

More significant information was observed at Rankin Inlet. Tailings pore water was impacted by saline water, which covered the surface tailings during unusually high tides. Oxidation of the sulphides was observed. Field work showed unfrozen tailings at -2ºC with appreciable ice bonding starting at -4ºC. Laboratory testing showed that the tailings that were impacted with seawater had more than 50% of their water in an unfrozen state.

These two case studies demonstrate that the design for closure of tailings based on permafrost should consider the temperature at which the majority of pore water freezes and forms a crystalline structure, rather than a 0ºC temperature.

9.5.4 Saturated zone cover

Previous sections demonstrated that using materials with low moisture content for tailings covers requires a considerable thickness of material. The most effective way to reduce the thawing depth is to increase the moisture level within the cover. This can be done by selecting material for the cover with high moisture retention capability and/or by completely saturating as much of the base of the cover as possible. Materials consisting of, or having a large percentage of fine-grained soils, have much greater capacity of holding moisture in the unsaturated condition than coarse uniform graded materials.

Complete saturation of the cover represents the highest possible moisture content for a given material at a given density (compaction). However, if saturation is adopted as a design criterion, the same effect as a stagnant water cover over tailings is created. This eliminates the requirement that the thaw front should not penetrate into the tailings.

In conclusion, a water cover is created by adopting a cover design that minimizes the thaw depth by maximizing the moisture content within the cover (complete saturation). A small depth of water creates an oxidation barrier as long as the water is stagnant (MEND 5.4.2d). A saturated zone at the base of a cover represents stagnant water conditions that will provide an oxygen barrier.

Cover design concepts of complete encapsulation of the tailings in permafrost are illustrated by designs proposed by Diavik and Raglan. The saturated cover and the proposed saturated zone cover concepts are also shown in Figure 9-2.

Brief descriptions of the four cover concepts follows:

Diavik –The closure plan for the tailings is to encapsulate them in permafrost by maintaining the thaw depth within a silty sand till layer. Thermal modelling showed that this can be achieved by covering the tailings with 0.5m of silty sand till followed by 3m of clean rockfill for a total thickness of 3.5m (Diavik 2001). The large thickness of the cover is a result of using rockfill with a low moisture content. The combination of material was selected based on the availability of, and ease of construction with, the materials.

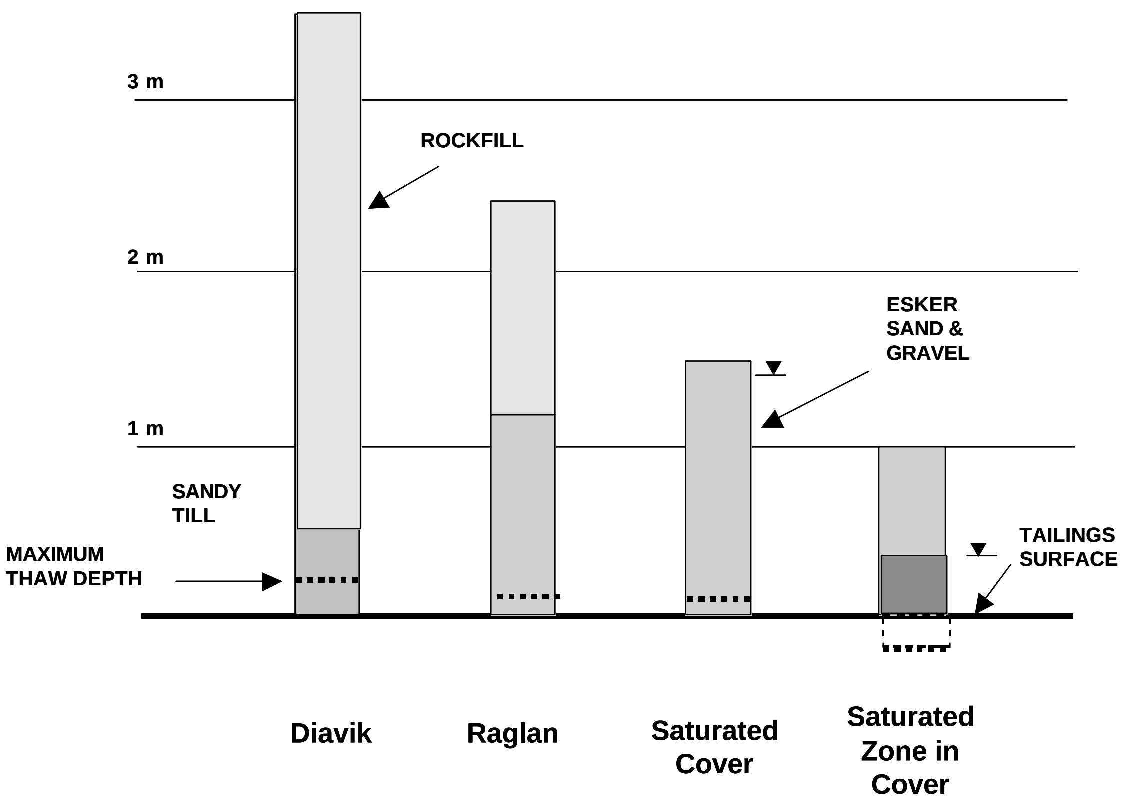

Figure 9-2. Unsaturated and saturated zone cover concepts

Raglan – Raglan is also proposing to encapsulate the tailings in permafrost. The design is based on a 1.2m moisture retention zone of crushed esker material covered with 1.2m of rockfill. Thermal analyses show that the thaw depth will reach the base of the 2.4m cover.

Saturated Cover – Monitoring at Lupin suggests (from **Figure 7-6**) that 1.3m of saturated sand and gravel would be required to contain the active layer within the cover.

Adding a safety factor for warmer years and some drying at the cover surface indicates a cover thickness of at least 1.5m for this design.

Saturated zone cover – This cover concept is based on providing a stagnant water zone within the cover and allowing the active layer to penetrate into the tailings. The Lupin study shows that a 1m thick gravely sand esker cover with a 0.3m saturation zone over the tailings will have the thaw front penetrating about 0.4m into the tailings for a period of less than 3 months. In this concept the 0.3m saturation zone at the base of the cover minimizes the oxidation of the tailings. Also the low temperatures that exists within the thawed tailings reduces oxidation for the relatively short summer period.

9.5.5 Saturated zone cover at Lupin

This design concept was adopted by Lupin (Holubec 2002) and its most recent data collection is aimed at demonstrating its effectiveness. Additional information on the amount of fluctuation of the water level within the cover and the flow of the water through the cover is being collected.

The cover concept assumes that the annual runoff infiltration will be sufficient to maintain saturation for the lower portion of the cover. This question has to be addressed because some permafrost regions have high evaporation potentials. It was assumed that evaporation will decrease during the summer as the water level falls within the cover, but a saturation zone of 0.3m should be maintained in a 1m thick cover by the annual runoff infiltration.

Another question is how to prevent the water from draining out of the cover in sloping areas. Low permeability baffles incorporated within the cover could be used to reduce and prevent the draining of the water. This could be done by excavating trenches normal to the flow of water, mixing 6 to 8% bentonite into the cover material and returning this mixture into the trench accompanied by compaction.

10.0 CONCLUSIONS

The cover test installations at Nanisivik, Raglan, Lupin and Rankin provide a wealth of information for future designs of covers over acid and non-acid generating tailings in permafrost. The four sites are diverse in location, concepts of tailings storage and cover designs. Conclusions reached from reviewing the permafrost conditions, temperatures and the monitoring results from these sites are as follows:

1) To consider encapsulating tailings within permafrost, the site has to be in a continuous permafrost region that is defined approximately by the -7.5ºC air temperature isotherm.
2) In the design of covers that will encapsulate tailings in permafrost, the potential of freezing point depression of the tailings pore water needs to be addressed. Pore water freezing depression may occur due to mill water chemistry; oxidation of the tailings prior to cover placement, or by seawater intrusion.
3) A review of Canadian Climatic Normals published by Environment Canada shows that the whole permafrost region is warming, though not at the same rate. The largest warming has occurred in the Western Arctic while the Eastern Arctic is now showing warming. Considering that global warming seems to be a reality, it can be anticipated that global warming will occur across the Canadian permafrost region and, that the rate may increase.
4) Mine sites that are planning to encapsulate the tailings in permafrost have to address the question of global warming and how their design may be affected.
5) Even though the locations for four case studies represent diverse climatic conditions and cover design, it was found that the main parameter that governs the annual depth of thaw (active layer) is moisture content within the cover. Increasing the moisture content of the cover material reduces the thickness of the cover that is needed to maintain the active layer within the cover.
6) As the moisture content is increased in the cover material, eventually full saturation or a stagnant water cover condition is reached. In this case, the penetration of the active layer into the tailings is not critical because the saturated zone within the cover will provide an oxygen barrier.
7) Lupin has adopted the design concept that the base of the cover will always be saturated to a minimum depth of about 0.3m through normal runoff infiltration. Available monitoring information confirms this concept.
8) Considerable inter-annual variability in air temperatures occurs. Due to this variation and the fact that the thawing index is the prevalent climatic parameter, aside from moisture content within the cover, thaw depths should be interpreted using the thawing index.

11.0 FUTURE WORK

Long-term data is needed to confirm encapsulation as a viable closure technology for mines located in permafrost. To meet this goal the test pad monitoring programs at Nanisivik, Raglan, Lupin and Rankin should be continued. Based on the observations made in this report, it is recommended that the monitoring program be expanded to include, for specific locations, the following:

11.1 Nanisivik

Five test pads were constructed at Nanisivik with various layering of materials and instrumented with frost gauges and thermistor cables. However, it is difficult to interpret their thaw depth data because of lack of moisture content, groundwater location and ice formation information. It would be important to find out if the base of the cover is becoming saturated and what the moisture content is in the cover materials overlying the saturated zone. It is suggested that:

1) At the end of August or in September, when the thaw depth is the greatest, test pits be excavated in each test pad to determine the moisture profile and the location of the water table. The installation of water well pipes within the cover to monitor the development and changes of the water table surface during thawed conditions is also recommended.
2) Two deep thermistor cables, about 20m, should be installed in natural ground in the adjacent upland to monitor the reference mean annual ground temperatures for the site.
3) Thawing index should be established for each year and used to interpret the changes of the thaw depth within the cover.

11.2 Raglan

One test pad was constructed at Raglan that was based on their preliminary cover design consisting of 1.2m of crushed esker material with 10% fines covered with 1.2m of rockfill. Considering the importance of moisture content in the cover to reduce the thaw depth and the benefits of having the base of the cover saturated, a second test pad with higher fines content should be constructed and monitored.

The recommendations provided for Nanisivik above also apply to Raglan.

11.3 Lupin

The Lupin site has the longest and most complete monitoring results of covered tailings in permafrost. Two tailings cells covered in 1995 and 1998 have been monitored since the applications of the covers. Monitoring of Cell 1 was expanded in 2002 and again in 2003. It is recommended that the monitoring program be continued and include:

1) Monthly reading of the thermistor cables within the covered tailings cells.
2) Water level readings to be taken in the pipe wells once at the end of July and again mid September. The level of standing water within the central depressed portion of Cell 1, if present, should be recorded.
3) Water sampling from the pipe wells to be taken during the mid September water level readings. Samples to be sent for analyses.
4) Dig several shallow test pits and take samples at 0.3m and 0.6m depths for moisture content determinations.
5) Installation of seepage baffles where the cover is placed on sloping tailings surface near the tailings discharge perimeter.

11.4 Rankin

Rankin surface tailings placed within Deep Pond have been rehabilitated by a 1m thick sand and gravel cover. Monitoring of cover shows that the active zone based on 0ºC criterion penetrates between 2.5 and 3m below the cover surface and that the groundwater level was about 2.3m below the cover surface. Considering that oxidation of the tailings does not diminish until a ground temperature of -2ºC is reached, the cover is not sufficiently thick to stop tailings oxidation.

Groundwater level should be monitored to see if with time the groundwater surface will rise into the cover. If this does not happen, baffles should be constructed through the cover to slow the groundwater seepage and thereby raise the groundwater level.

11.5 Other mines

It is encouraged that other mines install test pads with cover designs based on site-specific conditions and availability of cover materials. The main objective of these covers is to obtain an understanding of the moisture content and levels of saturation that develops in the cover system and how it changes over the years. These two parameters influence the depth of thaw and the existence of a fully saturated zone at the base of the cover that will prevent tailings oxidation even if global warming does persist and makes the option of permafrost encapsulation less feasible.

12.0 TEST PAD INSTALLATION AND MONITORING GUIDELINES

12.1 General

The following are general guidelines and comments for the design and monitoring of a test pad installation. It is recognized that each site has different climatic and topographic conditions and available construction materials. It can be used as a toolbox for the design of a site-specific test pad.

12.2 Cover and Test Pad Materials

The design and selection of cover materials should:

- Consist of a high fines content that retains high moisture in both the unsaturated and the saturated zone and minimizes the lateral flow of groundwater within the unfrozen zone during the summer.
- Provides erosion protection.

Compaction of the cover is not always necessary. Compaction reduces the pore space within the material and thereby reduces the amount of water it can store.

12.3 Test Pad Design

The test pad should be designed to be representative of the final cover. Location of the test pad and its design should take into consideration the slope of the tailings and the permeability of the cover material.

The design adopted for Lupin is illustrated on Figure 12-1. The rectangular outline of the cell was selected to obtain an indication of the flow of water within a cover placed on a sloping surface. Groundwater movement within the cover material and the changes of the water level over the thawing period is monitored by water wells installed within the upper and lower portions of the cell. To prevent any loss of groundwater within the cell, the cell has a lined perimeter barrier that is secured into the permanently frozen tailings. The design of this cell is suited for late summer installation when normally the tailings allow operation of construction equipment. In case the tailings are saturated, a winter construction may be required. In winter installation, the tailings are frozen and therefore it may be necessary to install the liner within a blasted trench as illustrated on Figure 12-2

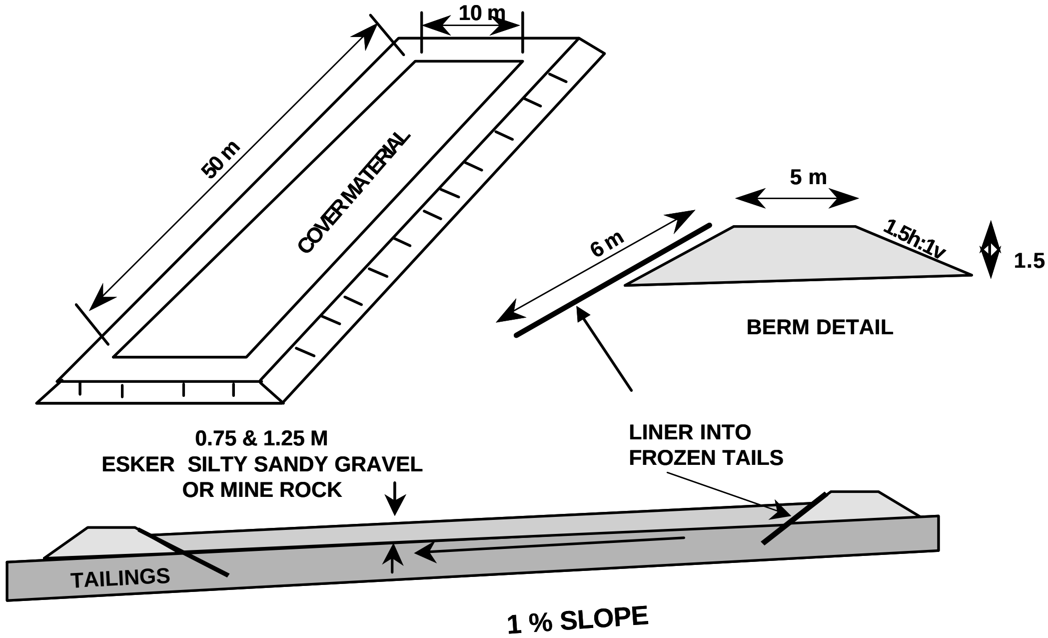

Figure 12-1. Schematic illustration of a test pad design

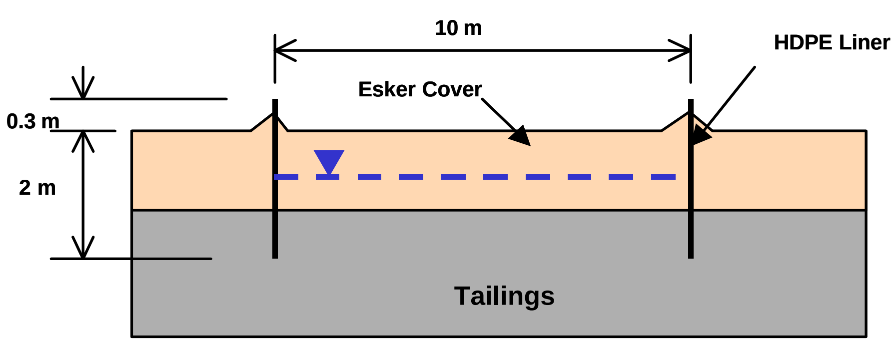

Figure 12-2. Alternate perimeter liner installation for test pads

In addition to thaw depth and vertical ground temperature monitoring, test pad monitoring should also measure moisture and groundwater surface movement within the cover and the tailings. This information can be used to assess the thaw depth and establish the presence of a fully saturated zone within the cover.

12.4 Pipe Water Wells

Pipe water wells shall have a diameter large enough to allow taking water samples for water quality testing. It is recommended that the base be installed within the cover. This will allow the water samples to be taken from within the saturated cover material (assuming that a saturation zone has developed). It is suggested that a 150mm OD HDPE pipe be used that is sealed at the base. Water should infiltrate through weep holes drilled at the lower section of the pipe. A pipe water well installation is illustrated on Figure 12-3.

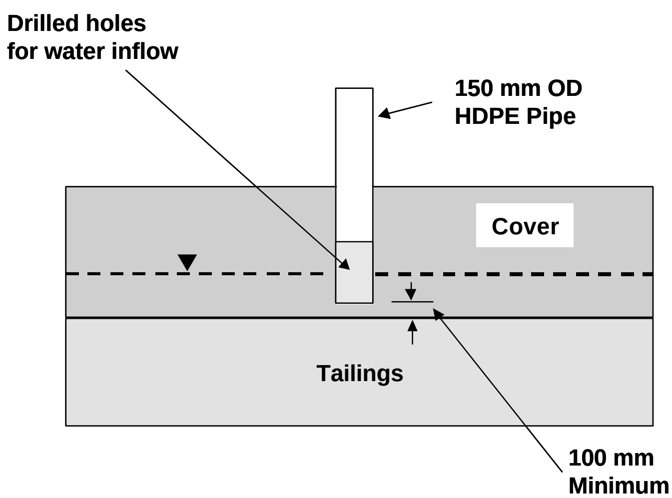

Figure 12-3. Typical pipe water well installation

12.5 Thermistor Installation

A minimum of two thermistor cables should be installed within each test pad to measure variations across cover and provide redundancy. One thermistor cable to a depth of about 5m would monitor the temperature changes and the maximum thaw depth. The second, to a depth of 15m, would establish the MAGAT at the tailings and be used as a backup a to monitor the temperature changes within the tailings. The thermistor cables should have a higher density of temperature sensor beads in the upper 3m depth to better define the temperature profile within the cover.

It is also recommended that at least one deep reference thermistor cable be installed at each site. This thermistor shall extend to a depth of about 20m.

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14.0 APPENDIX – Climatic Normals for the Canadian Permafrost Region.

Mean annual air temperatures and mean annual precipitation for periods of 1950 to 1980 and 1971 to 2000 obtained from Canadian Climate Normals, Environment Canada.

Yukon Territory

Station	Lat., N	Long, W	El., m	1951 to 1980		1971 to 2000		Change
				MAAT	MAP	MAAT	MAP	Warming
Beaver Creek A	62 24	140 52	649	-6.3	378	-5.5	416	0.8
Braeburn	61 28	135 47	716	-3.5	260	-3.1	280	0.4
Burwash A	61 22	139 03	807	-4.4	301	-3.8	280	0.6
Dawson A	64 02	139 07	370	-5.1	306	-4.4	324	0.7
Faro A	62 12	133 22	717	-2.8	288	-2.2	316	0.6
Johnson Crossing	60 29	133 18	690	-2	354	-1.5	376	0.5
Komakuk Beach A	69 35	140 11	7	-11.4	135	-11	161	0.4
Mayo A	63 37	135 52	504	-4	306	-3.1	313	0.9
Mayo Road	60 52	135 11	655	-4	306	-0.7	323	3.3
Old Crow A	67 34	139 50	251	-10.1	215	-9	266	1.1
Teslin A	60 10	132 44	705	-1.8	327	-1.2	343	0.6
Watson Lake A	60 07	128 49	687	-3.3	425	-2.9	404	0.4
Whitehorse A	60 42	135 04	706	-1.2	261	-0.7	267	0.5
Whitehorse Riverdale	60 43	135 01	643	-1	262	-0.2	283	0.8
			Average	**-4.4**	**295**	**-3.5**	**311**	**0.8**

Northwest Territories

Station	Lat., N	Long, W	El., m	1951 to 1980		1971 to 2000		Change
				MAAT	MAP	MAAT	MAP	Warming
Cape Parry A	70 10	124 43	87	-12.4	156	-12	157	0.4
Fort Liard A	60 14	123 28	215	-2.2	449	-1.2	447	1
Fort Reliance	62 43	109 10	166	-7	254	-6.6	272	0.4
Fort Simpson A	61 45	121 14	169	-4.2	355	-3.2	369	1
Fort Smith A	60 01	111 57	205	-3.3	349	-2.3	362	1
Hay River A	60 50	115 46	166	-3.6	340	-2.9	320	0.7
Holman A	70 46	117 48	36	-12.4	178	-11.7	162	0.7
Inuvik A	68 18	133 28	68	-9.8	266	-8.8	248	1
Mould Bay A	76 14	119 20	12	-17.8	93	-17.5	111	0.3
Norman Wells A	65 17	126 48	74	-6.4	328	-5.5	291	0.9
Sachs Harbour A	72 00	125 16	86	-14.1	114	-13.3	149	0.8
Tuktoyaktuk	69 27	133 00	18	-10.9	138	-10.2	139	0.7
Yellowknife A	62 28	114 26	206	-5.4	267	-4.6	281	0.8
Yellowknife Hydro	62 40	114 15	159	-6.1	298	-5.8	303	0.3
			Average	**-8.3**	**256**	**-7.5**	**258**	**0.7**

Legend
MAAT Mean Annual Air Temperature
MAP Mean Annual Precipitation

Mean annual air temperatures and mean annual precipitation for periods of 1950 to 1980 and 1971 to 2000 obtained from Canadian Climate Normals, Environment Canada.

(Continued)

Nunavut				**1951 to 1980**		**1971 to 2000**		**Change**
Station	**Lat., N**	**Long, W**	**El., m**	**MAAT**	**MAP**	**MAAT**	**MAP**	**Warming**
Alert	82 31	62 16	30	-18.2	154	-18	154	0.2
Baker Lake A	64 17	96 04	18	-12.2	235	-11.8	270	0.4
Cambridge Bay A	69 06	105 08	27	-15.1	136	-14.4	139	0.7
Cape Dyer A	66 35	61 37	393	-10.3	663	-11	602	-0.7
Cape Hooper	68 28	66 48	390	-11.8	272	-12	282	-0.2
Clinton point	69 35	120 48	101	-11.2	182	-10.6	168	0.6
Clyde A	70 29	68 31	27	-12.2	206	-12.8	233	-0.6
Coral Harbour A	64 11	83 21	64	-11.6	270	-11.6	286	0
Dewar Lakes	68 39	71 10	527	-13.2	244	-13.3	282	-0.1
Eureka	79 59	85 56	10	-19.7	64	-19.7	75	0
Iqaluit A	63 45	68 33	34	-9.3	433	-9.8	412	-0.5
Kugluktuk A	67 49	115 08	23	-11.6	202	-10.6	249	1
Lady Franklin Point A	68 30	113 13	16	-12.9	110	-12.4	121	0.5
Lupin A	65 45	111 15	490	-12	251	-11.1	299	0.9
Pond Inlet A	72 41	77 58	55	-15.2		-15.1	191	0.1
Resolute Cars	74 43	94 59	67	-16.6	131	-16.4	150	0.2
			Average	**-13.3**	**237**	**-13.2**	**245**	**0.2**

Legend **MAAT** Mean Annual Air Temperature
MAP Mean Annual Precipitation

	Temperature Change		
Over period in years	20	100	
Yukon	0.8	4.0	All stations warmer
Northwest Territories	0.7	3.5	All stations warmer
Nunavut	0.2	1.0	4 stations warmer out of 16 stations