# ROLES OF ICE, IN THE WATER COVER OPTION, AND PERMAFROST IN CONTROLLING ACID GENERATION FROM SULPHIDE TAILINGS

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# REVIEW AND ASSESSMENT OF THE ROLES OF ICE, IN THE WATER COVER OPTION, AND PERMAFROST IN CONTROLLING ACID GENERATION FROM SULPHIDE TAILINGS

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# EXECUTIVE SUMMARY

The natural weathering of mine/mill tailings and waste rock containing reactive sulphide minerals is known to generate acid rock drainage (ARD), under a wide range of climatic conditions. Where acidic drainage occurs, mine decommissioning costs can be significant. The Yukon and Northwest Territories combined, are estimated to account for 3.5% of mine tailings and 2.3% of waste rock that are reactive or potentially acid generating within Canada. This translates to an estimated current liability of over $77 million.

In the last two decades an increasing emphasis has been placed on the development and application of strategies to control and mitigate the reactivity of these sulphide wastes. Two of the most advanced technologies for ARD control in Canada are: the use of water in underwater disposal or wet barriers; and engineered dry barriers.

A water cover can significantly reduce the effective diffusion rate of oxygen into tailings and is considered both an economical and an effective technique for the control of sulphide oxidation in the longer term. The impact of cold temperature conditions on the water cover scenario are modelled. Despite significantly reduced relative reaction rate constants at lower temperatures, the flux of oxygen into the waste is only estimated to decrease by a factor of 2.5 from 25° to 0°C. This is not significant enough to preclude oxidation and thus freezing of reactive waste alone, under unsaturated conditions, is not considered sufficient to control ARD. In addition the effectiveness of saturating tailings to limit the oxygen influx is calculated to decrease as the temperature is lowered. In applying the water cover option to the Canadian north, the impact of reduced temperatures, ice formation and breakup, and snow cover are also discussed. An ice layer will isolate the water column from wind and wave related turbulence and limit the exchange of oxygen at the surface. It is suggested that ice scouring, and the resultant disturbance or resuspension of deposited tails, is the most negative impact related to the application of water covers in the north.

In addition to dry barriers, permafrost offers another option for ARD management in northern Canada. Successful encapsulation of tailings in permafrost may ensure year round in situ temperatures at or below 0°C with simultaneous reductions in chemical and bacterially assisted reaction rates. The characteristics of permafrost related to the active freeze-thaw layer, material transport, freeze-thaw cycles, potential for frost heave, and its use in tailings management are discussed. While acid generating reactions are slowed at temperatures approaching 0°C, they are not stopped. Freeze/thaw cycles may also promote frost weathering and heaving. In addition, permafrost has a finite permeability, a small but significant percentage of porewater remaining unfrozen within permanently frozen ground.

Permafrost, while a promising factor in the management of sulphide oxidation and ARD migration, will not provide an absolute control to ARD production. It is recommended that future work quantify the impact of below freezing temperatures on the rates of acid generation and the longer-term performance of various cover scenarios.

## SOMMAIRE


L'altération naturelle des résidus ainsi que des stériles contenant des minéraux sulfurés réactifs se traduit par une acidification des eaux de drainage, le drainage rocheux acide (DRA), et ce dans diverses conditions climatiques. Lorsqu'il y a acidification des eaux de drainage, les coûts de fermeture d'une mine peuvent être importants. Au Yukon et dans les Territoires du Nord-Ouest combinés se trouveraient 3,5 % des résidus miniers et 2,3 % des stériles qui sont réactifs ou susceptibles d'être acidogènes au Canada. Ces chiffres correspondent à une responsabilité financière estimée à plus de 77 millions de dollars.

Au cours des deux dernières décennies, l'accent a été mis sur l'élaboration et l'application de stratégies pour contrôler et atténuer la réactivité de ces déchets sulfurés. Deux des techniques les plus perfectionnées pour éliminer le DRA au Canada sont la déposition subaquatique et les couvertures aqueuses ainsi que l'utilisation de barrières sèches.

Une couverture aqueuse recouvrant les résidus peut réduire significativement le taux de diffusion effectif de l'oxygène dans les résidus en plus d'être une technique économique et efficace pour contrer l'oxydation des sulfures à plus long terme. Les répercussions des températures basses sur cette technique ont été modélisées. Malgré des constantes de vitesse de réaction relatives significativement réduites à basse température, le flux d'oxygène dans les déchets ne diminuerait, selon les estimations, que d'un facteur de 2,5 de 25 °C à 0 °C. Ce résultat n'est pas suffisant pour empêcher l'oxydation; par conséquent, le gel des seuls déchets réactifs, dans des conditions non saturées, n'est pas considéré suffisant pour éliminer le DRA. De plus, l'efficacité de la saturation des résidus pour limiter l'apport d'oxygène diminue à mesure que descend la température. L'application d'une couverture aqueuse dans le contexte du Nord canadien incite également à aborder les effets d'un abaissement de la température, de la formation de la glace, de la débâcle et de la présence d'un manteau nival. Une couche de glace isole la colonne d'eau de la turbulence créée par le vent et les vagues et limite l'échange d'oxygène à la surface. L'affouillement par la glace et la perturbation résultante ou la remise en suspension des résidus sont les effets les plus négatifs liés à l'application de couvertures aqueuses dans le nord.

En plus des barrières sèches, le pergélisol offre une autre méthode à la gestion du DRA dans le Nord canadien. L'encapsulage des résidus dans le pergélisol pourrait maintenir pendant toute l'année les températures in situ à au plus 0 °C et ainsi réduire simultanément les vitesses de réaction chimique  et de réaction soutenues par les bactéries. Les caractéristiques du pergélisol en ce qui a trait au mollisol qui dégèle, au transport des matériaux, aux cycles de gel-dégel, au soulèvement du sol par le gel et à son emploi dans la gestion des résidus sont traitées. Si les réactions d'acidification sont ralenties aux températures proches de 0 °C, elles ne sont pas nulles. Les cycles de gel-dégel peuvent également promouvoir l'altération et le soulèvement du sol par le gel. De plus, le pergélisol a une perméabilité finie, d'où un faible pourcentage, toutefois significatif, d'eau interstitielle demeure non gelée dans le pergélisol.

Le pergélisol, bien qu'il représente un milieu prometteur pour la gestion de l'oxydation des sulfures et la migration des eaux de drainage acides, ne permettra pas d'empêcher complètement l'acidification des eaux de drainage. Nous recommandons que des travaux soient entrepris pour quantifier les effets des températures de gel sur les vitesses d'acidification et le rendement à long terme de diverses méthodes de couverture.

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# 1.0 INTRODUCTION

## 1.1 BACKGROUND

Under tropical, moderate or arctic conditions, the natural weathering of mine/mill tailings and waste rock containing sulphide minerals may generate acidic effluent as a result of the exposure of reactive sulphide minerals to air (i.e. oxygen) and water. This kind of acidic effluent may also contain toxic heavy metal species. Known as acid mine drainage (AMD) or acid rock drainage (ARD), it can contribute to the deterioration of the quality of surface and groundwater under a wide range of climatic conditions.

In the last two decades an increasing emphasis has been placed on the development and application of management strategies to control and mitigate the reactivity of these sulphide wastes and therefore their impact on the surrounding environment. The strategies considered for application at active or abandoned sites must address both long-term control and economic reality.

Exclusion of oxygen from reactive tailings by the application of an appropriate cover material has been considered as an effective control strategy. A variety of applications involving either dry or wet barriers to oxygen diffusion continue to be assessed in Canada and internationally (MEND 1996). Water, with its low oxygen diffusion coefficient and low oxygen solubility is the most cost effective oxygen limiting cover.

A number of recently completed studies and workshops have underlined the fact that mines located in permafrost regions of the Canadian North can utilize cold climatic conditions as an additional controlling factor for the long-term management of mine waste. While a number of the reports have been broad in scope (SRK 1992a, Norecol, Dames and Moore 1994) others have addressed acid generation (NMEND#2 1994, NMEND#5 1994, Davé and Clulow 1996), prediction (SRK 1992b), or controls (Geocon 1993, EBA 1994, Dawson and Morin 1996) specifically. Generally, water cover is recommended as an oxygen barrier. Encapsulation in perennially frozen ground and/or dry barriers are suggested as a means to mitigate oxidation and transport of contaminants. However, the information related to key controlling parameters such as the depths of water, the impact of ice and snow covers and the effect of permafrost encapsulation need to be further developed. A unique opportunity exists in the north to incorporate permafrost, ice and snow covers in ARD mitigation, but their net impact must be well understood.

## 1.2 CURRENT STUDY OBJECTIVES AND SCOPE

The objective of this review is to prepare a summary report of information, data, and critical parameters in two primary areas: (i) the role of ice and snow cover in the water cover option for the disposal of reactive tailings, and (ii) the role of permafrost for the long-term management of acid generating tailings.

This summary review and assessment provides a basis upon which to consider the design and implementation of laboratory and field studies to evaluate the effects of ice and snow on water covers and the evaluation of the use of permafrost in freezing tailings permanently as a dry cover.

A brief overview of the climatic conditions in northern Canada, mining activity, and the environmental liability faced in the Yukon and Northwest Territories is followed by a review of the parameters which impact on the oxidation of sulphides and the application of wet and dry barriers as control options.

The role of ice and snow on the water cover option is addressed in Chapter 4. Water cover is an effective and proven oxygen diffusion barrier. A theoretical assessment of the impact of temperature on the oxygen diffusion flux for saturated (with and without water cover) and unsaturated tailings is presented. These scenarios are then further developed with respect to the effect of ice cover as well as freezing temperatures. Particular attention is paid to the issue of ice scour and its minimization.

Chapter 5 addresses the role of permafrost on tailings disposal. The condition of perennially frozen ground and its characteristics is described with respect to its suitability to inhibit sulphide oxidation. The impact of reduced temperatures, freezing and thawing cycles, frost heaving, and material transport in frozen ground is described. Two primary disposal options or strategies utilizing permafrost are summarized as are the concerns related to these options that remain unresolved.

## 2.0 THE CANADIAN NORTH

### 2.1 INTRODUCTION

Canada's north consists of the Yukon, Northwest Territories (NWT) and northern parts of several provinces along the provincial/territorial border. It extends northward from a land of boreal forests to treeless tundra and permafrost. The boreal region includes a large part of the NWT west of Hudson Bay and northern parts of the prairie provinces, Ontario, Québec and Labrador. The arctic climatic region covers practically all areas north of the tree line. The various climatic regions of Canada are shown in Figure 2.1.

### 2.2 CLIMATIC CONDITIONS IN THE NORTH

The climate in the Canadian North is characterized by large annual variations in temperature, low relative humidity and relatively low precipitation except near the Pacific region of the Yukon. The annual mean daily air temperature isotherms for Canada are shown in Figure 2.2. Temperature extremes, however, are considerable. Recorded highs range from 36°C at Mayo, Yukon and Fort Simpson, Northwest Territories, to 18°C at Resolute on Cornwallis Island and extreme lows range from -62°C at Mayo to -44°C at Koartak northwest of Ungava Bay. Northern Yukon and NWT normally experience nine months of below freezing temperatures annually.

Average air temperatures, measured about 1-5m above the ground, are generally applied to estimate the presence of permafrost. Permafrost is defined as ground that remains at or below 0°C for two or more years. Permafrost covers approximately one fifth of the world's land surface and approximately one half of that of Canada. Figure 2.2 also shows the distribution of permafrost regions of Canada. The boundary between continuous and widespread discontinuous permafrost approximates the -8.5°C mean annual air isotherm. The southern limit of sporadic discontinuous permafrost is generally accepted as the -1°C mean annual air isotherm.

The climate of the Yukon Territory, unlike the NWT, is influenced by the Pacific Ocean. The open plains to the east of the Cordillera provide an unobstructed path for the flow of arctic and tropical air streams. The climate regime in this area of the north is dominated by the penetration of intensely cold arctic air in the winter and warm, often humid, tropical air in the summer (Klohn Leonoff 1994).

Figures 2.3 and 2.4 respectively, show the mean dates of freeze-over and completion of ice clearance on lakes. By the end of October all but the largest two lakes north of 60°N freeze over. By the beginning of June the first lakes north of 60°N begin to clear of ice, although complete clearance of lake ice does not always occur in the far north.

The mean maximum ice thickness in lakes is illustrated in Figure 2.5. Thicknesses of over 2m are observed in water bodies in the Arctic Islands with decreasing ice thicknesses towards the south. The Mackenzie Delta contains about 25,000 lakes. These lakes are typically shallow (mean depth

<2m) but despite cold arctic temperatures, ice covers reach a maximum thickness of only 0.6 to 1.2m with a layer of water commonly remaining unfrozen beneath the ice cover.

Air freezing and thawing indices may also be applied to compare the different climatic regions. They are computed by summing the number of degree days below 0°C (freezing index) and above 0°C (thawing index) for each year. The mean annual freezing and thawing indices for various parts of Canada are shown in Figures 2.6 and 2.7 respectively.

Precipitation varies greatly but decreases gradually from south to north. The highest annual precipitation occurs in the coastal areas of the western Cordillera and in the eastern mountainous coasts of the Queen Elizabeth Islands and Baffin Island where it may reach up to 1.5m. The mean annual total precipitation north of 60°N is generally less than 400mm and decreases to about 100mm in the Arctic Islands (Figure 2.8). Rainfall accounts for approximately 100-200mm of total precipitation between 60°N and the Arctic coast and north of this point, less than 100mm except for the High Arctic and mountainous regions, where more than 50% of total precipitation occurs as snowfall. The mean annual total snowfall is shown in Figure 2.9. Much of the Arctic is essentially a polar desert because of low precipitation.

Despite low snowfall in the north, the duration of snow cover is relatively long. The maximum depth and dates of formation and loss of snow cover are shown in Figures 2.10 and 2.11 respectively. In general, all of the area north of 60°N is snow-covered by late October and will be essentially snow-clear no earlier than the beginning of May. Indeed, many high-alpine locations remain snow-covered all year, while some of the Arctic Islands plains may be snow-free for as little as two months during the summer (Figure 2.11).

Annual run-off in the Yukon Territory is generally between 200 and 500mm, but in the Northwest Territories, it is between 100 and 200mm. The mean annual lake evaporation and derived evapo-transpiration are shown in Figures 2.12 and 2.13, respectively. The mean annual lake evaporation decreases from approximately 250-400mm at 60°N to less than 100mm in the northeastern Keewatin district and the central portions of the Arctic Islands. Evaporation is greatest during summer and in the areas of low relief characterized by numerous bogs and lakes. In much of the north, evapo-transpiration exceeds annual precipitation.

## 2.3 MINING IN CANADA'S NORTH

The Yukon and NWT cover one third of Canada's total land area. Mining activities represent approximately 50% of the total economic base in the Yukon and NWT. The estimated value of metal and industrial minerals production in the Yukon in 1995 was $166 million, up from $63.6 million in 1994. For the NWT metal and industrial minerals production was estimated at $538 million, up from $485 million in 1994 (NRCan 1996).

In northern Canada, apart from small placer mines, there are an estimated 70 to 100 closed, abandoned and operating gold, silver, heavy metals, coal and uranium mines. A review by Klohn Leonoff (1994) identifies 67, while Geocon (1993) lists over 50 large mines which are either abandoned, operating, or under study. These mines happen to be equally distributed within the discontinuous permafrost zone in the western mountain range, the discontinuous permafrost zone east of the Rockies and in the continuous permafrost zone above the tree line.

Figure 2.14 shows the location of the major mining operations (closed or active) in various geological regions of the Yukon and NWT. Excluding placer deposits in the Yukon, most northern mineral deposits contain sulphide assemblages, typically iron sulphides (pyrite and pyrrhotite). Norecol, Dames and Moore (1994) and NMEND #2 (1994) classified the northern mineral deposits according to their location and their acid and neutralizing potential.

The Faro, Grum, Vangorda and Tom deposits in the Cordilleran Province (Figure 2.14) contain strata-bound lead-zinc mineralization. The waste rock and tailings at Faro are potentially acid generating as well as some waste rock from the Grum and Vangorda deposits. The sulphide rich country rock near MacMillan Pass in the vicinity of the Tom deposit is generating acid (Klohn Leonoff, 1994).

The silver-bearing lead-zinc veins associated with the Sa Dena Hes and Ketza River mines are located in a carbonate rock. The Sa Dena Hes deposits, for example, are low in sulphide content with the tailings and waste rock, having a neutralization and acid generation potential (NP/AP) in the ratio of 30:1 and little potential for generating acid mine drainage.

Porphyry deposits and veins containing precious metals, tungsten, tin, antimony, and molybdenum mineralization are associated with intrusions occurring on both sides of the Tintina Fault. The Keno Hill mine deposits in the east Cordilleran and Casino in the west have alkaline drainage potential containing arsenic and molybdenum.

Copper, nickel and gold mineralizations occur mostly in the volcanic rocks southwest of the Tintina Fault. The massive sulphide deposits located primarily in the southwestern Yukon and in nearby British Columbia (Windy Craggy) are volcanogenic and ultramafic intrusion hosted sulphides containing copper and zinc mineralization with high ARD potential. Copper and gold mineralization at the closed Whitehorse Copper mine occurred as intrusives in skarns in Triassic limestone with very little ARD potential.

The Northwest Territories, unlike the Yukon, are entirely within the old North American Continent and contain three of the Canadian Shield structural provinces: Slave; Bear; and Churchill Province.

The Slave Structural Province comprises basins filled with sedimentary and volcanic rocks of the Yellowknife sub-group. Gold is the only economic mineralization within these rocks and 24 mines from this province have contributed to the NWT's gold output since 1935. Gold is typically found associated with quartz veins or shear zones (Miramar and Giant mines); at the contact between volcanic and sedimentary rocks (Salmita and Tundra mines); or in iron formations with Archean sediments (Lupin Mine).

The Shear zone mineralization contains gold associated with iron and arsenic sulphides and carbonates. The tailings from Miramar and Giant mines are both reported to be net acid consuming by Klohn Leonoff (1994), whereas Norecol, Dames and Moore (1994) classify Con Mine tailings as having significant ARD and metal leaching potentials. The volcanic and sedimentary rock contact gold deposits of Salmita Mine are acid producing, and the tailings are disposed underwater. The gold mineralization associated with the Lupin Mine deposit is characterized by a high ARD potential for tailings and a low ARD potential for waste rock.

Rocks of the Churchill Province have been metamorphosed and deformed to some degree and host several gold and vulcanogenic sulphide deposits. The gold vein mineralization of the Cullaton Lake mine deposits contain low sulphides but the tailings are net acid producing. The ultramafic hosted iron, copper and nickel sulphide deposits of the Rankin Inlet mine are also known to have significant ARD and metal leaching potentials.

The Bear Province is a young and geologically simple province with the mineralogically important parts of the province comprising basins filled with post-tectonic sediments and volcanics. The sediments host the silver-rich veins of the Camsell River and Echo Bay Silver districts. Uranium vein mineralizations of the province are hosted by clastic sediments associated with carbonates.

These provinces are surrounded to the west and north by flat-lying sedimentary rock units, known as the Mackenzie and Arctic Platforms (Figure 2.14). The Arctic Platform stretches from north of Great Bear Lake to Baffin and Ellesmere Islands. Nanisivik is a Mississippi valley-like lead-zinc deposit located in the Eastern Arctic Platform on northwestern Baffin Island. Although the high sulphide lead and zinc mineralization at Nanisivik is associated with carbonates, the tailings are known to have high ARD potential and most have been deposited underwater in West Twin Lake. The waste rock at Nanisivik however has low ARD potential.

The Interior or Mackenzie Platform is similar to the Arctic Platform and comprises flat lying, shallow-water clastic and carbonate sediments which contain oil and gas as well as lead-zinc deposits, such as Pine Point. The high pyrite and pyrrhotite tailings content at Pine Point are expected to be net acid producing but the waste rock has excess alkalinity in its mineralization.

The rocks in the Innuitian Orogen Structural Province range from late Proterozoic to Cretaceous in age and are dominated by sediments with volcanics and felsic intrusions. Polaris mine, located on Little Cornwallis Island, is in the Innuitian Province near the border with the Central Arctic Platform. The massive lead-zinc sulphides are associated with carbonates (limestone and dolomite), having a high ARD potential for tailings and low for waste rock. The tailings at Polaris mine are deposited in Garrow Lake, a small but deep meromictic natural salt water lake with seasonal outflow, now moderated by a control structure.

Acid rock drainage is not unique to southern latitudes and many of the northern deposits, apart from those hosted in alkaline carbonate gangue minerals (such as at Sa Dena Hes), are highly susceptible. Tailings and waste rock from Faro and Vangorda are acid generating, and significant ARD potentials exist for tailings from Lupin, Nanisivik, Cullaton Lake, Discovery, Rayrock, North Rankin Inlet and Thompson-Lundmark. Conversely, waste rock from Polaris, Pine Point, Lupin and Nanisivik is expected to have little ARD potential. Today, approximately 3.5% of the 7 billion tonnes (41,000 hectares) of metal-mine and industrial mineral tailings estimated to exist in Canada are in the Yukon and NWT (Feasby, 1994). This inventory, however, is increasing and will require effective prevention and control techniques for northern climatic conditions.

## 3.0 ACID GENERATION AND ITS CONTROLS

### 3.1 THE PROBLEM OF ACID GENERATION

The problem of acid generation specific to northern Canada and the associated studies required are well reviewed in recent MEND and DIAND (Department of Indian and Northern Affairs) publications. A brief review is provided below for continuity and reference only.

#### 3.1.1 Sources of Acid Generation

Acid generation is caused by the exposure of rock and/or mine/mill tailings containing reactive sulphide minerals, such as pyrite ($FeS_2$) and pyrrhotite ($Fe_{x-1}S_x$) to air (i.e. oxygen) and water. The oxidation of sulphides results in the production of sulphuric acid which in turn may elevate concentrations of iron and other available metals. Under natural conditions, an overlying soil and/or groundwater minimizes contact between the sulphide minerals and oxygen. While oxidation of the sulphides may occur, it will do so at such a slow rate that impact on groundwater quality is negligible or not detected. The exposure of this rock to air and water through general surface disturbances such as construction (Guilcher 1987) or mining (Feasby 1994), may cause the rate of acid generation to be accelerated. While natural outcrops of acid generating rock exist, the major source of ARD in Canada is the large scale exposure of sulphide bearing ores due to mining activity which massively increases the surface area of the rock fragments.

#### 3.1.2 Process of Acid Generation

The chemical reactions of acid generation are usually illustrated by examining the oxidation of pyrite. Because of its natural abundance and its minimal economic value, pyrite is the most widespread sulphide mineral that can be found in any mine waste. By virtue of its low metal to sulphur ratio, it is also one of the most potent acid generators upon oxidation.

The acid generation process involves oxidation of both sulphur and iron, where the electron transfer occurs to the oxidant either chemically or biologically depending upon the pH and temperature of the medium. Initially, when the sulphide bearing waste or rock is freshly exposed, it has a near neutral or slightly alkaline pH as determined by the solubility of its carbonate minerals. Sulphur is first oxidized from $S^{1-}$ in pyrite for example, through various intermediate oxidation stages of elemental sulphur, thiosulphate, sulphite and ultimately to sulphate, as represented by:

$$FeS_2 + 3.5\,O_2 + H_2O = Fe^{2+} + 2SO_4^{2-} + 2H^+ \quad (3.1)$$

Thermodynamically, sulphides such as pyrite are stable in reducing aqueous environments. Under oxidizing conditions, pyrite is readily oxidized and dissolved to yield $Fe^{2+}$, as in $FeSO_4$ above, and eventually $Fe^{3+}$ species as in:

$$2Fe^{2+} + 0.5\,O_2 + 2H^+ = 2Fe^{3+} + H_2O \qquad (3.2)$$

At near neutral to weakly acidic conditions (pH 4-7), the ferric iron so produced is hydrolysed further producing acidity and ferric hydroxide precipitate:

$$Fe^{3+} + 3H_2O = Fe(OH)_{3(solid)} + 3H^+ \qquad (3.3)$$

The overall oxidation of pyrite above pH 4 is stoichiometrically summarized by the reaction below leading to ferric hydroxide precipitation and sulphuric acid production.

$$FeS_2 + 15/4\,O_2 + 7/2\,H_2O = Fe(OH)_{3\,(solid)} + 2SO_4^{2-} + 4H^+ \qquad (3.4)$$

When completely oxidized, one mole of pyrite thus produces two moles of sulphuric acid, or 1% sulphur in pyrite is equivalent to 31.25 kg $CaCO_3$/tonne acidity. When buffering carbonate minerals such as calcite are present, the sulphuric acid produced in the oxidation process is readily consumed and neutral pH conditions are maintained by the neutralizing process:

$$CaCO_3 + 2H^+ + SO_4^{2-} = CaSO_4 + H_2O + CO_2 \qquad (3.5)$$

In the presence of oxygen at neutral to alkaline pH's, ferrous iron is converted to ferric iron and precipitated as hydroxide (equation 3.3). The overall oxidation of pyrite is strongly pH dependant, as discussed later. At pH values less than 4, the ferric iron produced as a result of ferrous iron oxidation (equation 3.2), remains in solution and acts as an oxidant, further oxidizing pyrite in the absence of oxygen as:

$$FeS_2 + 14Fe^{3+} + 8H_2O = 15Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad (3.6)$$

This reaction (equation 3.3) is fast (McKibben and Barnes 1986 and Alpers and Nordstrom 1991), but its rate is limited in an acidic system because the reoxidation of ferrous to ferric iron by direct chemical oxidation is extremely slow at pH below 4. Singer and Stumm (1969 and 1970) reported that the oxidation of $Fe^{2+}$ to $Fe^{3+}$ (equation 3.2) was rate limiting and very slow under sterile conditions. The above reaction (equation 3.6) commonly occurs in tailings and waste rock below the water table or in zones where oxygen is depleted.

Biological oxidation is more prominent in acidic conditions and dominates in the pH range between 2-4. The oxidation of $Fe^{2+}$ to $Fe^{3+}$ is greatly accelerated by microbial activity of omni-present bacteria such as *Thiobacillus ferrooxidans*, which are present in natural environments, and reported to be five to six orders of magnitude greater than chemical oxidation under optimal conditions (Alpers and Nordstrom 1991, and Nordstrom 1985). The latter author also reported that when bacterially catalyzed, the rate of regeneration of $Fe^{3+}$ (equation 3.2) is about three orders of magnitude greater than the rate of pyrite oxidation by $Fe^{3+}$ (equation 3.6). In addition, at pH below 4, the solubility of $Fe^{3+}$ increases making it available for pyrite oxidation. For pH $< 2$ the chemical oxidation becomes again the dominant process (Knapp 1987).

Oxygen remains a critical reactant by serving to regenerate the ferric iron. Oxygen is also critical to the growth of iron and sulphur oxidizing bacteria, (e.g. *Thiobacillus ferrooxidans* and *Thiobacillus thiooxidans*). The growth of these micro-organisms also depends on dissolved $CO_2$ (as a source of carbon), and nitrogen and phosphorous. Hence, aeration of water is crucial to the continuation of ARD by oxidation of sulphide minerals.

In ore bodies containing mixed sulphide minerals, preferential oxidation through electrochemical processes usually occurs in specific metal sulphides. It has been long observed that the presence of two or more sulphides in an ore can significantly increase the rate of reactivity (Flann and Lukaszewski 1970). When a sulphide mineral assemblage is exposed to weathering conditions, especially in the presence of a continuous film of water adhered to the minerals, preferential weathering through a galvanic process commonly occurs. Mehta and Murr (1983) reported on galvanic interactions in bacterial leaching of mixed metal sulphides. However, according to Kwong (1993), a general weathering sequence for common sulphides may not exist except at a local scale.

### 3.1.3 The Extent of Liability Associated with ARD

The impact of ARD can be significant to the aquatic environment, if it is not collected and treated or contained. Where acidic drainage occurs, mine decommissioning costs can be considerable.

A total of about 7 billion tonnes (41,000 hectares) of metal-mine and industrial mineral tailings has been estimated to exist in Canada, while about 6 billion tonnes of waste rock are estimated to be deposited on surface. In addition, approximately 400 million tonnes of mine waste are generated annually. At least one quarter of the tailings is considered acid generating or potentially acid generating and that less than 12% of the waste rock is considered to be acid generating or potentially acid generating. In terms of reclamation, the liability associated specifically with ARD in Canada has been estimated to range from \$2-5 billion, while the cost of reclaiming non-acid generating mine waste sites to meet current standards is expected to be over \$1 billion (Feasby 1994). Less than 10% of the total \$3-6 billion liability is attributable to sites that have reverted to the Crown, leaving the Canadian mining industry with the major portion.

The Yukon and NWT combined, are estimated to contain approximately 3.5% of the acid producing and potentially acid producing mine mill/tailings, and approximately 3% of the neutral to basic mine/mill tailings in Canada. They also account for approximately 2.3% of the potentially reactive waste rock and less than 0.2% of the neutral to basic waste. This translates into an estimated current liability of over \$77 million for the Territories based on \$200k/ha of tailings and \$0.10/tonne of waste rock for treatment with neutral or alkaline material (Feasby 1994).

## 3.2 ARD CONTROLLING FACTORS

### 3.2.1 Control Versus Treatment of ARD

The impact of ARD on the receiving environment can be managed either by controlling the acid generation at the source or by collecting and treating the ARD prior to its discharge. The long-term costs associated with control of acid generation versus containment and treatment are considerable and estimated to be similar in magnitude (Feasby 1994), based on current control and treatment options. Although the control of ARD at the source is fundamental and desirable first, emerging technologies do not have established track records. Conventional treatment processes may be secondary but have established track records of industry-wide usage. Because of the need to treat "in perpetuity", uncertainty about future costs and long-term sludge disposal, the option to collect and treat is often simply not accepted from a regulatory perspective (Price and Errington 1994). For active or proposed mines,Williams (1994) considered treatment as the option of last resort, or no option at all. In the cold climatic regions of northern Canada, treatment is a seasonal batch operation (only during frost free season), and its continued application for inactive and decommissioned mines may not be considered viable.

A detailed approach to controlling acid generation was originally outlined in the "Draft Acid Rock Drainage Technical Guide" prepared by Steffen, Robertson and Kirsten in 1989 (SRK 1989). The factors associated with these controls may be grouped in the following two categories.

1. Removal of [Essential] Active Components:
   - ☐ removal or isolation of sulphides
   - ☐ exclusion of water
   - ☐ exclusion of oxygen

2. Control of Parameters at Source:
   - ☐ temperature control
   - ☐ pH control
   - ☐ bacterial action control

These factors can have a significant impact on the rate and extent of acid generation and are discussed briefly below.

### 3.2.2 Removal of Essential Active Components

Sulphide minerals are the principle source of ARD. If sulphide minerals can be removed, reduced to insignificant levels or deactivated by a coating then the ARD problem can be controlled. Sulphide removal via gravity separation and flotation has been examined (CESL 1994), and demonstrated (Stuparyk 1995). The resultant volume of potentially inactive low sulphur tailings represents not only a reduced liability but also a potentially cost-effective source of cover and dam construction material for the prevention of ARD. For cost effectiveness, de-sulphurized tailings need only to be placed above the water table or permafrost boundary in a tailings basin. In regions of discontinuous permafrost, placement of un-classified de-sulphurized tailings could also be used to elevate the local water table (MEND, March 1996).

The exclusion or diminution of water for the control of ARD generation requires the use of impermeable barriers such as synthetic membranes or composite covers, generally comprised of a saturated clay layer sandwiched between two coarse sand layers (Yanful 1991, Yanful and St-Arnaud 1991). The application of these covers, even where appropriate material is available, is expensive (SENES 1994), and their long-term rates of degradation, due to heaving, subsidence and root penetration, are unknown. In areas where evaporation exceeds precipitation, ARD migration may also be limited. While parts of the Canadian north experience an annual evapo-transpiration exceeding annual precipitation, a negative net influx of water is not in itself sufficient to ensure environmental protection.

The exclusion of oxygen is probably the most effective long-term acid generation control technique. Placement of a cover with extremely low oxygen diffusion characteristics such as water, low permeability soils and clay, synthetic membranes, or a combination of these materialsis used. Effectiveness of the water cover is based on the low solubility (8.6 $gm^{-3}$ at 25°C) and low diffusivity ($2x10^{-9}$ $m^2s^{-1}$) of oxygen in water and may be enhanced by the addition an oxygen-consuming barrier placed at the water-waste interface.

### 3.2.3 Control of Parameters at Source

The sulphide oxidation process is temperature dependant; both chemical and biological oxidation rates decrease with decreasing temperatures as shown in Figure 3.1. At temperatures below 3°C microbial activity is reported to be nearly absent (Ahonen and Tuovinen, 1989, 1991). As well, near 0°C the chemical oxidation rate is shown to be reduced to less than 15% of its value at 25°C (Knapp 1987). While Dawson and Morin (1996) report that chemical reactions and weathering in cold climates and permafrost are not negligible, there is no reported data on the impact of temperatures at or below freezing (0°C) on the oxidation rates of sulphide minerals. Temperatures below freezing reduce, but do not eliminate, the availability of liquid pore water in the immediate vicinity of the mineral grains. In addition, oxygen solubility in water increases with decreasing temperatures (Otwinowski 1994).

The overall (chemical and biological) oxidation of pyrite is also strongly pH dependant. Under optimal conditions the biological oxidation rate is several orders of magnitude greater than that for chemical oxidation. A pH range of 2-4 is considered optimal for bacterially-assisted sulphide oxidation (Knapp 1987, Otwinowski 1994), while the chemical oxidation rate essentially remains unchanged below pH 3, and increases for pHs above 3 (U.S. EPA 1971). Figure 3.2 shows the rate of bacterial oxidation, normalized to the maximum biological rate at pH ~3.5 with temperature and the normalized chemical oxidation rate of pyrite as a function of pH relative to that at pH 7.0. Thus, if the pH of the interstitial water in the waste is maintained within an alkaline range, acid generation by sulphide oxidation can be inhibited. The pH may be controlled by blending the acid generating waste with acid consuming wastes or by adding alkaline material such as ground limestone.

Bacterial activity, particularly that of *Thiobacillus ferrooxidans*, catalyzes the acid generation process and can increase the rate by several orders of magnitude (Lundgren 1980). Otwinowski (1994) suggests that at 30°C with a bacterial concentration in the order of 1 g/L water, bacterial oxidation is over a thousand times faster than in the absence of bacteria. Alpers and Nordstrom (1991) report that the oxidation rate of $Fe^{2+}$ to $Fe^{3+}$ increases by five to six orders of magnitude over the rate of chemical oxidation under optimal conditions. In addition to pH control mentioned above, acid generation can be minimized by controlling bacterial activity with applications of bactericides such as anionic surfactants, organic acids and/or some food preservatives. However, most of these additives are water soluble, require frequent reapplication, and are therefore considered suitable for acid generation control only in the short-term (MEND 1994).

## 3.3 ARD CONTROL TECHNOLOGIES AND THEIR ADAPTABILITY FOR NORTHERN CLIMATIC CONDITIONS

A variety of control technologies have been proposed and/or applied to mine waste for abating acid generation at source by inhibiting sulphide oxidation. The cost and resulting effectiveness of these technologies are, in large part, a function of the site specific topography, geology, mineralogy and availability of construction or cover materials. A detailed assessment of the various control options or their limitations is however beyond the scope of this review and the reader is referred to various MEND publications.

For a variety of site specific conditions, two of the most advanced technologies for ARD control in Canada are:

1) Engineered dry barriers; and
2) Underwater disposal and wet barriers.

Engineered dry barriers are constructed from a wide variety of natural and man-made materials in order to limit oxygen ingress and, in some instances, water infiltration to the waste material. Some cover designs include the use of organic-rich, oxygen consuming materials such as low grade municipal and yard compost which give the barrier oxygen-consuming properties. These covers are subject to degradation unless replenished. Engineered dry covers are generally expensive, costing in the range of $200k-300k/ha, but at some sites, other options may not be suitable.

Underwater disposal and wet barriers are two sub-classes of the water cover option. The first refers to sub-aqueous disposal of the waste material in natural or man-made water bodies and the latter, in situ flooding of previously surface deposited waste by constructing and/or raising impervious impoundment dams. Water covers are the most natural and economical option available for many geographic regions. Waste disposal in biologically productive natural lake and marine environments is more restrictive because of natural ecosystem and habitat conservation laws. Permission for disposal in small head ponds and man-made lakes is more easy to obtain and is given on a case by case basis.

Water cover by itself does not completely inhibit sulphide oxidation and acid generation, as the water is usually saturated with dissolved oxygen. The oxidation process, however, is severely limited and the low levels of acidity and metals so released underwater may be manageable through other passive treatment systems. Water cover therefore continues to be the most promising ARD control technology at sites where favourable terrain and climate conditions permit impoundment and/or maintenance of the cover. In the north there are thousands of small and isolated head lakes which could be utilized for underwater disposal of reactive wastes.

In applying the water cover option to the north, a number of factors need to be considered; such as role of ice, increased solubility of oxygen in cold water, role of snow cover on ice thickness/water depth management, minimum depths of water cover, and requirement of an additional layer at the water-waste interface. A discussion of these parameters is provided in Chapter 4.

Permafrost offers another latitude towards ARD management and control in northern Canada. It is generally suitable for encapsulating tailings in the frozen ground by appropriate placement and in situ freezing methods. Successful encapsulation of tailings in permafrost, below the seasonal freeze-thaw boundary, may ensure in situ temperatures at or below 0°C with simultaneous reductions in chemical and bacterially assisted reaction rates. The characteristics of permafrost in ARD control, role of active freeze-thaw layer and isolation covers, material transport, freeze/thaw cycles, potential for frost heaving and concepts for the use of permafrost in tailings management are examined in Chapter 5.

## 4.0 ROLE OF ICE AND SNOW ON THE WATER COVER OPTION

### 4.1 INTRODUCTION TO THE WATER COVER OPTION

Water covers can be an economically attractive as well as an effective technique for the control of sulphide oxidation in the longer term. The objective of sub-aqueous or underwater disposal is to minimize the long-term oxidation of the submerged waste, and thereby, the impact of the oxidation products and leached contaminants on the surrounding environment. A critical review of studies on subaqueous disposal of tailings to 1991 by the MEND program was completed in 1992 (MEND, 1992). Based on work covered by the review, the application of a single "generic" approach to subaqueous disposal is not considered practical, and site specific considerations must be addressed with respect to the following options:

- ☐ lake disposal;
- ☐ catchment disposal; and
- ☐ man-made structures.

Lake disposal is considered for fresh, unoxidized tailings only. Placement must be considered such that short-term impacts to the lake are minimized and long-term disturbance and resuspension of the solids are avoided. Despite many biological concerns, it is noted (MEND, 1992) that over the long term, the lake environment may offer the most secure form of disposal.

Catchment disposal, while also focussed on minimizing oxygen/fresh tailings interaction, results in the filling of an existing lake or depression such that a shallow water cover or wetland is maintained on the surface of the tailings. This disposal option results in a significant change in habitat type.

Man-made structures allow a water cover to be introduced over either fresh or partially oxidized tailings by flooding a reservoir or impoundment. Such structures can provide confined aquatic conditions without the loss of, or impact to, surrounding natural aquatic habitat. While this option allows for a high degree of site specificity and quality control, structural integrity and associated monitoring requirements over the long term could become an issue.

Water covers significantly reduce the effective diffusion rate of oxygen into tailings as noted in Table 4.1 and illustrated in the comparison of Figures 4.1 and 4.2. However, metals present in porewater solutions or in soluble mineral phases may still be released from a flooded tailings impoundment. Several laboratory leach tests, performed under ambient temperature, to evaluate metal release rates with time, showed limited metal releases (St-Arnaud 1994, Aubé 1995).

Although oxidation of sulphides and metal leaching may not be halted entirely by placing wastes underwater, the rates may be sufficiently reduced to make the impact negligible. This is particularly true where a combination of high organic load and rapid sedimentation ensure the establishment of anoxic conditions at shallow depths (Pedersen, 1991). Where significant sedimentation does not occur, the top layer of deposited tailings may oxidize and release limited quantities of metals over time. However, if the tailings remain undisturbed, this primarily diffusion controlled process will become less significant with time.

One of the two primary control options currently being advocated in the Yukon and NWT is the subaqueous disposal of tailings into lakes. The isolation and limited accessibility to most sites has required that abandonment and restoration plans involve a minimum of long-term maintenance and monitoring. In the Northwest Territories, Polaris and Nanisivik are the only mines which are currently depositing tailings subaqueously (private communication, Eric Madsen 1995). The tailings from Polaris are discharged into the naturally stratified or meromictic Garrow Lake. Tailings at Nanisivik were stored under a shallow water cover until 1991 when the underwater storage capacity of West Twin Lake was exceeded. Since that time the tailings have primarily been deposited, beached, above the water level (Klohn Leonoff, 1994).

## 4.2 WATER COVER AS AN EFFECTIVE OXYGEN DIFFUSION BARRIER

Water has low oxygen diffusivity as well as solubility which probably makes it the most economical and best oxygen limiting natural cover that is readily available for temperate climatic zones where average annual precipitation exceeds total evaporation losses.

The solubility of oxygen in water is low, approximately 8.6 mg/l (8.6 $g/m^3$) at standard conditions of temperature (25°C) and pressure (100 kpa) compared to 21% v/v (285$g/m^3$) concentration of oxygen in air. At colder temperatures, the oxygen solubility in water increases with decreasing temperatures and reaches a maximum of 14.5 $g/m^3$ at 0°C. Freezing of water often entraps air bubbles creating localized zones of increased oxygen concentration in turbulent conditions, but once frozen the oxygen remains immobile.

The diffusion coefficient of oxygen in water is ~2 x $10^{-9}$ $m^2/s$, which is nearly four orders of magnitude lower than in air at ~1.78 x $10^{-5}$ $m^2/s$ (Davé 1992), make the water cover an oxygen limiting barrier for reactive wastes.

Many of the technical features of water cover including the present status of the technology (knowns), regulatory and other requirements (unknowns) and required actions (how to get information) have been reviewed by Davé (1992) in "Water Cover on Acid Generating Mine/Mill Wastes - A Technical Review". In this review Davé used a simple one dimensional diffusion model to demonstrate the effectiveness of a shallow water cover in reducing the oxygen concentration as well as flux in a reactive material deposited underwater. The model predicted that water saturation of reactive tailings decreased oxygen flux by a factor of approximately 3100 in comparison to that of well drained tailings without any cover. The model concepts are briefly reviewed here and their application are further extended to include the impacts of cold temperature conditions in the water cover scenario as well as that without a cover.

### 4.2.1 Theoretical Considerations

According to Davé (1992), the oxygen concentration profiles in a media consisting of one or several layers of reactive material, other secondary oxygen barrier material overlain by a layer of water cover are given by the solution of the generalized diffusion equation of the form:

$$\frac{\partial c(t,z)}{\partial t} = D_e \frac{\partial^2 c(t,z)}{\partial z^2} - Rc(t,z) \qquad (4.1)$$

where:

| | | |
|---|---|---|
| c (t,z) | = | oxygen concentration at time t (sec) & depth z (metre); $g/m^3$ |
| z | = | depth measured from top surface of the water cover; m |
| $D_e$ | = | effective oxygen diffusion coefficient for molecular diffusion of oxygen in water or sediment layers; $m^2/s$ |
| R | = | oxygen consumption rate constant for chemical, biological and other oxidation processes, $s^{-1}$ |

The effective oxygen diffusions coefficient "$D_e$" in a porous media such as tailings or other substrates is related to the bulk diffusion coefficient "$D_o$" of molecular oxygen in that media by:

$$D_e = D_o \cdot \eta \cdot \tau \qquad (4.2)$$

where:

| | | |
|---|---|---|
| η | = | porosity of the substrate layer expressed as a ratio of void to bulk volumes ranging from 0.4 (tailings) to 0.8 (sediments), and |
| τ | = | tortuosity factor which accounts for the tortuous pathways in the waste or sediment pore sequences. Typical values of τ range from 0.2 to 0.6 for soils, and are close to unity for most bottom sediments (Van Rees et al. 1991). For tailings, η and τ are taken as 0.4 and 0.2, respectively (Yanful et.al. 1991). |

For most practical purposes, it is reasonably assumed that the system readily attains a steady state equilibrium which is represented by equating the time dependent term $\partial C(t,z)$ to zero in equation (4.1) resulting in a simplified equation of the form:

$$D_e \frac{d^2 c(z)}{dz^2} = Rc(z) \qquad (4.3)$$

where:

| | | |
|---|---|---|
| c(z) | = | oxygen concentration at depth z(m) below the interface in a single layer system; $g/m^2$ |

The generalized solution of the above equation (4.3) is given by:

$$c(z) \quad = \quad c(o)\exp(-\sqrt{R/D_e} \bullet z) \tag{4.4}$$

with the boundary condition c(z) = c(o) for z=0 at the interface, and c(z) = 0 for $z \rightarrow \infty$ .

The oxygen flux J(o) (g/m$^2$/s) at the interface, z=0 for the steady state condition is given by:

$$J(z) \quad = \quad D_e \frac{dc(z)}{dz} \Big|_{z=0} \tag{4.5}$$

and,

$$J(o) \quad = \quad c(o)\sqrt{R \bullet D_e} \tag{4.6}$$

Using the above referenced oxygen solubility (concentration) and diffusion coefficients for water and air, and experimentally determined oxygen consumption rate constant "R" by Halbert et al. (1982) from sulphate production rates observed in the oxidation of pyritic uranium tailings at various temperatures, (as given in Table 4.1), the ratio of oxygen flux crossing the interface boundary into the waste for water and air filled pore spaces of the reactive waste (tailings) is calculated as:

$$\frac{J(o)\ water}{J(o)\ air} \quad = \quad 0.32\ x\ 10^{-3} \tag{4.7}$$

The above relationship shows that for saturated tailings (water filled pore space), the oxygen flux into the waste at the interface is decreased by a factor of at least 3100 compared to that of air exposed and well drained unsaturated tailings (air filled pore space), as described previously.

Davé (1992) further illustrated the efficiency of a water cover in limiting available oxygen by considering the following five scenarios:

1) No Water Cover: Air exposed unsaturated waste;
2) Water Saturated Waste: Zero depth of water cover above the interface;
3) Water Covered Waste: 1 m depth of water above interface, water column un-mixed (stagnant);
4) Water Covered Waste: 2 m depth of water above interface, water column un-mixed (stagnant); and
5) Water Covered Waste: 1 m depth of water above interface, well mixed water column.

For each of these scenarios he calculated the individual oxygen concentration profile as well as oxygen flux at the interface for a hypothetical tailings basin, 100 ha in area and containing 10 million tonnes of tailings at 20% pyrite. He concluded that the oxygen flux is reduced from ~10, 926 g/m$^2$/y for unsaturated (air filled pore spaces) tailings to 3.49, 0.47, 0.25 and 3.49 g/m/y, respectively, for cases 2 to 5 above.

These five cases are re-examined in the present review, in the context of cold temperature conditions, at three temperatures of 25°C, 4°C and 0°C representing, respectively, warm, density inversion point for water and freezing point leading to ice conditions. The objective is to obtain insight into how the cooling of the system (tailings with and without a water cover) impacts the oxygen diffusion characteristics into the waste.

Table 4.1: Physical constants for oxygen solubility (concentrations), diffusion and consumption rates, and tailings porosity and tortuosity for air and water media.

| **Parameter** | **Air** | **Water** |
|---|---|---|
| Oxygen concentration, mg $L^{-1}$ (g $m^{-3}$) | 285 | 8.6 (25°C)<br>12.8 (4°C)<br>14.5 (0°C) |
| Molecular diffusion coefficient of oxygen, $D_o$, $m^2$ s-1 | 1.78 x $10^{-5}$ | 2 x $10^{-9}$ |
| Effective diffusion coefficient of oxygen, $D_e$ in tailings, $m^2s^{-1}$ | 1.43 x $10^{-6}$ | 1.6 x $10^{-10}$ |
| Oxygen consumption rate, R, $s^{-1}$ | 10.32 x $10^{-7}$ (25°C)<br>2.58 x $10^{-7}$ (4°C)<br>1.55 x $10^{-7}$ (0°C) | 10.32 x $10^{-7}$ (25°C)<br>2.58 x $10^{-7}$ (4°C)<br>1.55 x $10^{-7}$ (0°C) |
| Tailings porosity | 0.40 | 0.40 |
| Tailings tortuosity | 0.20 | 0.20 |

In solving the above oxygen diffusion equations, it is assumed, for simplicity, that the temperature effects are most significant for oxygen solubility in water and for oxygen consumption rate constant "R" for sulphide oxidation. The concentration of oxygen in air, bulk diffusion coefficients of molecular oxygen in air and water, tailings porosity and tortuosity are also temperature dependent, but for these computations their temperature variations are not considered. Table 4.1, gives the input parameters used for oxygen concentration, diffusion and consumption rate constant and tailings porosity and tortuosity at the three different temperatures. The dissolved oxygen concentrations in water are taken from Otwinowski (1994) and are respectively 8.6, 12.8 and 14.5 g/$m^3$ at 25°C, 4°C and 0°C. The reaction (oxygen consumption) rate constants are taken from Halbert (1982), Knapp (1987) and SENES (1991) and are taken as the combined total chemical as well as bacterial oxidations of reactive sulphides. At low temperatures, the latter process is however less dominant but is believed to exist even at 0°C as discussed in Section 4.3.1.

For these computations, it is further assumed that because of high salt concentration, the tailings interstitial water as well as water cover layer immediately above the tailings remain unfrozen at 0°C as the freezing point is depressed with increased dissolved solids. Freezing of interstitial water is further discussed in Section 5.3.2.

The calculated results for oxygen concentration c(z) at various depths, oxygen diffusion flux J(o) entering the tailings at the interface and the total time required, in years, for complete oxidation of a hypothetical tailings pile, 100 ha in area, containing 10 million tonnes of tailings at 20% pyrite, are summarized in Table 4.2 for the five different cover scenarios under consideration.

Table 4.2: Steady state oxygen diffusion flux J(0) in the waste at the interface boundary ($g\ m^{-2}\ y^{-1}$) and the total time (y) in years to completely oxidize a tailings pile, 100 ha in area containing 10 million tonnes of tailings at 20% pyrite.

| Scenario | | Flux J(0), $g\ m^{-2}\ y^{-1}$ | Time (y) Years |
|---|---|---|---|
| **Case 1:** | No cover: air exposed and unsaturated | 10,926 (25°C)<br>5,463 (4°C)<br>4,234 (0°C) | 181.2 (25°C)<br>362.4 ( 4°C)<br>467.6 ( 0°C) |
| **Case 2:** | Water saturated waste: zero depth of water cover above the interface | 3.49 (25°C)<br>2.60 ( 4°C)<br>2.28 ( 0°C) | $5.67 \times 10^5$ (25°C)<br>$7.61 \times 10^5$ ( 4°C)<br>$8.68 \times 10^5$ ( 0°C) |
| **Case 3:** | Water covered waste: depth of water 1 m above the interface without mixing (stagnant) | 0.47 (25°C)<br>0.62 ( 4°C)<br>0.65 ( 0°C) | $4.21 \times 10^6$ (25°C)<br>$3.19 \times 10^6$ ( 4°C)<br>$3.05 \times 10^6$ ( 0°C) |
| **Case 4:** | Water covered waste: depth of water 2 m above the interface without mixing (stagnant) | 0.25 (25°C)<br>0.35 ( 4°C)<br>0.38 ( 0°C) | $7.92 \times 10^6$ (25°C)<br>$5.66 \times 10^6$ ( 4°C)<br>$5.21 \times 10^6$ ( 0°C) |
| **Case 5:** | Water covered waste: depth of water 1 m above the interface and well mixed | 3.49 (25°C)<br>2.60 ( 4°C)<br>2.28 ( 0°C) | $5.67 \times 10^5$ (25°C)<br>$7.61 \times 10^5$ ( 4°C)<br>$8.68 \times 10^5$ ( 0°C) |

The computed oxygen concentration profiles for these scenarios are plotted in Figures 4.1-4.6, respectively, including an expanded scale oxygen concentration profiles for saturated tailings having water filled pore space (Figure 4.3). The temperature effects for these cases are discussed below.

### 4.2.2 Temperature Effects

**Case 1. No Cover: Air Exposed Unsaturated Tailings (Air Filled Pore Space)**

This scenario is considered for comparative purposes for evaluating the effectiveness of the water cover in controlling oxygen ingress into the waste material at various cold temperature conditions. Although the effects of cold temperatures on unsaturated tailings are considered separately in the next chapter under permafrost, the present computed results are helpful in understanding the oxidation characteristics of tailings at near freezing temperatures.

The oxygen ingress in unsaturated tailings increases as the temperature is lowered from 25°C to 0°C, when, at a given depth, the residual pore gas oxygen concentration is significantly elevated at low temperatures resulting from reduced oxidation reaction rates upon cooling (Figure 4.1). The oxygen diffusion flux at the interface, however, decreased from J(o) = 10,926 at 25°C to 5,463 at 4°C and 4,234 $g/m^2/y$ at 0°C with decreased oxygen consumption. The calculated time for complete oxidation of the hypothetical tailings basin increased from approximately 181 years (y) at 25°C to 362 at 4°C and 468 y at 0°C (Table 4.2). The overall impact of cooling the uncovered tailings from 25°C to 0°C has been to slow down the pyrite oxidation by a factor of approximately 2.5.

The above modelling results have several implications on management of reactive wastes at low and near zero temperatures. Although the lowering of temperature from 25°C to 0 °C, decreases the relative reaction rate constant to less than 15% of that at 25°C (Knapp 1987 & Senes 1991), the resultant oxygen flux into the waste is only decreased by a factor of 2.5, which is not considered significant enough to preclude oxidation at near zero temperatures. Thus encapsulation of waste in permafrost alone, where sub-surface temperatures are on the order of 0°C, is not sufficient to prevent acid rock drainage at northern latitudes. Temperatures below the freezing point of the interstitial water (dependent on its dissolved solid or salt contents) would however produce permanently frozen conditions within the waste and prevent migration of metal bearing leachates. As this condition may not be easily achievable (see Section 5.3.2), an oxygen barrier layer in the form of a simple or composite cover or unsaturated waste will generally be required. These findings are similar to those predicted by Dawson and Morin (1995), who concluded that frozen ground conditions do not necessarily halt acid rock drainage reactions but freezing of waste decreases its hydraulic conductivity by several orders of magnitude providing adequate containment of oxidation reaction products. Experimental results of Davé and Clulow (1996) further substantiate the above conclusions where they observed slightly delayed but continued oxidation and acid generation at 2°C under unsaturated conditions (further discussed in Section 5.3.2).

**Case 2. Water Saturated Waste: Zero Depth of Water Cover Above the Interface (Water filled pore space)**

In saturated tailings, because of low oxygen solubility and diffusivity, the oxygen ingress is limited to only a few centimetres below the exposed surface of the tailings (Figures 4.2 and 4.3). At 25°C, the dissolved oxygen concentration in the interstitial water reaches zero at a depth of approximately 8 cm, which increases to 16 and 20 cm, respectively, for 4°C and 0°C. Although the depth of oxygen ingress increases with decreasing temperatures, the oxygen diffusion flux J(o) entering the waste at the interface decreases from 3.49 at 25°C to 2.60 at 4°C and 2.28 $g/m^2/y$ at 0°C, and the corresponding time for complete oxidation of the hypothetical pile increases from $5.67 \times 10^5$ y at 25°C to $7.61 \times 10^5$ y at 4°C and $8.68 \times 10^5$ y at 0°C (Table 4.2). Contrary to the general belief that cooling of saturated tailings induces additional oxygen flux at low temperatures, the model predicted a reduced oxygen flux resulting from a significant decrease in reaction rate constant which off-sets the corresponding increase in dissolved oxygen concentration at low temperatures.

The effectiveness of saturated tailings, relative to un-saturated tailings, in limiting the oxygen influx decreases as the temperature is lowered. This relative reduction factor goes from approximately 3100 at 25°C to 1800 at 0°C, as the oxygen flux in unsaturated (air filled pore space) tailings is also reduced. Nonetheless, in the saturated tailings the oxygen ingress is limited, controlled primarily by the low oxygen diffusivity in water which limits/controls oxidation to very low rate and in a narrow zone near the surface of the tailings.

Freezing of saturated tailings at the surface limits air exchange with interstitial water below the frost layer. This may in turn produce anoxia or oxygen deficient conditions within the saturated tailings below the frost penetration depths. At northern latitudes, this anoxic condition may last eight months or longer when tailings are dormant or inactive, and a limited frost free period of very low oxidation activity exists near the surface of the tailings.

For minimal activity, the tailings need to be deposited and maintained in saturated conditions at all times. This can be successfully achieved by depositing whole tailings as a paste mix, without particle size segregation, which decreases hydraulic conductivity and retains near saturated moisture conditions, and using low permeability impoundment dams for retention. This option is particularly suitable for low precipitation regions where a water cover on tailings cannot be maintained. However, this option requires that frost heave and wind erosion be addressed.

**Case 3&4. Water Covered Waste - 1 and 2 Metre Depths of Water Cover Above The Interface With Un-mixed (Stagnant) Water column**

These two scenarios are hypothetical, as generally shallow water covers, 1 to 2 m in depths, are always well mixed. The mixing is caused by wind and wave induced motion, thermal gradients driven eddy currents and surface and ground water flows. Upon freeze-up however, some form of stagnant water column condition may develop below a complete ice cover for a certain time period which requires due consideration in the water/ice cover scenario.

The oxygen concentration decreases linearly in the stagnant water column above the tailings and decreases very rapidly in the tailings below the interface for both depths of water cover at all three temperatures (Figures 4.4 & 4.5). The lowering of water temperature resulted in much increased dissolved oxygen concentration at the interface, in comparison to increased oxygen solubility at low temperatures, contributing to increased oxygen ingress as well as oxygen influx into the tailings (Table 4.2). For 1 m water cover, the oxygen flux increased from 0.47g/$m^2$/y at 25°C, to 0.62 at 4°C and 0.65 at 0°C. The corresponding increase for 2 m cover depths is from 0.25 g/$m^2$/y at 25°C to 0.38 g/$m^2$/y at 0°C. The calculated complete oxidation time period for the hypothetical tailings pile decreased from 4.21 x $10^6$ y at 25°C to 3.05 x $10^6$ at 0°C for 1 m cover and from 7.92 x $10^6$ at 25°C to 5.21 x $10^6$ at 0°C.

The effects of water cover depths in attenuating oxygen diffusive flux is only realized in the stagnant water column case, where oxygen influx decreases with increasing water cover depth as seen from Table 4.2. In terms of cost-benefit analysis, the incremental gain in oxygen flux attenuation is, however, minimal by doubling the depths of water cover.

As discussed for the saturated tailings scenario above, the formation of a complete ice cover limits the available oxygen in the un-frozen water above the tailings and decreases oxygen ingress and influx into the tailings. The effects of increased dissolved oxygen concentrations at low temperatures can thus be reversed during prolonged ice cover periods.

**Case 5. Water Covered Waste: 1 m Depth of Water Cover Above the Interface With Well Mixed Water Column**

The well mixed water column and saturated tailings scenarios are similar in their oxygen ingress and oxygen influx characteristics into the tailings (Table 4.2) with the exception that the water cover above the tailings is uniformly saturated with oxygen which increases in concentration at decreasing temperatures (Figure 4.6). In this scenario, no advantage of water cover depth is realized. During the ice free period, the oxygen flux decreases from 3.49 g/$m^2$/y at 25°C to 2.60 at 4°C and 2.2 at 0°C. The corresponding complete oxidation period increases from 5.67 x $10^5$ at 25°C, to 7.61 x $10^5$ at 4°C and 8.68 x $10^5$ y at 0°C.

With the formation of a complete ice cover, the mixed water column is isolated from wind and wave related turbulence and air-water exchange, thereby developing poorly mixed and oxygen deficient conditions in the unfrozen water cover above the tailings which further decrease oxygen ingress as well as flux as discussed previously for scenarios 3 and 4.

In practical applications, the water column is generally well mixed in basins with a shallow water cover of depths less than 4 m. Un-mixed conditions may exist in sheltered bays or isolated locations such as open pits where mixing usually occurs seasonally in spring and fall turnovers. Deposition of mine waste in an un-mixed water column is preferable but as discussed further in Section 4.3.1, this scenario may exist only at very few sites. Mine waste, in general, is deposited in man made lakes with a shallow water cover, averaging in depths approximately 1 metre or in natural basins where depths greater than 2 metres of water cover can be provided.

As discussed previously, the depths of water cover in a well mixed column plays no role in limiting oxygen flux into the waste or its oxidation chemistry as long as saturation conditions are maintained within the waste material. The critical water cover depth is dependant on the hydrology of the basin for maintaining adequate water saturation during periods of extreme drought conditions, and on the requirements of erosion control at the surface of the underwater deposited waste caused by wind and wind induced shearing stress. The depth of ice cover formation and its role in the water cover option also need to be examined further.

## 4.3 WATER COVER AND THE NORTHERN CLIMATE

The objective of water covers in the north is the same as for elsewhere in Canada, to manage the long-term environmental impact of deposited, potentially reactive, mine waste. The impacts of cold temperatures and the formation of ice covers on this objective are discussed in general terms below.

### 4.3.1 Effect of Cold Temperatures

Solubility of $O_2$

The effectiveness of water cover is based on the low solubility of oxygen in water. Dissolved oxygen concentrations in water increase with decreasing temperatures from approximately 8.6 mg/l at 25°C to a maximum of 14.5 mg/l at 0°C. The saturated aqueous concentrations of dissolved oxygen are reported by Otwinowski (1994) for various temperatures from 5°C to 60°C. As discussed in Section 4.2, this increase in dissolved oxygen concentration is offset by the reduced rate of sulphide oxidation at low temperatures which impacts on the dissolved oxygen flux at the water-tailings interface.

Stratification

Most lakes are stratified to some extent with respect to temperature and density. This stratification is generally described in terms of discrete layers and has been modelled (e.g. Fang and Stefan, 1996). The upper-most region or surface layer is directly affected by ambient air temperatures, wind and solar radiation. This layer, referred to as the epilimnion, is often turbulent and can be highly spatially and temporally variable. The water beneath this surface layer, the hypolimnion, is often only weakly stratified, and without a direct source of oxygen, can become depleted of dissolved oxygen. Cases 3 and 4 in Section 4.2 represent unmixed or stratified water columns.

Generally, twice per year, just after ice-off and before freeze up, the water column becomes vulnerable to significant vertical mixing often referred to as "overturn". While a recent review indicates that there is no direct evidence that overturn need involve a complete exchange of surface and bottom waters (Stevens 1995), significant mixing can occur. Existence of a strong density stratification or chemocline near the bottom may preclude water column mixing. These include salt and fresh water stratification in some northern lakes and metal rich effluent deposited in open pits or isolated head lakes. Deposition of mine waste in these bottom waters can quickly establish anoxic conditions within the waste and in the un-mixed water column above it, leaving the waste isolated from the oxygenated water layer.

In the Territories lower average temperatures approaching inversion temperatures of 4°C may reduce stratification, resulting in deep lakes (> 10 m) which show little or no dissolved oxygen concentration gradient with depth. Representative ranges of dissolved oxygen with depth for lakes in the Northwest Territories were reported as being 10.6-14.4 mg/l for lakes greater than 10 m deep and 11.7-12.8 mg/L for lakes less than 10 m deep (Edwards 1987).

Sulphide Reaction Rates

The sulphide oxidation rate is also temperature dependant. As discussed in Chapter 3, at temperatures near freezing microbial activity is reported to be nearly absent and the chemical oxidation rate of sulphides is also reduced. Ahonen and Tuovinen (1989, 1991) note that while iron oxidation has been demonstrated to occur at temperatures as low as 4°C, the growth rate of *T. ferrooxidans* is reduced from the optimum by approximately a factor of 10. They further note that unlike the upper temperature limit beyond which the bacteria no longer function, no lower temperature limit has been defined for these bacteria.

The oxygen consumption rates used in the theoretical calculations in Section 4.2 are listed in Table 4.1. These calculations indicate that reductions in sulphide oxidation rates due to lower temperatures result in a lower oxygen diffusion flux and a net decrease in sulphide oxidation. Despite increased dissolved oxygen concentrations therefore, the net impact of lower water temperatures to 0°C is to reduce the amount of sulphides oxidized over time. The impact of temperatures below 0°C on sulphide oxidation rates is unknown and was not modelled.

Ice Cover

Finally, cold temperatures result in the formation of ice. The subaqueous disposal of tailings must address the management of ice as well as water. Most moderate sized lakes in the north require no more than two weeks to freeze over, as discussed in Chapter 2. By the mid to the end of October the majority of lakes north of 60°N have frozen over and, as illustrated in Figures 2.3 and 2.4, will remain ice covered until at least the beginning of June.

### 4.3.2 Effect of Ice Covers

Two stages may be said to be involved in the formation of lake ice covers (Zumberge 1964, Adams 1976, Barica 1987). The first is the freezing of the upper water layer itself, producing smooth, homogeneous black ice. The second is the fusion of individual masses produced by the breakup and refreezing of an ice sheet in its early stages of development, or by introduction of snow onto the surface water during the initial stages of freezing, thus producing agglometric or white ice.

Black ice is the strongest form of lake ice and is produced by rapid freezing of the surface water when there is no wind or snow. In very cold regions with low snowfall, growth may proceed more or less unhindered to produce a cover of black ice which may be over 3 m thick (Adams, 1981). Agglometric ice contains older ice or snow masses bonded together by frozen lake water. While not as strong as black ice, agglometric ice is more reflective and is therefore less affected by solar radiation under melting conditions.

The formation of ice, its long-term coverage of the water surface, and subsequent break-up in the spring will affect the ability of a water cover to control the oxidation of mine waste disposed subaqueously whether in a lake, catchment or flooded tailings impoundment.

Dissolved Oxygen

Any form of ice cover prevents gas and other mass exchanges between a water column and the atmosphere (Barica 1987, Adams 1976). During the extended periods of ice cover in the north, direct contact between the atmosphere and water column is restricted, limiting the replenishment of oxygen by diffusion into the water. Dissolved oxygen depressions under ice cover were reported by Whitfield (1986) for two northern rivers. The stagnant water column in Section 4.2 models the scenario where oxygen exchange with the air is restricted. Cases 3 and 4 illustrate that the effects of increased dissolved oxygen concentration at lower temperatures are reversed during prolonged ice cover. An ice cover may therefore restrict oxidation reactions during the winter months depending on the volume of the underlying water body and the potential rates of oxygen consumption.

Resuspension

Disturbance of the tailings surface not only disturbs the protective layer of oxidized tailings through which the available oxygen must diffuse, but also exposes fresh tailings. While comparison of Cases 2 and 5 in Section 4.2 illustrates that the depth of the mixed water column has no impact on the modelled oxygen diffusion flux at the water-tailings interface, this assumes that there is no exposure of fresh tailings due to resuspension. Where waste has been disposed under a water cover, wind induced wave action may introduce sufficient energy at the waste-water interface to overcome the critical shear stress and resuspend tailings, exposing fresh reaction sites.

A detailed study of the resuspension of fine tailings solids through wind action has been undertaken by Syncrude (Ward 1994, Ward 1992). While three main sources of potential energy for suspension of sediments were identified (wave derived currents originating from wind-waves and edge effects; convective current from cooling of the surface; and underflow from gravity driven inflow currents), only the first was studied. Their model, based on field measurements taken during the ice-free period, describes the relationship between suspended solids content in the upper, "free" water zone and the wind generated mixing in the pond. The model shows how the recycle water quality of an operational tailings pond at an oil sands plant is affected by wind speeds and depths of free water. In the case of these fine tailings and the large surface area of the lake (12 $km^2$) a minimum depth of water of 5 m was recommended.

For the most severe conditions observed in a recent 10 year wind climate, Zeman (1994) assessed the critical and maximum wave-induced shear stresses of two sand particle sizes. These materials were considered as a "cap" material, for placement under three water depths (8, 10, and 12 m) in Hamilton harbour.

The presence of an ice cover minimizes the disturbance of the water column and the underlying waste during the winter months by attenuating one of the main sources of potential energy, wind induced wave action. Indeed, during the summer months, when no ice cover is present, the average atmospheric pressure is much the same over the whole permafrost region and winds on average are lighter (Johnston 1981).

Thermal Exchange

Ice and snow cover also delays the warming of the underlying water layer. The high latent heat of fusion of water (334 kJ/kg) requires that a significant amount of energy must be used to melt the ice and snow cover before the underlying water body is significantly heated above freezing in the spring. As well, ice and snow cover have a relatively high albedo or reflectivity relative to water, giving some protection against solar radiation. Apart from reducing the absorbtion of solar radiation to begin heating the water layer, snow cover can also enhance thermal deterioration of the ice before actual breakup. Thermal deterioration is an important factor in minimizing damage due to ice break-up in spring.

Scouring

The primary negative impact related to ice covers in the water cover scenario is scouring. Damage to structures and shores may be the most visible indications of the impact of freezing and break-up of ice on water bodies. What may be less obvious is the potential impact to the bottom sediments. As illustrated in Figure 4.3, oxygen concentrations are significantly attenuated at depths of about 20 cm below the saturated tailings-water interface. Disturbance of tailings, via scouring or resuspension to depths greater than about 10-20 cm can be expected to have a significant impact on the oxygen flux and, therefore, the oxidation of the underlying tailings.

Referenced studies of ice scouring and ice jamming relate primarily to marine and lotic (river) environments respectively. While not specific to the water cover option directly, a brief discussion is presented. No references were found on the impact of scours on shallow lake sediments.

In the literature the term "ice scouring" appears to be nearly synonymous with a northern marine environment. Iceberg threats to offshore operations are severe and may be in the form of both direct hits and scouring of the ocean floor. Scours which have been observed in water depths of 155-275 m may be, for example 30 m wide on average with lengths of up to 3 km and a maximum depth of 6.5 m (Chari, 1986). Estimates of iceberg processes and the maximum scour depth is therefore essential and both experimental and theoretical studies have addressed the issue (e.g. Clark 1990, Been 1990, Paulin et al 1991). Small scale physical modelling is recognized as an important tool in the investigation of ice scour and there are numerous facilities available to perform testing. While the impact to the sea bed is dependant on the physical parameters (i.e. mass, velocity, drag) of the iceberg, it is also related to the slope and the soil shear strength of the seabed (Chari 1986).

In a study of Lake Erie (Comfort 1985), the depth of ice scouring was estimated based on earlier models of iceberg scouring of the seabed. Comfort suggested that these models overestimated the expected scours for lake bottom as a result of two assumptions. Firstly, that an ice ridge keel is much stronger than the lake bottom soil, and secondly that the ice mass does not deform during interaction.

Ice jams are a phenomenon associated primarily with rivers and streams (e.g. Doyle 1988, Ferrick 1988, Kamphuis 1983, Andres 1981, Kivisild 1975). In observations made along the Mackenzie River, which develops ice thicknesses of 1 to 2 m and becomes completely covered with snow, the ice near shore is frozen to the bottom while the main ice cover floats (Kamphuis 1983). The connection between shore fast and floating ice, and hence the impact on the bottom is dependant to some degree on the geometry of the shore.

Kamphuis and Moir underline that the degree of deterioration of the ice has a very important influence on the character of an ice jam, and thus on the potential for scouring. Ice strength is related to air temperatures, solar radiation and water temperatures preceding breakup. If the degree of melting of intact ice is very advanced, the ice will be weak and break up easily into mush upon impact or by compression.

Based on the above discussion, the following characteristics will affect the impact of ice scouring on subaqueously disposed waste: ice movement; ice thickness; ice strength; water depth between the ice and waste; and the physical properties of the waste or the waste/water interface. In addition, further, focussed assessments of the models developed to simulate ice scour in marine and lotic environments may be of some use in developing a similar understanding of ice movement and impact on lakes, catchments and impoundments, for which no detailed information was found.

## 4.4 MINIMIZING THE IMPACT OF ICE SCOUR

As discussed above, there are several positive impacts that ice cover may make to the water cover option for reactive mine waste disposal. However, the primary concern related to ice formation is the impact on the waste of scouring, jamming and freezing to the bottom. Control of certain parameters may minimize these impacts. For example, under condition of insignificant wind speed and optimally engineered impoundment banks, the net impact of freezing to depth, for the water cover option, could be negligible.

### 4.4.1 Minimizing Ice Thickness and Strength

In the north one must consider a water cover as a dynamic two layer system of ice and water, where under-water disposal becomes under ice-disposal. If the objective is to minimize the depth of the overall system, the system will freeze completely, or the ice layer must also be minimized. Lakes freeze from the upper layer down, that is, after a complete ice cover is established, it thickens largely by freezing on the underside. The rate of accretion of ice on the underside is controlled by the temperature gradient through the ice and snow on the surface. The thickness of an ice sheet, in the absence of snow, depends on the air temperature and time. The effect of snow, which is an efficient thermal insulator, is to increase the time required for the ice to reach a given thickness. Rates of ice thickening with and without snow have been predicted (S.L.D. 1986, Zumberge 1964, Assur 1956) based on simple equations using coefficients to represent snow cover and other local conditions. The density of snow, and hence its thermal conductivity, varies widely with age, from approximately 20 $kgm^{-3}$ for fresh snow, to 200 $kgm^{-3}$ or more for older snow (Liang and Zhou 1993).

Where snow can be deposited, ice thickness will be moderated and thawing will be delayed. Snow fences and other natural barriers may be used to promote deposition. Because the snow carrying capacity of the wind is approximately proportional to the cube of its speed, even small reductions in speed will produce substantial deposits of snow. A snow fence is therefore designed to reduce the wind speed (Verge 1981, Uematsu 1991). Baker et al. (1992) investigated the potential use of solid snow barriers, which are also effective, especially when used in tandem configurations. A systems effectiveness in collecting blowing snow is its "trapping efficiency" which is related to fence height, length, permeability, placement, and size and shape of the apertures.

The deposition of snow on ice not only limits its growth but also reduces its strength. If incorporated into the ice cover, snow is instrumental in the development of white or agglometric ice. The incorporated air pockets and its reduced density give this ice less cohesion and strength. During the early melt season, if an ice sheet is covered with snow, it must melt before the main ice sheet is attacked appreciably and "candling" (deterioration of the ice by solar radiation, creating melted vertical channels in the ice) is observed.

### 4.4.2 Depth of Ice Versus Water

The water cover option for tailings disposal in the north and elsewhere, requires a decision as to the depth of the overlying water layer that will be maintained. Protection of the underlying waste must be balanced with the capacity, stability and/or cost of the disposal option. Covers of 2 m or less are often referred to as shallow water covers. As illustrated in Section 4.2, in the case of a well mixed water column, the actual depth of shallow water cover has little to no impact on the oxidation diffusion flux to the submerged saturated tailings. However, the impact of ice on the water cover option is more significant for these shallow covers. Shallower depths of water result in an increasing likelihood of: freezing to the bottom, tailings resuspension, and expected frequency of scouring (Comfort 1985).

Where ice becomes bottom fast, melting of the overlying snow will induce flooding of both the snow and ice. Field observations in the Arctic (Woo and Drake 1988) showed that the bottom fast ice is released from the bottom at about the time when the basal ice of the snow cover is melted. Once floating, the ice will have little water ponded on its surface due to the drain holes developed from "candling". Engineering of the impoundment or lake shore beds may reduce the impact of bottom fast ice on breakup. Shengkui (1993) recommends smooth slope surfaces to allow the ice to climb freely under conditions of smaller water surface areas. Kamphuis and Moir (1983) note that steeply sloping shores are more likely to develop what they have termed "hinge cracks" between shore fast or bottom fast ice and the floating ice sheet. Hinge cracks result from slowly falling water levels, separating the bottom fast from the floating ice mass along clean, linear lines. Without such breaks the main ice sheet may break off in a ragged fashion from the bottom fast ice and it subsequent movement will be more likely to affect the bottom fast ice and scour the bottom or develop jams.

### 4.4.3 Minimizing the Impact of Wind

The prevailing wind direction in the NWT is north by northwest at 15-20 km/hr while along the western boarder of the Yukon, winds are generally easterly at 10-15 km/hr. Reported gust extremes in the Territories are generally all well over 100 km/hr. Control of wind velocities and gusts, particularly during freeze-up and break-up will reduce scouring.

While there is little control over lake dimensions, man-made impoundments may be designed to minimize fetch and the effect of wind. Orientation of the impoundment relative to the prevailing winds may limit wave action as will the incorporation of breakwater intermediate dykes. Natural or man-made barriers, as noted above in regards to snow deposition, will also reduce local wind velocities. Available options to minimize the impact of wind are site specific.

### 4.4.4 The Water-Waste Interface

Finally, the impact of ice scour as well as wind effects to disposed waste may be limited by the placement of an additional layer of material at the water-waste interface. Field and laboratory investigations on the impact of organic (peat) and non-organic (sand) layers to the diffusion of oxygen and flux of metals at the water/tailings interface are underway through the MEND program (MEND, 1996). Placement of such a layer on the submerged deposited tailings will: act as a diffusion barrier to oxygen dissolved in the overlying water cover; minimize resuspension or disturbance of the tailings due to the impact of wind or ice scouring; and may act as an oxygen and metal sink.

Subaqueous capping has been considered an appropriate technology for effective chemical and biological isolation of contaminants and is recognized as a management technique to rapidly render harmless contaminated in situ sediments and dredged material (Zeman 1994). In the Hamilton harbour a 0.5 m cap of clean medium to coarse sand was proposed as an effective long term barrier to the transport of heavy metals and organics from sediments into the overlying water. It should be noted that the proposed thickness is considered conservative. Similar existing capping sites, monitored over several years following cap placement, have shown no discernible long-term transport of either heavy metals or organics up into the caps (Sumeri et al, 1991). General guidelines for such contaminant sediment capping are recommended, including that the site be located in a relatively low energy environment (Zeman, 1994).

As an intermediate layer, coarse grained material is more resistant to erosion, however finer grained material will have a higher absorbing capacity, while the use of an organic layer may also act as an oxygen sink. Many lakes in Canada have sediments which are naturally anoxic at shallow depths and following cessation of tailings discharge, a veneer of natural sediments will accumulate. As noted above, ongoing MEND studies are assessing the impact of placing organic material over tailings on decommissioning. However, organic matter becomes generally less available the further north one goes. In central Keewatin, Northwest Territories for example, Edwards (1987) reported on the limited accumulation of post glacial sediment in lakes. For example, the sediment or "lake gel" which is rarely as much as one meter thick, has reported to have a water content greater than 80% and an organic matter content often less than 10% by dry weight.

## 4.5 CONCLUSIONS

The formation of an ice layer in the water cover disposal option for decommissioning of reactive mine tailings will isolate the water column from wind and wave related turbulence and the exchange of oxygen at the air-water interface for much of the year.

Preliminary assessment of the impact of ice cover underlines that the primary area of concern is ice scouring, and the resultant disturbance of the water/waste interface. Whereas, the formation of an ice cover leads to an oxygen deficient and stagnant water column condition, large blocks of floating and wind blown ice are problematic for shore erosion, dam stability and scouring of the waste surface. In man made lakes, where water depths are 1 metre or less, freezing of the entire water column extending into the waste may occur. Upon break-up, the material trapped in the ice will be resuspended, causing some short term exposure, disturbance of any protective diffusion barrier developed, and exposure of fresh reaction sites at the waste surface.

The depths of water cover in a well mixed column plays no role in limiting oxygen flux into the waste as long as saturated conditions are maintained. Water depth does however affect the potential for the water column to freeze to depth and the impact and frequency of scouring. The water cover should be designed to minimize freezing of the waste by allowing for an intermediate unfrozen water layer. In some regions this may require a significant water depth. In other situations it may be accomplished by incorporating a secondary cover/barrier layer on the surface of the waste at the water-waste interface. A non-reactive layer at the water/waste interface will minimize the effect of ice scour during freeze and break up, as well as wind-induced resuspension of the tailings during ice-free periods. The thickness of the ice cover may also be minimized in man-made lakes or impoundments by placing snow fences or natural barriers to enhance additional accumulation of snow in the basin. Promotion of snow deposition using natural barriers or snow fences is recommended where the increased water volumes during spring thaw can be handled. Incorporation of snow in the forming ice layer reduces its overall strength and hence its potential impact during break up. Snow also acts as an insulation barrier, minimizing the thickness and therefore impact of the forming ice layer, and reducing the potential to freeze to bottom.

Water depth will also affect the degree of expected scouring. In man-made impoundments, or relatively shallow water covers (<2 m) scouring may be frequent but less severe. As well positive impacts of an ice cover can also include: limitation of the availability of dissolved oxygen; attenuation of wave action; and delayed warming of the water column in spring. Under greater water depths (>2 m), such as in open pit or lake disposal, these impacts become less significant, and the frequency of scouring, while potentially more severe, decreases.

Table 4.3 Overview of the Effect of Ice Cover on the Water Cover Disposal Scenario Option

| EFFECT OF ICE COVER | DISPOSAL SCENARIO | IMPACT ON TAILINGS |
|---|---|---|
| Prevent/limit gas exchange between water layer and atmosphere | Reactive tailings below limited depth of water cover | Limit available dissolved oxygen during ice over |
| | Tailings of limited reactivity &/or significant depth of water cover | No significant benefit |
| Attenuate/reduce wave action | Tailings below limited depth of water cover | Halt resuspension of tailings due to wind induced wave action during ice over |
| | Tailings below significant depth of water cover &/or covered with additional layer of non-reactive material | No significant benefit |
| Delay water temperature increases during spring due to latent heat of fusion and reflectivity | Tailings disposed in closed system, below limited water cover | Reduce exposure time to waters significantly above freezing |
| | Tailings disposed in open system &/or under significant depth of water | No significant benefit |
| Ice scour or jamming | Tailings disposed below limited depth of water cover | Physical disturbance and displacement of tailings |
| | Tailings disposed below significant depth of water cover &/or covered with additional layer of non-reactive material | No significant impact |

In the absence of sufficient vegetative cover at northern latitudes, where wind and wave related erosion can be a problem, breakwater intermediate dykes are recommended. In natural basins (e.g. head lakes), where the depths of water cover is greater than 2 metres, the formation of a thick ice cover is of little significance unless it covers the entire water column when consideration should be given to minimize it for reasons and by means given above. For ice scouring, shore protection and dam stability, the ice thickness should preferably be minimal as well.

Table 4.3 presents an overview of the above conclusion related to the effect of an ice cover on the water cover disposal option. The depths of water cover referred to as 'limited' or 'significant' are dependant on site specific parameters but generally refer to depths of less than 2 m (man made impoundments) and more than 4 m (deep lake or pit disposal) respectively.

Table 4.4 Approach to Minimize the Effect of Ice on the Water Cover Disposal Option

| OBJECTIVE | APPROACH | OPTION |
|---|---|---|
| Minimize ice thickness | Optimize snow deposition | Use of engineered barriers, vegetation, or snow fences |
| Minimize ice strength | Optimize snow deposition | |
| Minimize disturbance of tailings below water cover | Do not allow ice cover to freeze to bottom | Maintain a significant minimum water depth |
| | | Minimize ice thickness |
| | | Engineer barrier and dam slopes to minimize impact of bottom fast ice at edges |
| | Minimize ice dynamics due to wind &/or current | Orient impoundment to minimize wind induced wave action |
| | | Utilize internal dyke system |
| | | Minimize water level variations during freeze-up and breakup |
| | Protect waste at water/waste interface | Place additional layer of non-reactive material at water/waste interface |

The disturbance or resuspension of deposited tails is the most significant negative impact in the control of oxidation of tailings disposed subaqueously. Table 4.4 presents an overview of the options discussed to minimize tailings disturbance as a result of ice formation and breakup.

## 4.6 RECOMMENDATIONS

- ☐ Freezing of reactive waste under unsaturated conditions may not be sufficient by itself in controlling ARD in mine wastes, and additional oxygen limiting barriers may be required.

- ☐ Disposal of waste as a whole, in the form of a saturated paste mix, where segregation of particle size does not occur, may maintain a near saturated state. This may be sufficient to reduce ARD potential by factors of 1860 at 0°C and 3130 at 25°C.

- ☐ The depth of water cover in a shallow, well mixed, water column is not a critical parameter in controlling oxygen influx and ingress in the underwater deposited waste, but should be determined by basin hydrology and erosion control requirements.

- ☐ Formation of an ice cover may lead to oxygen deficient and stagnant water column conditions which will further reduce oxygen influx and hence oxidation at low temperature. For both man-made and natural basins, it is recommended that the strength and thickness of the ice cover be minimized, if possible, to reduce the potential impact of ice scouring.

- ☐ The impact of short term cycling (between atmospheric exposure and resubmergence under a water cover) on the rates of sulphide oxidation and metal leaching should be assessed for frozen, reactive tailings.

- ☐ A method to assess the oxidation rates of sulphides in a non-oxygen limited environment at temperatures below 0°C should be developed. This may or may not require further assessment of contributions from chemical, biological and electrochemical processes.

# 5.0 ROLE OF PERMAFROST ON TAILINGS DISPOSAL

## 5.1 INTRODUCTION TO PERMAFROST

Permafrost is defined as the thermal condition of earth material (soil or rock) which remains below 0°C continually for more than two years. Moisture in the form of water and ground ice may or may not be present.

The southern limit of permafrost coincides roughly with the -1°C mean annual air isotherm while the boundary between discontinuous and continuous zones is roughly at the -8°C isotherm, north of which permafrost occurs everywhere beneath the exposed land surface (Figure 5.1). The vegetation of the north is dominated by tundra and polar desert to the north of the tree line while peatland or muskeg covers more than half of the southern part of the permafrost region in Canada (Figure 5.2).

In the discontinuous zone, permafrost exists together with areas of unfrozen ground. In the southern fringe of this zone, permafrost occurs in scattered islands ranging in size from a few square meters to several hectares and is confined mainly to peatlands, north facing slopes, and areas of thin snow cover. Northward, permafrost becomes increasingly widespread, and varies in thickness from a few centimetres to 60-100 m at the boundary with the continuous zone, north of which permafrost may increase to as much as 600 m in depth (Johnston, 1981).

The top layer of ground above the permafrost table that undergoes seasonal thawing is called the active zone. This zone does not always extend to the permafrost table in areas of discontinuous permafrost as illustrated in Figure 5.3. The thickness of the active layer impacts upon the position of the permafrost table and may vary from year to year.

The depth of zero amplitude is the distance from the ground surface to the point beneath which there is no annual fluctuation in ground temperature (Figure 5.4). The temperature at the depth of zero amplitude ranges from a few tenths of a degree below 0°C at the southern limit of discontinuous permafrost, to about -5°C at the discontinuous/continuous permafrost boundary, to -15°C in the extreme north.

The occurrence and distribution of permafrost are affected principally by climatic and various terrain factors. A broad relationship exists between mean annual air and ground temperatures as shown in Figure 5.1 while the terrain factors include: relief, vegetation, hydrology, snow cover, glacier ice, soil and rock type, and fire, the latter which may severely impact natural vegetation.

Vegetation, particularly the ground surface layer of moss and peat, insulates the ground from thawing during the summer. Removal or disturbance of the organic cover causes deepening of the active layer and degradation of the permafrost. Snow cover acts as an insulator to both frost penetration and spring thaw, and its net effect is dependant on both impacts. Surface and subsurface waters also influence the distribution of permafrost. In discontinuous permafrost zones poorly drained areas inhibit permafrost. A thaw basin always exists beneath lakes and rivers that do not freeze to the bottom in winter. The influence of exposed mineral soil and bedrock on permafrost conditions is controlled by the albedo (reflectivity) and thermal properties of these materials. The rate of permafrost aggradation and the thickness of the active layer are directly affected by variations in soil and rock type when the ground is not covered by vegetation, water or ice.

Considerable theoretical and empirical work has been done to address the engineering issues related to building and maintaining engineering works (roadways, foundations, pipelines etc) in permafrost. These studies continue to improve our understanding of the permafrost environment. Below, the suitability of the deposition of mine tailings in areas of continuous or discontinuous permafrost is discussed.

## 5.2 SUITABILITY OF PERMAFROST FOR TAILINGS DISPOSAL

Northern climatic conditions, and particularly permafrost, offer unique opportunities for ARD management. Simply put, disposal methods for reactive mine tailings are based on either control of ARD generation migration. Conditions related to areas of discontinuous and continuous permafrost show promise in both areas.

A recent publication, (NMEND #4), indicates that the rate of sulphide oxidation is inhibited by:

- ☐ snow and ice cover which provide a permeable barrier for oxygen diffusion;
- ☐ the lower temperatures which reduce the activity of bacteria responsible for catalyzing sulphide oxidation reactions; and
- ☐ the lower temperatures which slow both geochemical and biochemical oxidation processes.

Raising the permafrost table above the disposed mine tailings, also ensures that the macro temperature of the tailings remain at or below freezing. For the purposes of this report, the term *encapsulation* is used to refer to tailings which have been covered with sufficient material for the permafrost table to migrate above the tailings/cover interface.

Encapsulation may also be expected to mitigate ARD migration while another MEND publication (Geocon 1993) recommends the use of frozen perimeters to isolate mine waste and control the migration of sulphide oxidation products in areas of discontinuous permafrost. Migration of oxidation products may also be limited under climatic conditions of low or negative net annual precipitation. Norecol, Dames and Moore (1994) present broad evaporation/precipitation balance sub-regions which are reproduced in Figure 5.5.

Thus, both in its generation and migration, there appears to be less potential for ARD impact in a northern environment, particularly in zones of continuous permafrost, than elsewhere. However, as recognized by Cameron (1979), reported by Davé and Clulow (1996), and underlined by Dawson and Morin (1996), the generation of ARD is neither eliminated nor necessarily reduced to negligible levels in the permafrost environment.

There is first a need to identify and qualitatively assess the issues related to the use of permafrost (whether in the continuous or discontinuous zone) and these are identified for further consideration in the following section. Then more detailed quantitative assessments of the net impact of the disposal of mine tailings to northern environments must be developed.

## 5.3 CONSIDERATIONS FOR DISPOSAL IN PERMAFROST

### 5.3.1 Sulphide Oxidation Rates

Reduced sulphide oxidation rates have been predicted or documented for temperatures just above freezing (e.g. SENES 1991, Otwinowski 1994, Davé and Clulow 1996) and reduced but non-negligible biological activity have also been reported (e.g. Ahonen and Tuovinen 1989, 1991). Biological rates at temperatures near freezing were shown as being orders of magnitude lower than at 10°C (Otwinowski 1994) and the chemical oxidation rate near freezing was reported as about 15% of that at 25°C (SENES 1991). Davé and Clulow (1996) reported delayed onsets and reduced observed rates of sulphide oxidation at 2° versus 25°C. Biological and chemical oxidation rates of sulphides however at or below freezing have not been investigated.

Potentially available dissolved oxygen concentrations increase with decreasing temperatures to a maximum near 0°C. While the diffusive transport of dissolved oxygen in unfrozen water can lead to oxidation of sulphide minerals, its availability may not be rate limiting. As concluded by Tributsh (1976) the oxidation of sulphides can proceed in a series of chemical steps or can include electrochemical steps. Development of a layer of oxidized tailings at the waste surface may act as a diffusion barrier to oxygen ingress and slow chemical oxidation. The electrochemical oxidation of sulphides in a permafrost environment may however require only an inert "wick" that electrically connects the sulphides at depth to an oxygen richer near-surface environment (Cameron 1979). A sulphide body can act as a conductor, and in permafrost terrain the electrolyte is unfrozen water present as interfacial films in the permafrost and in the summer thawed active layer. The significance of the electrochemical reaction will be dependant on the conduction of the sulphide body. To date no known comparison of the relative significance of electrochemical, chemical and biochemical oxidation rates of sulphides has been made.

In addition, the fact that pyrite oxidation is exothermic might suggest that temperatures at the mineral surface will remain above freezing despite permafrost encapsulation. However, as noted by Dawson and Morin (1996), the heat generated by pyrite oxidation (0.012 kJ/kg), is significantly less than the latent heat of water (334 kJ/kg) and they conclude that fairly high pyrite concentrations would be necessary to promote thawing.

A permafrost environment is expected to lower the net oxidation rate of sulphide minerals relative to similar environments with temperatures above freezing. Assuming a temperature of 0°C in permafrost, this scenario is represented in Table 4.2 which shows pyrite oxidation rate reduction factors of 2.5 and 1.5 respectively for unsaturated (Case 1) and saturated (Case 2) tailings modelled at 25° and 0°C. A quantitative assessment of the impact of permafrost on the oxidation rates of sulphides would require an analysis of the impact of chemical, biological and electrochemical processes at and below freezing as well as the heat generation and oxygen and water availability in the micro-environment surrounding the sulphide mineral grains. The availability of water is discussed in more detail below.

### 5.3.2 Perennially Frozen Ground

Not all water freezes when fine-grained soils are subjected to freezing temperatures. The temperature decreases below 0°C required to freeze porewater vary with the forces at the particle surface (capillary and adsorption) and the concentration of dissolved impurities. At -3°C the unfrozen moisture content as a percent of total dry weight can vary from approximately 3% in a silt to 25% in a clay, based on four soil types tested (Williams, 1967). Apart from temperature, the other factors determining the unfrozen water content in saturated frozen soils are (Anderson, 1972):

- specific surface area of the solid phases,
- pressure,
- chemical and mineralogical composition of the soil, and
- solute content.

In addition as noted above, in the case of reactive sulphide minerals, the heat of reaction may also promote unfrozen water at the surface of the mineral.

The chemistry of the interstitial or pore water is particularly important. If the temperature of the frozen soil is decreased and ice is formed, dissolved impurities are concentrated in the residual unfrozen films and the freezing point of this residual liquid is further depressed. Further decreases in temperature below about -5°C have shown little reduction in unfrozen water content (Williams 1967, Anderson and Morgenstern 1973, Jinsheng and Wong 1983). Dubikov et al (1988) report freezing point depressions as well as other properties for a variety of saline soils and salt compositions.

Ground water movement in permafrost areas is restricted by the presence of both perennially and seasonally frozen ground, but it is not completely halted. Free water may occur in the ground above permafrost (suprapermafrost water), in unfrozen zones (taliks) within the permafrost or below the permafrost base (subpermafrost water). And, although permafrost is commonly assumed to be impermeable, it should be considered as a confining zone of low but finite permeability. Guodong and Chamberlain (1988) investigated the moisture migration in frozen soils under controlled laboratory conditions. Based on tests done with both silt and clay they observed water migration in the frozen portions of soils during thawing and concluded that the rate of water migration depends greatly on the hydraulic conductivity of frozen soil which is larger for clay than granular soil. Nakano and Tice (1988) also report on the rate of water movement, caused by temperature gradients, in unsaturated frozen soils. Both groups noted that the presence of ice may decrease the mobility of water caused by temperature gradients.

Marsh and Woo (1993) report observations on the total infiltration of meltwater into frozen soils during snowmelt at three study sites near Resolute, NWT where the mean annual daily temperature is -16.6°C and the typical active layer thickness is between 0.2 and 0.7 m. The infiltration of meltwater varied from 9 mm for sand to 38 mm for gravel.

Ostroumov (1988) examined the dynamics of ion and moisture flows related to temperature gradients in both frozen and unfrozen soils. In general the migration of both ions and water tended towards the colder temperatures in frozen sand whereas thawed sand saw a reverse of the migration of the ions, towards the warmer temperatures. This is further supported by Qui et al (1988) who noted that the direction of ion migration in freezing soils depends on the combined effect of temperature gradient, concentration gradient, moisture flow and pressure gradient. Thus for silt and clay, ions would migrate towards the freezing zone whereas in moist sand, the solutes would tend to migrate towards the unfrozen zone. Evaluation of ion transfer at the frozen soil / snow boundary is also reported (Ostroumov 1993).

For frozen and unfrozen soils, Yen and Nakano (1993) present a good summary review and discussion of thermal properties, unfrozen water content, and hydraulic conductivities. Where ground temperatures fall below 0°C, the thermal conductivity of soils cannot be assumed to be constant as freezing soils have a temperature dependent ice content and the thermal conductivity of ice is four times that of water. Woo and Xia (1996) assess the effect of hydrology on the active layer for soils at two arctic sites near Resolute, NWT. They also present thermal properties for components of the active layer (reproduced in Table 5.1) noting that the fraction of ice, water and air in the soil change with degree of freezing and saturation. This makes the thermal properties of the active layer highly variable. The ground heat balance was also calculated for the two sites, classified as polar desert and fen, and having pre-melt moisture contents of about 30% and 65% respectively.

Table 5.1 Thermal Properties of Soil Components (after Woo and Xia, 1996)

| **Component** | **Thermal Conductivity W/(m°C)** | **Heat Capacity MJ/(m$^3$C)** |
|---|---|---|
| Mineral | 2.93 | 1.926 |
| Organic | 0.25 | 2.508 |
| Ice | 2.20 | 1.900 |
| Water | 0.57 | 4.180 |
| Air | 0.025 | 0.00125 |

The authors noted that the latent heat consumption for permafrost soils is a significant component of the active layer heat balance. Latent heat is released during freezing and absorbed during thawing and means that a partially frozen soil behaves as if it has a greatly increased heat capacity.

Fawcett and Anderson (1994) present a 2-dimensional, physically based model, PERIMOVE. The model is capable of simulating processes governing moisture and heat transfers through soils, soil heave and creep (solifluction) in a freezing and thawing environment. The model allows the prediction of the volume changes that moisture redistribution and freezing create within the soil profiles and the resulting movement of material and loss of soil strength during freezing and thawing cycles.

Frozen soil or tailings is neither static nor impermeable. The degree to which moisture and solute transport within frozen ground are inhibited will be site specific and dependant on a number of parameters including: degree of saturation; soil composition and size distribution; and gradients of temperature, concentration, and unfrozen water pressure.

### 5.3.3 Freeze/Thaw Cycles

In addition to unfrozen porewater and its migration in perennially frozen ground, the impact of freeze/thaw cycles may be considerable in relation to the use of permafrost as a control for acid generation and migration. On a micro-scale, freeze/thaw cycles may impact the surface of the minerals directly while on a macro-scale, the distribution and surroundings of the minerals may be altered.

Frost weathering is defined in Uusinoka and Nieminen (1988) as "mechanical breakdown of rock by the growth of ice within the pores and discontinuities of a rock subjected to repeated cycles of freezing and thawing". This freeze/thaw action is also termed frost cracking, riving, shattering, splitting or wedging. The rate of acid generation is partially dependant on the surface area of reactive sulphide minerals exposed to oxygen and water and a friable or porous rock can result in significantly higher rates of reaction than might be expected (e.g. MEND #1.14.1). Uusinoka and Nieminen (1988) report an initial classification of rocks into resistant and less resistant types for freeze/thaw cracking, based on empirical data. The cumulative pore areas and in particular the amount of pores less than 1$\mu$m in diameter are reported to be greater in rocks prone to frost weathering. Dawson and Morin (1996) note that this freeze/thaw induced shattering can also occur in minerals. They highlight work done by Konishchev and Rogov published in 1983 which indicates that mineral disintegration can occur in permanently frozen material as well as under freeze/thaw cycles, although the latter dominates.

Seasonal freeze/thaw cycles of the ground are generally limited to the active layer in both continuous and discontinuous permafrost. As discussed by Fawcett and Anderson (1994) and outlined by Dawson and Morin (1996), moisture movement occurs during freezing of porous media as a result of two processes: expulsion of water due to a 9% volume change which accompanies the phase change from water to ice; and attraction of water due to capillary suction at the ice-water interface. The growth of ice lenses at the freezing front, due to the ice segregation process, is the main cause of frost heaving which can amount to 2-5 cm generally or as much as 15-20 cm of movement in one season.

Yen and Nakano (1993) also report that the hydraulic conductivity of saturated soils will increase after experiencing an initial freeze/thaw cycle. This effect is more distinct for fine grained soils and generally reaches a limiting value within a few cycles. An increase in hydraulic conductivity reduces the depth to which the freezing front penetrates. It also increases the total heave and the excess ice contents in the upper soil layers.

Generally, continued exposure of reactive tailings to freeze/thaw cycles has a negative effect due to the impact on both the mineral surface and the long term stability of the upper layers of the disposed waste.

### 5.3.4 Frost Heaving

Frost heaving may also take the form of a variety of land features. Patterned ground refers to the more or less symmetrical forms such as circles or polygons which are made prominent by the net soil circulation and segregation of fines and stones. Lewis et al (1993) introduce a model which may be able to describe formation of a number of types of patterned ground resulting from nonuniform ice lens formation within the soil. Net annual displacements of materials related to patterned ground have been reported as reaching 10 to 20 mm/year (Hallet et al 1988, Walters 1988). Fawcett and Anderson (1994) report a range of heave values for saturated ground from 33.8 mm to 1.2 mm for a test profile of conductivity ranges from $1 \times 10^{-6}$ $ms^{-1}$ to $1 \times 10^{-8}$ $ms^{-1}$.

Thermokarst is the term used to describe topographical depressions resulting from the loss of ice volume with increased depth of thaw of ice-rich permafrost ground, the most common of which is the thaw-lake, found throughout the Arctic and Subarctic. Once created, these depressions establish a new local thermal regime which further promotes thawing up to depths from a few meters to as great as 25 m (Burn and Smith, 1988, Hopkins and Kidd, 1988). The lifespan of these lakes is typically on the order of 3000 years although they may also drain rapidly (Brewer, 1993). On the western Arctic coast of Canada approximately 20 - 50% of the area is covered by lakes (Mackay, 1988) where nearly every summer at least one lake drains rapidly due to erosion of ice wedges at their outlets.

Pingos are large, ice-cored mounds which range in size from 6 - 60 m high and 20 - 365 m in diameter. Mackenzie-type pingos occur mainly in continuous permafrost and are very common near the Mackenzie Delta and the Arctic coastal plain. They form when the thaw bulb that formerly existed beneath a lake refreezes from the top after the lake or pond drains. Freezing of the excess water trapped below the advancing freezing front causes up-doming of the ground surface which develops radial tension cracks. Mackay (1973) estimates vertical growth rates to be about 1.5 m in the first one to two years. Palsas, mounds of peat with a permafrost core, and peat plateaus, perennially frozen peat deposits, also result from aggradation of permafrost and occur commonly in areas of discontinuous permafrost.

There are no generally accepted criteria to characterize material as frost-susceptible, although the most commonly accepted criterion is grain size. Frost heave is less significant in coarse, sandy soils while fine grain soils like clay, and particularly silt show much greater effects (Førland et al 1988).

Jiacheng and Guodong (1993) propose that the porosity, as well as size of material, also affects the degree of displacement during freezing. Chen et al (1988) report that the phenomenon of frost heave can however occur in sand in an open system where there is a certain content of fine grained material (e.g greater than 3% and 10% of grains < 0.02 mm for non uniform and uniform material respectively) and a relatively low rate of frost penetration (e.g. < 0.2 cm/day). A frost design soil classification system developed by the U.S. Corps of Engineers has been widely used (Johnston, 1981) in assessing frost-susceptibility of soils.

Frost heave occurs in discontinuous as well as continuous permafrost zones and can result in significant displacement of materials over time. If the disposal of tailings and placement of uni- or multi-layered engineered covers is contemplated, this potential displacement has to be carefully evaluated for its impact on the long-term management of mine waste.

### 5.3.5 Other Issues

Damage to the organic cover will have varying effects on both the thermal and moisture regimes of the area. If the vegetation is severely damaged or destroyed, considerable change may occur in areas underlain by ice-rich perennially frozen ground. The depth of the active layer will increase or even double, while water released as a result of the thaw may cause extensive erosion. Conversely, the controlled harvesting and stockpiling of the organic layer at mine sites for future use in site reclamation may have a significant net positive long-term effect on reestablishing the thermal regime.

While still a subject of much debate, global warming could also have a profound effect on the permafrost zones. Geothermal gradients have been measured ranging from 1°C/22 m to 1°C/160 m depending on the type of soil or rock and the effect of past climate periods. Using an average of 1°C/54 m, a change of 0.5°C in the mean annual air temperature could result over a long period of time in a change of permafrost thickness of 12 to 90 m depending on local conditions (Johnston, 1981). However, a key aspect of this potentially profound effect that must be considered is the slow pace at which it would take place. Nakayama et al (1993) also report on the effect of climatic warming. They propose an active layer index as an indicator of the degree of change in the active layer that may be expected under a warming trend.

## 5.4 OPTIONS FOR DISPOSAL OF TAILINGS IN PERMAFROST REGIONS

### 5.4.1 Primary Strategies

Two primary strategies continue to be proposed for the use of permafrost in the disposal of potentially reactive or reactive tailings in the Canadian North (e.g. Dawson and Morin 1996, EBA 1994, Geocon 1993). These are:

- ☐ Encapsulation of tailings within perennially frozen ground by addition of sufficient cover material to raise the permafrost table above the cover/tailings interface; and

- ☐ Containment of tailings and reaction products through the use of impermeable frozen core perimeter dams.

As mentioned in Section 5.2, disposal methods for reactive mine tailings are based on either control of ARD generation or control of ARD migration. The goal of encapsulation of tailings in permafrost is to control both acid generation and its subsequent migration. Containment is focussed primarily on control of the migration of reaction products.

### 5.4.2 Use of Control Strategies

A number of northern mine sites have used or proposed the use of one or both of these control measures and some examples are highlighted below.

Cullaton Lake
Cullaton Lake is situated in the continuous permafrost zone. In the summer of 1992, the exposed tailings surface was covered with a 1.5 m layer of waste rock and overburden to promote permafrost conditions in the tailings as an ARD control measure. Temperature profiles have indicated a cooling trend and upward migration of permafrost into the tailings over a period of four years. Placement of the cover over frozen tailings may however have increased the rate of upward migration.

Column leaching tests have been carried out for Cullaton Lake B and Shear (S) Zone tailings to evaluate their oxidation and leaching characteristics at 25°C and at 2° and 10°C (Davé 1992, Davé and Clulow 1996). The B Zone tailings contain 2.31% as S and total available alkalinity of 45.36 kg $CaCO_3$/tonne tailings while the S Zone tailings contain 0.4% as S and available alkalinity of 2.0 kg $CaCO_3$/tonne tailings. For both tailings, the low temperature leaching tests resulted in reduced but not negligible rates of acid generation. The B - Zone tailings cold temperature tests indicated not only very slow oxidation at 2°C but more effective utilization of buffering capacity. The S- Zone tailings however showed no significant reduction in the onset of acidic drainage at lower temperatures. This may be due in part to the minimal available buffering capacity in these tailings. Further data analysis has been recommended (Davé and Clulow 1996), and may be of particular interest with respect to the contribution of chemical, biological and possibly electrochemical oxidation processes.

Lupin Mine

The Lupin mine is located in the region of continuous permafrost. Some of the tailings have been reported to be acid generating (NMEND #2). Tailings are placed in a surface impoundment contained by frozen dykes. The initial tailings containment was created by damming a small watershed to create an enclosed basin. The tailings dam at the Lupin mine is of frozen core design which used a synthetic liner for initial containment prior to freezing of the core. An early leakage incident occurred not though the impermeable dam but through fractures in the bedrock where a thaw bulb remained from the original drainage pattern (Laflech, 1987).

Closure planning at Lupin calls for a non acid generating layer to be placed over the tailings (current active layer thickness is reported to be 3 m in depth) to bring the tailings entirely into perennially frozen ground.

Polaris Mine

Polaris is located on Little Cornwallis Island in the region of continuous permafrost. Tailings are disposed in Garrow Lake below a depth of 26 metres. Polaris utilizes a frozen core dam to control the lake discharge. The dam was constructed during winter months using layers of saturated coarse rock. Styrofoam and earth shell were used to maintain the dams frozen condition.

BHP's NWT Diamond Project

The BHP NWT Diamonds Project is located in the region of continuous permafrost. Approximately 133 million tonnes of mine tailings are expected to be produced in the mining of five diamond-bearing kimberlite pipes (Panda, Misery, Koala, Fox and Leslie). It is proposed that the tailings be deposited in the Long Lake tailings impoundment basin for the first 20 years of operation, and for the remaining 5 years, in the mined out Panda pit. Frozen core perimeter dams have been proposed to raise the water level in Long Lake by as much as 9 meters. The dams will contain a central core of frozen soil saturated with ice and bonded to the existing permafrost. A granular rockfill shell will surround the core to provide stability and thermal protection. Along one section where a natural stream channel has depressed the permafrost table, thermosyphons have been recommended to speed freezing. Thermosyphons are passive heat transfer devices, usually consisting of a sealed tube containing a liquid or a gas, which remove heat from the ground.

Raising of the active layer is proposed for long term tailings management. The tailings area, divided into five internal cells using pervious rock dikes, would be filled sequentially. Once filled, all surface water would be pumped from the cell and frost penetration encouraged to form a frozen crust. It is then proposed that the tailings be covered with an engineered cover of waste rock layered with coarse sand and gravel tailings, to form the new active layer, and eventually to be converted into a wetland. Permafrost is predicted to form in at least 80% of the tailings within the first 50 years (BHP 1996). Due to the fine nature of the tailings, suspended solids or turbidity of the water in the proposed tailings impoundment has had to be addressed in the management plan. BHP has proposed that the freeze/thaw cycles will aid in seasonal clarification of the overlying water. Freezing of segregated slurry will result in coagulation of suspended particles which will rapidly settle after thawing (BHP 1996).

Only a small percentage of waste and processed rock has the potential to generate ARD: biotite schist representing 27% of the waste rock from the proposed Misery Pit; and diabase representing 6% of the waste rock from the proposed Fox Pit. It has been proposed that this material be isolated and enclosed by granite, while still frozen, to minimize infiltration and preserve permafrost conditions.

### 5.4.3 Summary Control Strategies and Related Issues

In Table 5.1, the overall proposed strategies for tailings disposal options in permafrost regions are summarized and the reader is referred to Dawson and Morin (1996), EBA (1994), and Geocon (1993) for more details related to the engineering aspects. In each case there are a number of issues which require further consideration/assessment, many on a site by site basis. Many of these issues have been raised in previous reports as well as the current document and they are listed in Table 5.1. The italicized sections refer to issues which are discussed in more detail below.

(A) As concluded by Tributsh (1976) and Cameron (1979), the oxidation of sulphide can proceed through electrochemical as well as chemical and biochemical processes. The relative importance of these processes for any given mine tailing has however not been investigated. If the relative rates of these processes vary significantly with temperature, tailings characteristics or oxygen availability, it will be difficult to predict the reactivity of mine tails by extrapolation, without taking all oxidation processes into consideration. There is a need to assess the relative importance of the electrochemical oxidation process of sulphides at temperatures near and below freezing in a typical disposal scenario for tailings of varying conductance.

(B) Peatland covers more than half of the permafrost region in Canada as shown in Figure 5.2. As such, peat is probably the most readily available insulation material in permafrost regions. Peat dramatically reduces the depth of annual thaw because it acts as a good insulator in summer, but when frozen, the high ice content makes it an excellent heat conductor (Woo and Drake 1988). Other materials used as insulation for construction in northern environments include woodchips and synthetic insulation. In designing tailings impoundments, the peat layer may be removed prior to deposition and stockpiled for later use. In the short term, removal of the organic layer will lower the permafrost table, and the impact of this must be assessed. The organic mat of peat and moss is also difficult and expensive to harvest, haul and process. In the long term, the use of the organic material in a cover scenario as an insulation layer will significantly reduce the material required to raise the permafrost table as illustrated in Figure 5.7 and discussed by Geocon (1993). Optimization of the use of available organic material will be site specific and dependant on the disposal scenario.

Table 5.1 Summary of Control Strategies for Tailings Deposition in Permafrost Regions

| Strategy | Options or Variations | Issues for Consideration |
|---|---|---|
| ***Continuous Permafrost*** | | |
| Encapsulation of tailings in perennially frozen ground by addition of sufficient non acid generating material as cover to raise permafrost table to cover/tails interface | Use of cover of sandy gravel over tails (2.5 - 3 m for Yellowknife climate) (1).<br><br>Minimize cover thickness by using alternate materials (e.g. man-made insulation, organic matter) in composite cover(1)<br><br>Incorporation of capillary break in composite cover to minimize frost heave potential<br><br>Deposit and freeze thin layers of tailings within perimeter dykes(2).<br><br>Timing of placement of cover material over tailings | *Impact of electrochemical, chemical and biochemical oxidation processes* (A)<br><br>Depth and variability of active layer and impact of waste deposition to permafrost table position and local hydrology<br><br>Permeability of frozen material<br><br>Availability of cover and insulating materials<br><br>*Use of local organic materials in cover design* (B)<br><br>*Impact of snow cover* (C)<br><br>Total freezing layer thickness versus thickness of thin layers placed.<br><br>*Minimization of frost heaving and its impact on cover layer and buried tails.*(D) |

Table 5.1 (cont'd) Summary of Control Strategies for Tailings Deposition in Permafrost Regions

| Strategy | Options or Variations | Issues for Consideration |
|---|---|---|
| | ***Continuous Permafrost*** | |
| Containment of tailings and reaction products using impermeable frozen core perimeter dams | Maximize % solids to maximize impoundment storage capacity<br><br>Addition of a wind erosion cover to protect tailings(1).<br><br>Construction sequence to build perimeter dykes and deposit tailings(2)<br><br>Use of insulating material or thermosyphons to raise permafrost table in dykes(1,2).<br><br>Minimize snow deposition in early stages of construction and deposition to enhance freezeback (2) | Impact of frost weathering of mineral grains<br><br>Net annual site water balance and impact on dam stability and erosion/washout.<br><br>Position of frozen core in dykes relative to contained waste water level<br><br>Relationship of dyke height versus stability<br><br>Rate of continued oxidation in contained tailings.<br><br>Long term impact of contaminated, contained porewaters on freezing point depression<br><br>*Depression of permafrost table where contained water does not freeze to depth in winter* (E) |
| | | |
| | ***Discontinuous Permafrost*** | |
| Containment of tailings using artificially frozen core perimeter dams | Use of insulated dyke and thermosyphons(1)<br><br>Use of convective rock cover(1) | Sensitivity of permafrost regime to variations in climate or surroundings<br><br>Long term maintenance of artificially developed permafrost |

(1) From Geocon (1993), (2) From Dawson and Morin (1996)

(C) Snow coverage was discussed in Chapter 4 as a method of minimizing ice thickness and strength on water bodies. In very general terms, the absence of snow cover allows the ground surface temperature to follow the air temperature throughout the season. In areas where the average air temperature is below 0°C, permafrost may be expected to develop beneath those parts that remain snow free. Snow cover removed from a moss covered area also promotes permafrost, causing a decrease in ground temperatures (Figure 5.6). In areas where the mean annual air temperature is near or above 0°C, removal of snow cover may have a detrimental effect. Snow cover inhibits both warming of the underlying soil in the spring and freezing in the fall.

To freeze deposited tailings, as proposed in Table 5.1 in thin layers, snow cover should be avoided or minimized. While snow cover affects the underlying thermal regime (Hong, 1993), the utility of snow cover in the proposed tailings control scenarios in the long term may or may not be significant.

(D) Frost heaving is a common feature observed in the North as discussed in Section 5.3.4. Complete protection from frost heave is only possible in continuous permafrost for material that is well below the freeze/thaw boundary. In addressing the tailings disposal options in permafrost regions the potential for heaving must be considered, particularly with respect to the cover material. In the evaluation of dry covers for the inhibition of ARD (SENES 1994) the impact of frost heave in permafrost and non-permafrost regions on the long-term cover performance was not discussed, while Klohn Leonoff (1992) recommended that the effectiveness of dry covers under freeze/thaw conditions should be evaluated.

A wealth of information related to frost heave is available from other engineering work carried out in the north and should not be overlooked. Several methods have been used to prevent frost heave on structure foundation and the general approach is to eliminate one or more of the basic conditions which cause the growth of ice lenses and heaving. These include: maintaining granular material in the active layer; minimizing water supply; reducing the depth of the active layer; and minimization of capillary action. Regarding capillary action for example, frost heave can be prevented if the continuity of water between the water table and the freezing front is broken. A layer of coarse sand or gravel deep in soil, or ditches to drain the water, will reduce frost heave and this has been implicitly addressed in a number of the composite tailings covers proposed by Geocon (1993). Henry (1988) proposed the use of geotextiles placed horizontally in soil above the water table which will act as a capillary break or barrier and mitigate frost heave.

Frost weathering is defined as the mechanical breakdown of rock by the growth of ice within its pores and discontinuities over repeated freeze/thaw cycles. This freeze/thaw induced shattering is addressed primarily in the literature with respect to rock or outcrops. Although one study discussed in Section 5.3.3 notes that such cycles can also promote mineral disintegration, the impact of freeze/thaw cycles on mine tailings has not been reported. If significant, it will increase the rate of oxidation. A preliminary laboratory study of the variation in tailings surface area with cycles of freeze/thaw may be sufficient to assess the relative impact. The change, if any, of surface area will be expected to vary with ore characteristics.

The hydrology and permafrost at any site are interdependent. Perennially frozen ground is less likely to develop in areas where there is significant ground water movement, while the relatively impermeable nature of permafrost will limit this movement. During the thaw season, ice within the active layer and snow above it will melt. This water, limited by the permafrost table will remain in the active layer. In areas of positive net water balance in the north (see Figure 5.5) the capacity and stability of the impoundment dams may become a concern with an increasing volume of suprapermafrost water. While wet mineral soils are particularly susceptible to permafrost formation, and saturation of tailings may minimize the depth of zero amplitude (Johnston 1981). If the water cover is sufficiently deep and does not freeze to depth, it will degrade the underlying permafrost creating a thaw bulb beneath the ponded water. In a containment scenario for tailings disposal the engineering design must also allow for the management of excess suprapermafrost water.

## 5.5 CONCLUSIONS

A number of general conclusions can be reached with respect to permafrost and the disposal of reactive or potentially reactive mine tailings therein.

- ☐ Sulphide bearing tailings have been shown to generate acid under northern climatic conditions.
- ☐ Cold temperatures slow the rate of chemically and biologically assisted acid generation.
- ☐ Encapsulation of reactive waste in the permafrost under unsaturated conditions may not be sufficient by itself to control ARD from mine wastes, and additional oxygen limiting barriers may be required.
- ☐ The oxidation of sulphides may occur electrochemically as well as chemically, reducing the requirement for available oxygen directly at the reaction site.
- ☐ Sulphide oxidation is exothermic but the heat generated is approximately 4 orders of magnitude less than the latent heat of fusion of water.
- ☐ Permafrost has a finite permeability and limits but does not stop the mobility of water.
- ☐ A small but significant percentage of porewater remains unfrozen below the permafrost table due to capillary and adsorption forces and due to concentrations of dissolved contaminants which cause freezing point depression.
- ☐ An active layer overlays perennially frozen ground and will vary in depth depending on local climate and surface characteristics. This layer undergoes seasonal freeze/thaw cycles.
- ☐ Deposited tailings can be encapsulated in perennially frozen ground through the placement of sufficient cover material to raise the permafrost table above the tailings/cover interface.
- ☐ Freeze/thaw cycles will promote both frost weathering of waste material and the growth of ice lenses and other features causing frost heaving.
- ☐ There is no generally accepted criterion to characterize frost-susceptible material although saturated materials having sufficient fines and deposited without capillary breaks are more likely to heave.

Permafrost is recognized as a promising factor in the control of sulphide oxidation in the northern environment but will not provide an absolute control to ARD production. A broad parallel may be drawn to subaqueous disposal where, in the late 1980's, placement of acid-generating material underwater was believed to prevent sulphide oxidation. Despite current information which suggests that a water cover will mitigate but not eliminate sulphide oxidation, underwater disposal of mine waste is considered to be the favoured option to prevent the formation of acidic drainage (MEND 1996), a view that is supported by significant laboratory and field results.

## 5.6 RECOMMENDATIONS

Recent studies on permafrost, including this one, have identified the issues of concern and have discussed their expected impact in a qualitative manner. Empirical data is now required to begin to quantify these impacts and assess their relative importance on the overall resultant reactivity and control of mine tailings in the permafrost environment.

In Table 5.2 a summary of recommendations for future laboratory and field work proposed by this and other authors is presented.

Table 5.2 Recommendations of Future Work for Disposal of Tailings in Permafrost Regions

| Issue | Objective | Approach |
|---|---|---|
| Rate of acid generation | Quantify and develop predictive methods for the rates of sulphide oxidation at and below 0°C (1,2)<br><br>Determine release rates of alkalinity and acidity under cold temperatures (3)<br><br>Determine potential impact of frost shattering on tailings reactivity | Compare specific tailings and thermal site characteristics with acid generation (potential/actual) for northern sites (2)<br><br>Assess impact of electrochemical versus chemical and biologically assisted sulphide oxidation at and below 0°C<br><br>Assess and quantify acid generation potential at -10°C to +5°C with emphasis on frozen hydraulic conductivity, freezing point depression, and low temperature ARD rates using lab tests including Humidity cells (2)<br><br>Laboratory measurements of heat generation due to oxidation at low temperatures in un- and saturated conditions (1)<br><br>Assess the increase of total surface area for tailings subjected to varying freeze/thaw cycles |

Table 5.2 (cont'd) Recommendations of Future Work for Disposal of Tailings in Permafrost Regions

| Issue | Objective | Approach |
|---|---|---|
| Cover scenarios | Determine variability of available cover materials among mine sites (1)<br><br>Develop method to predict unfrozen water content with temperature for various cover materials (1)<br><br>Develop model to predict cover scenario for various materials, degrees of saturation, cover designs, and climatic conditions (1)<br><br>Assess long-term effectiveness of covers under freeze/thaw and heave conditions | Measure thermal capacity and thermal conductivity of base metal and gold tails (1)<br><br>Compare laboratory and field observations to existing theory and develop program to simulate % moisture content with temperature (1)<br><br>Conduct thermal analysis to develop model match with Lupin mine data and then use to extend information to other scenarios and sites (1)<br><br>Assess potential impact of various (organic) insulating materials to promote permafrost encapsulation of tailings<br><br>Document and assess potential freeze/thaw impacts and heave conditions related to mine waste disposal in discontinuous or continuous permafrost regimes |
| Demonstration Project | Construct two field test installations, in continuous and in discontinuous permafrost, to confirm designs (1)<br><br>Demonstrate effectiveness of engineered system using permafrost (2) | Field installation and monitoring of 4 cover scenarios in continuous permafrost zone. Construction and monitoring of horizontal thermosyphons plus insulation and convective rock cover in discontinuous permafrost zone (1)<br><br>Consider field assessment of: thin layer freezing; various insulated cover designs plus convective rock cover; and the validation permafrost use over long-term |

(1) From Geocon (1993), (2) From Dawson and Morin (1996), (3) From Klohn Leonoff (1992)

## 6.0 POSTSCRIPT

Heginbottom et al (1993) reported that a circumarctic map of permafrost and ground ice conditions was compiled by the International Permafrost Association and that there were plans to make the map and data available in digital form. The map is reported to show the estimated permafrost extent by percentage area, an estimate of relative abundance of ice in the upper 20 meters as percent volume, relative abundance of ice wedges, massive ice bodies and pingos, ranges of permafrost temperatures and thicknesses, and the location of subsea and relict permafrost, and cryopegs or unfrozen layers. The map is accompanied by eight cross sections of the permafrost region illustrating the thickness and nature of permafrost. An accompanying report discusses the regional variations in permafrost attributes and the confidence levels at which they are presented.

Heginbottom, J.A., Brown, J., Melnikov, E.S., Ferrians Jr., O.J. (1993). Circumarctic map of permafrost and ground ice conditions. 6th International Conference on Permafrost, Beijing China, July, 1993. pg 1132.

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## 8.0 LIST OF FIGURES

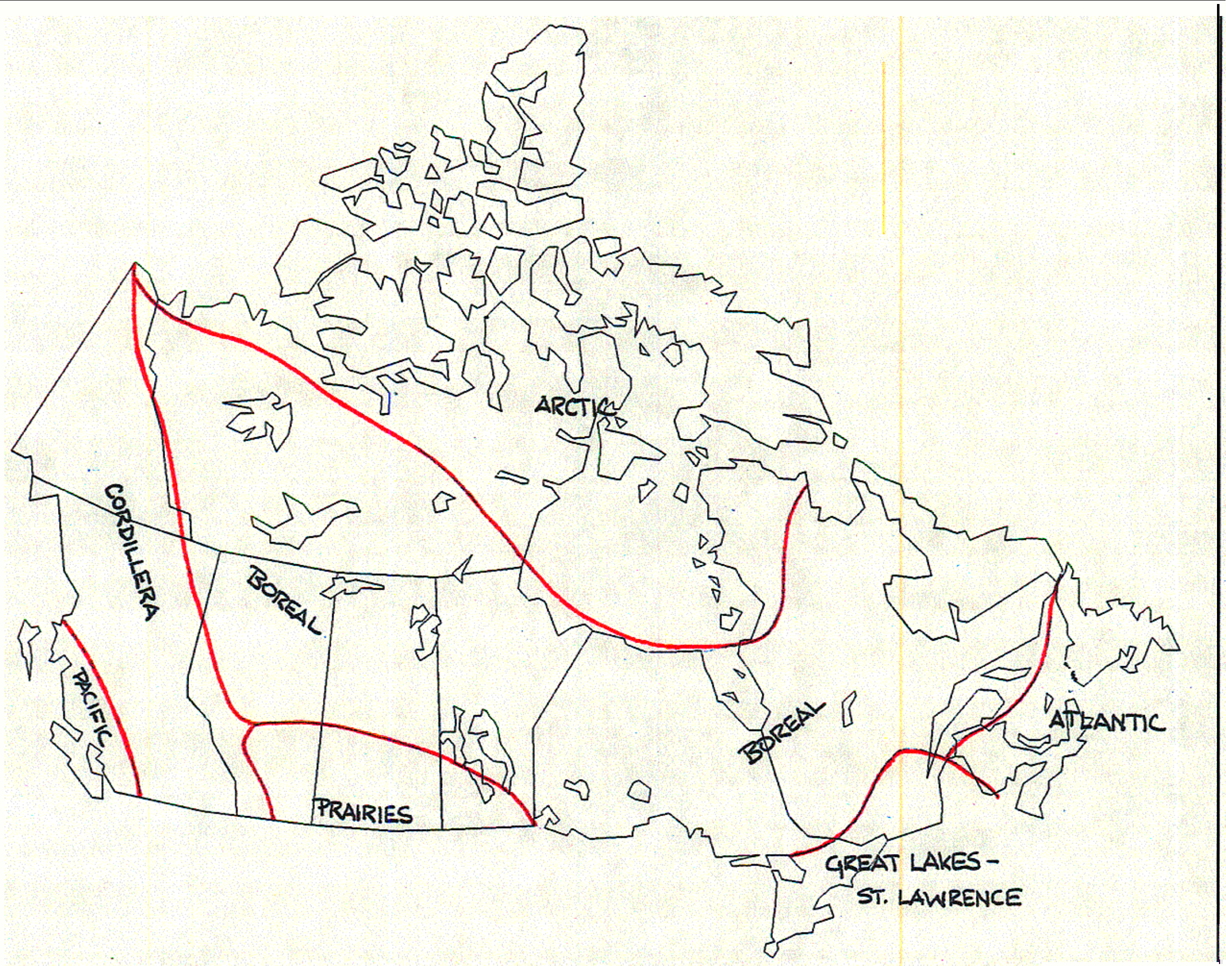
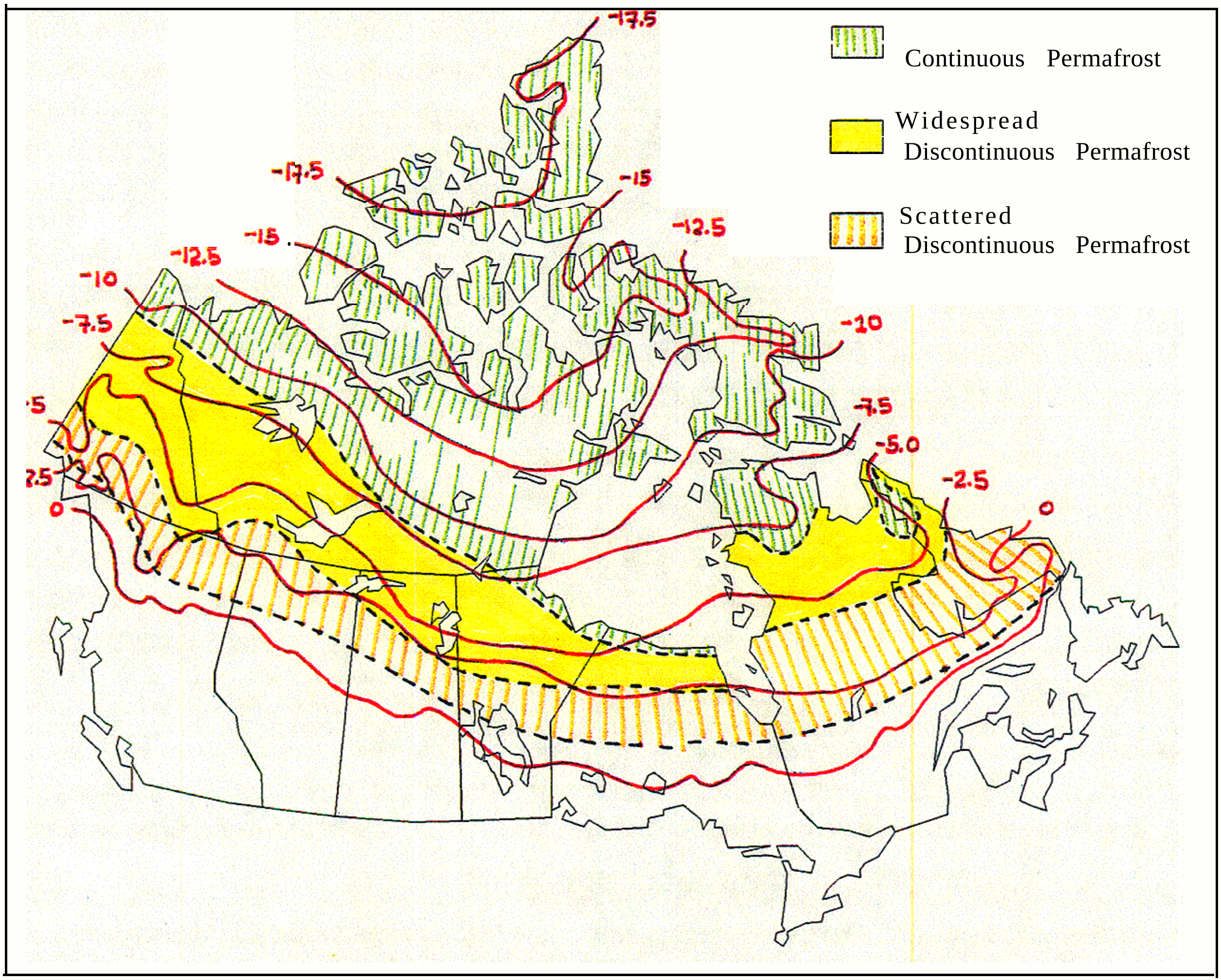
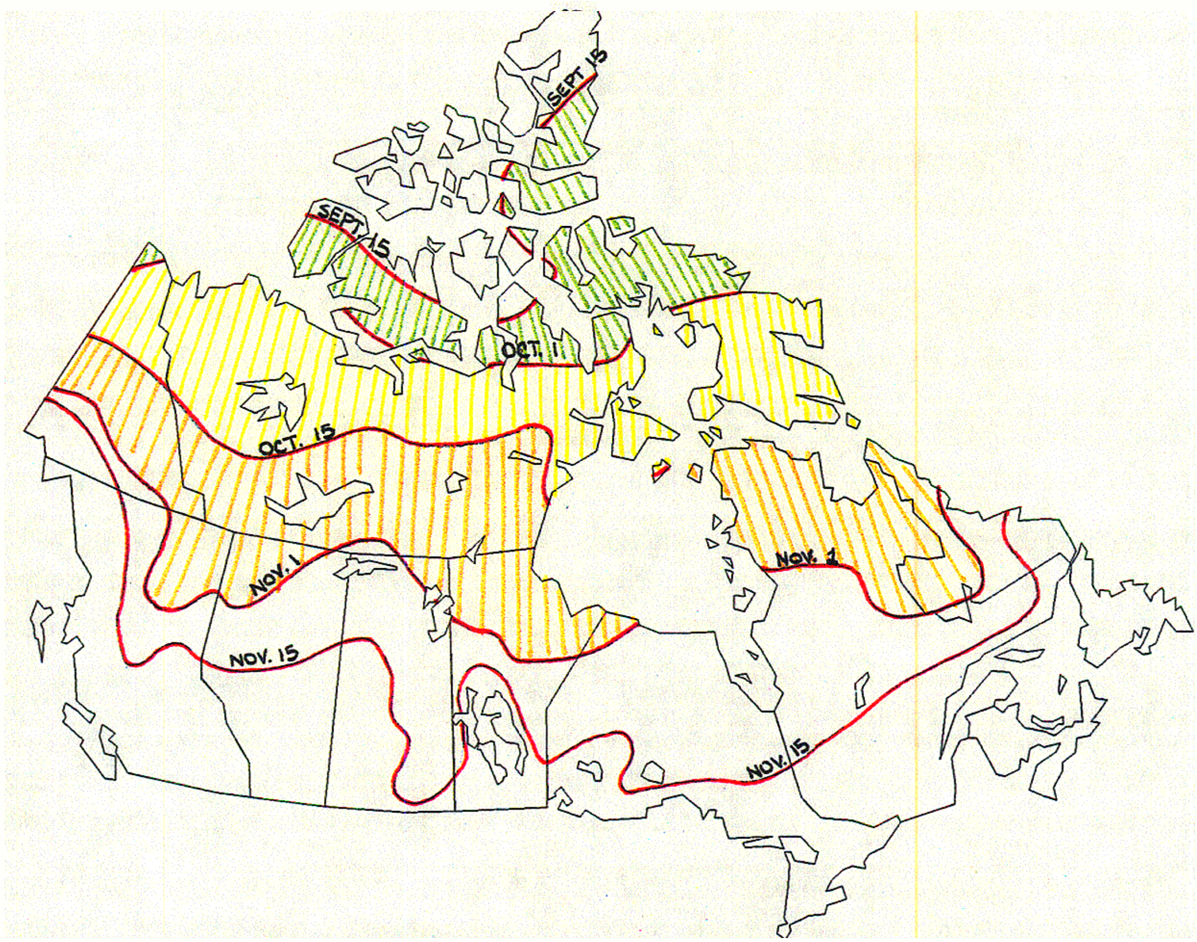



Figure 2.1 Climatic Regions of Canada
(after Johnston, 1981)




gure 2.2 Annual Mean Daily Air Temperature Isotherms and Permafrost Regions of Canada (after Climatic Atlas of Canada, 1987)




gure 2.3 Mean Dates of Lake Freeze-Over
(after Hydrological Atlas of Canada, 1978)

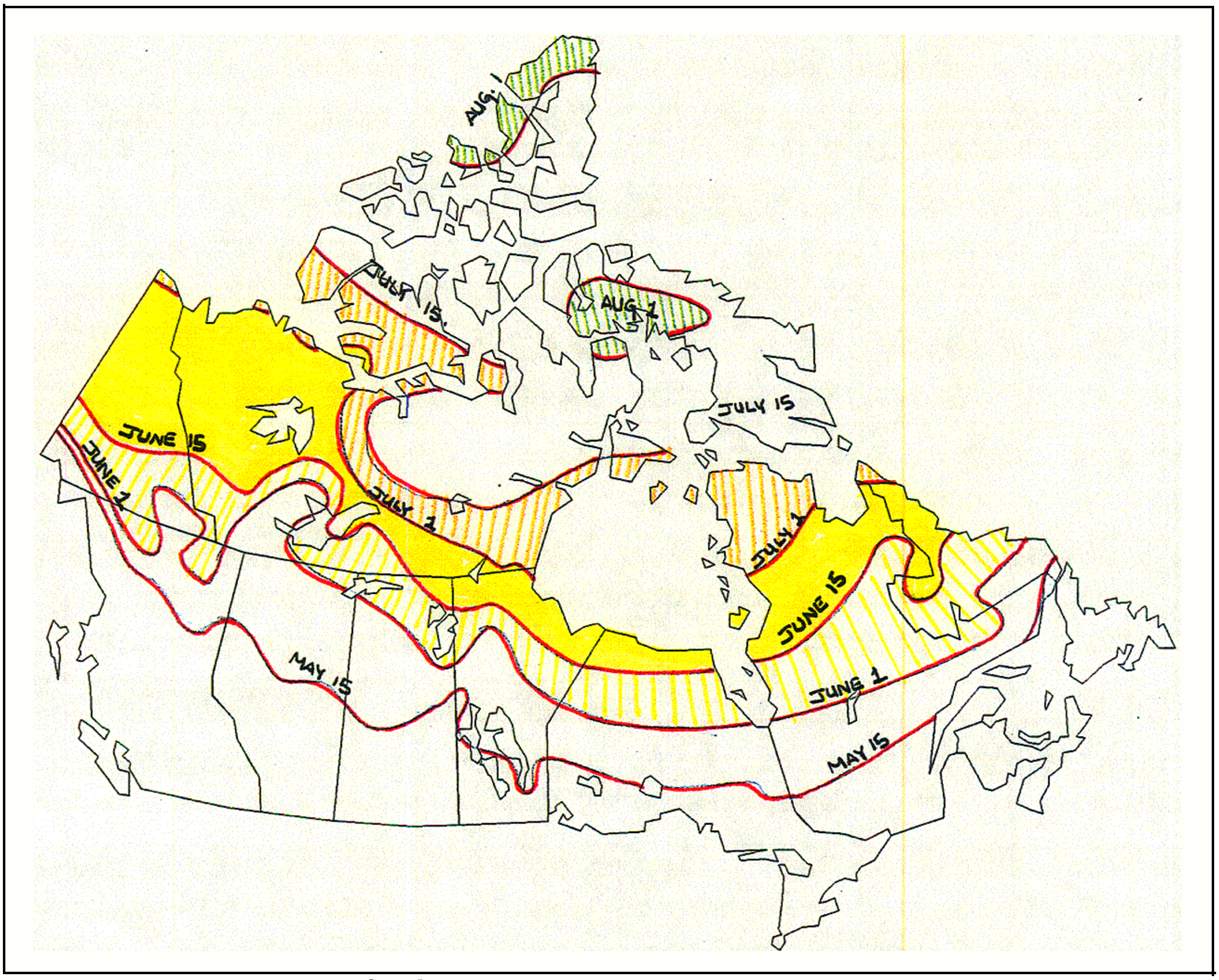


Figure 2.4 Mean Dates of Lake Ice-Free
(after Hydrological Atlas of Canada, 1978)

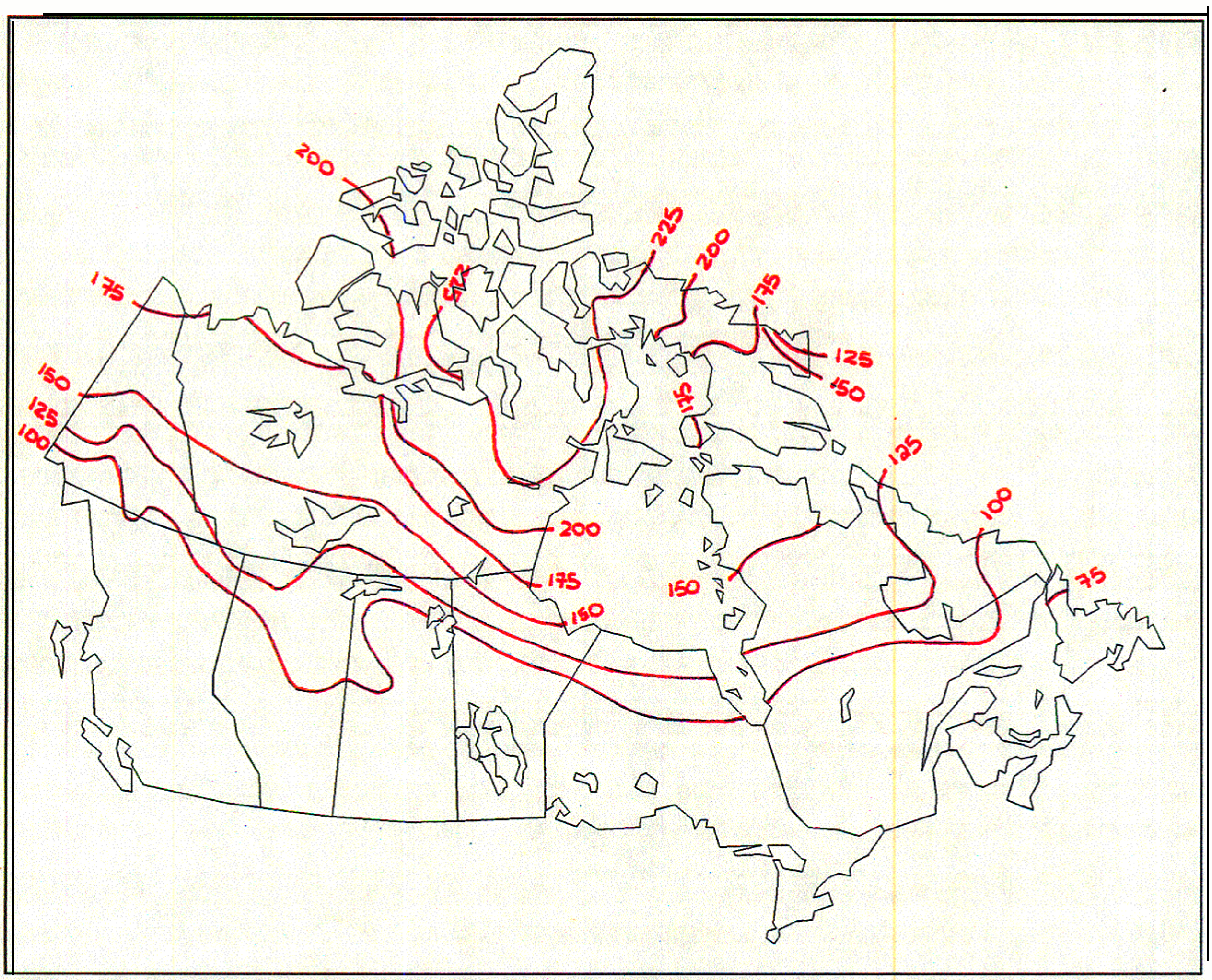



Figure 2.5 Mean Maximum Ice Thickness in Lakes (cm)
(after Allen, 1977)

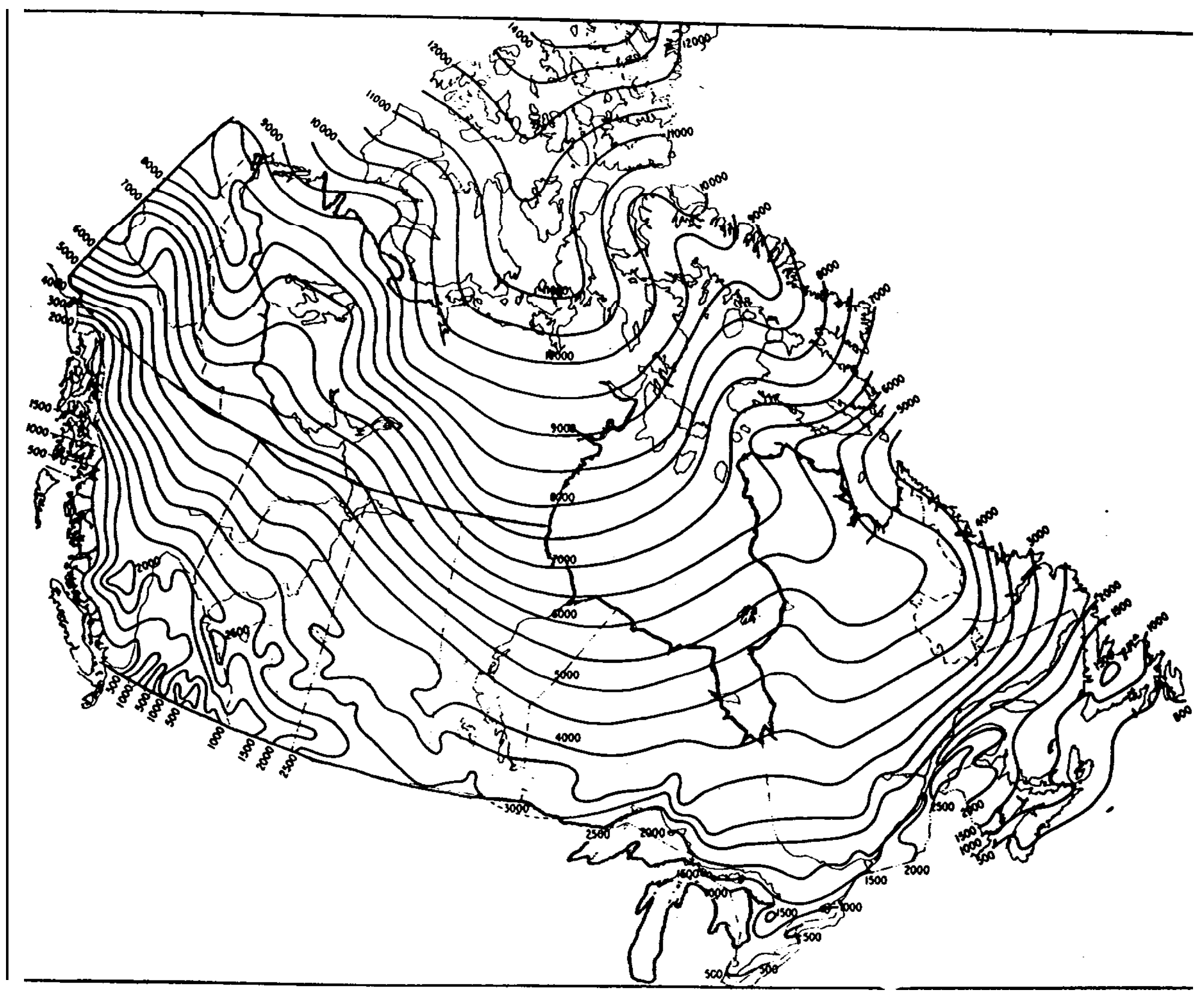


Figure 2.6 Mean Annual Freezing Indices of Canada (Fahrenheit degree days) (after Boyd, 1973)

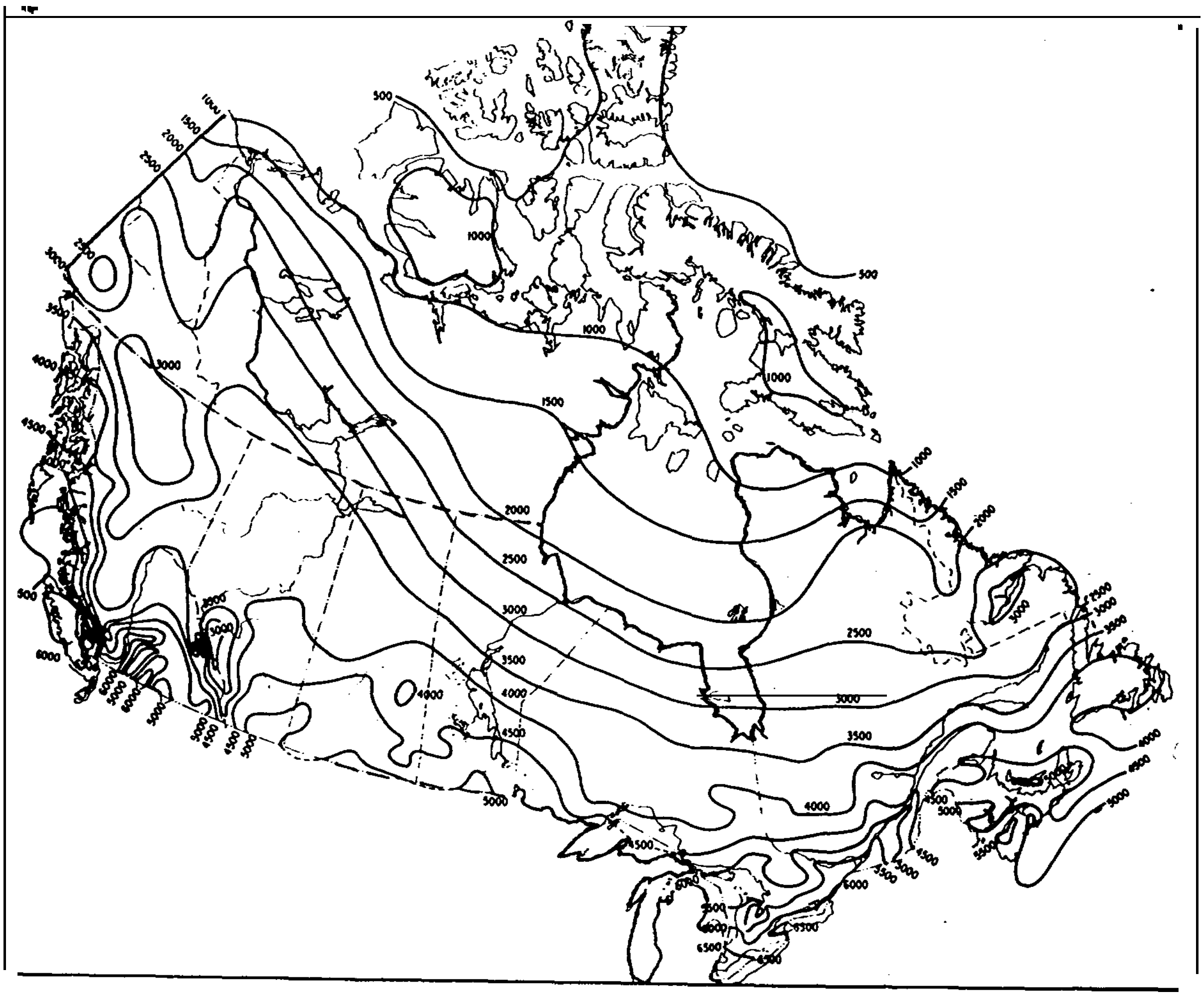


Figure 2.7 Mean Annual Thawing Indices of Canada (Fahrenheit degree days) (after Boyd 1973)

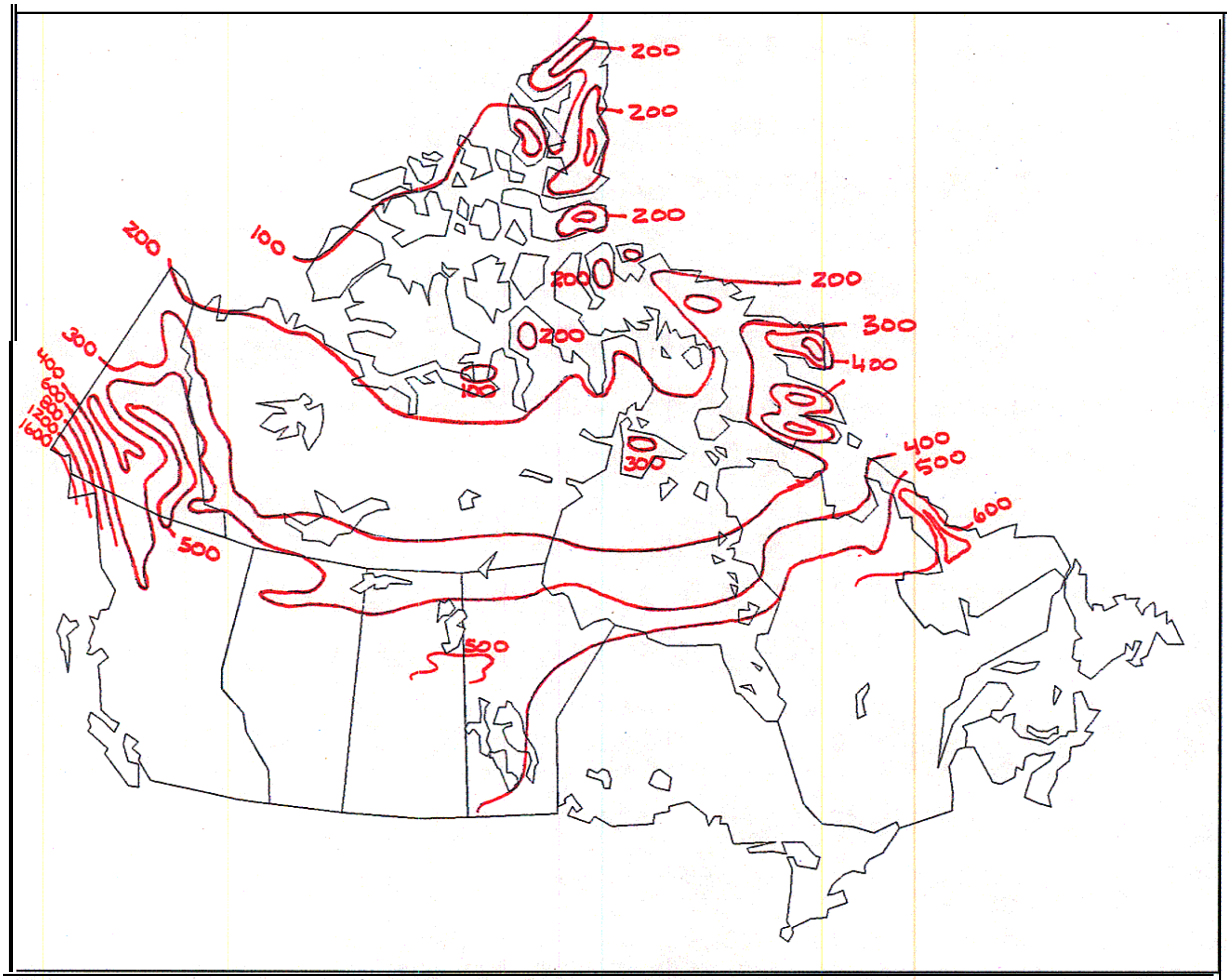



Figure 2.8 Mean Annual Total Precipitation (mm)
(after Climatic Atlas of Canada, 1987)

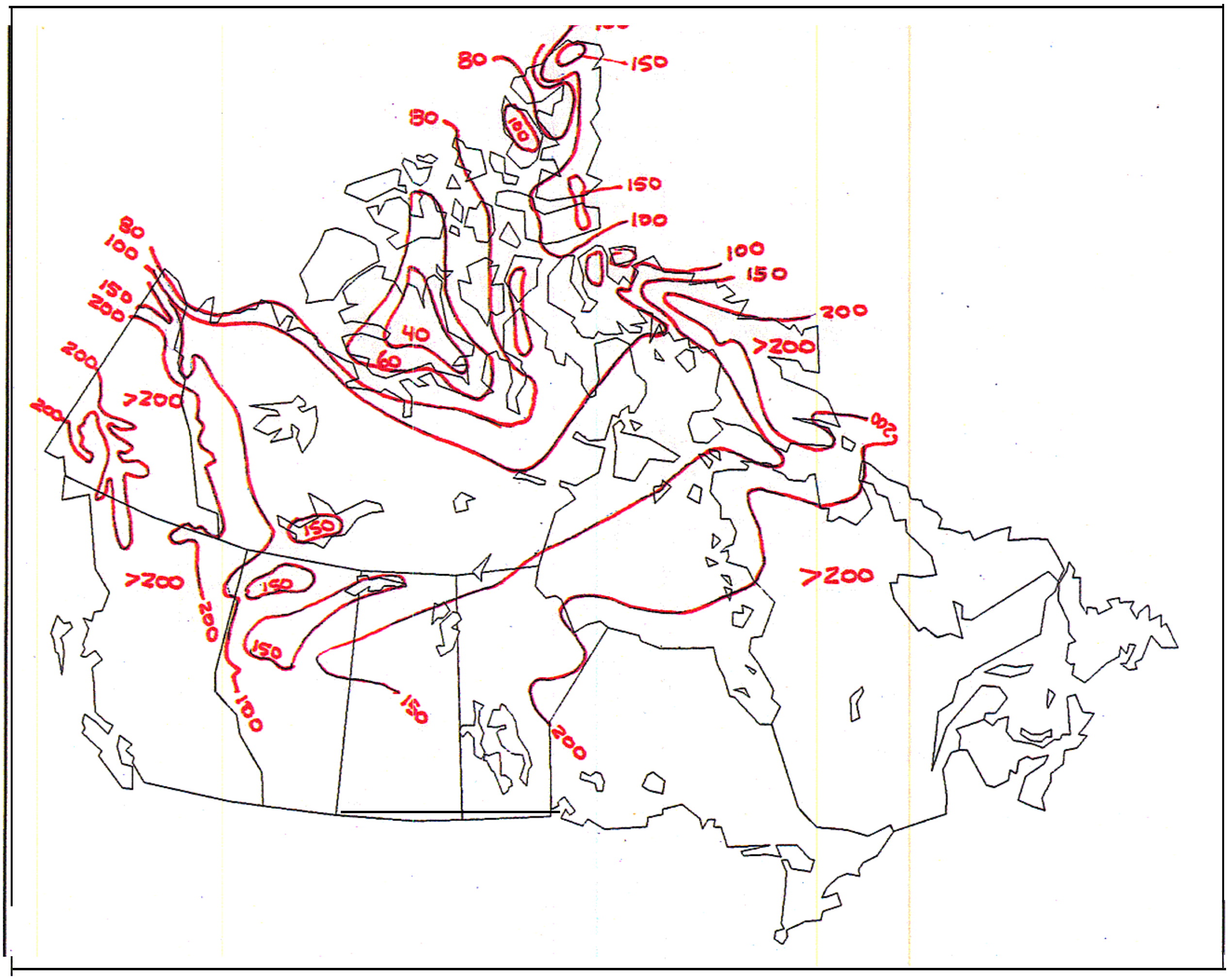


Figure 2.9 Mean Annual Total Snowfall (cm)
(after Hydrological Atlas of Canada, 1987)

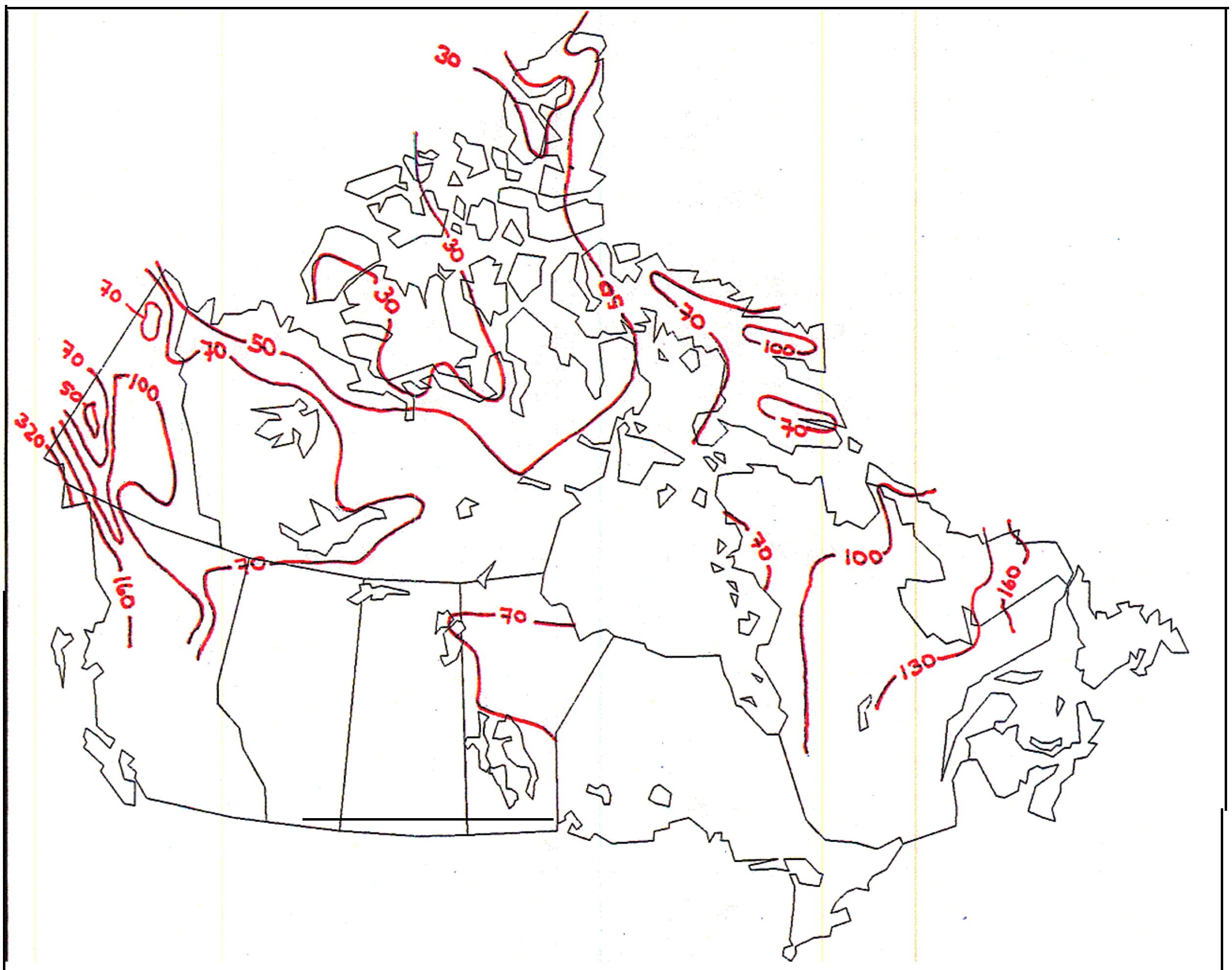
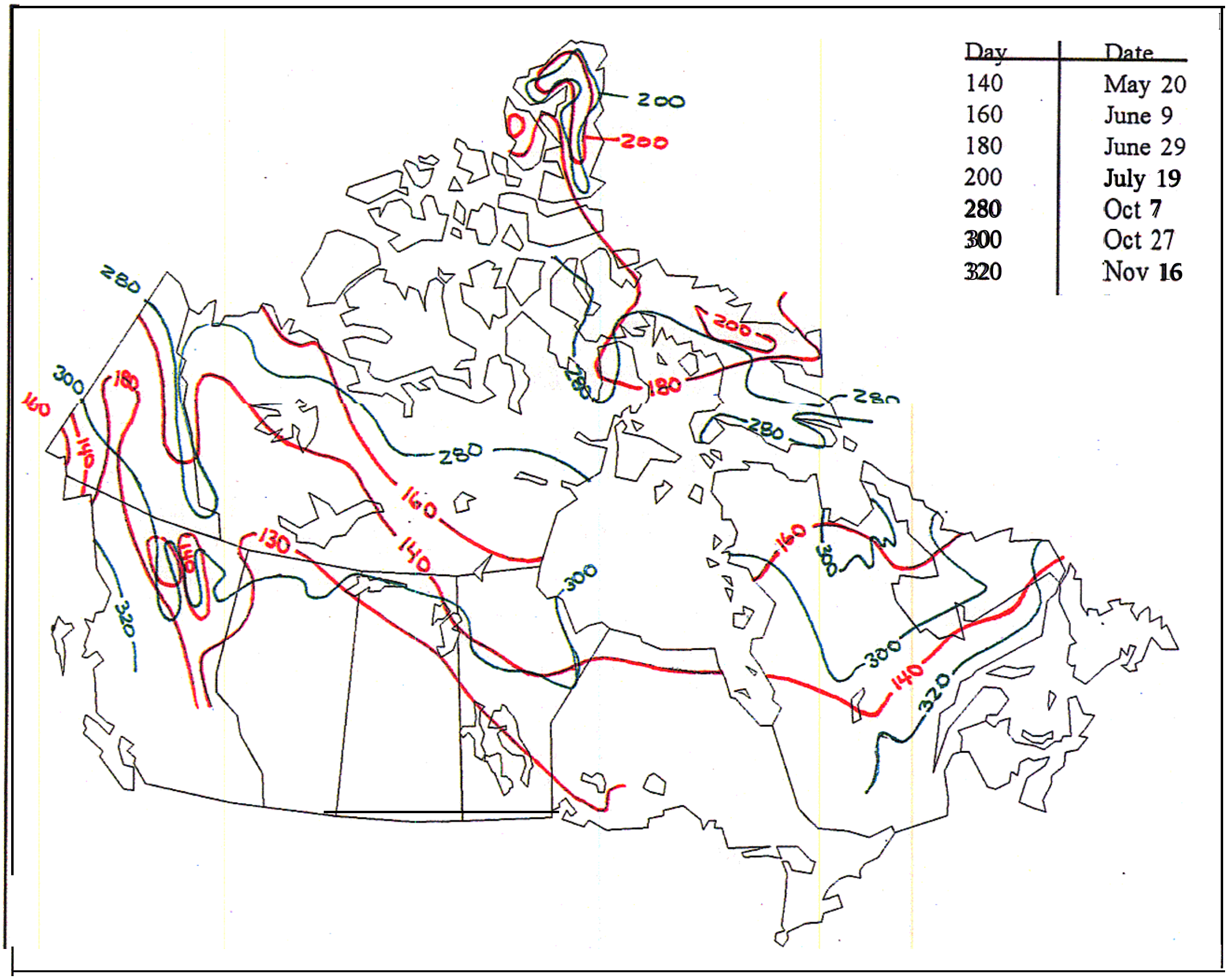



Figure 2.10 Mean Maximum Depth of Snow (cm)
(after Hydrological Atlas of Canada, 1978)

160 — Day of year when 12.5 cm of snow occurs and remains absent for 7 days or more.

300 — Day of year when ≥ 2.5 cm of snow occurs and remains for ) 7 days.




| Day | Date |
|---|---|
| 140 | May 20 |
| 160 | June 9 |
| 180 | June 29 |
| 200 | July 19 |
| 280 | Oct 7 |
| 300 | Oct 27 |
| 320 | Nov 16 |

Figure 2.11 Dates of Formation end Loss of Snow Cover (after Hydrological Atlas of Canada, 1978)

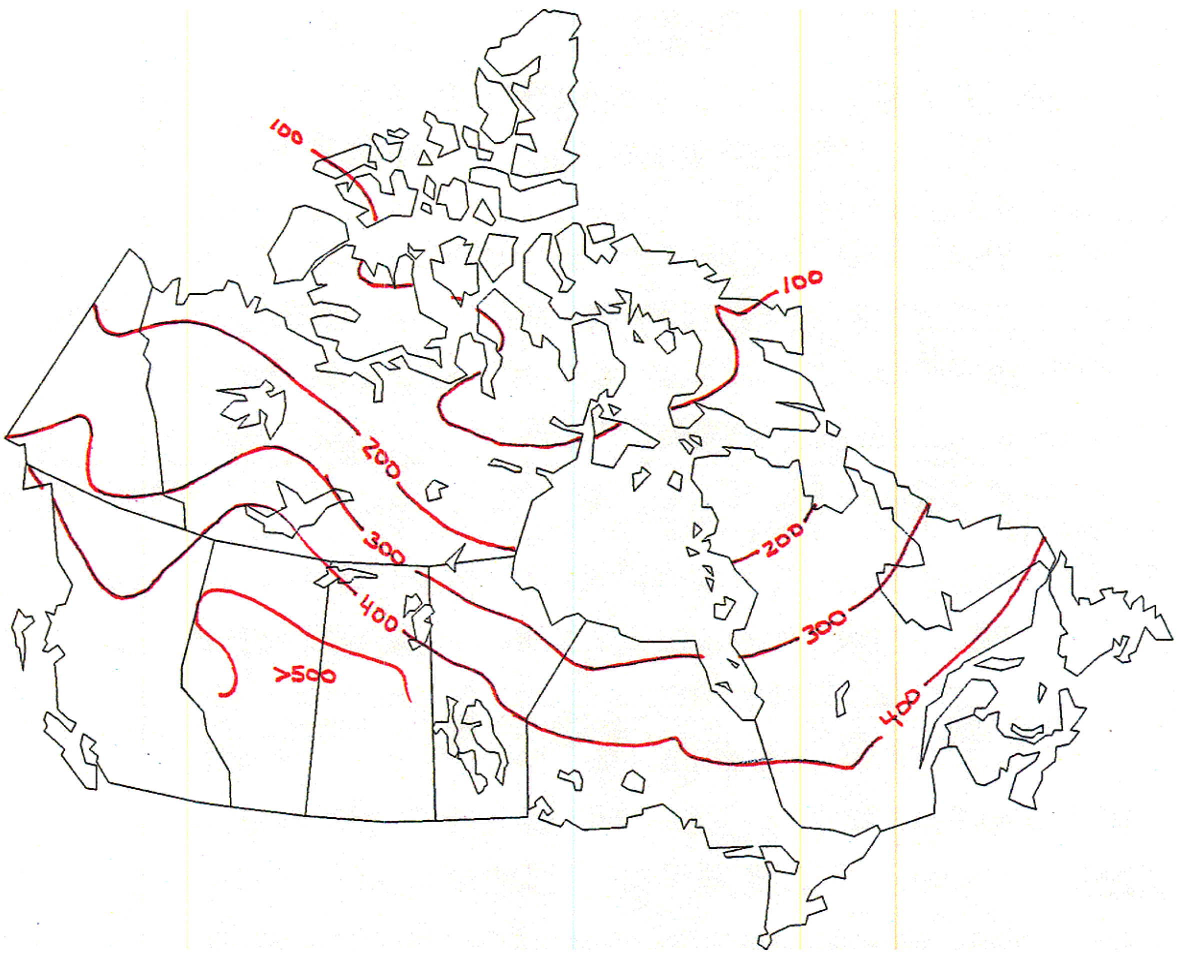



Figure 2.12 Mean Annual Lake Evaporation (mm)
(after Hydrological Atlas of Canada, 1978)

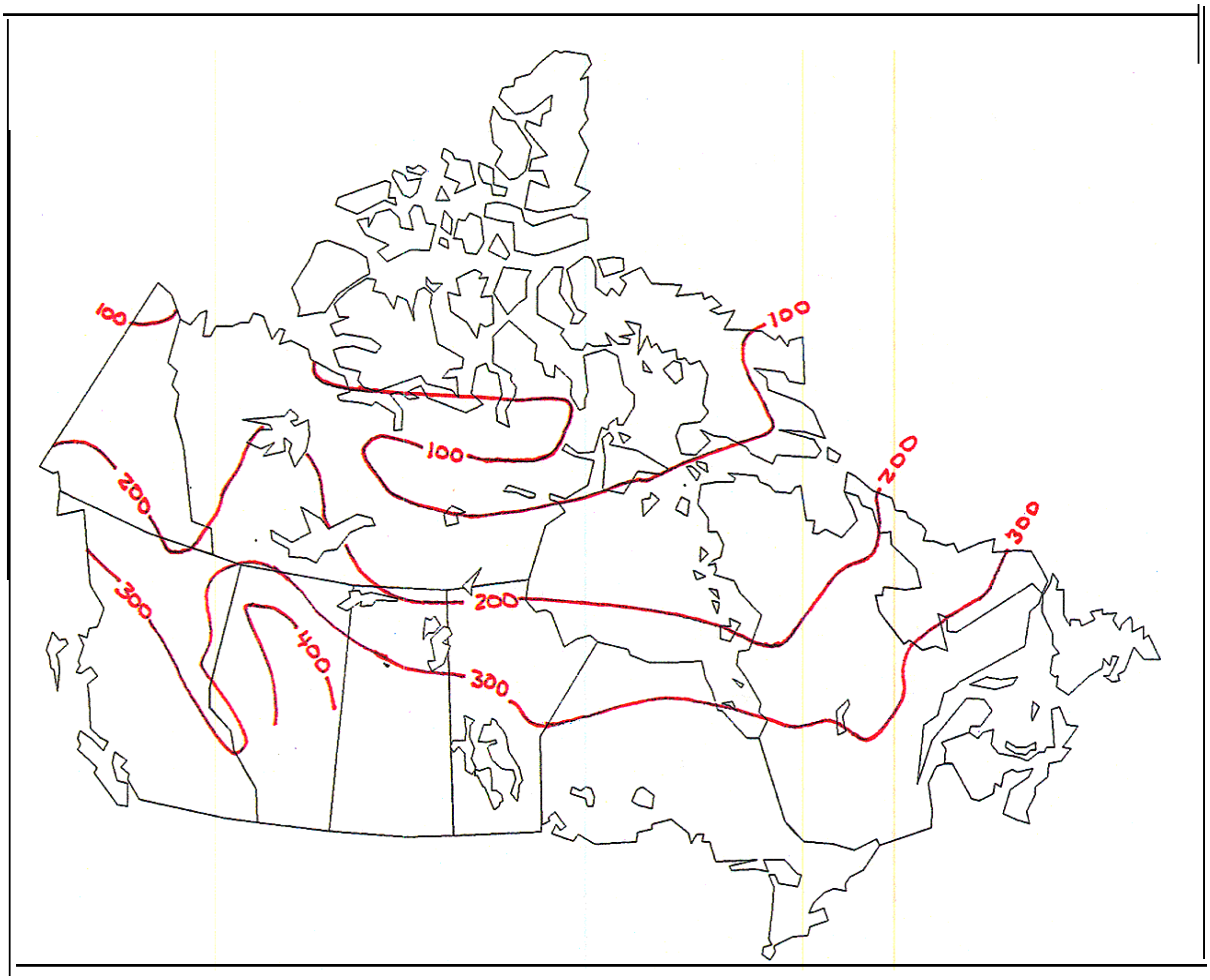



Figure 2.13 Derived Evapotranspiration in Canadian North (after Hydrological Atlas of Canada, 1978)

1 Sa Dena Hes
2 Ketza River
3 Faro
4 Keno Hill
5 Brewery Creek
6 Cantung
7 Polaris
8 Nanisivik
9 Lupin
10 Colomac
11 Mon & Discovery
12 Giant, Con, Ptarmigan, Tom
13 Salmita & Tundra
14 Rankin Inlet
15 Cullaton
16 Pine Point
17 Port Radium

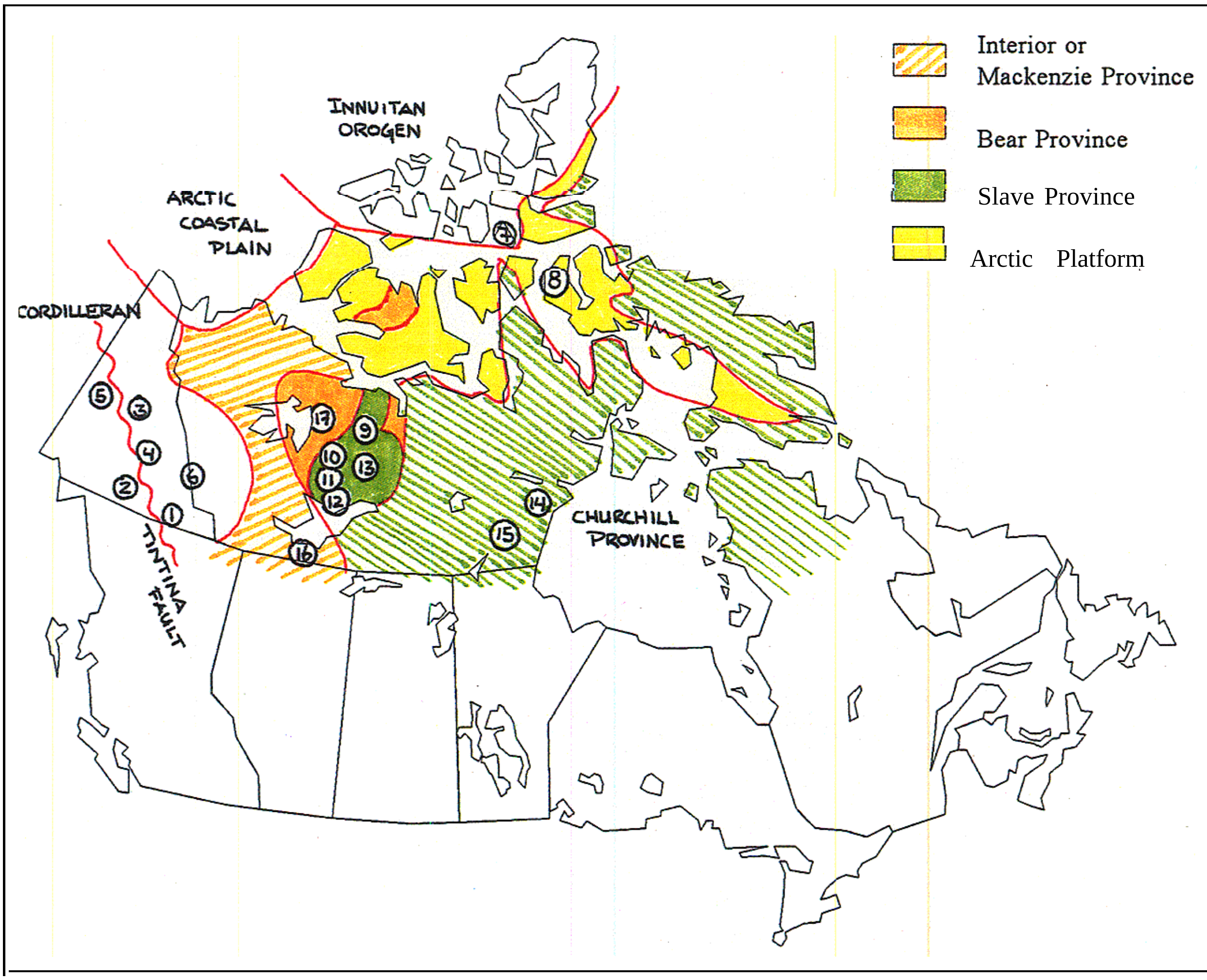



Figure 2.14 Locations of Major Mining Operations (Operating, Closed, or Abandoned) in the Yukon and NWT

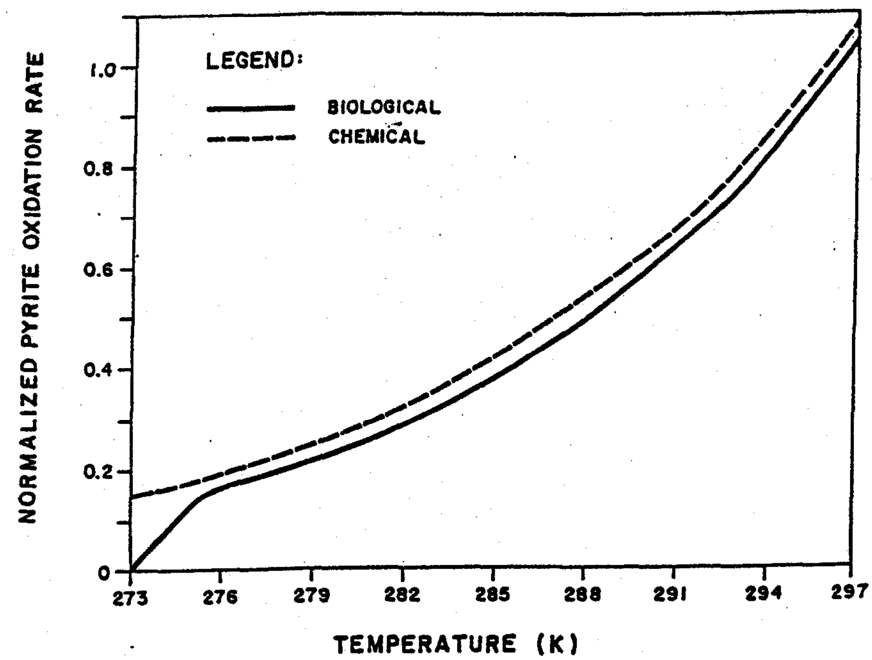



Figure 3.1 Effect of Temperature on Biological and Chemical Oxidation Rates (Knapp, 1987)

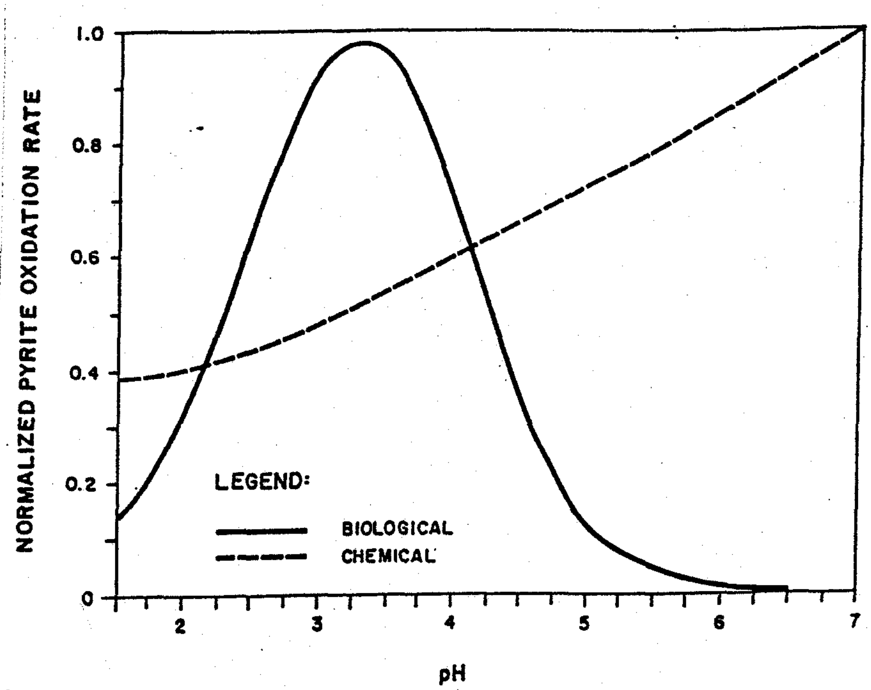



Figure 3.2 Effect of pH on Biological and Chemical Oxidation Rates (Knapp, 1987)

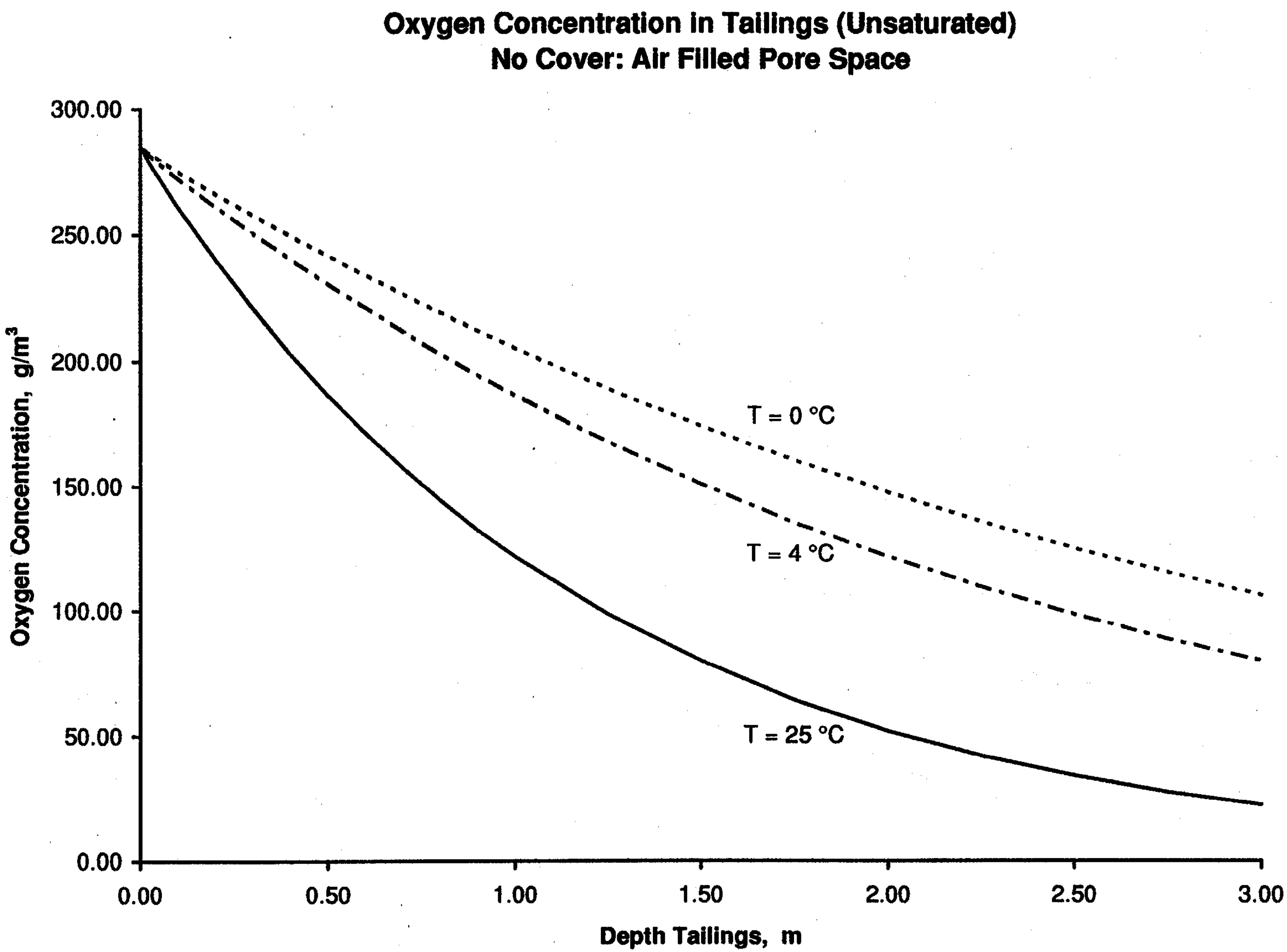



Figure 4.1 Oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in unsaturated tailings (air filled pore spaces) without cover. The air/tailings interface is at 0 m.

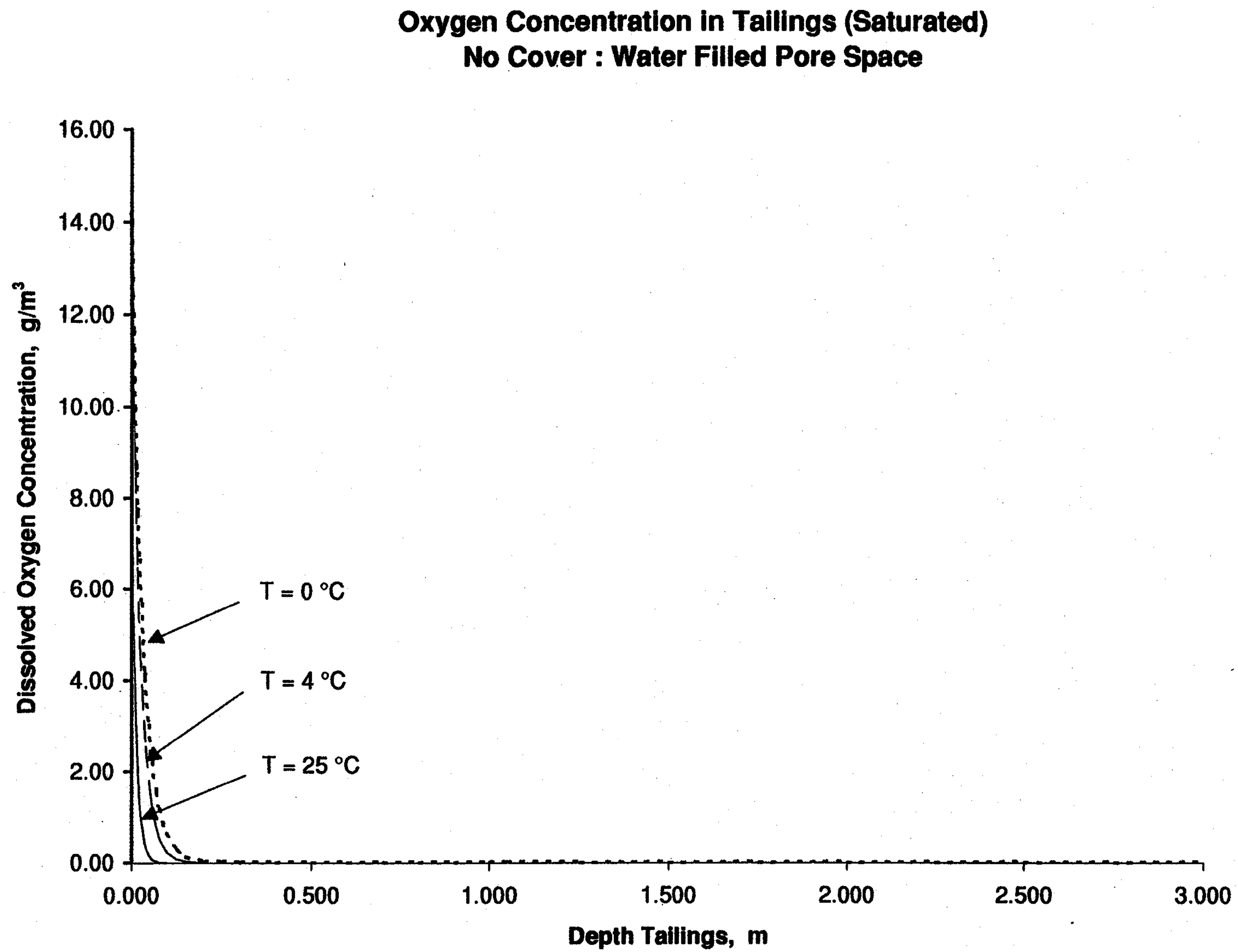



Figure 4.2 Dissolved oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in saturated tailings (water filled pore spaces) with no additional cover. The air/tailings interface is at 0 m.

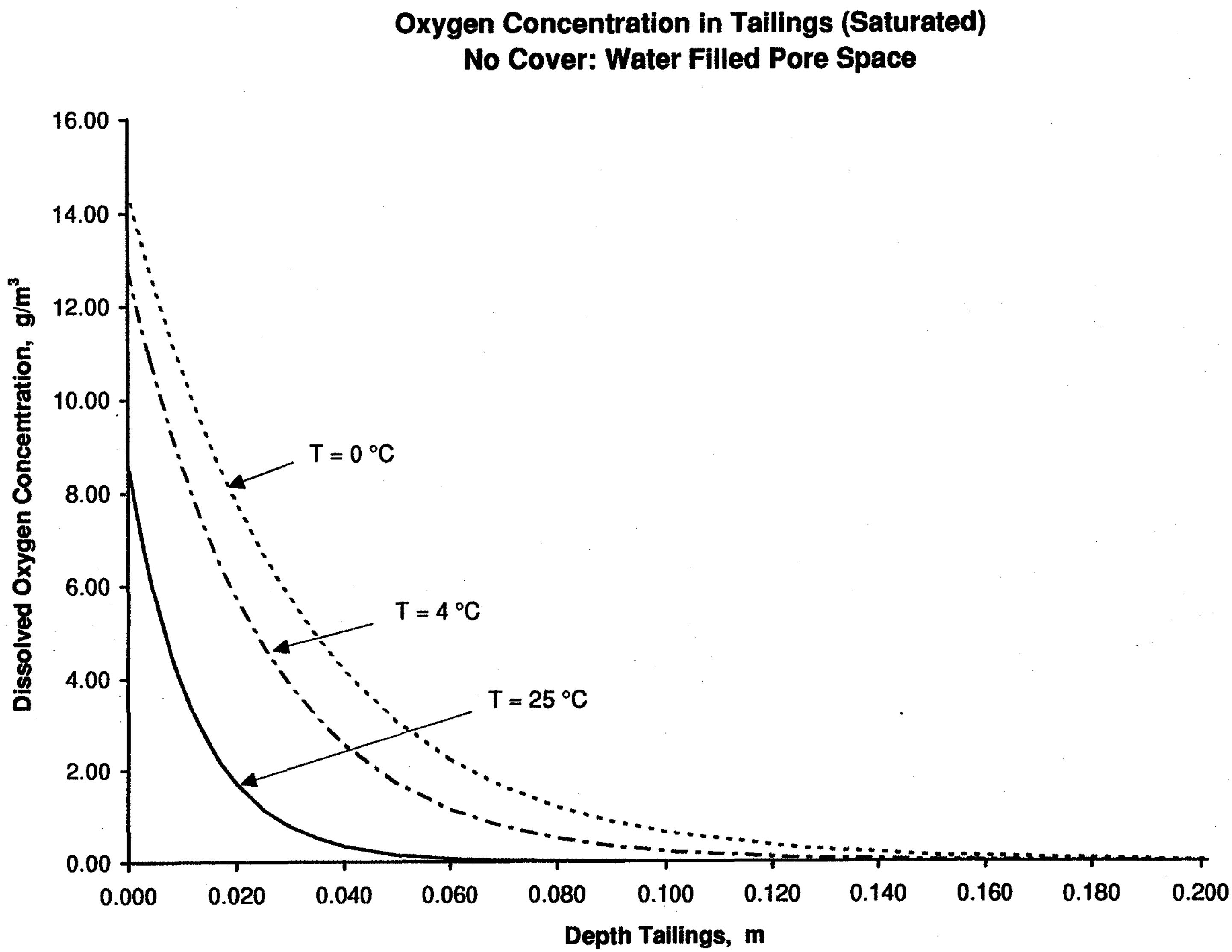



Figure 4.3 Dissolved oxygen concentration profiles (expanded scale) as a function of depth at 25°, 4°, and 0°C in saturated tailings (water filled pore spaces) with no additional cover. The air/tailings interface is at 0 m.

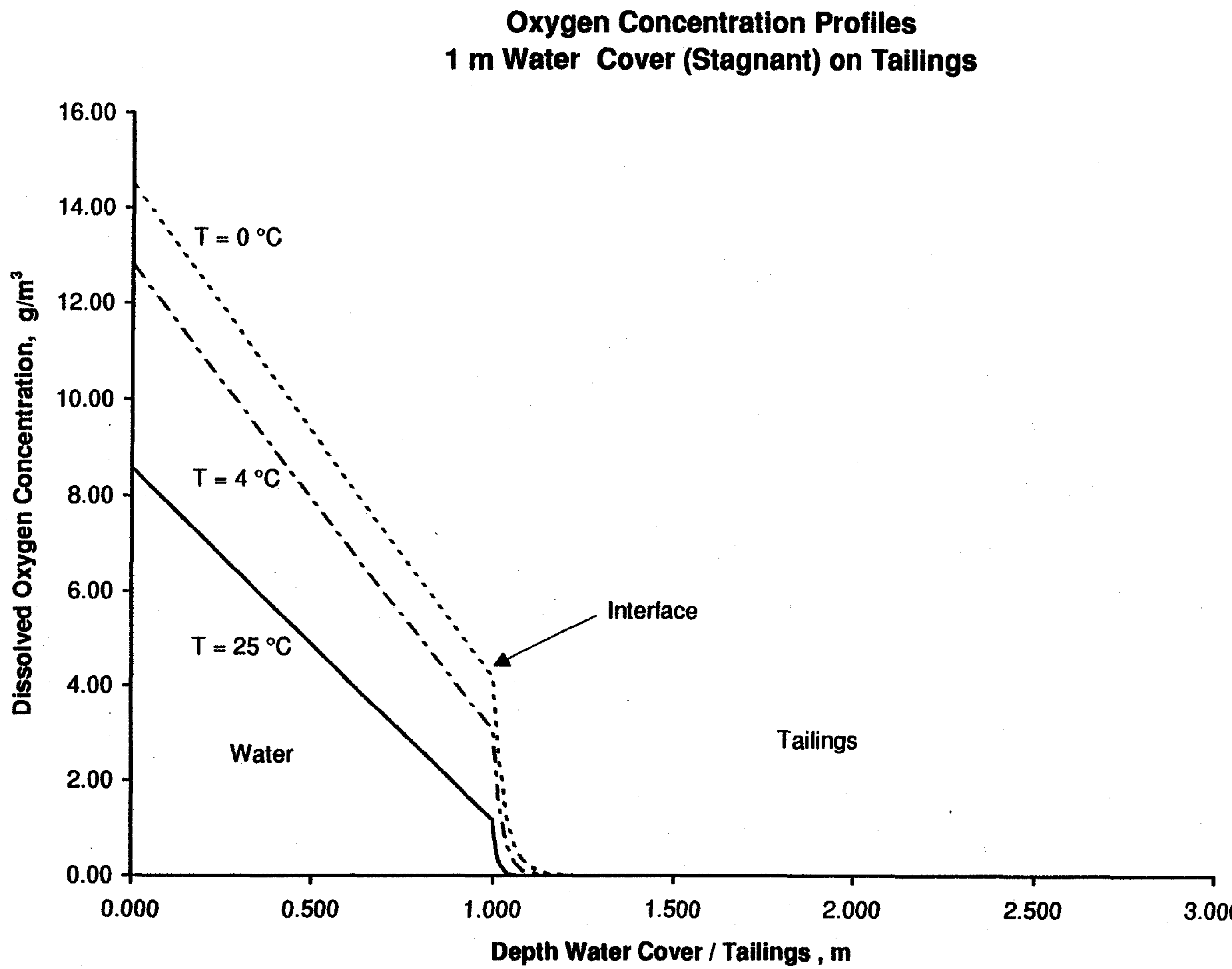



Figure 4.4 Dissolved oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in unmixed water cover of depth 1 m and underwater deposited tailings. The tailings-water interface is at depth 1.0 m from the surface of the water cover.

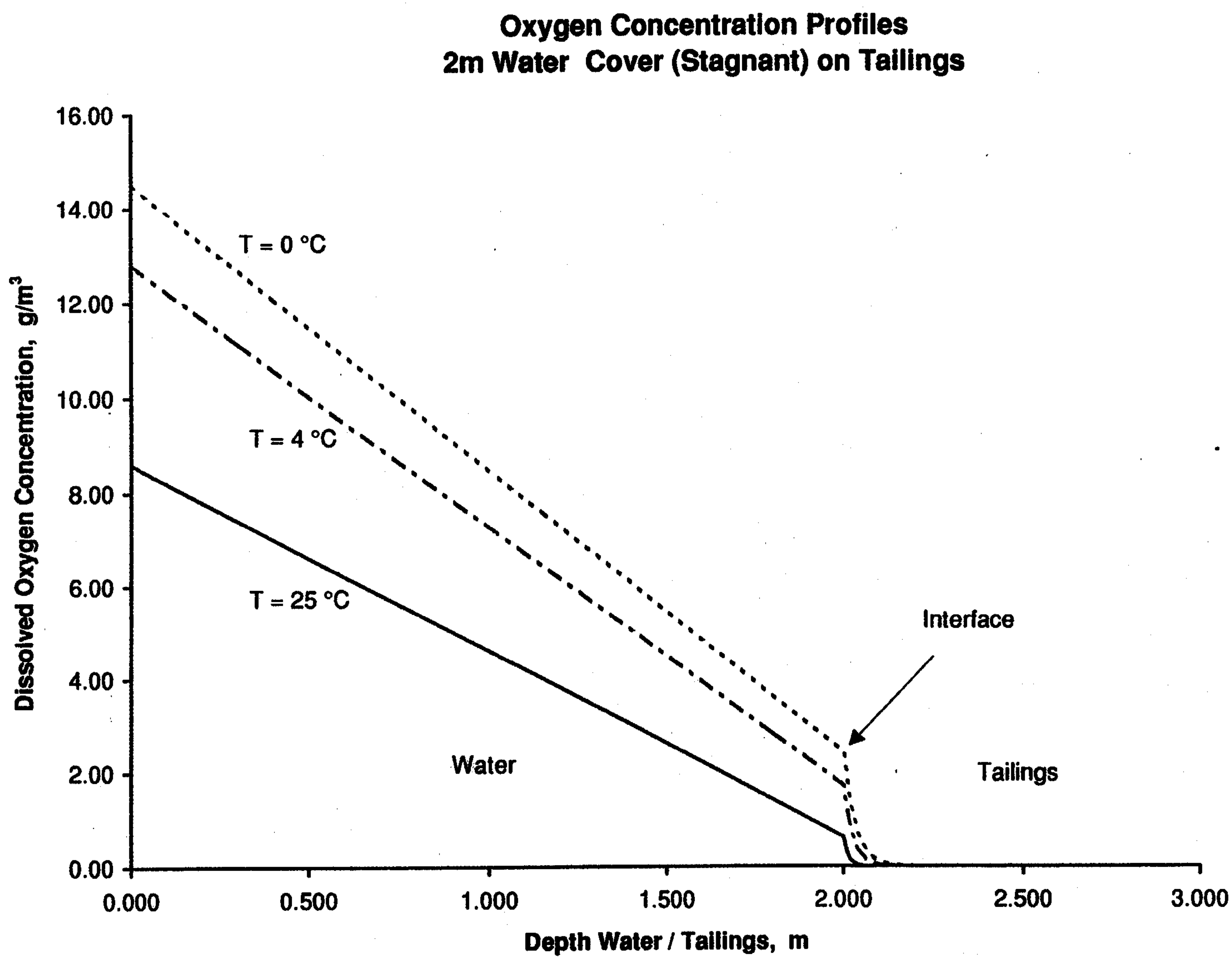



Figure 4.5 Dissolved oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in unmixed water cover of depth 2 m and underwater deposited tailings. The tailings-water interface is at depth 2.0 m from the surface of the water cover.

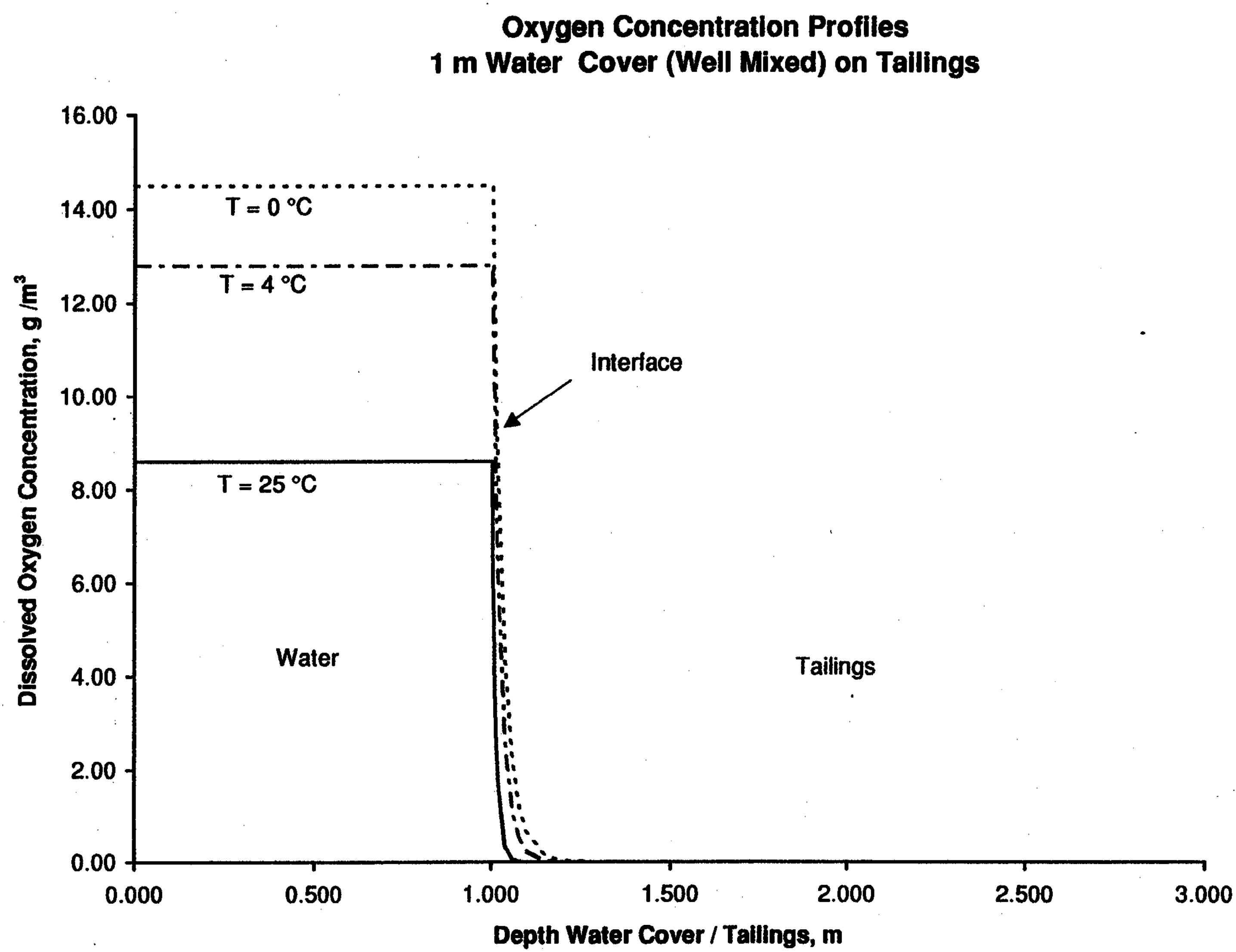



Figure 4.6 Dissolved oxygen concentration profiles as a function of depth at 25°, 4°, and 0°C in a well mixed water cover of depth 1 m and underwater deposited tailings. The tailings-water interface is at depth 1.0 m from the surface of the water cover.

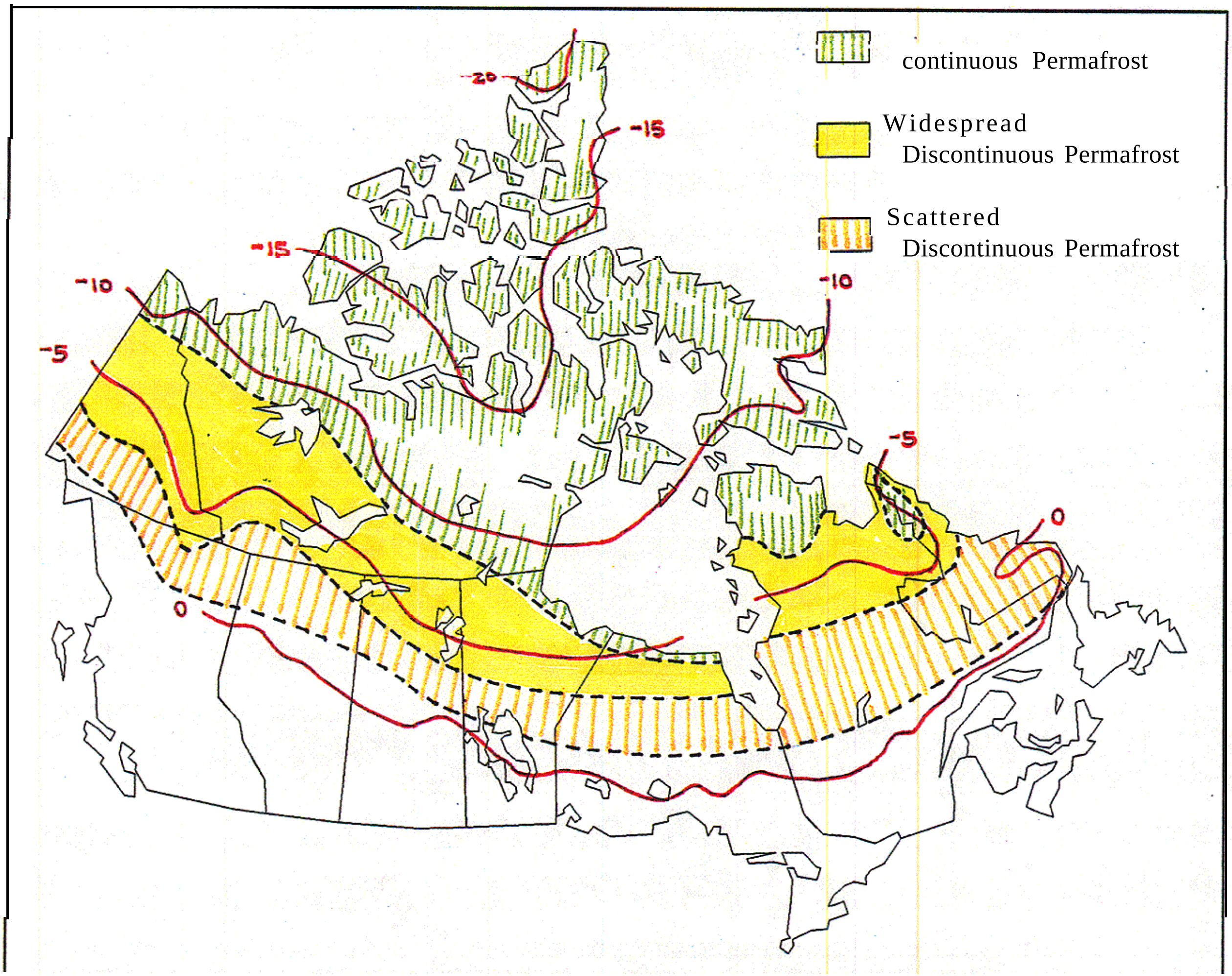
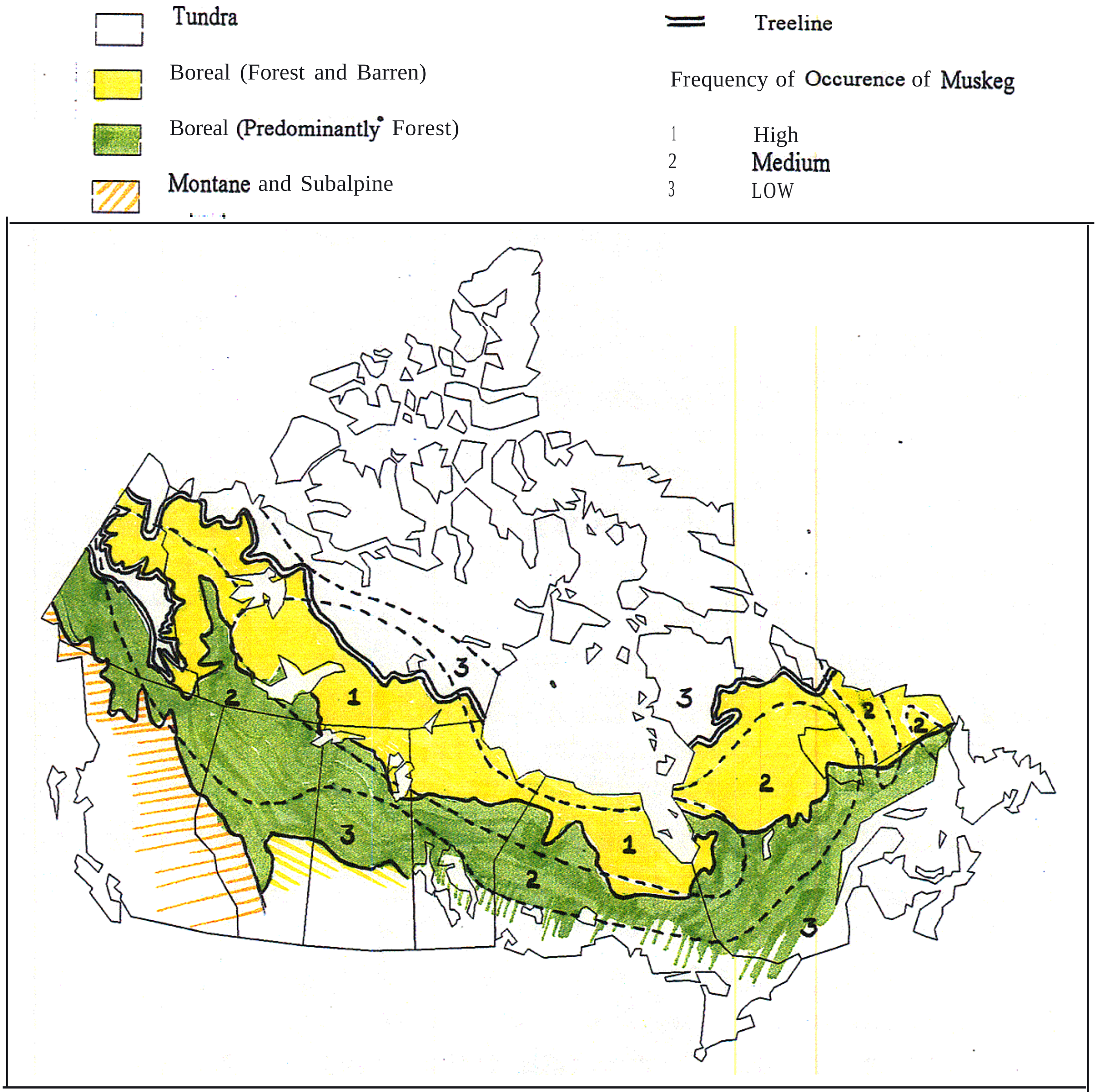



Figure 5.1 Mean Annual Air Temperature Isotherms and Permafrost Regions (after Johnston, 198 1)




igure 5.2 Vegetation Regions in the Canadian North (after Johnston, .1981)

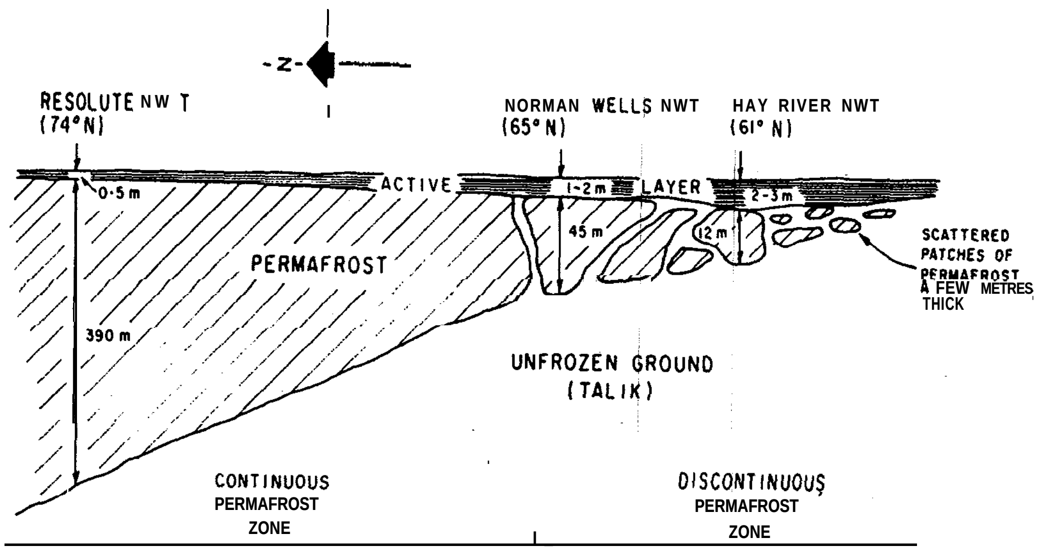



Figure 5.3 The Active Layer in Regions of Continuous and Discontinuous Permafrost (Johnston, 1981)

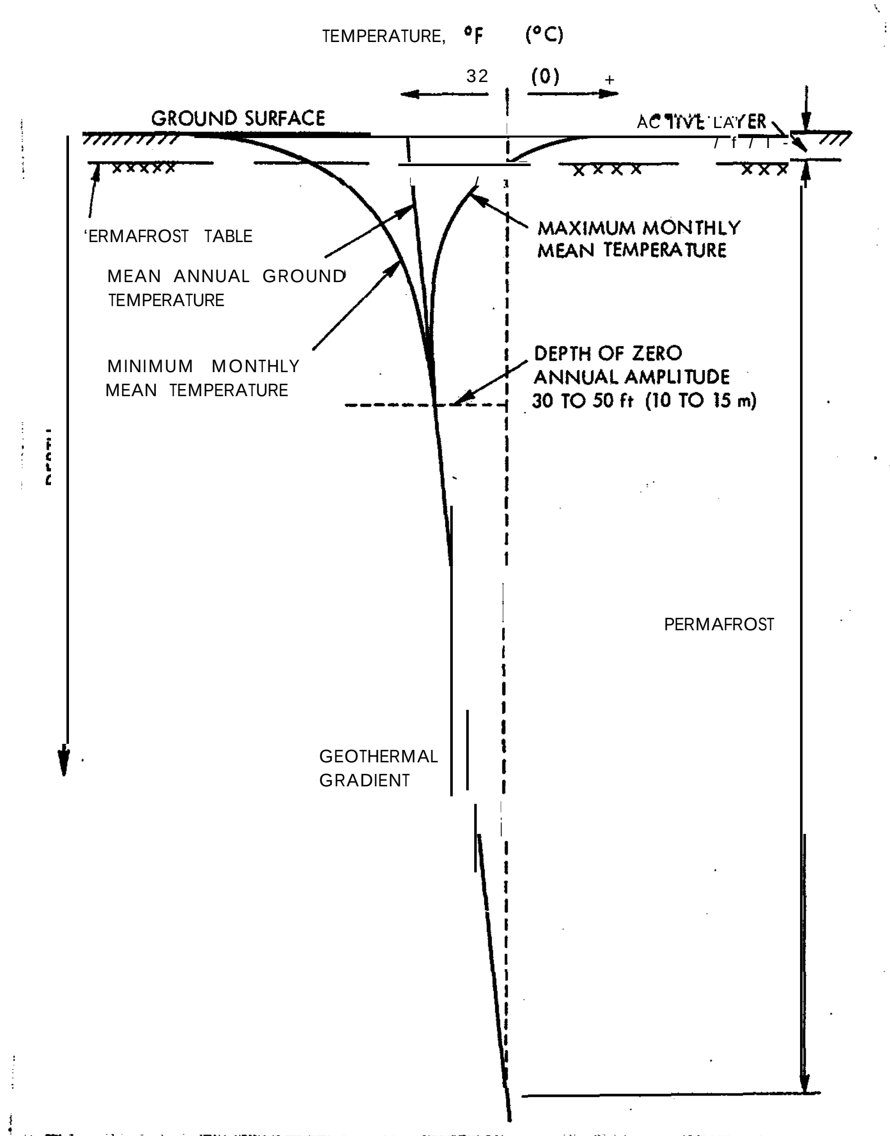



Figure 5.4 Depth of Zero Amplitude in Typical Permafrost Regime (Johnston, 198 1)

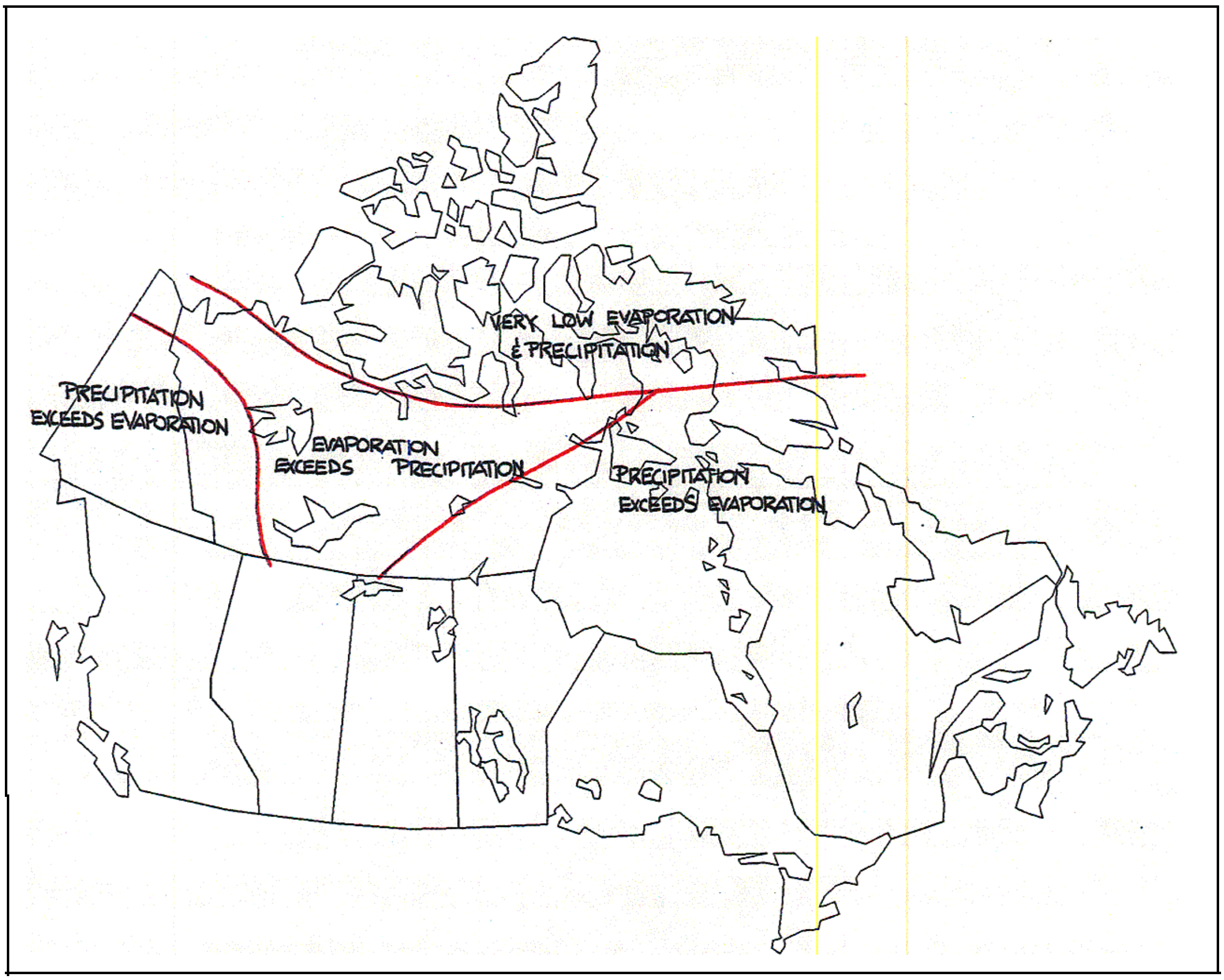



Figure 5.5 Evaporation/Precipitation Balance Subregions
(after Norecol, Dames & Moore, 1994)

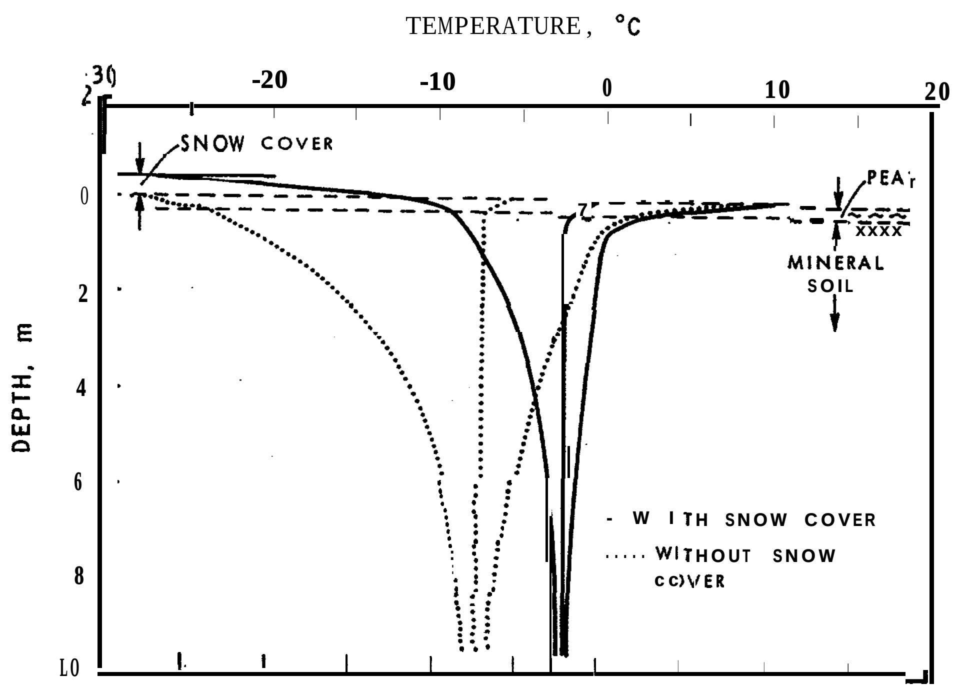



Figure 5.6 Impact of Snow Cover on Permafrost Regime (Johnston, 198 1)

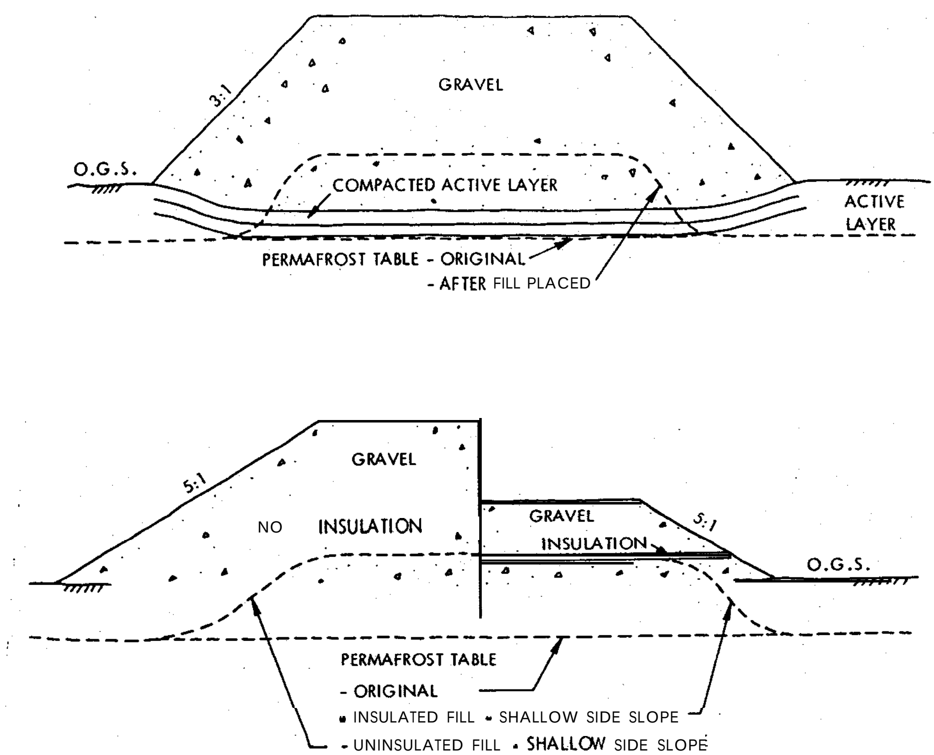



Figure 5.7 Impact of Insulated and Uninsulated Covers on Permafrost Table (after Johnston, 198 1)