Preventing AMD by Disposing of Reactive Tailings in Permafrost

MEND Project 6.1

This report results from solicitation of proposals in 1992 by the New Ideas Task Force of the Mine Environment Neutral Drainage (MEND) Program. The views and technical recommendations in this report are those of the author and do not necessarily reflect those of MEND or the Prevention & Control (P & C) Committee of MEND.

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MEND New Ideas Projects

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EXECUTIVE SUMMARY

In recent years the detrimental effect of acid water produced by sulphide oxidization of tailings and waste rock on the environment was recognized and is being combatted in southern regions of Canada. There are numerous abandoned, operating and proposed mines in Canadian permafrost regions. These northern mines have an additional tool to combat acid generation by freezing and keeping the tailings and waste rocks in a frozen state. This tool requires careful evaluation to determine where and how it may be used economically.

Permafrost is not homogeneous being greatly dependent on the mean annual air temperature and physiography that varies across the country. The permafrost is divided into discontinuous permafrost located near the 60 degree latitude and continuous permafrost located in the Arctic region. The permafrost area can also be divided by climatic regions, namely Boreal, Coridillera and Arctic climatic regions. The first two represent discontinuous permafrost and the last region, continuous permafrost.

The mean annual ground temperature is about 4 degrees Celsius warmer than the mean annual air temperature. However the ground temperature near the ground surface fluctuates greatly during the year with the fluctuation decreasing with depth. Steady temperature is reached some 10 to 15 m below the ground surface. The annual temperature fluctuations cause a surface layer to thaw annually, called the active zone. The thickness of the active zone in the continuous permafrost varies between 0.5 m under thick organics to 10 m under bare rock. In discontinuous permafrost the depth of this zone may be greater. For a given temperature regime, the thickness of the active zone is predominantly governed by the insulation of the organic layer and secondarily by the water content of the underlying soil/rock stratigraphy. Mineralogy of the underlying soil/rock has a small influence.

Acid generation is the result of chemical and biological oxidation of pyrite. Available

data and the RATAP model show that there is a considerable decrease in the rate of oxidation as the temperature approaches zero degrees Celsius. The relative rate of oxidation reduces to about 10% of the relative rate occurring between 25° to 30° C. However little is known about further decrease as the temperature drops below 0°C. Some unfrozen water occurs below 0°C. From geotechnical engineering studies it is known that the unfrozen water around particles freezes around coarse particles, such as sand and coarse silt. Around smaller particles a small film of unfrozen water may still remain to about -5° C or colder depending on the size and mineralogy of the particles. The volume of unfrozen water is small and is surrounded by ice. In silt at -3°C the unfrozen water represents less than 10 percent of the total weight of water.

Temperature monitoring at the Lupin mine tailings impoundment provides a good temperature data base showing the ground temperature changes through the year in several soil/tailings/bedrock stratigraphies. This data shows the depth of the active zone to be between 2.5 to 3 m in native silty sand till and tailings. In natural ground with a 500 mm organic layer the active zone was measured as 1 m and in bare fractured bedrock the active zone was 4 m.

The data from Lupin located in a cold continuous permafrost environment shows that about 3 m thick sand/gravel covers are required to bring the active zone out of the tailings and keep the tailings permanently frozen. This depth of granular cover is very costly. An alternative cover could be non-acid generating mine rock that may be more economical than sand/gravel fills at mines with surplus waste rock. Some savings would also be achieved by a thinner cover. A more economical solution may be to design a total surface water containment in the tailings pond. The total containment would be created by the construction of frozen core perimeter dykes. In this design the base of the active zone below the dyke crest would be above the high water levels in the pond. The raised permanently frozen material could be obtained by either increasing the height of the dykes or using polystyrene board insulation within the fill to decrease the fill requirement.

Total surface water containment may be feasible in most continuous and discontinuous permafrost regions because of high annual evaporation as compared to annual precipitation in the north. This design requires to limit the watershed to the tailings pond and a freeboard to store the water from extreme snowmelt and precipitation events.

In discontinuous permafrost regions it may be practically impossible to develop permafrost in the tailings. In this case total containment with a frozen perimeter dyke could be developed through artificial means. The most practical artificial design is the use of thermosyphons and polystyrene board insulation buried just below the ground surface. In this design the thermosyphons, non mechanical heat tubes, extract heat from the ground during the winter and the insulation reduces the heat re-entry during the summer. Thermosyphons have been used in Alaska and Canada in road, airfields and building applications.

A marginal and unproven alternative to develop and maintain permafrost in the discontinuous permafrost regions may be a convective rock cover. The principle of the rock cover is that during winter, heat is extracted from the ground by air convection through the large voids in the rock and during the summer the air in the voids acts as an insulation blanket. There is one documented case history from Russia (Robertson et al. 1982), and one thermal analysis conducted for uranium tailings in Canada, supporting this principle. Follow up of this design by further thermal analysis and field installation is recommmended because of its simplicity.

Future work to obtain further information and develop design principles for the use of permafrost to prevent tailings acid generation should be through laboratory and office analyses of sulphide oxidation in the near below zero temperatures; thermal analyses to improve the estimated cover thicknesses to keep the tailings frozen and field installation/monitoring in continuous and discontinuous permafrost of the recommended designs.

RÉSUMÉ

L'effet nocif de l'eau acide produite par l'oxydation des résidus et des stériles par les sulfures sur l'environnement a été reconnu récemment et est combattu dans des régions méridionales du Canada. De nombreuses mines sont abandonnées, en exploitation ou projetées dans les régions de pergélisol du Canada. Ces mines septentrionales offrent un outil additionnel pour combattre la production d'acide : le gel des résidus et des stériles et leur maintien à l'état gelé. Il faut évaluer judicieusement cet outil pour déterminer comment et où l'utiliser de façon économique.

Le pergélisol n'est pas homogène et dépend grandement de la température annuelle moyenne de l'air et de la physiographie, lesquelles varient d'une région à l'autre du pays. Le pergélisol se divise en pergélisol discontinu au voisinage du 60[e] parallèle et en pergélisol continu dans la région de l'Arctique. La zone de pergélisol peut aussi se répartir selon les régions climatiques boréale, de la Cordillère et de l'Arctique. Le pergélisol discontinu se trouve dans les deux premières régions et le pergélisol continu dans la dernière.

La température annuelle moyenne du sol est d'environ 4 degrés Celsius plus élevée que la température annuelle moyenne de l'air. Toutefois, la température du sol près de la surface fluctue grandement au cours de l'année et les fluctuations sont moindres en profondeur. La température est constante à quelque 10 à 15 m sous la surface. Les fluctuations de température annuelles entraînent chaque année le dégel d'une couche de surface appelée la zone active. L'épaisseur de la zone active dans le pergélisol continu varie entre 0,5 m sous une épaisse couche organique et 10 m dans le roc dénudé. Dans le pergélisol discontinu, l'épaisseur de cette zone peut être plus grande. Pour un régime de température donné, l'épaisseur de la zone active dépend surtout de la valeur isolante de la couche organique, puis de la teneur en eau de la séquence stratigraphique sol/roc sous-jacente. La minéralogie de cette séquence stratigraphique sous-jacente est peu importante.

La production d'acide est le résultat de l'oxydation chimique et biologique de la pyrite. Les données disponibles et le modèle RATAP montrent que le taux d'oxydation diminue beaucoup lorsque la température tend vers zéro degré Celsius. Le taux relatif d'oxydation tombe à environ 10 % du taux relatif observé entre 25 et 30°C. Toutefois, en-dessous de 0° C, le comportement du taux relatif est peu connu. De l'eau non gelée est observée en-dessous de 0°C. Des études géotechniques ont révélé que l'eau gèle autour des grosses particules comme les particules de sable et de limon grossier. Autour des petites particules, une fine couche d'eau non gelée subsiste jusqu'à -5° C environ ou moins selon le diamètre et la minéralogie des particules. Le volume d'eau non gelée est faible et entouré de glace. Dans le limon, à -3° C, l'eau non gelée représente moins de 10 % du poids total d'eau.

Les contrôles de température du bassin de résidus de la mine Lupin constituent une bonne base de données de température qui montre que la température du sol varie au cours de l'année dans plusieurs stratigraphies sol/résidus/roc. Ces données indiquent que l'épaisseur de la zone active se situe entre 2,5 et 3 m dans les tills et les résidus de sable limoneux natif. La zone active a une épaisseur de 1 m dans un sol naturel recouvert d'une couche organique de 500 mm, et de 4 m dans le roc fracturé et dénudé.

Les données de Lupin, qui proviennent d'un pergélisol continu, montrent que la couverture de sable et de gravier doit être de 3 m pour que les résidus ne comportent aucune zone active et demeurent gelés en permanence. Une couverture graveleuse de cette épaisseur est très coûteuse. Une solution plus économique dans les mines regorgeant de stériles serait une couverture de pierre abattue non acidogène. Une couverture plus mince permettrait aussi d'autres économies. Une solution plus économique consisterait à confiner complètement les eaux de surface dans le bassin de résidus en aménageant un périmètre d'endiguement dont l'intérieur de la masse serait gelé. Dans un tel aménagement, la base de la zone active sous la crête des digues se trouverait au-dessus du niveau des hautes eaux du bassin. Le matériau rapporté pourrait demeurer gelé en permanence si on augmentait la hauteur des digues ou si on enfouissait des panneaux isolant en polystyrène dans le remblai pour diminuer le remblayage.

Il serait possible de confiner toute l'eau de surface dans la plupart des régions de pergélisol continu ou discontinu parce que l'évaporation est chaque année supérieure aux précipitations dans le nord. Un tel aménagement exige que le bassin hydrographique soit limité au bassin de résidus et qu'un franc-bord soit mis en place pour emmagasiner l'eau pendant les périodes de fonte des neiges et de précipitation extrêmes.

Dans les régions de pergélisol discontinu, il peut s'avérer presque impossible de maintenir un pergélisol dans les résidus. Dans ce cas, un périmètre d'endiguement gelé peut être entretenu artificiellement pour assurer un confinement complet. L'endiguement artificiel le plus pratique consiste à enfouir des thermosiphons et de l'isolant en polystyrène juste en-dessous de la surface du sol. Dans un tel aménagement, les thermosiphons, constitués de caloducs non mécaniques, extraient la chaleur du sol l'hiver et l'isolant empêche la chaleur d'entrer l'été. Des thermosiphons ont été utilisés en Alaska et au Canada dans la constructions de routes, d'aérodromes et d'immeubles.

Une solution d'appoint non éprouvée dans les régions de pergélisol discontinu consiste, non pas à maintenir artificiellement le pergélisol, mais à aménager une couverture de pierre convective. Le principe de la couverture de pierre repose sur l'extraction de chaleur du sol l'hiver par convection d'air dans les gros interstices de la couverture et sur l'utilisation de ce même air comme couverture isolante l'été. Une étude a été documentée en Russie (Robertson et coll. 1982), et une analyse thermique a été effectuée sur des résidus d'uranium au Canada, à l'appui de ce principe. Il est recommandé de poursuivre l'analyse thermique de ce type d'aménagement et d'en faire l'installation sur le terrain à cause de sa simplicité.

Pour obtenir plus d'information et élaborer des principes d'aménagement concernant l'utilisation du pergélisol pour empêcher la production d'acide dans les résidus, il faudrait poursuivre les travaux en procédant à des analyses en laboratoire et de bureau sur l'oxydation par les sulfures au voisinage du point de congélation; à des analyses thermiques pour mieux estimer l'épaisseur des couvertures destinées à maintenir les résidus gelés; et à l'installation et au contrôle sur le terrain des aménagements recommandés dans des pergélisols continus et discontinus.

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1.0 INTRODUCTION

1.1 General

About half of Canada is underlain by permafrost (Figure 1) which contains numerous abandoned, operating and proposed mines. In recent years the detrimental effect of acid water produced by sulphide oxidization of tailings and waste rock on the environment was recognized and is being combated. Some common control and prevention measures include: water collection and treatment, placement of covers over the acid generating materials or placement of acid generating materials into disused open pits or underground mined-out areas. Mines relocated in permafrost have an additional tool to combat acid generation by freezing and keeping the tailings and waste rocks in a frozen state.

This report presents an overview of the pertinent topics related to acid mine drainage (AMD) in permafrost areas and its prevention by developing permafrost in tailings. As well, options to freeze and maintain the tailings frozen in continuous and discontinuous permafrost regions are discussed.

The report starts with an overview of the northern environment, identifies occurrence and distribution of permafrost in Canada and subsequently describes the permafrost temperature profile. This is followed by a review of acid drainage chemistry and the effect of temperature on the acid generation process. Case histories of thermal regimes at existing mines are then reviewed to provide understanding and baseline information of ground temperatures, temperature profile changes over the year, and the factors influencing the development of permafrost. This is followed with a brief outline of design considerations that can be used in the design of mines or in the development of closure plans in permafrost areas. Finally, the report provides conceptual cover options, designs, and cost estimates for tailings impoundments in continuous and discontinuous

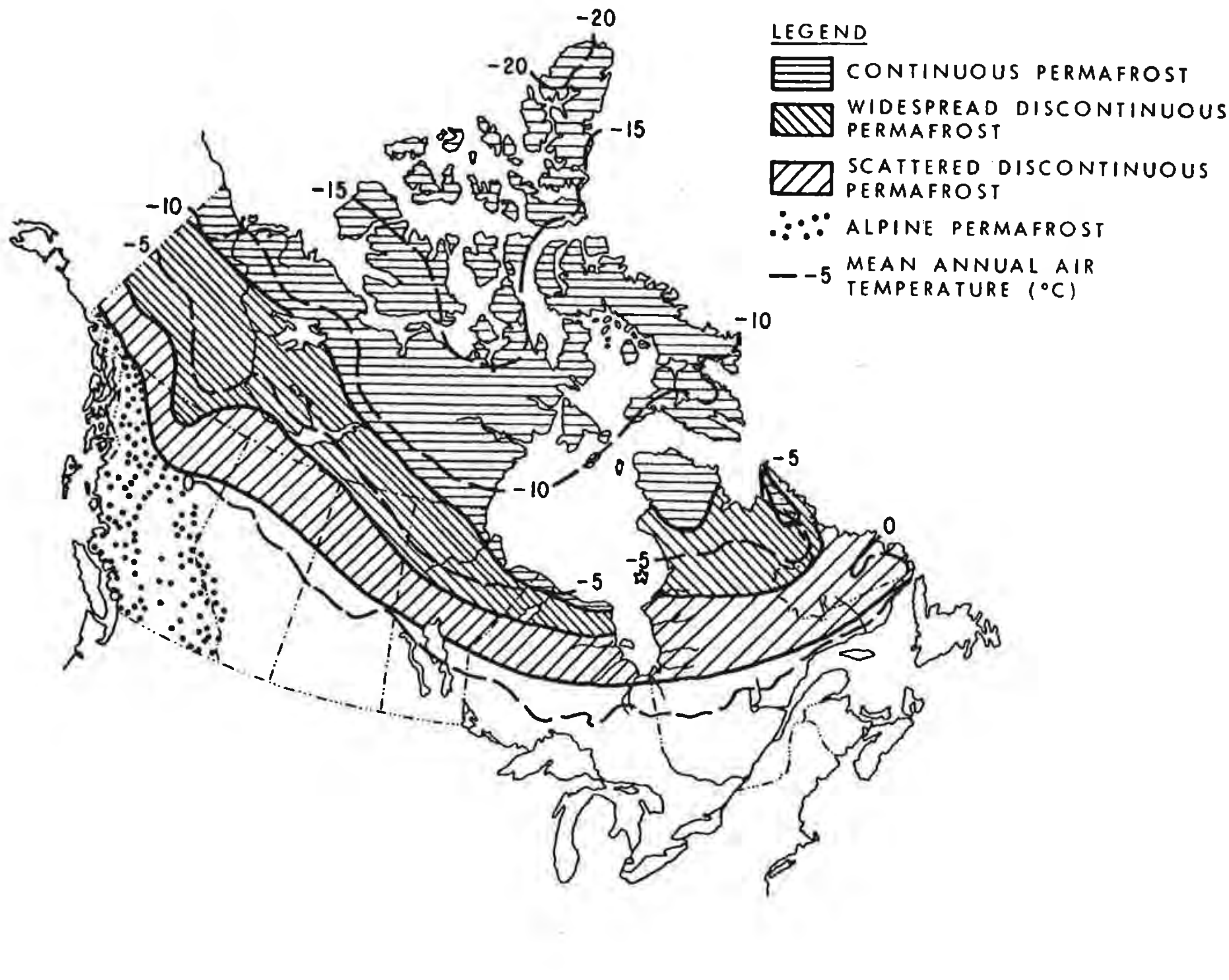


Figure 1 **Permafrost Regions**
(From Johnston 1981)

permafrost. The report concludes with recommendations for thermal analyses and field test programs to refine the proposed cover options.

1.2 Mines in Northern Canada

Mining in northern Canada started with the Klondike discoveries in 1896 (Udd 1989). This has developed into a large and diversified industry spanning from the Yukon Territory to Labrador. Northern Canada is defined broadly as the area underlain by permafrost. Neglecting the numerous small placer mines, there are some 70 to 100, closed, abandoned and operating, gold and silver, heavy metals, coal and uranium mines in northern Canada. Presently there is a large diamond exploration interest.

A brief review of available publications (Brown 1973, Udd 1989 and Caine and Brown 1986) indicate some 50 large mines in northern Canada which are either abandoned, operating, or in study phases. These mines are shown on Figure 2 and are listed in Table 1. This list does not include some 20 smaller abandoned mines (Kalin 1985) and the large number of identified and unidentified mineral deposits in northern Canada to be developed. The Northern Affairs Program of DIAND (Caine and Brown 1986) has listed 190 mines and important minerals deposits in the Yukon and Northern Territories. This list includes the previously listed mines.

The identified mines are about equally distributed within discontinuous permafrost in the western mountain range, discontinuous permafrost east of the Rockies, and in the continuous permafrost in northern Canada above the treeline. To take advantage of the permafrost environment in the design of tailings impoundments, the distinct natures of the three regions have to be considered.

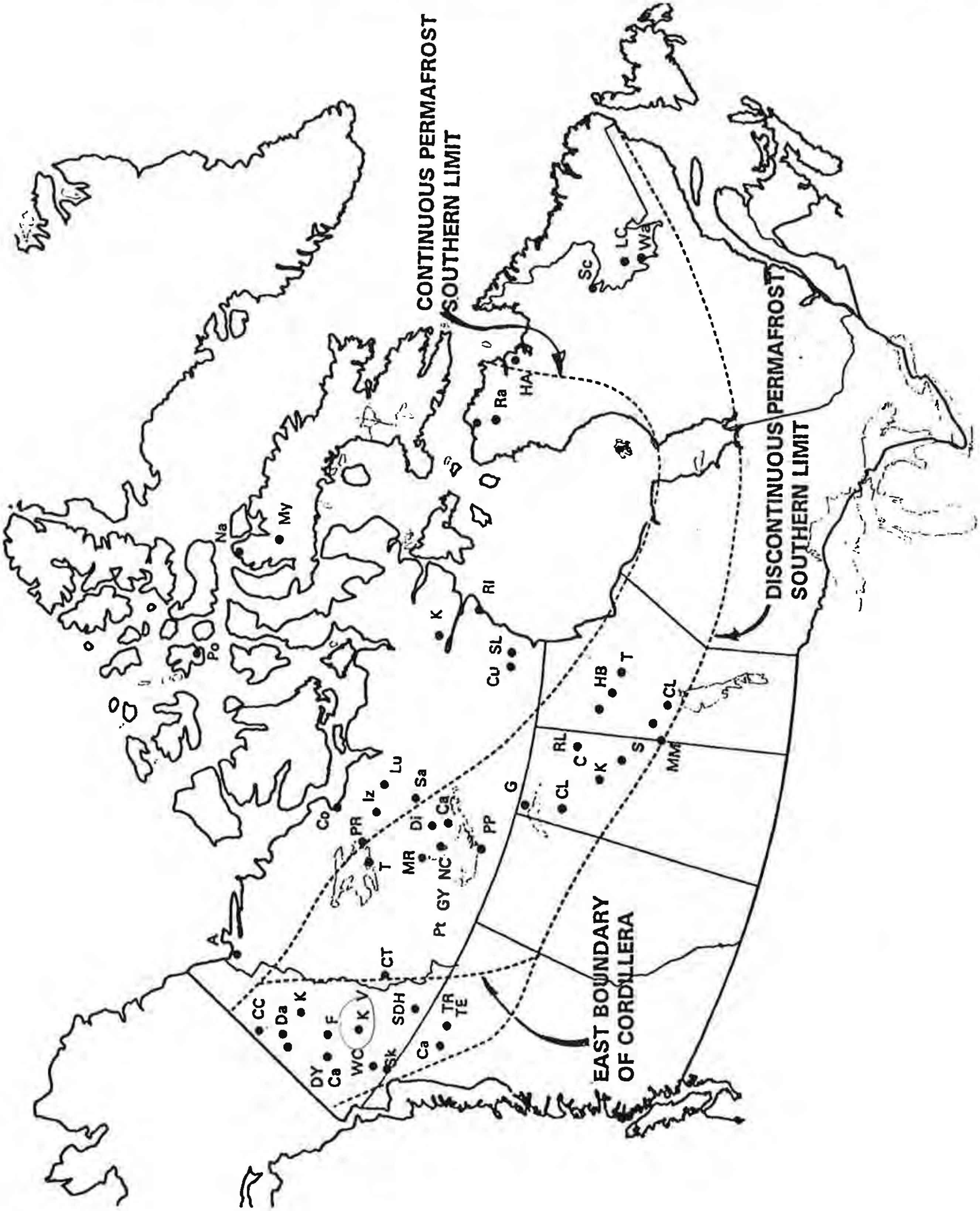


Figure 2 Location of Mines
(See Table 1 for Legend)

Table 1 List of Major Mines in Permafrost

SYMBOL	NAME	LOCATION	STATUS	SYMBOL	NAME	LOCATION	STATUS
CONTINUOUS PERMAFROST IN ARCTIC REGION				S	Star Lake Mine	LaRonge, Sk	C
A	Aklavik Mine	Tuktoyaktuk, NWT	C	C	Cigar Lake Mine	Walloston Lake, Sk	D
Co	Coppermine Mine	Coppermine, NWT	C	CL	Cluff Lake Mine	Cluff Lake, Sk	O
T	Terra Mine	Great Slave Lake, NWT	C	K	Key Lake Mine	Key Lake, Sk	O
PR	Port Radium Mine	Great Slave Lake, NWT	C	T	Thompson Inco Mine	Thompson, Ma	O
Lu	Lupin Mine	Contwoyto Lake, NWT	O	HB	HBMS Ruttan Lake Mine	Leaf Rapids, Ma	C
Po	Polaris Mine	Bathurst Island, NWT	O	MM	Main Mine	Flin Flon, Ma	O
Na	Nanisivik Mine	Bordon Peninsula, NWT	O	CL	Chisol Lake	Snow Lake, Ma	O
Iz	Izok Mine	Baker Lake, NWT	F	SC	Schefferville	Schefferville, Quebec	O
Sa	Salmita Mine	Courageous Lake, NWT	C	LC	Labrador City	Labrador City, Nfld.	O
My	Mary River Mine	Baffin Island, NWT	C	Wa	Wabush	Wabush, Nfld.	O
RI	Rankin Inlet Mine	Hudson Bay, NWT	C	DISCONTINUOUS PERMAFROST IN CORDILLERA REGION			
K	Kiggavik Mine	Baker Lake, NWT	F	CC	Clinton Creek Mine	Clinton Creek YT	C
Cu	Cullaton Lake Mine	Eskimo Point, NWT	M	Da	Dawson Mine	Dawson, YT	C
SL	Shear Lake Mine	Eskimo Point, NWT	C	K	Keno Hill Mine	Elsa, YT	C
Ra	Raglan Mine	Ungava Peninsula, Quebec	F	DY	Discovery Mine	Carmacks, YT	C
HA	Hopes Advance Bay Mine	Ungava Peninsula, Quebec	C	Ca	Carmacks Mine	Carmacks, YT	C
AH	Asbestos Hill Mine	Ungava Peninsula, Quebec	C	Sk	Mount Skukum Mine	Whitehorse, YT	C
DISCONTINUOUS PERMAFROST IN BOREAL REGION				F	Faro Mine	Faro, YT	O
Di	Discovery Lake Mine	Giaque Lake, NWT	C	V	Vangorda Mine	Faro, YT	O
Ca	CamLaren Mine	Gordon Lake, NWT	C	SDH	Sa Dena Hes Mine	Watson Lake, YT	O
MR	Marion River Mine	Marion River, NWT	C	K	Ketza Mine	Ross River, YT	M
NC	Nerco Con Mine	Yellowknife, NWT	O	WC	Whitehorse Copper Mine	Whitehorse, YT	C
GY	Giant Yellowknife Mine	Yellowknife, NWT	O	CT	Canadian Tungsten Mine	Tungsten, NWT	C
Pt	Ptarmigan Mine	Yellowknife, NWT	O	Ca	Cassiar Mine	Cassiar, BC	M
PP	Pine Point Mine	Pine Point, NWT	C	TR	Taurus Resources Mine	Cassiar, BC	M
G	Gunnar Mine	Uranium City, Sk	C	TE	Total Erikson Mine	Cassiar, BC	M
RL	Rabbit Lake Mine	Walloston Lake, Sk	O	O-Operating, M-Maintenance, F-Feasibility, D-Development, C-Closed			

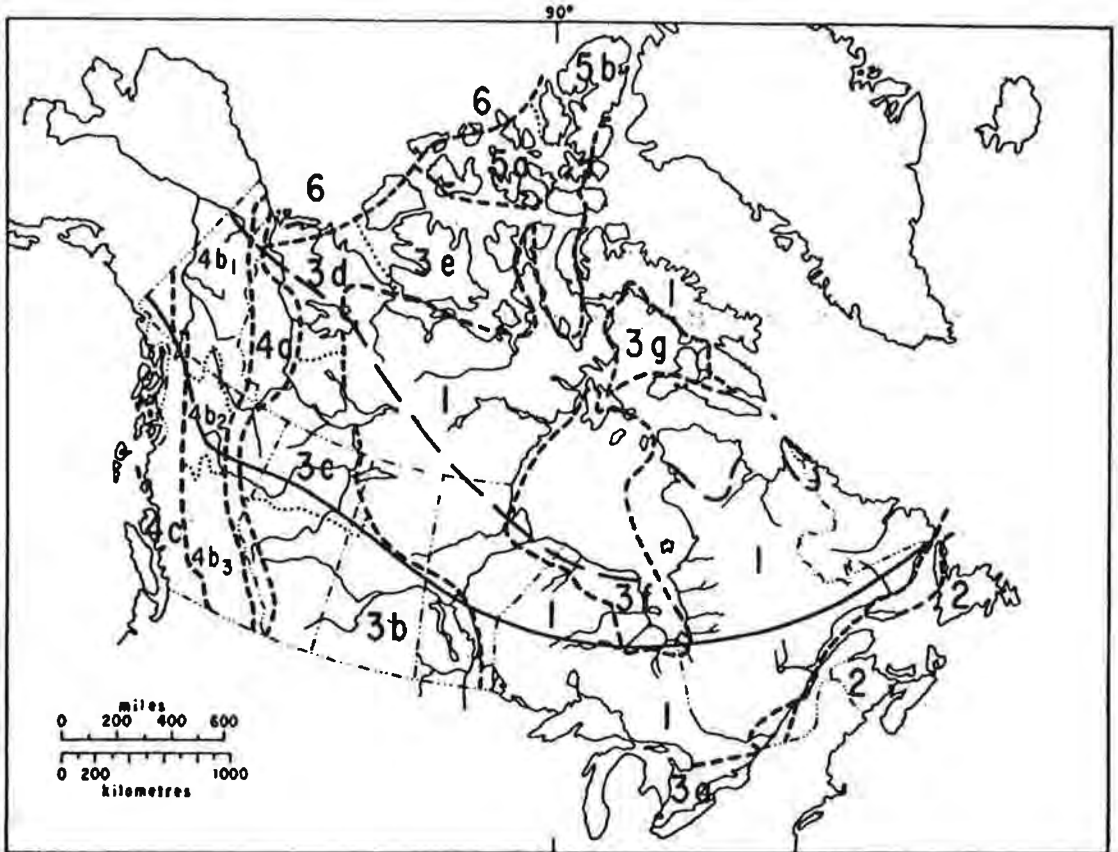
2.0 NORTHERN ENVIRONMENT

2.1 Physiography

The physiography of northern Canada is as varied as the rest of the country. It encompasses many different surface conditions such as: bedrock type, terrain, muskeg, rivers and lakes, with the addition of permafrost. The major part of permafrost is located in the Shield that covers central and eastern Canada. The Shield is underlain by Precambrian crystalline rocks, has a low relief with maximum elevation difference less than 600 m and contains large muskeg deposits. To the west and north lie a chain of lowlands, plains and plateaus of generally flat lying sedimentary rocks. The lowlands can be divided into the Interior Plains covering part of Saskatchewan, most of Alberta and western Northwest Territories and the Arctic Lowlands and Innuitian Region in northern Northwest Territories. Finally, further to the west, the mountainous Cordillera Region covers most of British Columbia and the Yukon Territory (Bostock 1970). The major physiographic regions of Canada are shown on Figure 3.

The bedrock geology has a large influence on the construction of tailings pond impoundments since it governs the nature of surface deposits available for construction of containment dams and it determines the dam foundation conditions in areas of shallow bedrock. Shallow or exposed bedrock is a common feature in the Shield Region. Unfrozen fractured bedrock may lead to excess seepage through the foundation below the tailings dams.

The surficial soils in the permafrost regions have been deposited during the Quaternary period that is characterized by numerous cycles of climate changes and glaciation (Fulton 1989). The surficial soils are related to the bedrock geology of the region. The dominant surficial soils in the Shield are tills that have been derived primarily from



1. THE CANADIAN SHIELD
2. THE APPALACHIAN-ACADIAN UPLANDS

3. THE INTERIOR PLAINS
   a) ST. LAWRENCE
   b) PRAIRIE
   c) PEACE-SLAVE LOWLAND
   d) MACKENZIE
   e) ARCTIC
   f) HUDSON BAY
   g) FOXE BASIN

4. THE WESTERN CORDILLERA
   a) EASTERN MOUNTAINS
   b) INTERIOR PLATEAUS AND MOUNTAINS
   c) COAST RANGES

5. INNUITIAN REGION
   a) SOUTHERN PLAINS AND HILLS
   b) NORTHERN MOUNTAINS
6. ARCTIC COASTAL PLAIN

Figure 3 Physiographic Regions
(From Johnston 1981)

crystalline and metamorphic rocks (Fulton, 1989). These tills consist of non-plastic sands and silts. In the Interior Plains region the tills are derived from shales, siltstones and sandstones and tend to be more fine-grained, including clays. The Shield and Interior Plain regions contain numerous glacial melt water deposits of sands and gravels in eskers and kames. The Cordilleran Region has a large variety of surficial deposits varying from coarse talus to non-plastic and clayey tills and granular stream deposits. The above illustrates that a great variety of foundation conditions and construction materials for dams can be found across the Canadian permafrost area.

2.2 Climate

The mean annual temperature is the largest single factor controlling the presence and type of permafrost dividing it into two or three regions, depending on the method of division. Temperature is one component of climate that varies across the permafrost area. According to Hare and Thomas (1974) the permafrost area contains three broad climatic regions, namely: Arctic, Boreal and Cordillera regions (Figure 4). The mean annual air temperature isotherms that determine the climatic regions are shown on Figure 5. The Arctic climatic region covers practically all areas north of the treeline. The Boreal climatic region includes large parts of the Northwest Territories west of Hudson Bay, and the northern parts of the Prairie Provinces, Ontario, Quebec and Labrador. The Yukon Territory lies within the Cordillera climatic region.

In permafrost design, it is necessary to use the mean annual air temperature because of the lack of good year-round ground temperatures profiles. The magnitude and variation of the ground temperature at shallow depths is governed by the air temperature changes during the course of the year. The knowledge of the magnitude and the variation of the ground temperature throughout the year and over the design life of the structures is important in the design of roads, dams and foundations within shallow ground and

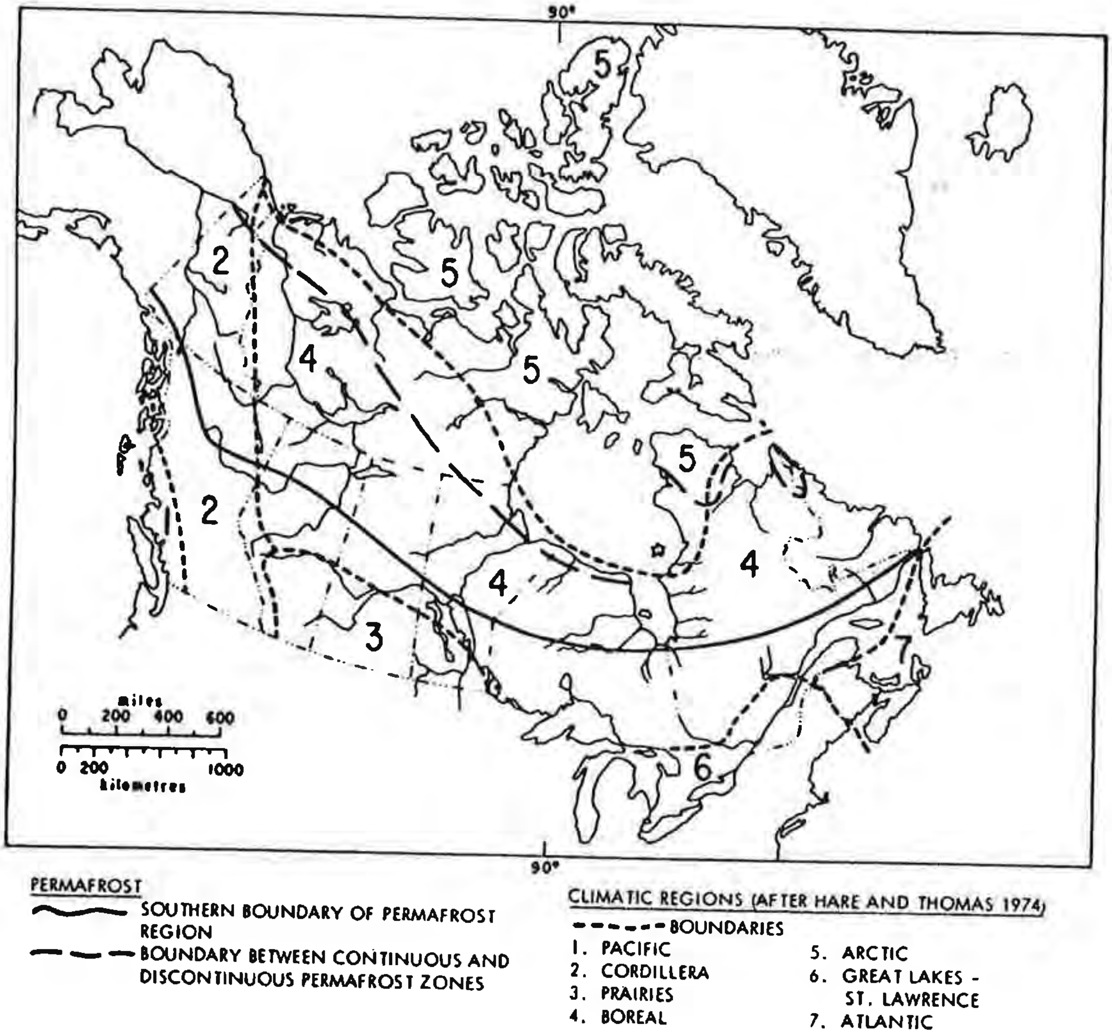


Figure 4 **Climatic Regions**
(After Hare and Thomas 1974)

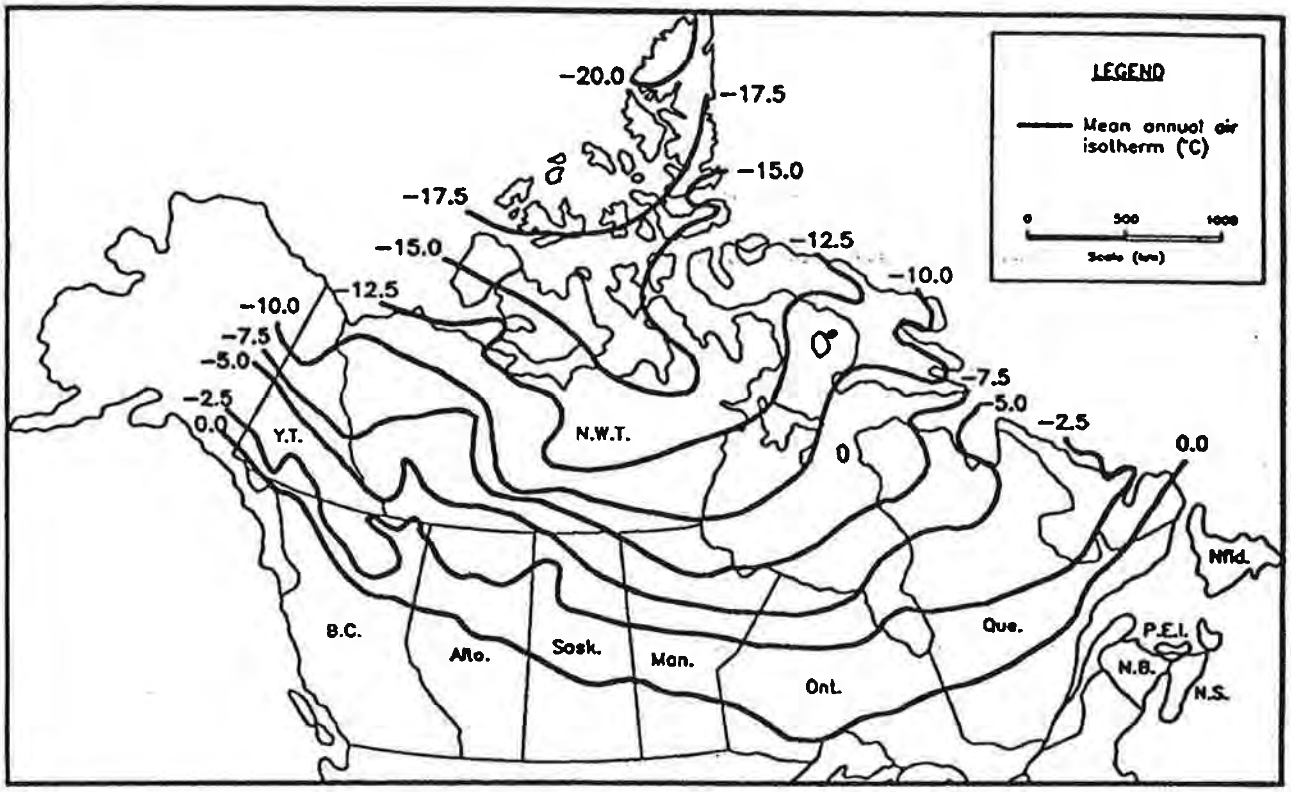


Figure 5 **Mean Annual Air Temperature**
(Cdn Climate Normals, 1931-1960)

bedrock. In the design of foundations and embankments in permafrost both the mean annual temperatures and the deviations of the mean annual temperature from the mean have to be considered. For example, the published mean annual temperature for Yellowknife obtained from 30 years of records is -5.4°C. However, the annual mean temperatures within the same period varied from -3.6 to -7.0°C. Even greater variations occur on a daily and monthly basis. These latter variations have be taken into consideration in the surface ground conditions.

Precipitation varies throughout northern Canada but generally decreases from the southeast to the northwest. The largest precipitation occurs around James Bay with an annual total of 650 mm. The precipitation decreases to about 100 mm in the Arctic Islands. In the south about two thirds of the precipitation falls as rain whereas in the Arctic Islands more than half of the precipitation is attributed to snow. The mean annual precipitation across Canada is shown on Figure 6.

In the mountainous Cordillera Region, local variations of temperature and precipitation occur and these should be taken into consideration if climatic data is not available at the mine site and is obtained from nearby Atmospheric Environment Stations. Altitude has a marked influence on temperature. Climatologists commonly use an average rate of temperature change of 6 C°/km in elevation to estimate temperatures at locations with different elevations based on observations made at lower elevations (Johnston 1981). The amount of precipitation in valleys is significantly affected by the shadow effects of surrounding mountains.

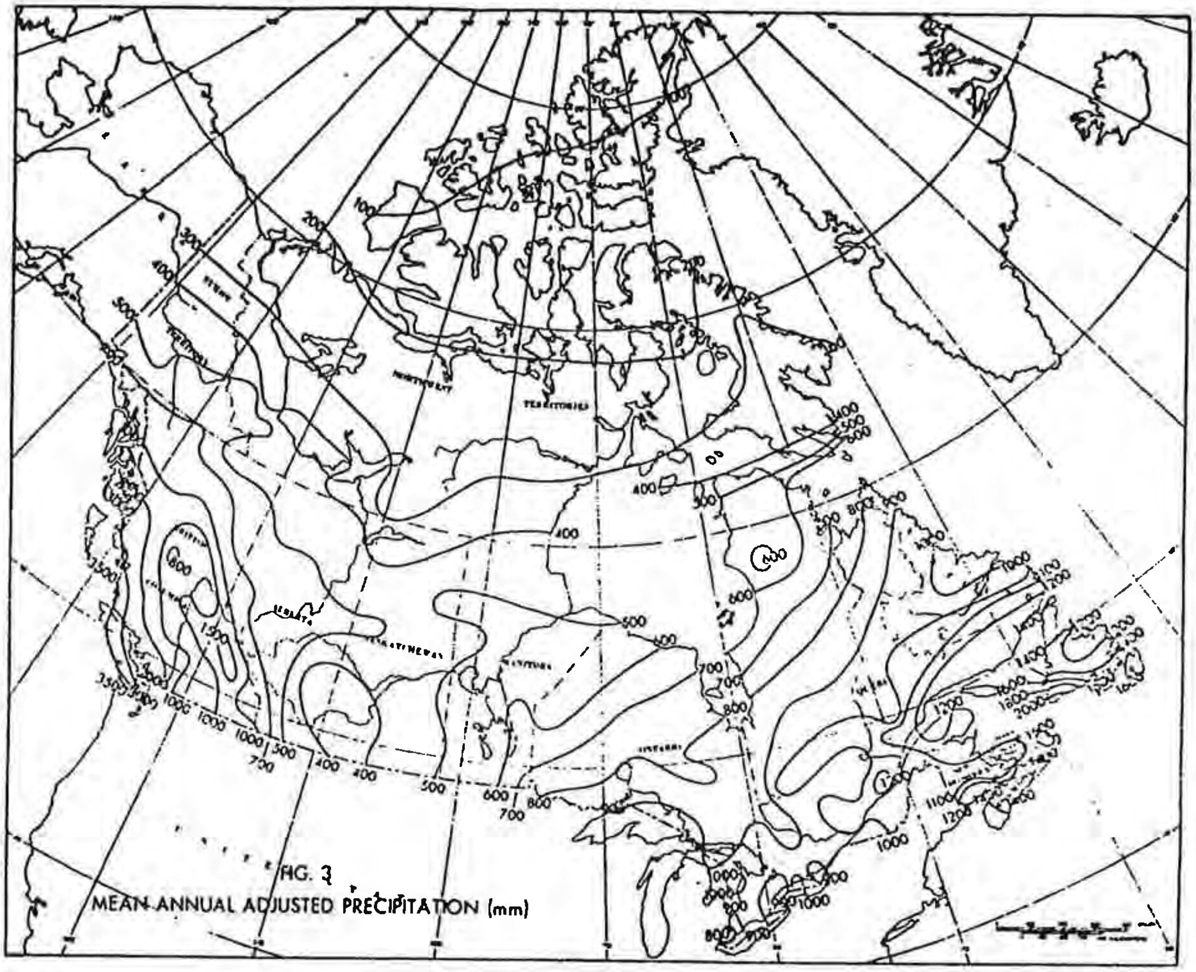


Figure 6 **Mean Annual Precipitation Distribution**
(Hartog and Ferguson, 1975)

3.0 PERMAFROST

3.1 Occurrence and Distribution

Permafrost is defined as "the thermal condition in soil or rock of having temperatures below 0°C persisting over at least two consecutive winters and the intervening summer" (Brown and Kupsh 1974). About one half of Canada's land surface is underlain by permafrost (Brown 1973) which is divided into two principal zones - the discontinuous zone in the south and the continuous zone in the north. The discontinuous zone is further subdivided into a widespread discontinuous zone adjacent to the continuous zone and scattered discontinuous zone adjacent to the southern non-frozen zone. Permafrost is also observed at high elevations in the Cordilleran mountains which is called alpine permafrost. The thickness of permafrost varies from a few centimetres at the southern limit to 60 to 100 m at the discontinuous/continuous boundary. The maximum depth of permafrost in the northern parts of Canada is greater than 600 m (Johnston 1981).

The occurrence and distribution of permafrost is affected by various climatic and terrain factors. A broad relationship exists between mean annual air temperature and ground temperatures in the permafrost regions (Brown 1966). The southern limit of permafrost coincides roughly with the -1°C mean annual air isotherm where the permafrost is restricted mainly to drier portions of peatlands, some northern-facing slopes and local shaded areas. North of the -4°C mean annual air temperature isotherm the permafrost becomes increasingly widespread and thicker. The -4°C isotherm divides the discontinuous zone into widespread and scattered discontinuous zones. Finally, the boundary between the discontinuous and continuous permafrost zones appears to be near -8°C. Figure 1 shows the boundaries of the above permafrost zones.

In the zones of discontinuous permafrost, the permafrost conditions are affected by relief, hydrology, snow cover, glacier ice, soil and rock type, and fire ((Brown 1973) as reported by Johnston (1981). Orientation and steepness of a slope influences the amount of solar radiation received by the ground and the snow accumulated on it. Snow and vegetation cover modify the distribution of permafrost. Surface and subsurface water may warm the ground and prevent or modify the permafrost distribution. Year round flowing streams will be underlain by unfrozen ground (talik) and lakes with water depths greater than about 2 m will have either a thaw basin or no permafrost at all. The actual conditions depend on the size and depth of the lake and climatic conditions of the areas.

3.2 Ground Temperature

Assuming equal terrain factors, the ground temperatures reflect the air temperatures. Figure 7 illustrates the permafrost temperature regimes in a typical permafrost. Near the surface, the fluctuations of air temperature during the year produce corresponding fluctuation in the ground temperatures. These fluctuations are large near the surface and decrease with depth until a steady temperature is reached some 10 to 15 m below the ground surface (Johnston 1981). This depth is referred to as the depth of zero annual amplitude. Below this depth the temperature remains constant at a given depth and rises with increasing depth according to the geothermal gradient which varies between 1°C/22m to 1°C/160m. The actual gradient depends on the type of soil or rock and the effect of past climatic periods. An average value of 1°C/54 m can be used for an initial ground warming with depth estimation (Johnston 1981).

The temperature fluctuations above the depth of zero amplitude whiplash back and forth annually and do not uniformly occur from one depth to another. This is a reflection of annual air temperature changes and a time lag temperature response which increases with depth. The temperature lag time varies from zero at the surface to about a year near the depth of zero temperature amplitude. (Holubec 1990). This whiplash is illustrated on

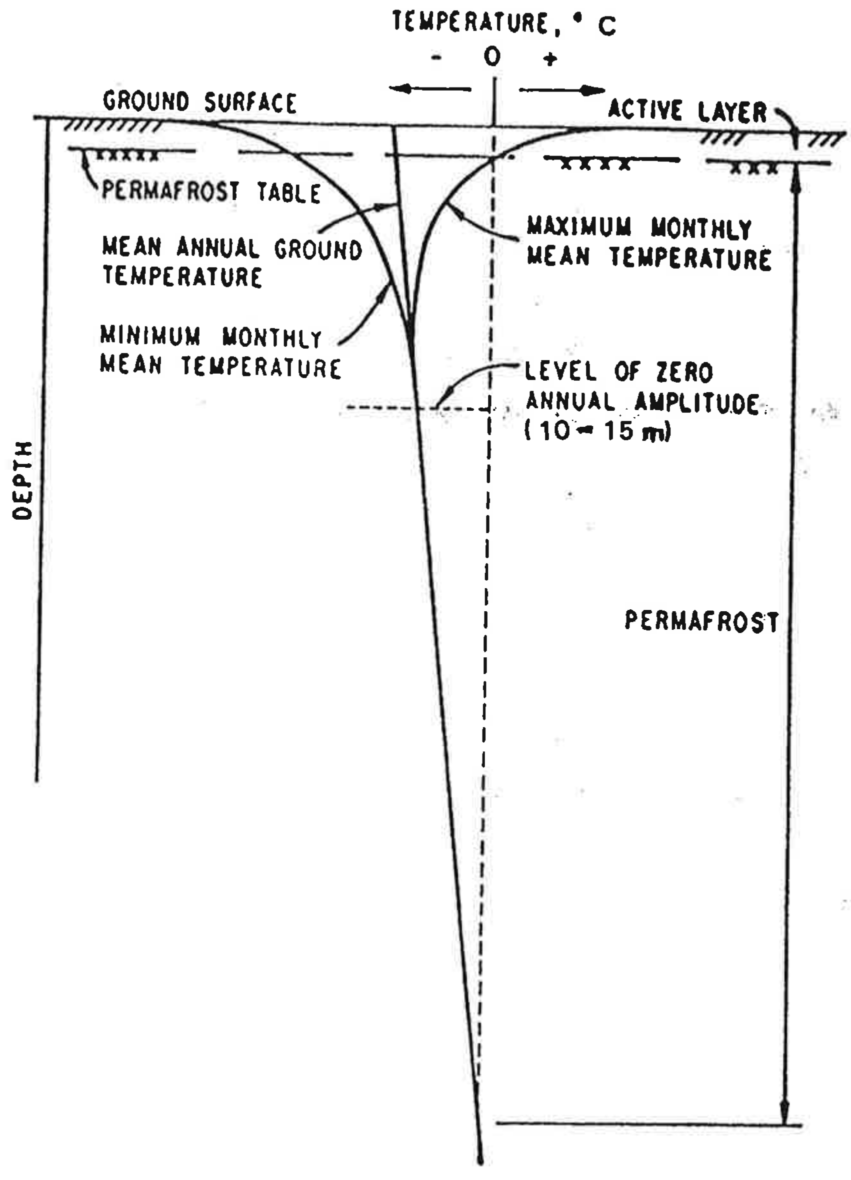


Figure 7 Typical Ground Temperature Profile (From Johnston 1981)

Figure 8. The temperature profiles measured in February, May, August and November 1989 illustrate the great changes of the temperature profiles in the 5 to 8 m depth within the year.

3.3 Active Layer

The surface of the ground which freezes and thaws annually is the active layer (Figure 7). In continuous permafrost, the base of the active layer coincides with the permafrost table. In the discontinuous zone, the active layer may or may not extend to the permafrost table (Johnston 1981) and may be separated from permafrost by a residual layer that remains unfrozen throughout the year. The thickness of the active layer is dependent on the same factors as the permafrost, namely, the thickness of the organic layer cover and the water content of the underlying soil/rock (discussed in Section 5.0) and may vary in thickness from 0.5 m under with a thick organic layer cover to greater than 10 m in exposed unsaturated bedrock.

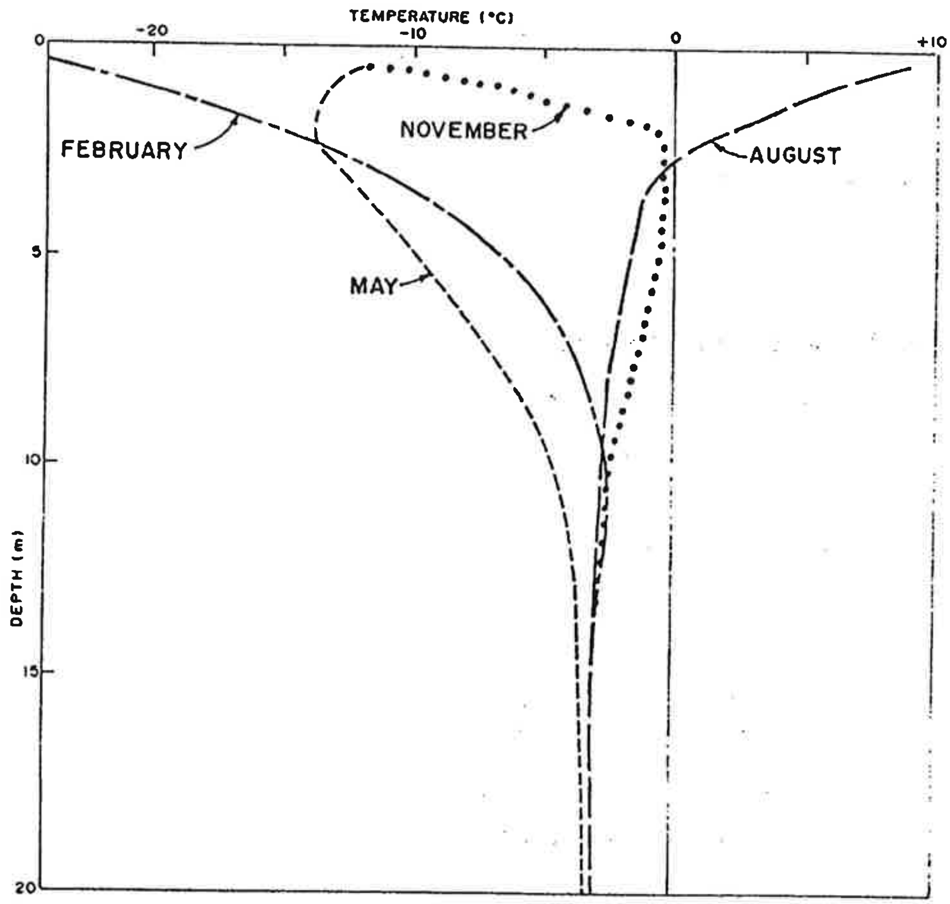


Figure 8 **Ground Temperature Fluctuations through the Year, Lupin Mine (1989)**

4.0 ACID DRAINAGE IN COLD CLIMATES

4.1 Acid Drainage

Acidic drainage is a consequence of geochemical reactions within a mass of tailings or mine rock. The relevant reactions can be divided into two basic categories: acid-generating and acid-neutralizing. These reactions usually take place on or near minerals surfaces and thus mineralogy is a major factor in acidic drainage.

Acid-generating minerals are primarily those containing sulphide represented by anions containing at least one sulphur atom with a valence of 2- (such as S_2^{2-} and S_4^{2-}). Examples of sulphide minerals are listed in Table 2. In a mill circuit, many of the minerals containing copper and nickel, for example, may be recovered due to their economic value, while iron-bearing minerals such as pyrite pass through into the tailings. Iron-bearing pyrite and pyrrhotite are particularly known for their ability to generate significant acidity under certain environmental conditions.

Acid-neutralizing minerals are primarily those containing carbonate (CO_3), hydroxide (OH), or silicate (e.g. Si_3O_8). Examples of such minerals are calcite ($CaCO_3$), boehmite (AlOOH) and albite ($NaAlSi_3O_8$), although the suites of acid-neutralizing minerals are as complex and varied as the acid-generating minerals.

The potential for acidic drainage can be assessed or predicted by a two-step process. For the first step, numerous samples are analyzed through acid-base accounting (ABA). ABA is a quantitative determination of the balance between the aforementioned acid-generating and acid-neutralizing minerals. An "expanded" version of ABA, involves direct measurements of: total sulphur, weak-acid-leachable sulphate, aqua-regia-digestible sulphide, insoluble barium-bound sulphur, 24-hour neutralization potential, total inorganic carbonate, and paste pH. This expanded version overcomes several limitations in the

Table 2 Examples of Sulphide Minerals (selected from Lowson 1982)

MINERAL NAME	CHEMICAL COMPOSITION	MINERAL NAME	CHEMICAL COMPOSITION
Alabandite	MnS	Linnaeite	Co_3S_4
Arsenopyrite	$FeAsS$	Marcasite	FeS_2
Bornite	Cu_3FeS_4	Millerite	NiS
Chalcocite	Cu_2S	Molybdenite	MoS_2
Chalcopyrite	$CuFeS_2$	Orpiment	As_2S_3
Cinnabar	HgS	Pyrite	FeS_2
Cobaltite	$CoAsS$	Pyrrhotite	$Fe_{0.8\text{-}1.0}S$
Covellite	CuS	Realgar	AsS
Cubanite	$CuFe_2S_3$	Sphalerite	ZnS
Enargite	Cu_3AsS_4	Stibnite	Sb_2S_3
Galena	PbS	Tennantite	$Cu_2As_2S_{13}$
Greenockite	CdS	Troilite	FeS
Greigite	Fe_3S_4	Violarite	$FeNi_2S_4$
Hauerite	MnS_2	Wurtzite	ZnS

basic ABA procedure pertaining to mineral balances. However, additional problems still exist (Morin 1990), particularly from the perspective of mineral solubilities and reaction rates. This is the reason for the second step in the assessment process (discussed below). Each acid-generating and acid-neutralizing mineral has a distinctive reaction rate and solubility, reflecting site-specific conditions. As a result, an assessment of acid-drainage potential should focus on the relevant site-specific conditions. The suite of minerals with the greatest abundance and/or highest reaction rates will often determine the long-term water chemistry, although short-term variations (such as initially pH-neutral) may exist.

In order to resolve reaction rates in a particular sample, the sample should be subjected to "kinetic testing", which is the second step in the assessment process. The most common kinetic test for determining long-term rates is known as "humidity cell" test. A sample is placed in a closed chamber or cell, and then humid air is continuously or intermittently passed over the sample. The sample is then typically soaked with water once a week and this water is drained off and analyzed. Humidity cells have been used with success at some minesites and the Canada-wide database of humidity-cell results supports their use (Ferguson and Morin 1991).

For this study, most of the factors which regulate reaction rates, mineral solubility, and acidic drainage will not be discussed or reviewed. Other references can be consulted for this information (Dave 1992; Ferguson and Morin 1991; BC AMD Task Force et al. 1989). Instead, only temperature, which is the most relevant factor in cold climates, will be examined.

4.2 Heat Generation Through Pyrite Oxidation

In cold climates, there is one unique potential technology for control of acid drainage that is not generally available in warm climates: freezing of acid-generating materials.

However, acid-generating materials generate heat which may cause them to resist freezing. Therefore, the design and success of temperature-control measures lies in understanding heat generation and transport within the materials. This first requires a basic discussion of acid-generating reactions.

For simplicity, this discussion focusses only on pyrite (FeS_2). The equation often reported in published literature for pyrite oxidation is:

$$FeS_2 + 7/2\ H_2O + 15/4\ O_2 \rightarrow Fe(OH)_3 + 2\ SO_4^{2-} + 4\ H^+ \quad (1)$$

Although not often explained, this equation assumes much about the environmental conditions including: (1) sulphur occurs only as S_2^{2-}, (2) S_2^{2-} oxidizes completely to sulphate, (3) pyrite is the only oxidizing sulphide mineral, (4) molecular oxygen and water are the only oxidants, (5) all iron oxidizes to the ferric (Fe^{3+}) state, and (6) all iron precipitates as $Fe(OH)_3$ (Morin, 1990). Obviously these assumptions do not always apply. For example, in saturated tailings, if there is insufficient oxygen to oxidize the iron, the overall equation becomes:

$$FeS_2 + H_2O + 7/2\ O_2 \rightarrow Fe^{2+} + 2\ SO_4^{2-} + 2\ H^+ \quad (2)$$

In this case, only 1/2 the amount of acidity (H^+) is generated for each mole of pyrite. If ferric iron is the sole oxidant, the overall reaction becomes:

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

This third reaction suggests a great deal of acidity is generated from each mole of pyrite, but this is only the case when the ferric iron is derived from a source other than preceding sulphide oxidation within the mass of tailings or mine rock (Morin 1990). The important observation to be drawn from Equations 1 through 3 is that environmental conditions and mineralogy will determine the overall balance of reactants and products, although Equation 3 may not be relevant to some sites (Morin 1993).

For Equation 2, Harries and Ritchie (1985 and 1987; summarized in Morin et al. 1991, p.66) indicated that 7×10^{-7} moles of pyrite would generate 1 joule (J) of heat energy, or, for each mole, 1.4×10^{6} J (mol $FeS_2)^{-1}$. This energy apparently does not include other reactions such as aqueous complexation and secondary-mineral precipitation/dissolution, which can generate or consume energy. Therefore, the aforementioned rate is only a rough approximation of site-specific values.

With the approximate value for heat generation by pyrite oxidation, the distribution of heat in cold-climate mining environments can be examined. However, a critical factor not yet discussed is the rate of oxidation, that is, how many moles of pyrite will be oxidized and how many joules of heat will be generated daily or weekly. This factor is difficult to assess because the rate of pyrite oxidation (heat generation) is partially dependent on temperature which in turn is partially dependent on the rate of heat generation and oxidation.

The dependence of rates on temperature can be seen in diagrams of oxidation rate versus temperature (Figure 9a). For chemical oxidation which predominates around neutral pH, the rate near freezing is about 15% of the rate around 25°C as predicted by the RATAP model (discussed below). For biologically mediated oxidation which dominates at acidic pH, the rate below 8°C is less than 20% of the rate at 30° and drops to zero as the temperature also decreases to zero (Figure 9b). (The implications of near-zero temperatures are discussed later in this section.) The interaction among oxidation rate, heat generation, and temperature results in an iterative, or repetitive, approach for answering questions on the potential for freezing (Figure 10).

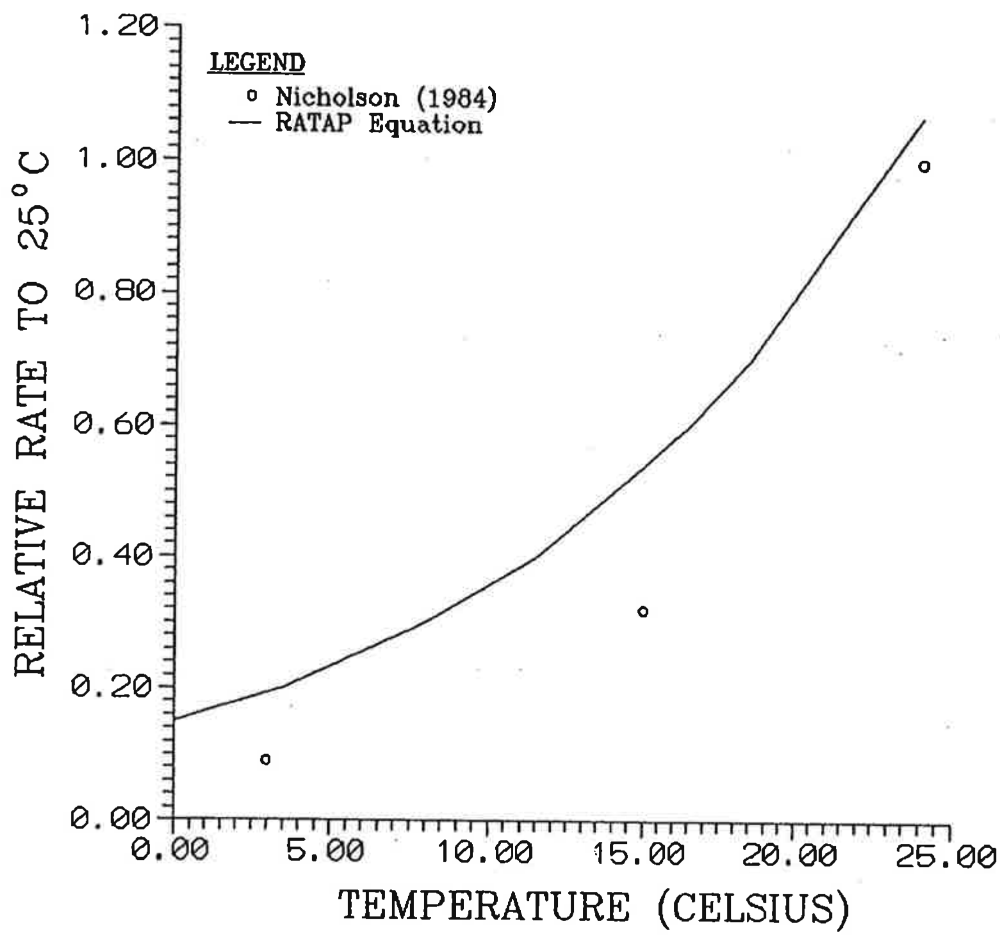


Figure 9a **Relative Rate of Chemical Oxidation vs. Temperature** (adapted from Senes, 1991)

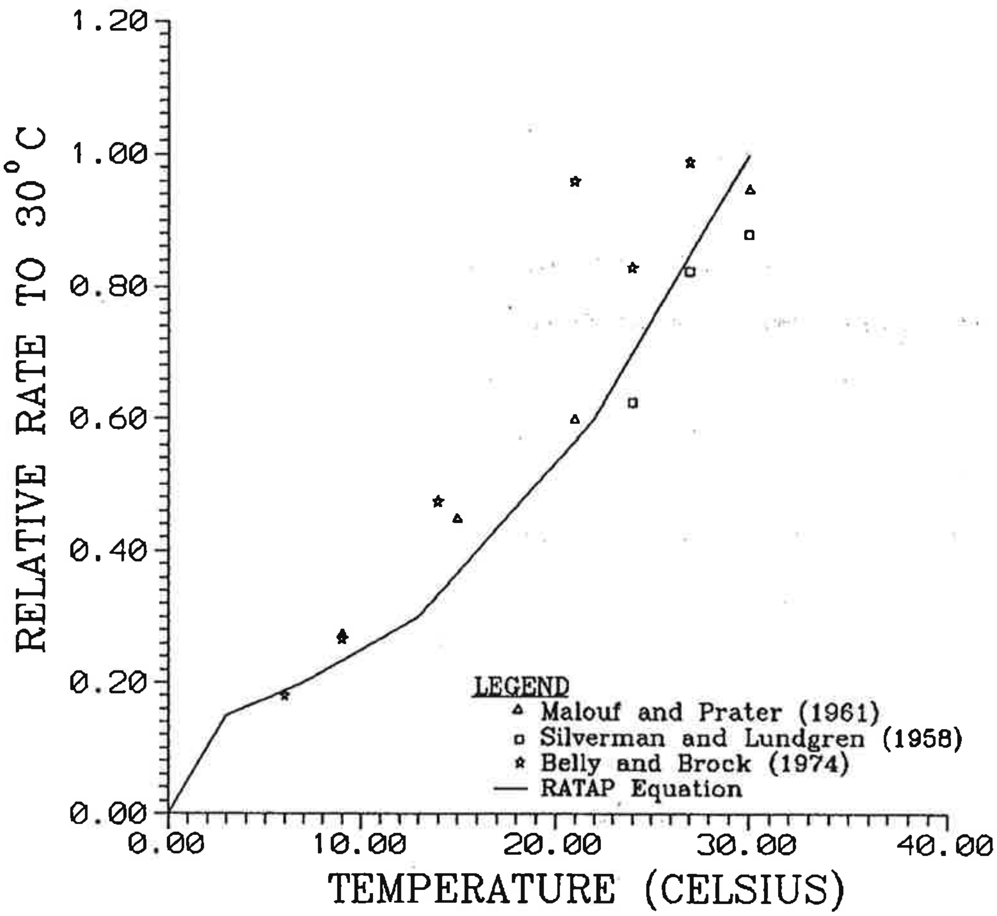


Figure 9b **Relative Rate of Biological Oxidation vs. Temperature** (adapted from Senes, 1991)

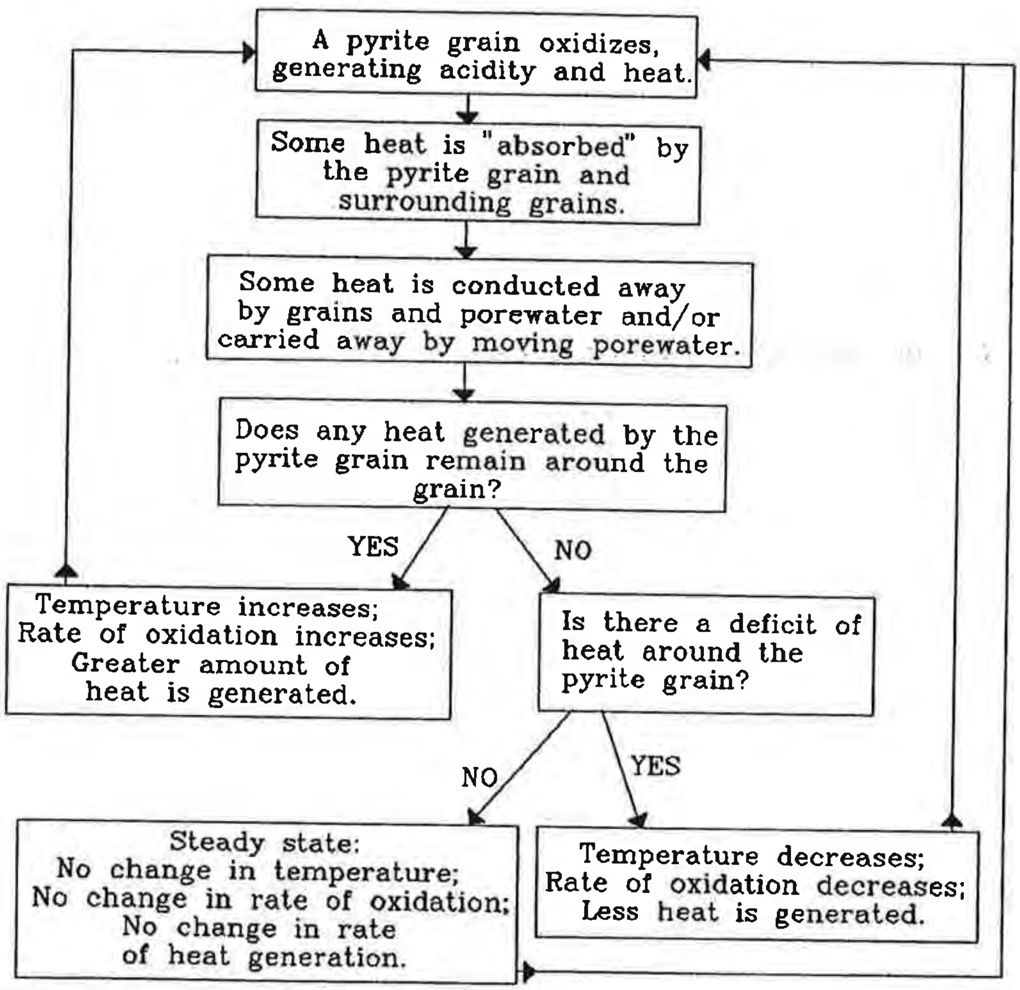


Figure 10 **Iterative Approach to Assessing Heat Distribution and Freezing Potential of Acid-Generating Materials in Cold Climates**

The primary conclusion from the iterative approach (Figure 10) is that acid-generating materials would never freeze and would become extremely hot if heat were not taken into the materials and transported away to the surrounding environment. The scientific terminology for these two factors are usually "thermal capacity" (C_p in J kg^{-1}) and "thermal conductivity" (K in J m^{-1} s^{-1} $°C^{-1}$) (e.g. Harries and Ritchie 1985 and 1987; Senes 1991).

Another important observation from Figure 10 is that the sulphide minerals can locally be warmer than the temperature measured in the bulk material, and this carries several implications for near-zero temperatures. Firstly, the bulk temperature of tailings may be below zero and frozen while microscale water films, around the warmer pyrite may remain unfrozen. Secondly, sulphide-oxidizing reactions (Equations 1 through 3) require (liquid) water as a reactant and thus these reactions will cease if the microscale water films are frozen. Consequently, the use of Figures 9a and 9b with bulk temperatures, rather than microscale temperatures, may not be appropriate. However, the sulphide-oxidizing reactions also require on-going transport of an oxidant. The bulk-scale freezing of tailings can block the movement of oxidizing fluids and thus sulphide oxidation would eventually cease when all local oxidant is consumed and oxidation products have accumulated. These implications are relevant to the "active layer" which freezes and thaws each year. If sulphide minerals in the active layer continue to generate acidity for a period of time after bulk freezing, this acidity will be released during the next thaw cycle.

Soil scientists have determined that the main factors determining the unfrozen water content in saturated unfrozen soils are temperature, specific surface area of the solid phase, pressure, chemical and mineralogical composition of the soil, other physio-chemical characteristics and solute content and composition (Johnston 1981). Of all these factors, temperature is the dominant one, followed closely by the specific surface area of the surface area of the soil matrix and the activity of soil minerals.

Anderson and Morgenstern (1973) have determined the unfrozen water content of several soils for temperature range of 0°C to -5°C shown of Figure 11. This figure shows that in case of silts and gravel the unsaturated water content decreases from 0.12 gm of water/gm of soil at 0°C to 0.03 gm of water/gm of soil at -3°C. This means that at or below -3°C soils with particles ranging from silt to gravel (including tailings) have about 25% of the water surrounding the particle unfrozen and the remaining 75% of water mass frozen.

The equations to simulate heat transport and temperature are similar to those for groundwater flow and electrostatic fields. With no porewater movement and no evaporation, heat transport and temperature can be calculated through:

$$Q + \partial\frac{Q}{\partial T}\Delta T = \rho C_p\frac{\partial T}{\partial t} = K\frac{\partial^2 T}{\partial z^2} \qquad (4)$$

where Q = internal heat generation ($J\ m^{-3}\ s^{-1}$)

ρ = density ($kg\ m^{-3}$)

C_p = thermal capacity ($J\ kg^{-1}\ K^{-1}$)

T = temperature (K)

t = time (s)

K = thermal conductivity ($J\ m^{-1}\ s^{-1}\ K^{-1}$)

z = distance (assumed vertical; m)

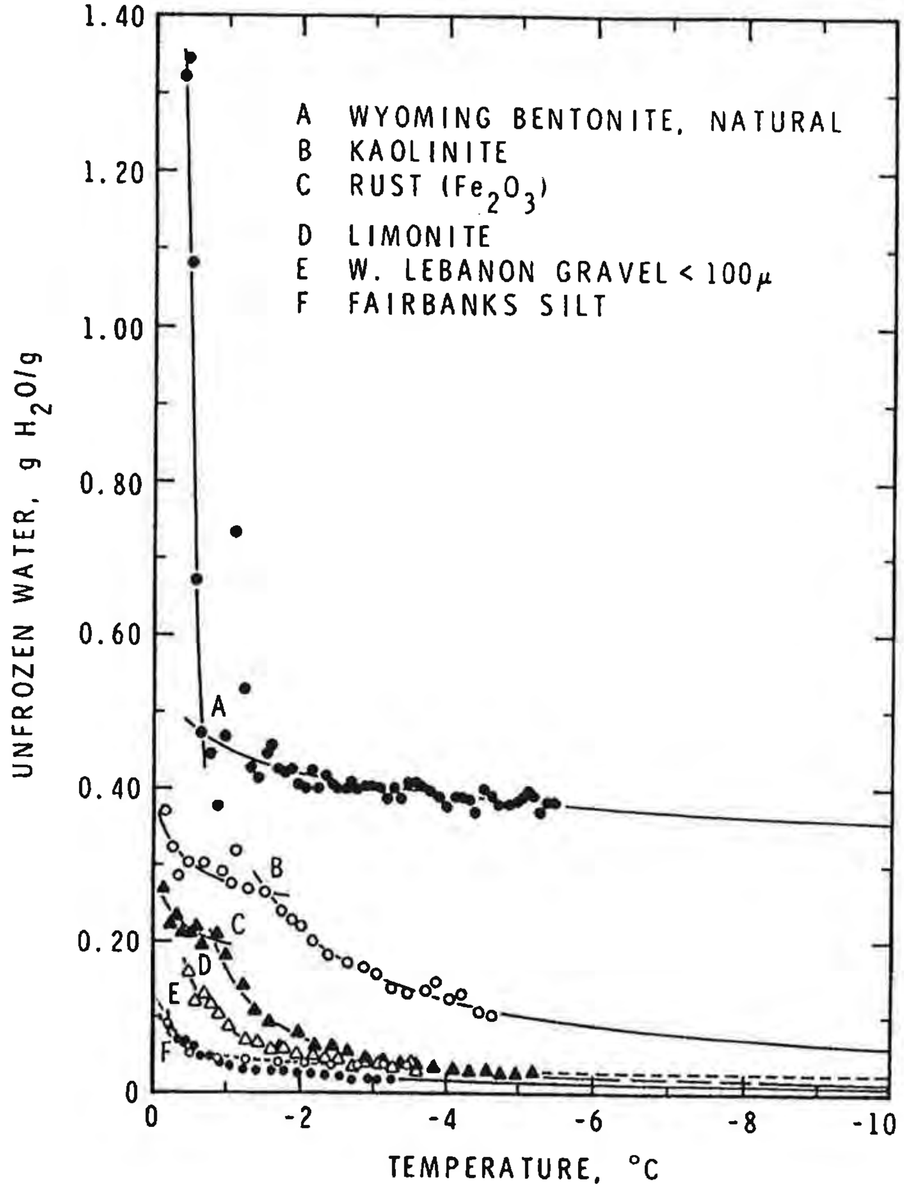


Figure 11 **Variation of Unfrozen Water Content with Temperature for Six Representative Soils.** (Anderson and Morgenstern 1973)

If there is porewater movement and evaporation, the expanded equation is (Senes, 1991):

$$\rho C_p \frac{\partial T}{\partial t} = K \frac{\partial^2 T}{\partial z^2} + F_W C_W \frac{\partial T}{\partial z} + \Delta H_v E_W \qquad (5)$$

where F_W = water flow (mol m^{-2} s^{-1})
C_W = thermal capacity of water (J mol^{-1})
ΔH_v = enthalpy of evaporation (J mol^{-1})
E_W = evaporative water loss (mol m^{-3} s^{-1}; corrected from Senes, 1991)

Obviously, the mathematical solution to these equations is not easy and a computer program is required. One such program for above-zero temperatures is CANMET's RATAP program (Senes 1991) that is being currently reviewed. (commercially available through CANMET). However, these equations are not difficult to program into a relatively simple finite-difference or analytical model for basic simulations of Figure 3. In any case, field studies and simulations of tailings have shown that oxidation and acid generation occur in the shallow depths in tailings due to the limitation of oxygen diffusion. In cold climates, this layer of active oxidation will coincide to some extent with the "active layer" of annual freezing and thawing. Therefore, the presence of an active layer within the tailings will determine the ability of the tailings to generate acidity.

The active layer of freezing and thawing is controlled by Equations 4 and 5. Although Equations 4 and 5 can not be solved easily, an examination of some parameters would be worthwhile. Again, C_p and K are often the most important and compiled literature values show relatively little variation (Table 3). This suggests an order-of-magnitude estimate can be made using approximate values in Equations 4 and 5 and a simplified computer program.

Table 3 Literature Values for C_p and K

MATERIAL	VALUE	SOURCE
THERMAL CAPACITY (C_p = J kg^{-1})		
DRY MINE ROCK	867	Harries & Ritchie (1987)
MINE ROCK WITH 11.5 wt-% MOISTURE CONTENT	1350	Harries & Ritchie (1987)
THERMAL CONDUCTIVITY (K = J m^{-1} s^{-1} $°C^{-1}$)		
VARIOUS SOILS IN LITERATURE (0.02-0.20 wt-%)	0.2 TO 1.7	Harries & Ritchie (1987)
MINE ROCK, MEASURED	2.3	Harries & Ritchie (1987)
MINE ROCK, CALCULATED	1.8	Harries & Ritchie (1987)
TAILINGS	0.56	Senes (1991)

There have been studies simulating permafrost in tailings (Woo and Drake 1988; EBA Engineering Consultants Ltd. 1991). However, these studies have focussed on heat transport and permafrost migration as determined by climatic conditions and the thermal properties of tailings with no emphasis on internal heat generation. Consequently, modelling of permafrost migration in heat-generating tailings is still in its infancy.

4.3 Field Studies

Detailed field investigations of acid-generating materials in cold climates are notably lacking in published literature. As a result, the large-scale and in-field complexities of permafrost migration into acid-generating materials remains largely unknown at this time.

Baker and Madill (1992) reported that freezing of tailings at the Discovery Mine near Yellowknife is one of many control options for acid drainage. However, the studies and requirements for implementing such an option were not discussed in detail.

5.0 Case Histories

5.1 Introduction

There are four known mines in the Canadian permafrost region that have site and temperature information relevant to this study. These mines representing the three major permafrost regions illustrate the typical permafrost conditions across northern Canada and the concepts which have to be taken into consideration in the closure design of tailings impoundments. The location of these four mines are shown on Figure 12 and relevant specifics and a summary of climatic data for each mine is given in Table 4. The temperature and permafrost conditions observed at these mine sites are discussed in the following sections.

Table 4 Location and Climatic Data for Mines with Available Permafrost Information

NAME	Lupin Mine	Giant Yellowknife Mine	Faro Mine	Rabbit Lake Mine
Location Permafrost Region Latitude Elevation, m	NWT - North Arctic 65°45' 450	NWT - South Boreal 63°30' 205	Yukon, Central Cordillera 63°15' 1070	Saskatchewan, North Boreal 58°15' 490
Temperature [a], °C Est. Permafrost Temperature @ Zero Amplitude, °C	-12.0 -8.0	-5.4 -1	-5.1[d] -1	-4.6 0 to -1
Precipitation[b], mm Lake Evaporation[c], mm Evapotranspiration[c], mm	251 320 130	267 420 200	288 450 190	523 470 220

NOTES:

[a] - Annual Mean Daily   [c] - Annual Mean

[b] - Annual Mean Total   [d] - Based on Faro and elevation correction

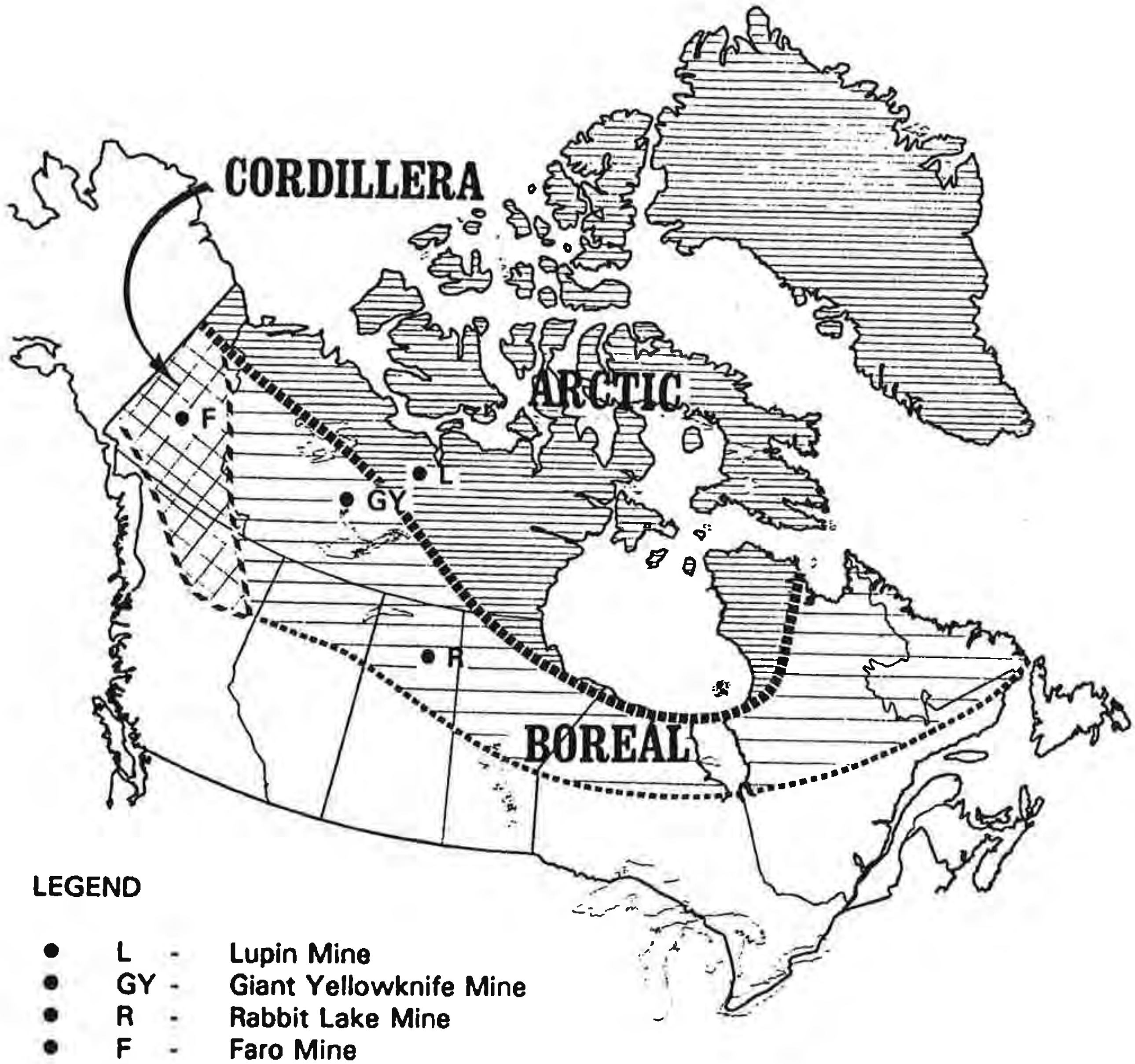


Figure 12 **Location of Mines with Thermal Information**

5.2 Lupin Mine

Lupin Mine (Echo Bay Mines Limited) is located on the west shore of Contwoyto Lake approximately 380 km northeast of Yellowknife. It is about 150 km north of the treeline in an area characterized by low relief, poorly developed drainage patterns with numerous shallow lakes and cold permafrost. Overburden is either absent or consists of a thin layer of silty sand till. Bedrock is generally phyllite, highly fractured near the surface and occurs either at a shallow depth or at the surface. Granular material is available from eskers and abandoned beaches (Holubec et al. 1982).

The mine and tailings complex were completed in 1982. The tailings have been stored in a 750 ha tailings area which has been subdivided into tailings cells and polishing ponds (Figure 13) (Wilson 1989). The lack of impervious material for the construction of dams and the need to prevent seepage through the foundation rocks led to the design and construction of frozen dams. To confirm the integrity of the frozen dam core during the water impoundment and subsequent interest in the development of permafrost in the tailings led to an extensive temperature monitoring program between 1983 and 1990. This provided a large volume of temperature data within natural ground, sand dam fills and tailings (Holubec 1990).

The annual mean daily air temperature at the Lupin Mine is -12°C and the ground temperature at a depth with zero temperature amplitude is estimated to be -8°C. Bimonthly temperature profiles measured in a reference thermistor string in shallow bedrock is shown on Figure 14. These profiles show that the active zone in shallow bedrock is about 3.5 m deep. The fluctuation within the upper 8 m depth is large and the depth at which zero temperature fluctuation occurs is greater than 15 m. The large temperature variation near the surface makes it difficult, if not impossible, to obtain meaningful temperature information with only a single point in time temperature profile.

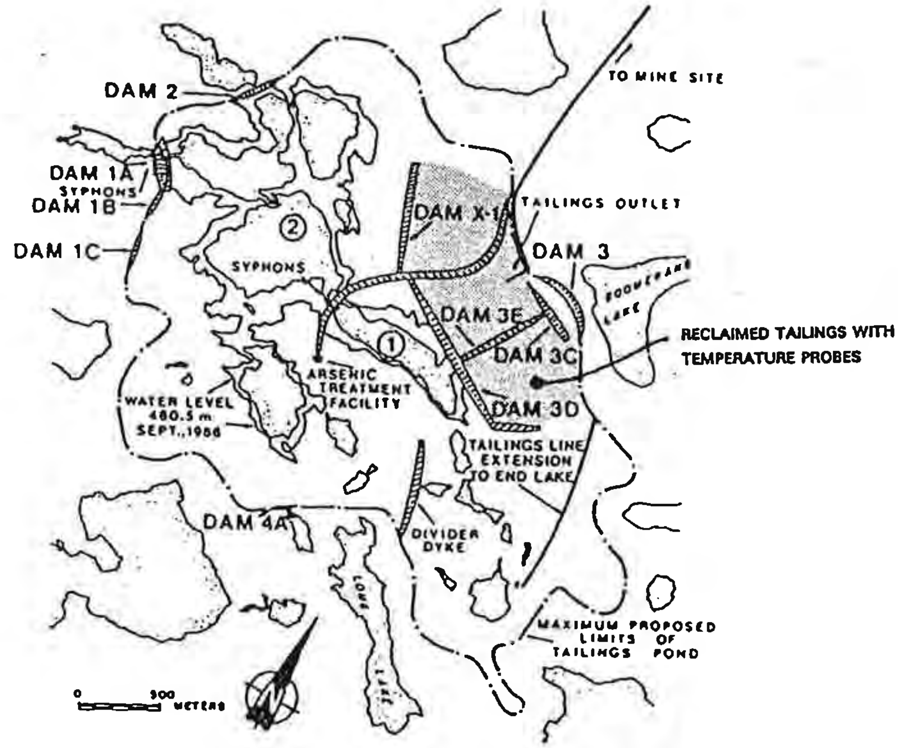


Figure 13 Lupin Mine Tailings Impoundment, 1988
(From Wilson 1989)

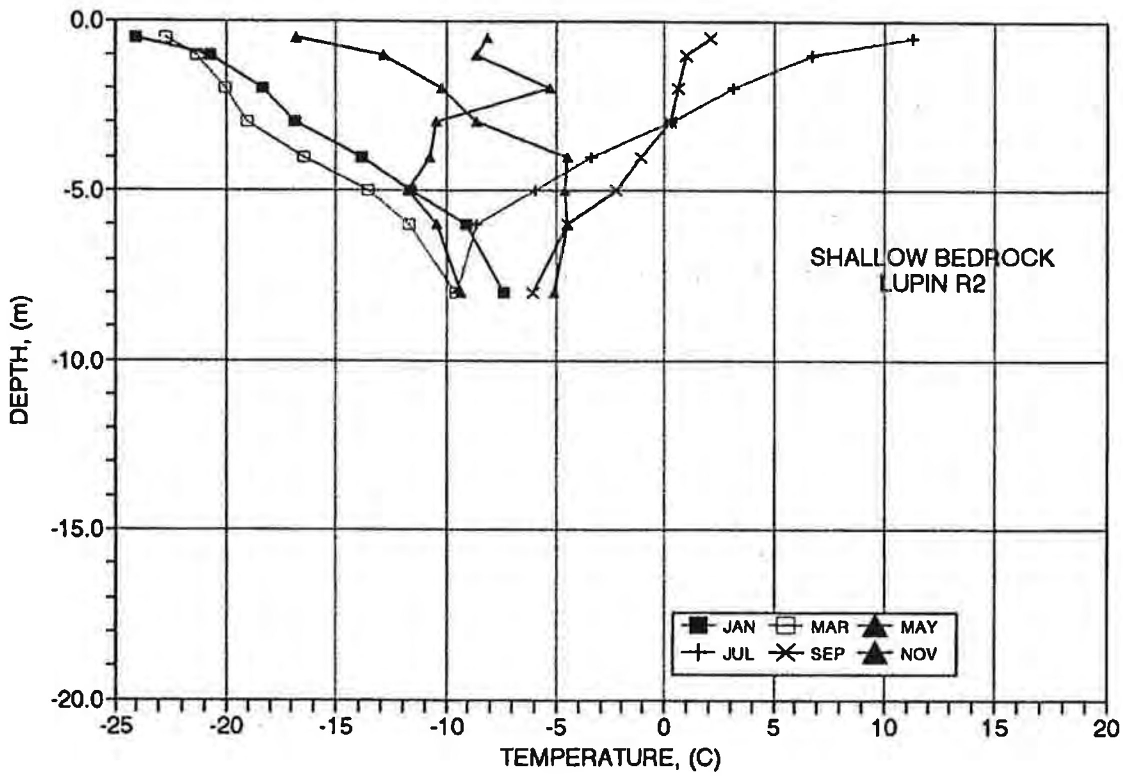


Figure 14 **Reference Thermistor String in Bedrock (Holubec 1990)**

The temperature fluctuation to 20 m, which represents about the depth of zero fluctuation (zero amplitude), is illustrated in the deep thermistor string through the silty sand dam fill and into natural silty sand and bedrock on Figure 15. This family of profiles shows the temperature at zero amplitude to be about -4°C. This zero amplitude temperature, warmer than the estimated zero amplitude permafrost temperature of -8°C, is the result of the warming effect of the adjacent ponded water.

Figure 16 shows the temperature fluctuations at six depths over a one year period. The temperature at 1.2 m fluctuated between 5°C and -24°C; at 2.2 m it varied between just above 0°C to -19°C and at 20.2 m depth it remained nearly constant at -4°C. A comparison of the dates of the peaks and troughs shows a time lag of the temperature changes with time that increases with depth. This lag in time of ground temperature to air temperature is shown for warm and cold fronts advancing into the ground on Figure 17.

Figures 18 and 19 provide temperature data from a reclaimed tailings cell where the tailings were covered with 600 mm of sandy gravel. The drilling for the thermistor string installation showed the tailings to be 4.9 m thick. They were frozen from the active layer down to natural ground. It is believed that the tailings discharge into this cell stopped in 1987, and that the cell was covered with sandy gravel the following year. This area is just south of Dam 3 shown on Figure 13. Figure 18 shows the temperature fluctuations in tailings at increasing depths to 5 m during 1989 and Figure 19 illustrates this information with temperature profiles at four months of the year. The temperature profiles show the active layer to be about 2.5 m deep and the warmest temperature at the bottom of the tailings (5 m depth) was about -2.5°C.

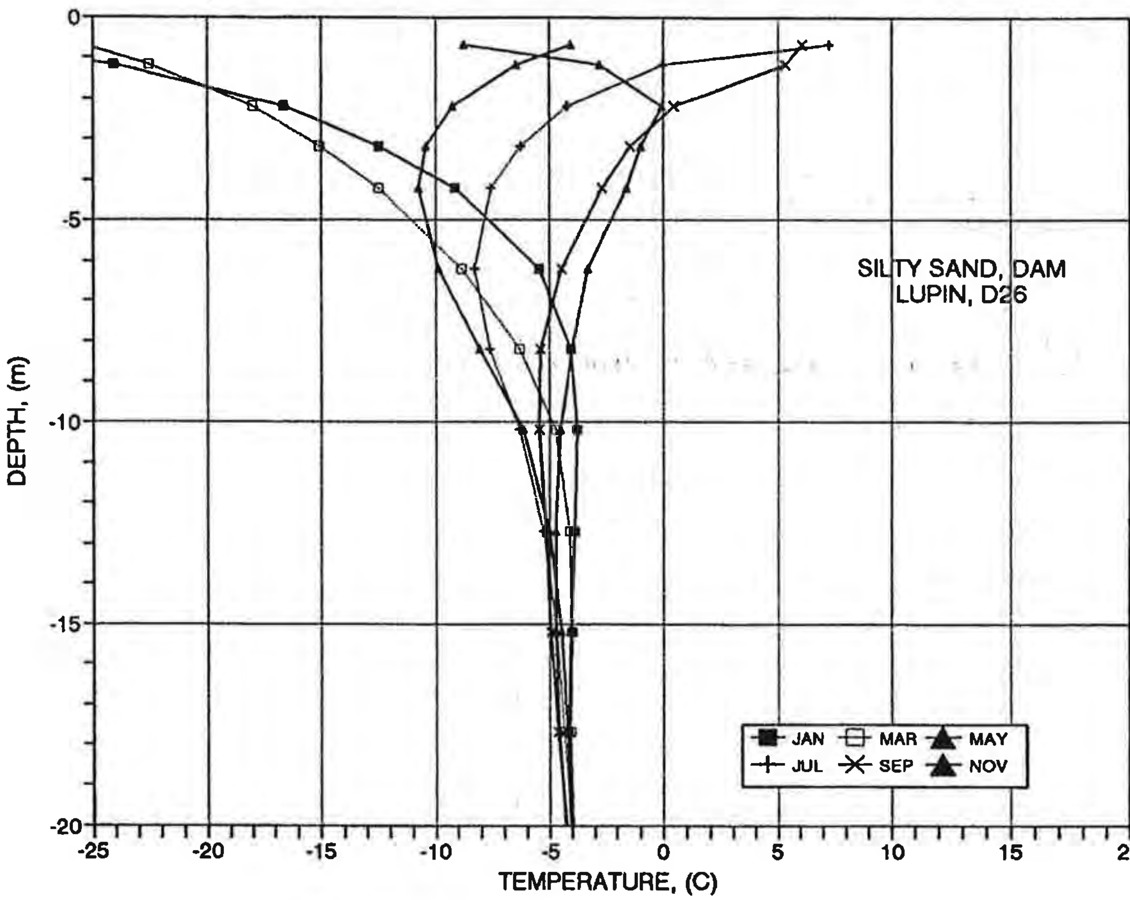


Figure 15 **Temperature Profile Fluctuations under Crest of Tailings Dam (Holubec 1990)**

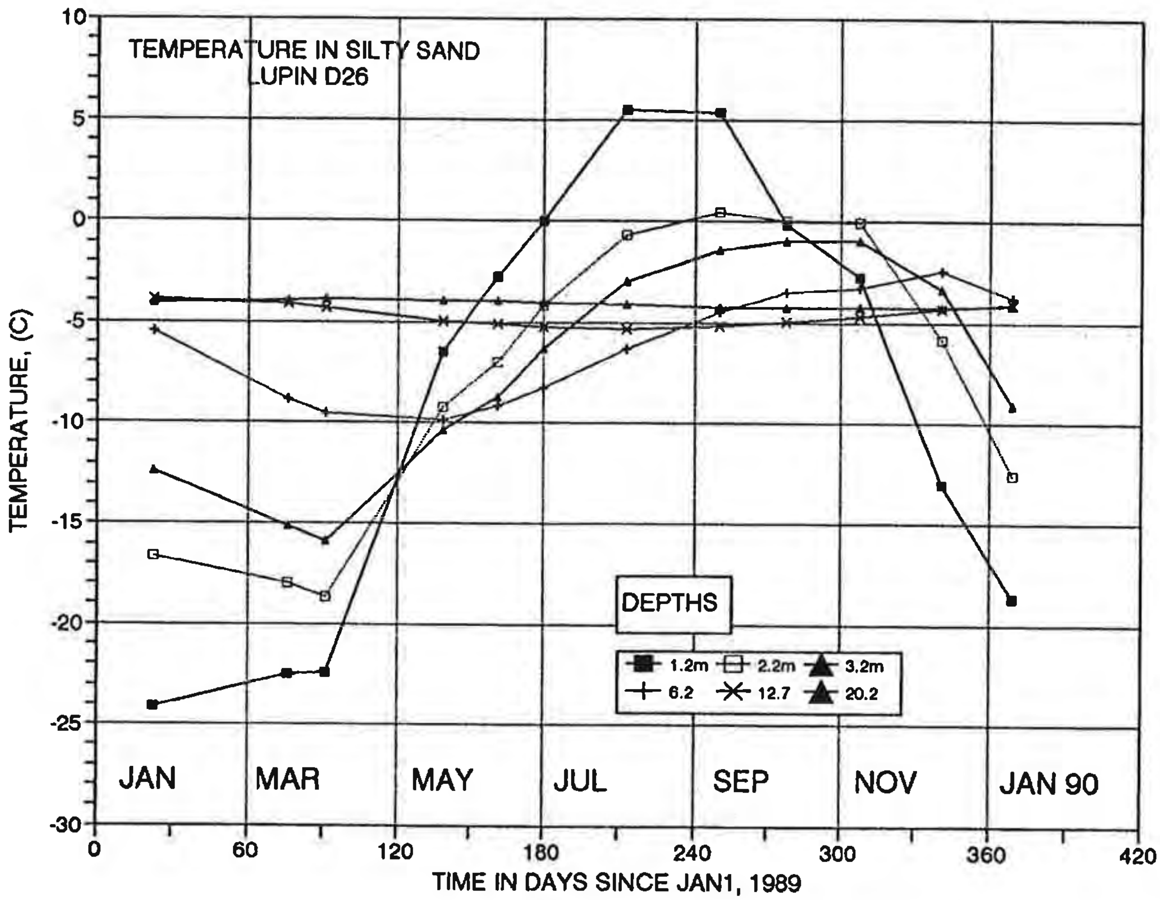


Figure 16 **Temperature Fluctuations over the Year at increasing Depths under a Dam Crest (Holubec 1990)**

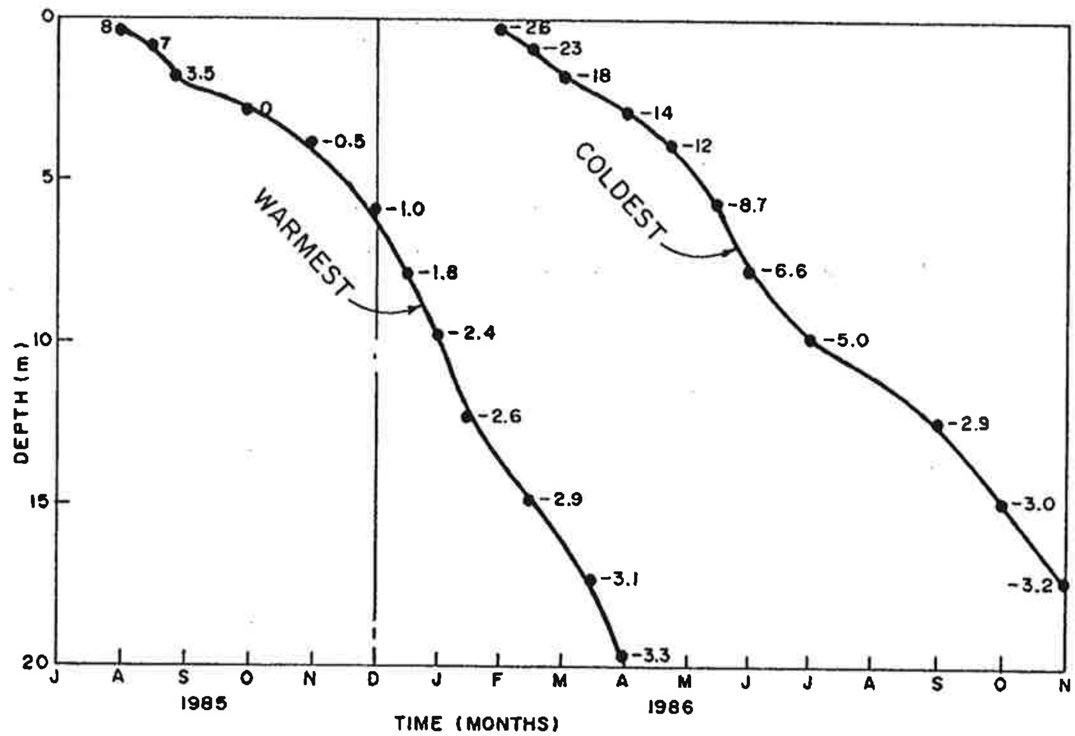


Figure 17 **Time Lag with Depth of Warmest and Coldest Temperatures (Holubec 1990)**

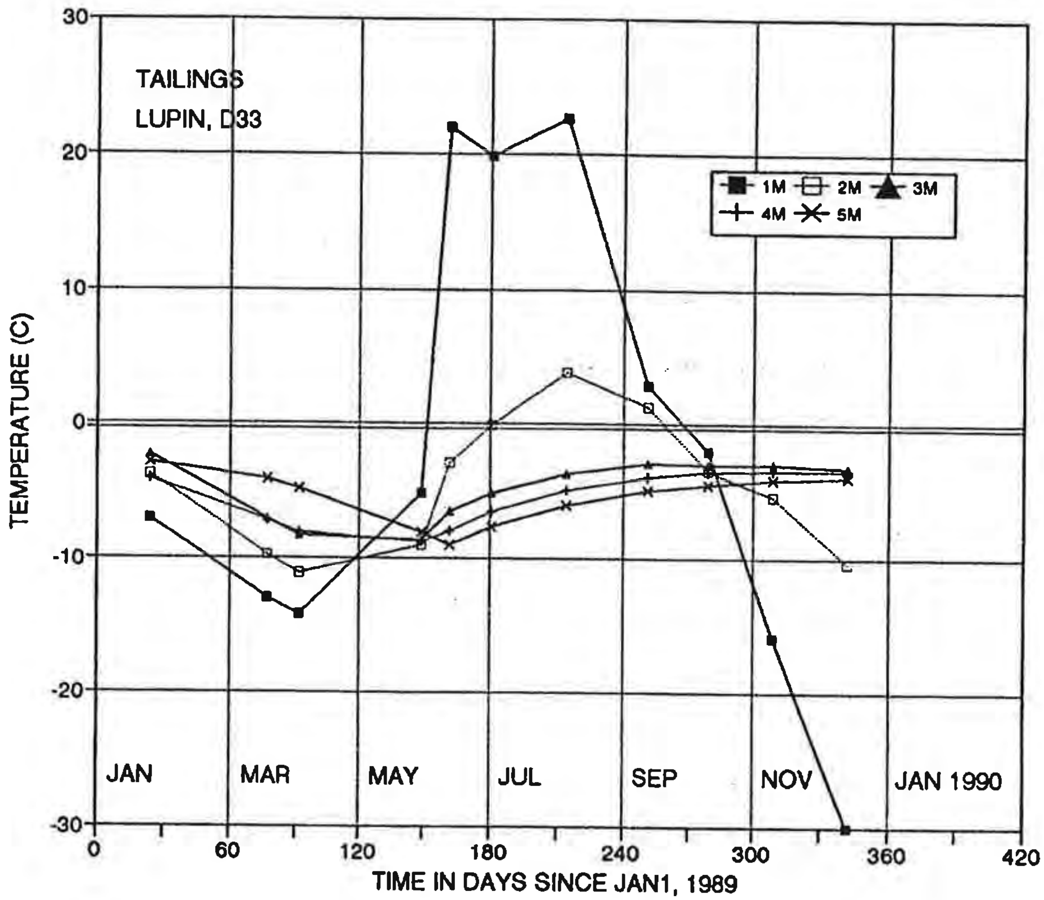


Figure 18 **Temperature Fluctuations over the Year at increasing Depth in Tailings (Holubec 1990)**

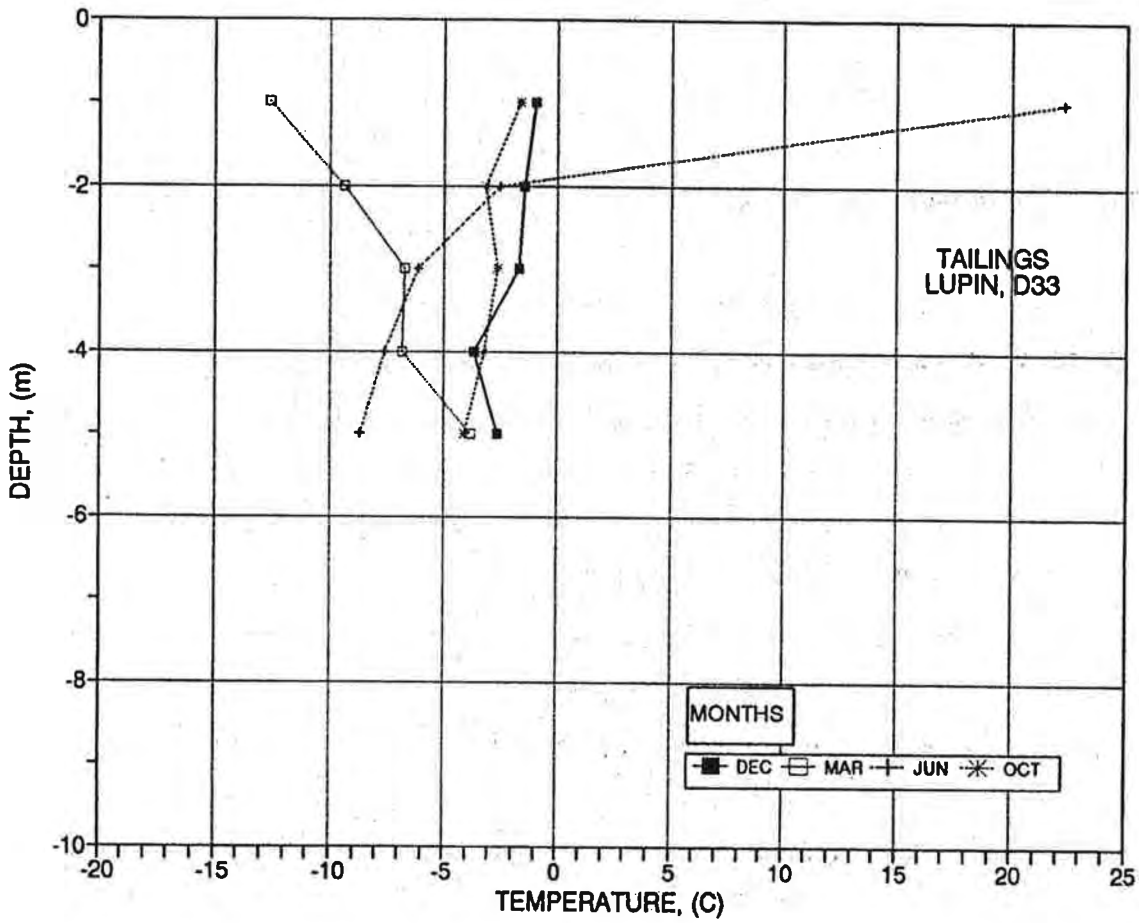


Figure 19 **Temperature Profile Fluctuations in Reclaimed Tailings** (Holubec 1990)

The temperature records from Lupin mine illustrate the active layer seasonal changes in several soil/rock/tailings profiles. For this purpose the ground temperature regime with time over the year are shown in terms of the frost table (bottom of the active layer) in four stratigraphies (Figure 20). Figure 20a shows frost table variations observed in two bedrock stratigraphies. These curves show that the active layer in bedrock starts to develop at the beginning of June and completely refreezes by end of September. The maximum thaw depths occur in August. The different frost table depths of 2.5 and about 4 m are due to different rock surface covers. The 2.5 m thaw depth was observed where the bedrock was covered with about 300 mm of organics while the 4.0 m thaw depth was observed below bare bedrock surface.

Figure 20b illustrates the thawing occurring in a natural ground stratigraphy consisting of 300 mm of organics underlain by silty sand till. The natural ground starts to thaw about June 1 and the maximum thaw depth of 1 m occurs at about the end of August. In September the frost table moves up; the active layer starts to freeze from both the surface and bottom in late September and is frozen completely in mid October.

Figure 20c illustrates the likely depth of thaw in a silty sand fill (no organic cover) as was observed under the tailings dam crest. In this case the maximum depth of the active layer varied from 2.5 to 3.2 m. The variation of the active layer depth is believed to be due to different water contents at the two locations. Finally the thermistor string in tailings covered with 600 mm sandy gravel showed a maximum active zone depth of 2.5 m (Figure 20d).

The above results representating the Arctic permafrost region show the depth of the active zone to vary from 1 m (silty sand with 300 mm organic cover) to about 4 m under bare rock surfaces. The large range of the active zone is predominantly governed by the presence and thickness of the organic layer and to a lesser extent by the water/ice content in the material. Tailings are similar to a silty sand (tailings particle size

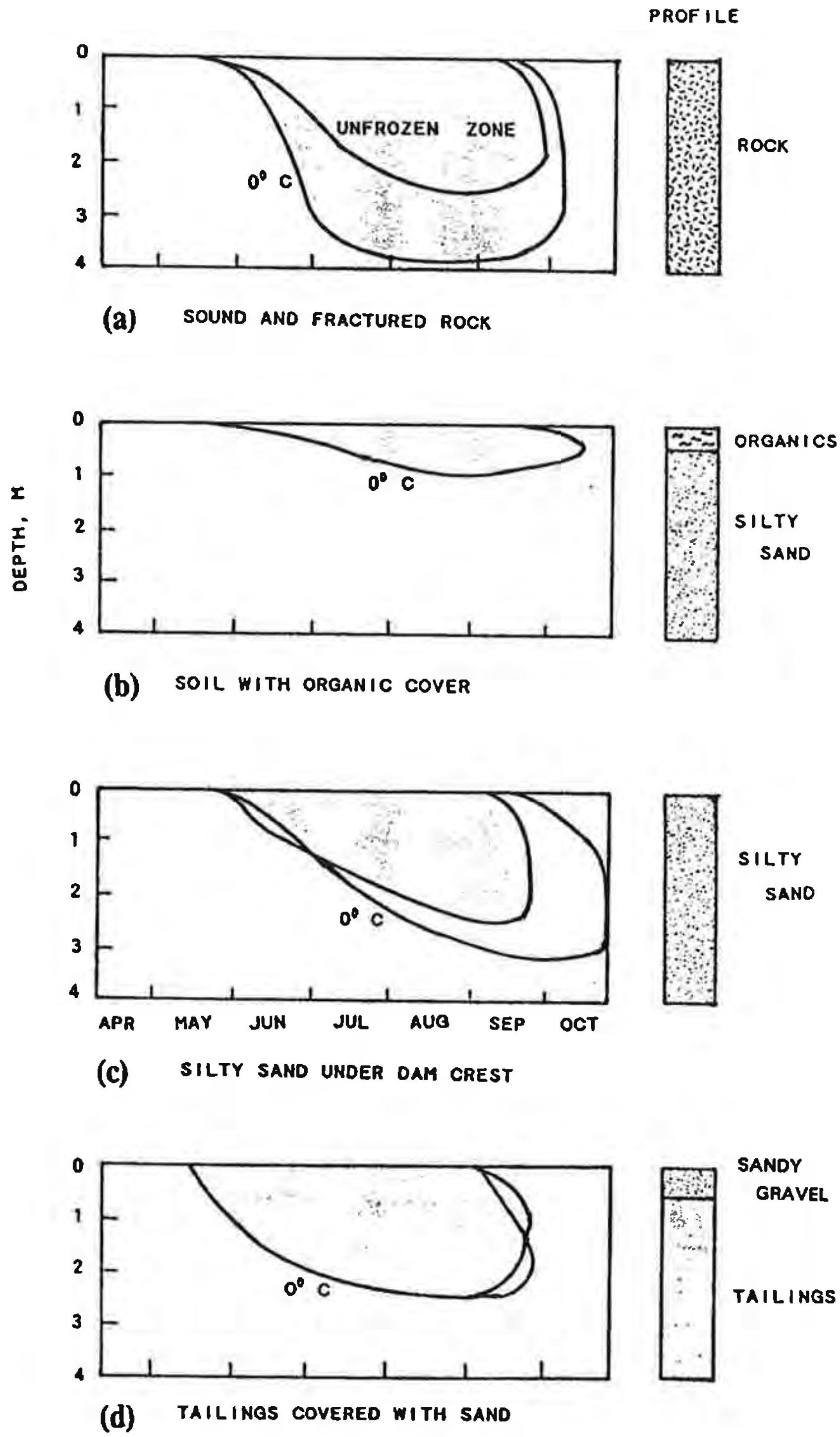


Figure 20 **Annual Active Zone Changes in Different Stratigraphies (Holubec 1990)**

distribution is representative of a sandy silt) and mineralogy and therefore show similar depth of the active layer. The active zone in the Lupin tailings was deep because of the absence of an organic layer but was less than the 3.5 m depth measured under the dam crest because of higher water/ice content in the tailings. The greatest thaw depth was observed in exposed bedrock with no organic cover because of the low water/ice content within the rock. The active zone exists for a period of 4 to 5 months and reaches its maximum depth between August and September. The time of the year of maximum active zone depth occurs later than the warmest month of the year because of the temperature time lag within the ground.

5.3 Giant Mine

In 1971 the Department of Indian and Northern Affairs sponsored a study of the stability of dyke embankments at two mines in the Yellowknife area under the Arctic Land Use Research program (Roy et al. 1973). Operational information of the mines was obtained and the tailings dykes were instrumented with thermocouple strings at the Giant Yellowknife (Giant Mine) and Cominco Mines. Deep thermocouple strings were installed downstream below the crest and upstream of the dams. The temperatures were recorded for two years with the results given in terms of temperature profiles on a monthly basis from December 1971 to November 1972. Of greatest interest to this study is the temperature monitoring at a Giant Mine tailings dam where temperature probes were installed in tailings upstream and downstream of a dyke (Figure 21). The upstream thermocouple string (GT1) was installed in an active tailings disposal area with 1.8 m water cover and the downstream thermocouple string (GT2) was installed in an old tailings area with 0.3 m water cover. Permafrost distribution with temperatures for the coldest and warmest conditions occurring during the months of May and October, 1971, respectively, are shown on Figure 22. Four temperature profiles showing the range of

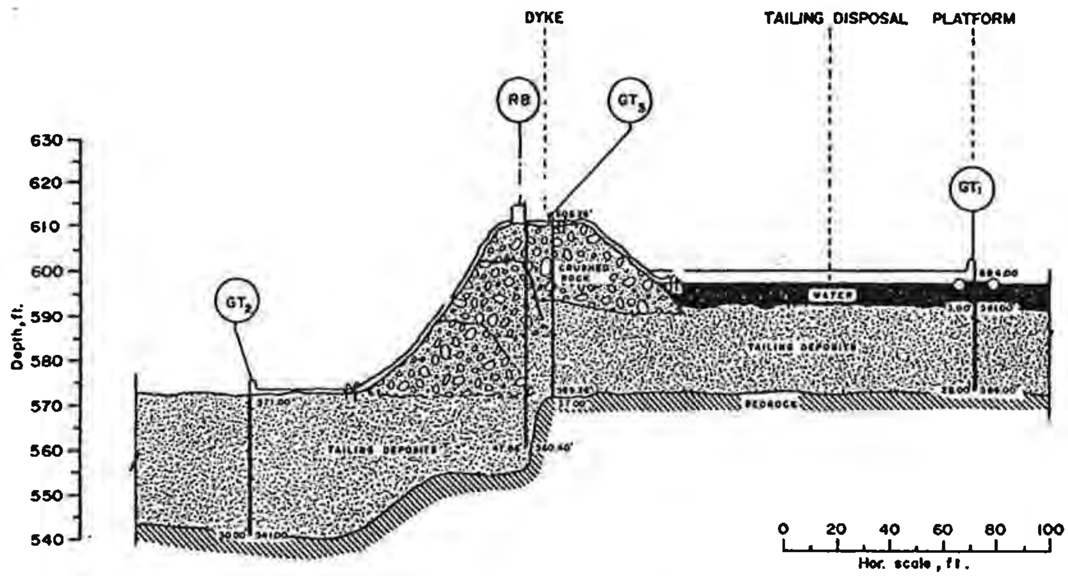


Figure 21 Giant Mine, Dyke No 3, Cross Section and Instrumentation (Roy et al. 1973)

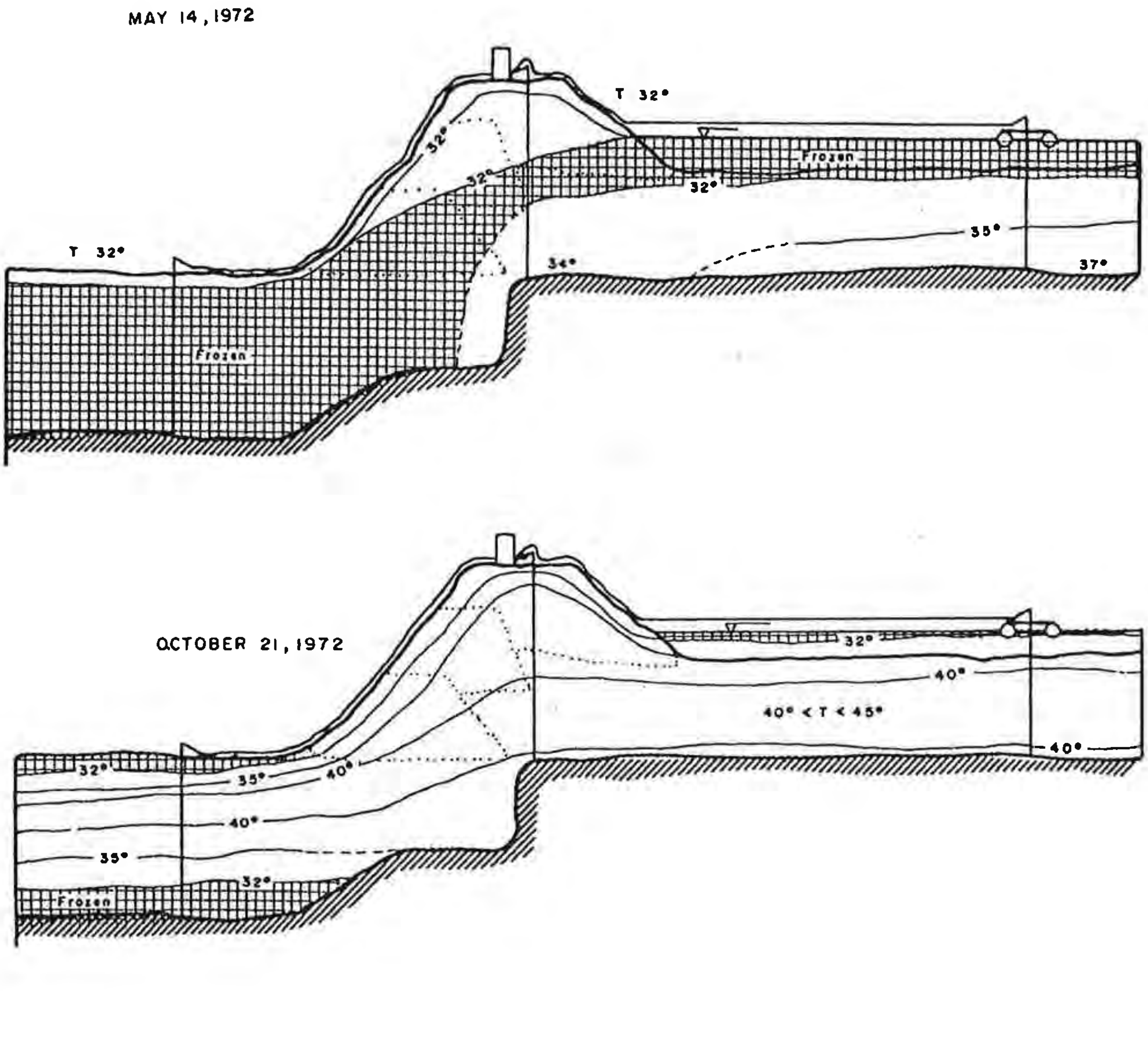


Figure 22 Temperature Sections during May and October 1972, Giant Mine (Roy et al 1973)

temperatures within the old tailings and the active tailings disposal areas are shown on Figures 23 and 24 respectively.

The temperature profile in the old tailings area (Figure 23) fluctuates with the air temperature, but with decreasing amplitude with depth, until a depth of about 6.8 m is reached. Above 6.8 m the tailings progressively freeze and thaw from the ground surface; being completely frozen during May and completely thawed from June to September. The tailings below a depth of 6.8 m remained frozen throughout the year. The tailings in the frozen zone were never very cold with the frozen tailings temperature fluctuating between, 0 and -1°C. The tailings in the active disposal area (Figure 24) were covered with 1.8 m of water. It is not known to what degree the heat from the discharged tailings slurry affected the temperature of the water and the underlying tailings. It is suspected that the influence was small. The temperature monitoring results showed that only the surface tailings froze to a maximum depth of about 4 m and below this depth the tailings remained unfrozen throughout the year. The ponded water froze to the bottom by the end of November, remained frozen to the end of May, and was completely thawed from June to near the end of November. With the exception of the upper 0.5 m of tailings, the tailings were observed to be not colder than 0 to -1°C.

5.4 Faro Mine

For the development of the abandonment plan for the Faro Mine tailings area, a set of 6 test plots were constructed in the old tailings area to investigate alternative cover designs for the mitigation of tailings acid generation (Robertson and Barton-Bridges 1990). One of the objectives for these test plots was to evaluate the effect of various covers on the tailings temperature since acid generation rate is also dependent on temperature. The lowering of the tailings temperature would reduce acid generation. Temperature profiles are reported for three test plots and a control profile installed

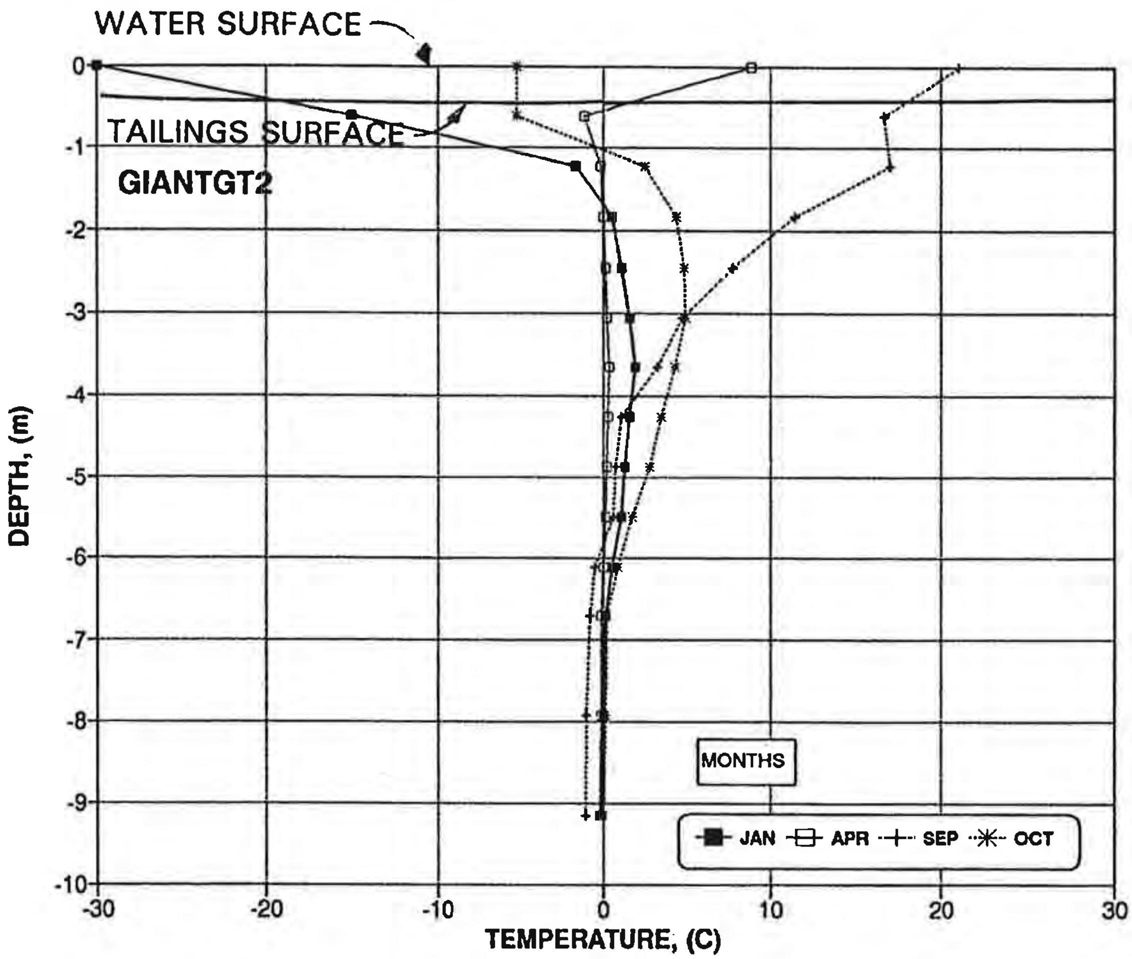


Figure 23 Temperature Profiles at Old Tailings Area with 0.3 m Water Cover, Giant Mine (Roy et al 1973)

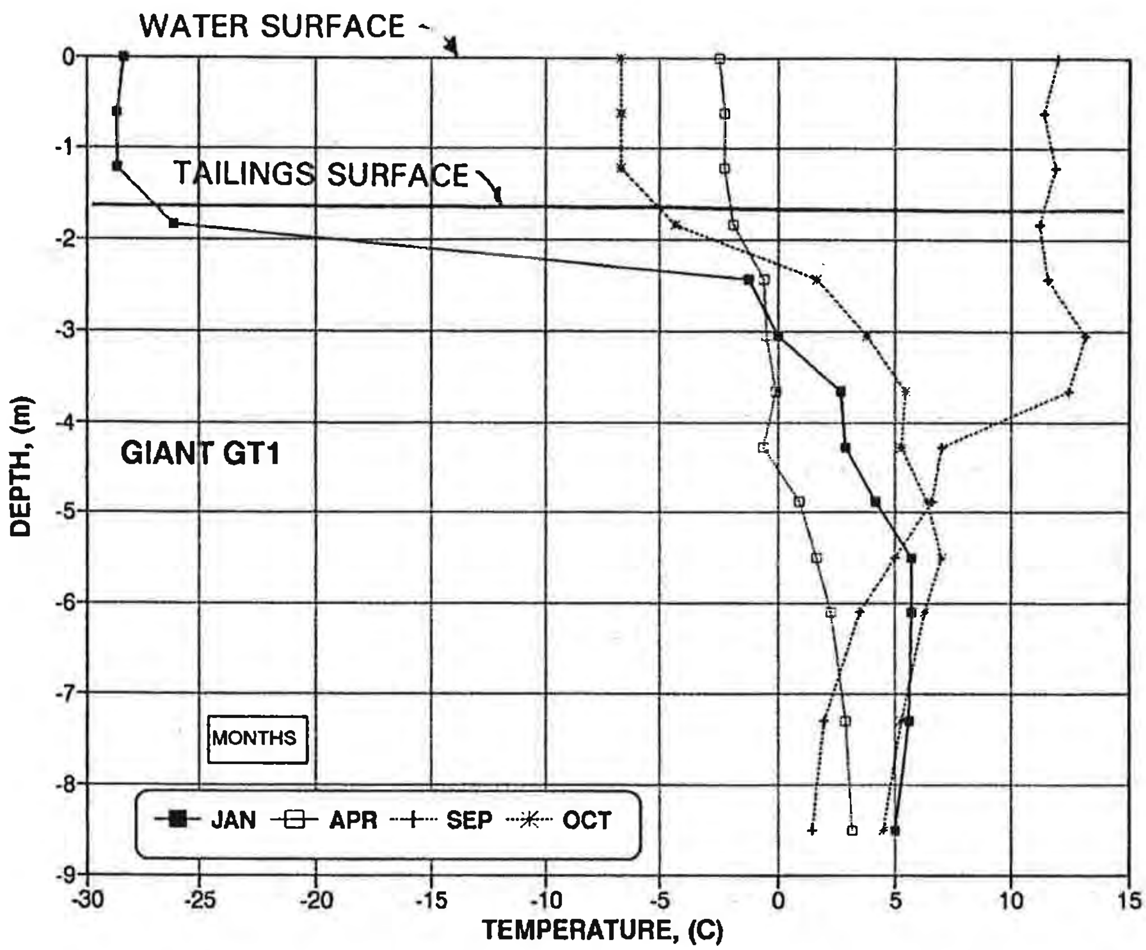


Figure 24 **Temperature Profiles at Tailings Disposal Area with 1.8 m Water Cover, Giant Mine** (Roy et al 1973)

outside of the test area in an old tailings area. The three test plots with temperature measurements are: tailings control plot, and two composite plots with one plot being unsaturated and the second plot being saturated. The stratigraphy of the composite plots from the surface consisted of 0.5 m waste rock followed by 0.5 m of till, 0.5 m of tailings slimes and 2 m of tailings placed under controlled conditions. The temperature profiles provide only limited information in regard to ground temperature changes with depth in the tailings because of the short length of the thermistor strings. The thermistor strings in the control plots extended to a depth of 1.6 m below the tailings surface while the total depth of the thermistor string was 4.0 m. Furthermore, a direct comparison of the test plot temperature information is difficult because the control plots were constructed within dyked enclosures that may have shaded the ground surface at the thermistor locations. It was postulated that shading produces lower temperatures in the tailings cells as compared to the old tailings area.

Temperature profiles in the old tailings area (Figure 25) show that the maximum ground temperature profile crosses 0°C at a depth of about 4.0 m and therefore below this depth the tailings are frozen. Based on Giant Mine information and the estimated annual mean air temperature, it can be postulated that the tailings below 4.0 m will likely be at a mean annual temperature between 0 to -1°C.

The results from the three test plots are given on Figure 26 (a, b and c) and Table 5. The overall results show that the composite rock cover decreased the temperature within the tailings. The following observations can be made from readings taken during the warmest months, mainly July and August. The composite unsaturated plot showed the temperature at the slime surface and 1.6 m below it to be 6°C colder than the temperature observed at exposed tailings surface. The saturated composite cover also showed a decrease in the warmest temperature profile but the decrease was not as large as the unsaturated cover.

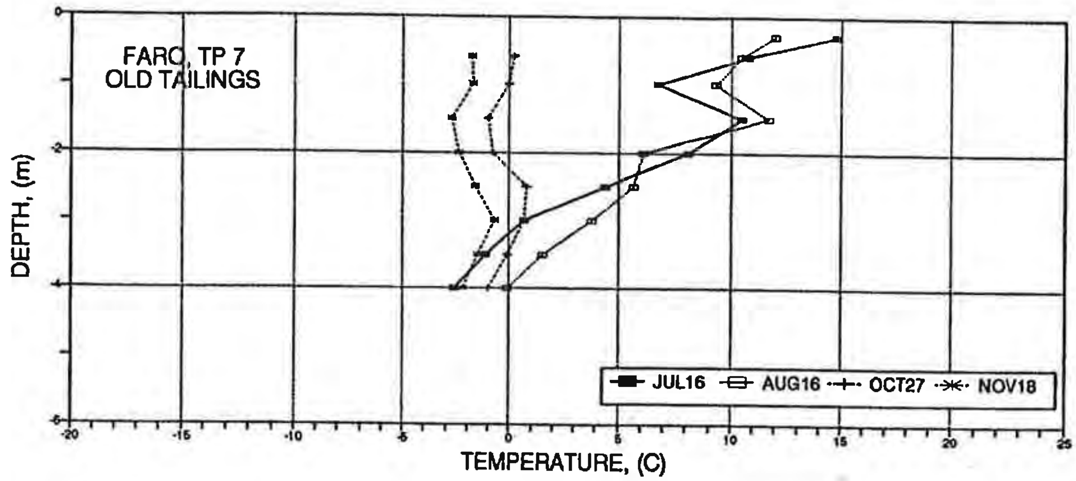


Figure 25 **Temperature Profiles at Old Tailings Area, Faro Mine** (Robertson and Barton-Bridges 1990)

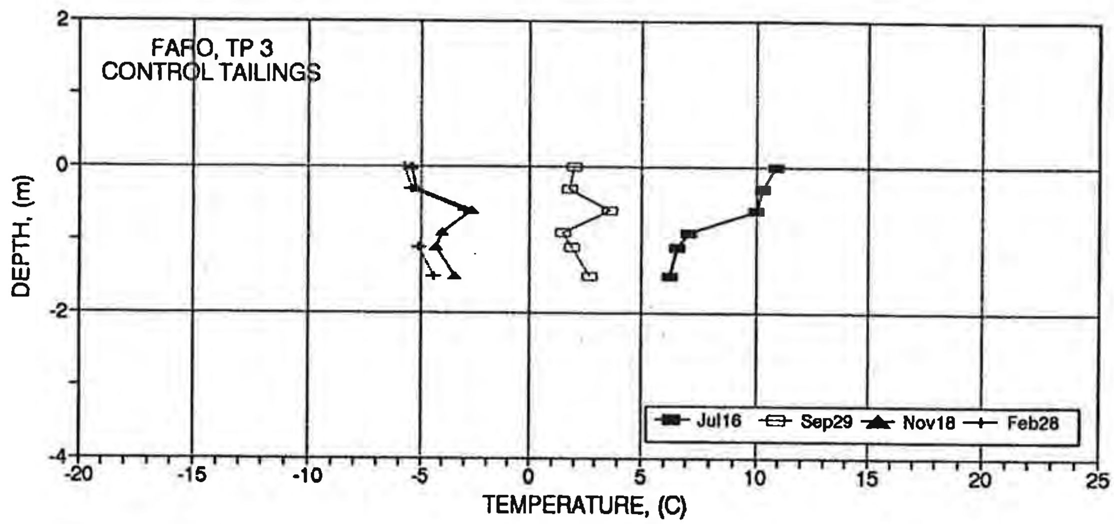
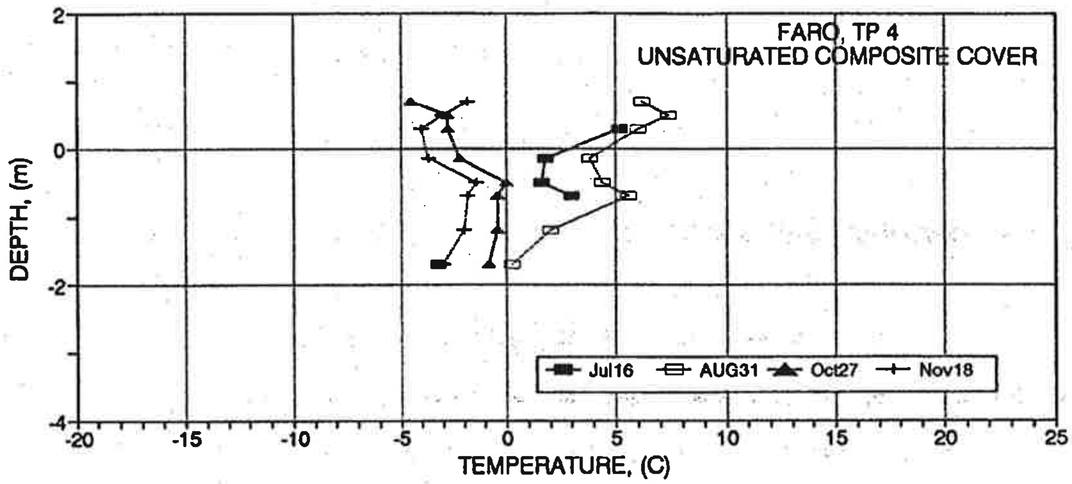
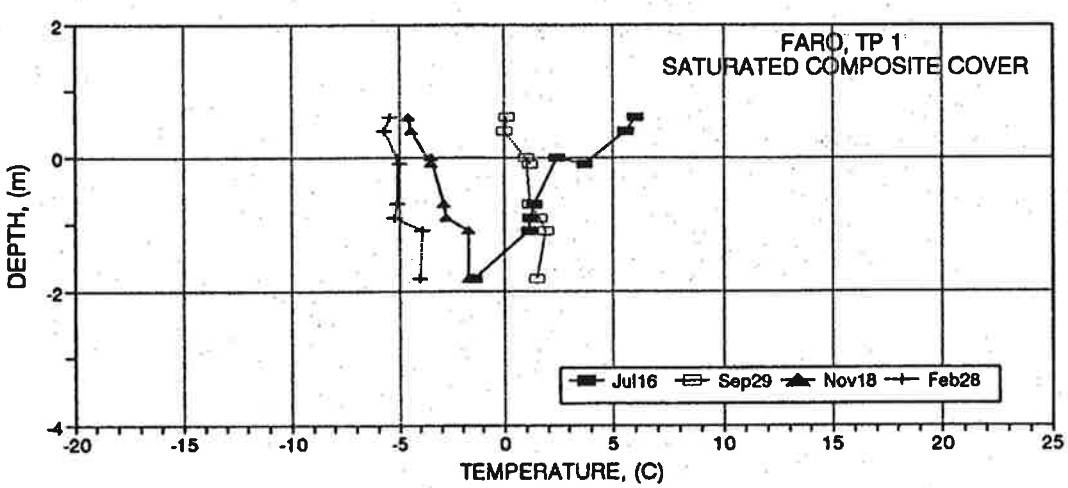


Figure 26 **Temperature Profiles at Tailings Plot, Faro Mine** (Robertson and Barton-Bridges 1990)

a) Tailings Control Cell



b) Composite Cover, Unsaturated



c) Composite Cover, Saturated

The Faro test plots show the rock cover acted as a cold trap. During winter, cold air enters the rock and cools the underlying tailings. During the summer months the cold dense air is trapped in the rock layer and acts as an insulator to the underlying tailings. This phenomenon was observed and used elsewhere to promote freezing (Mukhetoknov 1969 and 1971 as reported in Steffen, Robertson and Kirsten 1986). However, no conclusion can be made if the rock cover produced or enhanced permafrost because of the limited depth of temperature monitoring.

Table 5 Warmest Tailings Temperatures For Different Stratigraphies, Faro Mine

TEST PLOT	STRATIGRAPHY	TEMPERATURE DEPTH, M	WARMEST TEMP. °C
Old Tailngs	Tailings	At Surface 1.6 m Below Surface	16 14
Tailings Plot	Tailings	At Surface 1.6 m Below Surface	11 8
Composite Unsaturated	0.5 m Rock 0.5 m Till 0.5 m Tailings Slimes 2.0 m Tailings	At Surface of Slimes Tailings 1.6 m Below Slimes	 5 5 2
Composite Saturated	0.5 m Rock 0.5 m Till 0.5 m Tailings Slimes 2.0 m Tailings	At Surface of Slimes Tailings 1.6 m Below Slimes	 5.5 4.5 4.5

5.5 Uranium Mines in Northern Saskatchewan

Energy, Mines and Resources Canada sponsored a study of frost action in tailings at three uranium mines in northern Saskatchewan (Robertson et al. 1986). This study documented the site and climatic conditions at Gunnar, Key Lake and Rabbit Lake mines; conducted thermal analyses to predict under what conditions permafrost could increase or decrease, and evaluated potential covers to develop permafrost. The study did not provide any field temperature data. The locations of the three mines are shown on Figure 21 and site specific data on latitude, mean annual daily temperature and observed permafrost conditions is given in Table 6.

Table 6 Location and Permafrost Conditions at Uranium Mines in Saskatchewan (Robertson et al 1986)

MINE NAME	LOCATION	MEAN ANNUAL AIR TEMP, °C	PERMAFROST DESCRIPTION
Gunnar	59° 34' N 108° 29' W	-3.5	Frost boil features observed. Frost depth 0.8 m with max'm 4.8 m, unfrozen below
Key Lake	57° 21' N 107° 08' W	-2.7	Winter frost depth 0.6 to 1.2 m, unfrozen tailings below this depth
Rabbit Lake	58° 11' N 103° 42' W	-4.6	Permafrost in one drill hole near dam with little snow cover, other holes in central pond had unfrozen tailings

Gunnar Mine

Frost boil features were observed at several locations in fine grained tailings where water table was shallow. Frozen depth within these was 5 to 6 m. Boils were localized with unfrozen ground within few metres laterally. Frozen ground evaluation in March 1984 and 1985 showed the depth of frozen ground to be generally 0.6 to 4.4 m and at another localized site to vary from 3.7 to 4.8 m

Key Lake

Two sites were monitored for frozen ground. Frozen ground, developed during the winter, was observed to be to a depth of about 0.6 m. The greatest frozen tailings depth was observed in one area where 0.6 m of freshly placed tailings froze on top of existing 0.6 m of frozen tailings for a total thickness of frozen tailings being 1.2 m. Subsequent probing showed all tailings thawed by June the following summer.

Rabbit Lake

Drilling through the tailings in 1987 found one test hole with frozen tailings for a depth of 20 m. This hole had little snow cover. It is postulated that the frozen tailings developed during winter deposition on a beach. Other borings in the interior portion of the pond encountered unfrozen tailings.

Thermal Analyses

The ground thermal regime is controlled by heat exchange at the ground surface and heat conduction with depth. Heat exchange at the ground surface, in turn, is affected by site specific parameters such as vegetation, snow cover and evaporation. The three uranium mines are located in discontinuous permafrost that is in near balance between permafrost and non-permafrost conditions. As a result the local ground conditions play an important role in determining whether permafrost develops.

The seasonal depth of freezing and thawing and the ground temperatures for a given climatic area are controlled by:

- heat conduction within the soil
- heat exchange at the ground surface

Since the thermal conductivity of the tailings is relatively uniform, the development of permafrost is governed by evapotranspiration (function of vegetation and drainage), thickness of snow and depth of water over the tailings surface. Parametric thermal analyses were performed in this study (Robertson et al. 1986) to review the effect of the above three factors on permafrost development.

The results showed that normal depths of snow cover of about 250 mm will prevent permafrost development. However, where snow depths are considerably less than the normals and the tailings are saturated, evapotranspiration can lead to permafrost. The effect of ponded water and depth of groundwater are complex. The most favourable condition exists when the groundwater table is located at the tailings surface. Standing water over the tailings reduces the depth of frost penetration in the tailings and with sufficient depth of 1 to 2 m will prevent the development of permafrost. On the other

hand, if groundwater surface is substantially deep (2 to 5 m) so that the tailings become 'dry', permafrost degradation will occur.

It was concluded (Robertson et al. 1986) that the optimum conditions for the development of permafrost in northern Saskatchewan are by increasing the evapotranspiration by vegetation, maintaining a high groundwater table, and reducing the depth of snow cover.

6.0 DESIGN CONSIDERATIONS

6.1 Location

Canada is a vast country with greatly diverse physiographic, climatic and permafrost conditions that influence the design of tailings impoundments and the approach taken towards closure design. As a first step in the design of a tailings impoundment in northern Canada, it is necessary to establish in which permafrost region the mine is located. As stated earlier, the Canadian permafrost area can be divided into roughly three regions based on terrain, physiography and prevalent permafrost type. The majority of mines in permafrost in Canada are located in the Boreal permafrost region. This includes the case histories of Giant Mine and the Saskatchewan uranium mines discussed earlier. In the Boreal permafrost region the frozen ground is close to 0°C [equilibrium with unfrozen conditions]. Therefore, some form of permafrost enhancement has to be resorted to in order to produce permafrost in the tailings.

The Cordillera permafrost region encompasses all of the Yukon Territory and portions of northern British Columbia. This region is in the discontinuous permafrost area but it is distinguished by being in the mountains. The annual mean air temperature and the presence of permafrost is modified by the large elevation differences in the mountainous terrain. While discontinuous permafrost exists in the valley and lower mountain slopes, continuous permafrost exists at higher elevations.

Finally there is the Arctic region with continuous permafrost. The Arctic permafrost region covers most of the Northwest Territories and a small part of northern Quebec. In this region the ground below the active zone will remain frozen year round and the main challenge is to raise the active zone above the reactive tailings.

6.2 Hydrology

Hydrology plays two roles in the design of tailings impoundments. Firstly, it is desirable to locate the tailings facility so that it is at the head of a small watershed area or within a self-contained watershed which does not overflow due to high evapotranspiration. Secondly it is desirable to design the tailings impoundment so that a total precipitation containment is assured on mine closure. Total containment of direct precipitation and runoff water eliminates the need for decanting and thereby eliminates maintenance after closure. The concept of total containment of surface water within the tailings pond may be feasible in the majority of locations within the Canadian permafrost regions. It is feasible because of high evapotranspiration as related to precipitation and the fact that permafrost makes the perimeter dykes and the base of the tailings impoundment essentially impervious.

Total containment depends on the water balance of the tailings pond's catchment area. The catchment area should ideally consist of only the area contained within tailings pond perimeter. In some instances, it may include some natural ground if it was constructed within the area of an existing minor watershed area. After mine closure, the water balance is based on the precipitation of the catchment area, evapotranspiration from land and evaporation from the pond water surface. Based on these parameters, the criterion that decides between decanting and containment feasibility is the Wetted Watershed Fraction (WWF) (Latham 1988). WWF is a pond to total catchment area ratio. The pond area being defined by the maximum water surface within the tailings pond based on the dyke crest and an acceptable freeboard.

An equilibrium state, ie. no net change in pond level, is dependent mainly on the evaporation rate at the ponded water surface. The WWF for a watershed with no seepage and infiltration losses is given by:

$$\frac{P - ET}{E - ET}$$

where P is the annual precipitation, ET the annual land evapotranspiration and E the annual lake evaporation.

WWF equal to 1.0 would represent a condition where the P and ET and E are at balance. WWF greater than 1.0 means that precipitation is greater than ET and E and therefore annual outflow occurs. WWF smaller than 1.0 means that total containment is feasible. However, since the annual precipitation varies from year to year, the design requires a WWF approaching 0.5 to obtain total containment during wet years.

The WWF for an equilibrium condition was calculated for the four case history mines and is presented on Table 7.

Table 7 Wetted Watershed Fractions For Discussed Mines in Permafrost

LOCATION / ITEMS[a]	Lupin Mine	Giant Yellowknife Mine	Faro Mine	Rabbit Lake
Precipitation, mm	251	267	288	523
Lake Evaporation, mm	320	420	450	470
Evapotranspiration, mm	130	200	190	220
Wetted Watershed Fraction for Equilibrium	0.6	0.3	0.4	1.2

NOTE: (a) Values are mean annual values.

The information in this table was obtained from: precipitation (Canadian Climatic Normals for the North) lake evaporation (Morton 1983) and evapotranspiration (Hartog and Ferguson 1975). The results given in Table 7 indicate that total containment may be obtainable at Lupin Mine, Giant Mine and Faro Mine. If it is assumed that the tailings pond watershed does not receive any outside water, then the WWF ratios of 0.3 to 0.6 (assume average 0.5) calculated from the climatic data give a factor of safety of about 2 for storing the mean annual precipitation and providing total containment. This factor of safety provides extra capacity to evaporate precipitation greater than the mean annual precipitation for the years having precipitation greater than mean values.

Total containment can be considered for closure design of acid generating tailings in favourable precipitation / evapotranspiration balance. In this design the perimeter dam crest has to be essentially horizontal, and the basin has to have sufficient storage capacity for extreme precipitation events.

6.3 Permafrost

In the design of a tailings facility in permafrost, two thermal parameters are required, these are: the permafrost temperature at the zero amplitude depth and the depth of the active zone.

As discussed in Section 2.2, the temperature below the ground surface for some 10 m fluctuates greatly over the year and there is a time lag in the ground temperature response to the air temperature. In the 2 to 8 m depth below the ground surface the time lag in the temperature response may be 1 to 4 months respectively thereby producing a whiplash in ground temperature profiles within this zone. This means that ground temperature profile measured only at one point in time is practically useless for design purposes. For ground temperature measurements to be useful, the measurements have to be taken on a monthly, or bimonthly, basis for at least one year and the profile should extend to about zero amplitude depth located 15 to 20 m below the ground surface. In the absence of this type of information, the mean annual permafrost temperature should be obtained by either one time temperature measurement to a depth of at least 15 m or by estimation from published climatic normals from the nearest Atmospheric Environment Service station. This latter method is normally sufficient for preliminary design purposes. Haugen et al. (1983) have observed that the mean annual permafrost temperature is 3.6°C warmer than the mean annual air temperature. In general, the zero amplitude ground temperature within the discontinuous permafrost region ranges from about 0 to -4°C and from about -4 to -12°C within the continuous permafrost region.

The depth of, and the temperature fluctuation within, the active zone for a given climatic condition depends on snow cover, vegetation, soil/rock stratigraphy and location of the groundwater surface within the tailings and cover. The range of active zone thickness varies from 0.5 to 8 m with 1 to 4 m being more common. In a closure design of tailings impoundment in permafrost, it is desirable to keep the tailings permanently frozen by covering the tailings with fill and keeping the active zone within the fill. To minimize the cost of the fill, it is desirable to limit the fill thickness. This can be done by the selection of the cover materials/design and design the facility so that the groundwater is located at the cover surface. With time vegetation may develop over the cover which will further decrease the thickness of the active zone.

6.4 Permafrost Enhancement

6.4.1 General

Permafrost enhancement for a tailings surface in permafrost consists of raising the permafrost table to the top of the tailings surface, move the active zone above the tailings by adding a cover, and thereby keep the tailings permanently frozen. There are two basic methods of changing the heat balance in the tailings to enhance the permafrost, namely:

- change the surface condition
- provide artificial means.

The rate of thaw or freezing is a function of the following variables:

- air temperature and time
- thermal conductivity and volumetric heat capacity of the materials
- volumetric latent heat
- chemical/biological heats of reaction

Typical thermal properties governing heat transfer, namely conductivity and volumetric heat, are given in Table 8. These demonstrate the insulation effects of snow and extruded insulation (eg styrofoam board) as compared to mineral soils and rock. The other factor influencing the thickness of the active layer not shown in this table is the latent heat variable which in soil or rock is directly related to the water content.

The following is a list of permafrost enhancement methods which can be considered to develop permafrost and decrease the thickness of the active zone. The permafrost enhancement techniques are discussed under the Arctic; Boreal and Cordillera permafrost regions.

6.4.2 Arctic Permafrost

In the arctic permafrost region, the ground and tailings will be permanently frozen and the main consideration is the active zone. The depth of this zone can vary from as little as 0.5 m with fibrous muskeg cover to as deep as 4 to 6 m for dry tailings and rock fill respectively. In the case of non-acid generating tailings, it is sufficient to cover the tailings with a sand/gravel layer for dust control. In the case of acid generating tailings, it is desirable to freeze the tailings permanently by placing fill on top of the tailings and thereby raising the bottom of the active zone out of the tailings. Based on Lupin Mine temperature data, a sandy fill, which is the most common construction material in the Arctic permafrost region, requires a 2.5 to 3 m thick cover over the tailings. This is a costly proposition.

Table 8 Thermal Properties of Typical Materials

(Johnston 1981)

MATERIAL	Conductivity W/mK	Volumetric Heat MJ/m^3K
Air	0.02	0.001
Water	0.6	4.2
Ice	2.2	1.9
Snow	0.1	Variable
Soil Mineral	1.9	1.9
Bedrock	2.0	2.0
Rock Fill	1.8	1.8
Tailings	0.6	0.6
Extruded Insulation	0.035	0.04

To decrease the cover thickness and cost, the following alternatives can be considered.

Groundwater Table at Surface

The thermal parametric study conducted for uranium tailings (Robertson et al. 1986) demonstrated that the optimum level for groundwater to develop permafrost is at the tailings surface. On the other hand, there is a large volume of field data to show that the deepest active zones develop in dry granular material and massive bedrock.

Sand & Gravel Cover

Sand and gravel cover of sufficient thickness will raise the active layer above the tailings but it may not be economical or feasible because of lack of suitable material in the vicinity of the mine. A thickness of about 2.5 to 3 m is required and this would be only viable for small tailings areas. Since common tailings ponds have surface areas of 10 to 50 ha, this would require 250,000 to 1,500,000 m^3 of granular material. At a cost of \$5 to \$10 per m^3 for the cover material, this translates to 6 to 15 million dollars to cover a 50 ha tailings surface. This design is costly and there may not be sufficient quantities of material available within an economic distance.

Saturated Soil Cover

If there is sufficient till overburden beside the tailings impoundment area, it may be feasible to excavate the till (normally silts and sands), cover the tailings and shape the tailings pond to keep the till saturated to the maximum level. Natural sandy till permafrost can be excavated during the summer by progressive stripping and storing it in ridges before moving (Holubec et al. 1982).

Insulation and Sand/Gravel Cover

In areas with a lack of soil or granular fill, the replacement of fill with equivalent insulation can be considered. Insulation has been used extensively in permafrost regions to either prevent the warming of permafrost under buildings or to prevent permafrost degradation under roads and airfield fills. Several types of insulation have been used such as peat and wood chips (McRoberts et al. 1985) in addition to synthetic materials such as polystyrene and urethane foam. Wood chips are readily available below the treeline and are generally less expensive. However, their long-term effectiveness is questionable because of natural decay. Therefore they should be only considered for short-term solutions.

Extruded polystyrene board insulation (Styrofoam) has been used extensively in insulated road embankments (Olson 1984, Esch 1990). It has a low thermal conductivity and has proven to be stable in the long-term. Styrofoam should not be confused with expanded polystyrene bead board which has poor qualities in moist environments and has not been proven over long-term periods. Sulphur and urethane foams have not yet demonstrated long-term stability and insulation retention.

An approximate rule of thumb is that 25 mm of extruded insulation is equivalent to about 300 mm of sand/gravel. Therefore a 3000 mm granular cover could be replaced with 200 mm of insulation covered with 600 mm sand/gravel.

Convective Rock Cover

Archaeologists have found ancient human bodies that were preserved in rock cairns acting as a natural refrigerator (Rudenko 1970 and Artamonov 1965, reported by Robertson et al. 1982). The rock cairns act as convective rock covers during the winter that allow convective air currents to draw the heat out from the ground and as insulating air covers during the summer. Thermal analysis of a convective rock cover for Rabbit Lake (Robertson et al. 1986) showed that the optimum rock cover thickness is 1 m. The analysis showed no effect at all until the 1 m thickness was used and there was no appreciable improvement with thicknesses greater than 1 m. While the convection rock cover sounds as an attractive solution in some instances, there are still many outstanding questions regarding its design (ie rock sizes, zones, thicknesses etc). Therefore at this stage it can be considered only as a concept.

6.4.3 Boreal and Cordillera Regions

These regions have discontinuous permafrost with ground temperatures below the active zone in the range of 0 to -2°C and greater depths of the active zone. The permafrost condition is fragile and therefore it is necessary to enhance (reduce the temperature) of the permafrost, decrease the depth of the active zone and bring the active zone into a cover. The following are some permafrost enhancement methods which can be considered.

Peat Plateaus

Peat plateaus or palsas are naturally occurring permafrost aggradation features observed in discontinuous permafrost areas. They are perennially frozen peat deposits with thick ice lenses at the base of the organics. They occur as islands in unfrozen bogs or as very thick peat deposits on slightly sloping mineral terrain. They are generally flat with a raised surface about 1 m above the surrounding topography and range in area from a few square metres to several kilometres (Johnston 1981). The peat plateaus develop because of the unique heat conductivity of the peat. During the winter period when the peat is frozen it allows heat extraction from the underlying ground while during the summer the moist peat acts as an insulation blanket. Permafrost conditions have been observed under peat plateaus in areas with annual mean daily temperatures as warm as -1°C.

The short growing season in northern Canada makes peat development over tailings a long term proposition. However, it can be anticipated that peat cover may develop eventually in total containment closure designs and this cover will enhance the permafrost condition.

Insulation and Sand/Gravel Cover

It is unlikely that an insulation and sand/gravel cover would be sufficient to develop permafrost conditions in a discontinuous region. Insulation decreases the rate of heat exchange but does not change the long term thermal condition. Thus a heat extraction system has to be used in conjunction with insulation to enhance permafrost development.

Natural Convection Devices

Natural convection devices remove heat from the natural ground by natural means requiring no power to operate and have no moving parts. There are three basic convection devices divided into closed and open devices (Heuer et al. 1985). The devices illustrated on Figure 27 are: "thermosyphon" being a closed, two-phase device;

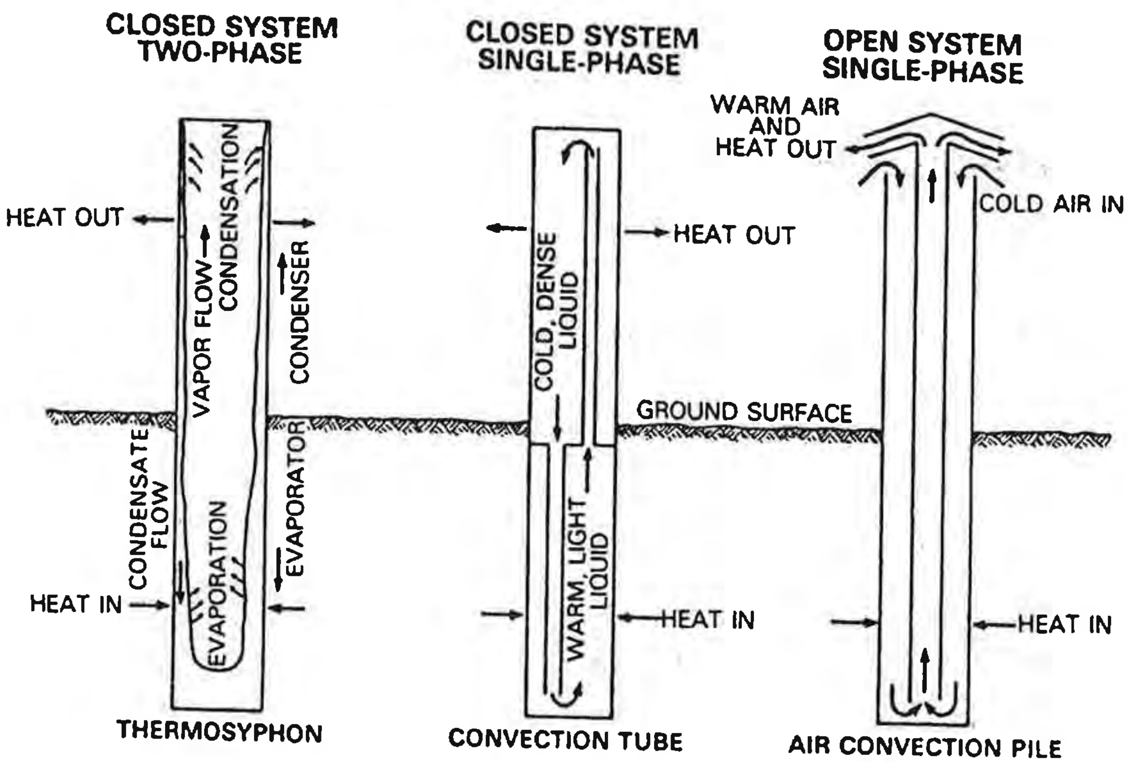


Figure 27 **Natural Convection Devices (Heuer et el. 1985)**

"convection tube" being a closed, single-phase device; and "air convection pile" being an open device.

The operation of all these devices is similar. Along the buried lower section of the device, heat transfer from the soil to the device occurs, warms the working fluid, decreases its density and causes it to rise. Along the upper section of the device, heat transfers from the device to the atmosphere occurs, cools the working fluid, increases its density, and causes it to sink. This cycle continues as long as the air temperature is colder then the soil temperature near the bottom of the device, ie. during the winter.

Thermosyphons are the most effective heat transfer devices of the three types because in this device the latent heat of vaporization is much greater than the heat capacity times the typical temperature difference of the other two devices. Thermosyphons consist of a sealed tube partially filled typically with propane, carbon dioxide or ammonia and are provided with a fin device at the surface to dissipate the heat (Zarling and Haynes 1985). The choice of the fluid effects the type of material used to construct the tube because of different working pressures and corrosiveness of the fluid. During the summer months carbon dioxide can create pressures over 500 psi while ammonia's working pressure is near 60 psi. The advantage of ammonia's lower working pressure is lost due to its greater corrosiveness.

Thermosyphons are usually selected over convection tubes and air convection piles because of superior heat transfer capability, greater flexibility in fabrication, easier maintenance and repair and lower costs (Heuer et al 1985). The most frequently used fluids used are carbon dioxide and ammonia.

The thermosyphons operate only during the winter time and some of the heat removed during this time is lost during the summer warming period. To improve the efficiency of the thermosyphons, insulation is placed near the ground surface to decrease warming during the summer.

Thermosyphons were first used by the Corps of Engineers to maintain permafrost around communications towers in Alaska (Richardson 1979). The benefits of the thermosyphons was subsequently demonstrated during the construction of the Trans Alaska pipeline where over 120,000 thermosyphons were used to support the above ground pipeline on piles (Heuer 1979).

7.0 PERMAFROST TO PREVENT ACID TAILINGS DRAINAGE

7.1 General

Studies of tailings impoundments have shown that acid generation begins at the surface and moves down with time. In tailings, the sulphide oxidation decreases with depth due to the low oxygen diffusivity of tailings and therefore the acid front advance decreases nearly exponentially with depth. In fine tailings, the depth at which acid generation practically stops is in the order of 3 to 4 m which is similar to the thickness of the active layer in 'dry' granular materials. The acid water from the surface zone either seeps downwards where it may be neutralized by the underlying tailings or flows laterally towards the perimeter of the tailings impoundment.

The concentration of acid generation at the surface layer coincides with the permafrost active zone in the continuous permafrost region or the depth of the freezing/thawing in the discontinuous permafrost region. Therefore if the tailings surface of about 3 to 4 m can be frozen, acid generation would be eliminated as a concern.

Previous discussions have shown that about a 3 m thick granular material cover may be required to raise the base of the active layer above the tailings surface. Since tailings impoundments have an area in the order of 10 to 100 ha, the provision of a granular cover to keep the tailings permanently frozen is very costly. Therefore it is necessary to look at alternatives to minimize the closure costs. The selection of a tailings impoundment and cover design is a site specific design that depends on the climate and the availability of cover fill materials. It is preferable to have several design options available from which one or a combination of designs can be selected for the closure design of a particular tailings impoundment. The following is a discussion of possible cover designs developed from the information presented in this report.

The cover design for a mine is site specific governed by the local climate and the availability of construction materials. In any design, be it conceptual or final design, a comparison of costs of different covers is essential. For this study unit construction rates assumed for a comparison of potential covers are given in Table 9. It should be noted that the unit construction rates in remote areas vary greatly and are governed by the accessibility of the site, the mine's construction costs and the proximity of the construction material to the tailings impoundment. These rates would be greatly different if the mine constructs the covers during the mine operation with equipment that is also used in other operations or by an outside contractor hired when the mine closes.

Table 9 Assumed Material Unit Rates for Comparison of Cover Designs

Material	Unit Cost, $
Sandy Gravel	8.00 m^3
Pit Run Mine Rock	5.00 m^3
Processed Mine Rock	8.00 m^3
25 mm Polystyrene (Styrofoam Board)	4.00 m^2

7.2 Arctic Region

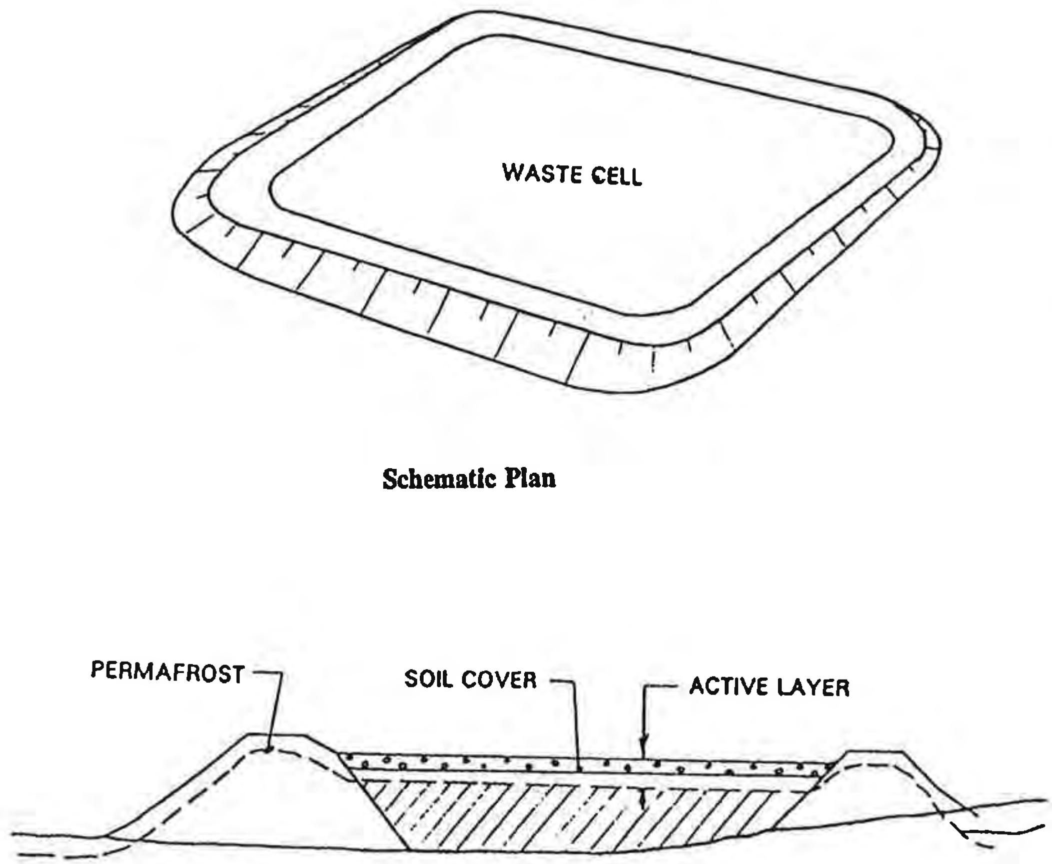
Mines located in the arctic region will freeze the tailings and keep the main tailings mass frozen. The main concern are the tailings in the active zone. Tailings without any cover will thaw annually to about 2.5 m. The active zone depth is similar for any granular material (eg. tailings, silty sand, gravel or mine rock). Some reduction of the active zone can be obtained by keeping the tailings and granular cover material saturated. The most effective method of reducing the active zone is by developing muskeg over the tailings. However, the natural development of muskeg over a short time period of several tens of years is impossible in the arctic. A design with saturated surface conditions will develop muskeg with time (more than 100 years) and will improve the closure conditions of the tailings impoundment.

One typical approach for development of new impoundments is to minimize the tailings surface area because of the large cover costs and construction of tailings impoundments in cells to permit the progressive reclamation of the tailings surface during mine operation. For the present study a tailings cell of 10 ha was assumed. This cell is square in area and two sides were assumed to be adjacent to either, other cell dykes or high ground. The typical cell and the permafrost regime is shown on Figure 28.

The closure design of a tailings cell in the arctic region can take two approaches. One is to provide a thick cover over the tailings so that the tailings mass will remain frozen throughout the year and the second is to develop total containment by means of a frozen dyked perimeter and provide wind protection cover on the tailings surface.

Thick Cover Option

This option prevents acid generation by keeping the tailings mass permanently frozen throughout the year. Figure 29 and Table 10 illustrate four potential cover designs and provide estimate costs based on a 10 ha area and the material unit rates as given in Table 9.



Schematic Plan

Schematic Section

Figure 28 Tailings Cell Disposal using Dyke Containment Scheme

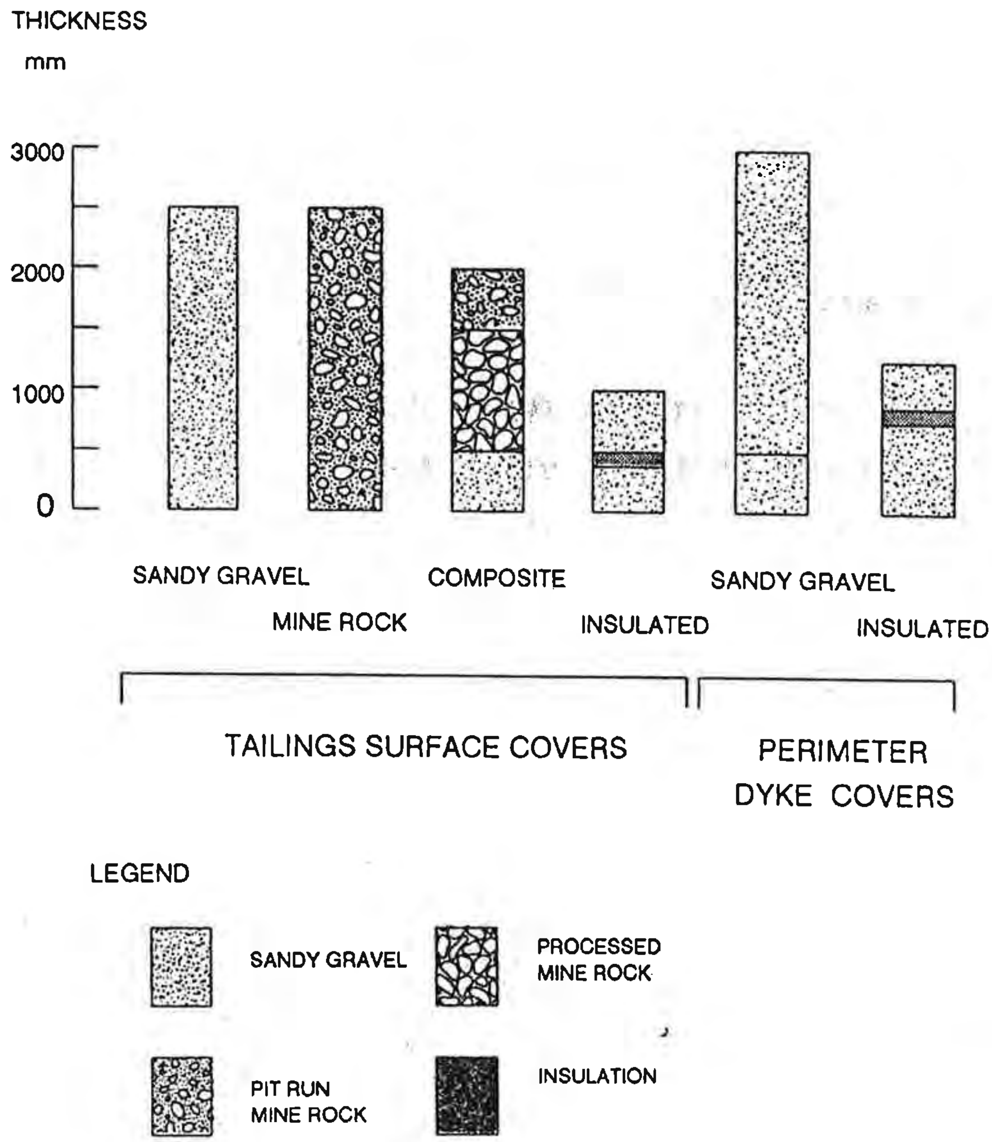


Figure 29 **Perimeter Dyke Cover Options For Arctic Permafrost Region**

Table 10 Cost Comparison of Potential Cover Designs for Arctic Region Based on 10 ha Site

COVER DESIGN	DESCRIPTION		COST,
	Material	Thickness, mm	$
SURFACE COVER			
Sandy Gravel	Sandy Gravel	2500	2,000,000
Pit Run Mine Rock	Mine Rock	2500	1,250,000
Composite	Sandy gravel Processed MR Sandy gravel	500 1000 500	1,600,000
Insulation	Sandy gravel Insulation Sandy gravel	500 150 500	3,200,000
FROZEN PERIMETER DYKE			
Sandy Gravel	Sandy gravel	3000	690,000
Insulated	Sandy gravel Insulation Sandy gravel	500 150 700	710,000

The sandy gravel cover option assumes that there is sufficient esker material within a reasonable distance (eg. 3 to 5 km). This may not be the case since the mine may have used up all the nearby sandy gravel for road, airstrip and mill construction. In this case, the sandy gravel could be substituted with sandy till if sufficient quantities are available nearby. Sandy till has been successfully used at the Lupin Mine (Holubec 1982) for dam construction. The total cost for a 2500 mm sandy gravel cover is estimated at $2,000,000 for a 10 ha site.

If the mine is an open pit and the country rock is non-acid generating, pit run mine rock could be used for the cover. It is believed that the thickness of the active layer in the waste rock will be similar to the sandy gravel since the lower moisture content of the mine rock will be compensated for by its propensity to act as an air convective rock cover. A 2500 mm pit run mine rock cover thickness was assumed. Because this material has to be disposed of anyway, a lower unit rate used for esker material, was assigned, which reduces the cover cost to $ 1,250,000.

A composite cover of sandy gravel and processed mine rock may be applicable where limited volume of sandy gravel but sufficient non-acid generating mine rock are available. The composite cover would represent an air convective rock cover design. During the summer, when the surface temperature is high, the warm air in the voids would be trapped at the surface and convective heat transfer would be low and act as an insulating cover. However, during the winter when air temperature is cold it would sink to the base of the rock where it could be warmed up by the underlying sandy gravel and tailings and rise to the surface (Robertson et al 1986). In this case the processed mine rock consists of uniform sized material which leads to higher unit cost. The reduction of mine rock thickness does not compensate for the higher unit rate leading to a more costly cover. The cost of this cover is estimated to be $ 1,600,000.

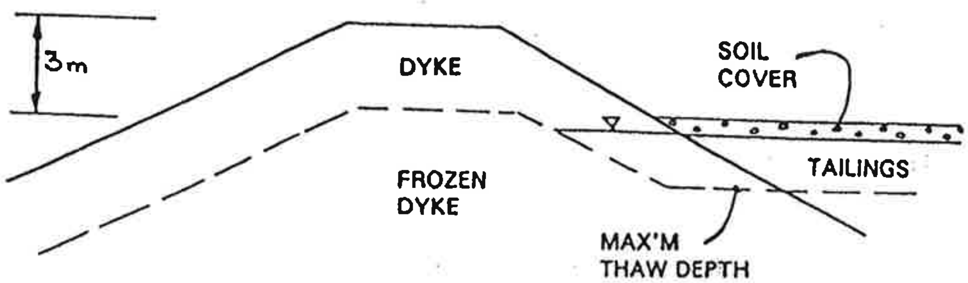
For comparison purposes a granular cover with insulation was costed. The unit cost of the insulation is based on the assumption that road access to the mine is available and that the transportation cost represents an additional 50% of the F.O.B. cost. The total cost for 10 ha tailings surface covered with a 300 mm sandy gravel bedding, 150 mm polystyrene insulation and 500 mm sandy gravel cover is $3,200,000. A cover based on insulation over the whole tailings surface is obviously the most expensive cover.

Total Containment Option

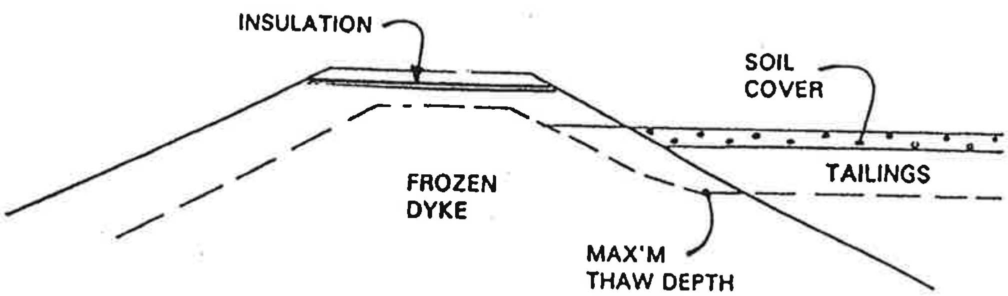
Since most of the Canadian permafrost regions have lower precipitation than potential evapotranspiration, a permanent tailings impoundment containment may be a viable closure design option. This design would involve the construction of frozen containment dykes and covering the tailings surface with a sandy gravel for wind erosion. This design could be applicable at three of the four mines studied, namely, Lupin, Giant and Faro mines (Table 7).

This design option consists of having an impervious perimeter dyke around the acid generating tailings to contain normal and extreme snowmelts and precipitation events. The selection of the elevation of the surface of the impervious layer is a function of hydrologic criteria and the precipitation evapotranspiration balance discussed earlier.

The impervious dyke can be obtained by using an impermeable clay zone, an impermeable liner, frozen core or a combination of the first three options. In the case of the impervious frozen zone, the depth of the active layer, if silty or sandy, of construction material used, has to be considered. In the design shown on Figure 30a, it was assumed that the active layer depth is 3 m and a freeboard of 1 m is required above the tailings surface. In Figure 30b the dyke height and material quantities were reduced by incorporating insulation below the dam crest.



a) Raised Dyke Crest with Sandy Gravel



b) Raised Dyke Crest with Insulation

Figure 30 Tailings Surface and Dyke Crest Cover Options

The costs for the above two design options were estimated and are given in Table 10. The raising of the dyke crest by an additional 3 m is shown on Figure 30a along with placing a 500 mm cover over the tailings represents a total cost of $690,000. This is the cheapest closure option being about 35% of the sandy cover cost and 65% of the pit run mine rock cover. The alternate design, with the insulation, yields about the same cost of $710,000.

7.3 Boreal and Cordillera Regions

It is unlikely that the total tailings mass can be kept completely frozen in the Boreal and Cordillera regions. A thick composite convective rock cover may be possible and could be considered where applicable. In this study it is assumed that the containment of the tailings mass with a frozen wall under the perimeter dykes is the most applicable design. Two options considered to be applicable in developing and maintaining a frozen wall consist of an insulated dyke with thermosyphons and a composite section with a rock convective core.

The insulated dyke with a thermosyphon design has a good chance of success since both components have been successfully used and are well documented with case histories. Polystyrene insulation boards have been extensively used in road and airstrip construction in Alaska and Canada (Esh 1988, Olson 1984, and Johnston 1983). Thermosyphons had a major application on the Trans Alaska oil pipeline where some 120,000 were used in 1975 (Heuer 1979). Since that time they have been used in Alaska and Canada for stabilizing roadways and for guarding against building settlement by preventing thawing of the foundation permafrost. In Canada there are two manufacturers of thermosyphons, Mobile Augers and Research, in Edmonton, and Arctic Foundation in Winnipeg. The first manufacturer uses ammonia while the other manufacturer uses carbon dioxide.

The thermosyphons were initially used in a vertical configuration. However, to provide a more efficient method of cooling beneath road subgrades and buildings founded on horizontal insulation, near horizontal thermosyphons were developed (Zarling and Haynes 1985). For this report both vertical and horizontal thermosyphons were considered to obtain a cost comparison given on Table 11. The vertical thermosyphons at 4 m spacing were used under 10 m wide dyke crest underlain by 50 mm polystyrene insulation (Figure 31 & 32). The total cost of the perimeter dyke bounding two sides of a square shaped 10 ha tailings pond and including a 500 mm sandy gravel cover over the whole tailings pond is $870,000.

Table 11 Cost Comparison of Potential Cover Designs for Boreal and Cordillera Regions Based on 10 ha Area

COVER DESIGN	DESCRIPTION	COST, $
Insulated Perimeter Dyke, 10 m crest and vertical single line of thermosyphons	Sandy gravel 700 mm Insulation 50 mm Sandy Gravel 500 mm Thermosyphons @ 4 m	870,000
Insulated Perimeter Dyke, 3 m crest and horizontal double line of thermoprobes	Sandy gravel 750 mm Insulation 100 mm Sandy gravel 750 mm Thermoprobes @ 66 m	700,000
Composite Rock Convection Cover	Sandy Gravel 500 mm Processed MR 2000 mm Sandy Gravel 1000 mm	900,000

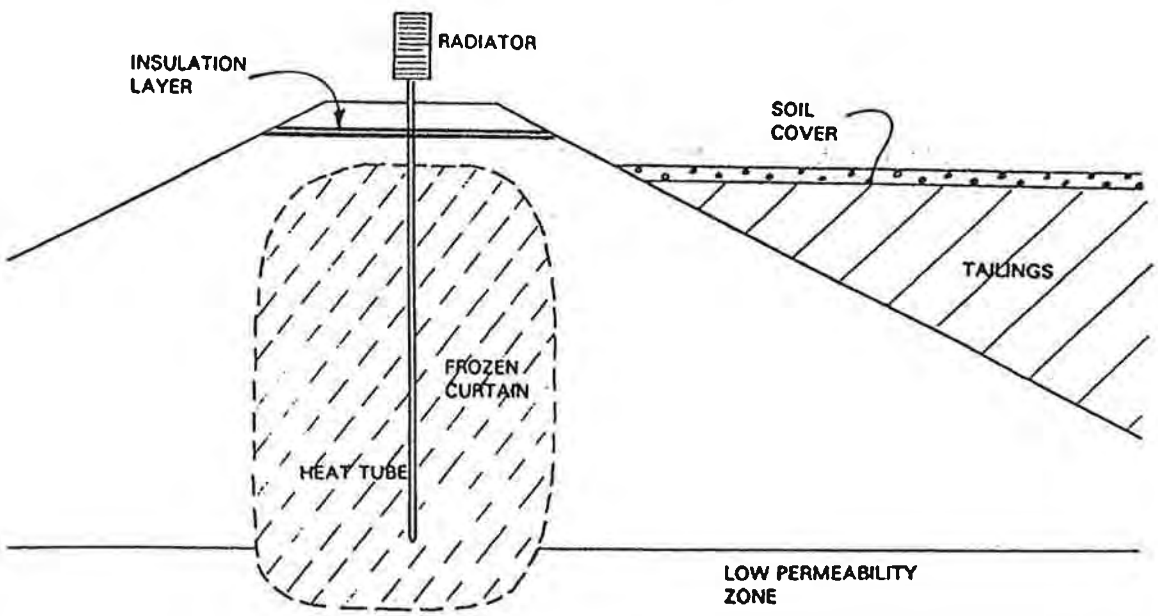


Figure 31 Perimeter Dyke with Insulation and Thermosyphons

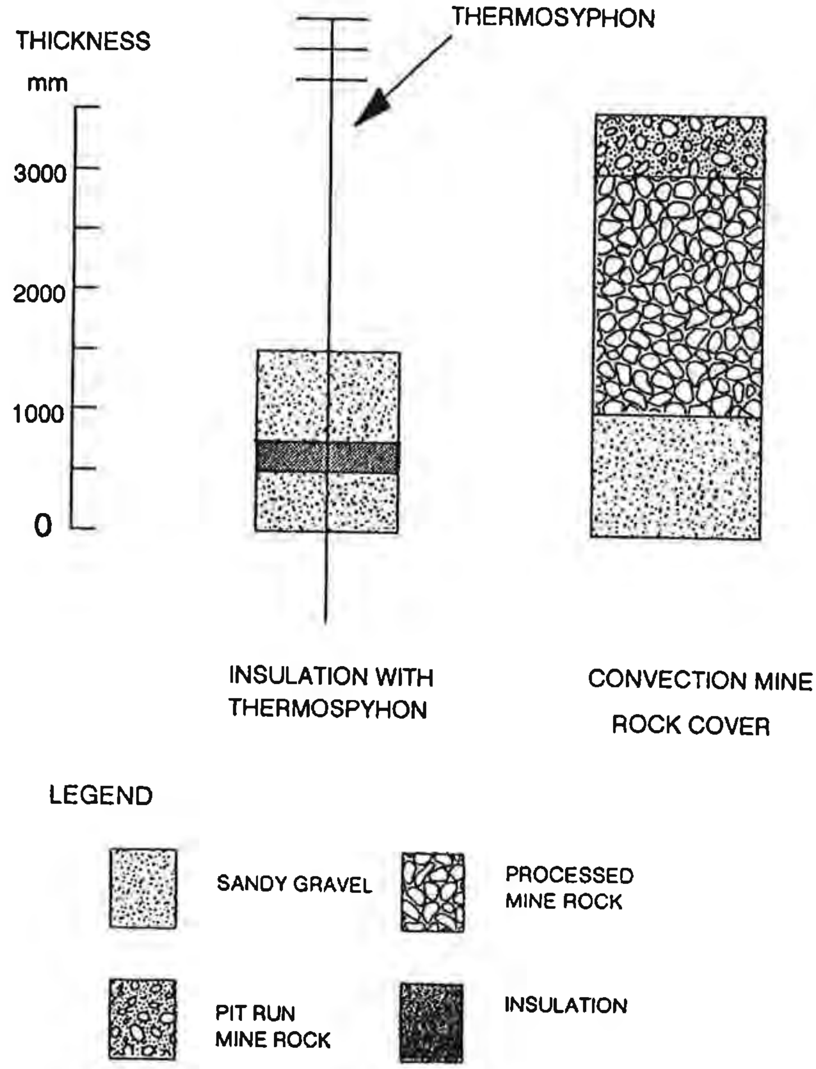


Figure 32 **Perimeter Dyke Cover Options For Boreal and Cordillera Permafrost Regions**

An alternative thermosyphon design involves the placement of two lines of thermosyphons horizontally below the dam crest edges. Designs with two insulation thickness were estimated by Arctic Foundations of Canada Inc. The designs show that dyke crest underlain by 50 mm thick insulation requires thermosyphons spaced at 30 m. Increasing the insulation to 100 mm increases the thermosyphon spacing to 66 m that results in some saving in the cost of thermosophons. The design with 100 mm insulation, shown on Figure 33, and including a 500 mm sandy gravel cover is estimated to cost $ 700,000. The lower cost of the horizonatally placed thermosyphons is the result of lower installation cost of the horizontal thermosyphons and fewer radiators. Finally the cost of a composite rock convection cover with a 10 m wide crest was made (Figure 33) and a cost estimate is given in Table 11. The cost of $900,000 is not that much greater than the thermosyphons with insulation treatment. Eventhough this latter design is appealing becasue of its simplicity, it is a distant choice because of unproven technology.

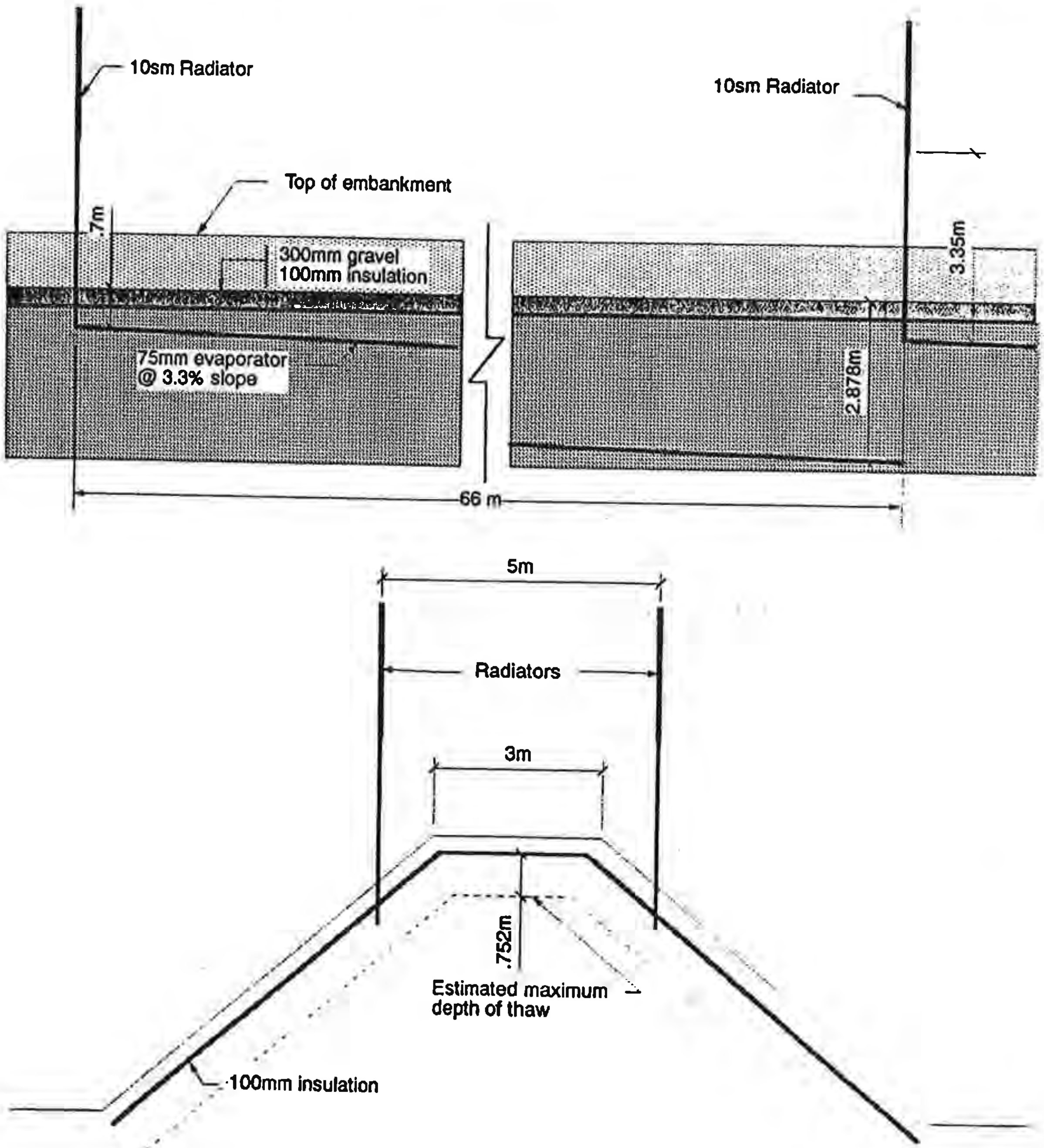


Figure 33 **Example of Horizontal Thermosyphon Design to Develop Permafrost in Discontinuous Permafrost Regions**
(Arctic Foundation of Canada Inc. 1993)

8.0 CONCLUSIONS

Permafrost regions differ from Canadian southern regions in that the ground below a surface layer remains perennially frozen. This layer, active zone, undergoes annual temperature changes throughout the year and thaws during the summer to depths ranging from 0.5 under thick organic mat to 10 m in exposed rock. The active zone also coincides with greatest rate of sulphide oxidation that generates acid drainage in tailings. An understanding and control of the active layer is key to using permafrost to prevent acid generation in tailings.

Available information shows that there is a large decrease of chemical and biological rates of oxidation as the tailings temperature approaches zero degrees Celsius. Little is known about what happens at and below zero degrees. It is surmised that the oxidation rate decreases rapidly below zero degrees Celsius because of a decrease of unfrozen water and the remaining unfrozen water being surrounded by ice.

In continuous permafrost, Arctic Permafrost Region, a 2.5 to 3 m thick cover has to be placed over the tailings to keep the tailings permanently frozen. Some reduction of the cover thickness can be obtained by keeping the cover saturated. There are indications that coarse mine rock may decrease the cover thickness. Coarse mine rock may remove a greater quantity of heat from the tailings, by convection during the winter, and reduce the depth of thawing during the summer, through the insulation of the trapped air, than a sandy/gravel cover.

An alternate solution to acid drainage from tailings in the arctic permafrost region is to provide total containment by enclosing the tailings with a frozen core perimeter dyke. The tailings surface still has to be covered with a wind erosion blanket. Total water containment is feasible in many northern areas because of excess annual potential evapotranspiration compared to the annual precipitation. This alternative provides considerable savings over a thick cover option.

It is difficult, if not impossible, to develop permafrost in the discontinuous permafrost regions (Boreal and Cordilleran permafrost regions). The most likely solution is to provide complete containment by developing a frozen core dyke around the tailings mass. Technology and experience is available to create permafrost in discontinuous permafrost regions by artificial means using a combination of insulation and thermosyphons. This design is too costly to cover the whole tailings area but may be justified for creation of an impermeable cut-off wall around the tailings pond perimeter. There may be a natural method to create a frozen zone by an air convection rock cover over the dyke crest. However, there is only limited theoretical work and only one known case history to support this concept. This design should be pursued because of its simplicity.

9.0 RECOMMENDATIONS FOR FUTURE WORK

Future work should continue in three areas: increase understanding and develop prediction methods for sulphide oxidation at and below zero degrees Celsius; conduct thermal analysis of covers to improve the estimated thicknesses used in this report and construct two field test installations, one in the Arctic region and one representing both the Boreal and Cordilleran regions, to monitor temperature changes required to confirm the designs. These areas are discussed below.

Heat generation at and immediately below zero degrees is poorly understood at this time. To improve data base and predictive methods for the permafrost regions, the following is recommended:

1) Laboratory measurements of heat generation due to sulphide oxidation and associated reactions at low temperatures should be made in both saturated and unsaturated conditions to determine the magnitude and variability. This is to determine at what temperature below 0°C sulphide oxidation stops.

2) Measurements of thermal capacity and thermal conductivity of tailings should be made to determine if significant variation exists within a mine site and among the mine sites located in permafrost areas. This is to establish the variation and obtain specific values for coarse tailings located at the beaches and fine tailings deposited in water and determine if there is variation between tailings obtained from base metal mines and gold mines.

3) A simplified computer program should be constructed to simulate Figure 11 in order to determine if laboratory and field observations correspond

to existing theory. If so, existing theory can then be used to extrapolate data to various environmental conditions and to predict the effects of various disposal scenarios. If not, existing theory should be revised. This approach should eventually lead to an integrated model for permafrost migration and internal heat generation, perhaps revising an existing program for permafrost migration.

The cover thicknesses used in this report are based on field measurements at Lupin Mine. It is recommended that thermal analysis be conducted to develop a model match with the Lupin data and then use this model to refine the cover designs used in section 7.0 in this report. This computer model could then be used to extend this information to other materials, degree of saturation, designs using insulation and locations.

Field installation of the recommended options to prevent acid generation using permafrost should be considered in continuous and discontinuous permafrost regions. The design options can be monitored along a perimeter dyke using the cover options illustrated on Figures 30 and 34. For the continuous permafrost the following designs should be constructed and monitored:

- Sandy Gravel
- Unsorted mine rock
- Composite cover containing mine rock without sand and silt sizes
- Sandy gravel with insulation layer.

For the discontinuous permafrost the following design should be constructed and monitored:

- Horizontal thermosyphons with surface insulation
- Convective mine rock cover.

The most likely location for the continuous permafrost field installation is the Lupin Mine because of the availability of a comprehensive temperature data bank, and because the existing tailings facilities can be readily modified for the field installation. The discontinuous permafrost installation could be constructed either at the Faro Mine in Yukon Territory or one of the two large mines in Yellowknife, i.e. Giant Mine or Nerco Con Mine.

It is recommended that the field installation involve one complete tailings pond cell that can encompass all the different tailings surface cover and dyke crest designs discussed in this report. The cell should be designed so that it represents total containment where the water level fluctuations and water quality can be monitored. Each cover design shall contain at least one thermistor string to a minimum depth of 15 m. The temperatures will have to be monitored on a bimonthly basis for a period of two to three years. During winter the location of snow will have to be described, and its thickness and density recorded. During the summer, the extent of ponded water and the water quality within the cell shall be monitored.

10.0 ACKNOWLEDGEMENTS

The material presented in this report is based on a review of literature of relevant subjects and the authors' experience with acidic drainage and permafrost. It was written by Drs. Kevin Morin, P. Geo. and Igor Holubec, P. Eng.

Respectfully Submitted
GEOCON

Igor Holubec, Ph.D., P.Eng.
Vice President, Special Projects

IH:dtj

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