ACID MINE DRAINAGE IN PERMAFROST REGIONS: ISSUES, CONTROL STRATEGIES AND RESEARCH REQUIREMENTS

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ACID MINE DRAINAGE IN PERMAFROST REGIONS: ISSUES, CONTROL STRATEGIES AND RESEARCH REQUIREMENTS

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EXECUTIVE SUMMARY

This report provides perspectives on issues, strategies, and research requirements for disposing of potentially acid generating mine tailings and mine waste rock in a permafrost environment. It is important to distinguish between the continuous and the discontinuous permafrost environment. Within the discontinuous region the warm permafrost conditions are very susceptible to thaw degradation.

Acid generation within mine tailings has been noted at two minesites in Canada’s permafrost regions. Acidic seepage and runoff have also been documented in the natural permafrost environment. Cold temperature leach column testing shows that acid generation is slowed down but not necessarily reduced to negligible levels at temperatures approaching freezing.

Processes related to acidic drainage in cold climates have been reviewed. Important processes that require further study include the influence of sulphide minerals and process chemicals on unfrozen water content, thaw degradation due to oxidation, reaction rates at low temperatures, and frozen hydraulic conductivity of saturated and unsaturated mine waste materials.

Control strategies that take advantage of permafrost conditions include freeze control and climate control. Freeze control of tailings would appear to be a viable strategy however there is a need for more cost effective insulating cover designs and a more thorough understanding of frozen tailings thermal properties. There is potential for using the beneficial permafrost climate for achieving modest engineering control strategies in waste rock dumps using zoning of different material types.

Implementation of reliable and economic AMD control strategies are impeded by a lack of understanding of important cold weather processes and demonstrated performance. A program for researching freeze control of mine tailings is scoped out. Development of freeze control and climate control strategies for mine waste rock requires a much better understanding of mass transfer and geochemical processes acting within waste rock dumps. A fairly substantial effort will be required to achieve this level of knowledge. A general program of research in this area should be considered.

SOMMAIRE

Ce rapport éclaire certains aspects des questions, des stratégies et des besoins en matière de recherche liés à l'entreposage des résidus miniers et des stériles potentiellement acidogènes dans un environnement pergélisolé. Il est important de distinguer entre le pergélisol continu et discontinu. Dans la région de pergélisol discontinu, le pergélisol est très sensible aux processus liés au dégel.

L'acidification des effluents dans les résidus miniers a été observée à deux sites situés en région pergélisolée au Canada. Le suintement infiltration et le ruissellement des effluents acides ont également été documentés dans le pergélisol naturel. Les essais en colonne de lixiviation sous température froide montrent que l'acidification est ralentie mais pas nécessairement réduite à des concentrations négligeables lorsque la température est proche du point de congélation.

Les processus liés au drainage acide dans les climats froids ont été étudiés. Les processus importants qui nécessitent une étude approfondie sont notamment l'influence des minéraux sulfurés et les processus chimiques sur la teneur en eau non gelée, l'altération due à un dégel par oxydation, les vitesses de réaction aux basses températures et la conductivité hydraulique gelée des déchets miniers saturés et non saturés.

Parmi les stratégies contre le drainage acide dans les zones pergélisolées, mentionnons le gel et le. climat. Le gel des résidus pourrait être une stratégie viable; cependant, il faudrait créer des couvertures isolantes plus rentables et mieux comprendre les propriétés thermiques des résidus gelés. I1 est possible d'utiliser les avantages qu'offre le climat des régions pergélisolées pour élaborer de s stratégi es de contrôle pas trop coûteuses dans les halde s de stéri les par la répartition de différents types de matériaux.

L'implantation de stratégies fiables et économiques contre le DMA est freinée par un manque de compréhension des principaux processus qui ont cours en climat froid et par le fait que leur rendement n'a pas été démontré. Un programme de recherche sur le contrôle par le gel des résidus a été mis sur pied. L'élaboration de stratégies de lutte par le gel et le climat contre le DMA dans les stérile s exige une connai s sance accrue de s proces sus de transiert de masse et de s processus géochimiques agissant dans les haldes de stériles. I1 faudra entreprendre des travaux d'envergure pour acquérir ces connaissances. Un programme général de recherche devrait donc étre envisagé dans ce domaine.

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1.0 INTRODUCTION

1.1 OBJECTIVES

Acid mine drainage (AMD) is recognized as one of the most important environmental issues affecting the mining industry today. AMD generally refers to acidic runoff and seepage water contaminated by heavy metals. In a mining setting, the acidity originates due to the chemical reaction of water, oxygen, and sulphide minerals contained in mine waste rock, processed tailings, and exposed rock surfaces in open pits and underground openings. Acidic drainage has also been observed in the natural environment.

The purpose of this report is to examine the current understanding of AMD in a permafrost mining environment and to discuss conceptual aspects of engineered control strategies that take advantage of frozen ground conditions and cold temperatures. This report has four objectives;

1. To summarize circumpolar experience with acid rock drainage in permafrost regions, both at minesites and in the natural environment;

2. Investigate the effect of temperature and ground freezing on processes controlling AMD potential;

3. Develop conceptual engineered AMD control strategies that rely on permanently frozen ground conditions and sub-freezing temperatures; and

4. Design a generic field and laboratory program of research for AMD control of tailings in a permafrost environment. Make recommendations for further research.

Each of these issues has been addressed as a separate chapter in this report with Chapters 2 to 5 corresponding to points 1 to 4 above respectively.

This project has been carried out under the auspices of the Mine Environment Neutral Drainage (MEND) program.

1.2 INFORMATION SOURCES

The scope of the work presented here has been to include information that applies to acid mine drainage in a cold climate, particularly where permafrost conditions exist. Thus the emphasis was on experience, processes, and strategies unique to cold temperatures and frozen ground conditions. The work here has mostly been compiled from three sources:

1. Literature Review - A computer database literature review was carried out in order to derive suitable references related to acid mine drainage, permafrost regions, and mine waste management. The databases used for the searches included DIALOG, CANOLE, US EPA catalogue, and POL/TOX. Relevant technical papers and articles were acquired and

incorporated where appropriate into the study. In addition to this computer data-base search, information was gathered from the University of British Columbia library and the Boreal Institute library at the University of Alberta.

The Boreal library carries the publications from the US Army Cold Regions Research Engineering Laboratory (CRREL) and translated information from the Russian literature. This was mostly used to summarize information on frozen dam construction from the Russian literature. This summary is contained as an appendix and relevant information drawn from this work is incorporated as necessary into the main body of the report.

There was very little English language information related specifically to acid mine drainage and mining originating from Russia or Scandinavia. Publications in the native languages of these countries should be reviewed if additional information is desired from these countries.

2. MEND studies - A number of reports prepared under the Mine Environment Neutral Drainage (MEND) program were reviewed and relevant material was reviewed and incorporated mostly as background material for this report. Of particular related interest is a recent publication entitled “Preventing AMD by Disposing of Reactive tailings in Permafrost” (MEND 6.1, 1993) and a set of reports by the Canadian Department of Indian Affairs and Northern Development (DIAND) entitled the Northern Mine Environment Neutral Drainage studies (NMEND#’s 1,2,3,4, and 5) published as a series on northern issues related to AMD.

3. Minesite Communication - A number of Canadian northern minesites were contacted by telephone in order to acquire site specific information that might be incorporated in the report. Some useful information was acquired and has been included in the report where appropriate.

In addition to the above sources of information some of the ARD control concepts were developed based on the primary author’s doctoral dissertation (Dawson,1994).

1.3 BACKGROUND

1.3.1 Canada’s Permafrost Regions

Permafrost regions comprise 20% of the world’s landmass. In North America, permafrost is defined as soil or rock having temperatures below 0°C over at least two consecutive winters and the intervening summer. Interestingly, this definition does not necessarily include the requirement that the ground be frozen.

In Canada, 50% of the land is underlain by permafrost. Canada's permafrost regions are shown in Figure 1.1. The 0°C average air temperature isotherm lies to the south of the permafrost limit indicating that average air temperatures are colder than average ground temperatures by about 6°C. Figure 1.2 shows some typical average seasonal ground temperature profiles (natural ground conditions) at selected stations in different permafrost regions. These profiles known as trumpet curves, illustrate some important points:

1. Seasonal variations in ground temperature are about 5-15°C in the discontinuous permafrost region and 15-25°C in the continuous region. These variations converge to a constant temperature at depths of 10 to 15 meters below the ground surface. This depth is known as the depth of zero annual amplitude.

2. Near the surface there is a zone of seasonal thawing which is called the active zone. The active zone is very sensitive to local ground conditions. In general, the active zone is less than 1m in the high Arctic and 1 to 5m in the discontinuous permafrost zone.

3. Zero amplitude ground temperatures are very close to 0°C in discontinuous permafrost and vary from about -4 to -12°C within the continuous permafrost region (MEND 6.1, 1993).

The above discussion illustrates that the discontinuous permafrost region is in a relatively sensitive frozen condition with temperatures close to 0°C. Most of the continuous permafrost region, however shows ground temperatures well below 0°C. As a result, opportunities for creating permanently frozen ground conditions in the discontinuous permafrost region are limited. Thus, permanent freezing of mine wastes is feasible mostly in the continuous permafrost regions. Engineering strategies that rely on permanent freezing are discussed in this report.

Within a large portion of Canada's northern permafrost regions, very low precipitation causes an "arctic desert" climate. With the exception of the southern Yukon, average annual precipitation in Canada's permafrost regions ranges from 100 to 450mm per year. Although evaporation potential is low compared to warmer desert climates, most of Canada's permafrost regions have a net water balance (average annual precipitation minus average lake evaporation) of 0 to 200mm per year. Opportunities for using modest engineering strategies that take advantage of the relatively low "net" precipitation coupled with cold temperatures that slow AMD reaction rates are discussed in this report.

1.3.2 Mine Waste Materials and ARD Generation

Mine waste rock consists of unsaturated chunks of rock or overburden transported via truck, dragline, or conveyor to waste dumps (also known as spoil heaps, tips, and overburden piles). Tailings result from the processing of ore and are usually transported to the disposal area by slurry pipeline. These two types of materials have very different hydrogeological, geochemical, and geotechnical characteristics pertinent to AMD potential. Thus control strategies differ significantly between tailings and waste rock materials.

Table 1.1 derived from a document entitled "Guidelines for Acid Drainage Prediction in the North" (NMEND#1, 1993) provides a comparison of some of the different factors affecting tailings versus mine waste rock. The important distinction of interest to this study is the manner in which heat is transferred in tailings versus waste rock piles. In tailings, most of the heat is transferred via conduction in the solid material and the porewater. In waste rock, heat is transferred partially by conduction but also by convection between the pore spaces of the coarser particles. Convection is a significant heat and oxygen transfer process in a waste rock pile.

Published literature values for thermal capacity (specific heat) and thermal conductivity are shown in Table 1.2. The most important factors affecting thermal properties of waste rock, tailings, and other particulate geo-materials are saturation and porosity. For this reason, loose, unsaturated waste rock materials freeze and thaw much more readily than saturated tailings materials.

Table 1.1 Comparison of AMD in Tailings and Mine Rock Piles

PARAMETER	TAILINGS	MINE ROCK
Particle Size	Tailings can be 100 percent finer than 0.2mm.	Pit rock D_{50} size (diameter of the mean particle size determined by weight) is typically greater than 20cm.
Sulphide/Alkali Distribution	Grinding produces fine, comparatively homogeneous tailings in terms of the whole mass.	Distribution dependent on particle size, mineralogical occurrence and pile construction method.
Oxidation Rate	Initiated at the exposed surface layer after deposition of fresh, alkaline tailings slurry ceases (not during operation) and in vertical cracks in sub-aerial deposits.	Oxidation may develop at any place throughout the unsaturated rock mass immediately upon deposition.
Air (Oxygen) Entry	Air enters from surface and through cracks at a rate limited by diffusivity of surface layer and tailings. Ice lenses may restrict the flow of oxygen.	Air can enter from top, sides and along toe and flow freely along conductive flow paths, and also by convection and barometric pumping.
Temperature	Related to the degree of saturation in tailings, with possible localized elevated temperatures.	In an unsaturated rock pile with rapid oxidation, convection can result in elevated temperatures throughout pile.
Seepage Flow Path	The primary flow is surface run-off, with seepage pore-water gradually displaced by ARD.	Preferential seepage flow-paths develop in rock piles with rapid release of drainage (hours to months). Given the heterogeneity of a pile, seeps of varying quality can issue from a single dump.

Table 1-2 Literature Values for Thermal Capacity (Cp) and Thermal Conductivity (K) of Mine Materials

MATERIAL	VALUE	SOURCE
Thermal Capacity (C_p, J Kg^{-1} K^{-1})		
Dry mine rock	867	Harries & Ritchie (1987)
Mine rock with 11.5 wt-% moisture content	1350	Harries & Ritchie (1987)
Non-saturated frozen sand (7.4% water content) from permafrost	784.8	Aziz (1993)
Non-saturated thawed sand (7.4% water content) from permafrost	940.3	Aziz (1993)
Saturated frozen sand from permafrost	928.8	Aziz (1993)
Saturated thawed sand from permafrost	1378.8	Aziz (1993)
Thermal Conductivity (K, J M^{-1} S^{-1} K^{-1})		
Various soils in literature (0.02-0.20 wt-% moisture content)	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)
Non-saturated frozen sand (7.4% water content) from permafrost	1.56	Aziz (1993)
Non-saturated thawed sand (7.4% water content) from permafrost	1.73	Aziz (1993)
Saturated frozen sand from permafrost	3.40	Aziz (1993)
Saturated thawed sand from permafrost	1.98	Aziz (1993)

2.0 ACID MINE DRAINAGE IN PERMAFROST REGIONS

2.1 INTRODUCTION

The climatic conditions in northern regions offer several unique opportunities and constraints for acidic mine drainage (AMD) management. A recent document on northern issues related to AMD management (NMEND# 4, 1994) states:

- snow and ice cover provide a permeability barrier for oxygen diffusion, thereby limiting the rate of sulphide oxidation;
- bacteria responsible for catalysing sulphide oxidation reactions and accelerating the release of acidity have lower activity at temperatures below 5°C;
- cryogenic processes are enhanced under extremely low temperatures, controlling oxygen diffusion and progression of AMD;
- permafrost encapsulation is a promising method for controlling AMD;
- high precipitation events prevailing during seasonal snowmelt periods can have detrimental effects on receiving environments by flushing accumulated oxidation products from rock surfaces, although offset by dilution effects; and
- low temperature conditions slow both geochemical and biochemical oxidation processes associated with sulphide minerals.

These points indicate that, on the whole, there would appear to be less potential for AMD in a Northern environment than elsewhere. Nonetheless, as shown in Figure 2.1, AMD has been documented (mostly in tailings) at several minesites in Canada's northern regions. This chapter discusses field occurrences and laboratory experiences with cold weather AMD production in tailings, in waste rock, and in the natural environment.

2.2 TAILINGS

In theYukon and Northwest Territories, two recently completed studies (NMEND #'s 2 and 3) have been carried out that provide useful site information on AMD potential (measured from static acid/base accounting tests) and mine drainage water quality. A brief summary of the surveys that were carried out for these reports is as follows:

1. The results of acid/base accounting (ABA) testing showed that significant quantities of excess potential acidity were present at 15 sites (a total of 27 sites were reviewed). Sulphur contents at these sites ranged from about 1 to over 30%.

2. Acidic drainage waters were noted at 7 sites, 5 of which were abandoned and at two active sites. At the abandoned sites, AMD is mostly being generated from uncontained tailings. At the two active sites, one is generating acid from old uncovered tailings and, at the other, AMD is believed to be limited to the seasonally thawed active zone.

3. Several sites containing waste materials with a net acid generating potential do not seem to be generating AMD although they have been closed for several years. At one of these sites "the tailings pond fills up with several metres of meltwater during spring breakup, but by midsummer, large portions of the tailings surface are exposed." The tailings decant at this site has a pH of about 7.0.

4. Closure plans for at least two sites indicate that reclaimed tailings are to be frozen following close-out as a means to curb AMD production.

The preceding points indicate that a permafrost environment is not a complete deterrent to AMD generation. However, there is some indication that AMD is lessened in this environment. Further information, compiled below, provides further insight into AMD production in mine tailings.

2.2.1 Lupin Mine

The Lupin Mine is located on the west shore of Contwoyto Lake, Northwest Territories, about 400 km northeast of Yellowknife. Production of gold/silver ore began in October 1982 and milling capacity is currently 2200 tonnes/day. The ore is located in metamorphic rock containing up to 15% pyrrhotite, locally 3-4% arsenopyrite, and trace amounts of pyrite, scheelite, and chalcopyrite. Tailings are placed in a surface impoundment contained by frozen dykes. A review of engineering issues associated with the design and construction of these dykes is contained in the appendix.

Leaching of arsenic is considered the major water quality issue in the tailings impoundment (Wilson, 1992). Holubec (1990) reported that tailings remained frozen throughout the year below a depth of 3 m (Figure 2.2), indicating the active layer in the tailings is no more than 3 m thick. Closure planning called for a layer to be placed over the tailings so that the tailings would lie entirely below the active layer.

Kalin (1987) presented one-year leaching tests using 1 kg of pH-neutral tailings with 1 L of tap water. Two sets of containers were stored: in a refrigerator (6-8^{o}C), outside (15^{o}C, but frozen during winter), and at room temperature in darkness (21-23^{o}C). Kalin reported that pH values in the water and tailings solids after one year indicated acidification was occurring in all samples. However, pH fell below 5 only in the room-temperature containers. This led to a conclusion that net acidity would not be generated at low temperatures. Nevertheless, there are now reports that portions of tailings are now generating acidic drainage (Hohnstein, 1993; NMEND #2, 1994). This information shows that acid is being generated in "old" tailings.

2.2.2 Nanisivik Mine

The Nanisivik Mine is located on the northern end of Baffin Island, Northwest Territories. The mine is adjacent to Strathcona Sound, a deep-water fjord. Production of lead/zinc concentrate began in September 1976 (de Ruiter, 1983). Tailings were placed underwater in a tailings impoundment. However, recent reports indicate new tailings are no longer deposited underwater and have the "potential" to generate acidic drainage due to 75-95% pyrite content (NMEND #2, 1994).

Kalin (1987) conducted a water-chemistry survey around the Nanisivik area. Near natural pyrite outcrops, pH levels in creeks at 3^{o}C were as low as 2.6, increasing to above 6 with a short distance from the outcrop. Sulphur concentrations reached nearly 4000 mg/L. These results are consistent with those of Cameron's discussed below.

2.2.3 Polaris Mine

Keen (1992) reported on a water-cover disposal technique at Polaris Mine, a lead-zinc mine on Little Cornwallis Island. Tailings at 2800 tonnes/day are placed in Garrow Lake, a meromictic lake with no vertical circulation. The halocline transition zone extends from 11-20 m depth. Beneath the halocline, the "black" water contains abundant hydrogen sulphide, a salinity three times greater than seawater, and a temperature of 9^{o}C. Above the halocline, the water is brackish with limited aquatic life.

Polaris' operating license required that tailings be discharged subaqueously below a depth of 26 m to prevent metal release to the water above the halocline. With the use of divers, floating pipe, and holes cut in ice, the depth of tailings discharge is controlled and adjusted periodically. Keen (1992) reported that metal levels have been increasing above the halocline.

As a safeguard against unacceptable metal release, Polaris Mine constructed a frozen-core dam to control lake discharge. The dam was constructed during winter months with thin layers of saturated coarse rock. Each layer was allowed to freeze before another layer was placed, and styrofoam and an earth shell were used to maintain frozen conditions.

2.2.4 Izok Project

Klohn Crippen (1994) reported on results of laboratory-based humidity cells used to determine oxidation rates from tailings at the Izok Lake copper-zinc-lead prospect located 360 km northwest of Yellowknife. Cells were operated either under damp conditions inoculated with *Thiobacillus ferrooxidans*, inoculated saturated conditions, or uninoculated saturated conditions. Rates (reported as aqueous concentrations rather than true rates) from all cells varied only within a factor of two and pH remained near neutral. Two additional tailings cells were run under standard conditions and freeze-thaw cycling. The freezing cycle took place over 3 days each week during exposure to -10^{o}C. There was no verification that freezing of the sample occurred and, if it did, whether it thawed during the subsequent 4 days of each cycle. In any case, the freeze-thaw cycle resulted in a stabilized oxidation rate 3.4% that of the standard conditions, based on aqueous concentrations. Leaching rates of copper and zinc in the freeze-thaw cell were 0.5% of the standard cell.

2.2.5 Cullaton Lake Mine

A cold temperature column testing program of tailings from the Cullaton Lake underground gold mine (not currently in production) has been completed. Although the draft report was not available for this study, communication with Bill Napier of Homestake Canada Inc. indicates that "although acid generation continued at the lower temperatures, the rate of acid generation was lowered, and its onset delayed, when the temperatures were lowered from 25 to 2°C."

Tailings at the Cullaton Lake Mine do not currently generate AMD despite their potential to do so (NMEND #2, 1994). Tailings from the B-Zone ore body contain 1% sulphur and net negative neutralization potential values. A short thaw period (4 months), seepage dilution, and high ground water table (tailings are mostly submerged) appear to account for the lack of acidity at this site (NMEND #2, 1994).

2.3 WASTE ROCK

The same studies discussed above (NMEND #'s 2 and 3) also provide information on current experience with AMD generation in waste rock piles in the Yukon and Northwest Territories. Site information from 18 active and abandoned sites show that waste rock at only two sites have potential to generate significant AMD. At one of these sites acidity is currently being generated then neutralized along the seepage pathway. At the other site, AMD generation is anticipated and treatment of seepage water is planned. Both studies note that there is less information available for waste rock than tailings and thus additional assessments are recommended. NMEND #5 (1994) reports on results from laboratory columns used to determine the effect of underwater disposal on acid generation in waste rock. The results from three columns, initially unsaturated and then flooded, showed only a factor of two decrease in rates after flooding. These columns were operated at 31^{o}C under the assumption that every physical, chemical, and biological process would be accelerated by a 52:1 ratio according to the Arrhenius Equation discussed in the next chapter. This may not be a valid scaling factor.

Klohn-Crippen (1994) reported on four laboratory-based humidity cells for Izok waste rock. One cell was exposed to freeze-thaw cycling each week, apparently by lowering the temperature to -10^{o}C for three days weekly. There is no report if the sample froze and, if it did, whether it thawed completely before weekly sampling. All samples remained near neutral pH, but the freeze-thaw cell showed slightly higher rates of oxidation and metal leaching than the other three cells.

For the Windy Craggy Project in northwestern British Columbia, Norecol, Dames and Moore (personal communication, 1995) operated humidity cells of rock for at least one year, maintained under various temperatures. The temperature regimes were ambient (around +20^{o}C), +6^{o}C, and

-20^{o}C. The one sample tested at all three temperatures (Figure 2.3) shows a number of interesting points:

1. Figure 2.3A shows that the rate of pH decrease towards 4.5 slowed with decreasing temperature.

2. The rate of acid generation, as indicated by sulphate production (Figure 2.3B), was highest on average at +6^{o}C, and the rate at -20^{o}C was a factor of 5-10 lower than the rate at +20^{o}C (ambient temperature). The peaks at the ambient temperature and +6° are out of phase by about 3 months presumably due to temperature effects. In contrast to Figure 2.3B, additional cells at only +20 and +6^{o}C showed the rate of sulphate production was lower at +6^{o}C (15-45% of the rate at +20^{o}C) as shown in Table 2.1.

3. The rate of zinc leaching in the Windy Craggy cells generally decreased with decreasing temperature over the three temperatures (Figure 2.3C). However, in a set of four samples at two temperatures (Table 3-1), the rate was higher at lower temperature by 43-110%.

4. Interestingly, the rate of copper leaching was lowest at +6^{o}C and highest at -20^{o}C (Figure 2.3D).

In general, this work highlights some inconsistencies related to cold-temperature effects in AMD laboratory test work. Possible reasons for the inconsistency are examined in Chapter 3. It is notable, however that the subzero results indicate very low AMD production rates.

Asmund (1992) reported on metal leaching from 320,000 t of waste rock in West Greenland. At the zinc-lead-silver Black Angel Mine (Anonymous, 1976), which operated from 1973 to 1990, waste rock was dumped down a slope reaching to a fjord. In the fjord, water below the sill depth of 27 m was already "strongly polluted" with zinc, cadmium, and lead from 8x10^6 t of tailings disposed at the bottom of the fjord. However, the upper 27 m was relatively unpolluted, except for runoff from the exposed waste rock. A decision was made to carry the waste rock out into the fjord and dispose of it with the submerged tailings at 65 m depth. Asmund does not present any pH data, so it is not clear if acidic drainage is involved. Additionally, aqueous concentrations in the seepage are not provided, only loadings such as kg/yr.

Asmund (1992) reported on leaching tests with Black Angel waste rock placed in containers with excess seawater, maintained at 0^{o}C. After an initial shaking, the containers were not disturbed and leaching of metals upwards into the overlying seawater was periodically monitored. Based on this work, the 320,000 t of waste rock was expected to immediately release 4.7 t of accumulated zinc. Afterwards, annual leaching of lead from the submerged rock was expected to decrease with the square root of time, from 48 kg/yr to 3.4 kg/yr after 50 years.

The exposed Black Angel waste rock was pushed downslope to the edge of the fjord in June 1990. The dump was partly frozen and required blasting to move it. The rock was loaded on a barge with 800 t capacity, carried 2 km to the disposal site, and released. Detailed monitoring before, during, and one year after disposal showed good agreement with the aforementioned predictions. For example, the rapid release of accumulated metals included approximately 10 t zinc, 57 kg cadmium, and 1 t lead.

2.4 NATURAL PERMAFROST ENVIRONMENTS

Most field studies located during this review focus on general impacts on vegetation, soil moisture, permafrost thickness, and non-acidic drainage (Wang and Tong, 1993; Klimovsky and Gotovtsev, 1993; Elchaninov, 1988; Jackson, 1989; Wilson, 1992; Norland, 1992; Rassudov et al., 1992; Zemansky et al., 1975; Walker, 1991). Other studies address geotechnical issues (Izakson et al., 1988; Krzewinski et al., 1988; Vakili, 1993). As shown in Sections 2.2 and 2.3, detailed field studies on acid drainage and metal leaching in tailings and waste rock piles have yet to be carried out. Acid drainage is known to occur in the natural permafrost environment and this section reviews some important observations from this work.

Cameron (1977) reported a study of a massive sulphide body, named the Agricola Lake prospect, located approximately 480 km northeast of Yellowknife, Northwest Territories, in continuous permafrost. Apparently, "intensive" sulphide oxidation was occurring near the surface and at depth and, due to the lack of carbonate minerals in the area, had resulted in natural acidic drainage and metal leaching. This oxidation has presumably been occurring since glacial retreat several thousands of years ago. Measurements of moist-soil pH revealed a minimum pH of 2.4 with values between 3 and 4 most common. One spring near the deposit had a pH of 3.4. Away from the deposit, soil pH was typically 5 to 6. The presence of jarosite minerals indicated that pH, at least on a microscale, may be less than 1.6-1.8.

Patterned ground at Agricola Lake, including mudboils, suggests that convection of weathered massive sulphide may replenish the surface exposure of sulphide minerals. The boils are largest directly over the massive sulphide body, presumably indicating the greatest rate of convection. Additionally, Cameron (1977) attributed the increased thickness of active layer over the body to heat generation through sulphide oxidation. Cameron also observed the presence of thawed channels or taliks within the permafrost. Cameron concluded:

"Permafrost is no deterrent to active oxidation of sulphide bodies. In fact O_2 is more soluble in cold water and the exothermic nature of many oxidation processes provides a continuing energy source. In frozen ground, thin, intergranular water films allow chemical processes to be active, even in winter.... The presence of springs and sink holes in the vicinity of the mineralization show that taliks (thawed channels) exist in the permafrost."

Many of the processes and mechanisms in this quote foreshadow the discussions following in Chapter 3.

Cameron (1979) also examined massive sulphide deposits on Melville Peninsula, Northwest Territories, in continuous permafrost. Around the outcrop of the metasedimentary Penrhyn Group, containing the massive sulphide, the surface waters had pH as low as 3.1. By the time this acidic drainage flowed into nearby lakes, calcareous outcrops and till had successfully neutralized the acidity. Although the active layer in the area was roughly 1 m thick, Cameron hypothesized that oxidation was occurring at depths of metres to tens of metres. This was attributed to abundant graphite and/or various sulphide minerals that acted as inert conductors of electrons, which passed from the deep sulphide minerals to atmospheric oxygen. Like Cameron's 1977 work at Agricola Lake (above), this study indicated that permafrost is "no deterrent to active oxidation".

Experience in Russia's permafrost region seems to corroborate Cameron's observations. Shastkewich (1966) describes oxidation at temperatures below zero in rich sulphide bearing rock at depths up to 70m.

Kwong and Whitley (1992) and Kwong et al (1994) have conducted field studies of several natural acidic drainages in discontinuous permafrost within the Yukon. This work provides insights into heavy metal attenuation processes active in northern environments. These authors document the occurrence of cryogenic precipitation, coprecipitation, sorption, dilution, and galvanic interaction in providing natural buffers to acid production.

Work by Kwong (1995) at the Yukon's Clear Lake massive sulphide deposit shows comparable observations of acidity in a permafrost environment to those of Cameron discussed above. Pore water samples from soils located close to the massive sulphide outcrop (pyrite contents of 40% are common) show pH values less than 2 and very high values of zinc and sulphate. A pH of 2.8 was measured in the surface water of Clear Lake, which is within the massive sulphide drainage basin. Significantly lower values of zinc and sulphate were also measured. About 1km downstream of Clear Lake neutral pH values were measured along with low sulphate and negligible zinc levels. Kwong attributes the attenuation at Clear Lake to dilution, neutralization with carbonate minerals, and organic attenuation in boggy areas through sulphate reduction.

2.5 CONCLUSIONS

Information compiled in this chapter shows that AMD is not eliminated or reduced to negligible levels in the permafrost environment. Potentially acid generating materials within the seasonally thawed "active zone" of a permafrost environment are capable of generating AMD. Also, frozen ground can apparently generate AMD under some conditions. The following chapter reviews fundamental information and mechanisms that can affect AMD reaction rates under cold temperatures and transport processes in frozen ground.

Table 2-1 Statistical Summary of Reaction Rates from Humidity Cells Operated at +20°C and +6°C, Windy Craggy Project (Norecol, Dames and Moore, personal communication, 1995)

Sample	High/Low pH	Avg pH	SO4 Rate (mg/kg/wk)	Cu Rate (mg/kg/wk)	Zn Rate (mg/kg/wk)
BHC-15 +20°	7.7/5.4	7.0	27.4	1.52	5.15
BHC-15 +6°	7.9/6.5	7.4	9.44	1.46	8.76
BHC-16 +20°	7.8/2.9	4.4	289	4.78	8.58
BHC-16 +6°	7.7/5.4	6.6	44.4	1.56	11.9
BHC-17 +20°	8.9/7.3	7.8	46.1	2.07	5.11
BHC-17 +6°	9.3/7.2	8.1	17.6	1.45	10.8
BHC-20 +20°	7.9/6.9	7.4	24.2	1.55	3.44
BHC-20 +6°	8.0/7.0	7.6	11.0	1.55	4.91

3.0 PROCESSES RELATED TO ACIDIC DRAINAGE IN COLD CLIMATES

3.1 INTRODUCTION

Acidic drainage from mining operations is partly a consequence of the exposure of acid-generating sulphide minerals, such as pyrite, to air and water. This oxidation reaction leads to the production of acidity, sulphate, and metals. If acid-neutralizing minerals are present, some portion of the acidity, sulphate, and metals may be attenuated.

The oxidation of sulphide minerals and concurrent acid generation are typically illustrated through the "standard" chemical equation for pyrite oxidation:

$$FeS_2 + 7/2H_2O + 15/4O_2 \rightarrow Fe(OH)_3 + 2SO_4^{2-} + 4H^+ \qquad (3\text{-}1)$$

The use of Equation 3-1 implies a great deal is known about the site-specific environmental conditions in which sulphide oxidation is occurring. For example:

- pyrite (FeS_2) is the only acid-generating mineral;
- [unfrozen] water or moisture is available;
- oxygen is available, and this oxygen and the water act as the only oxidizing agents;
- sufficient oxidizing agents are present to oxidize both pyrite and ferrous iron to ferric iron;
- ambient pH is greater than roughly 3.0-3.5 so that ferric iron precipitates as $Fe(OH)_3$;
- ferric iron precipitates only as $Fe(OH)_3$; and
- all sulphide oxidizes completely to sulphate rather than to intermediate sulphur species.

Each of these conditions represent one or more reactions that, when combined, lead to Equation 3-1. However, the existence of all these conditions at a minesite is not verified, or sometimes one condition is known to be invalid. Consequently, the use of Equation 3-1 is not warranted at all sites, but is used here as a general indicator of the reactants and products of sulphide oxidation.

Virtually all studies sponsored and directed by the federal MEND Program have been directed towards some aspect of Equation 3-1. For example, studies of water covers document the effect of limiting oxygen availability on Equation 3-1. Studies of dry covers address the effects of limiting oxygen and/or water infiltration. Studies of some soil amendments focus on coating pyrite, rendering it unavailable for oxidation. Studies of treatment technologies address the handling of reaction products produced by Equation 3-1 or some variation on it.

The purpose of this section is to address only the effects that cold temperatures can have on Equation 3-1. Most aspects of water covers, for example, are not addressed here, although the change in dissolved-oxygen solubility with water-cover temperature is relevant and discussed.

Readers interested in non-temperature related issues should consult the numerous MEND-sponsored and related studies available from CANMET and elsewhere.

The most widely reported effect of cold temperatures on Equation 3-1 or a variant of it is that of a decreased rate of reaction. This is often described through the *Arrhenius Equation* (e.g., summarized in Otwinowski, 1994, and Lasaga, 1981):

$$\ln(k_1/k_2) = E_a(T_1-T_2)/RT_1T_2 \quad (3\text{-}2)$$

where k_1 is the reaction rate at temperature T_1
k_2 is the reaction rate at temperature T_2
E_a is the "activation energy" of the reaction
R is the gas constant

From a quantitative perspective, the logarithmic change in reaction rate is dependent on E_a, R, and the change in temperature. The most important non-quantitative observation to be gained from Equation 3-2 is that, if temperature decreases from T_1 to T_2, then the reaction rate also decreases in a non-linear manner. This relationship has been invoked in many references, over many years, as the "evidence" that cold temperatures will slow reaction rates. Laboratory and field verification of this relationship for Equation 3-1 and its associated conditions are generally lacking and contradictory when available (Chapter 2). In fact, Milburn et al. (1994) identified research on AMD in permafrost climates as a consistently important research target.

In spite of the implications of Equation 3-2, chemical reactions and weathering in cold climates and permafrost are not negligible. On a regional scale, Åkerman (1983) documented chemical karst weathering of dolomitic limestone and also reported observations of oxide rinds, carbonate coatings, and desert varnish. Xie (1988) reported on chemical weathering and transport in permafrost soils and rock of Antarctica, finding that K, Na, Ca, and Mg were leached downward and Co, Ti, Fe, and Mn were carried upwards to the surface.

3.2 GENERAL IMPLICATIONS OF TEMPERATURE ON ACID GENERATION

Pyrite oxidation is an exothermic reaction, meaning heat is given off during the reaction. The greater the amount of pyrite oxidized (Equation 3-1), the greater the amount of heat generated. Equation 3-2 then shows that the reaction rate and the rate of heat production increases as the temperature increases. This leads to a coupled process in which the rate of pyrite oxidation and heat generation is dependent on temperature which in turn is partially dependent on the rate of heat generation.

As an example of heat generation, Harries and Ritchie (1985 and 1987; summarized in MEND 1.11.1, 1991, p.66) indicated that $7x10^{-7}$ moles of pyrite would generate 1 joule (J) of heat energy, or, 0.012kJ for each kilogram of FeS_2. For comparison, the latent heat of water is 334kJ/kg. This energy apparently does not include other reactions such as aqueous complexation and secondary-mineral precipitation/dissolution, and is thus only an approximation of site-specific values. Nevertheless, the heat generation implies that oxidizing sulphide minerals can be warmer than the bulk temperatures measured in the surrounding materials, even if only on a microscale.

The coupled relationship between pyrite oxidation and heat transfer is illustrated as a flow chart in Figure 3.1. Recent theoretical work by Otwinowski (1995) provides the theoretical basis for this coupling of temperatures above freezing and where heat transfer occurs by conduction only. Based on the amount of heat generated due to oxidation of pyrite, it would appear that fairly high pyrite concentrations are necessary to promote thawing due to chemical reaction.

Although the effects of temperature on sulphide oxidation and Equation 3-1 can be complex, particularly under field conditions, there have been several studies that display relatively simple relationships between temperature and oxidation rate. Senes (1991) reviewed literature for the RATAP model and Nicholson (1984) conducted laboratory experiments and compiled information on the chemical and biological rates of oxidation (Figures 3-2 and 3-3). They found that the general trend suggested by Equation 3-2 holds. For chemical oxidation which predominates around neutral pH, the rate near freezing is about 15% of the rate around 25^{o}C. For biologically mediated oxidation which dominates at acidic pH, the rate below 8^{o}C is less than 20% of the rate at 30^{o} and drops to zero as the temperature also decreases to zero. However, zero biological oxidation at 0^{o}C in Figure 3-3 appears to be simply an assumption. In any case, Cameron's work discussed in the previous chapter indicates that oxidation is apparently operative in frozen ground.

3.3 COLD TEMPERATURE ISSUES RELATED TO WATER

Published literature has revealed a great deal of theory and test work that can be extended to the aqueous transport of reactants and products for Equation 3-1 in cold climates. This information is condensed and summarized in the following subsections as related to the simple movement of water and to the transport of solutes in stagnant water.

3.3.1 Moisture Movement During Freezing

During freezing of porous media, moisture transfer takes place as a result of two processes:

1. Expulsion of water due to the 9% volume change that accompanies the water-to-ice phase change; and

2. Attraction of water as a result of capillary suctions established at the ice-water interface.

These two opposing advective processes are a function of many factors including drainage conditions, overburden stresses, temperature gradients, soil composition, and pore fluid chemistry. A substantial effort has been devoted to understanding the relationships among these factors, principally focused towards issues related to frost heave and frost susceptible soils. In general, sandy soils tend to expel water and finer grained soils (silts and clay) tend to attract water.

Davilla (1992) has conducted tests and has proposed criteria for determining whether a soil will attract or expel water during freezing. Davilla proposed relationships, correlated with frost heave cell test data, between percent clay minerals and specific surface area in order to explain whether or not a sandy or silty soil will attract or expel waste during freezing. Davilla showed that soils containing non-clay minerals expel water. Silty sand soils tended to exhibit very little volume change during freezing. Clay soils showed a net water attraction during freezing.

Non-plastic tailings materials could be expected to either expel water or to exhibit little net volume change during freezing. In the former case, water-borne acidity, metals, and dissolved oxygen can be driven downward into deeper materials if freezing from the top. However, field studies, laboratory test work, and theoretical considerations indicate that aqueous solutes are not significantly driven downward before the freezing front on a macroscale (Kay and Groenevelt, 1983). Instead, some solutes are driven downward on a microscale, but this leads to locally increased concentrations and a depressed freezing point. In turn, this causes the freezing front to encapsulate this unfrozen local water. As a result, this behaviour does not lead to major macroscale expulsion of aqueous solutes during freezing.

The simple movement of water in freezing material can be significant and can lead to solute transport. For example, in clay soils, Fukuda (1983) found that negative porewater pressures at the freezing front can exceed 1 m H_2O, providing a relatively strong suction to draw deeper water upwards towards the land surface as it freezes. Xu et al. (1988) reported velocities of water drawn towards freezing fronts on the order of 10^{-8} to 10^{-7} m/s, and Yershov et al. (1988) reported fluxes on the order of 10^{-3} g/(m^2×s). These effects can eventually lead to the transport of deeper water-borne acidity and metals upwards into an unsaturated active layer, where they can be released during the next thaw.

Once a soil is frozen, the remaining unfrozen water is reportedly not mobilized by the surrounding ice or any thermal gradient below 0.3°C/cm (Murrmann, 1973). However, Nakano and Tice (1988) did report some migration at this thermal gradient using a newer, more sensitive technique. Additionally, solute migration can occur even in the absence of water movement, as explained in the following subsection.

Van Gassen and Sego (1991) reported ion and unfrozen water migration at temperatures below zero under an electrical gradient. Expressed through an electro-osmotic conductivity, the migration was relatively constant to a temperature of -0.5°C, then decreased by 1 to 2 orders of magnitude at lower temperatures to -1.7°C.

3.3.2 Unfrozen Water and Freezing Point Depression

An obvious limitation to the supply of dissolved oxygen as well as to the operation of Equation 3-1 is the freezing of water. Frozen water blocks the transport of dissolved oxygen or simply eliminates one of the reactants needed for sulphide oxidation. From this simple perspective, freezing of mine materials will preclude acid generation.

In reality, porewater does not entirely freeze below 0^oC. This is due to various factors, such as temperature, surface-energy effects of grain surfaces, ionic strength (salt content) of porewaters, and pressure. The prediction, assessment, and implications of unfrozen water in frozen soils has been the topic of research for several decades (e.g., Williams, 1964). Most of this subsection addresses the implications of this unfrozen water on acidic drainage and metal leaching (Equation 3-1).

For clays and silts, simple empirical relationships have been developed between grain size, temperature, heat capacity, and unfrozen water content. For example, Anderson et al. (1973) examined data on freezing-point depression in eleven soils with specific surface areas between 0.02 to 800 m^2/g based on ethylene glycol retention. This leads to:

$$\ln(w_u) = 0.2618 + 0.5519 \ln(S) - 1.449\, S^{-0.2640} \ln(q) \quad (3\text{-}3)$$

where w_u = unfrozen content as g H_2O/100 g soil
S = specific surface area as m^2/g
q = absolute value of temperature in ^oC

Also, Anderson and Morgenstern (1973) presented an often reproduced graph of unfrozen water contents against ambient temperature (Figure 3-4).

Akimov et al. (1983) qualitatively expanded on Equation 3-3 by pointing out additional factors controlling unfrozen water contents, including average size of porespaces, heteroporosity, mineral-surface energy, mineralogical structural bonds, and porewater concentrations.

Horiguichi and Miller (1983) reported that unfrozen water contents fell sharply between 0.0 and -0.2^oC, and then became relatively steady to -0.4^oC in six materials. Jinsheng and Rong (1983) reported relatively constant unfrozen water contents of roughly 4% in silt and clay below temperatures of approximately -5^oC. However, hundreds of hours were required after temperature adjustment until the unfrozen water content reached its long-term maximum value. In contrast, other researchers (Akimov et al., 1983) reported only an hour was required to obtain a stabilized unfrozen water content. The cause of this discrepancy cannot be resolved with the published information.

In sands, the amount of unfrozen water is mostly dependent on the freezing properties of the pore water. Hivon and Sego (1995) believe that unfrozen water in coarse saline soils occurs as isolated brine islands separate from the soil particles. This is in marked contrast to finer grained soils where the unfrozen water is believed to be present as adsorbed films around the soil particles. Figure 3.5 shows a comparison of the association between ice, unfrozen water, and soil particles in frozen soils. Hivon and Sego report volumetric unfrozen water in excess of 30% for different sandy materials with salt contents approaching that of seawater.

The flow of unfrozen water is regulated by a hydraulic conductivity and a hydraulic gradient. These factors can be used to estimate the flow rate of unfrozen water using various steady-state or transient, saturated or unsaturated equations (e.g., Freeze and Cherry, 1979).

Horiguichi and Miller (1983) tested six materials including natural silts, clays, and zeolite. They found that hydraulic conductivity decreased sharply by three to four orders of magnitude (below 10^{-10} m/s) as unfrozen-water content fell to 50-70% of total water content when temperature reached -0.2 to -0.4^{o}C (Figure 3-6). Similar conductivities at similar unfrozen water contents were also reported by Oliphant et al. (1983) and Williams and Perfect (1980). Below these near-zero temperatures, Ratkje et al. (1982) indicated that conductivity decreased relatively slowly as temperature decreased, falling approximately two orders of magnitude by -30^{o}C. For the transport of reactants and products of Equation 3-1, these low values of hydraulic conductivity would probably transport less loadings than diffusion through the unfrozen water. Consequently, diffusive transport through unfrozen water may be the key control on Equation 3-1 in frozen mine materials, although field and laboratory work often points to higher rates of solute transport as shown below and in Chapter 2.

Murrmann (1973) investigated ion mobility in frozen silts and clay through a series of interesting experiments on a limited number of samples. Since Murrmann established that the unfrozen water content was not convective, ion mobility was attributed to diffusion. Based on sodium ions, Murrmann found that the diffusion coefficient decreased sharply from -1 to -4^{o}C, then generally stabilized to temperatures as low as -16^{o}C (Figure 3-7). The stabilized coefficients reflected a five- to ten-fold decrease from -1^{o}C and reportedly a ten- to twenty-fold decrease from the coefficients expected at +25^{o}C. In more recent work, Ostroumov (1988) reported higher diffusion coefficients in frozen sand (-7.5^{o}C) between 10^{-8} and 10^{-7} m^2/s for chloride, potassium, and moisture under a thermal gradient.

If directly applicable to acidic drainage and metal leaching (Equation 3-1) and to transport of dissolved oxygen, this work indicates diffusion-controlled reaction rates may decrease only about an order of magnitude upon freezing, but not cease. In areas where the rate of water movement in a thawed active layer is slow and residence time for sulphide contact is long, a depressed rate of acid generation may still be sufficient to create acidic-pH water with elevated metal concentrations.

Murrmann (1973) conducted additional test work to explain the mechanism accounting for the observed temperature-dependent diffusion in frozen silts and clays (Figure 3-7). Several hypotheses were tested, such as the effect of total water content and diffusion through ice, but only the unfrozen water content could explain Figure 3-7. In other words, the diffusion coefficient was directly proportional to the amount of unfrozen water.

Ostroumov (1988) examined in greater detail ion diffusion under thermal gradients in both frozen and unfrozen soils. His test work showed thermally driven diffusion was affected by a complex play of liquid and vapour diffusion, pressurization of trapped gases, thermocapillary movement, and thermoosmotic transfer. In general, ions and water migrated towards the colder end of the thermal gradient in frozen sand, whereas thawed sand showed ions moving towards the warmer end and water moving towards the colder end. Ostroumov presented a conceptual diagram (Figure 3-8) to explain the complex diffusion of ions and water under thermal gradients in frozen and thawed sand. As temperature decreases, the thickness of the Intermediate Layer decreases so that opposing diffusion in the Inner Layer dominates.

In addition to diffusion through frozen soils, Ostroumov et al. (1993) demonstrated that snow cover can remove ions from frozen soils, drawing them upwards where they can be readily mobilized during snowmelt. The diffusion upwards into snow from frozen soil can generate fluxes of metals between 10^{-6} to 10^{-5} $g/m^2/hr$, with heavy metals moving at the lower rate.

The final issue in this subsection deals with the retention of frozen and unfrozen water in sub-zero mine materials. The water and ice can be evaporated and sublimated through various mechanisms (Komarov, 1983), leading to the loss of water in frozen materials. During freeze-thaw cycling, this may then lead to the physical redistribution of water accompanied by the transport of any reactants or products from Equation 3-1. This sublimation and freezing of water also reportedly leads to interesting geochemical reactions, the precipitation of metastable mineral phases in frozen soils and rock due to local supersaturation of liquid water. Siegert (1993) documented the formation of aluminum oxides (including a rare form of secondary corundum), iron and manganese oxides, iron sulphides (greigite and mackinawite), and manganese calcites. There is evidence that the aluminum oxides formed at optimum temperatures of -4^{o}C, highlighting some active geochemical reactivity at subzero temperatures.

3.4 COLD TEMPERATURE ISSUES RELATED TO OXYGEN AND OXIDIZING AGENT

A key requirement in Equation 3-1 for sulphide oxidation is the presence of oxygen. When the porespace of mined materials is saturated with water, dissolved oxygen in the water will be the primary source of oxygen. Otwinowski (1994) calculated from references the saturated aqueous concentration of dissolved oxygen at various temperatures and oxygen contents of the gas phase in contact with the water (Table 3-1). This shows that the saturated dissolved-oxygen content increases as temperature decreases and as the percentage of oxygen in the gas phase increases. Notably, this means that colder water can supply greater amounts of oxidizing agents to submerged sulphide minerals, leading to increased oxidation (e.g., Morin, 1993). Although saturated concentrations are often considered maximum values, there are factors that can lead to higher or lower levels than those reported in Table 3-1. For example, the values of Table 3-1 change with ionic strength of the water and additional oxygen can be entrained in turbulent water as air bubbles.

The transport of dissolved oxygen in unfrozen water can lead to oxidation of sulphide minerals. However, the saturation levels of dissolved oxygen (Table 3-1) would not often generate significant amounts of acidity (Morin, 1993). On the other hand, Cameron (1979) and Kwong (1995) reported that minerals which are electrochemically reactive may allow oxidation of sulphide minerals below the active layer in the absence of dissolved oxygen. This hypothesis calls for exchange of electrons from sulphide minerals in the ground to oxygen in the air through adjoining electrochemical minerals. If true, acid generation and metal leaching may occur at depths of tens of meters in the absence of oxygen. In any case, theory and test work do not indicate that freezing will necessarily prevent the entry and transport of oxidizing agents into frozen mine materials as explained in Section 3.3.

3.5 COLD TEMPERATURE ISSUES RELATED TO SULPHIDE MINERALS

The rate of acid generation and metal leaching (Equation 3-1) is partly dependent on the surface area of pyrite exposed to moisture and oxygen. Any process that leads to additional exposure of pyrite surfaces can lead to enhanced acid generation.

In cold climates, freeze-thaw cycling can cause the physical breakdown of rock and soil into smaller particles, referred to as "frost wedging", "frost shattering", and "frost weathering" (e.g., Fukuda, 1983; Hallet, 1983). On a smaller scale, this shattering can also occur in minerals. As a result, there is at least one mechanism in cold climates that may actually increase the rate of acid generation. For example, if shattering leads to the exposure of 20 times more pyrite surfaces, but the unit-area rate of oxidation decreases by a factor of 10, then the overall loading of acidity may be twice as high than in a warmer climate, particularly during the thaw cycle.

As a rough analog to pit walls and waste rock, Pancza and Ozouf (1988) examined the effect of frost action on limestone rock faces in the Swiss Jura Mountains facing various compass directions. Laboratory tests showed that frost shattering of rock from all faces was similar under identical conditions. This led to the conclusion that the direction of the face accounted for differences observed in the field. Field work revealed that south-facing slopes were exposed to 30% more freeze-thaw cycles, at a depth of 12 cm into the slope, than north-facing slopes. This apparently accounted for the smaller size of rock particles weathered from south slopes and the notable physical weathering rates of 1 mm/yr. As a result, the degree of weathering in pit walls and waste-rock dumps may also be dependent on the orientation of the faces. Additionally, the dependence on the number of freeze-thaw cycles suggests that High Arctic mines may have less physical weathering due to less annual freeze-thaw cycles.

In order to better quantify small-scale mineral disintegration, Konishchev and Rogov (1983) subjected monomineralic (non-sulphide) minerals to heating-cooling cycles. Some cycles remained consistently below $0^{o}C$ and some cycles crossed the freezing point. These researchers found that mineral disintegration still occurred in sub-zero cycles, but that disintegration increased by a factor of two to ten in the freeze-thaw cycles. This work shows that mineral disintegration and exposure of new, reactive surfaces can still occur in permanently frozen mine materials, sometimes at rates one-half of those of the freeze-thaw rate.

The freeze-thaw cycling can also lead to convection or overturn of material throughout the active layer and perhaps just below it (Burn and Smith, 1993). This convection is often indicated at the land surface by mounds or patterned ground, including "mudboils". Convection of high-carbonate tills were found to be successful in maintaining original carbonate levels at the land surface (Figure 3-9) despite ongoing leaching (Dredge, 1988). From the perspective of acidic drainage (Equation 3-1), this convection could also bring new supplies of sulphide minerals to the surface for oxidation. This may explain, at least in part, the observations of ongoing acid generation in massive sulphide deposits of northern Canada millennia after post-glacial exposure (Cameron, 1977).

3.6 COLD TEMPERATURE ISSUES RELATED TO BIOLOGICAL ACTIVITY

Specific studies of biological activity on acid generation (Equation 3-1) are generally lacking at cold temperatures. However, observed empirical effects on reaction rates, attributed to biological activity at changing temperature, are available. Senes (1991) determined a numerical relationship between biological oxidation and temperature for the RATAP model to simulate above-zero tailings (Figure 3-2). However, this relationship seems to be based on an assumption that the rate reaches zero at $0^{o}C$.

Otwinowski (1994) reviewed reaction rates related to *Thiobacillus ferrooxidans* and reported that the biological mediated oxidation reached a maximum at $30^{o}C$ (Figure 3-10). Beyond 30°C biological rates decreased with increasing temperature, and thus the Arrhenius Equation (Equation 3-2) did not hold for biological activity at higher temperatures. Unlike Senes (1991), Otwinowski did not show the biological rate as zero at $0^{o}C$, but showed the rate was orders of magnitude less than at $10^{o}C$.

In any case, Figures 3-3 and 3-10 should only be taken as general depictions of temperature effects on biologically controlled oxidation. In reality, bacteria can adapt to conditions not commonly reported for them. Activity of thermophilic bacteria has been reported at $90^{o}C$ (Brierly, 1978). In contrast, Kalin (1987) reported on slow-growing *Thiobacillus* at the Nanisivik Mine that had apparently acclimatized to cold temperatures and would generally not reproduce at a warmer temperature of $12^{o}C$. Since temperatures near freezing are generally accepted as limiting to bacterial activity but still significant at $2^{o}C$ (Lundgren and Silver, 1980), it is possible that *T. ferrooxidans* could adapt to unusual conditions, perhaps even to sub-zero temperatures where sufficient oxygen and unfrozen water existed.

Ahonen and Tuovinen (1989, 1990, 1991) found that growth rates of *T. ferrooxidans* fell by 90% as temperature fell from 28^{o} to $4^{o}C$. At the same time, the oxidation rate of aqueous ferrous iron decreased following the Arrhenius Equation (Equation 3-2), with an activation energy of 83±3 kJ/mol noted for a mineral-salt solution and other activation energies measured for sulphur and sulphide substrates. Extrapolation of these results suggests that inactivation of bacterial growth may occur at -2 to $-5^{o}C$. However, this extrapolation may be incorrect as non-linearity of growth rates have been noted at low temperatures (Herbert, 1986). Another study suggested *T. ferrooxidans* may be active to $-6^{o}C$ (Mehling, 1993).

3.7 OTHER ISSUES

One issue pertinent to Equation 3-1 is the presence of minerals capable of neutralizing the generated acidity and precipitating metals from the water. The most reactive neutralizing minerals are carbonates, primarily those containing calcium (calcite and dolomite). These minerals do not require air to react and thus are capable of reacting wherever unfrozen water is present. As a result, the issues raised in Section 3.3 for maintaining sulphide reactivity are also valid for neutralizing minerals.

3.8 CONCLUSIONS

This review of processes related to acid mine drainage in cold climates raises important questions. Some of these questions will need to be addressed prior to proceeding with confidence on any strategy that involves using permafrost to mitigate acid mine drainage. The current information suggests the following conclusions:

1. Frozen-ground and cold-climate conditions do not necessarily halt acid-generating and metal-leaching reactions. For example, sulphide oxidation can still occur with unfrozen water at sub-zero temperatures, and the process chemicals contained in tailings pore water could result in elevated levels of unfrozen water. Once sulphide oxidation is initiated, the exothermic chemical reaction could cause accelerated thawing to take place.

2. Oxidizing and biological agents may not be eliminated at sub-zero temperatures. There is no published evidence located by this review to show that oxidizing bacteria are inactive at sub-zero temperatures. Also, field observations, reported in the previous chapter, indicate electrochemical processes may also be important as oxidizing agents.

3. In spite of the foregoing conclusions, hydraulic conductivity is decreased by up to several orders of magnitude due to freezing. However, below a certain point, conductivity becomes unimportant and then diffusion, particularly under a thermal gradient, controls transport rates. Nevertheless, this may be sufficient to provide adequate containment under many conditions provided that accelerated thawing does not take place.

These conclusions can explain some of the inconsistencies noted in Chapter 2 for field and laboratory studies. However, the field studies and research needed to examine these conclusions specifically in acid-generating systems are still generally lacking, and sorely needed.

Scientific evidence shows that permafrost will not provide an absolute control on AMD production, however, the production levels may be sufficiently small that engineered solutions are worth considering.

Some strategies that could be used to mitigate AMD in a permafrost environment are considered in the next chapter. The strategies are limited by some of the uncertainties presented here, but provide a framework within which to explore further technological developments.

Table 3-1 Saturation Concentrations of Dissolved Oxygen in Water Based onTemperature and Percentage of Oxygen in the Adjacent Gas Phase[1] (from Otwinowski, 1994)

	DISSOLVED OXYGEN CONCENTRATION AT SATURATION (mg O_2/L)				
T (^oC)	**$[O_2]_{gas}$=21%**	**$[O_2]_{gas}$=15%**	**$[O_2]_{gas}$=10%**	**$[O_2]_{gas}$=5%**	**$[O_2]_{gas}$=1%**
5	12.79	9.60	6.02	2.92	0.50
10	11.30	8.03	5.31	2.59	0.41
15	10.11	7.16	4.72	2.27	0.32
20	9.12	6.45	4.23	2.01	0.23
25	8.30	5.86	3.77	1.82	0.14
30	7.60	5.33	3.44	1.56	0.05
35	7.00	4.88	3.12	1.43	0.00
40	6.47	4.47	2.81	1.15	0.00
45	6.00	4.10	2.52	0.94	0.00
50	5.57	3.75	2.25	0.74	0.00
55	5.17	3.55	1.96	0.50	0.00
60	4.89	3.38	1.64	0.25	0.00

[1] calculated by Otwinowski (1994) from various references; water is at atmospheric pressure (1013.25 hPa)

4.0 CONTROL STRATEGIES FOR ACID MINE DRAINAGE IN PERMAFROST REGIONS

4.1 INTRODUCTION

This chapter examines some strategies that could be used to control acid mine drainage (AMD) in a permafrost environment. The strategies are presented in a conceptual manner only as this chapter is not meant to be a design guide. Further research is also required and recommendations for further research are contained in the next chapter.

As part of this study, information on cold weather dam design, construction, and performance experience was compiled. This compilation is included as Appendix A. Most of the cold weather dam design and construction technology is fairly well established permafrost engineering practice. A significant number of frozen dams have been designed and built in the former Soviet Union. Information from Appendix A of direct significance to the objectives of this chapter has been incorporated where appropriate.

The freeze control and climate control design concepts discussed here reference one dimensional freezing and thawing calculations. The calculations are based on closed form analytical solutions derived and discussed in reports published by the US Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL , 1981 and CRREL, 1988) and Dawson (1994). The estimated freeze and thaw depth calculations that result from the analyses generally embrace the following assumptions:

1. Heat transfer through mine waste materials is by conduction only. Thus the calculations do not apply for convective flow through coarse waste rock. Solar radiative heating has been left out of the calculations.

2. Heat is gained for thawing and lost for freezing due to the phase change only. This is a reasonable assumption as it requires the same amount of heat to achieve phase change (between solid and liquid) in a unit weight of water as that required to change the temperature by 80°C.

3. Thermal properties (thermal conductivity and latent heat) have been estimated based on porosity (or void ratio) and degree of saturation. A typical sandy gravel waste rock is considered to have a porosity of 33% (void ratio of 0.5) with 40% saturation. A typical tailings material is considered to be fully saturated at a porosity of 41% (void ratio of 0.7). The freeze and thaw calculations do not apply to coarse waste rock where heat transfer by convection is dominant.

4. A heat transfer coefficient of 20 watts per square metre is assumed as a convective heat flux between the ground and the atmosphere.

4.2 GENERAL DISCUSSION

In general, AMD control strategies are founded on three basic approaches:

1. Control of acid generating reactions;
2. Control of migration of contaminants; and
3. Collection and treatment.

Table 4.1 lists various AMD control strategies which embrace one or more of the above approaches. It is not a complete list but represents those strategies most likely to be considered in a permafrost setting. In this report emphasis is placed on freezing and climate controlled strategies, where the unique frozen ground conditions and cold, relatively dry climate of permafrost regions can be used to advantage. However, in order to provide a more complete perspective on AMD control in a permafrost environment each of the strategies listed in Table 4.1 is briefly discussed below:

FREEZE CONTROL - Freezing immobilizes pore fluids controlling both AMD reactions and migration. It is clear from the review of natural sulphide systems presented in this report that acid production can still occur if the system is not designed against thaw degradation processes. This report also emphasizes the importance of pore water chemistry and unfrozen water. Freezing large quantities of mine waste is also a challenge. Pertinent issues and strategies for using freeze control to advantage are discussed below.

CLIMATE CONTROL - Climate control is used here to embrace strategies that rely on cold northern climates to slow down acid production and low net precipitation to limit pore fluid migration. Climate control strategies discussed here are analogous to the "arid climate" mine waste management concepts proposed by the California Mining Association (1992):

"A typical dry waste disposed of in arid areas obviously would pose a significantly lower risk of impact to ground or surface water than if the same waste were disposed of in a facility in a wetter climate. The waste disposed of in an "arid" climate requires far less and, in some cases, no additional engineered containment to ensure protection of the beneficial uses of water."

It is considered that the relatively low net precipitation and cold temperatures of permafrost regions are natural buffers to AMD production and that there are modest engineered strategies that can be used to advantage for controlling AMD in a permafrost setting. Climate control strategies are best applied to situations where the waste can be placed at a moisture content lower than the specific retention value as it is probably necessary to control seepage and infiltration with more conventional strategies where waste materials are completely or nearly saturated. Climate control is only considered here for mine waste rock materials.

ENGINEERED "DRY" COVER - Layered engineered covers have been used to effectively reduce oxygen and water movements into mine waste piles. Typically, an engineered dry cover system constructed from natural materials consists of a fine grained layer sandwiched between two coarser grained layers. The upper layer acts as an erosion and evaporation barrier, the middle layer serves as a moisture and oxygen barrier layer, and the lower layer provides a "capillary" barrier to prevent drainage of the overlying fine layer. There is a current need for more cost effective "dry" barrier systems and alternative materials have been screened and prioritized for further research (MEND 2.20.1, 1994). This would suggest that alternative approaches such as those embracing climate controlled concepts may also be a subject for further research.

The main design distinction for engineered "dry" covers in a permafrost environment is freeze-thaw cracking due to seasonal freeze-thaw. Note that in areas underlain by permafrost it is the thaw depth that governs the freeze-thaw design criteria in contrast to non-permafrost areas where the frost depth is of concern. The thaw depth (active layer thickness) generally ranges between 1 and 4m in permafrost regions, depending on climate and soil conditions. Frost depths are commonly in the 1.5 to 2m range in non-permafrost regions. Engineered covers require special considerations to protect against freeze-thaw damage in permafrost regions.

Frost susceptible natural materials include soils with high silt content and high moisture content clay rich soils. Many clay tills are reasonably resistant to freeze-thaw effects and due to their availability are often the material of choice. In the permafrost regions many of the till deposits are sandy and may not possess the required compaction/permeability characteristics.

SUBAQUEOUS DISPOSAL - Disposal of potentially acid generating mine waste beneath a water cover is a very attractive strategy as the water slows down the ingress of oxygen so that the rate of oxidation proceeds very slowly. The disposal strategy is especially attractive for tailings which can be transported by slurry pipeline and placed beneath a natural water body in a controlled fashion. MEND 2.11.1(d) provides a review of studies conducted on subaqueous disposal and states that site-specific preference for disposal are as follows:

- infilling of a small headwater lake
- disposal in an artificial structure
- in-lake disposal (tailings represent a small portion of total lake volume)

Natural permafrost water bodies tend to be more biologically barren than those in non-permafrost regions and this may reduce the amount of disturbance during placement relative to non-permafrost areas. Considerations for cold climate ecology is required for subaqueous disposal in permafrost regions.

Another consideration for sub-aqueous disposal in a permafrost setting is the difficulties related to preventing pipeline freeze-up and maintaining ice clearance for the pipelines. As noted in Chapter 2, the Polaris Mine currently practices underwater tailings disposal and successfully operates underwater pipelines in a very harsh environment.

BLENDING AND SEGREGATION - Blending and segregation of acidic and alkaline materials can result in a net neutral waste product that produces a non-acidic leachate. Where sufficient quantities of alkaline materials are economically available this can be a very effective strategy. It is understood that MEND is undertaking a study examining the use and effectiveness of waste rock blending and segregation at various minesites. Segregation of acidic and non-acidic waste rock is included as part of the climate controlled strategies discussed below.

COLLECTION AND TREATMENT - Collection and treatment (usually with lime) of acidic leachate is a proven and demonstrated control strategy. In a permafrost environment, collection and treatment would be expected to be a seasonal operation. Maintaining a seasonal collection and treatment facility at a remote northern minesite following closure will be a costly and logistically difficult undertaking.

4.3 THAWING CONSIDERATIONS

Permafrost environments are biologically and physiologically sensitive. Maintenance of frozen ground is a prime consideration for most development activities in the north. The main design considerations in this regard involve thaw degradation of the surrounding permafrost during and following waste placement, seasonal thawing, and thaw degradation due to perpetual disruptive processes such as AMD induced heating and climate warming. Each of these issues is discussed briefly below.

4.3.1 Thaw of Original Ground

The thermal regime surrounding the waste disposal area requires careful consideration. Within the discontinuous permafrost region the zero amplitude ground temperature generally ranges between -1 and 0°C. Small changes in the heat balance can lead to accelerated thaw within these areas. Large quantities of saturated mine tailings contain significant quantities of heat which can have a particularly detrimental effect on marginally frozen permafrost ground conditions.

Site specific thermal conditions also require careful evaluation (sun and wind exposure, thaw zones beneath water courses, peat cover). Baseline permafrost information is a prerequisite to all mine waste disposal projects in permafrost regions.

4.3.2 Seasonal Thawing

The depth of seasonal thawing is an important design consideration. Figure 4.1 shows estimated active layer thicknesses for unsaturated waste rock and saturated tailings at various mean air temperature thaw indices encountered in the continuous and discontinuous permafrost regions. The figure shows that the active layer in saturated tailings varies between 1 and 3m over a thaw index range of 250 to 2200°C days. Similarly, unsaturated waste rock shows an active layer thickness of between 2 and 6m. The difference is mainly due to the lower quantities of water that needs to be thawed in unsaturated waste rock. Unsaturated materials freeze and thaw much faster than saturated materials.

Within the discontinuous permafrost region, the thick active layer (generally greater than 2.5m) makes provision of a specially designed insulating cover an expensive proposition unless the waste material itself can be used to advantage.

4.3.3 Perpetual Thaw Processes

Perpetual processes are those that act continuously over time. They generally have a longer term effect. Two perpetual thaw processes have been identified: thawing due to AMD heat production and thawing due to climate warming.

The review of naturally occurring acidic drainage in chapter 2.0 illustrates several cases where acidic drainage appeared to be taking place below the active layer in permanently frozen ground. Despite this observation, the amount of heat produced due to oxidation of pyrite (0.012 kJ/kg) is very low compared to the amount of heat required to melt ice (334kJ/kg). Materials with large quantities of sulphide minerals, low porosities, and high unfrozen water contents may be susceptible to geochemical thaw effects. Naturally occurring sulphide deposits may meet these criteria possibly explaining the observations discussed in Chapter 2.0.

Climate warming is a contentious issue and consensus on whether or not the global climate is actually getting warmer remains unresolved. Nevertheless it would seem prudent to consider some warming effects. A 2°C warming trend over a 100 year period would increase the thaw index by about 500°C days. Referring to Figure 4.1 this could result in an increase in the active layer thickness of about 1m for waste rock and 0.5m for saturated tailings.

4.4 FREEZE CONTROL FOR TAILINGS

Strategies for controlling AMD in tailings materials are considered in this section. As noted in Chapter 2.0, at least two mines are planning to use freezing for achieving their AMD control reclamation objectives. Successful application of freeze control strategies requires providing an insulating cover and ensuring that the frozen materials limit AMD production and migration to within acceptable limits. Two strategies are examined here; total freezing and perimeter freezing. Table 4.2 provides a summary of each strategy for continuous and discontinuous permafrost regions.

4.4.1 Total Freezing

Total freezing entails freezing the whole tailings mass in order to reduce or eliminate the rate at which AMD is produced and to reduce seepage fluxes of any contaminants that are produced. Total freezing is not considered a viable strategy in the discontinuous permafrost regions as ground temperatures are not cold enough to maintain frozen conditions where large quantities of tailings are being placed. In continuous permafrost, total freezing could be carried out after the containment area is filled or during filling by freezing thin layers. Allowing tailings to freeze-back after filling requires perimeter dykes. Freezing control with perimeter dykes is discussed in the next section.

Insulating cover design strategies for frozen tailings containment have been examined by MEND 6.1 (1993). This study proposed various cover design options for Arctic permafrost regions (similar to the continuous permafrost region) and the Boreal/Cordilleran regions (similar to the discontinuous permafrost region). The report suggests that total insulation protection of tailings in the Boreal and Cordilleran regions may be difficult and prohibitively expensive.

Figure 4.2 shows cover design options for insulating cover design in continuous permafrost regions, following the MEND 6.1 (1993) study. Cover thicknesses using natural materials generally range between 2 and 2.5m which is within the range shown in Figure 4.1 for schemes using natural materials. An interesting observation derived from this work is the benefit of using coarse rock as an insulating medium:

"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."

Design guidance for using coarse rock as an insulating medium is lacking although it is noted that coarse rockfill and wooden shields have been used as insulation for protecting frozen Russian dams (see the Appendix) from summer thaw. At the Portovy Creek dam in the Western Russian Arctic (mean annual air temperature of -10.5°C), about 0.3m of rockfill rip-rap helps to maintain frozen conditions.

Cost estimates for insulating covers in continuous permafrost regions over a 10 hectare site ranged from 1.25 to 3.2 million dollars (MEND 6.1, 1993) with the lowest costs being for waste rock covers and the highest for covers containing insulation (see Figure 4.2). Total insulating cover design costs for a typical tailings containment area would be several tens of millions of dollars. There would seem to be a requirement for more cost effective insulating cover designs. It may not be necessary to design for total active layer thickness as long as the temperature below the cover can be kept low enough to ensure that acid drainage reactions are maintained at very low rates. In addition further research on the insulating benefits of coarse rock-fill may reveal that fairly thin covers (less than 1m) can be effective.

Allowing the containment facility to freeze following closure requires perimeter dykes and thus this option is similar to the perimeter concept discussed above. Further discussion here pertains to thin layered freezing controlled concepts.

Waste management systems designed for frozen containment can take advantage of freezing several thin layers rather than one thick layer in order to maximize the total frozen thickness. The hydraulic transport and disposal systems (slurry pipelines) normally used for tailings management make this a viable option as it is relatively easy to place thin layers of material by hydraulic deposition. Figure 4.3 shows total frozen thickness estimates for tailings sand frozen under different freezing indices. Note that the total freezing layer thickness varies in a nonlinear fashion with the placement layer thickness. For example, at a freezing index of 3900°C days (approximate division between continuous and discontinuous permafrost regions), the total freezing thickness varies between 3.6m for a single placement layer to over 10m for a 1m multiple layer placement. In the high Arctic total frozen thicknesses in excess of 15m are predicted to be possible by placing and freezing thin layers of about 1m.

It is clear from the calculations shown in Figure 4.3 that significant quantities of material can be frozen by placing and freezing thin layers. Even in the southern extremes of the discontinuous permafrost zone (freezing index of 2200°C) it is possible to freeze 5m of saturated sand tailings by placing and freezing 1m thick layers. A strategy that takes advantage of this process for providing total containment by freezing thin layers is presented below (see Figure 4.4):

1. A compacted fill starter dike is first constructed in order to provide initial containment. The starter dike would eventually freeze.

2. In the first winter season following completion of the starter dike (A in Figure 4.4), frozen perimeter dikes are constructed from tailings sand. The perimeter dikes could be constructed using cell construction techniques. Specialized frozen cell construction techniques would need to be developed that maximize frozen thickness and control overboarded decant water and fine tails. The construction would also require an interactive thermal monitoring program to ensure that the dikes are frozen. The perimeter dike would need to be designed to allow for sufficient freeboard that takes the active layer thickness into account.

3. In the first summer season (B in Figure 4.4) tailings could be overboarded into the pond area. The overboarded unfrozen tailings would cause some of the underlying frozen tailings to thaw.

4. In the second and subsequent winters (C in Figure 4.4), frozen cell construction would continue. A layer of unfrozen tailings would be trapped beneath the frozen tailings. This trapped layer of unfrozen material would freeze by the end of the winter, before thaw was initiated at the surface the subsequent summer (D in Figure 4.4).

The construction sequence of the thin layered freezing strategy presented above is essentially the same as an upstream construction tailings dam. The difference is that in addition to designing for adequate control of sand, fines, and water, the construction must also allow for adequate freezing and thawing control that will assure long term containment. At the end of construction it is likely that there will be thick accumulations of unfrozen fine tails beneath the pond area. The reclamation plan could allow for freezing this material by pumping it up onto itself in the winter months.

4.4.2 Perimeter Freezing

Perimeter freezing involves constructing a frozen dam around a tailings containment area in order to prevent lateral migration of seepage waters. The frozen dam should be constructed with material that has virtually no potential for acid generation.

A typical frozen dam profile (see Figure A.1 in the appendix) consists of a frozen core keyed into a frozen foundation, an upstream sandy "prism" overlain by a rock fill blanket, and a downstream rockfill "prism". In addition a freezing column may be necessary during construction, following construction, or not at all if the dam is being constructed in winter and in the continuous permafrost region. The frozen core zone can be constructed from compacted earthfill or from hydraulically placed material. The dam profile is not unlike an unfrozen rockfill dam. The central design issue is the freezing and subsequent freezing maintenance in the foundation and seepage barrier materials. Some useful comments drawn from the summary of experience contained in the appendix is summarized as follows:

- successful performance, in terms of maintaining frozen conditions, has been achieved where the average annual air temperature is less than -7°C. At the Russian Petrovsk Dam, where the mean air temperature is -4°C, frozen conditions could not be maintained and the entire dam had to be re-built.

- frozen dams are generally less than about 20m high. Higher dams are difficult to keep frozen as larger surface areas thaw more readily.

- snow acts as an insulator and should be kept clear of areas requiring freeze-back.

- at the Lupin Mine, the freezing point depression due to process chemicals in the tailings was estimated at -0.3°C.

- older Russian dams built in the 1940's and 1950's employed wooden shields along downstream faces to enhance convection cooling in winter and provide insulation in the summer. Rockfill is also used for the same purpose.

Experience suggests that perimeter freezing is best applied to the continuous permafrost regions. In the discontinuous regions, a thick active layer and thermally sensitive foundation conditions may pose restrictions on design and construction. It may be possible to construct low dams (<5-10m) over competent frozen foundations in the discontinuous region although the design would need to include special consideration for thermal stability considering the current experiences in regions underlain by warm permafrost.

MEND 6.1 (1993) has proposed perimeter dyke insulating cover options for the boreal and cordilleran regions (similar to the discontinuous permafrost region) and the Arctic region (similar to the continuous permafrost region). Figure 4.5 shows different insulating cover schemes derived from the MEND 6.1 (1993) study. The schemes for the discontinuous region involve using thermosyphons and coarse waste rock. Estimated costs for the insulating cover designs in continuous permafrost regions were about $700,000 for a cover on two sides of a 10 hectare dyke. Similarly, estimated costs for insulating a dyke in the discontinuous permafrost region ranged between $700,000 to 900,000. The lower cost was for the design entailing using insulation and horizontal thermosyphons.

The main disadvantage of perimeter freezing is that the tailings are still able to generate acid during the thaw period. In the continuous permafrost regions freeze-back would occur over time.

4.5 CONTROL STRATEGIES FOR WASTE ROCK

Waste rock poses challenges for acid rock drainage (ARD) control. There is a general lack of understanding of mass transfer and geochemical processes within waste rock piles. MEND 1.11.1 (1991), Smith et al. (1995), Dawson et al. (1995), and Herasymuik et al (1995) provide some insights into these processes and these reports provide a background for the design concepts advanced here. An integrated program of research is required before these or other similar design concepts can be reliably implemented.

Mine waste rock has a very wide range of (grain) size distributions. Figure 4.6 shows various grain size distributions derived from different sites (Dawson et al., 1995). It is useful to distinguish between soil-like and rock-like materials on the basis of grain size.

Soil-like waste rock has a sand content (%-2mm) greater than about 20%. This material can be potentially collapsible (Dawson, 1994) and has fairly high moisture retention properties. Figure 4.7 shows measurements of void ratio versus %saturation for in-place waste rock samples carried out by Dawson (1994). Over the void ratio range normally encountered in waste rock dumps (0.3 to 0.5), Figure 4.7 indicates that saturation levels at field capacity can be around 50%. Herasymuik et al (1995) shows that the unsaturated hydraulic conductivity (k_{unsat}) of soil-like waste rock is many orders of magnitude higher than the k_{unsat} of rock-like waste rock at suctions greater than about 0.1kPa. Preferential water flow through soil-like versus rock-like waste rock materials is controlled by the infiltration fluxes.

Rock-like waste rock has a sand content less than 20% and behaves like a rock-fill. This material has very low moisture retention, air flow is mainly by convection, and water flow is highly channelized. In end-dumped waste rock piles the coarser rock-like material tends to roll down to the toe allowing easy access of oxygen into the base of the piles.

The strategies presented here are based on selective placement of soil-like and rock-like materials to produce a dump zonation that is less likely to produce ARD. Table 4.3 provides a summary of the freeze control and climate control strategies proposed here and a discussion of each follows.

4.5.1 Freeze Control of Waste Rock

Freezing should reduce AMD potential in waste rock in the same way as in tailings. The main difference is that waste rock is unsaturated and much coarser. Therefore the frozen material could still be fairly permeable and the seasonally active layer is much greater (see Figure 4.1). The freeze control strategies proposed here consider that it is only necessary to freeze the soil-like sandy gravel materials, that the unsaturated frozen permeability is sufficient to limit air and water transport, and that there is sufficient non-acidic material to provide adequate insulation.

The first two assumptions need to be validated and the last assumption is dependent on the geochemical characteristics of waste rock at a particular site.

Figure 4.8 shows the total thickness of sandy gravel waste rock that can be frozen in one year for various placement layer thicknesses. Very substantial thicknesses can be frozen, especially in the continuous permafrost region where it is estimated that 20 to 34m can be frozen in one winter season by placing and freezing 3m lifts. The main challenge is to provide adequate insulation over the frozen material.

Figure 4.9 shows strategies that could be used for freeze control of mine waste rock. In heaped dump construction (Figure 4.9.A), where the dump is being raised in lifts normally about 2-3m high, acidic frozen material could be placed and encapsulated in non-acidic material for insulation protection. Where warm permafrost conditions are present, such as in the discontinuous permafrost regions, a coarse convective insulating blanket could be placed at the base of the pile to protect the underlying foundation from thaw degradation. A similar approach could be applied for end-dumped construction. Figure 4.9.B shows a lower acidic frozen waste, frozen in layers parallel to the dump face, encapsulated by non-acidic material. This configuration requires dumping at two different elevations. Other configurations that achieve similar benefits due to freezing are easily envisaged.

4.5.2 Climate Control for Waste Rock

Selective placement could also be used to advantage for zoning a dump without freezing to provide environmentally acceptable solutions. It is assumed that the low rainfall and cold temperatures of permafrost regions are natural buffers to ARD production such that more modest control strategies that rely mostly on the waste itself for control can be implemented. Most of the permafrost regions have annual average precipitation in the range of 100 to 400mm. Considering an average waste rock pile runoff and evaporation balance of 50%, the average annual infiltration rate is in the 10^{-7} to 10^{-6} cm/sec range. As shown in Figure 1.1, average annual temperature throughout most of the permafrost regions is less than -5°C. Data presented in Chapter 3.0 of this report indicate that sulphide oxidation reaction rates are lowered by about an order of magnitude as temperatures approach freezing. While it is clear that reliable control strategies cannot be advanced based on average climatic factors, there should still be an opportunity to use the permafrost climate to advantage to mitigate against AMD.

Some modest zoning of mine waste rock materials might provide the required environmental protection for ARD control in a permafrost environment. Consider the following zoning strategies.

1. Finer material placed over-top of the whole pile could serve to significantly reduce convective air-flow. The permeability of air in a sandy gravel material at the field capacity moisture content should reduce oxygen by several orders of magnitude compared to "dry" rock-like material commonly found at the base of waste rock piles. If the layer is thick enough (>2m) most of the evaporation should occur in the upper portion of the fine grained blanket.

2. Zoning of coarser material in a waste rock dump could also be used to advantage. Coarse material could be used for drainage control where high seepages are expected. Alternatively, at low moisture fluxes the coarse material could act as a capillary barrier to flow.

Figure 4.10 shows a design concept for end-dumped terrace construction that takes advantage of these zoning ideas. Figure 4.10.A shows the constructed end-dumped geometry with individual lifts exhibiting grading of finer to coarser material from the dump crest to the dump toe. By placing a non-acidic lift at the top underlain by a coarse drainage layer, infiltration can only reach a small portion of the acidic material. Following dump construction, re-sloping allows the finer material to seal off the lower portion of the dump limiting convective air transport through the coarser material. As with the freeze control strategies other configurations that take advantage of dump zonation are easily envisaged.

4.6 CONCLUSIONS

Freeze control of tailings would appear to be a viable strategy that takes advantage of permafrost conditions. There is a requirement for information on unfrozen water contents and frozen permeability of typical tailings materials as well as additional information on AMD reaction rates at low temperatures. In addition, there needs to be research and development of economic cover designs.

There is potential for developing modest freeze controlled and climate controlled strategies that take advantage of permafrost conditions. A general lack of understanding of water flow, air flow, and geochemical processes within waste rock dumps is an impediment to further development of reliable control strategies.

Table 4.1 AMD Control Strategies for Permafrost Regions

NOTE: Strategies in italics are considered further in this report.

STRATEGY	TAILINGS	WASTE ROCK
FREEZE CONTROLLED	*-total or perimeter freezing options can be considered* *-can freeze up to greater than 15m annually if freezing in thin layers* *-process chemicals could cause high unfrozen water contents*	*-requires considerable volumes of non-acid waste rock for insulation protection* *-better understanding of air and water transport through waste rock required for reliable design*
CLIMATE CONTROLLED	-may not be a reliable strategy for saturated tailings.	*-requires control of convective air flow through waste rock, infiltration control with modest measures and temperature control* *-better understanding of waste rock air, water, and heat transport for reliable design.*
ENGINEERED COVER	-special consideration for freeze-thaw effects -availability and cost of cover materials are major impediments	-same as for tailings -consider modest strategies offered by climate control
SUBAQUEOUS DISPOSAL	-special considerations for winter ice conditions and pipeline freeze-up.	-very difficult to dispose of waste rock beneath winter ice.
COLLECTION AND TREATMENT	-costly to maintain at remote locations -long term maintenance cost.	
SEGREGATION AND BLENDING	-tailings are normally geochemically homogeneous	-may be very effective -research and development ongoing

Table 4.2 Tailings Freeze Controlled AMD Strategies

STRATEGY	DISCONTINUOUS PERMAFROST	CONTINUOUS PERMAFROST
PERIMETER FREEZING	- established technology for design and construction of frozen dams (see appendix). - ultimately results in total freezing strategy.	- thick covers or enhanced freezing (ex. thermosyphons) required. - restricted to low dams (<5-10m)
TOTAL FREEZING	-difficult to maintain freezing conditions in discontinuous region.	- thin layered freezing could reduce containment design. - can freeze greater than 15m annually if freezing proceeds in thin layers.

Table 4.3 Waste Rock Freeze and Climate Controlled AMD Strategies

STRATEGY	DISCONTINUOUS PERMAFROST	CONTINUOUS PERMAFROST
FREEZE CONTROL	- layered freezing. - requires non-acid waste rock insulating cover. - special consideration for insulation of underlying permafrost	- layered freezing - requires non-acid waste rock insulating cover.
CLIMATE CONTROL	- ability to segregate fine (soil-like) and coarse (rock-like) waste rock. - main impediment is lack of understanding of mass transfer and geochemical processes within waste piles.	

5.0 RESEARCH RECOMMENDATIONS

Overall, this report indicates potential for developing reliable and economic strategies for AMD control in permafrost regions. However it is clear that an engineered approach is necessary. This chapter includes some research recommendations necessary for developing these strategies. First, a fully scoped out program of research for freeze control of tailings is discussed. Secondly, suggestions for an integrated program of research for waste rock dumps is proposed. The latter research is not necessarily unique to permafrost regions and could be carried out in conjunction with other research work on ARD control in mine waste dumps.

5.1 A PROGRAM FOR RESEARCH ON FREEZE CONTROL OF TAILINGS

Although this report indicates that AMD reactions are not eliminated in cold climates, there are still several advantages for encapsulating saturated frozen materials in areas containing continuous permafrost. The main advantages of this approach are that colder weather slows down chemical reactions, a large portion of porewater is immobilized in frozen ground, and frozen ground has a much lower hydraulic conductivity than unfrozen ground. However, experience in Canada's North suggests that an engineered approach is required. A lack of understanding of the properties of frozen mine waste materials and the kinetics of the acid generating reactions at temperatures below about 5°C is an impediment to the development of reliable engineered strategies. This chapter describes a research program designed to characterize acid generation in a permafrost minesite setting, quantify parameters required for predicting cold weather acid generation processes, and finally to show the effectiveness of an engineered system with a demonstration program.

The research program is designed in three phases. The first phase consists of a site characterization study. The second phase is a laboratory study using samples collected from the phase I study. The third phase is a demonstration project. Most of the discussion here is relevant to the first two phases as the final phase will rely strongly on the results of the first two phases. The following are the terms of reference used as a basis for the research program:

1. Ideally, the site will be one that shows evidence of acid generation. Minesites currently indicating AMD in a continuous permafrost setting include the active Lupin minesite and the abandoned North Rankin Inlet property (MEND, 1994a)

2. The site should be an active minesite. This will help to keep costs down and will increase the likelihood of being able to obtain reliable site records. Note that only the Lupin site meets terms of reference for 1 and 2.

3. The program has been designed for an estimated cost of about $50,000 to $75,000 for the Phase I program and $75,000 to $100,000 for the Phase II program. Program costs are difficult to estimate until a site has been chosen, although typical budgets are included here

for reference to the program descriptions that follow. Budgets included here are for guidance only and should not be relied upon for detailed costing purposes.

4. Each phase of the program, although complimentary, has been designed on a stand alone basis. Thus each phase could be carried out independently.

5.1.1 Phase 1 Program - Site Characterization and Sampling

The objective of the Phase I site characterization and sampling program is to "map" the relationship between acidic drainage, tailings materials, and thermal conditions at a minesite and to collect samples for the Phase II laboratory program. Of primary interest is to map out AMD occurrence and potential with respect to the seasonally thawing active zone.

By carrying out the program at an active site (as opposed to an abandoned site), access should be easier and better site records should be available. It is anticipated that the program would consist of preparation of background data followed by the field investigation and sampling program. A site characterization report would then be prepared that describes the site from an acid generating perspective relative to the geothermal environment.

Table 5.1 shows a typical budget for the Phase I program. A budget of $54,600 is indicated in Table 5.1 although it should be recognized that a more detailed budget needs to be prepared specifically for the site to be investigated. Note that the program has been developed based on estimated costs in the range of $50,000 to 75,000. A discussion of each part of the Phase I program follows.

5.1.1.1 Background Data Compilation

Information on the tailings containment area should be compiled prior to the site investigation. It is anticipated that the mining company would provide this information as their contribution to the study. Some of the information that will need to be compiled is as follows:

- present topography and topography underlying the tailings area.
- local and regional geological and hydrogeological conditions.
- tailings mineralogy and porewater chemistry.
- ground temperature profiles.
- site hydrology and meteorology.
- history of tailings deposition.

Most of the information should be compiled for presentation on representative plans and cross sections. Figure 5.1 shows a schematic plan and cross section showing the kind of information that needs to be compiled based on the background data compilation. Once this information has been properly compiled the field program can be planned in detail.

5.1.1.2 Field Investigation

The field investigation has been planned as a field reconnaissance and shallow drilling/sampling program. In frozen ground, the shallow (2m. deep) drilling and coring could be carried out with a CRREL core barrel attached to a hand-held power auger. This is a proven and inexpensive technique for coring permafrost soils and works especially well in sandy soils. Figure 5.2 shows a photograph of the power auger/core barrel system and a drawing showing details of the CRREL core barrel. The core barrel in the photograph was used to obtain 103mm (4 inch) diameter core in frozen oil sands fine tailings.

Approximate locations for obtaining core samples can be determined based on the background study discussed above (see Figure 5.1) and in consultation with the mine operator. The cored samples should be wrapped in plastic and stored in coolers for transport to laboratory freezer storage. As part of the characterization program the core should be visually logged and some characterization "index" testing should be carried out in order to produce a geotechnical/geochemical log for each corehole. Samples for the characterization test work can be obtained by sawing the core at selected locations, thawing the material, and carrying out the required test work. It is anticipated that the following information should be obtained as input to the corehole logs.

- moisture content
- grain size (including hydrometer and specific gravity)
- atterberg limits (to indicate clay fraction activity)
- acid base accounting
- pore water sulphate and electrical conductivity
- paste pH

Note that these are standard laboratory tests that can be carried out at a commercial soils laboratory. The main costs for the characterization labwork are for the grain size analysis (approximately $200), atterberg limits (approximately $70), and the acid base accounting tests (approximately $100) This is not meant to be a comprehensive testing program but is for characterization purposes to indicate variations in material properties and the degree of weathering that has taken place.

In addition to the frozen core samples, slurried tailings should be obtained from the tailings discharge lines. This material will be required for the test work in Phase II. Process water should also be collected for preparing samples in the Phase II program.

5.1.1.3 Site Characterization Report

All of the information collected during the Phase I investigation should be compiled and presented in a site characterization report. The synthesis of information from the Phase I study should be compiled to show the relationship between tailings materials with acid generating potential (net acid generating), tailings actually generating acid (acid pore water), and the geothermal regime (active zone, unfrozen ground, and permafrost). The report should serve both as a stand alone case history and as a document that provides input to the subsequent phases of the research program.

5.1.2 Phase II Program - Low Temperature Acid Drainage Laboratory Testing

The objective of the PHASE II laboratory program is to conduct laboratory tests designed to assess and quantify the acid generating potential of tailings at low temperatures (<5°C). The results of the testing program should provide design guidance for strategies involving freezing of mine tailings to control AMD. The key parameters that require measurement at low temperatures are frozen hydraulic conductivity, freezing point depression, and low temperature AMD reaction rates.

The program should use specially prepared "standard" samples derived directly from the tailings discharge lines in the Phase I program or fresh tailings discharge samples taken from another source. The main variables to be controlled are sulphide content and pore water chemistry. These are the most important factors that will control the reaction rates and amount of unfrozen water in sandy tailings at low temperatures.

Table 5.2 shows a typical budget for the Phase II program indicating a total cost of $90,300 (the program has been developed based on costs in the range of $75,000 to $100,000). As with the Phase I program, the budget is not a detailed cost estimate. Most of the test work is highly specialized and can only be carried out at specialized research laboratories. As a result testing costs may seem high. It is noted however that some of the equipment will need to be specially manufactured for the intended purpose, some additional replicate testing and calibration will be required, and all the tests will require very careful temperature control. Specific quotes from specialized laboratories for this work were not obtained for the purposes of the budget estimates but some enquiries were made to bracket the costs within reasonable limits.

Recent research work by Otwinowski (1995) provides insights into the thermal and chemical kinetics of the acid generating reactions in sulphide bearing mine waste. A mathematical framework for analyzing the reactions has been developed for non-frozen materials. An extension of this theory for frozen materials (which includes heat losses due to the phase change from ice to water) may be a useful extension to the program. An earlier draft of this report included this consideration but differences of opinion as to the utility and practicality of the theory remain. Thus further development of the theory for evaluating frozen materials has been left out of the program at this time.

5.1.2.1 Sample Preparation and Analysis

The program budget has been prepared based on preparing 6 "standard" samples for analysis. Clearly this may change as a more detailed research program is developed. The rationale for choosing 6 samples is to accommodate 3 samples of varying sulphide content and 3 samples of varying pore water chemistry (ie. Different freezing temperatures).

Each sample will need to have a detailed pore water chemistry and mineralogic analysis. The budget allows for $550 per sample which includes ICP scan and petroleum hydrocarbon analyses for water chemistry and X-Ray diffraction for mineralogy. The details of this analysis will depend on the specific tailings used.

5.1.2.2 Thermal Properties Testing

Specialized testing should be carried out to determine unfrozen water content, thermal conductivity, and frozen hydraulic conductivity of sulphide bearing mine tailings. Each of these parameters should be measured at a range of temperatures ranging from -10 to +5°C. Thus each of the "standard" samples should be tested in order to obtain a relationship between each of the thermal properties and temperature. A brief discussion of each of the test methods follows. Note that each sample requires measurements at 6 to 8 temperatures (over the range -10 to +5°C) in order to define the temperature dependent characteristics.

Unfrozen Water Content of soils can be measured by NMR (nuclear magnetic resonance) and TDR (time domain reflectrometry) techniques. Although TDR appears to be a more common technique for permafrost soils, the NMR provides an independent verification. This may be necessary in sulphide bearing materials. CRREL 88-18 (1988) discuss the two techniques and present data that confirms their validity for a range of soil types. Data from the testing should be compared to the pore fluid phase change behavior so that a relationship between the pore fluid freezing point depression, tailings porosity, temperature, and unfrozen water content can be obtained.

Thermal Conductivity of frozen soils can be measured by a number of different techniques. CRREL 90-24 (1990) discusses the measurement of thermal conductivity using a thermistor based system. This system can measure thermal conductivity over a wide range of values. Typical values of "fully" frozen and unfrozen thermal conductivity should be compared with typical values for natural sandy and silty soils materials.

Frozen "saturated" hydraulic conductivity can be measured by conventional techniques (flexible wall permeameter tests) under controlled temperature conditions. Clearly it is essential to ensure that the circulating fluid does not melt the frozen mass). The frozen hydraulic conductivity is related to the unfrozen water content in an analogous manner to the way unsaturated hydraulic conductivity can be related to volumetric saturation. CRREL 90-5 (1990) examines the validity of using empirical functions developed for estimating unsaturated hydraulic conductivity to estimate hydraulic conductivity from unfrozen water content.

5.1.2.3 Low Temperature Kinetic Testing

Isothermal tests to determine the low temperature AMD rates should be carried out using specially designed humidity cells. It is important that the cells are maintained at a constant temperature inside and out, although this may be very difficult due to the exothermic nature of the AMD reactions. The cells should be equipped with both external and internal temperature and oxygen detection sensors.

The program budget assumes that about 8 tests can be carried out for $48,000 ($6,000 per test). Costs include weekly chemical analyses for periods up to one year. It is thought that each of the 6 standard samples could be tested at a temperature just above freezing (say 2°C) and then one sample could be chosen for testing at sub-zero temperatures (say -10 and -5°C). By testing most of the samples above the freezing point, testing is much easier as it may not be practical to flush the sample without thawing due to the very low permeability. Clearly other testing scenarios will need to be evaluated as the program is developed in more detail.

5.1.2.4 Laboratory Report

The laboratory report will integrate the findings of the test work into a coherent framework. It is hoped that the results will provide a quantitative understanding of the relationship between temperature and freezing point depression, unfrozen water content, frozen hydraulic conductivity, and AMD reaction rates for each of the prepared samples. This should provide insights into threshold values of pyrite and unfrozen water beyond which freezing should not be considered as a viable strategy for AMD mitigation. Thus the phase II program should provide valuable data for an enhanced scientific understanding of the AMD problem at low temperatures and for the engineered design of freezing systems to mitigate AMD.

5.1.3 Phase III Program - Field Demonstration Test

The main purpose of the PHASE III program is to conduct a demonstration experiment that integrates findings of engineering significance from the PHASE I and PHASE II programs. There are several aspects of ambient engineered systems that may require field appraisal such as:

- practical aspects of thin layered freezing systems may require field demonstration. Cold weather poses problems for tailings disposal systems.

- history matching of the thermal environment with numerical models may help to define their validity.
- field demonstration of different insulated cover designs should be part of the Phase III program. A test site should be established to investigate insulating properties of 2 or 3 different concepts. One of the concepts should be a convective rockfill cover.

- a long term monitoring site would be useful to validate the approach.

The phase III program should be scoped out once the previous phases are underway. Thermistor strings installed during the phase I program would provide useful baseline data for the demonstration program.

5.2 WASTE ROCK RESEARCH RECOMMENDATIONS

Acid drainage control strategies discussed in this report are focused on an "engineered" approach to waste dump construction. A lack of understanding of processes acting within waste dumps is an impediment to further development of these approaches. A research program focused towards controlling ARD through dump zoning, segregation, and blending is required. It is understood that MEND is already carrying out studies focused towards segregation and blending of alkaline and acidic waste rock to produce a neutral leachate. Additional work is required to understand heat and mass transfer processes within waste rock piles. A specific program is not outlined here as this work is not necessarily unique to permafrost conditions. Some recommendations for an integrated program of research follow:

- conduct waste rock characterization studies at several sites. Information collected should include source rockmass properties, grain size, moisture content, and in-situ measurements of field capacity, suction, permeability, and void ratio. Develop a classification system.

- conduct laboratory investigations to establish soil water characteristics, compressibility relationships, thermal properties, and acidic reaction rates at low temperatures (low temperature humidity cell tests)..

- construct bench scale physical models with different dump stratigraphies, monitor mass transfer processes, and calibrate suitable numerical models.

- design and carry out field experiments to measure performance of suitable strategies.

Table 5.1 Typical Budget for Phase I Program

1. BACKGROUND DATA COMPILATION	
-Office Work : 40 hours @ $80.00/hr	$3,200
-Miscellaneous (drafting, typing, long distance, typing, etc.)	$1,000
SUBTOTAL	**$4,200**
2. FIELD INVESTIGATION	
-Site Work : 2 persons for 4- hours ea. @ $80.00/hr	$6,400
-Travel:2 persons @ $2,500 ea. for 1 weeks travel (includes airfare, meals and accommodation)	$5,000
-Characterization Test work: 30 samples @$500 ea.	$15,000
-Field Supplies	$2,000
SUBTOTAL	**$28,400**
3. SITE CHARACTERIZATION REPORT	
-Report Preparation: 200 hours@$80.00/hr	$16,000
-Drafting: 50 hours @$60.00/hr	$3,000
-Typing: 40 hours @$50.00/hr	$2,000
-Miscellaneous (long distance, faxes, couriers)	$1,000
SUBTOTAL	**$22,000**
TOTAL	**$54,600**

Table 5.2 Typical Budget For Phase II Program

1. SAMPLE PREPARATION AND ANALYSIS	
-Pore water chemistry: 6 samples @$350.00 ea.	$2,100
-Mineralogy: 6 samples @ $200 ea.	$1,200
SUBTOTAL	**$3,300**
2. THERMAL PROPERTIES (measured over a temperature range varying from -10 to 5°C)	
-Thermal conductivity: 6 Samples @ $1,000 ea.	$6,000
-Unfrozen water content: 6 TDR and NMR Samples @$1,000 ea.	$7,000
-Unfrozen/frozen hydraulic conductivity: 6 samples @ $1,000 ea.	$6,000
SUBTOTAL	**$19,000**
3. LOW TEMPERATURE KINETIC TESTING	
-Isothermal humidity cell tests: 8 tests @$6,000 ea.	$48,000
SUBTOTAL	**$48,000**
4. LABORATORY REPORT	
- Analyses of laboratory data	$10,000
- Report preparation	$10,000
SUBTOTAL	**$20,000**
TOTAL	**$90,300**

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APPENDIX A A REVIEW OF EXPERIENCE RELATED TO COLD WEATHER DAM DESIGN AND CONSTRUCTION

Large areas of the North American and Asian continent are controlled by cold weather. Construction in these cold regions has to account for some very specific conditions which are not encountered in more temperate environments. The engineering design of a structure subjected to these conditions has to address issues associated with the specific properties of perennially frozen ground, consider implications of its thawing, incorporate appropriate measures for protecting or removing the permafrost and account for the length of the construction period, when the summers are typically short but the winter season is long and severe. This appendix provides a review of design and construction practices for impoundment structures constructed on permafrost. The objective is to identify the governing design issues, engineering solutions and approaches and demonstrate them on outstanding case histories.

A.1 STATE OF THE EXPERIENCE

Generally two concepts may be adopted for dams in cold climates primarily according to the severity of the weather, and the character and size of the structure: the frozen (or cold) or unfrozen (or warm) dam design and construction approaches. The main design issues for unfrozen dams in cold climate is accounting for the frost penetration into the core, shells, and foundation, and assessment of implications of foundation settlement and thaw weakening on the stability and integrity of the structure. While the unfrozen dam is technically no different than a conventional dam, the frozen dam concept is fundamentally different. The integrity of the dam relies on strength and seepage control provided by the material in a frozen state. Hence the main design and construction issues are in producing and maintaining the frozen foundation and body of the dam. This frozen dam design approach is of the primary interest in this appendix. The main literature source for this appendix were review papers by D.L. Kane (1974) and R.N. Seemel (1976), Guidelines For Tailings Impoundment In The Northwest Territories (1977), and Permafrost Engineering Design and Construction edited by Johnston (1981).

There are some undisputed advantages to the frozen dam concept :

- Virtually any construction material is conceivable even for the core
- Frozen body of the dam and foundation can provide both structural and seepage integrity
- Liquefaction susceptibility is virtually eliminated
- Construction season may be shifted into the longer winter period

However, consideration must be given to the fact that frozen dams may operate under very delicate thermal regime and relatively minor disturbance can result in uncontrollable permafrost thawing (Petrovsk Dam, Russia) or in an expensive remedial artificial refreezing program.
Dams utilizing both the frozen and unfrozen design concepts have been successfully built and operated. However, this conceptual choice must be explicit and the full implications of the decision must be transferred in the design.

The most extensive experience with dams in permafrost is, without any doubt, from Russia. The database of published cases dates back as far as 1792 for a dam which operated satisfactorily till 1929. Unfortunately, it appears that the reporting activity from the former USSR decreased during the last two decades and most of the available information is on projects undertaken in the 1930's to the 1960's. Typically these projects are water impoundment structures about 5 to 15 m high. The literature describes a number of such successful projects and it appears that the comfort level with a low to medium head dams in Russia is relatively high. The frozen dam design concept has been typically adopted for dams to a maximum height of 20 m. For larger dams, up to 126 m high (Kolyma Dam, Russia), the unfrozen, i.e., classical, design concept is typically adopted, apparently due to risks associated with developing and maintaining of large frozen zones above ground.

The North American experience is less extensive and is mainly from Alaska, N.W.T., and from Greenland. Well documented case histories are from water impoundment projects (Hess Creek, Alaska) and gold mine tailings pond dyke (Lupin mine dykes, N.W.T.) .

Scandinavian experience appears to be limited to the unfrozen dam construction system. The reason is that the climate is milder due to the weather controlled by the Gulf stream.

Most of the dams in cold weather regions were built for water management purposes either as water impoundment structures or as hydroelectric reservoirs. Applications of cold weather design concepts to dams as tailings impoundment structures are less frequent. A very specific issue associated with this application is accounting for the change in the water freezing temperature due to contamination of the stored material.

Construction methods differ according to the type of the structure and the design concept. They range from hydraulic fill dam construction (Hess Creek Dam, Alaska), fill freely dumped into the water (Lupin Mine Dyke J), to the prevailing compacted fill construction method.

A.1.1 Russian Experience

In a typical case of a Russian frozen dam the core is artificially frozen by a cooling system and the downstream slope is left to freeze naturally. Ultimately, when the thermal equilibrium is established the cooling system is shut off and the dam is further operated without cooling assistance. A typical Russian frozen dam (Fig.A.1) is built on a competent foundation after removal of the ice-rich surficial soil and all the thawed under-river talik. Sometimes only a core trench is excavated in the competent material and the core is refrozen to provide a reliable seepage barrier. The construction schedule is arranged so that the stripped foundation will be well frozen when the initial unfrozen fill is placed. Failures of the frozen dams typically occurred because of inadequate cut-off resulting in excessive seepage and/or settlement as thawing took place.

Different types of cooling systems were used for freezing the core and/or refreezing of the foundation. The first cooling systems used brine as the coolant. However, these systems proved inefficient and were replaced by cold-air and later by vapor-liquid cooling systems. During the 1940's and 1950's it was common to build a wooden shield along the downstream slope to enhance convectional cooling in the winter and provide insulation in the summer (Portovyy Creek Dam, Nalednaya River Dam). The following case histories describe projects which demonstrate important design and construction issues. The main sources for this compilation work were reports by N.A. Tsytovich, N.V. Ukhova, and S.B. Ukhov (1972), technical note by T.C. Johnson and F.H. Sayles (1979).

Petrovsk Dam on Mykyrt River (Fig. A.2) was completed in 1792. Mean annual air temperature in the area is -4.1^{o}C. This water retaining structure was 9.5 m high and 320 m long. The dam was built during several winter periods by consecutive freezing of piled soil with the intention of maintaining it in a frozen condition during operation. The body of the dam was built of heavy powdered sandy loam with a hydraulic conductivity of 10^{-8} m/s. The construction was conducted in a wooden trough installed in a wooden cribwork through which the material was first dumped and then flooded with water and frozen. The dam operated satisfactorily for 137 years. In 1929 the investigation during the repair work on the spillway revealed that substantial parts of the dam and the spillway foundation were still in frozen condition. The repair works were undertaken during the warm season with no protective measures adopted for the open excavation. As a result a talik formed in this zone which could not be successfully curtailed. By 1934 the entire body and the dam base had thawed and in 1938 the condition of the dam became threatening and a decision was made to rebuild the entire dam.

It is not entirely clear, whether the failure was caused by disturbing the thermal regime of the dam during the spillway repair work. Some Russian scientists argue that it is possible that by that time the cold "reserve" accumulated during the construction had become exhausted and the errors during the repair operation only accelerated the thawing process. Nonetheless, this case is an example of delicate thermal regimes which may exist in frozen dams.

Another good example of the thermal regimes affecting the performance of the structure is the Upper Kumakhskaya Dam on Kumakh River in the North of Yakutskaya Republic (Fig. A.3). This dam was built from 1940 to 1942 and was 7 m high and 90 m long. The permafrost in the area reaches to depths of about 300 m. The dam was built in the summer around a watertight wooden sheet pile diaphragm in manually placed 10 cm thick lifts of sandy loam on river foundation with gravelly-pebbly interbedding. In the fall, the reservoir with the partly finished dam was filled and the dam was finished during the next spring. During this initial period of operation a seepage was reported and transverse cracks showed in the body of the dam. Following the 1942-43 winter, without implementation of any remedial measures, the seepage practically stopped and the dam functioned properly. The experience gained from the performance of the Upper Kumakhskaya Dam is valuable in view of the effect of the cold reserve in the surrounding permafrost which provided the necessary cooling action which froze the dam from the sides and the bottom and averted the development of an extensive seepage threatening the global stability of the dam.

The importance of the above described phenomena can be appreciated in the view of the performance of the Pravaya Magdacha Dam (Fig. A.4) built in 1930's in Siberia. The dam was built as a low head dam adopting an unfrozen dam concept and was about 7.3 m high. The body of the dam was formed of clayey soil built directly on intensively eroded fissured porphyrites. As a watertight element a rigid concrete diaphragm was embedded 0.5 m into the bedrock. Immediately following the filling of the reservoir the porphyrites in the dam base began to thaw and seepage of water began. The seepage gradually increased to 60% of the total discharge of 8000 m^3. This thawing led to major subsidence and stress redistribution within the dam. Eventually cracks in the concrete diaphragm and in the spillway area developed and the dam failed. In this case the surrounding cold reserve was not capable of sustaining a frozen foundation. However, deeper embedment of the concrete diaphragm could have limited the seepage and precluded the thawing in the dam base. Similar failures were also reported from dams on several tributaries of the Kolyma River where foundation thawing resulted in excessive seepage and deformations and resulted either in dam failure or in an expensive continuous maintenance program.

The dam on the Portovyy Creek in the Western sector of the Russian Arctic (Fig. A.5) is a good example of a frozen dam built gradually by freezing in layers. The climate in the area is extremely severe with mean annual temperature of -10.5^{o}C. This 2.5 m high water supply dam was built in 1942 and was gradually raised to 7.5 m by 1965. The body of the dam was built of loam. For protecting the downstream slope from the warming effects of solar radiation and to allow free circulation of cold air in the winter a wooden shield was provided along the downstream face. The upstream slope was built at shallow dip of 4(H):1(V) and was protected by 0.3 m of rockfill rip-rap which also augmented the freezing affect of air convection on the body of the dam. Currently the dam maintains a stable thermal regime with temperatures in the base and the body between -3 to -5 ^{o}C.

Similar construction system was adopted for the Nalednaya River Dam near Noril'sk (Fig. A.6); impounded in 1951. This frozen dam was 7 m high and had a clay concrete core with shells of thawed compacted loam on the upstream part and a frozen downstream shell. The downstream shell was built in the winter in layers, flooded with water and frozen. A wooden shield similar to that built on the Portovyy Creek Dam was built along the downstream slope. The dam was equipped with one line of air-based cooling pipes to support freezing of the core and river talik. The dam operates well with fully frozen talik at an average body temperature of -2^{o}C.

In order to gain experience with frozen dam construction, an experimental dam on Irelyakh River (Fig. A.7) was built in 1961 near the city of Mirnyi. The mean annual air temperature in the area is -8.2 ^{o}C and the permafrost reaches depths of 300 m. Apart from the water supply function to one of the industrial enterprises, the purpose of this 4 m high experimental dam was to develop a design procedure for dams built of local materials with a frozen core erected during one winter season. Natural freezing of the dam core in the process of construction and its subsequent operation without forced cooling was envisaged by the designers. The construction of the core took place in the winter and was carried out in layers which were flooded with water and left to freeze. The upstream and downstream shells and the crest were piled in the spring and compacted. The submerged portion of the upstream face was constructed at a dip of 5(H):1(V) to provide insulation of the core from the impounded water. The structure performed well except for some seepage in the spillway area which was eliminated.

A short distance upstream from the experimental dam, the much larger Irelyakh River Dam (Fig. A.8) was constructed from 1961 to 1964. This 20 m high dam introduced a new approach to dam construction in cold regions, since it was operated as an unfrozen dam during the first year and later was converted into a frozen dam after implementation of an air-based cooling system. The core was successfully frozen using 207 pipes spaced 1.5 m. Nevertheless, additional cooling pipes had to be installed in the downstream toe to support freezing of the downstream shell. Despite the original plan of only a temporary use of cooling systems, it was found necessary to operate the system at least for about 1.5 months each winter. A horizontal cooling system was used to protect the spillway bed which is now in deplorable condition and requires continuous maintenance. Presently the dam operates satisfactorily.

The design of the above Irelyakh River Dam's cooling systems was based on the experience gained during construction of the Dolgoye Lake Dam near Noril'sk (Fig. A.9) from 1941 to 1943. This 10 m high and 130 m long dam was designed as a frozen dam with an assistant cooling system. The cooling system was expected to operate only until the clayey concrete core and the downstream sandy shell froze. However, due to major problems with the efficiency of the cooling system, it had to be used for 13 years. Initially a brine-based cooling system was adopted and proved highly inefficient, since the brine was at times actually warmer than the ambient air due to self-heating caused by the energy generated as it circulated through the pipes. Moreover, the brine precipitated inside the pipes and caused plugging which also decreased the efficiency of the cooling system and caused corrosion of the pipes. Moreover, the insulation effect provided by the 4 m thick snow cover on the downstream shell of the dam during the winter diminished the contribution of the natural freezing. Eventually the brine-based cooling system was replaced by an air-based cooling system which ultimately delivered the necessary freezing effect. The thermal regime achieved stability after 13 years at which time the cooling system was put on reserve.

Another dam whose success depended heavily on implementation and operation of the proper cooling system was the Anadyr' Dam on Chukotka peninsula in the far East of Russia (Fig. A.10). The mean annual air temperature in the region is -7.4 ^{o}C with perennially frozen soil of up to 150 m deep. The construction of this 17 m high dam commenced in 1976. The dam was designed as a frozen dam constructed in two lifts. The core is a broken rock with 30% sand and the upstream shell is built of gravelly soil while the downstream shell is a rockfill. The base of the dam was constructed in the summer and left to freeze in the winter. The second lift was put on the next summer and again left to freeze the following winter. Due to the great thicknesses of the lifts the layers did not freeze during the winter and some unfrozen material was left inside each layer. Recognizing the disadvantages of a cross-section that would have a partially unfrozen core and 6 m deep river talik of alluvial deposits for several years a decision was made to freeze these unfrozen zones using newly developed vapor/liquid freezing piles utilizing freon as the cooling medium. These piles proved superior to the air-based cooling systems used on the Irelyakh Dam. Currently the entire dam is frozen and stable.

The Vilyuy Dam (Fig. A.11) built during 1970-1974 100 km North of Mirnyi in Yakutia in Russia is an example of an unfrozen dam built in an extremely cold region with continuous permafrost. The mean annual air temperature in the area is -8.2 ^{o}C and the permafrost in the area extends to 200 to 350 m depth with through-talik under the river. The dam was to be 75 m high. Such a height was entirely unprecedented for the frozen dam design. It is a good example of a dam, where the natural factors favored a frozen dam design concept but the size of it eliminated that design option and the dam was designed as unfrozen. The core of the dam was built of silty clay, the shells were rockfill. The foundation was fissured and fractured but thaw-stable (does not deform during thawing) dolerite bedrock. In order to restrict the seepage through the foundation, a sequential foundation grouting program was designed to grout the bedrock as it was thawing from a specially designed gallery during the operation of the dam. Core freezing was prevented by building an inclined core and in so doing exposing a larger area to the upstream water. An unexpected phenomenon developed in the downstream rockfill shell. Air convection in the rockfill caused freezing of the downstream shell and extended to freeze the river talik to about 54 m depth by 1977. This frozen talik limited the need to grout and eventually the grout curtain only to about 70 m depth was needed. Currently the dam performs satisfactorily.

Another instructive example of an unfrozen dam in an extremely cold region is the Kolyma River Dam (Fig. A.12) built during 1979-1984 in a region with an exceptionally low mean annual air temperature of -12^{o}C and permafrost depths varying between 20 and 300 m. Again, due to the size of the dam the unfrozen dam design system had to be adopted. This dam is 128 m high. The foundation of highly fissured granite (k=10^{-3} m/s) and through-talik under the river required special attention since possible consequences of thaw deformations could be catastrophic for such a large dam. Unlike in the case of the Vilyuy Dam, where a sequential grouting program was adopted, the highly fissured bedrock was prethawed and grouted to a maximum depth of 65 m before filling the reservoir. The thermal analysis showed the 0^{o}C isotherm would be in the downstream transition zone which was found favorable since the vertical silty clay core could retain some flexibility to accommodate moderate frost or seepage related deformations. To ensure that the core would not freeze and that the downstream rockfill shell remained unfrozen, special design measures had to be adopted to limit the phenomenon observed in the Vilyuy Dam - air convection through the shell. This was accomplished by covering the outer slope of the downstream rockfill with an insulation blanket of broken rock and finer material. Information about the current performance of the dam could not be obtained.

A.1.2 North American Experience

The North American experience is somewhat less extensive, however some outstanding cases are well documented in the literature. Several low head dams have been constructed near villages in Alaska for the purpose of water supply. No special measures were needed for these projects because of the low hydrostatic heads that result in minimum seepage.

The Hess Creek Dam (Simoni 1975, Rice, Simoni 1963) (Fig. A.13) built from 1940 to 1946 in Alaska near Livengood, which was built by hydraulic fill construction. The purpose of the dam was to retain and divert water into a tunnel that supplied water to a nearby gold mining operation. The dam was designed as a frozen dam 24 m high and 485 m long. The construction proceeded in two stages with an unplanned 5-year interruption. The first stage consisted of subgrade preparation, sheet pile cut-off wall installation in a steam-thawed trench and toe-area rolled-fill coffer dam construction to contain the hydraulically placed fill. To ensure a positive frozen bond between the foundation soil and the hydraulic fill a horizontal freezing system was implemented along the centerline of the foundation. Vertical freezing pipe was installed in the embankment foundation where the cut-off wall crossed the creek to assure freezing of the sheet piles in the creek bed talik. Another horizontal freezing system was installed in the toe areas to enhance the resistance between the fill and the foundation. Fill was then placed hydraulically between the two cofferdams to about 15 m height. The fill material from nearby borrows ranged from silts to skip-graded silty sands and gravels. The fill was placed by discharging from the coffer dams towards the centerline of the dam which produced the natural segregation and development of the finer-grained center zone. After each lift the coarser shell material was leveled and shaped. There is no mention in the literature of any additional compaction of the hydraulically deposited material. Although the records are inconclusive, it is speculated that some silt was separately added to the central zone to augment fines in the core. The works were suspended during the winter of 1941 and halted until spring 1946. The remaining portion of the dam about 10 m high was mechanically placed and compacted during the summer of 1946 by standard methods for roll-fill dams. Considerable difficulty was encountered in rolling equipment operation caused by liquefaction of the core.

According to the available records, the Hess Creek Dam operated satisfactorily during the gold mining activity from 1946 to 1958. Shrinkage cracks about 3 m deep appeared across the crest and extended into the downstream face of the dam. It is speculated that the cracks on the upstream face were not reported since they were covered by the rip-rap. The observed cracks were repaired by manually excavating and backfilling with an impervious material. Also 2 minor slides appeared at the base of the upstream face. Seepage through the dam during the operation in the summer periods was steady around 0.21 m^3/s. An extensive wave action in the reservoir due to extremely windy conditions produced 0.5 to 1 m wide berms spaced 0.5 to 1.5 m apart. A shore-anchored log boom was floated in the reservoir near the dam face to minimize wave action.

Apart from the artificial cooling system described above, which was utilized during the construction period till 1946, the reservoir was emptied each fall (1946 - 1958) to enhance natural freezing of the dam body in the winter period. However, the dam did not freeze and in 1964 the permafrost boundary was found just above the native ground. As a result the dam fill settled 0.5 m during the period from 1941 to 1946 and by another meter after construction of the rolled fill. These magnitudes are considered typical for unfrozen hydraulic fill dams. Nonetheless, this rather large settlement did not affect the performance of the dam since it was rather uniform along the length of the dam and did not extend into the foundation which remained frozen during the operation of the dam. The hydraulic fill provided a good insulation and seepage barrier which inhibited foundation thaw-out. This fact was the key to the successful performance of the dam, since the loss of stable frozen foundation is the most common cause of frozen dam failure. It is speculated that the hydraulic fill resisted freezing because it was loosely placed. The dam was abandoned after the reservoir overflowed during the 1962 spring run-off which severely scoured the spillway channel.

The Lupin Mine Dykes (Dyke 1A and Dyke 2) (Dufour, Holubec; LaFlache et al 1987) (Fig. A.14) were built to contain gold mine tailings in the continuous permafrost region of the

Northwest Territories, Canada. The mean annual air temperature in the area is -12.1^{o}C. The project is composed of several dykes built of compacted silty sand overburden on frozen silty sands with no excess ice on phyllite fractured to 1.5 to 3 m depth. The dykes reviewed here are the 6.5 m Dyke 1A and the 8.5 m Dyke 2.

The construction of the dykes proceeded in two stages. In 1981, during the first stage, immediately after stripping the surficial organics and hummocky soil, a 5 to 7 m core of compacted silty sand overburden was built on downstream drainage blanket. The subgrade stripping was immediately followed by fill placement to minimize permafrost degradation of the in situ till. The core was covered with an impermeable PVC liner to control seepage during the first few years until the foundation permafrost aggraded into the dam core. The liner was then covered with clean sand and protected by rip-rap. During the second construction stage in 1984 an additional 1.5 m of end-dumped random borrow was placed to form a shell on the downstream side of the dyke.

During the first winter the fill of Dyke 2 froze completely. The fill of Dyke 1A located over a former creek section froze completely but the talik beneath the old creek bed remained unfrozen. In the summer 1982, immediately after the first tailings impoundment, a seepage through the talik appeared on the downstream slope of the dam and a downstream blanket was built to ballast the dam toe along with an upstream silty sand blanket to lengthen the seepage path. It is believed that most of the seepage took place through the upper 2 m of the highly fractured bedrock. The talik froze about 4 years later. It is believed that snow clearing at the dam toes played a significant role in the talik freeze-back. Scheduled lowering of the pond elevation proved to be beneficial for freeze-back of the talik. In the summer of 1984 the pond water level reached above the base of the active layer of the hill between the two dykes and produced some seepage through the abutments.

Currently both dams perform highly satisfactorily. No seepage was ever recorded through the Dyke 2. The seepage through Dyke 1A was primarily controlled by the unfrozen talik of fractured bedrock and was almost eliminated after the talik freeze-back.

Dyke J was built in 1985 within the above described Lupin Mine tailings pond to divide the pond into two parts for water treatment purposes. The dyke is 13 m high and was built in the winter by dumping (waste rock) through the ice in a 7 m deep pond. The dumped material is relatively permeable and was unable to maintain a fluid head across the dam. Hence during the summer dry tailings were placed against the upstream side in a thin layer. During the following years the dyke was widened in an attempt to seal the dam. It was observed that the contamination in the tailings pond caused depression of the freezing point by an estimated 0.3 ^{o}C. This observation emphasizes the need for thorough understanding of the chemical and physical processes taking place in the tailings pond and their effect on behavior of a frozen structure. Ground radar was successfully used to map unfrozen areas within all dykes.

The Crescent Lake Dam (Fulwilder 1973) was built on the west coast of Greenland from 1952 to 1959 for water supply purposes. The mean annual air temperature in the area is -11.4 ^{o}C. The dam was built as a frozen dam constructed in several lifts. In September of 1952 the dam was built to 3.6 m height and was raised to 6 m by 1955. It reached its final height of 6.25 m in 1959.

At that time the dam was 400 m long. After the first lift, freeze-back of the embankment fill and the subgrade occurred well before the end of the freezing season. However, one more winter was needed to establish a stable thermal regime within the dam. After the lift to 6 m was placed in July of 1954, some seepage occurred in September through the freshly placed fill. The seepage stopped by late October and no significant seepage was reported afterwards. Also this lift required 2 winters to establish a stable thermal regime. It is speculated that the limiting height in that area for complete freeze-back in one winter may be as much as 6 m. Currently the dam performs well even though the operational requirement to keep the water elevation below the base of the active zone was not strictly adhered to.

A.2 DESIGN AND CONSTRUCTION ISSUES OF FROZEN DAMS - SUMMARY

In North America only a few small structures have been built on permafrost unlike in the former USSR, where a number of large and small structures have been founded in the permafrost region. The majority of these dams are earth fills because of the technical advantages of flexible structures requiring less strength in the foundations and the economy in utilizing local materials. Both frozen and unfrozen concepts are used. In the zone of discontinuous permafrost, maintaining the dam in a frozen condition is difficult and virtually impossible to achieve economically. Regardless of the nature of the permafrost and the climate, broad cross-sections with flat slopes are almost always the rule. The Russian experience recommends constructing unfrozen dams on rock or soil foundation with a settling factor (relative deformation ?) of less than 0.05 with no interlayers of ice. Frozen dams are recommended for non-rock foundations with settling factor over 0.05 (Biianov 1976). The frozen dam concept is an extremely viable concept for dam construction in cold areas with perennially frozen soil where it was found to be most expedient from the technical and economic standpoint. Apparently no concrete dams have been founded on permafrost.

For the frozen dam concept the most pressing designing and construction issues are those associated with maintaining frozen foundation and producing a frozen barrier within the dam. Both issues are primarily addressed by limiting the seepage, which may cause thawing of the frozen soil, and by insulation of the frozen zone from the retained water. All documented failures of the dams on permafrost were seepage and NOT strength/stability related. Typically a failure was initiated when a concentrated seepage path developed either in the dam foundation or in the body of the dam.

A.2.1 Foundation Considerations

Most of the practical experience is derived from projects involving river water retaining structures. These structures are typically founded on sometimes rather extensive taliks. Sealing-off of these zones of unfrozen soil has to be addressed in the design since they are typically composed of alluvial deposits on fractured permeable bedrock. The measures may include implementation of the cut-off trenches or walls along with a temporary assistance cooling system. For mine waste retaining ponds having to deal with an unfrozen talik may be avoided by an appropriate selection of the construction site.

Frozen foundation failure typically occurs when the cut-off is not sufficiently deep and an active seepage pattern can develop and cause foundation thaw out. However, in cases of rather narrow channels and an extensive surrounding permafrost, the foundation may be able to refreeze due to the great cold reserve in the area before the seepage develops into dangerous proportions (Kumakh River Upper Dam). Spillways, for that matter, are exceptionally sensitive construction elements since the water is not isolated by large volumes of soil from the surrounding permafrost. Maintaining a frozen zone around the spillway channel may be very challenging from a design point of view and still may require a continuous maintenance program (Irelyakh River Dam) or if the situation becomes unmanageable it may lead to redesign (Petrovsk Dam) or abandonment of the dam (The Hess Creek Dam).

To protect and/or maintain frozen foundation the following measures and issues are typically considered :

- to prevent thawing of the foundation seepage prone alluvium should be removed, however if the alluvial deposits do not contain ice in the soil structure and are of low permeability, the alluvium deposits may be left in place

- to prevent thawing of the foundation during construction, there should be no delay after stripping

- to prevent seepage through the foundation, frozen loam cut-off trenches to the depth of intact permafrost or impermeable bedrock, should be installed; the function of these cut-off trenches may be enhanced or replaced by implementing a sheet pile wall or a concrete diaphragm

- for mine waste storage applications the need to refreeze the foundation may be reduced by appropriate selection of the construction site to avoid existing taliks and unfrozen zones

- large cold reserve in the surrounding area may be taken into the account to assist freezing of smaller taliks (Kumakh River)

- to enhance freezing of the dam foundation as well as the body of the dam an unhindered exposure to the winter cold should be maintained by regular snow removal

- for smaller dams the thin surficial organic-rich layer may be left between the dam and the foundation to provide insulation

- construction of unfrozen dams on frozen, potentially permeable, alluvium should be avoided unless an expensive continuous grouting program can be implemented to cut-off the seepage as the foundation thaws

A.2.2 Dam Cross-Section Considerations

Typically, a frozen dam has a frozen central and downstream part while the upstream zone which is in contact with the water acts as an insulation buffer and remains unfrozen. In some instances the upstream water level control was used to enhance freezing from the upstream side (Lupin Mine Dykes, The Hess Creek Dam). To provide insulation of the downstream frozen part from the upstream water, upstream slopes of 5(H) :1(V) may be adopted. Cold air convection through the rockfill shell may be beneficial for the freezing of the core, however, for unfrozen dams it can be detrimental since frozen core would become brittle and could crack on an unfrozen compressible foundation. Air convection may be created on the downstream face by sheltering the slope with a shield. The draft of the cold air in the winter period through the gap between the shield and the downstream slope face is controlled by a system of closed or open vents. The vents are closed in the summer and the entrapped air provides insulation from sun rays. Turf cover has been used on the downstream slope to provide insulation.

In frozen rock-earth dams the core is constructed of nonfrozen soil with assistant artificial freezing (Anadyr' Dam). It is possible to construct frozen dams of frozen soils with layer by layer freezing. Freezing may be augmented by flooding the layers with water. The system of building the dam by the layer by layer freezing appears to be a very reliable construction method. All of the dams constructed using this approach performed well and the initial seepage which may have taken place in some eventually ceased as the dam froze. Experience from the Crescent Lake Dam and Anadyr' Dam suggests that lifts of up to 6 m may be frozen during just one winter period.

Special attention has to be given to the compaction of the construction soil, since good compaction cannot be obtained if the soil is frozen. However, some experience has been gained in the construction and successful use of dams of frozen soils which were allowed to thaw during use.

Design freeboard of water retaining structures is controlled by the depth of the active zone. Some seepage has been recorded through the abutments of the Lupin Mine Dykes when the pond level reached above the base of the active zone. Temporary higher pond water level elevations did not cause any core thawing in the Crescent Lake Dam.

For waste storage operations a consideration has to be given to the effect of the retained material on the freezing point of the water. In the Lupin Mine tailings pond the depression of the freezing point was estimated at about 0.5 ^{o}C.

It is difficult to categorize the construction systems of frozen dams into distinct categories, since the experience is relatively limited and there is no universally accepted construction system. Rather, each dam has its distinct character based on its size, climate, construction material, purpose and importance. The following summary presents one way of categorizing for the frozen dams :

- dams constructed with the use of freezing systems (Irelyakh River Dam, Myaundza River Dam, Dolgoye Lake Dam, The Hess Creek Dam)

- dams constructed in layers with artificial freezing system assistance (Anadyr' Dam)

- dams constructed in relatively thin layers which are left to freeze during the winter period (Crescent Lake Dam, Petrovsk Dam, Portovyy Creek Dam, Kumakh River Upper Dam)

- dams where the core and the shells are constructed separately using different methods Irelyakh River Experimental Dam : core constructed in frozen layers during one winter upstream and downstream shells and the crest piled in the spring and compacted

Nalednaya River Dam :
core constructed of clay concrete
downstream shell constructed in frozen layers
upstream shell constructed of thawed soil

Lupin Mine Dyke 1A and 2 :
core built at once, covered with PVC liner and left to freeze
downstream shell and crest constructed later

In summary, to produce and/or protect a frozen dam the following measures and considerations are typically contemplated :

- shallow upstream slopes up to 5(H) : 1(V)
- winter cold air convection - summer insulation downstream shields
- air convection through the shells constructed of rockfill
- winter snow disposal to reduce its insulation effect
- emptying or lowering of the reservoir in the winter to augment cold air freezing
- to ensure sufficient compaction the material has been dried in rotary kiln dryers which also extends the summer construction period, however this solution does not appear practical for most projects
- in case of no construction compaction the layers of material can be flooded with water and left to freeze
- the upstream slope of The Hess Creek Dam constructed of hydraulic fill had to be protected by a shore-anchored log boom floated in the reservoir near the dam face to minimize wave action which was producing rather extensive berms when the reservoir level was below the rip-rap·storage of contaminated material may lead to a change of the freezing point

- hydraulically placed fill may be susceptible to liquefaction during both localized operation of heavy vehicles and from the overall stability point of view.

A.3 LITERATURE

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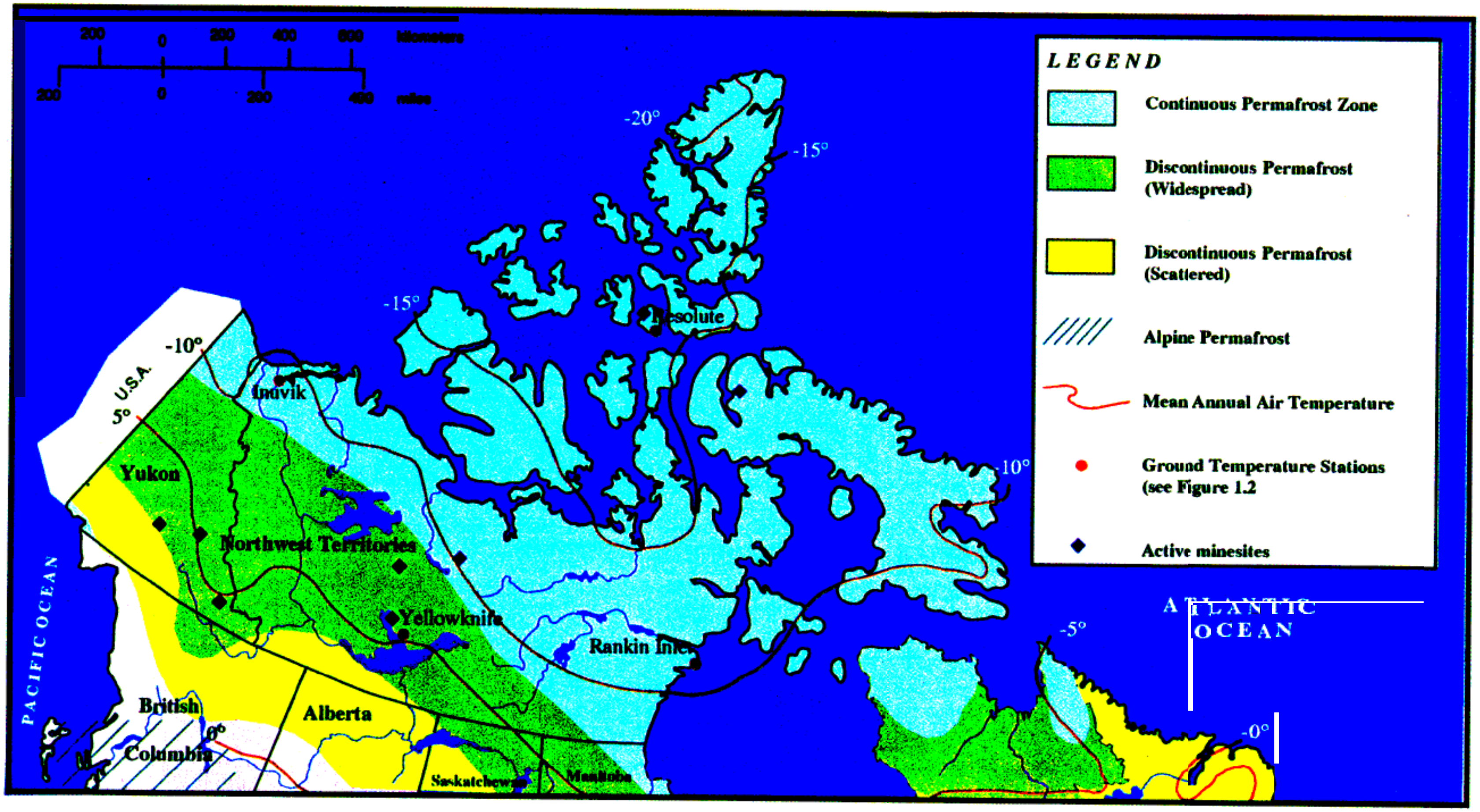
FIGURES

Figure 1.1 Canada's Northern Permafrost Regions



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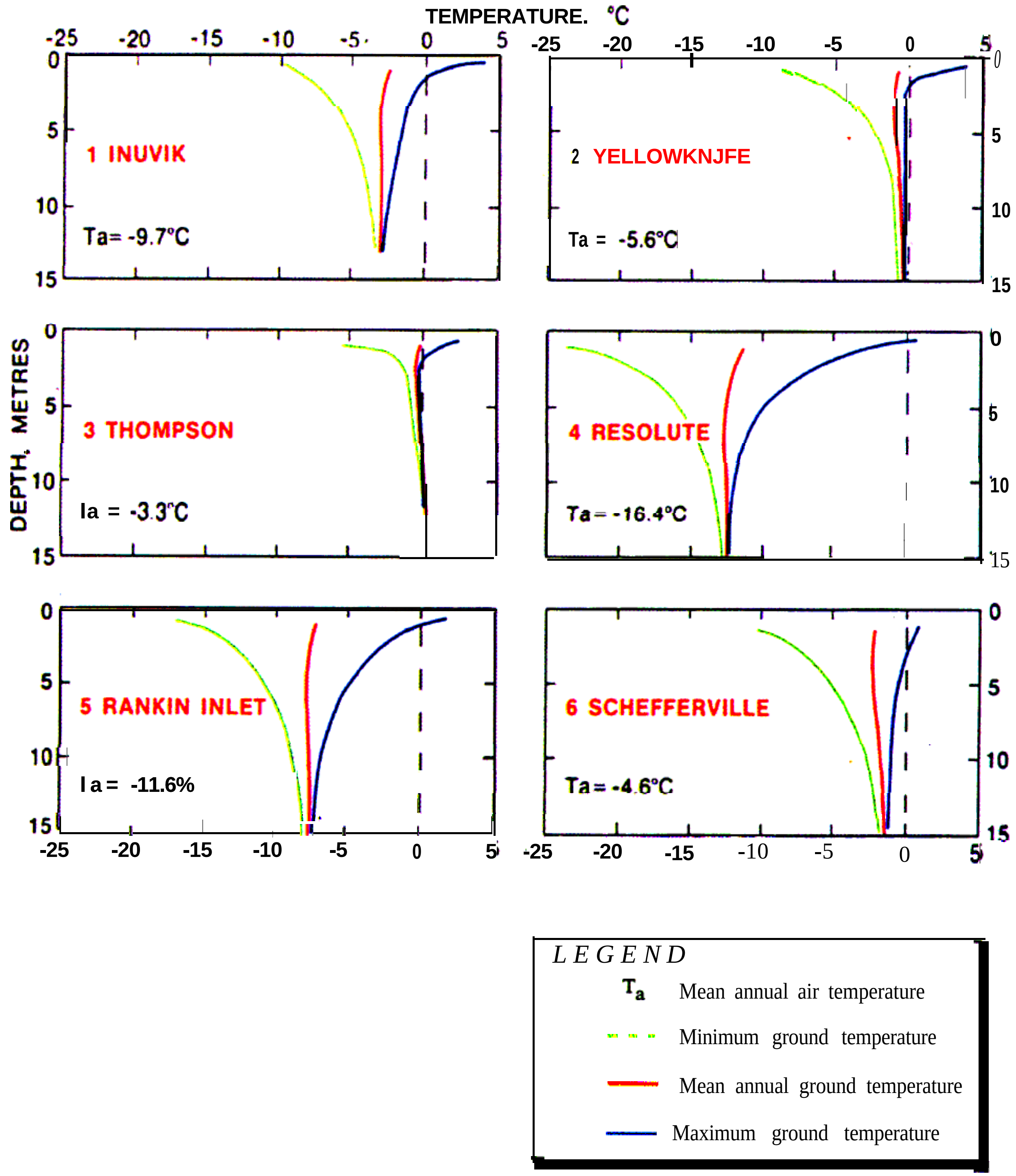

Figure 1.2
Ground Temperature Envelopes for Selected Stations
(after Hydrological Atlas of Canada, 1978)

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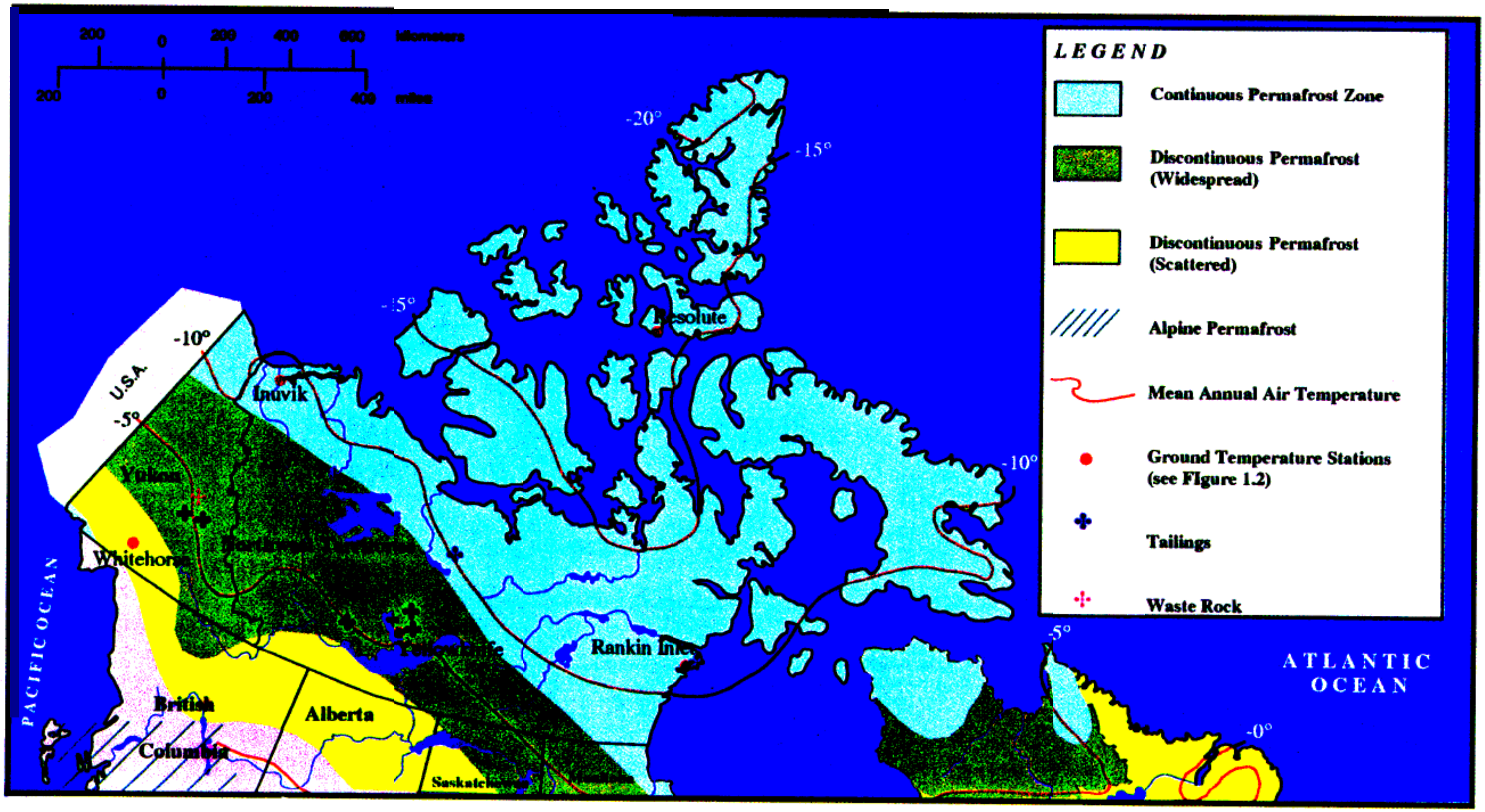
Figure 2.1 NWT and Yukon Minesites Exhibiting Acid Mine Drainage



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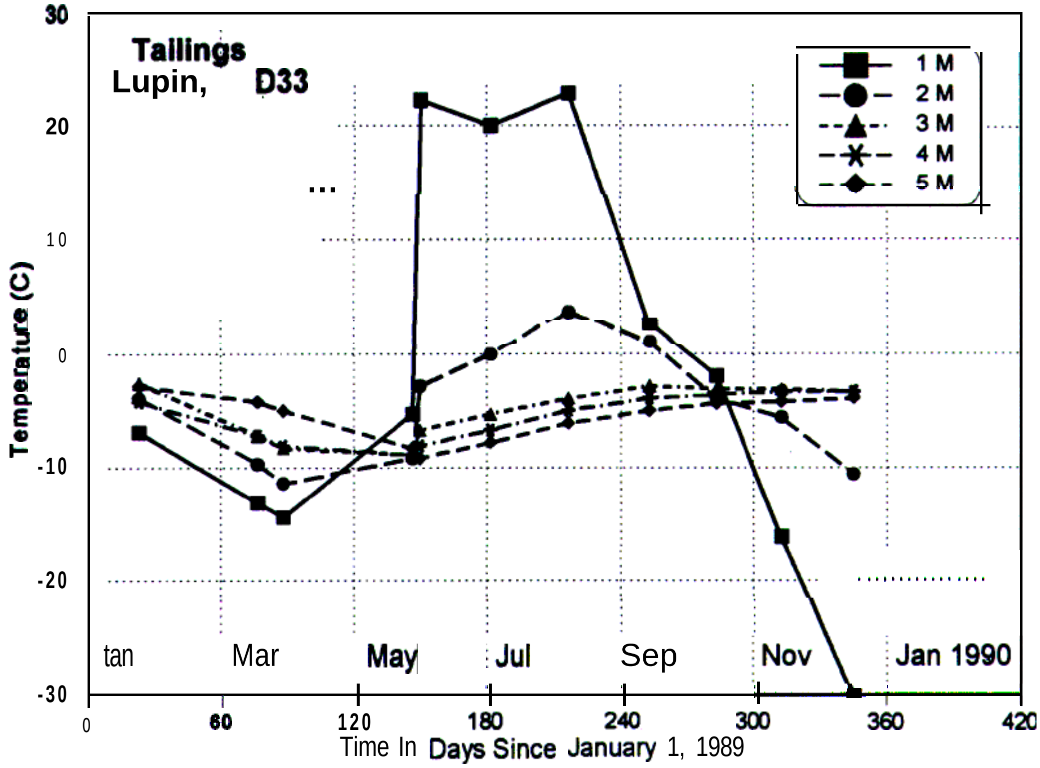


FIGURE 2.2 Temperature! Fluctuations withTime and Depth in Lupin Tailings (from Holubec, 1990).

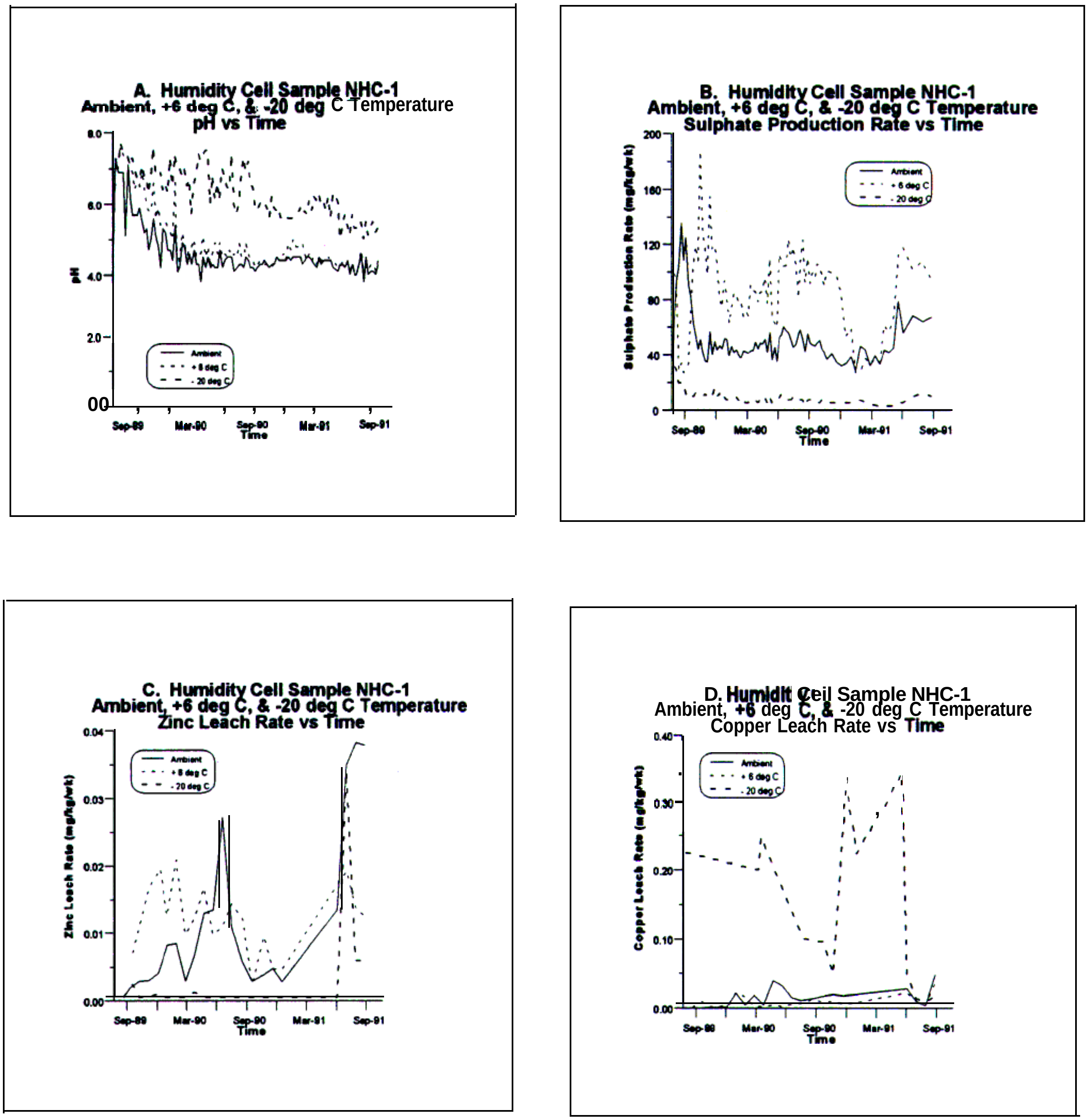


Figure 2.3: Graphs Showing Temperature Dependent Humidity Cell Results of Windy Craggy Waste Rock

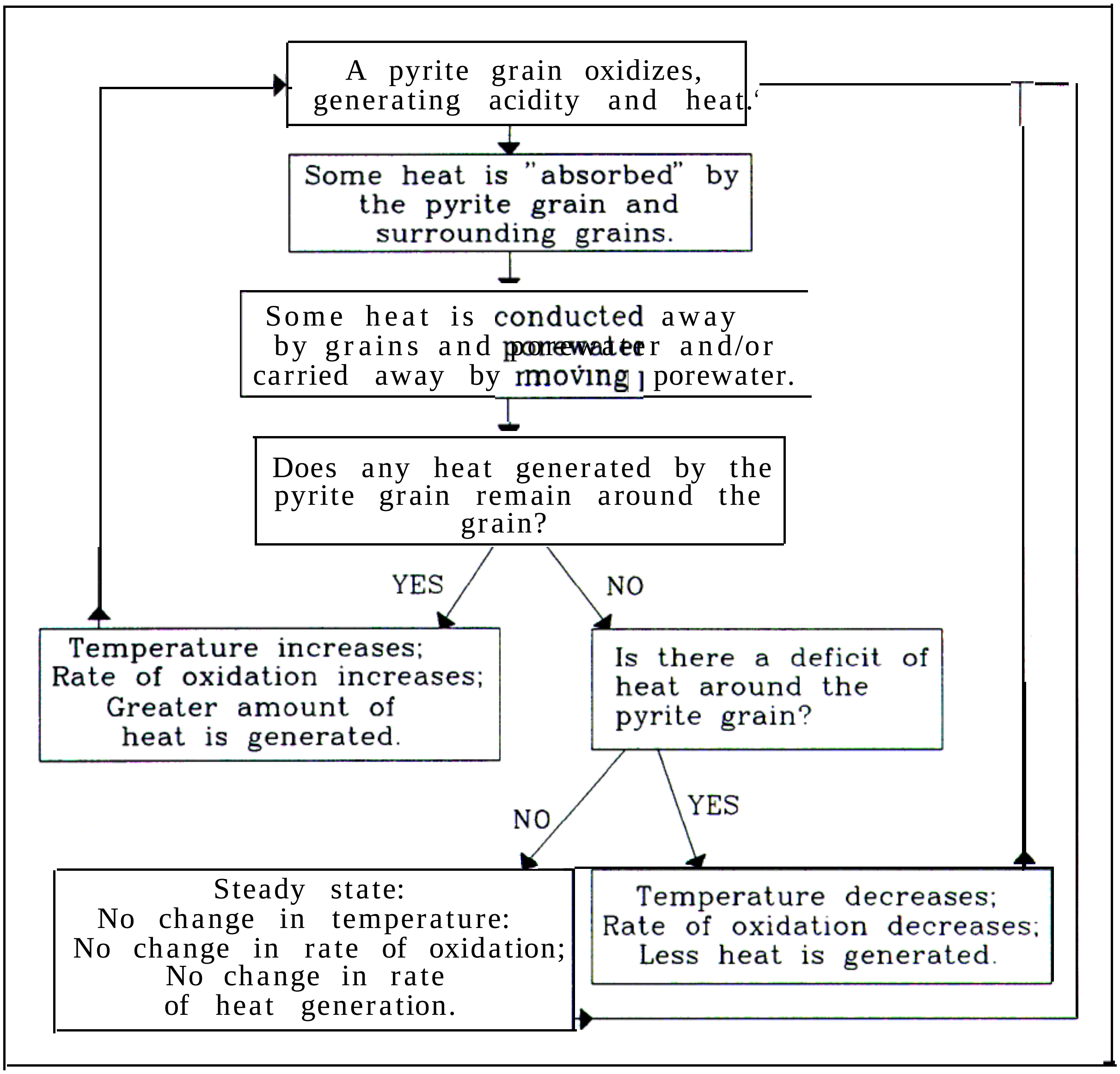


FIGURE 3-l. Flow Chart of Coupled Relationship Between Pyrite Oxidation and Heat Transfer (after MEND, 1993).

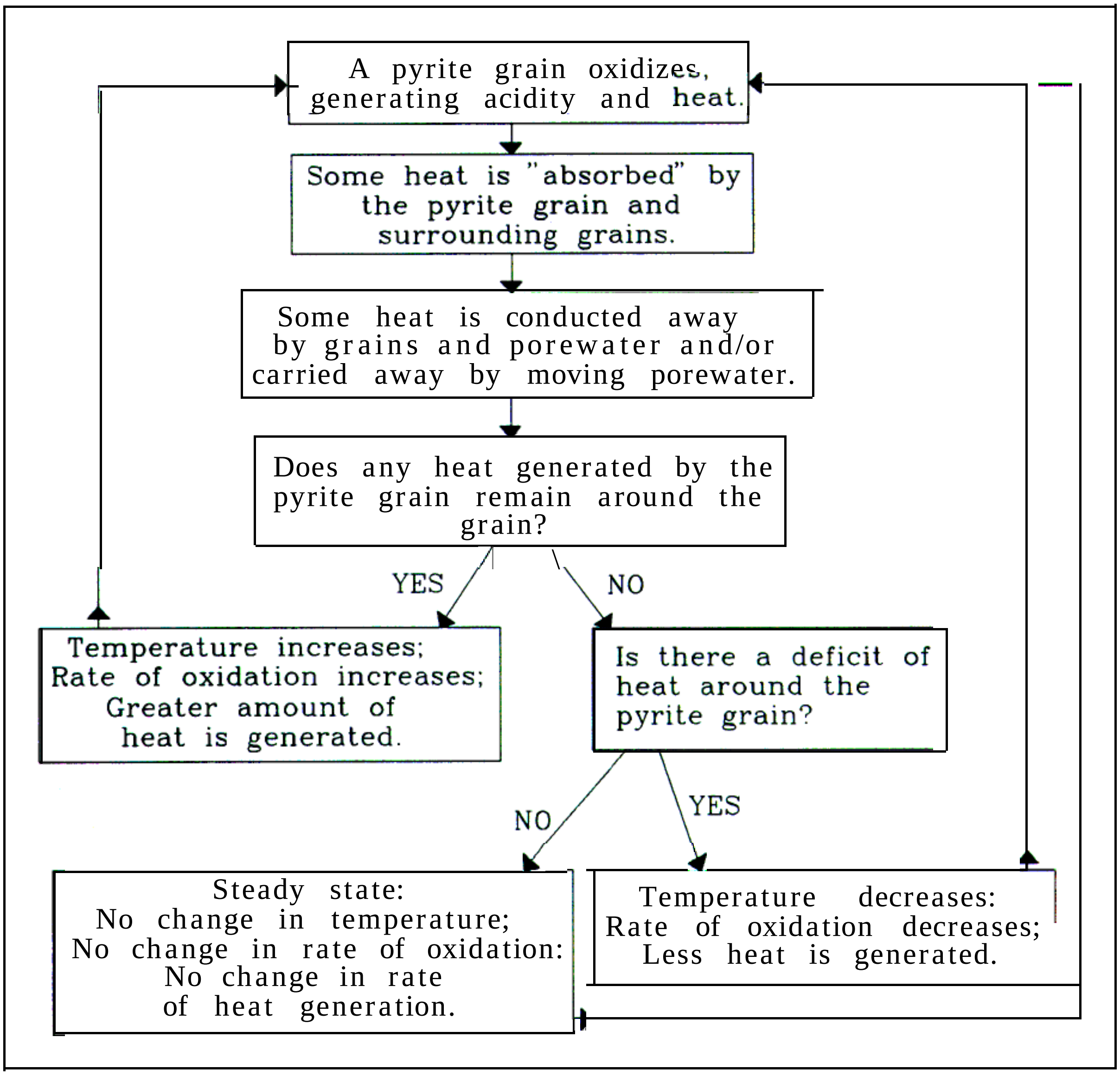


FIGURE 3-1. Flow Chart of Coupled Relationship Between Pyrite Oxidation and Heat Transfer (after MEND, 1993).

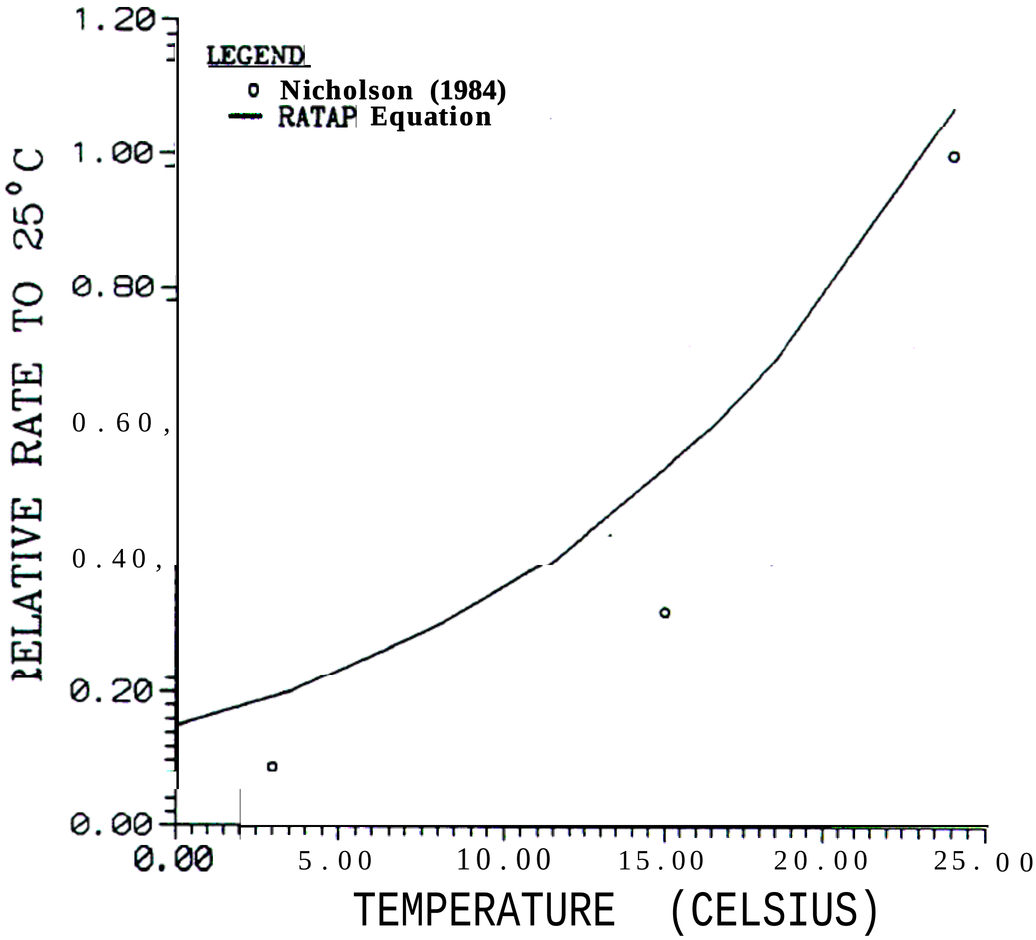


Figure 3.2: Relative Rate of Chemical Oxidation versus Temperature (adapted from Senes, 1991)

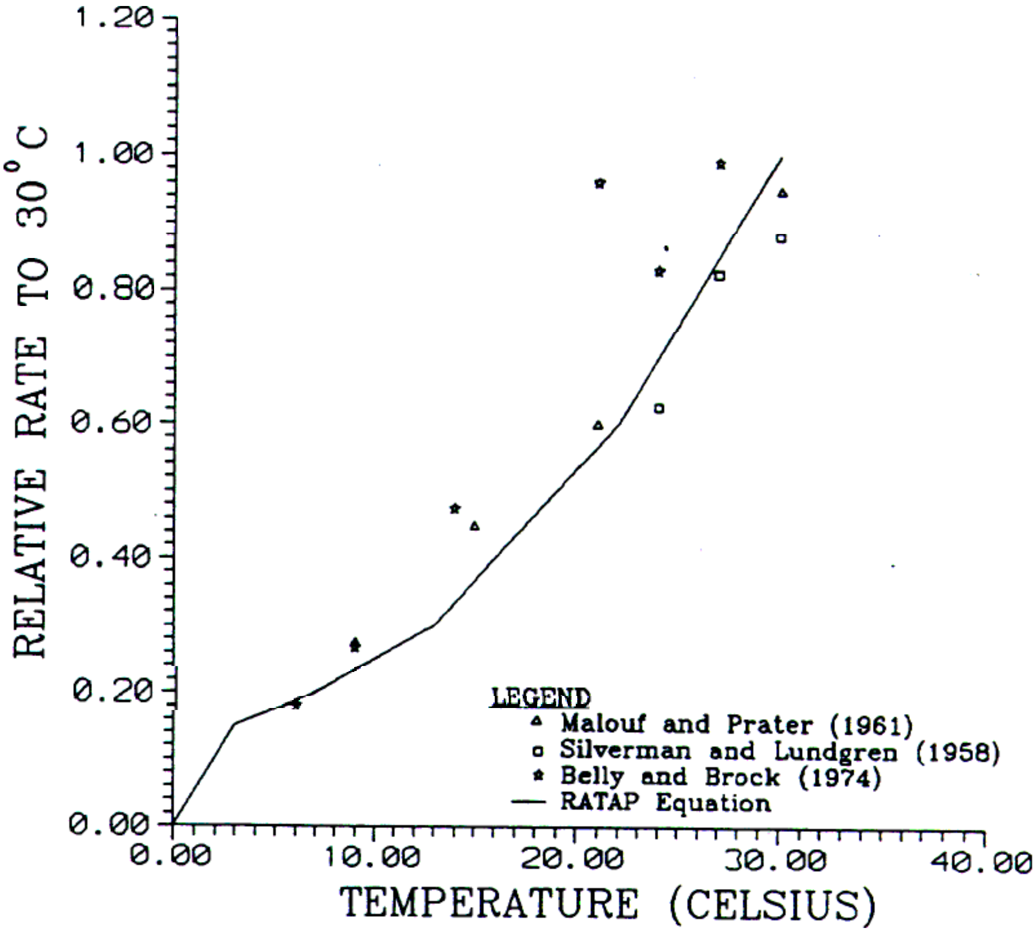


Figure 3.3: Relative Rate of Biological Oxidation versus Temperature

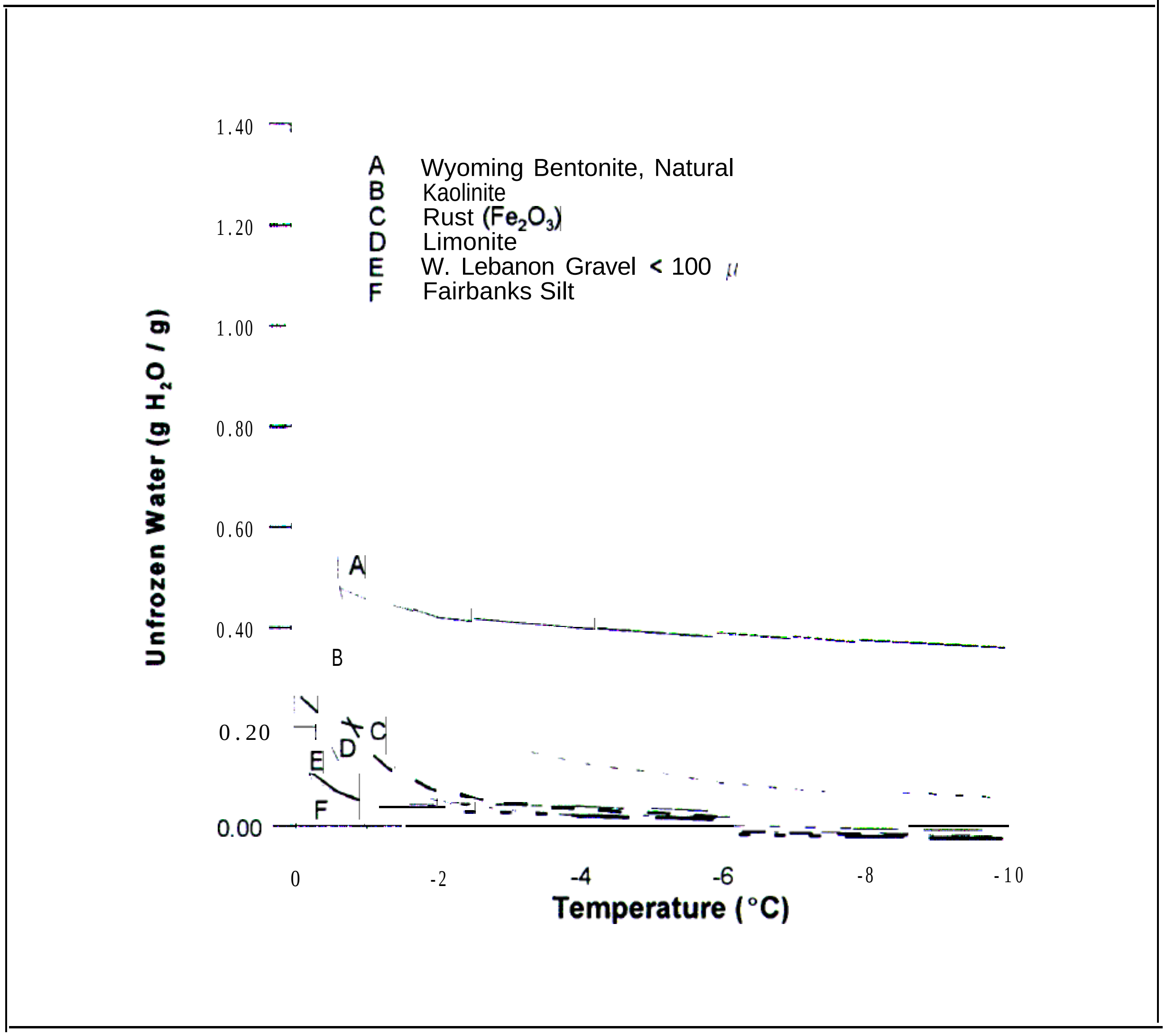


FIGURE 3-4. Unfrozen Water Content vs. Temperature (from Anderson and Morgenstern, 1973).

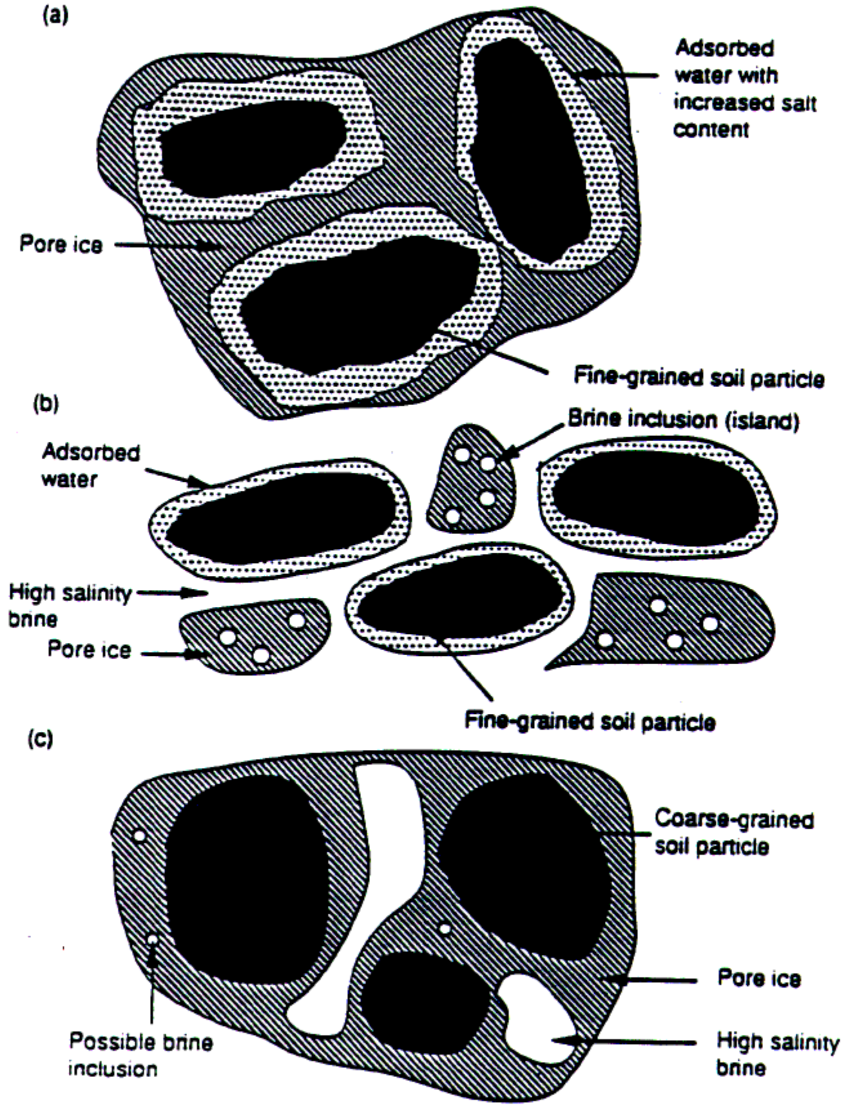


Figure 3.5 Distribution of Unfrozen water in frozen soils.
(a) Low salt concentration pore fluid in fine - grained soil.
(b) High salt concentration pore fluid in fined - grained soil.
(a and b) following Sheeran and Yong (1975).
(c) High salt concentration pore fluid in coarse - grained soil.

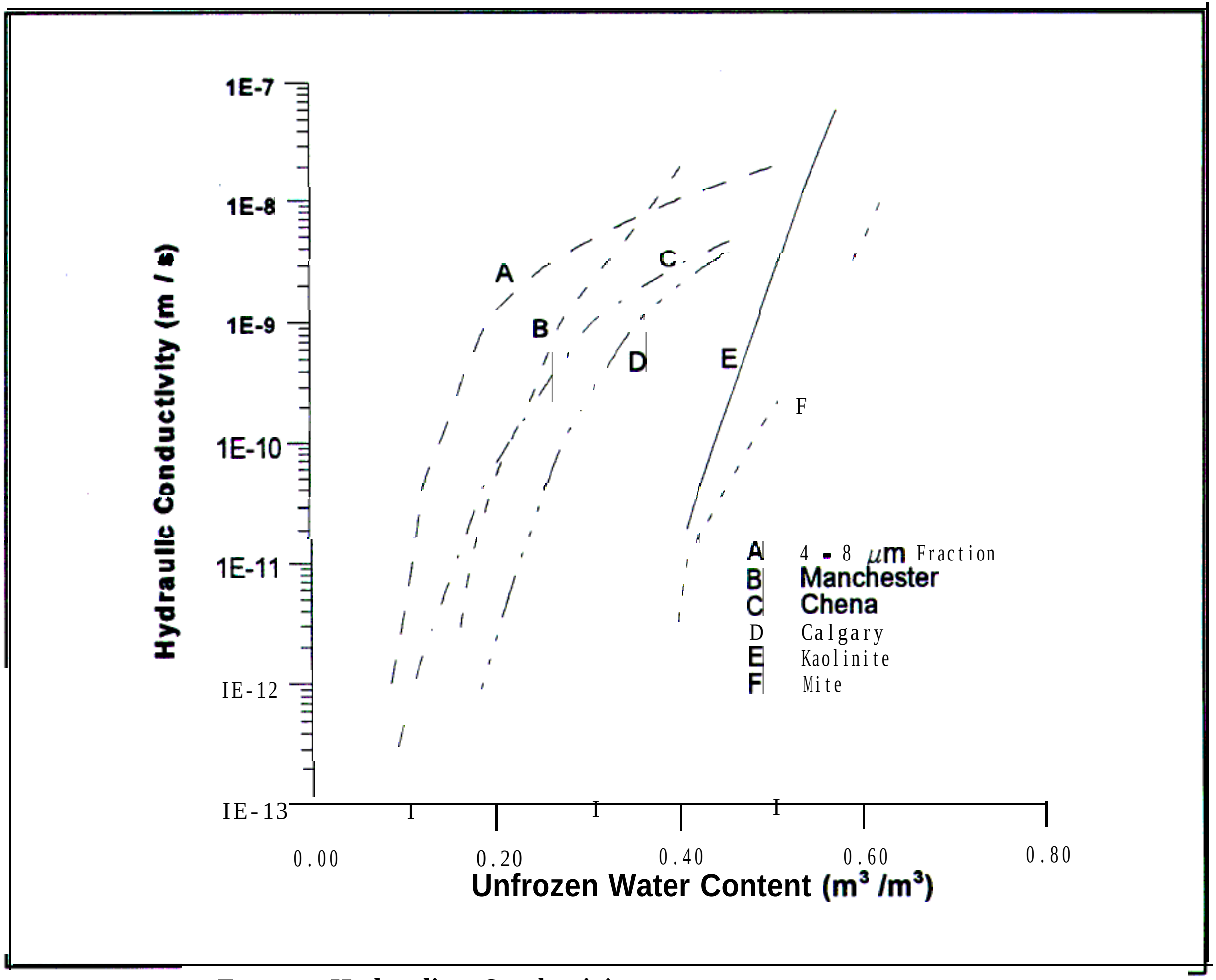


FIGURE 3-6 Frozen Hydraulic Conductivity vs. Unfrozen Water Content (after Horiguichi and Miller, 1983).

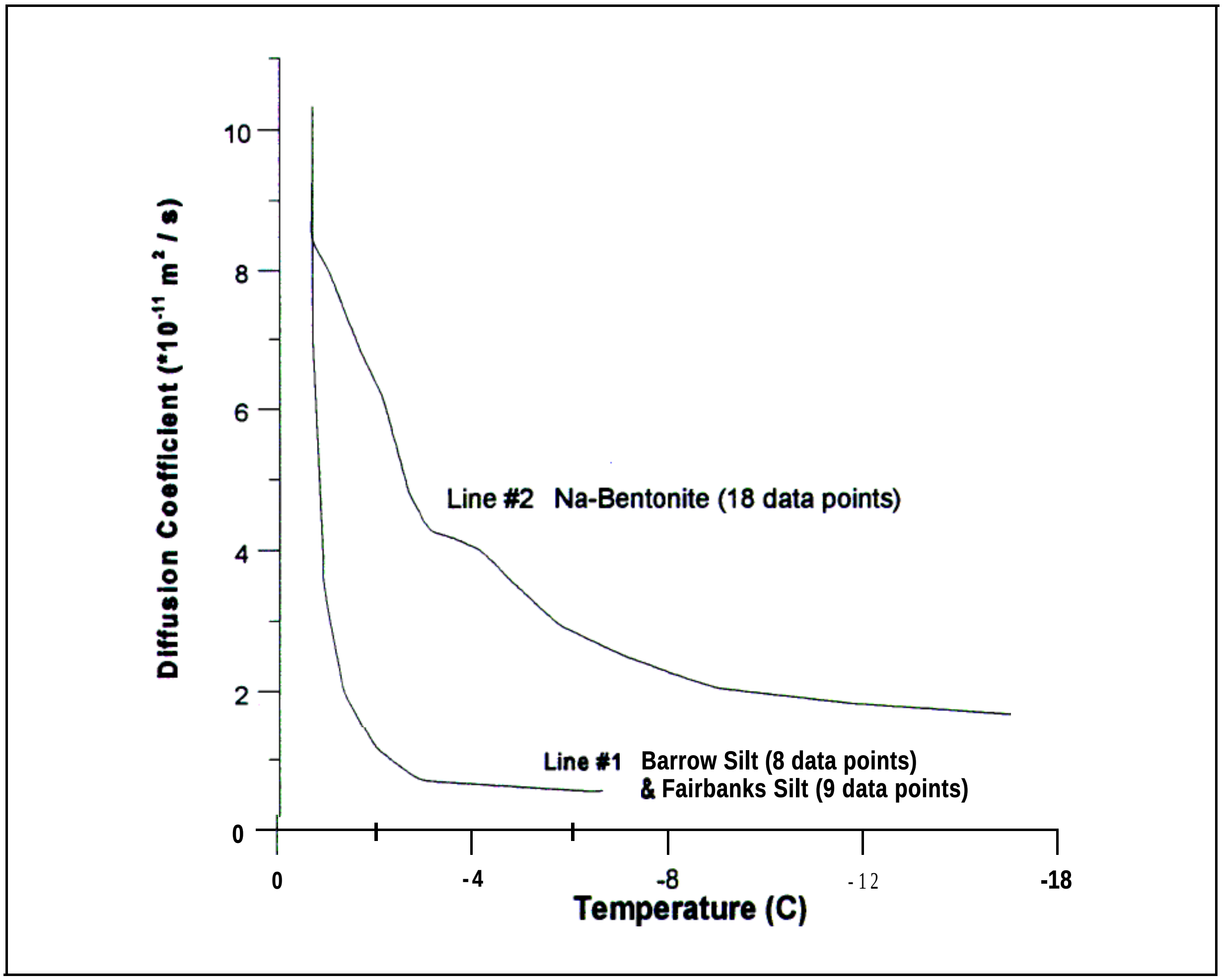


FIGURE 3-7 Diffusion Coefficients vs. Temperature ,(After Murrmann, 1973).

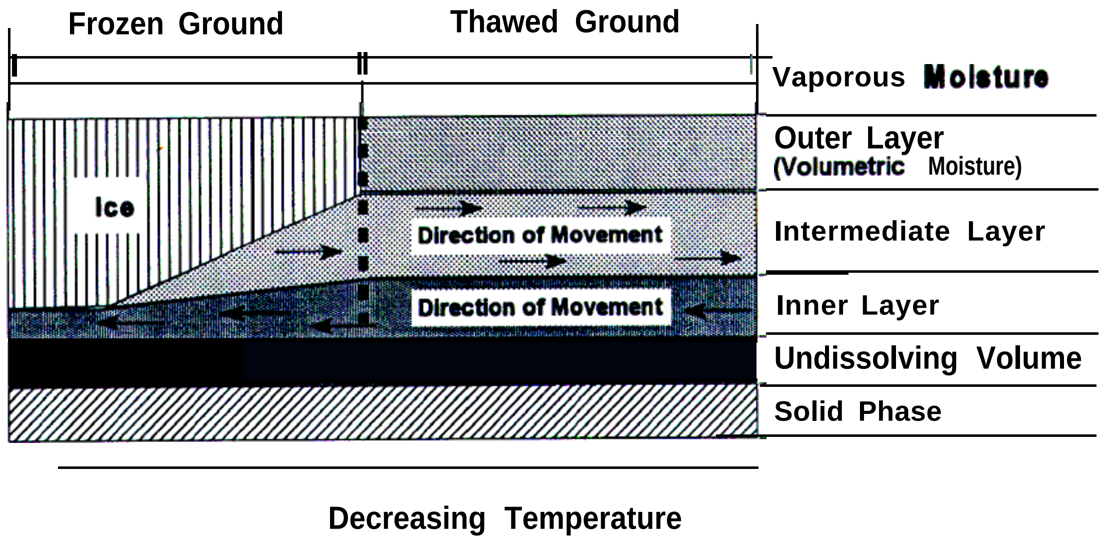


FIGURE 3-8 Conceptual Model of Ionic and Moisture Diffusion under Thermal Gradients (from Ostroumov, 1988).

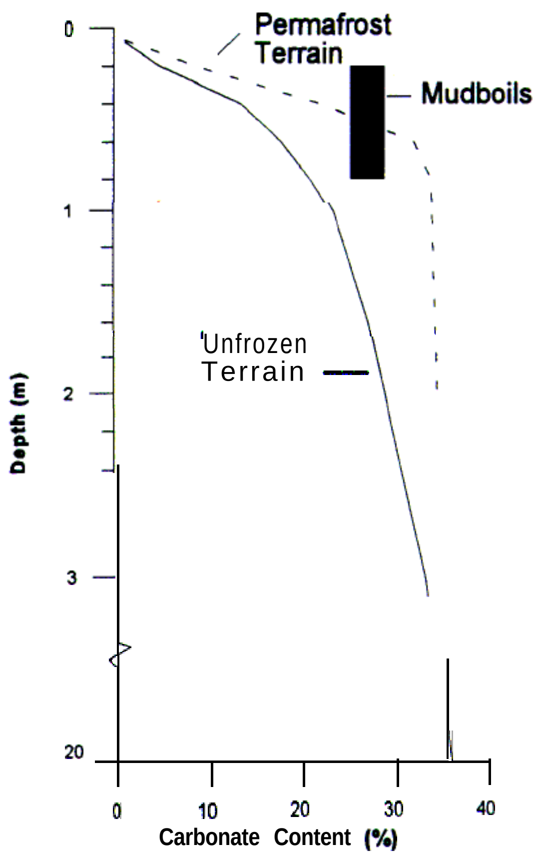


FIGURE 3-9 Convection Effects of High Carbonate Tii

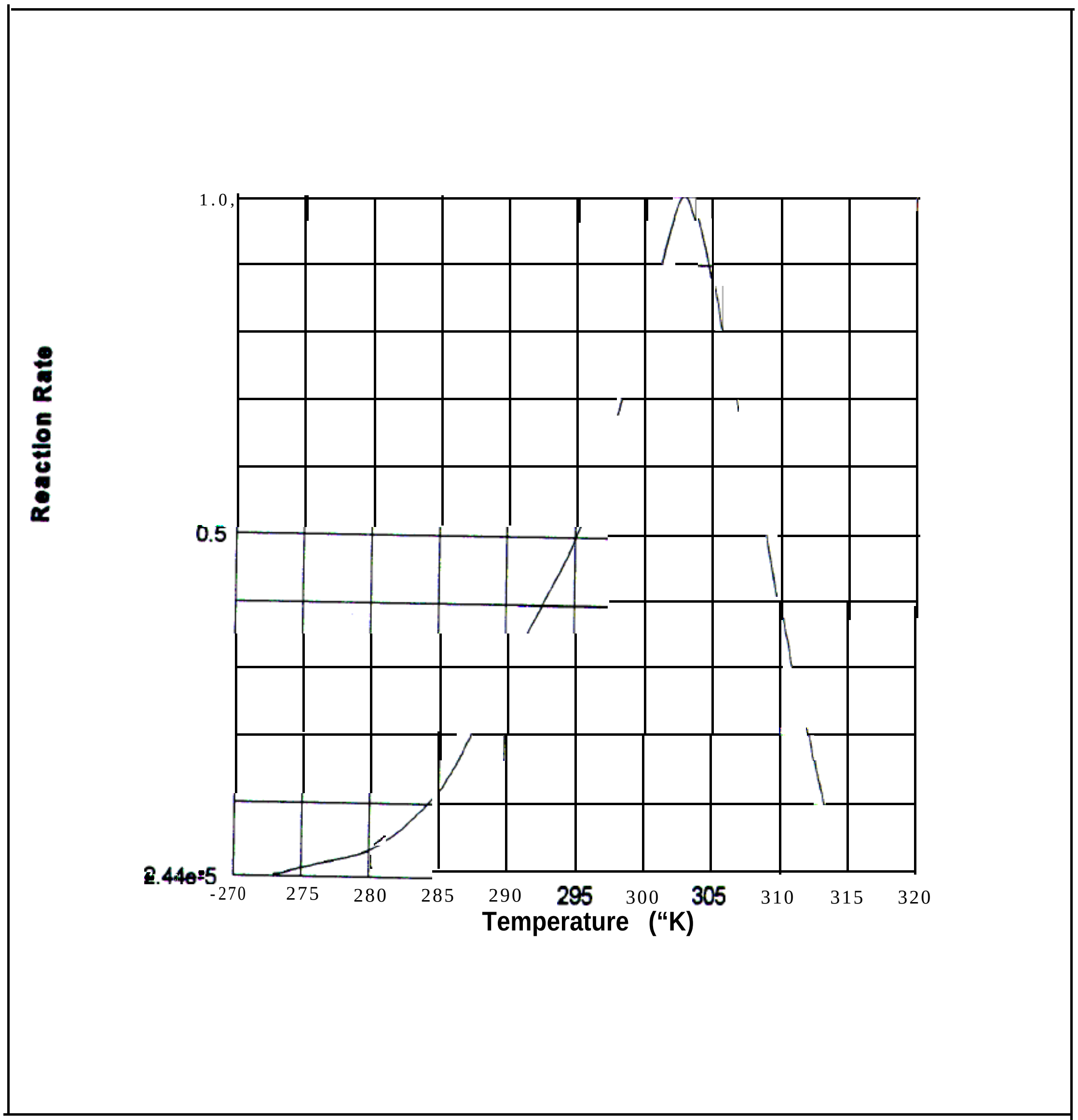


FIGURE 3-10. Activity of *Thiobacillus ferrooxidans* vs. Temperature (from Otwinowski, 1994).

ESTIMATED ACTIVE LAYER THICKNESSES

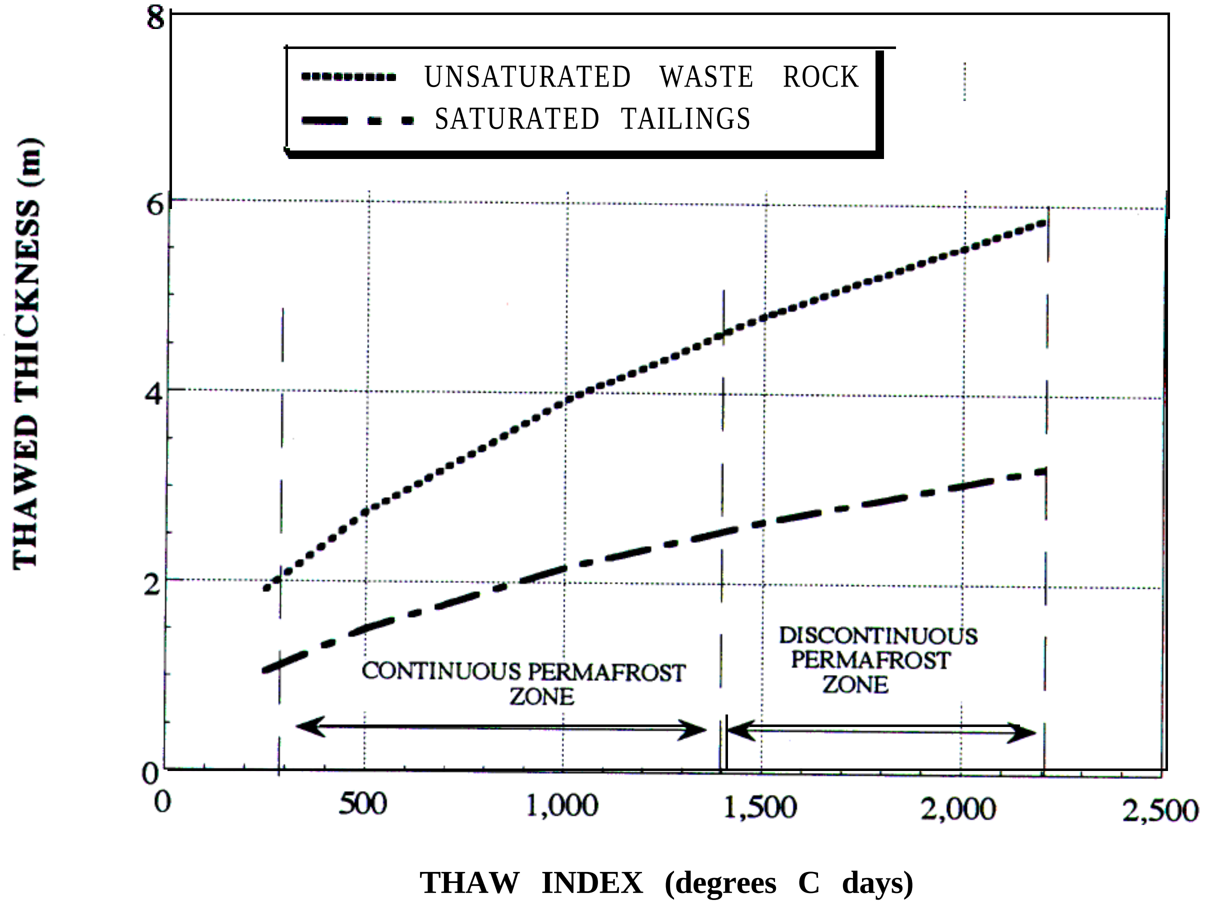


Figure 4.1: Seasonal Thawing Thickness for Mine Waste in Permafrost Regions

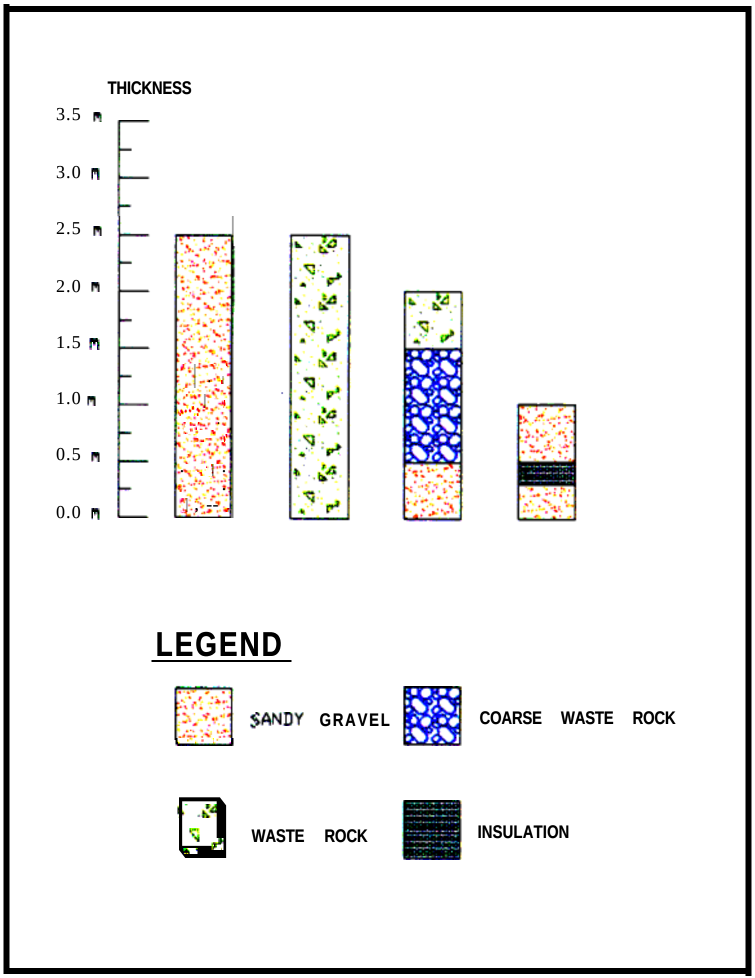


Figure 4.2: Insulating Cover options for Total Freezing in Continuous Permafrost Regions (after MEND 6.1, 1993)

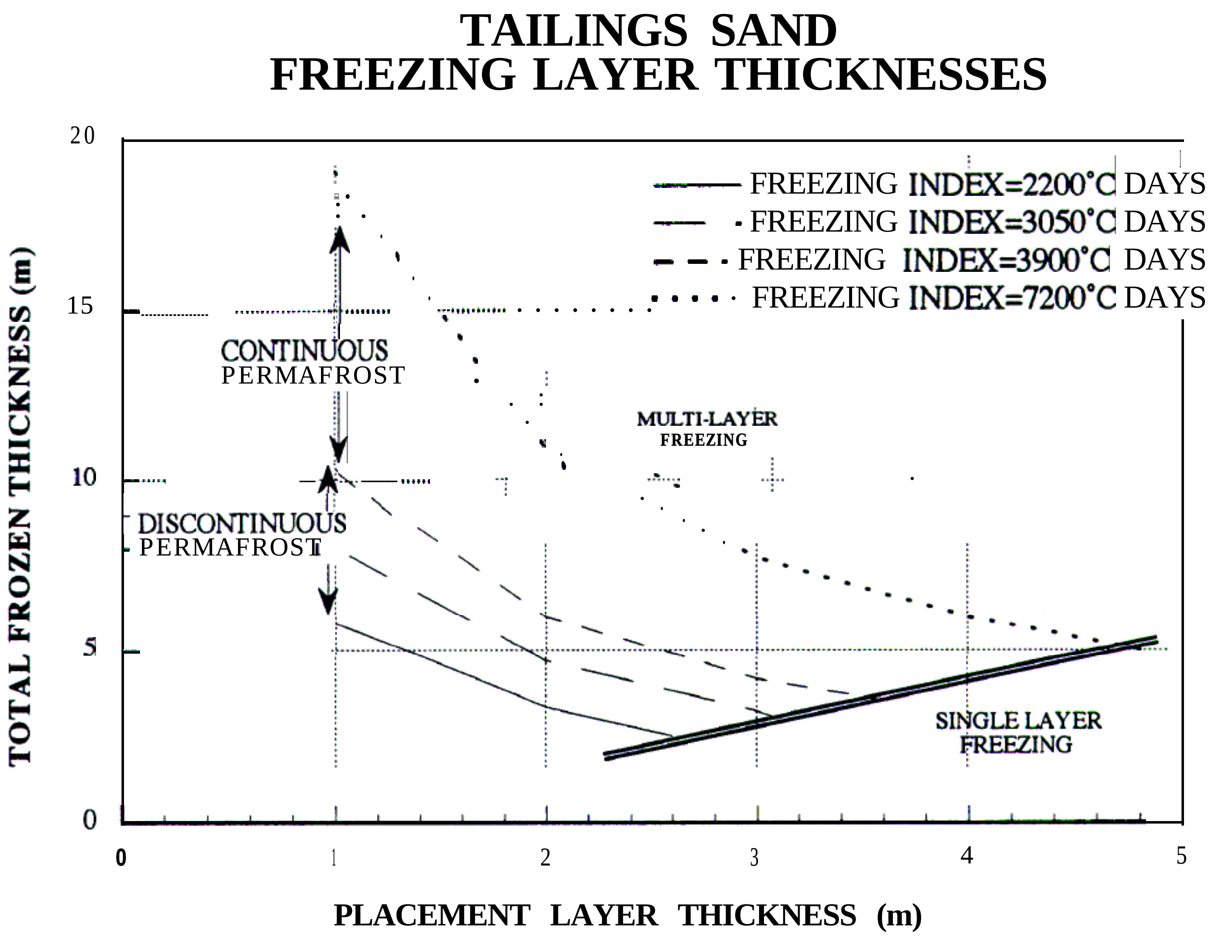


Figure 4.3: Tailings Sand Freezing Layer Thicknesses

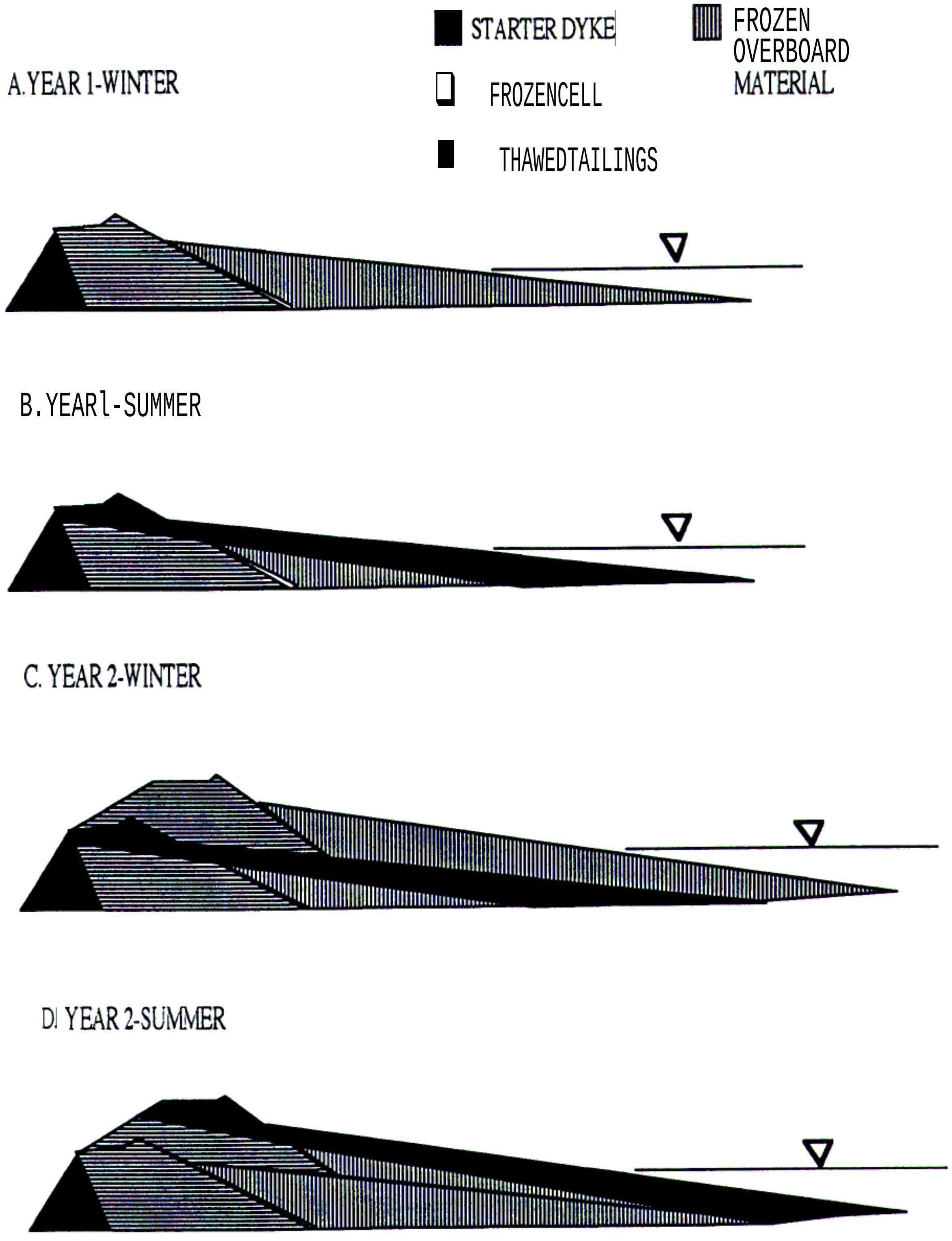


Figure 4.4: Tailings Thin Layered Freezing Design Concept

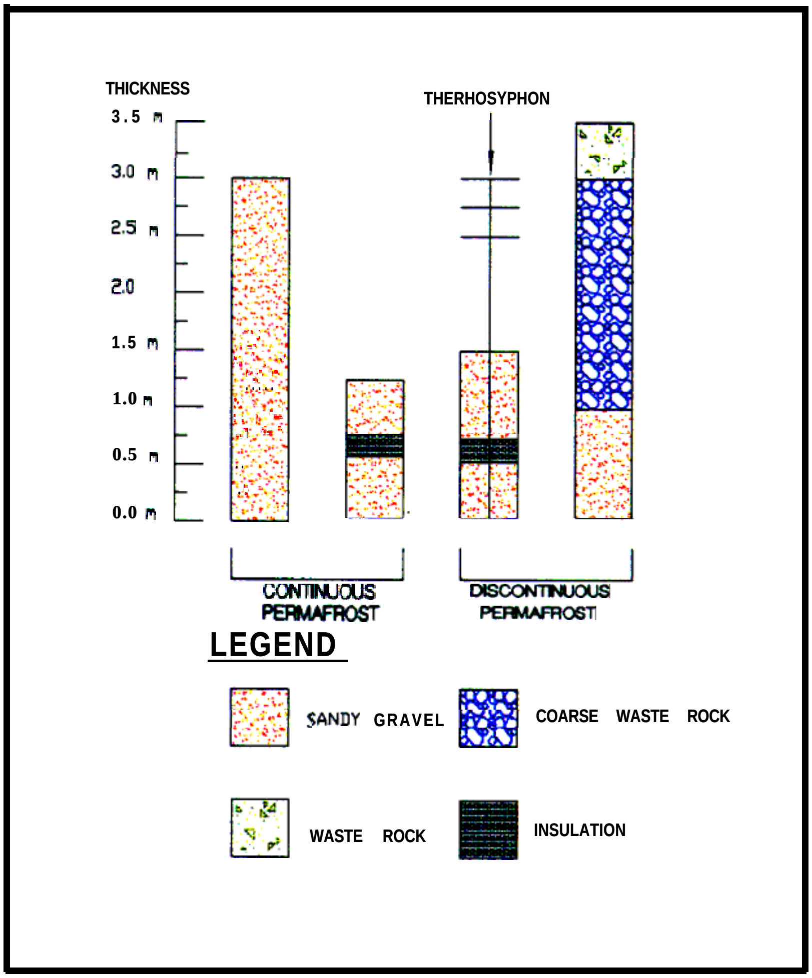


Figure 4.5: Insulating Cover Options for Perimeter Freezing (after MEND 6.1, 1993)

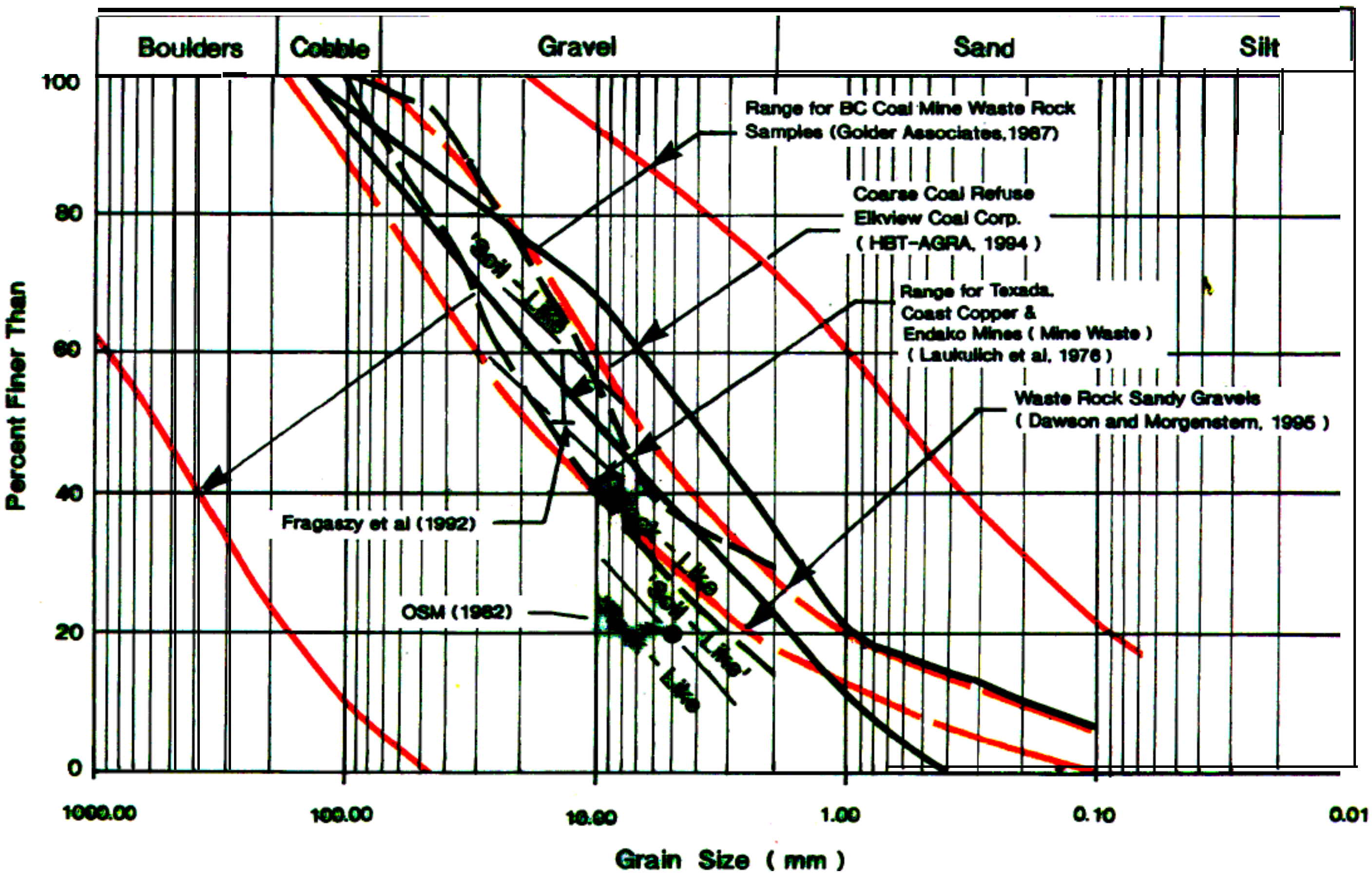


Figure 4.6: Typical Grain Size Distributions of Waste Rock Materials

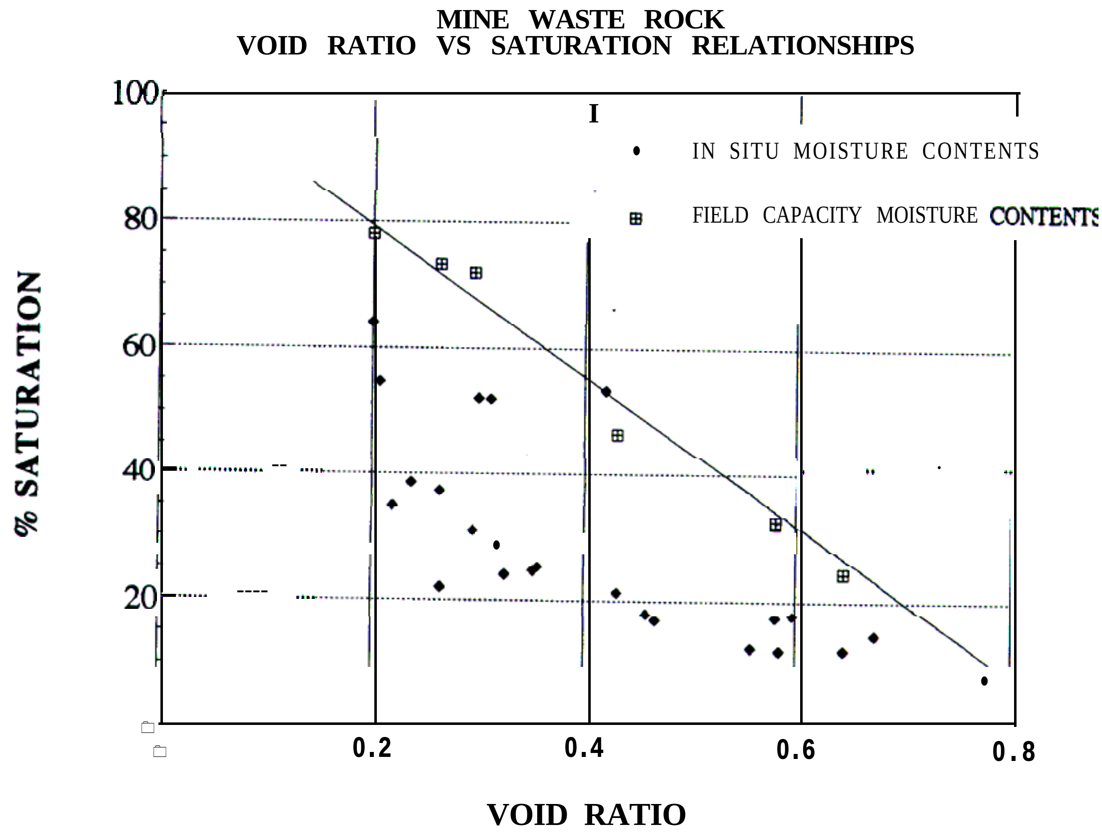


Figure 4.7: Saturation Relationships for Sandy Gravel Mine Waste Rock Materials

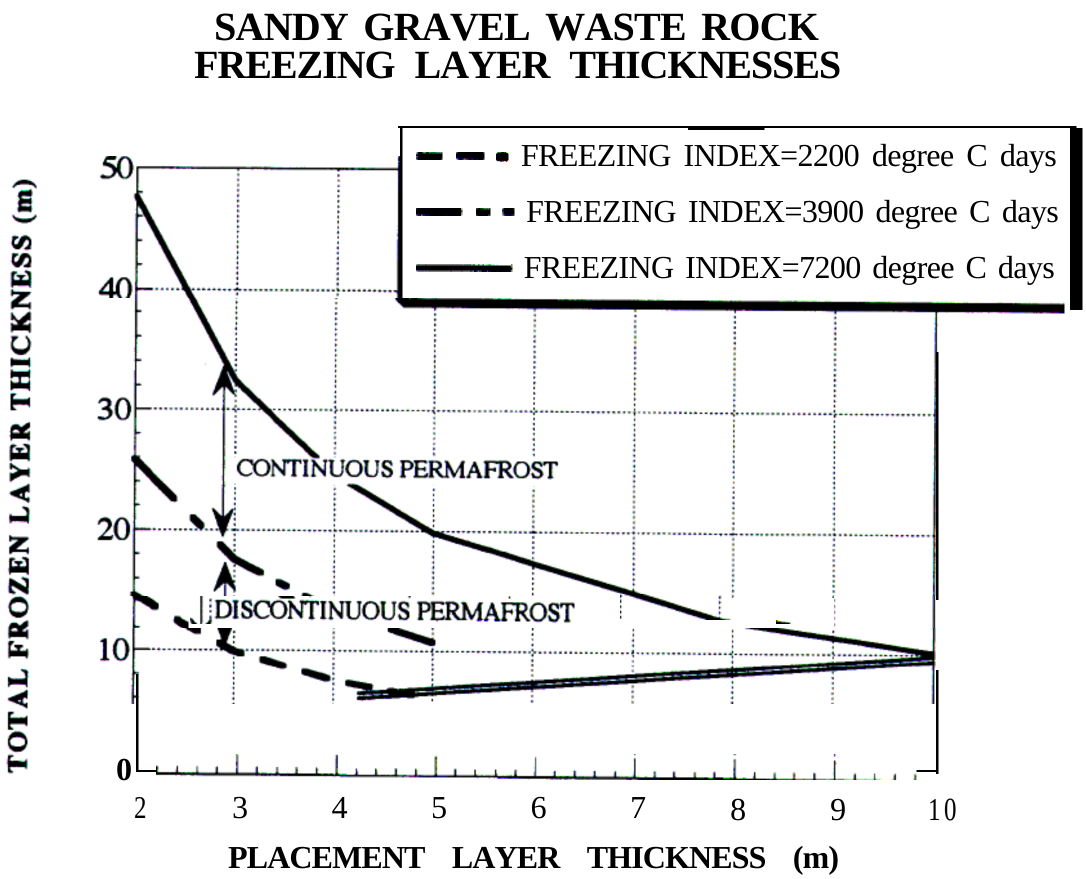


Figure 4.8: Sandy Gravel Waste Rock Freezing Layer Thicknesses

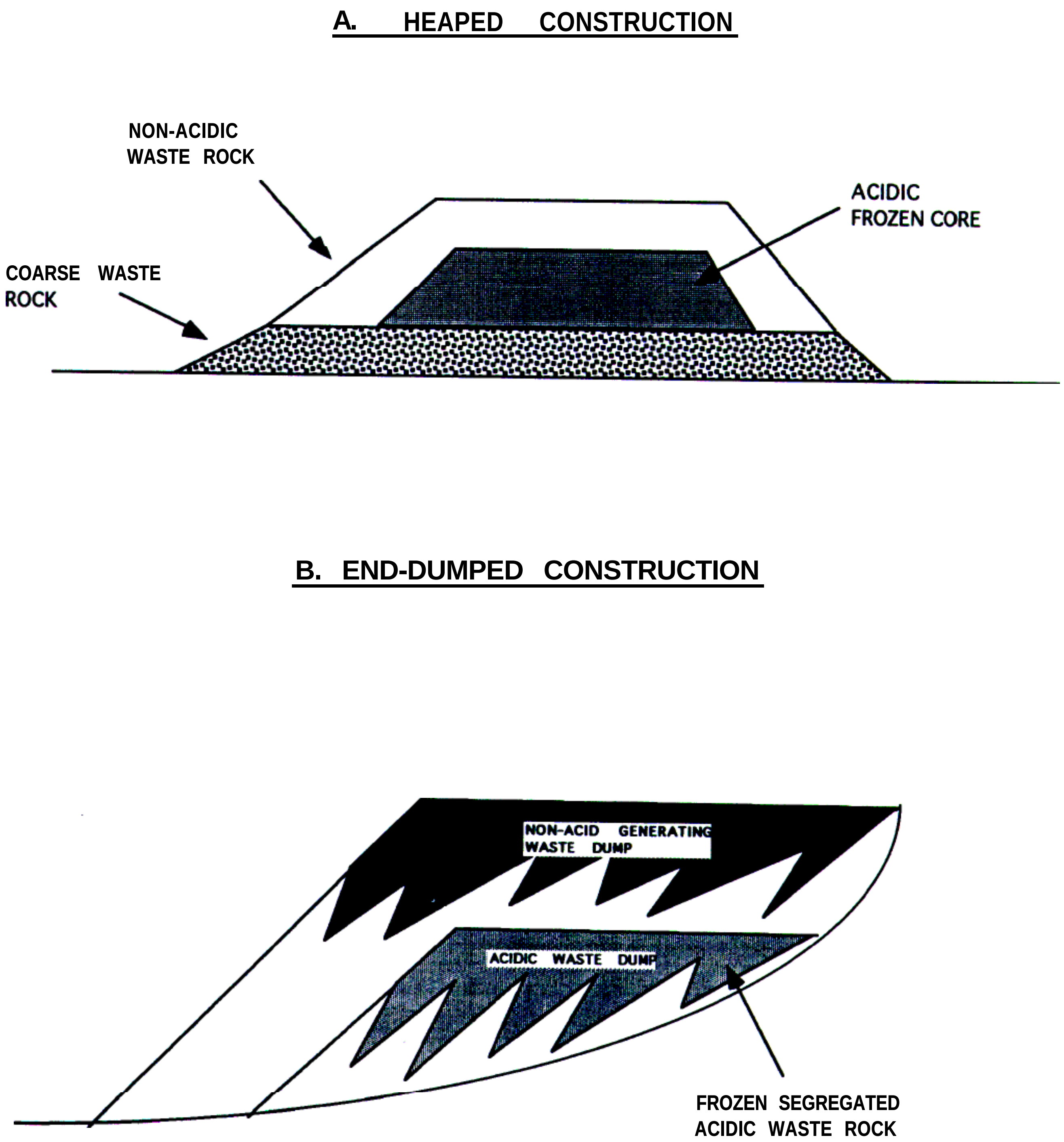
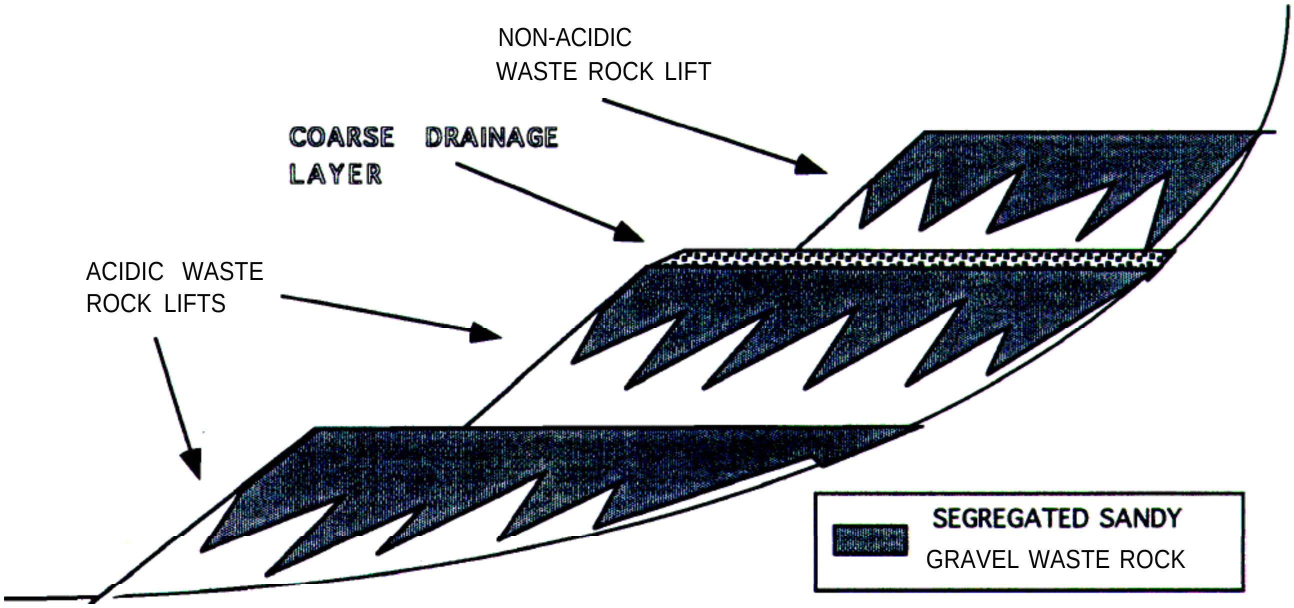


Figure 4.9: Freeze Controlled ARD Control Strategies for Waste Rock

A. CONSTRUCTION CONFIGURATION



B. RE-SLOPED CONFIGURATION

NOTE: RE-SLOPING OF FINER SANDY GRAVEL WASTE SERVES TO REDUCE AIR FLOW THRU BASE OF PILE. COARSE DRAINAGE LAYER BENEATH NON-ACIDIC UPPER LIFT LIMITS INFILTRATION INTO ACIDIC WASTE

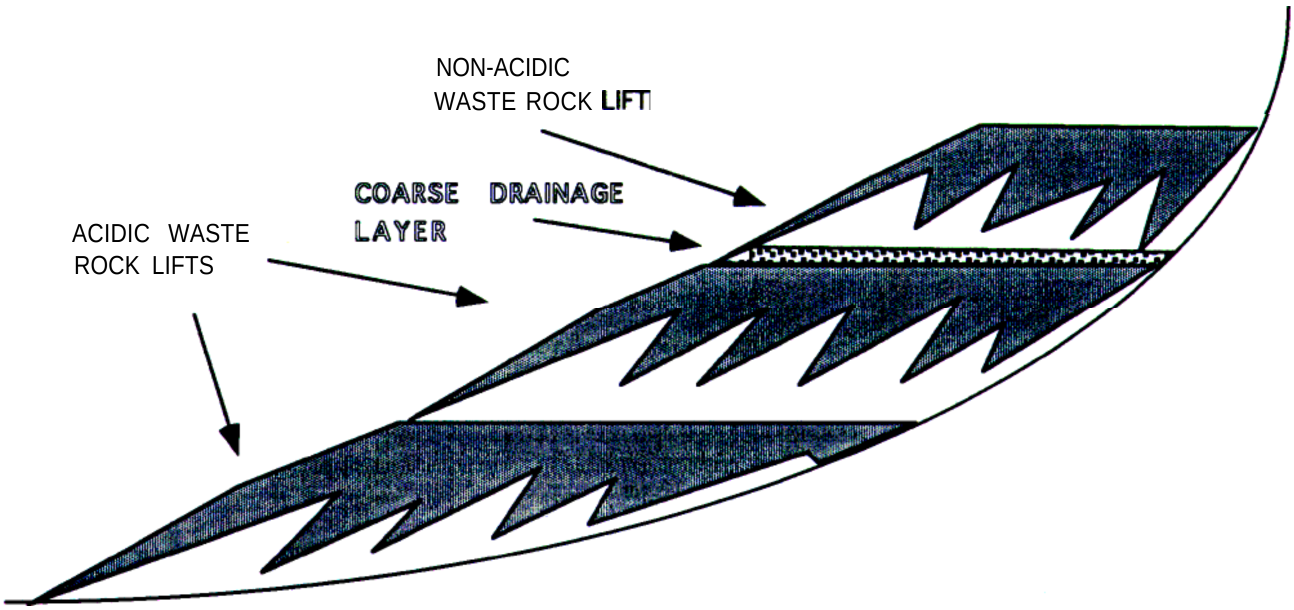
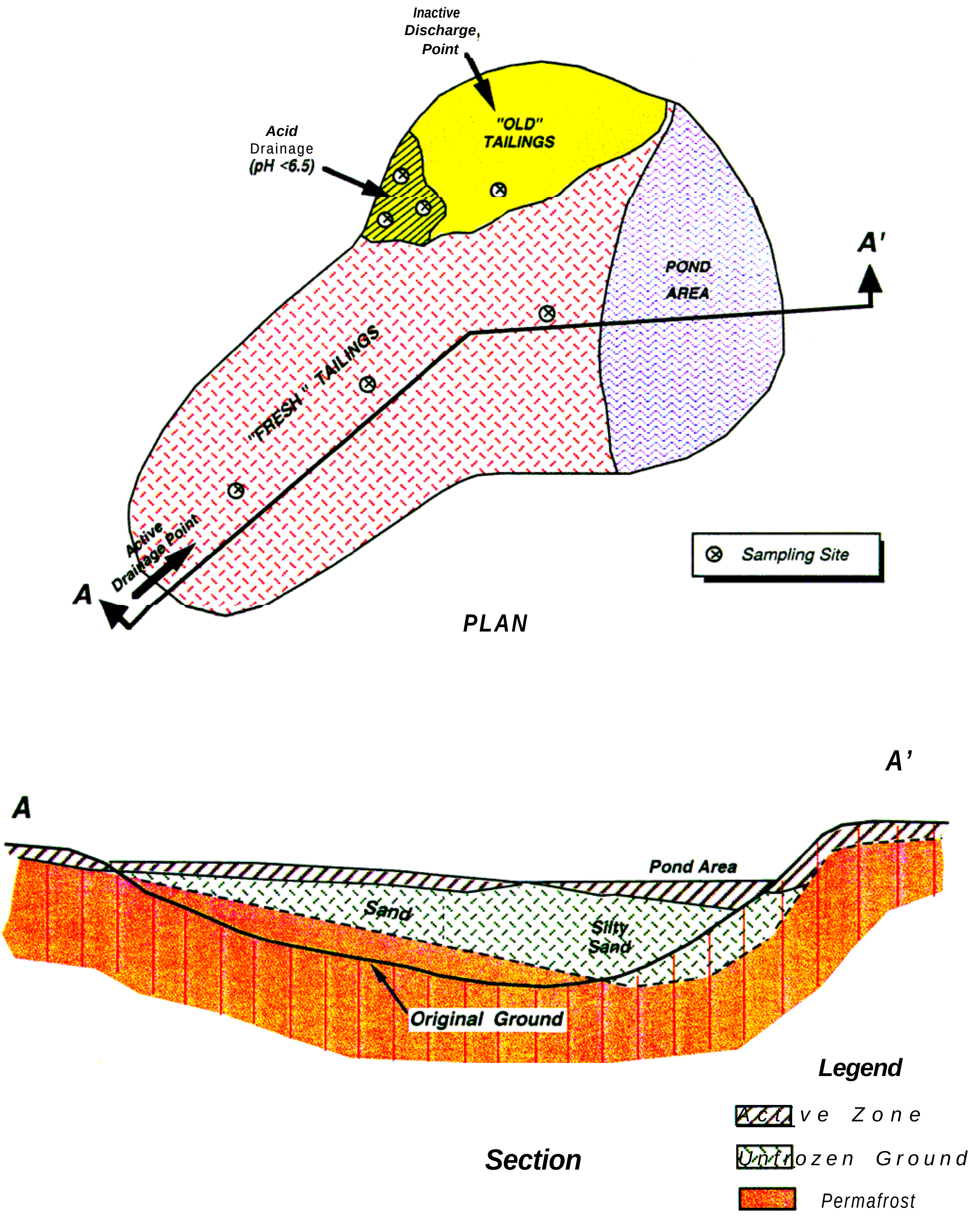


Figure 4.10: Climate Controlled ARD Strategy for Terraced End-Dumped Construction



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Schematic Showing Tailings Containment Area in Permafrost

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Figure 5.1

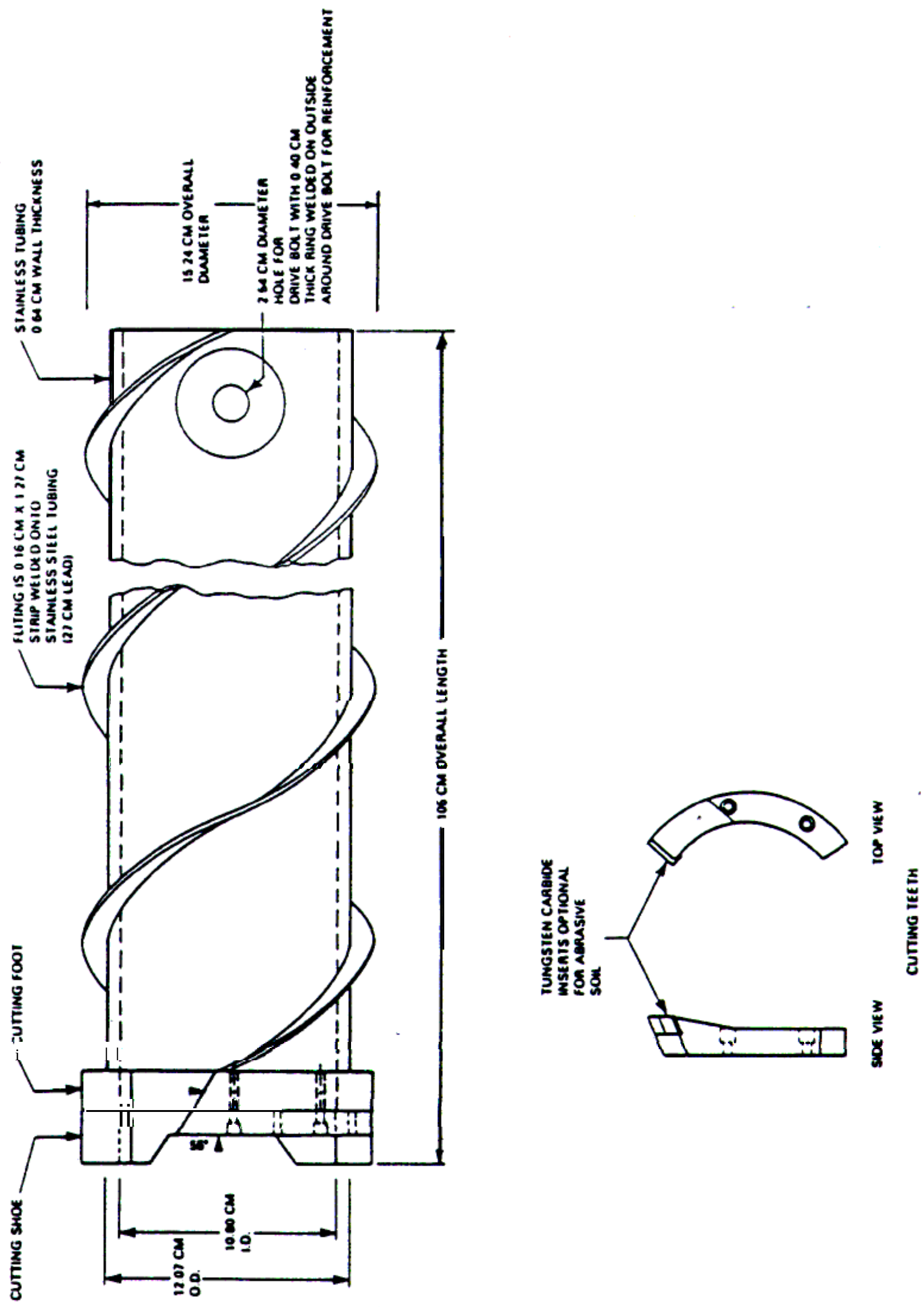

Figure 5.2 Modified CRREL Core Barrel Assembly