Effects of Ground Conditions and Mine Waste Deposition on Permafrost

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ABSTRACT
Operations started at De Beers’ Snap Lake Mine, about 220 km northeast of Yellowknife, Northwest Territories, in late August 2007. The Snap Lake Mine is located in the Canadian low arctic in a region of continuous permafrost. A number of “firsts” are associated with the Snap Lake Mine:

- The mine is De Beers’ first mining operation outside of Africa;
- The mine is Canada’s first completely underground diamond mine; and
- The mine will be the first mine located in the Low Arctic, Canadian or otherwise, to deposit mine waste on surface as a paste.

The surface disposal facility at the Snap Lake Mine is referred to as the North Pile. The North Pile will be sequentially developed in phases. Each phase, including the completed facility, will have perimeter water control structures, comprising ditches and sumps, to collect seepage and runoff from the facility for treatment. Although the facility design is not dependent upon permafrost conditions, thermal conditions are monitored during the development of the North Pile.

The paper presents a general discussion of the thermal monitoring program. Pre-development baseline conditions will be compared to those being collected during operations. The effects of ground conditions and North Pile deposition and development activities will be discussed.

RÉSUMÉ
Les opérations à la mine Snap Lake, propriété de De Beers, ont débuté à la fin d’août 2007. La mine Snap Lake est située à environ 220 km au nord-est de Yellowknife, aux Territoires du Nord-Ouest, dans le Bas Arctique canadien, dans une région de pergélisol permanent. Un nombre de « premières » sont associées à la mine Snap Lake :

- La mine est la première exploitation minière de De Beers en dehors de l’Afrique;
- La mine est la première mine de diamants complètement souterraine au Canada;
- La mine sera la première exploitation située dans le Bas Arctique, canadien ou autre, a déposé ses résidus miniers sous forme de pâte en surface.

L’installation de stockage des résidus en surface de la mine Snap Lake est nommée la North Pile. La North Pile sera développée en étapes successives. Chaque étape, incluant l’accomplissement de l’installation, aura des structures de contrôle des eaux en périphérie, comprenant des fossés et puisards, pour collecter les eaux d’exfiltration et de ruissellement en provenance de l’installation de stockage des résidus pour traitement ultérieur. Bien que la conception de l’installation de stockage ne soit pas dépendante des conditions du pergélisol, les conditions thermiques sont surveillés durant le développement de la North Pile.
Cet article présente une discussion générale des programmes de surveillance thermique. Les conditions directrices de pré-développement seront comparées aux conditions observées durant les opérations. Les effets des conditions de terrain et des activités de déposition et de développement de la North Pile seront discutés.

1 INTRODUCTION

De Beers Canada Inc. (De Beers) owns and operates the Snap Lake Mine located about 220 km northeast of Yellowknife, Northwest Territories, Canada, at a latitude of 63^{o}36’19”N and a longitude of 110^{o}52’00” as shown on Figure 1. The mine is located in the Canadian low arctic in the region of continuous permafrost. Operations at the Snap Lake Mine started in late August 2007.

The mine is an underground diamond operation following a kimberlite dyke that dips beneath Snap Lake. The nominal daily processing rate is 3,150 tonnes per day. The material remaining following the removal of the diamonds is referred to as processed kimberlite (PK). The operation will generate about 22.8 million tonnes of PK over the 22 year mine life.

The PK and mine waste rock form the mine waste. The mine waste stored on surface is disposed of into the facility referred to as the North Pile. Backfilling of the mine will start early in the operations. Backfill will comprise cemented PK paste. About 50% of the PK generated during the life of the mine will be used as backfill; the remainder will be placed in the North Pile.
A number of “firsts” are associated with the Snap Lake Mine:

- The mine is De Beers' first mining operation outside of Africa;
- The mine is Canada's first completely underground diamond mine; and
- The mine will be the first located in the low arctic, Canadian or otherwise, to deposit mine waste on surface as a paste.

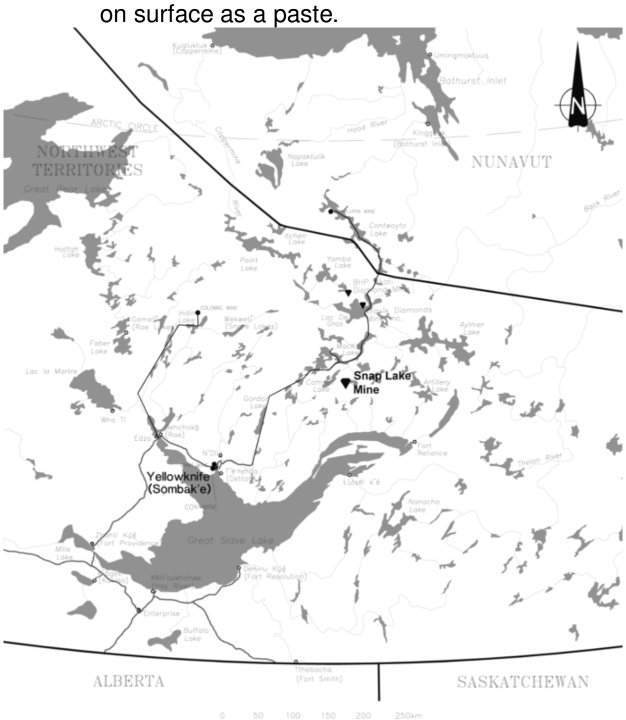

Figure 1. Site location.

The paper presents a general discussion of the thermal monitoring program. Pre-development baseline conditions will be compared to those being collected during operations. The effects of ground conditions and North Pile deposition and development activities will be discussed.

2 SITE CONDITIONS

2.1 General

The layout of the Snap Lake Mine is shown on Figure 2. The Plant Site is located on the northwest peninsula on the western shore of Snap Lake. The site is an isolated area with no permanent surface access. Access to the site is by a winter road spur or by aircraft.

The topography of the site is gently sloping with occasional knolls referred to as "tundra." The surface elevation varies between about 445 m to 484 m. The site is generally barren of vegetation with the exception of some isolated small trees and dwarf shrubs. Bedrock outcrops are common with a veneer of overlying till of varying thickness. Deposits of organic material are present in most of the low-lying areas. Surface drainage does not follow a defined pattern as there are no major water courses on the site.

The underground mine dips beneath Snap Lake from the Plant Site to the east at about 15 degrees from the horizontal to follow the kimberlite dyke. The North Pile facility is located about 500 m west of the Plant Site.

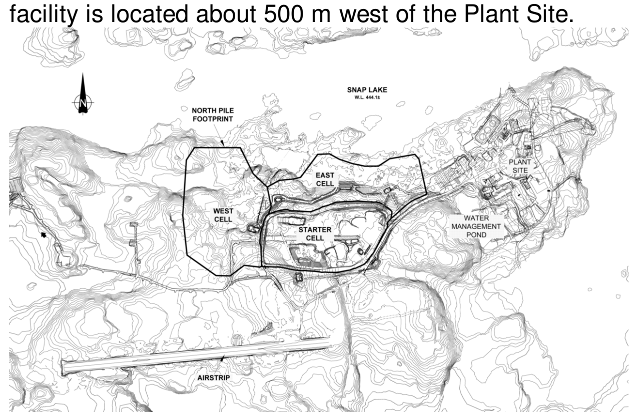

Figure 2. Site layout.

2.2 Climate

The site is located in the Canadian low arctic. Long, cold winters with short, cool summers are experienced. Typical maximum and minimum average monthly temperatures are 15^{o}C and -30^{o}C, respectively. Annual rainfall and snowfall totals are about 148 mm and 225 mm, respectively. Wind is a common occurrence at the site; speeds in excess of 30 km/h are commonly experienced.

2.3 Permafrost

Permafrost is defined as bedrock or soil at a temperature at or below 0^{o}C for a continuous period of two or more years. It is important to note that permafrost is not permanent nor does the term imply the presence of ice in the bedrock or soil. The ground above the top of permafrost is the active layer; this layer freezes and thaws seasonally.

The site is located just north of the diffuse boundary between the discontinuous and continuous permafrost zones. Based on the results of monitoring performed on-site, the average thickness of the active layer is about 6 m. The permafrost thickness is expected to be at least 100 m based on the available literature; no site-specific investigation to determine the permafrost thickness has been performed to date.

3 MINE WASTE MANAGEMENT STRATEGY

3.1 General

The surface disposal facility at the Snap Lake Mine is referred to as the North Pile and is shown on Figure 3. Located to the west of the Plant Site (refer to Figure 2), the North Pile is planned to be about 90 hectares in area with a maximum thickness of about 40 m. The North Pile will be sequentially developed in three phases: the Starter Cell, the East Cell and the West Cell. The development strategy of the North Pile includes the use of progressive closure of the facility; as each cell is developed and filled, it will be covered with non-reactive rock. The closure surface for each cell ties into that for the entire North Pile. Progressive closure allows for the monitoring of closure conditions during operations for assessment and application of learning.

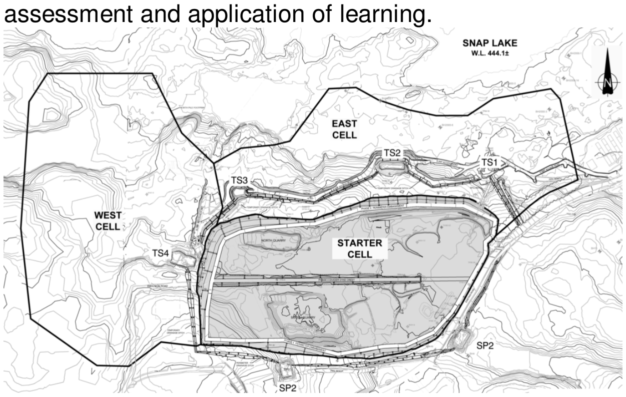

Figure 3. General arrangement of North Pile.

The design objective of the North Pile is that neither the operation of the mine nor the process plant will be impacted by activities at the North Pile. This requires that the North Pile must be capable to receive all waste materials produced at all times.

The North Pile is not designed as a water retaining facility. The facility is operated to promote drainage of water through the perimeter embankments for routing and collection by the perimeter water control structures. Water collected in the perimeter sumps is transferred to the water management pond on an on-going basis. Should water pond inside the North Pile, it will be transferred to the water management pond. A permanent pond is not maintained within the North Pile facility.

The North Pile will be developed using the PK materials and mine waste rock. The deposition and development plan for the North Pile have been developed with the recognition that the PK materials will be variable in properties during operations; especially during start-up. The plan is flexible due to the realization that the PK materials to be pumped to the North Pile will be paste and slurry. A primary goal of the deposition plan is to limit ice entrapment to increase the storage capacity for PK and mine waste rock. The plan includes monitoring activities to enable the optimization of the waste management operations.

3.2 Mine Waste Materials

3.2.1 Processed Kimberlite

The process plant produces PK materials in three size fractions: coarse, grits and fines. The approximate average proportions of the three fractions and the solids content (by mass) at which they be produced will depend on the actual process. The design proportions and solids contents of the three fractions are presented in Table 1; some day-to-day variations may occur.

To date, the fines fraction is deposited as slurry. The coarse and grits are dewatered to a solids content of about 84% (by mass) at the process plant and are hauled and placed in the surface disposal facility using conventional earth moving equipment. Following start-up activities, the process plant will produce paste from the PK materials, comprising fines, coarse and grits fractions, for disposal on surface.

Full mix paste, comprising coarse, grits and fines fractions, will be pumped to the North Pile. It is expected that the process plant will be able to produce a "good quality" paste during the development of the Starter Cell. A "good quality" paste, from a depositional point-of-view, is defined as a material which is non-segregating, exhibits little bleed and has the ability to remain static in a pipe for a period of time followed by the restarting of flow.

Placement of underground backfill is expected to commence following adequate advancement of mining operations and using an average of about 50% of the PK paste quantity produced. It is anticipated that this will involve underground backfilling operations requiring 100% of the paste for periods of time and 0% for others.

Table 1. Processed kimberlite size distribution.

Processed Kimberlite Fraction	Particle Size (millimetre)	Proportion of Processed Kimberlite	Solids Content (by mass)
Coarse	1.5 to 6.0	45%	90%
Grits	0.125 to 1.5	35%	78%
Fines	Less than 0.125	20%	47% to 55%
Total (Full Mix)		100%	72% to 76%

3.2.2 Mine Waste Rock

Mine waste rock will be placed within the North Pile. Depending upon the schedule of material, the mine waste rock may be used to construct the embankments of the North Pile. Rock type and geochemistry (*i.e.,* non-acid generating or potentially acid generating) will dictate where within the North Pile the mine waste rock will be placed.

3.3 Perimeter Water Control Structures

The North Pile is not designed as a water retaining facility. The facility is operated to promote drainage of water through the perimeter embankments for routing and collection by the perimeter water control structures. Water collected in the perimeter sumps is transferred to the water management pond on an on-going basis.

Each cell of the North Pile will be surrounded by perimeter water control structures comprising ditches and sumps. To date, the only perimeter water control structures constructed are the temporary sumps (TS1, TS2, TS3 and TS4), perimeter sumps (SP1 and SP2) and ditches of the Starter Cell, as shown on Figure 3. Water collected in the sumps is pumped to the water management pond prior to treatment and release to the environment.

3.4 Perimeter Embankments

An important objective will be to develop a methodology to construct stable embankments using paste, especially throughout the year. Perimeter embankments will be constructed for each cell. The initial embankments will be constructed on a prepared foundation surface to provide stable conditions in frozen and thawed conditions.

4 THERMAL MONITORING RESULTS

4.1 General

Thermistors comprise one part of the North Pile monitoring program at the site. Thermistors are installed during the development of the North Pile and are located within the footprint and outside the perimeter of each cell to determine the baseline conditions (pre-deposition) and monitor the changes during operation and into the post-closure period. Thermistors will be installed within the deposited materials of the North Pile as each cell is progressively closed; to date no thermistors have been installed in the deposited materials.

Select thermistor installations and respective results from the monitoring data are discussed below as a comprehensive discussion of all the installations is not within the scope of this paper. The locations of the thermistor installations discussed below, TH06-03, 04, 05 and 08, are shown on Figure 4.

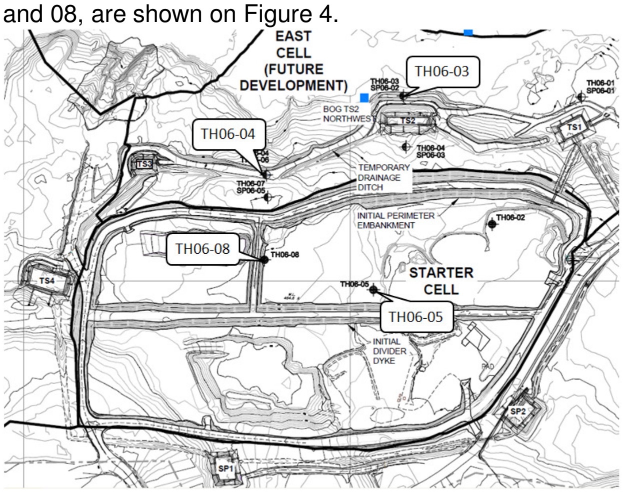

Figure 4. Thermistor location plan.

4.2 Thermistor Installations

A series of eight thermistors were installed in the Starter Cell area between February and April 2006. The thermistor strings have 10 nodes each at depths of 0.3 m, 1 m, 2 m, 4 m, 7 m, 10 m, 15 m, 20 m, 30 m and 40 m below ground surface. The four thermistor installations discussed herein are TH06-03, 04, 05 and 08. TH06-03 is located outside of the footprint of the Starter Cell and has yet to be covered by deposition materials. The simplified stratigraphy at this location is approximately 8.5 m of sand and gravel over bedrock.

TH06-04 is also located outside of the footprint of the Starter Cell and also has yet to be covered by deposition materials. The instrument is located in a natural drainage course which is also a preferential drainage path from the Starter Cell to the perimeter water control structures; water flows through this location year-round. The simplified stratigraphy at this location is approximately 1.5 m of organics over 3.5 m of sand and gravel over bedrock.

TH06-05 is located within the footprint of the Starter Cell. Materials were deposited over this instrument starting in August 2007. The simplified stratigraphy at this location is approximately 3 m of sand and gravel over bedrock.

TH06-08 is located within the footprint of the Starter Cell. Materials were deposited over this instrument starting in August 2007. The simplified stratigraphy at this location is approximately 1 m of organics over 4 m of sand and gravel over bedrock.

4.3 Effect of Ground Cover

The temperature profile of TH06-03 is presented on Figure 5. The depth at which the maximum temperature profile remains below 0°C is the top of the permafrost. The thickness of material above this depth is the active layer; about 4 m at this location. The ground temperature below 20 m ranges between about -2°C and -4°C; this temperature range at depth is similar with all of the thermistor installations of the North Pile.

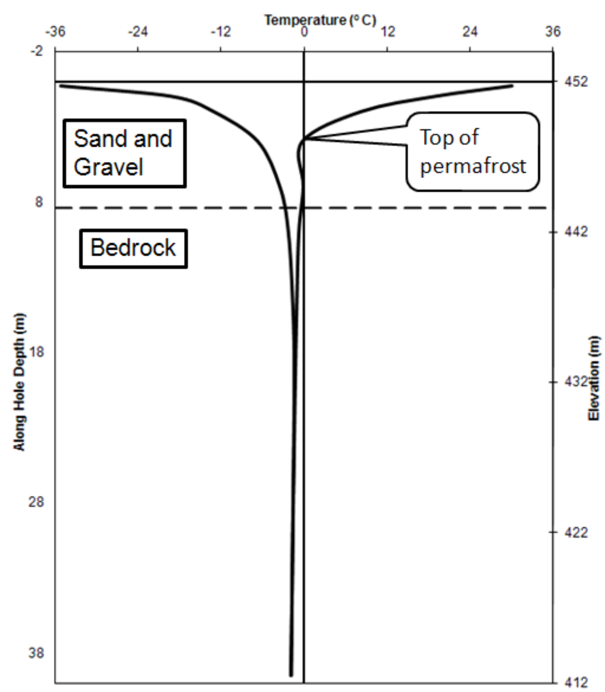

Figure 5. TH06-03: Ground temperature profile.

The temperature profile of TH06-08, showing the pre-deposition conditions, is presented on Figure 6. The active layer, at this location, is about 2 m. The thinner active layer at TH06-08 is due to the presence of the organics at surface. The organics insulates the ground and reduces the heating of the ground at depth and thereby reduces the thickness of the active layer.

4.4 Effect of Groundwater Flow

The temperature profile of TH06-04 is presented on Figure 7. The thickness of the active layer is about 11.5 m at this location. It is to be noted that the data presented on Figure 7 is prior to the start of deposition activities.

This location is within a drainage course (see above) and water flows through this area year-round. The effect of the flowing water increases the depth of thaw and increases the thickness of the active layer. Not only does the flowing water serve to increase the thickness of the active layer to greater than that at TH06-03, the insulating effect of the 1.5 m thick layer of organics is also negated (*cf.* the 2 m active layer thickness at TH06-08 on Figure 6).

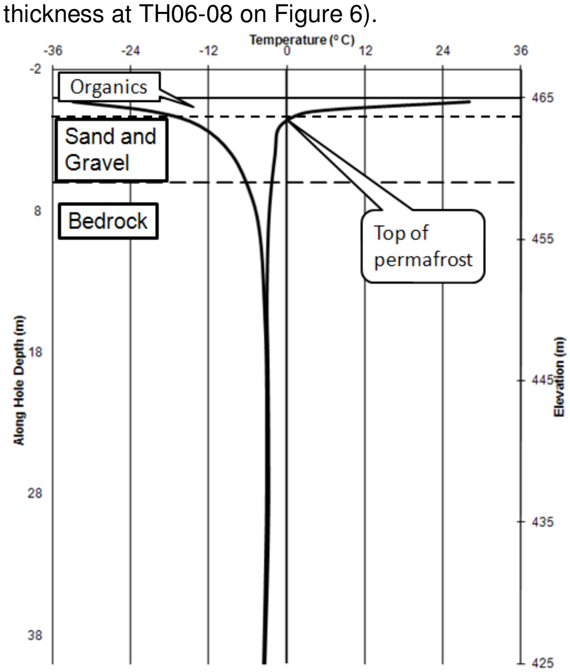

Figure 6. TH06-08: Pre-deposition ground temperature profile.

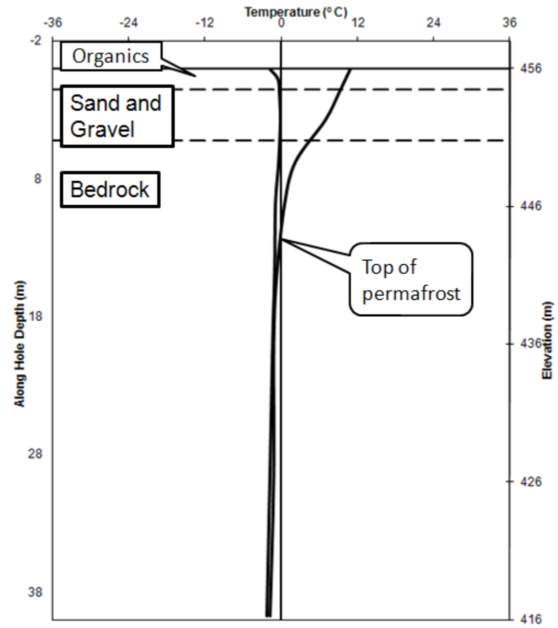

Figure 7. TH08-04 Ground temperature profile.

4.5 Effect of Deposited Materials

The pre-deposition temperature profile of TH06-05 is presented on Figure 8 along with that measured in 2009 (*i.e.,* during deposition activities). The pre-deposition seasonal depth of thaw (thickness of the active layer) is about 7 m. By the end of 2009 (deposition activities having started in August 2007), the maximum ground temperature is below 0^{o}C beneath the original ground surface.

Between August 2007 and the end of 2009, an estimated thickness of 4 m to 5 m of slurry had been deposited in the area of TH06-05. The maximum ground temperature is below 0^{o}C beneath the original ground surface as shown on Figure 8. The top of permafrost is not possible to determine as no thermistors have yet been installed in the deposited materials.

The temporal temperature variations for the thermistor nodes of TH06-05 are shown on Figure 9. Prior to the start of deposition in August 2007, the node temperatures follow the trend of the air temperature (note shown on the figure for clarity). The ground temperature responds to the air temperature with a time lag and the time lag increases with depth; this observation is noted for all of the thermistors of the North Pile with the exception of TH06-04 (due to the presence of flowing water).

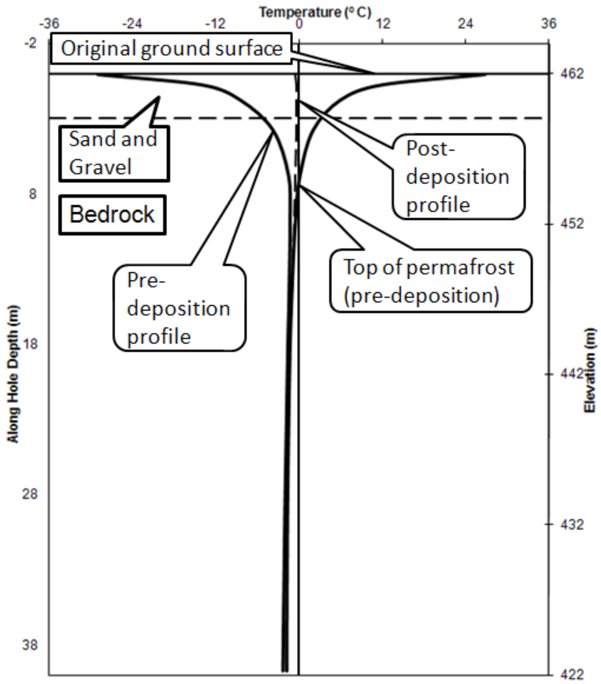

Figure 8. TH06-05: Pre- and post-deposition ground temperature profiles.

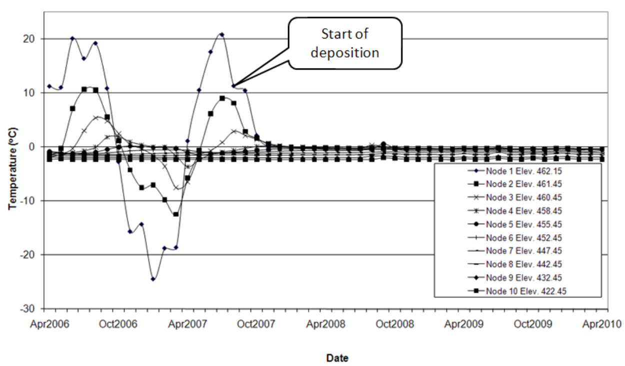

Figure 9. TH06-05: Nodal temperature timelines.

The materials deposited in the Starter Cell insulate the original ground and promotes its freezing. The short time required to achieve this effect is shown on Figure 9 for TH06-05. Prior to the start of deposition activities, the near surface nodal temperatures fluctuate in a sinusoidal fashion. The near surface nodal temperature fluctuations reduce to essentially zero (to match the trend of the deeper nodal temperature fluctuations) almost immediately following the start of deposition activities,

5 COMMENTARY

A brief summary of the Snap Lake Mine and its mine waste rock and processed kimberlite facility, the North Pile, has been presented. The site is located in the continuous permafrost zone of the Canadian low arctic. Thermal monitoring in performed as part of the North Pile monitoring program; the design of the facility does not depend upon the thermal condition of the native foundation materials (soil and bedrock) or the deposited materials.

A summary of select results from the thermal portion of the North Pile monitoring program have been discussed herein. The results show:

- The presence of organics on the ground surface reduces the summer heating of the ground, resulting in a thinner active layer.
- The presence of year-round groundwater flow increases the thickness of the active layer. The presence of organics at this location did not reduce the depth of seasonal thawing.
- The deposition of materials within the Starter Cell insulated the ground and promoted the aggradation of permafrost to at least the location of the original ground surface. This effect was noted to occur within a couple of months following deposition activities in the area.

The monitoring program will involve the installation of additional thermistors in and around the North Pile during its development, including installations within the deposited materials. The instruments will be monitored during operations and into the post closure period.