5.2.2.3 Effect of Compaction on Shale Grain Size Distribution

In order to determine the effect of compactive effort on the grain size distribution of quarried and placed shale, the pre- and post compaction grain size distributions were compared. Figure 17 shows the pre- and post-compaction test grain size distribution of the shale sample collected in 2003 from the ETL Quarry. The D_{50} values and fines content were used to compare the pre- and post-compaction grain size distributions. For comparison purposes, the D_{50} and fines content values for the pre-compaction samples were recalculated without considering the material greater than 20 mm in diameter. The sample was observed to become more fine grained, post-compaction. The D_{50} of the sample reduced from 9 to 6 mm and the fines content increased from 3.9 to 5.3%.

Considering the minimal change in D_{50} values after compaction, it appears that application of compactive effort results in a minor generation of fines. This is also reflected in the minimal difference in fines content observed between the shale samples collected from borrow areas and the samples collected from the West Twin Dike and test covers as discussed in Section 5.2.2.1.

5.2.2.4 Moisture Characteristics of Shale

The results of moisture content testing completed by BGC in 2003 and Terratech (1993a) were reviewed to assess the moisture characteristics of the shale.

Moisture contents were determined for the shale samples collected by BGC in 2003 from the ETL and Mt. Fuji quarries and in-situ samples collected from the Surface Cell Test Cover and Test Cell Test Cover #1. The moisture content was observed to range between 2 and 6%. This range is not considered reflective of in situ moisture conditions considering the granular nature of the material and the time between sample collection and testing. It should also be noted that the test pit excavated into Test Cell Test Cover #1 encountered flowing water into the test pit above the frozen ground/ thawed ground interface. This is visually documented on the photo in Figure 18. The presence of water flowing into the test pit at this depth suggests saturation of the cover material has been obtained. Although the shale is saturated, the observed moisture contents of the in situ shale samples are low since thawed samples do not retain all of the pore water when sampled due to their granular nature.

The moisture contents of the frozen samples collected by Terratech during geotechnical drilling of the West Twin Dike in 1992 indicate moisture contents ranging between 15% and 25%. This is considered to more accurately reflect in situ moisture conditions of the saturated shale because the samples were collected in a frozen state and tested soon after collection at the on site lab at the mine. As a result, this is the resultant moisture content that would be expected when the ice saturation zone becomes effective in preventing thaw.

As reviewed in Section 6.1, the active layer thaw progresses rapidly into the top of the cover. Once it reaches the depth of the ice-saturated shale, very little additional thaw occurs due to the latent heat of fusion in the ice. This observed phenomena confirms the existence of ice saturation at depth in the cover.

5.2.2.5 Durability

Golder (1999) evaluated the geotechnical durability of the shale from the Mt. Fuji and East Twin Lake quarries; the Twin Lakes sand and gravel was also evaluated. Samples of the materials were collected and sent to Golder's laboratory where sieve analyses, relative absorption, bulk specific gravity, Los Angeles abrasion, slake durability index, freeze/thaw durability and petrographic analyses were conducted.

The results are summarised in Table 12. The results indicate that Twin Lakes sand and gravel is a relatively competent material appropriate for capping and erosion protection. The shale samples have higher abrasion and freeze-thaw losses than the Twin Lake sand and gravel and these materials were not recommended for use as capping and erosion protection. Golder (1999) suggested that the shale could be used to provide thermal insulation for the underlying frozen tailings and to restrict infiltration of water/oxygen into the subsurface.

5.2.2.6 Permeability

In warmer climates, an engineered cover is required to be constructed of low permeability material in order to mitigate leachate generation from infiltration of precipitation (i.e., promote surface runoff). The permeability of the final cover must typically meet regulatory requirements. However, the geothermal regime at Nanisivik provides the opportunity to use a more permeable (thawed state) insulating cover, which will keep the waste and a portion of the cover in a frozen state. Infiltration of surface water into the cover material will increase the water and ice saturation level, which will result in a reduction in hydraulic and thermal conductivity. Freezing of pore water in a saturated granular soil has been observed to result in a decrease in hydraulic conductivity of over five orders of magnitude (Burt 1976).

Samples of shale collected from the WTL and Shale Hill quarries and Test Cell Test Cover #1 were sent to Golder Associates laboratory in Calgary, AB for hydraulic conductivity testing. A grain size distribution analysis was conducted on each sample and only the particles smaller than 10 mm diameter were used for the testing. A constant head permeability test was conducted on the remaining sample which had been compacted into the test cylinder in 3 lifts. The test was conducted according to ASTM test procedure D2434-68. The results of the testing are included in Appendix II. The test results indicate saturated permeability ranges between $1x10^{-3}$ and $1x10^{-4}$ m/s. This is comparable to the range of $1x10^{-2}$ and $1x10^{-5}$ m/s suggested by Fetter (1994) for well sorted sands and gravels. As discussed previously, Burt (1976) estimated a decrease in hydraulic conductivity of greater than five orders of magnitude due to freezing of saturated sand. As such, it is anticipated that the hydraulic conductivity of the reclamation cover will reduce significantly once saturation and freezing of pore water has been achieved.

5.2.3 Filtering Capacity

The filtering capacity of the Twin Lakes sand and gravel was assessed to determine if the material is effective in limiting the upward migration of the underlying shale particles. The Sherard and Dunnigan method for the design of critical filter design for sands and sandy gravels with small contents of fines was used for the analysis. The Sherard and Dunnigan method is described by Fell et al. (1992) as the following:

> For silty and clayey sands and gravels with 15% or less by weight (of the portion finer than the 4.76 mm sieve) finer than the 75 μm sieve, the allowable filter for design should have $D_{15F} \leq 4D_{85B}$ where D_{85B} can be the 85% finer size of the entire material including gravels.

The available grain size data for the Twin Lakes sand and gravel was reviewed in order to conduct the assessment. For conservatism, the finest grain size distribution of shale was compared to the coarsest grain size distribution of the sand and gravel. The D_{15F} value of the portion of the filter material (Twin Lakes sand and gravel) finer than 4.76 mm is approximately 0.1 mm, and the D_{85B} value of the base layer (shale) is approximately 16 mm. Therefore, the Twin Lakes sand and gravel meets the filter criteria for the shale using the Sherard and Dunnigan criteria.

5.2.4 Summary of Geotechnical Analyses

The following is a list of the principal conclusions based on the geotechnical properties discussed in earlier sections:

- The shale cover is a granular material that generally consists of more than 50% gravel and larger sized particles and less than 10% silt and smaller sized particles;
- The Twin Lakes sand and gravel is a granular material that generally consists of more than 70% gravel and larger sized particles and less than 5% silt and smaller sized particles;
- The application of compactive effort to the shale appears to result in a minor amount of fines (smaller than 0.075 mm) generation;
- The SPMDD of the shale was calculated to range between 1870 and 2092 kg/m^3 and the optimum moisture content was calculated to range between 6% and 9%;
- The specific gravity of the shale has been determined to range between 2.60 and 2.65;
- The moisture content of shale samples ranged between the following:
  - Thawed samples from quarries ranged between 2% and 4%;
  - Thawed samples from Test Cell Test Cover #1 ranged between 4% and 6%
  - Frozen samples from the West Twin Dike ranged between 15% and 25%.

- The saturated moisture content of the shale was estimated to range between 14% and 18%;
- Twin Lakes sand and gravel is a durable material suitable for application as erosion protection;
- Limited laboratory tests indicate that the shale is not a highly durable material and may break down when subjected to repeated freeze thaw cycles. However, additional lab testing and visual observations of in situ shale from the test covers has indicated that the shale composition varies only minimally from the composition of shale samples collected directly from the borrow areas;
- The shale is highly permeable, but will likely form a low permeability barrier upon saturation and freezing.

5.3 Geochemical Characterization of Shale

5.3.1 Potential for Acid Generation and Acid Consumption

The acid generation and acid consumption potentials for shale have been investigated by Lorax Environmental. A report titled "Acid Generation Potential of Tailings and Shale Cover Material" dated September 1999 describes metals analysis, acid base accounting, mineralogical examination, grain size analysis and humidity cell testing. The sample investigated was shale collected from the West Twin Dike. A second report titled "Acid Generation Potential of Soil, Waste Rock and Shale" dated April 2001 presents acid base accounting of additional samples of shale from the West Twin Dike (7), the East Twin Lake Quarry (10), the Mt. Fuji Quarry (10) and the Area 14 Quarry (11).

A select set of five samples of shale that were collected from the East Twin Lake Quarry (1), the West Twin Quarry (3), the Shale Hill Quarry (1) during a drill program conducted by BGC in May 2003 were analysed for metal content and acid base accounting. The samples were selected to increase the aerial coverage of the previous studies and to test subsurface samples.

The determinations of total metals for all of the samples analysed ranged from: 1.5% to 2.11% iron, 11 ppm to 150 ppm zinc, <2 ppm to 48 ppm lead, <0.5 ppm to 0.5 ppm cadmium and <0.2 ppm to 0.7 ppm silver, which are all at least one order of magnitude less than tailings, as expected.

The acid base accounting analyses confirmed the general expectation that the shale is acid consuming. The shale samples contained low concentrations of total sulphur (0.11 to 2.34%) of which most was in the form of sulphides (0.09 to 2.10%). The shale samples contained large neutralizing potential ("NP") (87 to 627 kg $CaCO_3$/t) that was primarily in the form of carbonates (84 to 589 kg$CaCO_3$/t). The resulting net neutralization potentials were uniformly large and positive (+84 to +585 kg$CaCO_3$/t) and the resulting ratios of NP to acid potential were uniformly greater than three (3.7 to 69.4). These results clearly demonstrate the classification of shale as acid consuming. The data suggests that shale from the Area 14 Quarry may contain slightly less sulphur than other locations. However, the difference is slight and may be related to a number of variables. Regardless, all of the shale is clearly acid consuming and there were no substantive differences noted in the data between locations and depths.

The mineralogical analysis indicated that the sample analysed consisted primarily (>90%) of carbonate rock that was considered to be dolomite. The remainder of the shale sample consisted of bituminous material (2.5%), quartz (2%), microdiorite (1%) and sulphides (0.5%).

Grain size analyses demonstrated that the sample analysed was generally within the size ranges for sand and gravel with approximately 48% gravel (+2 mm), approximately 47% sand (0.06 to 2 mm) and approximately 5% silt (-0.06 mm). Additional grain size analyses have been performed on samples of shale for geotechnical design purposes that are not reported here.

A humidity cell test was conducted for 37 weeks at 20°C for 28 weeks and then at 2°C for the remainder of the test to determine the effect of colder temperatures. The primary observations of the tests are as follows:

1. Leachate remained neutral (pH>7.5) throughout the test;
2. Sulphate production rates were low, generally decreased throughout the test and were not clearly affected by the decrease in temperature;
3. The calculated rate of carbonate depletion increased slightly throughout the test and was not clearly affected by the reduction in temperature; and
4. Calcium and magnesium were released at rates of at least two orders of magnitude greater than other metals.

The general conclusions of the humidity cell tests were:

1. The shale sample was confirmed to be acid consuming (sulphate depletion faster than neutralization); and
2. Neutralizing potential was present primarily in the form of carbonates.

5.3.2 Summary

The primary conclusion regarding the geochemistry of the shale that stems from the information described above is that the shale is acid consuming (i.e., no risk of acid generation).

This conclusion is as expected given the low sulphur content and given that the dominant host or "country" rock in the mine area is dolostone, of which a shale sample was confirmed to contain 90%.

6.0 VERIFICATION OF COVER DESIGNS

Since 1988, several studies on potential cover design alternatives have been undertaken. Of these studies, the most significant related to development of a cover design include the following:

1. Test Cell Test Cover Study:
   The assessment of several cover design alternatives was undertaken by constructing test cells. The test cells were instrumented with thermocouples and frost gauges and monitored to determine the effect of different design options on the depth of active layer thaw.
2. Geothermal Modelling:
   Geothermal modelling of tailings cover thickness was undertaken by BGC. This model used the results of the test cell evaluation for calibration. The steady state depth of active layer thaw was determined under mean annual climatic conditions and for global warming scenarios.
3. Area 14 Waste Rock Cover:
   The waste rock pile located at Area 14 was covered with a layer of shale in 1988. The cover and waste rock was instrumented with thermocouples and has been monitored since 1991. BGC undertook a review and interpretation of the thermal monitoring data collected from the Area 14 shale cover.

These studies and reports, and their significance towards cover design are summarized in the following sections.

6.1 Test Cell Test Cover Study

6.1.1 On-Site Field Tests

MEND recommends direct measurement of field performance as the best method for demonstrating that a cover system will perform as designed. Part of Nanisivik Mine's reclamation planning process has included a field program that was initiated in 1990 through consultation with Terratech (a division of SNC). Terratech was contracted to supervise and report on the drilling of eight boreholes to clarify permafrost aggradation processes that were observed in man made fills in the Nanisivik area. The resultant report "Geotechnical Investigation of Permafrost Aggradation – Nanisivik Mine" showed that permafrost aggradation had occurred in tailings deposited in West Twin Lake as foundations for internal causeways.

This information indicated that it would be possible to manipulate the local permafrost table and induce aggradation into a cover material, thereby protecting the underlying tailings from thaw. Further fieldwork to qualify the natural freeze/thaw process and potential anthropogenic influences was planned, carried out, and is described in the following sections.

6.1.2 Test Cover Construction

Under the continued supervision and direction of Terratech, field testing of various tailings cover materials began in 1991. Five "test covers" were constructed in the WTDA, along the north shore of the West Twin reservoir. The test covers were placed on exposed tailings having a surface elevation of 370 to 371 m.

Detailed construction information concerning the test covers is included in Terratech (1993b). The test covers were constructed mainly of a 2 m thick lift of shale, with some pads incorporating internal layers of sand and gravel. Some of the pads were also constructed with a capping layer of sand and gravel. The pads were constructed using varying degrees of compaction and saturation.

6.1.3 Geothermal Instrumentation

Thermocouples and frost gauges were installed within each test cover to assess the effect of different construction details on the depth of active layer thaw. Frost gauges have a distinct advantage over thermocouple strings, in terms of the detailed monitoring of the active layer. Thermocouple strings must have separate thermocouple contacts with dedicated wiring for each depth monitored. Thermocouples will provide temperature records to within 1°C of accuracy; they are generally placed at intervals greater than 0.25 metres. Frost gauges are capable of providing freeze/thaw determinations at increments of 1 to 2 cm. For active layer behaviour, the level of detail provided by the frost gauges is considered more informative.

6.1.4 Geothermal Monitoring

The frost gauge network was used to monitor the active layer on both the West Twin Dike and the Test Cell Test Covers. Monitoring consisted of visual readings/measurements twice per week during periods of thaw (typically June through September). Systematic monitoring began in 1993 and continued until 2000.

The data collected between 1998 and 2000 is not considered in this interpretation because, during these years, tailings were poured in the Test Cell area, in the immediate vicinity of the test covers. Tailings are discharged at +11°C and at an approximate rate of 120,000 m^3/month (as a relative comparison the test cover volumes range from 500 to 1,800 m^3). The tailings volume introduced a heat source which biased the thermal monitoring during this time period.

First year results (1992 data) were expected to be of little value as it was the first thawing season. While the results were described as erratic and inconclusive, the following notable observations were made:

1. Areas with lighter coloured surface material on Test Cell Test Cover #1 experienced approximately 30% less thaw than proximate areas with (darker) shale cover.

2. Susceptibility of the Airport sand to wind erosion was evident from the significant reduction in the sand capped areas after one year.

Subsequently, data from 1993 to 1997 has been used to assess the performances of the different test covers. A summary of the maximum annual penetration of thaw is shown in Table 14.

The maximum thaw recorded in 1993 (first year monitored after installation) ranged between 0.95 and 1.63 m below ground surface. The best results (minimum thaw) in 1993 occurred in F3 and F7 (Test covers 1 and 2) with thaw depths of less than 1.0 m.

In 1997 (the last year monitored), the maximum thaw had decreased to a range 0.73 and 1.40 metres. Thaw depths of less than 1.0 m were recorded in F3, F4, F6 and F7. Thaw depths of <1.25 metres were recorded on all gauges except F9 and F10. Again, the best results occurred in F3 and F7 (Test Cell Test Cover #1 and #2) with thaw of 0.73 and 0.87 m respectively. Test Cell #1 had an average thaw depth of 0.92 m, based on the 1997 readings for F3, F4, F5 and F6.

6.1.4.1 Temporal Trends

As noted previously in Gartner Lee (2002) temporal trends will be referred to in this document as either "annual" or "life of project". Annual trends refer to behaviour that can be observed over the course of one melting season. Life of project (LOP) trends refer to observations made over the entire construction and monitoring period (1991 – 1997).

In the evaluation of **annual trends**, three distinct thaw behaviours occur:

1. Each melt season begins with a steep migration of permafrost out of the surficial cover layer. During the first few weeks of the 12 to 18 week melting season, approximately 80% of the active layer thaw occurs.
2. Following the initial steep frost migration period, the rate of thaw slows to a very gradual scale. Generally, less than 20% of the annual thaw occurs during this longest (and warmest) portion of the melt period.
3. As the cold air temperatures return in the fall, there is a very steep frost aggradation period. Generally, from the time the first indication of frost aggradation is observed, until complete freeze-up, is 1 to 3 weeks.

This annual trend is illustrated on Figure 19 which contains the geothermal performance of Test Cell Test Cover #1 in 1997.

The following **life of project trends** were observed:

1. The depth of thaw for all locations decreased by an average of 28% between the installation date and the first year of readings in 1993 (i.e. the depth of thaw for F1 was 2.00 metres in 1991 and had decreased to 1.43 metres in 1993).
2. The depth of thaw for all locations decreased by an average of 47% between the installation date and the last year of readings in 1997.
3. The maximum depth of thaw, averaged for all locations, continued to decrease by a diminishing percentage each successive year. This is to say that between successive years (i.e. 1991/2 and 1993, 1993 and 1994, 1994 and 1995, etc) depth of thaw decreased by 28%, 11%, 8%, 4%, and 4% respectively.
4. In 8 of the 10 frost gauges, the thaw depth was continuing to diminish annually when the program was terminated (as shown in Figure 20).

A direct comparison between pairs of frost gauges in Test Cell Test Cover #1 was made to evaluate the influence of the water reservoir in the Test Cell as a heat sink. Frost gauges F5 and F6 were located on the south end of the pad. Results from F3 are compared with results from F6 as both instruments were in the area with the lighter coloured surface material. This comparison shows that F6 (which was closer to the water) thawed an average of 0.40 metres deeper than F3. Similarly, F5 thawed an average of 0.48 m deeper than F4.

Another direct comparison between pairs of frost gauges in Test Cell Test Cover #1 was made to evaluate the effects of the lighter coloured surface material. The west half of the surface area of Test Cell Test Cover #1 (containing F3 and F6) was covered with a 15 cm layer of light coloured material (sand). The results show that the gauges in the area with light coloured surface cover (F3 and F6) experienced an average of 0.26 m less thaw depth than their darker coloured counter parts (F4 and F5).

6.1.5 Discussion

Active layer thaw results presented above meet with the expected results of the geotechnical test program initiated in 1990. General observations in the Nanisivik area at that time noted that, in areas of fine grained materials, the active layer was often less than 1 metre. Terratech (1993b) reported that natural processes (i.e. runoff, precipitation) provide a high degree of saturation at the approximate base of the active layer, and that finer grained materials have a higher degree of saturation than coarse materials.

Further, the ice content at the base of the active layer is usually greater than the minimum amount of moisture which would completely saturate the overburden forming a diffusive barrier to air and water infiltration. With this in mind, the test covers were constructed with local fine grained materials (i.e. shale) and were monitored as natural processes (snow melt and run-off) annually increased the ice zone.

The annual trends reported above support the expected results. The steep downward trend of thaw in the early part of the melt season can be seen to reach a depth after which the rate is abruptly slowed. If this observation were explained by the consistent thermal properties of the shale alone, one would expect the point (depth) at which the thaw rate changes (slows), to remain approximately the same each year. However, as can be seen in the graphs, the thaw depth for the initial steep thaw period, generally diminishes each year (i.e. thaw depth becomes shallower). This becomes more apparent on examination of the graphs of F3, F4, F5 and F6 on Figures 19 and 20. This observation is supported by the principle of the latent heat of fusion, which is the heat required to melt ice, without a change in temperature. This parameter amounts to 334 kJ/kg and results in extra energy that must be input to melt included ice.

Mackay (1997) noted a similar increase in ice saturation levels in the active layer in the bottom of drained arctic lakes, where he notes "in summer, water in the thawing active layer may move downward by gravity, aided by the temperature gradient, to refreeze at the bottom of the active layer and even at the top of permafrost and thereby, increase their ice contents". The reference also notes three other references including Mackay (1983).

These principles would enforce the rapid thaw behaviour in the early melt period and the sudden retarding of the rate when thaw reaches the ice saturated zone at the base of the active layer. Another significant observation noted during the monitoring period was the influence of the Test Cell water reservoir as a heat sink. It has already been pointed out, as one of the **life of project** trends discussed above, that the water reservoir had a measurable effect on the frost indicators in Test Cell Test Cover #1. In addition, the relatively deeper thaw results noted in Test Cell Test Covers #3, 4 and 5 are believed to be attributed to this same influence. Covers 3, 4 and 5 were built on a causeway projecting into the reservoir, while covers 1 and 2 were built on the original shoreline of the lake and are "shore fast". In terms of relative thaw, the averaged results from covers 3, 4 and 5 at the end of the program (1997) reached 0.41 m deeper than the averaged results from covers 1 and 2. It is postulated that there was some amount of influence from the Test Cell water reservoir on all the test covers due to their proximity. Considering this, the performance of a cover on the Surface Cell would be expected to be somewhat better.

Finally, it should be noted that at the end of the observation period (1997), the depth of thaw had not yet reached stability and had continued to lessen (improve) annually, albeit by a diminishing annual improvement as noted in the **life of project** trends. This imparts an additional level of conservatism to the proposed cover depth that is based on the 1997 results.

6.1.6 Summary of Field Observations

The proposal for the Surface Cell cover is based largely on the performance observed from Test Cell #1, which is summarized as follows:

1. Test Cell Test Cover #1 was constructed of a nominal thickness of shale fill, from the Mt. Fuji Quarry, without controlled saturation or compaction.

2. Thaw depth in the four frost gauges in this cover (F3- F6) showed that the maximum depths of thaw improved continuously between 1991 and 1997 and were continuing to improve, albeit slowly, at the termination of the monitoring period. This is attributed to the gradual build-up of the ice layer at the bottom of the active zone.
3. Results in 1997 (end of program) showed thaw depths at each of the instruments measuring 0.73, 0.95, 1.05 and 0.97 m respectively (or an average value of 0.92 m).
4. Direct comparison of the two pairs of frost gauges in Test Cell Test Cover #1 (F3 vs. F4; and F5 vs. F6) indicates that areas with light surface coloured material (F3 and F6) experienced an average of 0.26 m less thaw depth than their darker coloured counter parts (F4 and F5).

This field trial information is used within the geothermal modeling and the climate change considerations and is used as a basis to develop the details of the final cover design. This provides for a level of conservatism because thaw conditions were continuing to improve at the end of the test program and the influence of water as a heat sink will not be a factor in the Surface Cell, as it was for the test covers.

6.2 Geothermal Modelling of the Shale Cover

A geothermal modeling assessment was conducted to evaluate the potential variations in the depth of active layer thaw within the shale cover due to extreme temperature events. The results of this thermal model, calibrated to site test cover data, were then extended for extreme warm years and for global warming scenarios over the next century. The modeling reviewed herein serves as the basis for the required cover thickness for the closure phase of this facility.

It should be noted that this modelling assessment was undertaken previously and reviewed in the Water Board Hearing of July 2002. The modelling provided herein provides a refinement of the previous work based on measured values and refinement of warming events.

The results of geothermal analyses are based on assumed parameters correlated between some site specific measurements, measured values for the tailings and published values from various references. A calibration of the geothermal model, based on extensive site-specific measurements, has been made. In addition to the input assumptions, 1 in 100 year warm year and global warming estimates have been made for the next 100 years, not accounting for any potential variations in precipitation and/or associated climatic conditions.

6.2.1 Geothermal Software

Geothermal analyses were undertaken using the commercially available, explicit finite difference program, THERM1 written by Nixon Geotech Ltd. This program solves one-dimensional heat transfer problems involving freezing and thawing, including the latent heat of fusion. A power law function represents the relationship between unfrozen water content and temperature in each soil / rock unit. The program requires a variety of standard physical properties as input, but it is versatile in accommodating several alternative combinations of meteoric input. In the analyses reported herein, mean monthly air temperatures, solar radiation, wind velocities, and snow cover thicknesses are specified and a surface energy balance routine was used to calculate the ground and snow surface temperatures.

Input for THERM1 can be categorized as either meteoric or physical. The values used for the analyses are described in detail below.

6.2.2 Meteoric Input

Climate data was obtained from either the Nanisivik Airport AES site or from the Resolute weather station. Where available, site-specific data (e.g. temperature) was used. Where applicable, the climate data were modified based on the calibration geothermal modeling undertaken. The climate data is summarized in Table 15.

The first day and last day of snow cover were assumed to be August 25 and June 25, respectively. These dates are based on the mean monthly temperature data.

6.2.3 Physical Properties

Snow

A snow cover thermal conductivity of 0.30 W/m°C was used. This corresponds with a snow pack density representative of average conditions between fresh snow and wind-toughened snow (Johnston, 1981). A snow cover albedo of 0.75 was used (Savigny et al. 1995).

Soil / Rock

Relationships between the thermal conductivity of a soil and its porosity and degree of saturation are reported by Kersten (1949) and others, mainly on the basis of experimental data. The thermal conductivity of ice is much higher than that of water; hence the thermal conductivity of a frozen soil generally exceeds its unfrozen equivalent. As soil porosity approaches 100%, frozen and unfrozen thermal conductivity values in a saturated system approach those of ice and water, respectively. Conversely, as the porosity of a soil approaches zero, frozen and unfrozen thermal conductivities converge on average values related to mineral constitutes.

For the purpose of the thermal modeling, laboratory tests were conducted by EBA Engineering Consultants Ltd. on samples of the tailings deposits from Nanisivik. These tests were conducted to determine the following parameters:

- Thermal conductivity in both frozen and unfrozen states;
- Unfrozen water content versus freezing temperature; and
- Index tests to measure the frozen bulk density, water content, particle size distribution, and specific gravity.

Additional reference sources were consulted for the material properties of the bedrock and the shale cover materials. Thermal conductivities and other soil and rock properties for the various materials used in the geothermal analyses are listed in Table 16.

Albedo is a parameter in the geothermal model and it is defined as the ratio of solar radiation that is reflected back by a material to the atmosphere. Numerous references provide a range of possible values for soil albedo factors as partially summarized below:

- Bare black soil – 0.07.
- Open soil cover with low shrubs – 0.08 to 0.23.
- "Light" soil albedo – 0.11 to 0.15

For the model, a ground surface albedo of 0.10 was used in the analyses (Savigny et al. 1995).

Unfrozen Water Content

Soils that are below 0°C still contain some portion of unfrozen water within their pore space. The power law relation below represents the relationship between unfrozen water content and temperature in each soil and rock unit.

$$w_u = A(-T)^B / w_{tot}$$

where:

w_u = unfrozen water content (fraction of total water content);
A = gravimetric unfrozen water content at -1°C;
B = exponent in power law function;
T = temperature in °C (negative); and,
w_{tot} = total water content.

Values of the A and B parameter used in the geothermal analyses are shown in Table 16 that come from Nixon (1992).

In addition, a nominal freezing point depression of –0.05°C was assumed as the phase change boundary within the soil pore space.

Geothermal Gradient

A geothermal gradient of 0.0396°C/m was used based on measurements reported by Brown (1966).

6.2.4 Model Calibration - Test Cover #1

The one-dimensional geothermal model was calibrated to site conditions using data collected from Test Cover #1, which was constructed in late 1991. This test cover consists of nominally 2 m of truck-compacted shale (sand and gravel) overlying 1.8 m of saturated, frozen tailings over a 30 by 30 m area. There was no moisture control on the shale when placed. Although a 2 m shale gravel was indicated, a 2.5 m thickness was noted in the borehole logs for thermocouple T3. Consequently, a thickness of 2.5 m was used for the shale gravel cover in the calibration model.

The western half of this test cover was covered with 0.05 to 0.10 m of light coloured "Airport Sand" to test the effect of albedo change on the geothermal regime. In comparing the various frost gauge readings, there appears to be a significant difference (approximately 0.22 m) in the thaw depths recorded for F3 (under light coloured cover) versus F4 (under shale cover). Thaw depth differences between F5 and F6 are not so apparent (only 0.08 m). For the purposes of calibration, no cover layer of sand and gravel was used.

The data from the four frost gauges (F3 through F6) in Test Cover #1 was analyzed, and any erroneous or unstable data was discarded. Based on the 1997 data, an active layer of 0.72 to 1.05 m was observed, for an average thaw depth of 0.92 m in Test Cover #1. The monitoring data collected in 1997 from the frost gauge (F7) installed in Test Cover #2 indicated 0.87 m of thaw. The data from the thermocouples was considered unsuitable for the purposes of calibration (node spacing of 1 m and rated accuracy of +/-1°C) and consequently ignored.

An active layer of 0.90 m was predicted using the geothermal model created for the test cover stratigraphy. This is in the range of the active layer thicknesses measured in the frost gauges in this test cover.

6.2.5 Surface Cell Cover Model - Base Case

Based on the calibration model of Test Cover #1, a Surface Cell (or Test Cell) cover model was generated to evaluate the effectiveness of a shale cover to maintain frozen conditions in the underlying tailings. The model stratigraphy consists of 1.25 m of shale gravel overlying 17 m of tailings, which in turn overlies 11.75 m of shale bedrock. The model was run for a 10-year period under average climate conditions to ensure model stability.

An active layer thickness of approximately 0.87 m was predicted. This geothermal regime is shown in Figure 21.

If the albedo value of the surface was changed to 0.15 from 0.1 to reflect a lighter-coloured surface, then the depth of thaw reduced by 6 cm to 0.81 m. This result is based on the output of the geothermal model and may not be reflected in actuality, given the potential angle of inclination of the sun at this site.

A 0.25 m thick protective cap of Twin Lakes sand and gravel was then added to the model. The surface albedo was not changed from the 0.1 value due to the limited effect on the calibration run noted earlier. With the sand and gravel protective cap added on top, an active layer thickness of 0.87 m was again predicted indicating that the protective cap moved the active layer up by the amount of its thickness.

It should be noted that this base case model was also conducted for a lower moisture content of 10%, rather than the 20% value used initially. When the 10% value is used, the thaw depth increases to 1.02 m, or by 0.15 m.

6.2.6 Surface Cell Cover Model – 1:100 Year Event

A 100 year warm year, which is equivalent to a mean annual air temperature of –13.3° C, was added to the end of the 10 year base case scenario. The result of this change to the mean annual air temperature for a one-year period was a small increase in the thaw depth to a total depth of 1.00 m. This geothermal regime is shown in Figure 21.

6.2.7 Cover Model - Global Warming

The base case model with no sand and gravel surface layer was run for a 100 year period for the High Sensitivity value. An active layer thickness of 1.22 m was predicted for the end of the 100-year (Year 2100) run. The predicted geothermal regime is shown in Figure 21.

If a sand and gravel protective cap is added, the thaw penetration depth is expected to remain the same (1.22 m below the surface of the protective cap). It is possible that the effect of a protective cap layer may be more pronounced over the longer term, but this aspect was not modeled.