TO: Bill Horne **DATE:** March 5, 2007

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SUBJECT: **One-Dimensional Thermal Analysis of Landfill over Tailings Pond Area Roberts Bay Abandoned Mine Site, Nunavut**

1.0 INTRODUCTION

Roberts Bay and Ida Bay abandoned silver mines are located approximately 68°10'45" N by 106°33'29" W (AMEC, 2007). As a part of remediation plan, a non-hazardous waste landfill has been proposed to be constructed over an existing small tailings pond at Roberts Bay to contain the dry non-hazardous waste at Roberts Bay and Ida Bay and to cover the tailings. The design intent of the landfill is to place sufficient fill cover (including the non-hazardous waste) over the tailings pond area such that permafrost condition will be developed and then maintained in the tailings under long-term climatic conditions.

Thermal analyses were carried out to estimate the required cover thickness to maintain the long-term frozen condition of the tailings. This memo summarizes the input data and results of the thermal analyses.

2.0 LANDFILL SITE CONDITIONS

The site conditions at the proposed location of the non-hazardous landfill have been described in AMEC (2007). The landfill will be designed to completely cover the existing tailings pond. The tailings pond area including the existing waste rock berm (0.5 to 1.0 m high) surrounding the pond has a surface area of approximately 700 m^2 in a roughly circular shape. The actual thickness of the tailings is unknown and estimated to range from 0 to 2 m when the original ground surface beneath the tailings is projected from the surface slope of the ground surrounding the tailings pond area. Basaltic bedrock outcrops are observed nearby the tailings pond area.

The information for the geotechnical assessment at Roberts Bay and Ida Bay abandoned silver mines is presented in EarthTech (2006). Shallow boreholes using hand auger and shovel were drilled/excavated to depths from 0.30 to 1.37 m within potential borrow areas. Limited geotechnical information was obtained from the site investigation.

The non-hazardous waste to be placed in the landfill includes 84 m^3 steel/metal products and 178 m^3 miscellaneous inert wastes from Roberts Bay and 9 m^3 of steel/metal products and miscellaneous inert wastes from Ida Bay. The wood waste without hazardous materials will be burned at the site and the resulted ash will be placed in the landfill.

No measured ground temperature data are available at the site for this study.

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3.0 CLIMATIC DATA FOR THERMAL EVALUATIONS

Climatic data required for the thermal model include air temperature, wind speed, snow cover, and solar radiation. There is no meteorological station at Roberts Bay and Ida Bay. Local climatic data, in association with the nearby Doris North Project, has been collected at the Windy Lake and Boston mineral exploration camps since 1993 (AMEC, 2007). However, the local climatic data at the two camps are not publicly available and therefore cannot been used for this study. The closest Environment Canada meteorological stations (and the year when the station began collecting climatic data) with a long-term climatic record are as follows:

- Cambridge Bay (operating since 1929), located approximately 120 km northeast of Roberts Bay;
- Coppermine/Kugluktuk (operating since 1931), located approximately 360 km west of Roberts Bay;
- Contwoyto Lake/Lupin (operating since 1959), located approximately 360 km southwest of Roberts Bay; and
- Lady Franklin Point (operating from 1957 to 1993), located approximately 260 km northwest of Roberts Bay.

The climatic data for these meteorological stations are available from the National Climate Data and Information Archive operated by Environment Canada (http://www.climate.weatheroffice.ec.gc.ca/climateData/canada_e.html).

3.1 MEAN CLIMATIC CONDITIONS

Long-term monthly mean air temperatures at Roberts Bay were estimated by averaging the monthly mean air temperatures at Cambridge Bay, Coppermine/Kugluktuk, and Contwoyto Lake/Lupin stations during the period from 1971 to 2005. The mean annual air temperature at Roberts Bay was estimated to be -12.1°C.

Long-term monthly mean wind speeds (1971 to 2000 climate normal period) are available from the Kugluktuk, Cambridge Bay and Lady Franklin Point stations. The average annual wind speed ranges from 16.1 km/h at Kugluktuk to 21.2 km/h at Cambridge Bay. Monthly wind speeds at Roberts Bay were estimated to be the same as at Lady Franklin Point, which has an average annual wind speed of 20.1 km/h.

Long-term snow cover data (1971 to 2000 climate normal period) are available from Kugluktuk, Lady Franklin Point and Cambridge Bay. On average, Kugluktuk gets approximately 50 percent more snow cover than Lady Franklin Point and Cambridge Bay. The long-term monthly snow cover at Roberts Bay was estimated to be the same as the monthly average of Lady Franklin Point and Cambridge Bay.

Daily solar radiation data are available for only a limited number of sites in the Canadian Arctic. The closest meteorological station with solar radiation data is Cambridge Bay. Daily solar radiation at Roberts Bay was assumed to be the same as that at Cambridge Bay (based on the climate normal period of 1951-1980, Environment Canada 1982).

The mean climatic data used for thermal analyses are summarized in Table 1.

TABLE 1: SUMMARY OF CLIMATIC DATA USED IN THERMAL ANALYSIS

Month	Monthly Air Temperature (°C)		Monthly Wind Speed (km/h)	Month-End Snow Cover (m)	Daily Solar Radiation (W/m²)
	Mean (1971-2005)	1 in 100 Warm			
January	-30.3	-25.6	19.5	0.22	2.2
February	-30.2	-25.5	20.5	0.26	21.1
March	-27.1	-22.9	19.6	0.28	87.6
April	-18.1	-15.3	20.0	0.28	185.5
May	-6.6	-5.6	20.4	0.16	251.9
June	4.4	6.6	20.0	0	268.1
July	10.0	14.9	18.7	0	214.6
August	8.0	11.8	19.4	0	138.5
September	1.6	2.4	21.4	0.02	71.8
October	-8.9	-7.5	22.3	0.12	33.0
November	-20.7	-17.5	19.9	0.16	4.5
December	-27.2	-22.9	19.3	0.20	0

3.2 1 IN 100 WARM YEAR AIR TEMPERATURES

A probabilistic analysis was carried out to determine the mean monthly temperatures representative of a 1 in 100 warm year. The freezing index and thawing index for each year were calculated from the estimated monthly air temperatures at Roberts Bay for the period of 1959 to 2005. The freezing index for each winter was ranked in ascending order and plotted in probability scale figure. A "best-fit" line was drawn through the set of points to estimate the 1:100 warm year freezing index. A similar procedure was repeated for the summer temperatures to obtain the 1 in 100 warm year thawing index. Winter air temperatures for a mean climatic year were multiplied by the ratio of the 1 in 100 year freezing index to the mean freezing index to estimate monthly temperatures during winter for a 1 in 100 warm year. Similarly, summer air temperatures for a mean year were increased by the ratio of the 1 in 100 warm year thawing index to the mean thawing index to obtain summer monthly air temperatures for a 1 in 100 warm year.

The estimated monthly air temperatures for a 1 in 100 warm year are also listed in Table 1. The annual air temperature for a 1 in 100 warm year is approximately 3.2°C warmer than the mean annual air temperature for the period of 1971 to 2005.

3.3 AIR TEMPERATURES CONSIDERING GLOBAL WARMING TRENDS

According to Environment Canada's "Climate Trends and Variations Bulletin" (http://www.msc-smc.ec.gc.ca/ccrm/bulletin/national_e.cfm), seven of the ten warmest years on record in northern Canada have occurred since 1994. There is an international scientific consensus that most of the warming observed over the last 50 years is attributable to human activities, namely in the emissions of greenhouse gases through the burning of fossil fuels (ACIA, 2004).

Global Circulation Models, or GCMs, are mathematical representation of the atmosphere, land surfaces, and oceans that have been developed to predict future climate behaviour in response to changes in the composition of the atmosphere. Several scenarios have been developed to estimate the likely range of future emissions that may affect climate (IPCC, 2000). Different GCMs have been developed, resulting in different degrees of projected global warming. In this study, using results from the Canadian Climate Impact Scenario project (http://www.cics.uvic.ca/scenarios/index.cgi), seasonal temperature changes for the Jericho Mine site area were estimated for the "B21 scenario" from four GCMs: a) CGCM2 (Canadian Centre for Climate Modelling and Analysis, Canada); b) GFDL-R30 (Geophysical Fluid Dynamics Laboratory, United States); c) ECHAM4 (Max-Planck Institute of Meteorology, Germany), and d) HadCM3 (Hadley Centre for Climate Prediction and Research, United Kingdom).

The average seasonal changes in temperatures over 110 years estimated from the four GCMs for the Roberts Bay mine site area are 6.3°C, 4.8°C, 3.6°C, and 5.1°C during winter, spring, summer, and fall, respectively.

Table 2 compares the estimated/predicted mean annual air temperatures and freezing/thawing indexes for mean, 1 in 100 warm year, and long-term global warming (GCMs) climatic conditions.

TABLE 2: SUMMARY OF AIR TEMPERATURE CONDITIONS AT ROBERTS BAY			
Climate Scenario	Mean Annual Air Temperature (°C)	Freezing Index (°C-days)	Thawing Index (°C-days)
Mean (1971 - 2005)	-12.1	5115	740
1 in 100 Warm Year (based on estimated air temperature data from 1959 to 2005)	-8.9	4318	1097
Predicted 2107 (average of GCMs warming trend)	-6.7	3687	1264
Predicted 2108 (one 1:100 warm year after 100 years of assumed global warming following average of GCMs warming trend)	-3.6	2890	1621

The monthly air temperatures for the 1:100 warm year (Year 2108 in Table 2) following 100 years of assumed global warming (average of GCM's warming trend) were roughly estimated by adding the monthly air temperature differences between a 1:100 warm year (based on historic data from 1959-2005) and a mean year (1971-2005) to the monthly air temperatures estimated for Year 2107 after 100 years of assumed global warming following average of GCM's warming trend.

Thermal analyses were conducted for all the climatic conditions summarized in Table 2 for the landfill thermal design at Roberta Bay.

4.0 THERMAL EVALUATION OF LANDFILL

4.1 THERMAL ANALYSIS METHODOLOGY

Analyses were carried out using EBA's proprietary two-dimensional finite element computer model, GEOTHERM. The model simulates transient, two-dimensional heat conduction with change of phase for a variety of boundary conditions. The heat exchange at the ground surface is modelled with an energy balance equation considering air temperature, wind velocity, snow depth, and solar radiation. The model facilitates the inclusion of temperature phase change relationships for saline soils, such that any freezing depression and unfrozen water content variations can be explicitly modelled. The model has been verified by comparing its results with closed-form analytical solutions and many different field observations. The model has formed the basis for thermal evaluations and designs of a substantial number of projects in the arctic and sub-arctic regions, including dams, ground freezing systems, foundations, pipelines, utilidor systems, and landfills.

The thermal model was calibrated to match the observed thaw depths at both BHs ET-1102 and ET-1107. Good agreements were obtained between the observed and predicted thaw depths based on assumed snow and soil properties, and ground surface conditions.

One-dimensional thermal analyses were then conducted to estimate the landfill cover thickness required to maintain the long-term frozen conditions of the tailings for mean, 1 in 100 warm year, and long-term global warming climatic conditions.

4.2 SOIL INDEX AND THERMAL PROPERTIES

The studied soil profile for the thermal analyses consisted of a landfill cover fill (including a waste rock layer over a gravely sand fill layer) over 1.0 m landfill waste (including intermediate fill layers) and 0.5 m waste rock layer overlying 1.0 m tailings placed on bedrock.

The soil index properties for the materials in the thermal analysis were estimated based on limited information from the site investigation reported in EarthTech (2006) and past experience for similar materials. Thermal properties of the materials were determined indirectly from well-established correlations with soil index properties or based on past experience. Table 3 summarizes the material properties used in the thermal analyses.

TABLE 3: MATERIAL PROPERTIES USED IN THERMAL ANALYSES

Material	Water Content (%)	Bulk Density (Mg/m^3)	Thermal Conductivity (W/m-K)		Specific Heat (kJ/kg°C)		Latent Heat (MJ/m^3)
			Frozen	Unfrozen	Frozen	Unfrozen	
Waste Rock Fill	2	2.14	1.39	1.56	0.76	0.80	14
Gravelly Sand Fill	4	2.08	1.23	1.53	0.79	0.87	27
Placed Landfill Waste	1	2.53	2.00	2.00	0.75	0.77	8
Existing Tailings	20	2.10	2.60	1.66	0.97	1.31	113
Bedrock	1	2.83	2.20	2.20	0.75	0.77	9

4.3 RESULTS, DISCUSSIONS, AND RECOMMENDATIONS

Parametric thermal analyses were carried out to determine the minimum required cover thickness over the tailings under mean, 1 in 100 warm year, and long-term global warming climatic conditions. The soil profile for the final thermal analyses consisted of a total of 3.0 m fill cover over the tailings (a waste rock layer of 0.5 m, a gravely sand fill layer of 1.0 m, a landfill waste layer of 1.0 m, and 0.5 m waste rock layer overlying the tailings).

The predicted maximum depths of thaw penetration into the cover for the final soil profile under various climatic conditions are summarized in Table 4.

TABLE 4: SUMMARY OF PREDICTED MAXIMUM DEPTH OF THAW PENETRATION INTO LANDFILL COVER	
Air Temperature Conditions	**Predicted Thaw Depth (m)**
After ten consecutive mean years	2.4
After one 1 in 100 warm year following ten mean years	2.8
After ten consecutive 1 in 100 warm years following ten mean years	2.9
After 100 years of global warming, average of four GCMs	3.0
After one 1 in 100 warm year following 100 years of global warming, average of four GCMs	3.2

Table 4 suggests that the predicted maximum depths of thaw penetration range from 2.4 to 3.2 m for various climatic conditions. The required cover thickness is a function of the climatic conditions selected as the design criteria for the landfill. Additional factors of safety can also be applied to account for uncertainties in the geothermal model, soil input parameters, and climate input parameters.

Given these uncertainties, it is recommended that the landfill at the Roberts Bay mine site be designed for 100 years of long-term climate warming (average of four GCMs) to maintain the tailings in long-term permafrost condition. Therefore, the recommended minimum cover thickness over the tailings is 3.0 m.

The predicted depth of thaw penetration is 3.2 m into the landfill cover or 0.2 m into the tailings under an assumed extreme warm climatic condition—one 1 in 100 warm year following 100 years of global warming, average of four GCMs. There are some uncertainties in estimating the air temperatures for the 1 in 100 warm year following 100 years of global warming. The risk of the potential thaw of the tailings should be evaluated in the final design of the landfill to determine whether the landfill will be designed based on this extreme climatic condition.

REFERENCES

ACIA, 2004. Impacts of a Warming Arctic: Arctic Climate Impact Assessment. Cambridge University Press, 2004. 139 p., http://www.acia.uaf.edu.

AMEC, 2007. Roberts Bay and Ida Bay Abandoned Mine Sites - Remediation Plan. Report submitted to Public Works and Government Canada Environmental Services, Northern Contaminated Sites, Edmonton. Submitted by AMEC Earth & Environmental, 440 Dovercourt Drive, Winnipeg, MB, January, 2007.

EarthTech, 2006. Roberts Bay and Ida Bay Abandoned Mine sites - Geotechnical and Geophysical Assessment Final Report. Submitted to Public Works & Government Services Canada, Environmental Services, Western Region, Edmonton. Submitted by Earth Tech Canada Inc., Edmonton, April, 2006.

Environment Canada, 1982. Canadian Climate Normals, Volume 1, Solar Radiation, 1951 - 1980, 57 p.

IPCC, 2000. Emissions Scenarios: A Special Report of the Intergovernmental Panel on Climate Change Working Group III, Nebojsa Nakicenovic and Rob Swart (eds.), Cambridge University Press, UK, 570 p.