APPENDIX

APPENDIX B THERMAL ANALYSES MEMO

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SUBJECT: **Thermal Analysis of East and South Dams Jericho Diamond Mine, Nunavut**

1.0 INTRODUCTION

The Jericho East and South East Dams were designed as zoned dams with a geomembrane liner anchored within a frozen fill key trench (EBA, 2005). The design intent is to maintain the geomembrane liner anchor in the key trench in a frozen condition over the mine life.

Thermal analyses were carried out to predict the short and long-term thermal conditions of the East and South Dams under various assumed conditions. The thermal model was calibrated using the measured ground temperatures at the site and considered the thermal impacts of a nearby lake on the initial ground temperatures within the dam footprint. This memo summarizes the input data and results of the thermal analyses.

2.0 THERMAL ANALYSES 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.

3.0 CLIMATIC DATA FOR THERMAL EVALUATIONS

3.1 MEAN CLIMATIC CONDITIONS

Climatic data required for the thermal analyses includes monthly air temperature, wind speed, solar radiation, and snow cover. There has been no meteorological station at the Jericho Diamond Mine site. The closest meteorological station is at Lupin/Contwoyto Lake, which is approximately 30 km south of the mine site. The climatic data for air temperature, snow cover, and wind speed were obtained from Environment Canada's meteorological station at Lupin/Contwoyto Lake, which has been operating since 1959. Mean monthly air temperatures for the thermal analyses were based on the 1971–2000 climatic normals at Lupin/Contwoyto Lake (data from Environment Canada's webpage). Monthly wind speed data were based on the 1951-1981 climatic normals at Contwoyto Lake (Environment Canada, 1982a). Month end snow cover data were based on the 1961-1991 climatic normals at Contwoyto Lake (Environment Canada, 1993). The solar radiation data were obtained from the meteorological station at Norman Wells, which is at a similar latitude as that for the Jericho mine site. The solar radiation data were based on the 1951-1980 climatic normals at Norman Wells (Environment Canada, 1982b). Table 1 summarizes the climatic conditions used for the thermal analyses.

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 (1971-2000)	1 in 100 Warm			
January	-30.4	-25.2	20.2	0.44	5.4
February	-28.5	-23.6	13.3	0.52	31.6
March	-24.9	-20.6	13.8	0.60	97.3
April	-15.9	-13.2	14.3	0.65	179.2
May	-5.7	-4.7	16.5	0.30	233.1
June	6.5	9.2	14.6	0	267.2
July	11.5	16.3	16.8	0	234.5
August	8.8	12.5	18.8	0	166.8
September	1.8	2.5	23.0	0.02	93.9
October	-8.6	-7.1	19.8	0.15	32.5
November	-20.7	-17.1	16.9	0.28	9.6
December	-26.8	-22.2	16.3	0.37	2.0
Mean Annual	-11.1	-7.8			
Freezing Index (°C-days)	4884	4044			
Thawing Index (°C-days)	878	1243			

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 at Lupin/Contwoyto Lake from 1959 to 2004 were calculated. The freezing index for each winter was ranked in ascending order and plotted on probability paper. A "best-fit" line was drawn through the set of points to estimate the 1 in 100 warm year freezing index. A similar procedure was repeated for the summer temperatures to obtain the 1 in 100 warm year thawing index. Mean winter air temperatures were multiplied by the ratio of the 1 in 100 year freezing index to the mean freezing index to estimate the monthly winter air temperatures of a 1 in 100 warm year. Similarly, mean summer air temperatures were multiplied by the ratio of the 1 in 100 year thawing index to the mean thawing index to estimate the monthly summer air temperatures of a 1 in 100 warm year.

Monthly air temperatures for a 1 in 100 warm year are also listed in Table 1. As shown in Table 1, the 1 in 100 warm year annual air temperature is approximately 3.3°C warmer than the mean annual air temperature for the period of 1971 to 2000.

3.3 AIR TEMPERATURES CONSIDERING GLOBAL WARMING TRENDS

Measured air temperatures for the period of 1959 to 2004 indicate that there was generally a warming trend in the air temperatures at Lupin/Contwoyto Lake. Panel on Energy Research and Development (PERD) for Environment Canada (PERD, 1998) reported on estimates of temperature change due to global warming. The "best estimate" scenario and the pessimistic "high sensitivity" scenario were presented in the PERD (1998) report. The predicted temperature changes vary with month and latitude. Table 2 lists the estimated monthly air temperature increases per decade for the "best estimate" case and "high sensitivity" case at a latitude similar to that for the Jericho Diamond Mine site (N65.8°) based on the data from PERD (1998).

TABLE 2: PREDICTED AIR TEMPERATURE CHANGE BY SEASON PER DECADE AT N65.8° LATITUDE

Year	December January February	March April May	June July August	September October November
Best Estimate	0.51	0.38	0.12	0.10
High Sensitivity	0.89	0.63	0.19	0.17

4.0 CALIBRATION THERMAL ANALYSIS

4.1 MODELLED SOIL PROFILE AND PROPERTIES

A thermistor cable was installed in borehole BH-03-10 within the footprint of the East Dam during the 2003 geotechnical program conducted by SRK Consulting. The subsurface soil profile for BH-03-10 consists of a thin (0.1 m) organics layer overlying 23 m thick till and granite bedrock. The till is silty sand and gravel with cobbles and boulders. The index properties for the soils were estimated based on the geotechnical data from the site investigation and past experience. Thermal properties of the soils were determined indirectly from well-established correlations with soil index properties (Farouki 1986; Johnston 1981). Table 3 summarizes the material properties used in the calibration thermal analysis.

TABLE 3: MATERIAL PROPERTIES USED IN CALIBRATION THERMAL ANALYSIS							
Material	Water Content (%)	Bulk Density (Mg/m³)	Thermal Conductivity (W/m-K)		Specific Heat (kJ/kg°C)		Latent Heat (MJ/m³)
			Frozen	Unfrozen	Frozen	Unfrozen	
Moss/Organics	200	1.20	1.38	0.52	1.96	3.36	267
Till	9	2.33	2.65	2.08	0.85	1.02	64
Bedrock	1	2.53	3.00	3.00	0.75	0.77	8

4.2 THERMAL MODEL CALIBRATION AND ANALYSIS RESULTS

One-dimensional calibration thermal analyses were carried out to calibrate the thermal model with the measured ground temperature at BH-03-10. Input such as snow properties, ground surface conditions and evapotranspiration factor were modified to calibration thermal analyses to obtain a good agreement between the modelled and measured ground temperatures. Table 4 compares the calibrated ground temperatures with those measured on September 29, 2003 at BH-03-10.

TABLE 4: MEASURED AND MODELLED GROUND TEMPERATURES ON SEPTEMBER 29, 2003		
Depth below Ground Surface (m)	Measured at BH-03-10 (°C)	Model at BH-03-10 (°C)
2	-2.5	-0.6
5	-3.7	-3.7
9	-6.2	-5.8
15	-6.3	-6.0

Table 4 indicates that there is generally a good agreement between the measured and calibrated ground temperatures for BH-03-10 except for the depth of 2.0 at which the measured ground temperature was approximately 2 °C colder than the calibrated. However, warmer measured ground temperatures at a depth of 2.0 m below the ground surface at other borehole locations at the mine site suggest that the measured ground temperature at the depth of 2 m for BH-03-10 appears too cold for some unknown reasons. The measured ground temperature at a depth of 2 m was 0.5 °C on September 29, 2003, and -0.4°C on October 18, 2005 for BH-03-06. BH-03-06 was on a slightly higher ground surface on the west side of the West Dam. This borehole had a similar soil profile within top 6 m as that for BH-03-10.

In summary, the calibrated ground temperatures were generally consistent with the measured data and on the slightly conservative (warmer) side.

5.0 INITIAL GROUND TEMPERATURES BENEATH DAM FOOTPRINTS

A thermal analysis was carried out to evaluate the thermal influence of the nearby water bodies (lakes) on initial ground temperatures at the East and South East Dams locations. A lake with a diameter of 140 m was simulated in a two-dimensional axisymmetric thermal analysis to represent the presence of Long Lake upstream of the East Dam or the lake downstream of the South East Dam. The lake was simulated as temperature boundary with assumed lake water temperatures similar to those measured at northern lakes. The soil profile and properties used in the analysis were the same as listed in Table 3.

The thermal analyses results estimate that the ground temperatures are warmer closer towards the lake edge; however, the lake has little thermal influence greater than 30 m away from the lake edge. The majority of dam footprint is more than 50 m away from the closest nearby lake. Estimated ground temperatures at a location 50 m away from the lake edge were used as initial ground temperatures prior to the dam construction for the thermal analyses of the two dams. The estimated initial ground temperatures on January 30 were selected to represent the winter construction conditions of the two dams. The estimated initial ground temperature at a depth of 15 m from the ground surface was –5.6°C, which is 0.7°C warmer than the measured ground temperature at the same depth at BH-03-10.

6.0 THERMAL EVALUATION OF EAST DAM

6.1 SOIL INDEX AND THERMAL PROPERTIES

The soil index properties for the construction materials and native soils were estimated based on the geotechnical data from the site investigation and past experience. Thermal properties of the soils were determined indirectly from well-established correlations with soil index properties or based on past experience. Table 5 summarizes the material properties used in the thermal analyses.

TABLE 5: MATERIAL PROPERTIES USED IN THERMAL ANALYSES							
Material	Water Content (%)	Bulk Density (Mg/m³)	Thermal Conductivity (W/m-K)		Specific Heat (kJ/kg°C)		Latent Heat (MJ/m³)
			Frozen	Unfrozen	Frozen	Unfrozen	
Run-of-Mine	3	2.16	1.65	1.82	0.77	0.83	21
Till Fill (unsaturated)	7	2.14	1.69	1.66	0.82	0.96	47
200 mm Minus (unsaturated)	4	2.18	1.84	1.93	0.79	0.87	28
Bedding Sand (unsaturated)	5	2.15	1.83	1.87	0.80	0.90	34
Coarse Tailings (unsaturated)	6	2.01	1.44	1.51	0.81	0.93	38
Overburden Till	9	2.33	2.65	2.08	0.85	1.02	64
Bedrock	1	2.53	3.00	3.00	0.75	0.77	8
Till Fill (saturated)	13	2.26	2.77	1.94	0.89	1.13	87
Coarse Tailings (saturated)	15	2.18	2.76	1.88	0.91	1.18	95
Fine Tailings	162	1.31	2.32	0.77	1.58	2.87	269

6.2 CASES SIMULATED AND ASSOCIATED ASSUMPTIONS

The typical design cross-section for the East Dam is identical to that for the South East Dam. The lowest original ground surface elevation at the centreline of the East Dam is 517 m, and at the South East Dam is 518 m. A vertical cross-section perpendicular to the axis of the East Dam through its lowest original ground surface was simulated in the thermal analyses.

Three cases were simulated in the thermal analyses as listed in Table 6, to evaluate various climate scenarios. Individual thermal analysis runs were conducted to simulate gradual rises of the upstream water and fine tailings surface elevations with time. The fine tailings elevation rise with time was based on the data presented in SRK (2004) for fine tailings without entrained ice. All analyses assumed that the water level in the PKCA was maintained at highest possible level. This is a conservative assumption, as it results in warmer ground temperatures. The operation water levels are expected to be lower than that assumed.

Case 1 assumed mean climatic conditions. Case 2 was analyzed to evaluate the global warming impacts on the long-term thermal conditions of the dams. Air temperatures associated with the "high sensitivity" case of the global warming were used in the analyses. Case 3 was analyzed to estimate the maximum thaw depth after two consecutive 1 in 100 warm years.

TABLE 6: CASES SIMULATED AND ASSOCIATED ASSUMPTIONS					
Case	**Run No.**	**Simulated Time Period**	**Upstream Water Elevation (m)**	**Upstream Fine Tailings Elevation (m)**	**Air Temperature Assumed**
1	1	Jan. 30, 2006 to Jun. 1, 2006	< 517.0	< 517.0	Mean
	2	Jun. 1, 2006 to Jun.1, 2007	518.0	<517.0	
	3	Jun. 1, 2007 to Jun.1, 2008	521.0	517.0	
	4	Jun. 1, 2008 to Jun.1, 2009	523.0	518.0	
	5	Jun. 1, 2009 to Jun.1, 2010	523.0	520.0	
	6	Jun. 1, 2010 to Jun.1, 2012	523.0	521.0	
	7	Jun. 1, 2012 to Jun.1, 2022	523.0	523.0	
2	6a	Jun. 1, 2010 to Jun.1, 2012	523.0	521.0	"High Sensitivity" Global Warming
	7a	Jun. 1, 2012 to Jun.1, 2022	523.0	523.0	
3	6b	Jun. 1, 2010 to Jun.1, 2012	523.0	521.0	1 in 100 Warm

A water/ice temperature boundary was applied on the upstream side of the dam and fine tailings that are below the water level. The assumed water temperature was based on measured lake water temperatures in northern lakes and past experience in design some frozen core dams at EKATI Diamond Mine (EBA, 2003). Table 7 lists assumed water temperatures for shallow lakes (≤ 1.5 m deep) and deep lakes (> 1.5 m deep).

TABLE 7: ASSUMED WATER TEMPERATURES IN THERMAL ANALYSES												
Lake Depth	**Mid-Month Lake Water Temperature (°C)**											
	J	F	M	A	M	J	J	A	S	O	N	D
≤ 1.5 m	0	-1	-1	-1	1	3	15	14	5	2	1	0.5
> 1.5 m	2	2	2	2	2	4	10	14	7	3	2	2

Climatic conditions were applied at the surfaces exposed to air. The snow cover on the dam was assumed to be affected by wind. The assumed snow cover on the dam crest was 50% of the mean monthly snow cover and on the slopes increased linearly to four times the mean monthly snow depth at the downstream toe. It was assumed that there would be no ponding water on the original ground surface downstream of the dams. Climatic conditions with mean monthly snow depths were applied to the original ground surface 15 m from the downstream toe.

The initial temperatures of the dam construction materials on January 30, 2006 were assumed to be 2°C for the coarse tailings and -4°C for the other materials. Prior to impoundment, the upstream till is frozen; however, water will infiltrate the upstream dam shell as water rises against the dam. It was assumed that impounded water will seep through the coarse tailings and into the originally unsaturated till fill, thereby raising the temperature of the coarse tailings and till fill. The temperatures of the upstream till fill and coarse tailings upon initial submergence were assumed to be 0.5 °C on June 1. The initial temperature of the submerged fine tailings on June 1 was assumed to be 3 °C.

6.3 RESULTS AND DISCUSSION

The thermal analyses indicate that the ground temperatures adjacent to the key trench were the warmest in early December. Figures 1 to 4 present predicted temperature distributions under mean climatic conditions in early December 2006, 2008, 2010, and 2014, respectively. The analyses indicate that the ground beneath the dam generally warms with time; nevertheless, the ground temperatures within the key trench remain colder than -2°C at the end of the mine life (2014).

The predicted temperature distribution in early December of 2014 under the "high sensitivity" global warming conditions is shown in Figure 5. The ground temperatures in global warming case are slightly warmer at depth for the mean climate case (Figure 4). The ground temperatures within the key trench area remain colder than -2°C for the global warming case.

The water and fine tailings elevation assumptions in Table 6 are generally conservative. The actual upstream water elevation is expected to be lower than the assumed values; and the actual fine tailings elevation may be higher than the assumed values in Table 6 if ice is entrained in the fine tailings. As a result, the actual ground temperatures for the upstream portion of the dam would be colder than predicted, since the water body (as a heat source) in front of the dams would be pushed further away from the dams and key trenches.

The ground temperatures for the downstream portion of the dam could be warmer if water is ponded against the downstream slope of the dams. Should this happen, engineering measures, such as placing fill on the toe of the downstream slope or diverting the water away from the downstream toe, should be implemented to alleviate the negative thermal impacts of the ponding water.

Thermal analysis results indicate that the thaw depth below the dam crest will be deepest in early October. Table 8 summarizes the maximum thaw depths below the dam surface under the air temperatures of mean, "high sensitivity" global warming, and 1:100 warm year conditions. The predicted ground temperatures in early October of 2011 after two consecutive 1:100 warm years are shown in Figure 6. The dam design included a minimum cover of 5 m of fill over the liner to ensure 1.5 m of frozen fill above the liner.

TABLE 8: PREDICTED MAXIMUM THAW DEPTHS IN EARLY OCTOBER			
Air Temperature	**Year**	**Thaw Depth below Dam Centerline**	**Thaw Depth below Crest of Downstream Slope**
Mean	2014	2.8	3.7
"High Sensitivity" Global Warming	2014	3.1	4.0
Two Consecutive 1:100 Warm Years after June 1, 2010	2011	3.4	4.3

REFERENCES:

EBA Engineering Consultants Ltd., 2003. Two Rock Sedimentation Pond Final Design Report, Ekati Diamond Mine. EBA File No. 0101-94-11580.067. Submitted to BHP Billiton Diamonds Inc., July 2003.

EBA Engineering Consultants Ltd., 2005. Jericho Project East and SouthEast Dam Design Report. EBA File No. 0101-1100060.004. Submitted to Tahera Diamond Corporation, August 2005.

Environment Canada, 1982a. Canadian Climate Normals, Volume 5, Wind, 1951 - 1980, 283 pp.

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

Environment Canada, 1993. Canadian Climate Normals, 1961-1990, Yukon and Northwest Territories, 58 pp.

Farouki, O.T., 1986. Thermal Properties of Soils. TransTech Publications, Germany, 136 p.

Johnston, G.H. (Editor), 1981. Permafrost, Engineering Design and Construction. Wiley & Sons Toronto, 540 p.

PERD, 1998. Climate Change Impacts on Permafrost Engineering Design, funded by Panel on Energy Research and Development, Environment Canada, 42 pp.

SRK Consulting, 2004. Technical Memorandum P. Design of Processed Kimberlite Containment Area, Jericho Project, Nunavut.