APPENDIX XI

SUPPLEMENTAL THERMAL MODELLING

THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NORTH COUNTRY ROCK PILE, DIAVIK DIAMOND MINE, NT, CANADA

PRESENTED TO

Diavik Diamond Mines (2012) Inc.

APRIL 18, 2017
ISSUED FOR USE
FILE: 704-ENG.EARC03073-01

Tetra Tech Canada Inc.
14940 - 123 Avenue
Edmonton, AB T5V 1B4 CANADA
Tel 780.451.2121 Fax 780.454.5688

THIS PAGE INTENTIONALLY LEFT BLANK.

TABLE OF CONTENTS

1.0 INTRODUCTION 1

2.0 PROJECT DESCRIPTION 1
2.1 SITE DESCRIPTION 1
2.2 PERMAFROST CONDITION 1

3.0 NORTH COUNTRY ROCK PILE 2
3.1 GENERAL 2
3.2 NCRP DEVELOPMENT HISTORY 2
3.3 NCRP CLOSURE STRATEGY 3

4.0 EXISTING THERMAL CONDITIONS IN THE NCRP 3
4.1 GTCs FD1/FD2/FD3 4
4.2 GTC FD5 5

5.0 THERMAL ANALYSIS CALIBRATION 6
5.1 THERMAL ANALYSIS MODEL 6
5.2 THERMAL ANALYSIS METHODOLOGY 6
5.3 INPUT PARAMETERS 7
5.3.1 Climatic Data 7
5.3.2 Initial Subsurface Condition 8
5.3.3 Material Properties 8
5.3.4 Ground Temperature Initialization and Boundary Conditions 9
5.3.5 Internal Heat Generation 10
5.4 THERMAL CALIBRATION RESULTS 10

6.0 THEMAL EVALUATION OF CLOSURE COVER FOR TYPE III ROCK UNDER LONG-TERM CLIMATE CHANGE 11
6.1 PROJECTED CLIMATE CHANGE AT DIAVIK 11
6.2 THERMAL ANALYSIS OF NO COVER SCENARIO 12
6.3 THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER 13
6.3.1 Lakebed Till at A21 13
6.3.2 Thermal Properties 13
6.3.3 Assumption Adopted for Thermal Evaluation (Base Case) 14
6.4 RESULTS OF THERMAL EVALUATION 14
6.5 SENSITIVITY STUDY 15
6.5.1 Water Content of Till 15
6.5.2 Period of Heat Generation 16
6.5.3 Thickness of Closure Cover 17

7.0 SUMMARY AND DISCUSSION 18

8.0 CLOSURE 19

REFERENCES 20

LIST OF TABLES IN TEXT

Table 1: Ground Temperature Cable Installation Summary 3
Table 2: Mean Climatic Conditions at Diavik Project Site 7
Table 3: Material Properties Used in Thermal Calibration 9
Table 4: Predicted Mean Air Temperature Warming Rate at Diavik 12
Table 5: Predicted Monthly Air Temperatures for the Selected Years Used for Thermal Evaluation..... 12
Table 6: Lakebed Till Geotechnical Parameters.. 13
Table 7: Material Properties Used for Cover Evaluation... 14
Table 8: Material Properties of Till Used for Sensitivity Study 15
Table 9: Summary of Predicted Maximum Thaw Depth for Various Till Water Contents 16
Table 10: Summary of Predicted Maximum Thaw Depth for Various Cover Thicknesses 17

APPENDIX SECTIONS

FIGURES

Figure 1 Diavik Site Location Map
Figure 2 Diavik Site General Site Layout Plan
Figure 3 North Country Rock Pile Plan View
Figure 4 North Country Rock Pile Plan Section A and Section B
Figure 5 Measured Ground Temperature Profile at GTC FD1
Figure 6 Measured Ground Temperature Profile at GTC FD2
Figure 7 Measured Ground Temperature Profile at GTC FD3
Figure 8 Measured Ground Temperature Profile at GTC FD5
Figure 9 Comparison of Predicted and Measured Ground Temperature at FD1
Figure 10 Comparison of Predicted and Measured Ground Temperature at FD5 (2012 to 2014)
Figure 11 Comparison of Predicted and Measured Ground Temperature at FD5 (2015 to 2016)
Figure 12 Projected Annual Air Temperature Trend at Diavik
Figure 13 Predicted Maximum Thaw Depth on the Top Surface under No Cover Scenario after 100 Years under the Mean Climate Change Scenario
Figure 14 Predicted Maximum Thaw Depth on the Side Slope under No Cover Scenario after 100 Years under the Mean Climate Change Scenario
Figure 15 Predicted Long-Term Temperature Profile on End-September in 2020, 2040, 2060, 2080, and 2100 at FD1
Figure 16 Predicted Long-Term Temperature Profile on End-September in 2020, 2040, 2060, 2080, and 2100 at FD5
Figure 17 Predicted Maximum Thaw Depth on the Top Surface after 100 Years under the Mean Climate Change Scenario
Figure 18 Predicted Maximum Thaw Depth on the Side Slope after 100 Years under the Mean Climate Change Scenario

Figure 19 Predicted Bedrock Temperature with Time at 5 m, 10 m, and 20 m Depth below the Base of QUAR under the Mean Climate Change Scenario
Figure 20 Comparison of Predicted Temperature Profile after 100 Years under the Mean Climate Change Scenario for Base Case, Case 9, and Case 10

APPENDICES

Appendix A Tetra Tech's General Conditions
Appendix B Project Team Resumes

LIMITATIONS OF REPORT

This report and its contents are intended for the sole use of Diavik Diamond Mines (2012) Inc. and their agents. Tetra Tech Canada Inc. (Tetra Tech) does not accept any responsibility for the accuracy of any of the data, the analysis, or the recommendations contained or referenced in the report when the report is used or relied upon by any Party other than Diavik Diamond Mines Inc., or for any Project other than the proposed development at the subject site. Any such unauthorized use of this report is at the sole risk of the user. Use of this report is subject to the terms and conditions stated in Tetra Tech's Services Agreement. Tetra Tech's General Conditions are provided in Appendix A of this report.

1.0 INTRODUCTION

Tetra Tech Canada Inc. (Tetra Tech) was retained by Diavik Diamond Mines (2012) Inc. (DDMI) to conduct a thermal evaluation for the current closure design of the Type III rock pile within the North Country Rock Pile (NCRP) at the Diavik Diamond Mine (Diavik), NT. Under the current closure and reclamation plan, the Type III rock (potentially acid-generating rock) stored in the NCRP will be regraded to a slope of 18.4º (3 Horizontal to 1 Vertical slope). The Type III rock will then be covered with a 1.5 m layer of till which will act as a permafrost aggradation layer and will prevent water and oxygen infiltration into the Type III rock pile. A 3 m layer of Type I rock (non-acid generating rock) will be placed over the till layer to serve as a thermal blanket and erosion protection (DDMI 2010).

It is understood that the thermal evaluation of the current closure cover design for the Type III rock will be part of the NCRP Final Closure Design package. Tetra Tech carried out a series of one-dimensional and two-dimensional thermal analyses to evaluate the current closure cover design for the Type III rock pile under a long-term climate change scenario. Sensitivity studies of key parameters (i.e. water content and period of heat generation) were also performed to investigate the long-term performance of the current cover design. This report summarizes the analysis methodology, input parameters, assumptions, and findings of the thermal analyses.

2.0 PROJECT DESCRIPTION

2.1 SITE DESCRIPTION

The project site (64°29’46’’N, 110°16’24’’W) is located within the North Slave Region of the Northwest Territories, Canada. It is approximately 300 km northeast of Yellowknife and 220 km south of the Arctic Circle (Figure 1). Diavik also lies within Lac De Gras on a 20 km^2 island informally known as East Island. The area is remote, and major freight must be trucked in using a seasonal winter road from Yellowknife. Worker access is by aircraft to Diavik’s private airstrip.

Diavik is situated within the Canadian Shield and is underlain by predominately granitic rocks. The bedrock consists of glacially eroded granite that is covered in many places by glacial till. The till is composed of sand, gravel, cobbles, and boulders in varying proportions in a rock flour matrix.

The mean annual air temperature at the project site is approximately -7.5ºC with an average monthly maximum temperature of 12ºC in July, and an average monthly minimum temperature of -30ºC in January/February. These air temperatures have been determined using climate data collected on site at the Diavik weather station from 1998 to 2016. Annual precipitation on site is low with an average of 280 mm; 60% of the precipitation occurs as snow. The dominate winds on site are from the north and east with an average speed of 17 km/h (Environment Canada 2008).

2.2 PERMAFROST CONDITION

Diavik is located just north of the diffuse boundary between widespread discontinuous and continuous permafrost, which generally coincides with the northern extent of the treeline (Heginbottom 1989; Johnston 1981).

The distribution of permafrost at the Diavik site is fairly complex due to the proximity of Lac De Gras, and the presence of small inland lakes and offshore islands. The typical permafrost depths measured under the various islands range from 60 m to 100 m, while the permafrost under East Island has been measured at 380 m in thickness (Mareschal et al. 2004).

The seasonal active layer in the vicinity of the project site is approximately 1.5 m to 2.0 m deep in till deposits, 2.0 m to 3.0 m deep in well-grained granular deposits (eskers), and 5.0 m in bedrock. In poorly drained areas including bogs with high water content and thicker vegetation cover, the active layer is less than 1.0 m in depth (DDMI 2010).

Measured permafrost temperatures at the depth of zero annual amplitude typically range from -3°C to -7°C at the project site, depending on the ground temperature cable location. The presence of snow, organic matter, or nearby lakes impacts the thermal regime and the permafrost temperature in any given location. Based on the thermistor data from site, the geothermal gradient is approximately 1°C/100 m (Mareschal et al. 2004), which is consistent with typical published values (GSC1995).

3.0 NORTH COUNTRY ROCK PILE

3.1 GENERAL

Diavik mines four diamond-bearing kimberlite pipes: A154 South, A154 North, A418, and A21. Operations officially began in January 2003. The open pit mining of the A154 and A418 pits was completed in 2012; however, the underground mining of these pipes is still on-going. The A21 pipe is currently in development. Production from the A21 pipe is expected to commence in late 2018 and is anticipated to be complete by 2020. The general site layout plan at Diavik is presented in Figure 2.

The NCRP provides permanent storage for waste rock generated from the development and operation of the open pits and underground mines at Diavik. Waste rock from the A154 and A418 open pits and underground operations was placed into designated areas within the NCRP. Based on the concentration of sulfur in the rock, waste rock is generally classified into one of the following three categories (DDMI 2010):

- Type I waste rock: total sulphur in percent by weight (wt %) is less than 0.04 wt % sulphur (S). This type of rock is predominately granites. It is considered as having no acid-generating potential ("clean") and can be used as construction material.
- Type II waste rock: total sulphur in wt % is between 0.04 wt % and 0.08 wt % S. This type of rock is generally granites with little biotite schist. It is considered as intermediate or mixed rock with low acid-generating potential.
- Type III waste rock: total sulphur in wt % is greater than 0.08 wt % S. This type of rock is generally granites with some biotite schist. It is considered as potentially acid-generating.

Based on the mean particle size distribution data from test piles, the Type III rock at Diavik is classified as well graded gravel with sand, cobbles, and boulders with C_c (coefficient of curvature) ranging from 1.53 to 1.60 and C_u (coefficient of uniformity) ranging from 61.6 to 80.6 (Pham 2013).

3.2 NCRP DEVELOPMENT HISTORY

The NCRP is located north east of the PKC Facility and west of the A154 and A418 pits (as shown in Figure 2). A quarry (QUAR) cell was developed for construction of Dikes A154 and A418 between 2001 and 2002. The QUAR area, as shown in Figure 3, forms the north-east portion of the NCRP and stores the majority of the Type III rock. Type I and Type II rock is stored in other designated cells (i.e. CLR, NWR, and CLAR) within the NCRP as shown in Figure 3.

The QUAR area began to receive Type III rock with the commencement of operations in 2003, and served as an active storage zone until the rock pile reached its final elevation in 2008. The CLR cell of the NCRP also temporarily stores Type III rock that is designated for underground back-fill. Re-mining of the Type I rock in the CLR cell began in 2015 and continued through 2016 to provide rockfill for the construction of the A21 dike.

The final elevation of the NCRP above the QUAR area is approximately 498 m based on the latest survey data (from 2016) and the pile height typically ranges from 57 m to 82 m. The historical development of the NCRP was recreated using survey data (from 2005 to 2016) collected by DDMI during its construction. The construction history prior to 2005 is unavailable. Figure 3 presents the plan view of the NCRP. Figure 4 presents the recreated development history of the NCRP along Sections A and B.

3.3 NCRP CLOSURE STRATEGY

Under the current closure and reclamation plan, the Type III rock stored in the QUAR cell will be regraded to a slope of 18.4º (3 Horizontal to 1 Vertical slope), and will then be covered with a 1.5 m layer of till covered by an overlying 3 m layer of Type I rock (DDMI 2010). It is understood that the low permeability till material will come from the development of the A21 Pit.

4.0 EXISTING THERMAL CONDITIONS IN THE NCRP

Nine ground temperature cables were installed within the NCRP to monitor the thermal behavior of the waste rock pile. The locations of the GTCs are presented in Figure 3. Most of the GTCs have been reliable and have provided consistent readings since their installation; however, some of the instrumentation has demonstrated malfunction. Summary information of the GTCs is listed in Table 1.

Table 1: Ground Temperature Cable Installation Summary

Cable ID	Location (m)	Date Readings Begin (year-month-day)	Comments
FD1	N7152777.1 E534210.8	2010-10-31	-Relatively complete and reliable data set -Thermistor malfunction from 2015 to 2016 -Missing data from: 2010-12-17 to 2011-02-07 2011-12-11 to 2012-20-05
FD2	N7152772.7 E534208.2	2010-07-25	-Reliable data collected in upper portion of thermistor -Recordings demonstrate malfunction in lower portion of thermistor -Missing data from: 2011-01-16 to 2011-02-07 2014-10-19 to 2015-04-08
FD3	N7152772.7 E534213.2	2010-10-31	-Consistent data collected in lower portion of thermistor -Recordings demonstrate malfunction in upper portion of thermistor -Missing data from: 2010-12-17 to 2011-02-07 2011-10-07 to 2011-10-09 2011-11-14 to 2012-05-20
FD4	N7152966.4 E534000.1	2011-09-06	-Relatively complete and reliable data set -Located on the edge of the pile, close to slope

Table 1: Ground Temperature Cable Installation Summary

Cable ID	Location (m)	Date Readings Begin (year-month-day)	Comments
FD5	N7152763.7 E534055.6	2011-09-06	-Relatively complete and reliable data set -Recordings demonstrate malfunction in lower portion of thermistor from 2012 to 2014 -Missing data from: 2010-10-30 to 2011-01-12 2011-04-21 to 2011-07-04 2011-10-03 to 2012-05-20 2013-02-27 to 2013-06-06
FH1	-	2011-09-06	-Relatively complete and reliable data set -Horizontal thermistor at elevation 455 m -Missing data from: 2010-10-30 to 2011-01-12 2011-04-21 to 2011-07-04 2011-10-03 to 2012-05-20 2013-02-27 to 2013-06-06
FH2	N7152984.8 E532825.3	-	-No available data
SCW-TW1	N7152817.5 E532917.8	2013-07-13	-Located on bench of the NCRP -Recordings demonstrate malfunction in upper portion of thermistor during small periods from 2013 to 2016
TN1A/B	N7153091.4 E533349.9	2013-08-01	-Located on bench of the NCRP -Relatively complete data sets -Thermistor TN1A measures from El. 414.3 m to El. 429.3 m -Thermistor TN1B measures from El. 430.3 m to El. 445.3 m

As shown in Figure 3, GTC FD4 is located along the edge of the Type III rock zone, and close to the north slope of the NCRP. GTCs SCW-W1 and TN1A/B are located on the bench of the waste rock pile and have been influenced by seepage from the PCK facility. Given the location of the GTCs and the reliability of the measured ground temperature data, it is believed that the measured ground temperatures at GTCs FD4, SCW-W1, and TN1A/B do not represent the general thermal conditions of the Type III rock within the QUAR area.

GTCs FD1, FD2, FD3, and FD5 are located at approximately the center of the NCRP, and provide relatively reliable measured ground temperature data. Therefore, it is believed that the measured ground temperature data at GTCs FD1, FD2, FD3, and FD5 represent the general thermal conditions for the Type III rock within the QUAR area. These GTCs have been collecting data from 2010 to 2016 and their depths extend to approximately 32 m, 31 m, 40 m, and 78 m below the top rock surface for GTCs FD1, FD2, FD3, and FD5, respectively. Figure 4 shows the locations of GTCs FD1, FD2, FD3, and FD5 along Sections A and B, respectively.

Figures 5 to 8 present the measured ground temperature profiles on selected dates at GTCs FD1, FD2, FD3, and FD5, respectively.

4.1 GTCs FD1/FD2/FD3

The initial recording at GTC FD1 was taken November 15, 2010, and the last available reliable reading was taken March 15, 2015. The selected measured ground temperatures at GTC FD1 from 2010 to 2015 are presented in

Figure 5. The measured ground temperature data in Figure 5 indicates that the majority of the rock around the FD1 area is in a frozen condition with the exception of the seasonal active layer. The measured data demonstrates that the active layer was approximately 10.5 m in 2010 but reduced to approximately 6 m in 2014. It is likely that the thermal regimes at GTC FD1 have still not reached equilibrium due to the drilling activity for the GTC installation. The active layer thickness could further reduce with time until equilibrium is reached; however, the time required for reaching equilibrium is unknown. The ground temperatures measured at GTC FD1 are relatively warm when compared to the ground temperatures measured at the other GTC locations (i.e. Figure 8). This is likely due to the initial temperature of the placed material and the time of its placement. The measured ground temperatures at GTC FD1 (Figure 5) indicate that the majority of the Type III rock at this location is in a frozen condition (0ºC to -1ºC). The ground temperatures are relatively stable except for the top 15 m from the ground surface where ground temperatures are fluctuating with the seasons.

As shown in Figure 6, the measured ground temperatures below elevation 485 m at GTC FD2 exhibit bead malfunction resulting in unreliable data below this elevation; however, the measured ground temperatures above elevation 485 m exhibit the same trend as measured at GTC FD1. The majority of the measured ground temperatures above elevation 488 m at GTC FD3 did not register as shown in Figure 7. The measured ground temperatures below elevation 488 m are similar to the measured values at GTC FD1.

Overall, the data set collected at GTC FD1 is relatively complete and reliable compared to GTCs FD2 and FD3. Therefore, the measured ground temperature data at GTC FD1 was selected for the thermal calibration.

4.2 GTC FD5

The initial recordings at GTC FD5 did not register until September 2011. Thereafter, a malfunction continued in the lower portion of the thermistor from 2012 to 2014; the affected temperature beads consistently recorded the waste rock temperatures as 1.5°C from a depth of 37 m to 73 m (El. 455 m to El. 420 m). During 2014 the affected lower portion of the thermistor cable later assumed the same measured temperature trend as initially recorded in 2011. Measured temperatures in 2015 and 2016 also assumed this trend. This demonstrates that the constant readings of 1.5°C were a malfunction of the thermistor. As of 2014, the thermistor has provided a relatively complete and reliable set of temperature measurements.

The measured ground temperatures at GTC FD5 indicate that the Type III rock at this location is in a frozen condition with the exception of the seasonal freezing/thaw layer. The active layer is estimated to be approximately 7.0 m based on the data measured in 2012. The measured ground temperatures from 2011 to 2015 range from -1.4°C to -5°C to a depth of 78 m below the ground surface. The temperatures in the middle zone of the waste rock were recorded as the coolest. They reached approximately -5°C at 40 m from the ground surface (El. 455 m). The waste rock below this depth (lower portion of the thermistor cable) demonstrated warmer measured temperatures reaching approximately -1.4°C at 65 m from the ground surface (El. 425 m). The readings from the thermistor malfunction that occurred from 2012 to 2014 were discounted. These temperature trends stayed consistent and were maintained throughout this period.

The measured ground temperatures from 2016 indicate a large deviation from the temperature trends observed during 2011 to 2015. As seen in Figure 4, the excavation undertaken in 2015 through to 2016 moves the outside boundary of the waste rock pile (within CLR cell). The deviation of the temperatures recorded in 2016 is likely a result of the excavation activities close to the GTC and the convection cooling effects that may be taking place in this area. The measured temperatures from October 2016 are all within the range of -4.3°C to -5.8°C, which are approximately 1 Cº to 4 Cº cooler than previously measured data (2011 to 2015).

Overall, the data set collected from GTC FD5 is relatively complete and seems reliable. Furthermore, it is the only GTC monitoring waste rock temperatures to the bedrock interface. As a result, the measured ground temperature data at GTC FD5 was also selected for use in the thermal calibration.

5.0 THERMAL ANALYSIS CALIBRATION

5.1 THERMAL ANALYSIS MODEL

Geothermal analyses were carried out using Tetra Tech's proprietary two-dimensional finite element computer model, GEOTHERM. The model simulates transient, one-dimensional, and two-dimensional (or three dimensional axisymmetric) heat conduction with phase change for a variety of boundary conditions. Boundary conditions include conductive or convective heat flux, ground to air heat exchange, and temperature boundaries. As opposed to other commercial finite element analysis software packages, GEOTHERM also models heat exchange at the ground-air interface, which considers the effects induced by climate conditions including air temperature, wind speed, snow density and thickness, solar radiation, evaporation, and even the long-term influence of climate change. GEOTHERM also accounts for progressive latent heat release during freezing and thawing in both fine-grained and saline soils.

GEOTHERM results are checked with closed form solutions and field observations. The software has been used successfully for thermal design and evaluations in a large number of projects in the arctic and subarctic, including tailings, dykes, dams, foundations, pipelines, utilidor systems, landfills, and ground freezing systems, as well as the design of several structures at Ekati including: Panda Diversion Dam, Long Lake Outlet Dam, the Misery Site Dams, Bearclaw Diversion Dam, and Panda/Koala and Misery WRSAs (EBA 1997a; 1997b; 2000; 2002; 2006).

5.2 THERMAL ANALYSIS METHODOLOGY

Two-dimensional thermal models were developed along Sections A and B, as shown in Figure 4, for the thermal calibration at the NCRP. Assumptions were made for the thermal calibration due to various unknowns and uncertainties such as: the construction history prior to 2005, the initial rock temperatures, and the physical properties of the Type III rock. The initial waste rock temperatures were selected to best match the initial set of temperature observations at GTCs FD1 and FD5. They have little influence on the thermal predictions beyond the first year of ground temperature monitoring. The physical properties of waste rock were selected based on both the results of field measurements and literature review to obtain the best match of ground temperature predictions with the measured data on site.

The thermal calibration model assumes that the heat transfer mechanism is governed by conduction although some convection cooling is expected within the waste rock material as discussed in Section 4.2. Furthermore, field temperatures measured by thermistor cables within the covered test pile indicate that conduction dominates because the low permeability layer eliminates formation of air convection currents (Pham 2013). Convection heat transfer is expected to cool the waste rock by 4 Cº to 6 Cº more than the typical regional permafrost temperature (EBA 2006). Therefore, the assumption of no convection cooling within the Type III rock pile can be considered as conservative in terms of predicting permafrost conditions and seasonal thaw depth in the Type IIII rock.

5.3 INPUT PARAMETERS

5.3.1 Climatic Data

Climatic data has been collected at Diavik since 1996; however, this data set is considered to be of too short a duration for evaluating long-term climatic trends at this site. The nearest station with long-term data is Lupin, located approximately 140 km north of Diavik. The Lupin station was originally referred to as Contwoyto Lake and was located on the west shore of an island in Contwoyto Lake. The Contwoyto Lake Station was in operation from 1956 to 1981. In 1982 the Lupin station was constructed to the north on the west side of Contwoyto Lake. Lupin replaced the Contwoyto Lake station as the monitoring site for that area. Data collected from this area is a composite of the Contwoyto Lake and Lupin station data. Other nearby stations with long-term data are Yellowknife (located approximately 300 km southwest of Diavik) and Fort Reliance (located approximately 200 km south of Diavik). Climatic data has been collected from the Yellowknife and Fort Reliance stations since 1942 and 1948, respectively.

The monthly air temperature record from Lupin was compared with the corresponding monthly record from Diavik for the period of 1998 to 2016. The results show that monthly air temperatures are typically warmer (by between 0.4 C° and 2.1 C°) at Diavik. On average, annual air temperatures at Diavik have been 1.0 C° warmer than at Lupin. Long-term temperatures at Diavik for the period of 1971 to 2000 were estimated by adding the mean monthly difference in air temperatures between Diavik and Lupin for the period of 1998 to 2016 to the mean monthly air temperatures at Lupin for the period of 1971 to 2000. The mean annual air temperature at Diavik was estimated to be -8.7°C for the period of 1971 to 2000. The average mean annual air temperature at Diavik was measured to be -7.5°C for the period of 1998 to 2016.

Monthly wind speeds and daily solar radiation information have been collected at the Diavik project site since 2007. Monthly snow depths at Diavik were estimated by adopting the same values that were estimated for the Ekati Diamond Mine (Ekati) due to Ekati’s comparable elevation and proximity to Diavik. The monthly snow depths for Ekati were estimated by interpolating the monthly data proportional with latitude from Contwoyto Lake/Lupin and Fort Reliance for the climate normal period of 1961 to 1990 (EBA 1995). This data was then multiplied by a fixed factor based on the calibration of the geothermal model against measured ground temperature data and on anecdotal observations of snow cover on top of the waste rock pile surface at Ekati as reported by EBA (2006). The estimated long-term monthly climatic conditions at Diavik used for thermal analysis are summarized in Table 2.

Table 2: Mean Climatic Conditions at Diavik Project Site

Month	Estimated Monthly Air Temperature [(a)] (°C) (1971-2000)	Measured Monthly Air Temperature [(b)] (°C) (1998-2016)	Monthly Wind Speed [(c)] (km/h)	Monthly Snow Cover [(d)] (m)	Daily Solar Radiation [(e)] (W/m^2)
January	-30.0	-27.7	19	39	4.3
February	-28.8	-26.4	17	47	23.8
March	-25.6	-23.1	18	54	88.1
April	-14.6	-14.2	19	56	178.3
May	-4.1	-2.9	19	38	232.3
June	7.3	7.9	18	0	244.7
July	12.9	13.5	17	0	214.1
August	10.3	10.9	19	0	146.2
September	3.2	4.2	22	0	74

Table 2: Mean Climatic Conditions at Diavik Project Site

Month	Estimated Monthly Air Temperature [(a)] (°C) (1971-2000)	Measured Monthly Air Temperature [(b)] (°C) (1998-2016)	Monthly Wind Speed [(c)] (km/h)	Monthly Snow Cover [(d)] (m)	Daily Solar Radiation [(e)] (W/m^2)
October	-6.5	-5.1	21	7	30.3
November	-19.9	-17.8	18	19	8.2
December	-25.8	-24.5	15	31	1.5
MEAN	**-8.7**	**-7.5**	**-**	**-**	**-**

Notes:

[(a)] Based on measured long-term temperatures at Lupin (1971-2000) adjusted by the mean monthly difference in measured air temperatures between Diavik and Lupin (1998-2016)

[(b)] Based on measured data at Diavik (1998-2016)

[(c)] Based on measured data at Diavik (1998-2016)

[(d)] Based on snow depths estimated at Ekati (2006)

[(e)] Based on measured data at Diavik (1998-2016)

5.3.2 Initial Subsurface Condition

Several boreholes were drilled close to the NCRP for the PKC facility design. Based on the available borehole information, the subsurface within the NCRP footprint generally consists of a layer of 0 m to 3.0 m thick organic cover, and a layer of 0 m to 6.0 m thick till overlying bedrock (EBA 1998; Golder 2016). The initial lithology was assumed to be uniformly 5 m glacial till overlying bedrock for the thermal analysis.

5.3.3 Material Properties

Due to the method of placement of material in the NCRP, there is likely considerable vertical and lateral heterogeneity in the physical properties of materials within the NCRP. The presence of snow and ice trapped in the waste rock during construction is not known and cannot be directly accounted for. Similarly, there is little information about the original in situ conditions, apart from visual observations during borehole drilling for ground temperature cable installations.

The thermal conductivity of dry, crushed rock, k_{dry}, can be estimated from the following equation (Johansen 1975):

$$k_{dry} = 0.039\, n^{-2.2}$$

where n is the porosity of the material. The thermal conductivity, heat capacity, and latent heat of a material all depend on the water content and even small amounts of water may be required for adjusting k_{dry} for non-zero water contents. Farouki (1986) reported that Johansen's method was the best among available methods for frozen and unfrozen soils with a degree of saturation above 10%. Farouki also reported that Johansen's method gave excessive deviations for degrees of saturation less than 10% (i.e. dry materials), but it remained the best of all available methods.

The water contents of the Type III rock within the NCRP were measured using ECH2O probes at the ground temperature cable locations. The recorded volumetric water content of the Type III rock ranges from 0.02 to 0.163, which corresponds to gravimetric water content ranges of 1% to 8% with an assumed average rock dry density of 2.0 t/m^3.

Table 3 lists the material properties used for the thermal calibration. The soil thermal properties were determined indirectly from well-established correlations with soil index properties (Farouki 1986; Johnston 1981; Johansen 1975).

Table 3: Material Properties Used in Thermal Calibration

Material	Water Content (%)	Bulk Density (Mg/m^3)	Porosity	Thermal Conductivity (W/m-°C)		Specific Heat (kJ/kg°C)		Latent Heat (MJ/m^3)
				Frozen	Unfrozen	Frozen	Unfrozen	
Bedrock	1	2.66	0.003	3.0	3.0	0.75	0.77	9
Glacial Till	12	2.04	0.2	2.16	1.76	0.88	1.10	73
Type III Rock	1.0	2.00	0.25	0.85	0.93	0.75	0.77	7
	2.0	2.04	0.25	1.07	1.27	0.76	0.80	13
	2.5	2.05	0.25	1.15	1.35	0.77	0.82	17
	6.0	2.12	0.25	1.80	1.83	0.81	0.93	40

The thermal conductivity of the waste rock at Diavik was measured at the scaled test pile from 2006 to 2010. The measured thermal conductivity ranged from 0.8 W/m-°C to 2.6 W/m-°C with mean values of 1.8E0.4 W/m-°C and 1.7 E0.5 W/m-°C for uncovered and covered Type III test piles, respectively (Pham 2013). These measured thermal conductivities at Diavik are similar to in situ measurement of waste rock reported by Cote and Konard (2005), and conclude that:

- The thermal conductivity of dry waste rock typically ranges from 0.5 W/m-°C to1.5 W/m-°C;
- The thermal conductivity of unfrozen waste rock with a water content of 5% to 6% ranges from 1.1 W/m-°C to 3.7 W/m-°C; and
- The thermal conductivity of frozen waste rock with a water content of 5% to 6% ranges from 1.2 W/m-°C to 4.4 W/m-°C.

The thermal conductivities of the Type III rock used for the thermal calibration are within reasonable ranges of the site measurements at Diavik and the reported values by Cote and Konard (2005).

5.3.4 Ground Temperature Initialization and Boundary Conditions

The initial ground temperatures prior to the development of the NCRP were estimated by applying the mean climatic conditions described in Section 3.2 over a 35 year period by which time ground temperatures had stabilized and varied very little from year to year. The predicted permafrost temperature at a depth of 15 m from the original ground surface is approximately -3.1°C. This value is within the range of the typical permafrost temperatures (-3°C to -7°C) at Diavik, and is warmer than the measured ground temperatures recorded from GTC PKC-05 (-4.5°C between depth of 10 m to 50 m below the ground surface) which is located within the footprint of the NCRP (EBA 1998). Furthermore, the predicted seasonal thaw depth is approximately 2 m which coincides with the typical thaw depth of 1.5 m to 2 m observed at site (DDMI 2010).

Snow drifting on the waste rock pile was considered due to the slopes and changes of topography in the NCRP. Reduced snow cover at the crest of the pile was also assumed due to wind-blown snow cover that typically occurs at topographic highs in the area after construction. Gray and Others (1978) reported the relative amounts of snow deposited on different topographic facets in the Ural Mountains. The published data indicated that accumulation factors (snow cover depth for other landscape types to mean snow cover depth for a flat landscape) is typically 0.25

and 1.2 for upper and lower slopes, respectively. The snow cover over the crest was assumed to be approximately one-third of the mean monthly snow depth as listed in Table 2 for the thermal analyses. One and half times the mean snow cover depth listed in Table 2 was assumed on the side slope of the pile to account for the snow accumulation created from the elevation difference made by construction of the NCRP.

A heat flux boundary was assigned at the model base (i.e. 100 m below the original ground surface) in the thermal analyses to simulate the natural geothermal gradient at depths in the region. The heat flux value was calculated based on the typical thermal gradient measured at Diavik (1.0°C/100 m) and the thermal conductivity of the bedrock.

5.3.5 Internal Heat Generation

The heat generation rate for the uncovered Type III scaled test pile at Diavik is estimated to be 4.1×10^{-4} W/m^3 based on the calculated oxidation rate of the Type III rock (Amos et al. 2009). The increase of the waste rock temperature is estimated to be approximately 6.1×10^{-3} C° annually considering a bulk volumetric heat capacity of 2.2×10^6 J/(m^{3}K) for the Type III rock at Diavik, which is negligible. Amos et al. (2009) concluded that the heat released due to the oxidation of pyritic material at Diavik had no impact on the internal thermal regime of the test pile.

The heat generation rates for other waste rock piles are estimated to be 5.0 W/m^3 at Rum Jungle, Northern Territory, Australia (Harries and Ritchie 1981) and 2.0 W/m^3 within the arctic area (Hollesen et al. 2011). The variation of the heat generation rates estimated at these sites compared to Diavik is likely a result of the amount of oxygen allowed to diffuse into the pile and oxidize potential waste rock material. Oxygen diffusion into waste rock piles is impacted by the air temperatures of the site and the water content of the till layer within the cover (Pham 2013).

For the thermal calibration model, no heat generation is assumed except for the Type III rock in the seasonal active layer. The heat generation rate was assumed to be 0.075 W/m^3 to 0.2 W/m^3 in the seasonal active layer. The heat generation rates assumed in the thermal calibration model were higher than estimated for the uncovered Type III scaled test pile. High heat generation rates were used to improve thermal predictions against the measured data.

In cold arctic regions, it is well known that cold temperatures can significantly reduce the sulphide oxidation rate. Meldrum et al. (2011) reported that oxidation is significantly reduced at -2ºC due to freezing-point depression of pore water, and is not measureable at -10ºC based on the test results from a tailings disposal area near Rankin Inlet. For the thermal calibration, a ground temperature of -2ºC was assumed to be the sulphide oxidation cut-off limit in this study.

5.4 THERMAL CALIBRATION RESULTS

A series of two-dimensional thermal analyses were carried out to calibrate the measured temperature data at GTCs FD1 and FD5 locations. Figures 9 to 11 present the comparison of the measured and predicted ground temperatures at GTCs FD1 and FD5. The results in Figures 9 to 11 indicate that:

- The thermal calibration model at GTC FD1 (Figure 9) provides a reasonably consistent match against the measured data, especially below elevation 482.0 m (approximately 16 m below the top of rock pile surface). Above elevation of 482 m, the predicted temperatures exhibit less seasonal variations than the measured values. However, the predicted ground temperatures are warmer than the measured data, which is on the conservative side for long-term prediction.
- The thermal calibration model at GTC FD5 (Figures 10 and 11) provides a fairly good match with the measured data at all depths. There are some slight variations from elevation 448 m to elevation 470 m as the predicted ground temperatures are approximately 1.0 C° to 1.5 C° warmer than the measured data (on conservative side for long-term prediction).

- As described in Section 4.2, the measured data collected throughout 2016 at GTC FD5 indicate a large deviation from the temperature trends observed during 2011 to 2015 (approximately 1 C° to 4 C° cooler). This is likely a direct result of the excavation that occurred near FD5 throughout 2015 and 2016 and the associated convective cooling. The thermal calibration model did not capture the cooling trend observed in 2016 (Figure 11) as the convection heat transfer mechanism was not modelled in the thermal analyses. However, the warmer ground temperatures predicted by the calibration model will result in a conservative estimation for long-term performance evaluation.

Overall, the thermal calibrations were conducted with a fairly reliable set of site air temperature data and reasonable model input parameters. The predicted results match fairly well against the measured data and indicate that the input parameters are reasonable and can be used for long-term thermal performance prediction and evaluation.

6.0 THEMAL EVALUATION OF CLOSURE COVER FOR TYPE III ROCK UNDER LONG-TERM CLIMATE CHANGE

6.1 PROJECTED CLIMATE CHANGE AT DIAVIK

The global air temperature has increased over the last seventy years. According to Environment Canada's Annual 2015 climate trends and variations bulletin (https://www.ec.gc.ca/sc-cs/default.asp?lang=En&n=7150CD6C-1), the Canadian national annual air temperature has increased over the period from 1948 to 2015. The annual air temperature increasing trend indicates that the annual temperatures averaged across Canada have warmed by 1.6 C° over the past 68 years. Historical warming trends in the annual air temperatures from Yellowknife and Contwoyto/Lupin were observed as increasing approximately 0.5 C° per decade since 1959 as shown in Figure 12. It is expected that a similar warming trend may have existed in the past at the Diavik site. Based on the observed warming trend in the historical air temperatures and state-of-practice, the thermal evaluation for the Type III rock closure cover system should consider the long-term effects of climate change (particularly global warming).

Future climate modelling analyses at Diavik were conducted by Environmental Modelling and Prediction P/L Australia (EMPA) for the period between 1970 and 2060 (EMPA 2008). This climate study was conducted using numerous mathematical and physical climate model schemes in combination with refined versions developed at Oklahoma University (2008). The climate models were run in two different sets: one set to simulate the historical climate of the world, and another set to simulate the future predicted climate using an up-to-date adjustment, valid as at early as 2007 to the Intergovernmental Panel on Climate Change's (IPCC's) A2 scenario (High Green-House Gas Emission Scenario). Six different climate models were applied to the sets to identify the best performing climate model. The calculated mean results of the six models was determined as the best predictor for future climate change at Diavik rather than results generated from a single model.

The predictions of the annual air temperature rise at Diavik (warmest, mean, and coldest temperatures) between 1970 and 2060 are: +0.061 C°/year, +0.056 C°/year, and +0.060 C°/year for the warmest, mean, and coldest air temperatures, respectively (EMPA 2008). The predicted mean air temperature warming rates for the months in the middle of the four seasons are presented in Table 4.

Table 4: Predicted Mean Air Temperature Warming Rate at Diavik

Month	Predicted Mean Air Temperature Warming Rate	
	1970 to 2060 (°C)	Rate (C°/year)
January	-30.3 to -22.6	+0.086
April	-15.7 to -11.0	+0.052
July	11.6 to 13.7	+0.023
October	-7.4 to -2.5	+0.054

The predicted mean air temperature warming rates presented in Table 4 were used to account for climate change in the long-term thermal evaluation of the Type III rock closure cover design. It should be noted that the predicted mean air temperature warming rates are valid until Year 2060; however, the mean air temperatures for the remaining period of thermal evaluation (from Year 2061 to Year 2120) were estimated using the same predicted rates as listed in Table 4. Table 5 presents the predicted monthly air temperatures for the selected years used for the long-term thermal evaluation of the Type III rock closure cover design. Figure 12 illustrates the projected mean annual air temperature trends for Diavik.

Table 5: Predicted Monthly Air Temperatures for the Selected Years Used for Thermal Evaluation

Month	Measured Monthly Air Temperature in 2016 [(a)] (°C)	Predicted Monthly Air Temperature in 2060 [(b)] (°C)	Measured Monthly Air Temperature in 2080 [(b)] (°C)	Measured Monthly Air Temperature in 2120 [(b)] (°C)
January	-24.8	-21.0	-19.3	-15.8
February	-29.9	-26.1	-24.4	-20.9
March	-23.1	-20.8	-19.8	-17.6
April	-18.6	-16.3	-15.3	-13.2
May	0.7	2.9	3.9	6.1
June	9.4	10.4	10.9	11.8
July	14.4	15.4	15.9	16.8
August	12.3	13.3	13.7	14.6
September	5.3	7.6	8.7	10.8
October	-5.8	-3.4	-2.3	-0.2
November	-12.7	-10.3	-9.2	-7.0
December	-26.3	-22.5	-20.8	-17.4
Mean	**-8.3**	**-5.9**	**-4.8**	**-2.7**

Notes:

[(a)] Based on measured data at Diavik weather station (1998-2016)

[(b)] Predicted based on measured air temperature at Diavik and predicted mean air temperature warming rates listed in Table 4

6.2 THERMAL ANALYSIS OF NO COVER SCENARIO

A thermal analysis was carried out to predict the thaw depth in the Type III rock without a closure cover under the projected mean climate change scenario. This analysis was conducted using the thermal calibration model for GTC FD1. The same thermal properties and boundary conditions that were used for the thermal calibration model were adopted with the exception of the internal heat assumption; no internal heat generation is assumed for this analysis.

Figures 13 and 14 present the predicted maximum thaw depth into the top surface and side slope of the Type III rock without a closure cover after 100 years under the mean climate change scenario, respectively. As illustrated in Figures 13 and 14, the predicted maximum thaw depth into the Type III rock is approximately 6.3 m on the top surface and 7.1 m on the side slope after 100 years under the mean climate change scenario.

6.3 THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER

As described in Section 3.3, a 1.5 m layer of low permeability lakebed till and a 3.0 m layer of Type I rock will be used for the Type III rock closure cover. The till and Type I rock will come from the development of the A21 Pit.

6.3.1 Lakebed Till at A21

Till underlies the soft lakebed sediments over the entire A21 area. The average thickness of the till layer is approximately 4.0 m to 5.0 m, with a maximum thickness of approximately 27 m (within the bathymetric low to the west of the A21 kimberlite pipe) (BGC 2014). Investigations of the A21 open pit area indicate that the till is a well graded silt, sand, and gravel mixture with a fines content (particle sizes less than 0.075 mm) generally between 15% and 45% (Golder 2006; 2007).

A summary of the engineering design parameters for the till as reported by Golder (2006 and 2007) is presented in Table 6.

Table 6: Lakebed Till Geotechnical Parameters

Properties	Range	Suggested Design Value
In Situ Void Ratio		0.36
Bulk Density (T/m^3)	1.56 - 2.30	2.24
Dry Density (T/m^3)	1.03 - 2.13	1.98
Specific Gravity	2.61 - 2.72	2.69
Gravimetric Water Content (%)	5 - 16	N/A
Degree of Saturation (%)	100	100
Plasticity Index	Non-plastic	Non-plastic
Hydraulic Conductivity, k (m/sec)	$7x10^{-9}$ - $6 x10^{-3}$	$4x 10^{-5}$

In order to maximize the use of the pre-striping till material from the A21 Pit and to promote water saturation of the fines matrix, the following till gradation specification has been proposed by DDMI:

1) 30% to 70% passing the No. 40 sieve (0.42 mm)
2) 100% passing 1.5 m

6.3.2 Thermal Properties

The same thermal properties used for Type III rock, overburden till, and bedrock in the calibration model were adopted for the thermal evaluation. The thermal properties for the till cover and the Type I rock are presented in Table 7.

Table 7: Material Properties Used for Cover Evaluation

Material	Water Content (%)	Bulk Density (Mg/m^3)	Porosity	Thermal Conductivity (W/m-°C)		Specific Heat (kJ/kg°C)		Latent Heat (MJ/m^3)
				Frozen	Unfrozen	Frozen	Unfrozen	
Till	15	2.21	0.29	3.1	2.1	0.91	1.18	96
Type I Rock	3	2.06	0.25	1.32	1.57	0.77	0.83	20

6.3.3 Assumption Adopted for Thermal Evaluation (Base Case)

The assumptions adopted for the thermal evaluation are listed as follows:

- The till cover will be placed in the Summer/Fall season and Type I rock cover will be placed in the Winter/Spring season;
- The initial temperature of till is assumed to be +5ºC;
- The initial temperature of Type I rock is assumed to be -5ºC;
- The water content of till is assumed to be 15%;
- The water content of Type I rock is assumed to be 3%;
- No heat generation occurs after till placement within the top unfrozen zone of Type III rock; and
- The same assumption for snow cover as used in the thermal calibration was adopted in the long-term thermal evaluation.

6.4 RESULTS OF THERMAL EVALUATION

Thermal evaluations of the Type III rock closure cover were carried out for both sections. For simplification purposes, only the predicted ground temperature profiles at the end of September (which represents the time of maximum thaw depth at Diavik) for selected years under the long-term mean climate change scenario are presented.

Figures 15 and 16 present the predicted long-term temperature profiles at the end of September in 2020, 2040, 2060, 2080, and 2100 at FD1 and FD5, respectively under the mean climate change scenario.

Figures 17 and 18 present the predicted maximum thaw depth at Section A after 100 years under the mean climate change scenario for the top cover and side slope cover, respectively.

Figure 19 presents the predicted bedrock temperatures with time at 5 m, 10 m, and 20 m depths below the base of QUAR area under the mean climate change scenario at FD1 and FD5, respectively.

The results indicate that the Type III rock in the NCRP will remain in a frozen condition after 100 years under the projected mean climate change scenario at Diavik. Figures 15 and 16 illustrate that the predicted ground temperatures profiles are very similar at FD1 and FD5 regardless of the initial ground temperatures after 100 years under the projected mean climate change scenario. The predicted ground temperatures at depths (i.e. below 15 m depth) after 100 years were generally within the range of -1.5ºC to -2.2ºC.

The maximum thaw depth on the top cover is predicted as approximately 3.65 m (seasonal thaw penetrating approximately 0.65 m into the till layer). Due to snow accumulation on the side slope, the predicted maximum thaw depth on the side slope is slightly deeper than predicted on the top, and has a maximum thaw depth of 4.10 m after 100 years under the mean climate change scenario.

The predicted bedrock temperatures at depths of 5 m to 20 m below the bedrock surface (Figure 17) indicate that the bedrock temperatures will initially warm for a short period while the Type III rock cools, but will soon after begin to cool until approximately 2065 and 2075 (at the FD1 and FD5 locations, respectively) when the bedrock temperatures will begin to warm due to climate change. However, the bedrock will remain in a frozen state after 100 years under the mean climate change scenario.

The results from the thermal evaluation indicate that the current closure design cover (1.5 m layer of till covered by a 3 m layer of Type I rock) is sufficient to prevent the thaw front from penetrating into the Type III rock and will maintain the frozen condition of Type III rock after 100 years under the mean climate change scenario with the assumptions described in Section 6.2.3.

6.5 SENSITIVITY STUDY

A series of sensitivity analyses were carried out for thermal evaluation of the Type III rock closure cover in this study. The key parameters considered for the sensitivity study include the water content of the till material, the thickness of the closure cover, and the impact of internal heat generation. As described in Section 6.4, the predicted long-term ground temperatures in the Type III rock will be similar throughout the waste rock pile regardless of the initial ground temperatures. Furthermore, the impact from the initial ground temperatures on the long-term thermal performance of the closure cover is expected to be insignificant. The placement time of the closure cover will only affect the freezeback time required for the top unfrozen layer and will not have significant impact on the long-term thermal performance of the closure cover. Therefore, both the initial ground temperatures and placement time of the closure cover were excluded from the sensitivity study.

6.5.1 Water Content of Till

The water content of the till in the Base Case thermal evaluation was assumed as 15%. Various other water contents ranging from 8% to 25% were considered for the till material in the sensitivity study (Cases 1 to 8). Table 8 presents the thermal properties of till under various water content used for the thermal sensitivity study.

Table 8: Material Properties of Till Used for Sensitivity Study

Case	Water Content (%)	Bulk Density (Mg/m^3)	Degree of Saturation (%)	Thermal Conductivity (W/m-°C)		Specific Heat (kJ/kg°C)		Latent Heat (MJ/m^3)
				Frozen	Unfrozen	Frozen	Unfrozen	
Case 1	25	2.01	100	2.94	1.69	1.0	1.42	134
Case 2	22.5	1.97	90	2.37	1.65	0.98	1.37	121
Case 3	20	2.10	100	3.0	1.86	0.96	1.31	117
Case 4	18	2.07	90	2.70	1.82	0.94	1.26	105
Base Case	15	2.21	100	3.1	2.1	0.91	1.18	96
Case 5	13.5	2.18	90	2.83	2.04	0.89	1.14	87
Case 6	10	2.34	100	3.2	2.4	0.86	1.05	71
Case 7	9	2.32	90	2.98	2.37	0.85	1.02	64
Case 8	8	2.30	80	2.7	2.3	0.83	0.99	57

For simplification purposes, only the predicted maximum thaw depths are presented herein, as listed in Table 9.

Table 9: Summary of Predicted Maximum Thaw Depth for Various Till Water Contents

Case	Water Content (%)	Degree of Saturation (%)	Predicted Maximum Thaw Depth after 100 Years under Projected Mean Climate Change Scenario (m)	
			Top Surface	Side Slope
Case 1	25	100	3.30	3.75
Case 2	22.5	90	3.40	3.95
Case 3	20	100	3.45	4.00
Case 4	18	90	3.60	4.10
Base Case	15	100	3.65	4.10
Case 5	13.5	90	3.70	4.20
Case 6	10	100	3.80	4.30
Case 7	9	90	4.00	4.50
Case 8	8	80	4.30	5.10
:Thawing front penetrating into Type III rock after 100 years under the mean climate change scenario				

Based on the thermal results presented in Table 9 for the sensitivity study of till water content, the following conclusion can be made:

- The predicted maximum thaw depth into the top surface of the cover ranges from 3.3 m to 4.3 m with water contents of till ranging from 25% to 8%, respectively (Case 1 to Case 8). The seasonal thaw depth is retained within the 4.5 m thick closure cover (1.5 m of till covered by 3 m of Type I rock) after 100 years under the projected mean climate change scenario.
- The predicted maximum thaw depth on the side slope surface of the cover ranges from 3.75 m to 4.30 m with water contents of till ranging from 25% to 10%, respectively (Case 1 to Case 6).
- The maximum thaw depths predicted on the side slope surface of the cover for till water contents of 9% and 8% (Case 7 and Case 8) exceed the 4.5 m closure cover thickness and the thawing fronts penetrate into the Type III rock. In order to retain the seasonal thawing front within the closure cover system after 100 years, the till material placed on the side slope should contain sufficient fine fraction which can maintain a minimum of 10% water content in the till layer for the long-term condition.

6.5.2 Period of Heat Generation

The Base Case assumes that no heat generation occurs after till placement within the top unfrozen zone of the Type III rock. Two sensitivity cases (Cases 9 and 10) were carried out to investigate the impact of internal heat generation on the long-term thermal performance of the closure cover. Cases 9 and 10 assumed that the heat generation in the top 8.0 m of Type III rock will last two years and five years, respectively, with the same heat generation rates assumed in the calibration model. The other input parameters were kept consistent with those used in the Base Case. Figure 20 presents the comparison of the predicted temperature profiles for the Base Case, Case 9, and Case 10 after 100 years under the mean climate change scenario.

As shown in Figure 20, there is a negligible difference for the predicted temperature profiles for the Base Case, Case 9, and Case 10 after 100 years under the mean climate change scenario. The predicted maximum thaw depths are the same for the Base Case, Case 9, and Case 10. It can be concluded that the heat generation assumed within the top 8.0 m of Type III rock is not expected to change the design intent of the closure cover for Type III rock.

6.5.3 Thickness of Closure Cover

The current closure cover design consists of a 3.0 m layer of Type I rock overlying a 1.5 m layer of till material. Three sensitivity cases (Cases 11 to 13) were carried out to investigate the impact that different cover thicknesses have on the long-term thermal performance of the closure cover. The closure cover for Cases 11, 12, and 13 consist of: a 1.0 m layer of till material under a 3.0 m layer of Type I rock, a 1.5 m layer of till material under a 2.0 m layer of Type I rock, and a 1.0 m layer of till material under a 2.0 m layer of Type I rock, respectively. The other input parameters were kept consistent with those used in the Base Case.

Table 10 presents the predicted maximum thaw depth for various cover thicknesses after 100 years under the projected mean climate change scenario. The results for the Base Case were also presented in Table 10 for comparison purpose.

Table 10: Summary of Predicted Maximum Thaw Depth for Various Cover Thicknesses

Case	Water Content (%)	Degree of Saturation (%)	Predicted Maximum Thaw Depth after 100 Years under the Projected Mean Climate Change Scenario (m)	
			Top Surface	Side Slope
"Base Case" (1.5 m Till and 3.0 m Type I Rock)	15	100	3.65	4.10
Case 11 (1.0 m Till and 3.0 m Type I Rock)	15	100	3.65	4.30
Case 12 (1.5 m Till and 2.0 m Type I Rock)	15	100	3.30	3.80
Case 13 (1.0 m Till and 2.0 m Type I Rock)	15	100	3.50	4.15
[shaded]:Thawing front penetrating into Type III rock after 100 years under the mean projected climate change scenario				

Based on the thermal results presented in Table 10 for the sensitivity study of the closure cover thickness, the following conclusion can be made:

- The predicted seasonal thawing front on the top surface is retained within the closure cover for Cases 11 and 12 after 100 years under the projected mean climate change scenario. However, the thawing front will penetrate into the Type III rock (approximately 0.5 m deep) for Case 13 after 100 years under the projected mean climate change scenario.
- For all three sensitivity cases analyzed (Cases 11, 12, and 13), the predicted thawing fronts on the side slope surface will penetrate into the Type III rock after 100 years under the projected mean climate change scenario. The depth of thaw penetration into the Type III rock ranges from 0.8 m to 1.3 m depending on the closure cover thickness.

7.0 SUMMARY AND DISCUSSION

A series of thermal analyses and sensitivity studies were carried out to evaluate the current closure cover for the Type III rock within the NCRP at Diavik. The results of the thermal analyses indicate that the Type III rock within the NCRP will be in a frozen state under the current closure cover design (a 1.5 m layer of till material covered by a 3.0 m layer of Type I rock) after 100 years under the mean climate change scenario, with ground temperatures at depths (i.e. below 15 m depth) ranging from -1.5ºC to -2.2ºC. The current closure cover for the Type III rock is sufficient to prevent the thawing front from penetrating into the Type III rock on the top surface of the pile after 100 years under the mean climate change scenario. It is recommended that till material to be used on the side slope of the pile should contain sufficient fine fraction which can maintain a minimum of 10% water content in the till layer for the long-term condition in order to retain the seasonal thawing front within the closure cover system after 100 years.

The thermal results for the sensitivity study of internal heat generation (Cases 9 and 10) indicate that the heat generation assumed within the top 8.0 m of Type III rock is not expected to change the design intent of the current closure cover for Type III rock. The predicted maximum thaw depths in Table 10 indicate that the closure covers for Case 11 (1.0 m thick till and 3.0 m thick Type I rock) and Case 12 (1.5 m thick till and 2.0 m thick Type I rock) are able to retain the thawing front on the top surface within the closure cover system, but not sufficient to retain the thawing front on the side slope within the closure cover system after 100 years under the projected mean climate change scenario. The closure cover for Case 13 (1.0 m thick till and 2.0 m thick Type I rock) is not sufficient to retain the thawing front on both the top surface and side slope within the closure cover system after 100 years under the projected mean climate change scenario.

In order to monitor the performance of the closure cover for the Type III rock in the NCRP, Tetra Tech recommends at least eight multi-bead ground temperature cables (GTCs) be installed within the Type III rock zone in the NCRP. A minimum of four GTCs shall be installed on the top surface of the closure cover and a minimum of two GTCs shall be installed on each side slope (i.e. north and south facing slopes). It is recommended that each GTC be 15.5 m long and include 16 beads. The following bead spacing is recommended: 0.5 m interval for beads 1 to 10, 1 m interval for beads 11 to 13, and 2.5 m interval for beads 14 to 16. Dataloggers (i.e. Lakewood Ultra-Logger) can be used to automatically collect the readings twice a day or the manual readings can be obtained from each GTC by using a digital multi-meter and switch box. The recommended minimum frequency for obtaining manual GTC readings is four times per year which typically occurs in April, July, September, and November.

The thermal performance of the closure cover for the Type III rock has been evaluated based on current available measured ground temperature data, limited information on the physical properties of rock, construction history prior to Year 2005, and site specific conditions such as snow cover and accumulation. In the absence of such information, assumptions have been made and engineering judgement has been used to evaluate the long-term performance of the closure cover.

8.0 CLOSURE

We trust this report meets your present requirements. If you have any questions or comments, please contact the undersigned.

Respectfully submitted,
Tetra Tech Canada Inc.

Prepared by:
Chantal Pawlychka, B.Sc., E.I.T.
Geotechnical Engineer, Arctic Region
Direct Line: 780.451.2130 x377
Chantal.Pawlychka@tetratech.com

Prepared by:
Hongwei Xia, Ph.D., P.Eng.
Geotechnical Engineer, Arctic Region
Direct Line: 780.451.2130 x343
Hongwei.Xia@tetratech.com

REGISTERED PROFESSIONAL ENGINEER
H. XIA
LICENSEE
April 18, 2017
NT/NU

REGISTERED PROFESSIONAL ENGINEER
KEVIN W. JONES
April 18, 2017
LICENSEE
N.W.T.

Reviewed by:
Kevin Jones, P.Eng.
Vice President - Arctic Development
Direct Line: 780.451.2125
Kevin.Jones@tetratech.com

PERMIT TO PRACTICE
TETRA TECH CANADA INC.

Signature ______

Date April 18, 2017

PERMIT NUMBER: P 018
NT/NU Association of Professional Engineers and Geoscientists

/jf

REFERENCES

Amos, R.T., Smith, L., Neuner, M., Gupton, M., Blowes, D.W., and Sego, D.C. (2009). Diavik Waste Rock Project: Oxygen Transport in Covered and Uncovered Piles. In The 8th ICARD International Conference on Acid Rock Drainage, Skelleftea, Sweden, 2009.

BGC Engineering Inc. 2014. A21 Dike Design Report Update_Final. Diavik Diamond Mines Inc. November 28, 2014.

Cote, J. and Konrad, J.M. (2005). Thermal Conductivity of Base-course Materials. Canadian Geotechnical Journal 42 (1), 61-78.

Diavik Diamond Mines Inc. (DDMI), 2010. Interim Closure and Reclamation Plan Version 3.1. Diavik Diamond Mines Inc. December 2010.

EBA Engineering Consultants Ltd. (EBA), 1995. Tailings Management Plan and Preliminary Design of Retention Structures, NT Diamond Project. Report submitted to BHP Diamonds Inc. EBA Project No.: 0101-94-11580.2, December 1995.

EBA, 1997a. Construction Drawings and Specifications, Panda Diversion Dam. Report submitted to BHP Diamonds Inc. EBA File: 0101-94-11580.007, January 1997.

EBA, 1997b. Final Design Report, Long Lake Outlet Dam, NT Diamonds Project. Report submitted to BHP Diamonds Inc., Project No. 0101-9411580.003, September 1997.

EBA, 1998. 1997/98 Geotechnical Site Investigation, Diavik Project, Lac De Gras, NT. Report submitted to Diavik Diamond Mines Inc., Project No. 0101-97-13133.001, May 1998.

EBA, 2000. Ekati Diamond Mine, Misery Site Dams. Report submitted to BHP Diamonds Inc., Project No. 0101-94-11580.019, March 2000.

EBA, 2002. Bearclaw Diversion Dam Final Design Report, Ekati Diamond Mine. Report submitted to BHP Billiton Diamonds Inc., Project No. 0101-9411580.066, October 2002.

EBA, 2006. Thermal Evaluation of Waste Rock Piles, Ekati Diamond Mine. Report submitted to BHP Billiton Diamonds Inc., Project No. 0101-9411580.033, September 2006.

Environment Canada (2008), Climate Data Online. National Climate Data and Information Archive. Technical Report, Environment Canada.

Environmental Modelling and Prediction P/L Australia, 2008. Climate Change Adaptation Project, Rio Tinto, Climate Change Impacts in the Diavik Region of Northern Canada. 4 July, 2008.

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

Geological Survey of Canada (GSC), 1995. Permafrost, map of permafrost distribution in Canada.

Golder Associates Ltd. (Golder), 2006. A21 Dike and Pit Geotechnical and Hydrological Data Interpretation Data, Diavik Diamond Mine. Report submitted to Diavik Diamond Mines Inc., No. RPT-120 Ver. 0, September 1, 2006.

Golder, 2007. Winter 2007 A21 Dike and Pit Geotechnical and Hydrological Site Investigation, Diavik Diamond Mine Volume 1. Report submitted to Diavik Diamond Mines Inc., No. RPT-362 Ver. 0, August 16, 2007.

Golder, 2016. Diavik Diamond Mine North Country Rock Pile Closure Design. A Technical Report submitted to Diavik Diamond Mines (2012) Inc. February 5, 2016.

Gray, D.M. and Others. 1978. Snow Accumulation and Distribution. Paper presented to the workshop/meeting on "Modelling Snow Cover Runoff" U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, U.S.A. 26-29 September, 1978.

Harries, J.R. and Ritchie, A.I.M. 1981. The Use of temperature profiles to estimate the pyritic oxidation rate in a waste rock dump an opencut mine. Water, Air, and Soil Pollution. 15(4):405-423.

Heginbottom, J.A. 1989. A survey of Geomorphic Processes In Canada. Chapter 9 in: Fulton, R. J. (ed.) Quaternary geology of Canada and Greenland. Geology of Canada No. 1, Geological Survey of Canada, Ottawa, Ontario and Vol. K-1, Geology of North America, Decade of North American Geology, Geological Society of America: 573-644.

Hollesen, J., Elberling, B., and Jansson, P. 2011. Modelling temperature-dependent heat production over decades in High arctic coal waste rock piles. Cold regions Science and Technology, 65(2):258-268.

Johansen, O., 1975. Thermal Conductivity of Soils. U.S. Army Cold Regions Research and Engineering Laboratory, Translation 637.

Johnston, G.H. 1981. Permafrost: Engineering Design and Construction. Associate Committee on Geotechnical Research, National Research Council of Canada, John Wiley and Sons Canada Ltd. Toronto. 540 p.

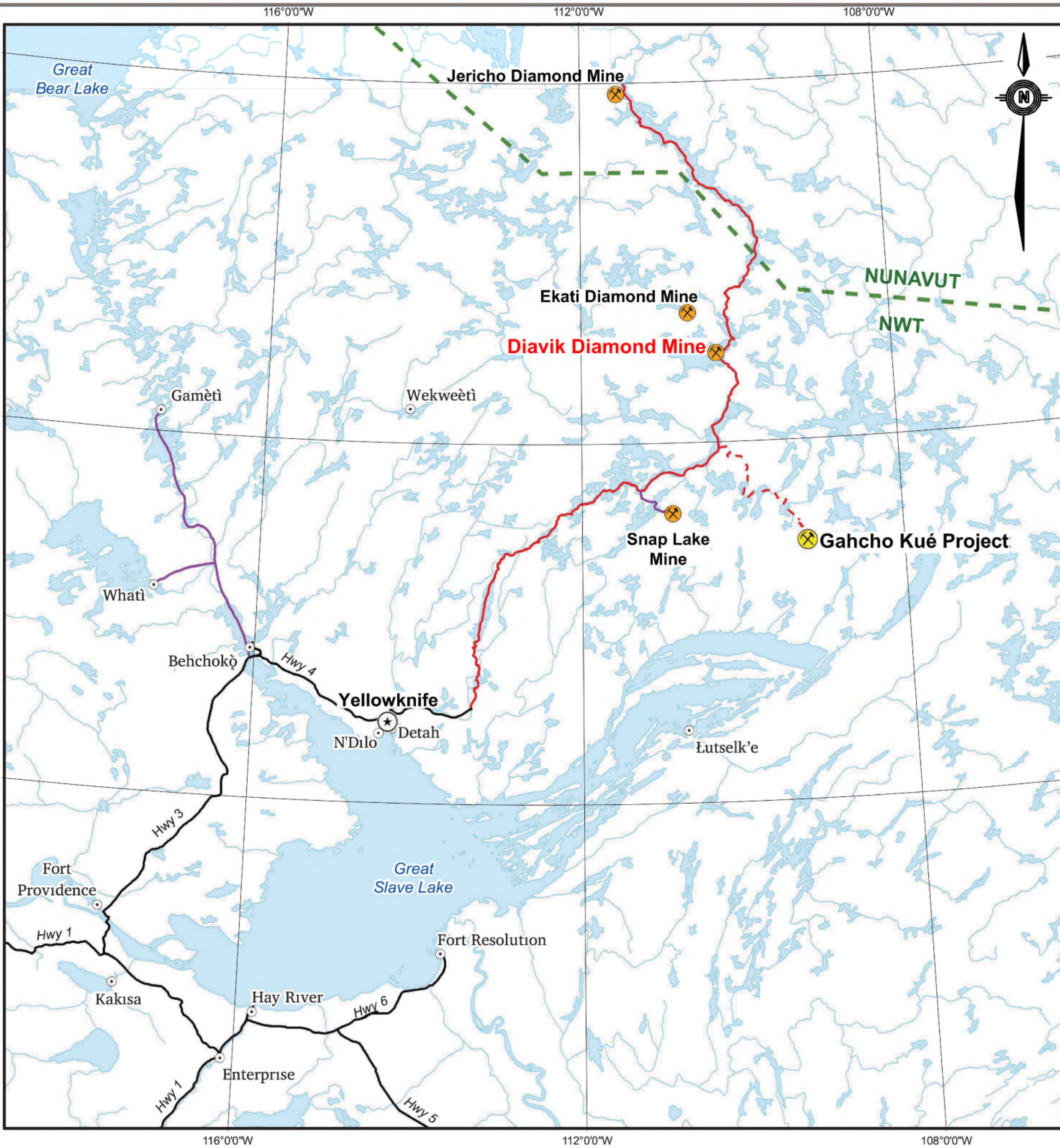
Mareschal. J.C., Nyblade, A., Perry, H.K.C., Jaupart, C., and Bienfait, G. (2004). Heat Flow and Deep Lithospheric Thermal Structure at Lac de Gras, Slave Province, Canada. Geophys. Res. Lett. 31(12):L12611-.

Meldrum, J.L., Jamieson, H, and Dyke, L (2011). Oxidation of Mine Tailings from Rankin Inlet, Nunavut, at Subzero Temperatures. Canadian Geotechnical Journal. January 2011. DOI: 10.1139/cgj-38-5-957.

Pham, H.N., 2013. Heat Transfer in Waste-Rock Piles Constructed in a Continuous Permafrost Region. Ph.D Thesis. Department of Civil and Environmental Engineering, University of Alberta. Spring 2013.

FIGURES

Figure 1	Diavik Site Location Map
Figure 2	Diavik Site General Site Layout Plan
Figure 3	North Country Rock Pile Plan View
Figure 4	North Country Rock Pile Plan Section A and Section B
Figure 5	Measured Ground Temperature Profile at GTC FD1
Figure 6	Measured Ground Temperature Profile at GTC FD2
Figure 7	Measured Ground Temperature Profile at GTC FD3
Figure 8	Measured Ground Temperature Profile at GTC FD5
Figure 9	Comparison of Predicted and Measured Ground Temperature at FD1
Figure 10	Comparison of Predicted and Measured Ground Temperature at FD5 (2012 to 2014)
Figure 11	Comparison of Predicted and Measured Ground Temperature at FD5 (2015 to 2016)
Figure 12	Projected Annual Air Temperature Trend at Diavik
Figure 13	Predicted Maximum Thaw Depth on the Top Surface under No Cover Scenario after 100 Years under the Mean Climate Change Scenario
Figure 14	Predicted Maximum Thaw Depth on the Side Slope under No Cover Scenario after 100 Years under the Mean Climate Change Scenario
Figure 15	Predicted Long-Term Temperature Profile on End-September in 2020, 2040, 2060, 2080, and 2100 at FD1
Figure 16	Predicted Long-Term Temperature Profile on End-September in 2020, 2040, 2060, 2080, and 2100 at FD5
Figure 17	Predicted Maximum Thaw Depth on the Top Surface after 100 Years under the Mean Climate Change Scenario
Figure 18	Predicted Maximum Thaw Depth on the Side Slope after 100 Years under the Mean Climate Change Scenario
Figure 19	Predicted Bedrock Temperature with Time at 5 m, 10 m, and 20 m Depth below the Base of QUAR under the Mean Climate Change Scenario
Figure 20	Comparison of Predicted Temperature Profile after 100 Years under the Mean Climate Change Scenario for Base Case, Case 9, and Case 10



Q:\Edmonton\Engineering\E141\Projects\EARC03073-01-Diavik Thermal Modelling\Reporting\ENG.EARC03073-01 Figure 1.dwg [FIGURE 1] April 17, 2017 - 3:18:27 pm (BY: LEE, ELVIN)

Legend

- Gahcho Kué Project
- Existing Mine
- Territorial Capital
- Populated Place
- Highway
- Existing Winter Road
- Tibbitt-to-Contwoyto Winter Road
- Winter Access Road
- Watercourse
- Waterbody
- Territorial/Provincial Boundary

Notes:
Source: Figure 1.1-1 in De Beers 2010
Base data source: The Atlas of Canada

ISSUED FOR USE

TETRA TECH

DIAVIK DIAMOND MINE PROJECT
NWT, CANADA

LOCATION OF DIAVIK DIAMOND MINE

PROJECT NO.	DWN	CKD	REV
ENG.EARC03073-01	EL	HX	A
OFFICE	DATE		
EDMONTON	MARCH 28, 2017		

FIGURE 1

Notes:
Source: Google Earth Pro. Image dated August 22, 2014.

0 1,000m
Scale: 1:25,000 @ 11"x17"

ISSUED FOR USE

TETRA TECH

DIAVIK DIAMOND MIND PROJECT
NWT, CANADA

GENERAL SITE LAYOUT PLAN

PROJECT NO.	DWN	CKD	REV
ENG.EARC03073-01	EL	HX	A
OFFICE	DATE		
EDMONTON	MARCH 2□, 2017		

FIGURE 2

Q:\Edmonton\Engineering\E141\Projects\EARC03073-01-Diavik Thermal Modelling\Reporting\ENG.EARC03073-01 Figure 2.dwg [FIGURE 2] April 17, 2017 - 3:19:30 pm (BY: LEE, ELVIN)

LEGEND

DESIGNATED ROCK STORAGE AREA BOUNDARY

GTC

0 500m

Scale: 1:10,000 @ 11"x17"

NOTES:
SOURCE: GOOGLE EARTH PRO. IMAGE DATED AUGUST 22, 2014.

ISSUED FOR USE

TETRA TECH

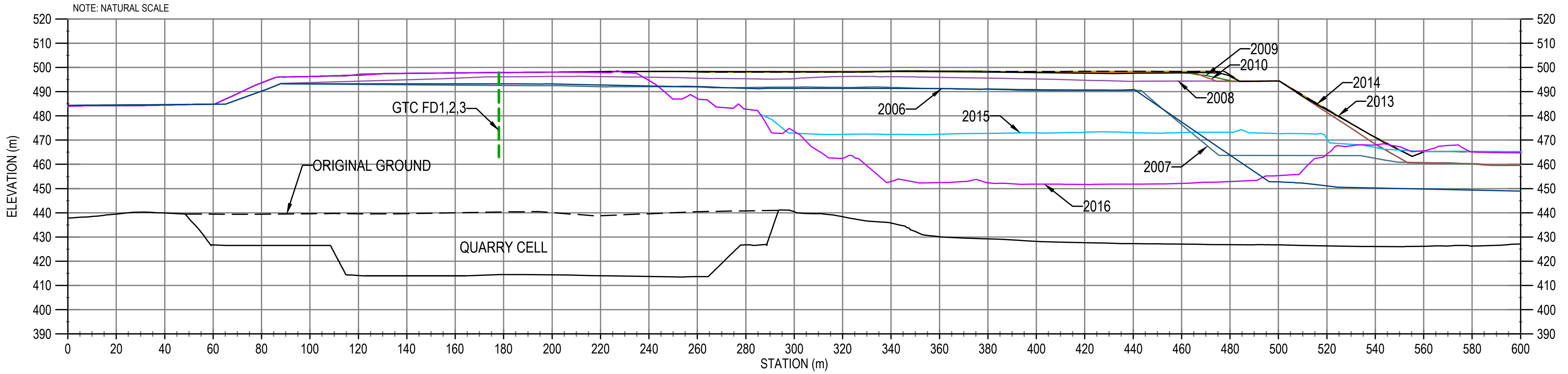
DIAVIK DIAMOND MIND PROJECT
NWT, CANADA

WASTE ROCK PILE
PLAN VIEW WITH GTC

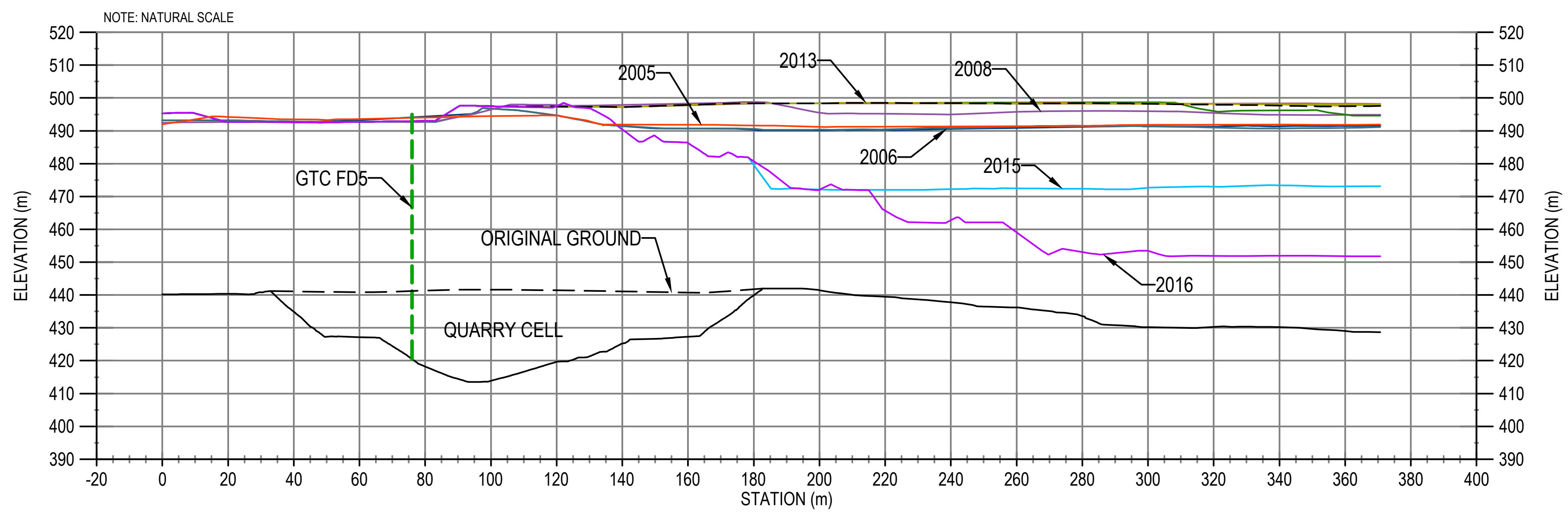
PROJECT NO.	DWN	CKD	REV
ENG.EARC03073-01	EP	HX	0

OFFICE	DATE
EDM	March 2017

Figure 3



SECTION A-A

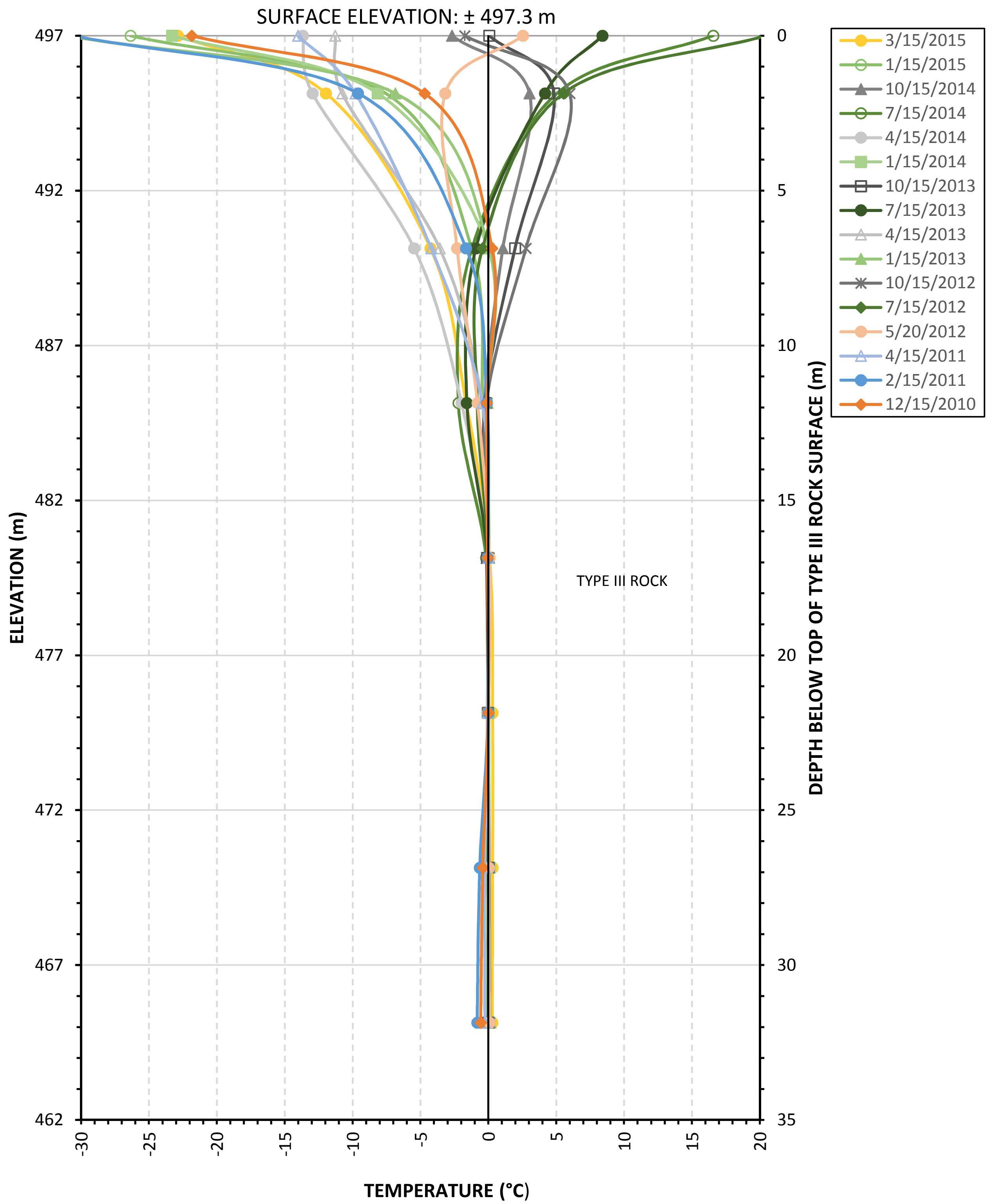


SECTION B-B

ISSUED FOR USE

TETRA TECH

DIAVIK DIAMOND MIND PROJECT NWT, CANADA				
NORTH COUNTRY ROCK PILE SECTIONS A-A AND B-B				
PROJECT NO. E14103079-02	DWN EP	CKD HX	REV 0	**Figure 4**
OFFICE EDM	DATE March 2017			



LEGEND

NOTES

FD1 Soil Temperature Profile from 2010 to 2015

STATUS

ISSUED FOR USE

TETRA TECH

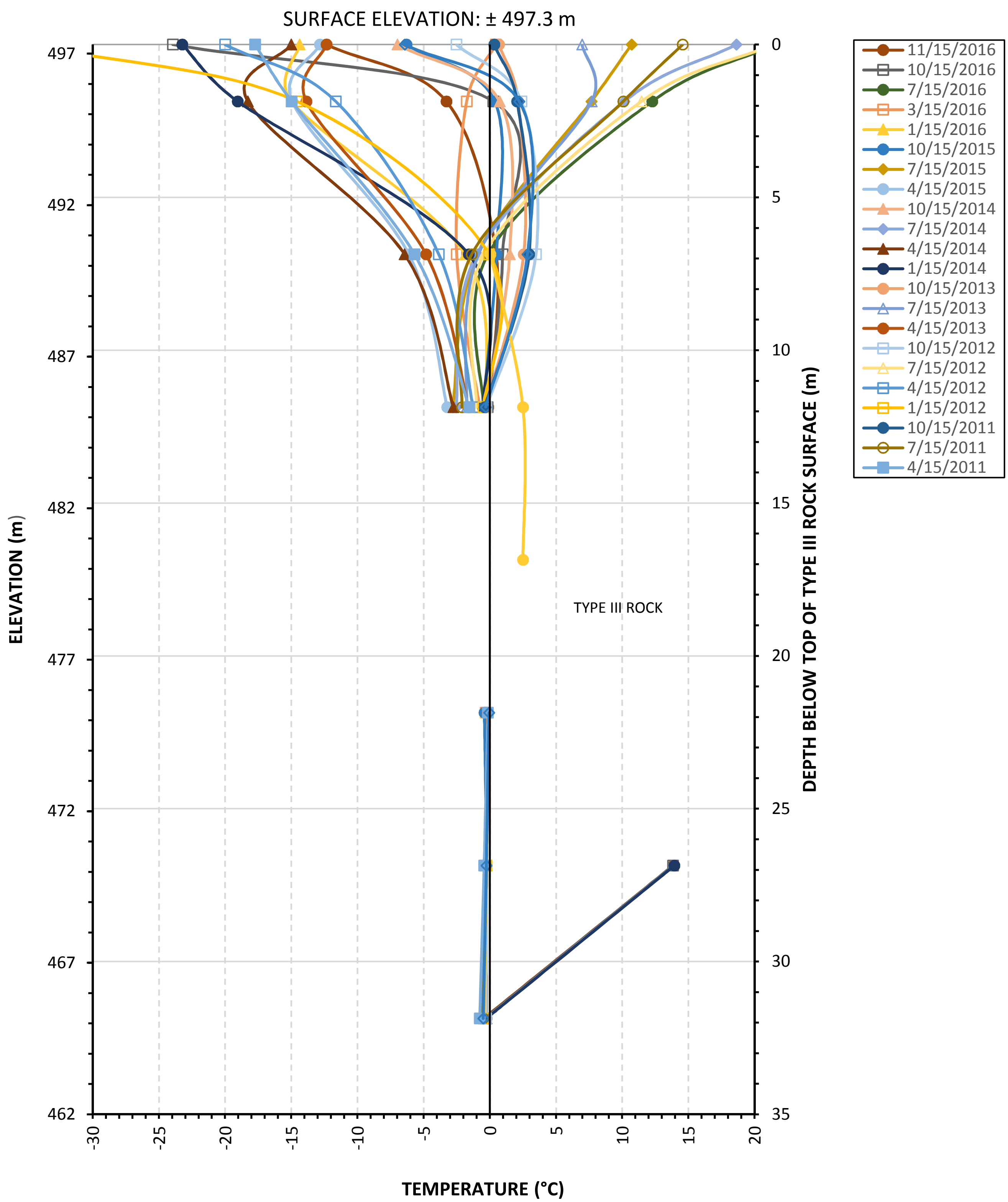
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

MEASURED TEMPERATURE PROFILES AT SELECTED DATES FOR FD1

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 5



LEGEND

NOTES
FD2 Soil Temperature Profile from 2010 to 2016

STATUS
ISSUED FOR USE

TETRA TECH

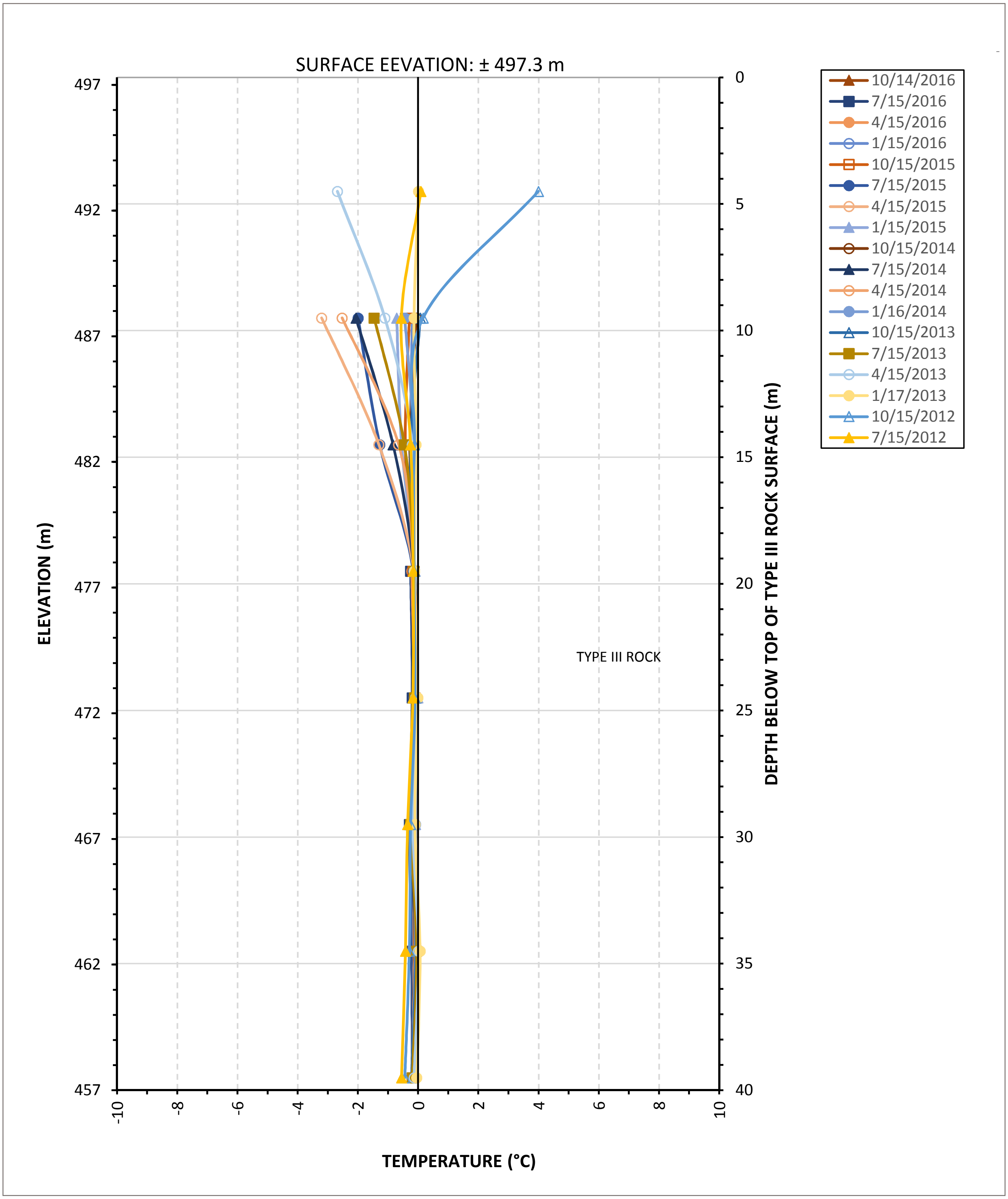
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

MEASURED TEMPERATURE PROFILES AT SELECTED DATES FOR FD2

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 6



LEGEND

NOTES
FD3 Soil Temperature Profile from 2012 to 2015

STATUS
ISSUED FOR USE

TETRA TECH

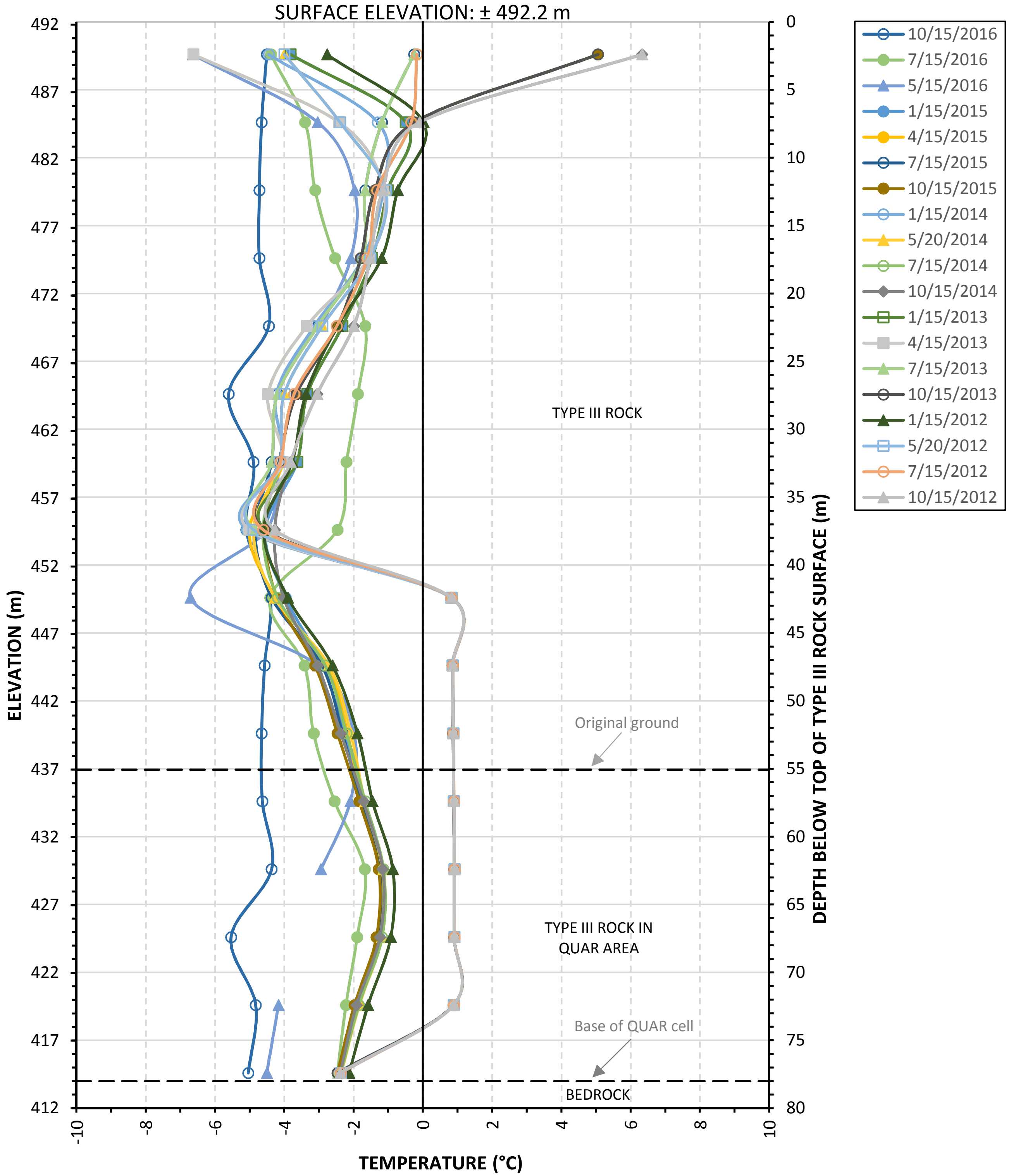
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

MEASURED TEMPERATURE PROFILES AT SELECTED DATES FOR FD3

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 7



LEGEND

NOTES
FD5 Soil Temperature Profile from 2012 to 2015

STATUS
ISSUED FOR USE

TETRA TECH

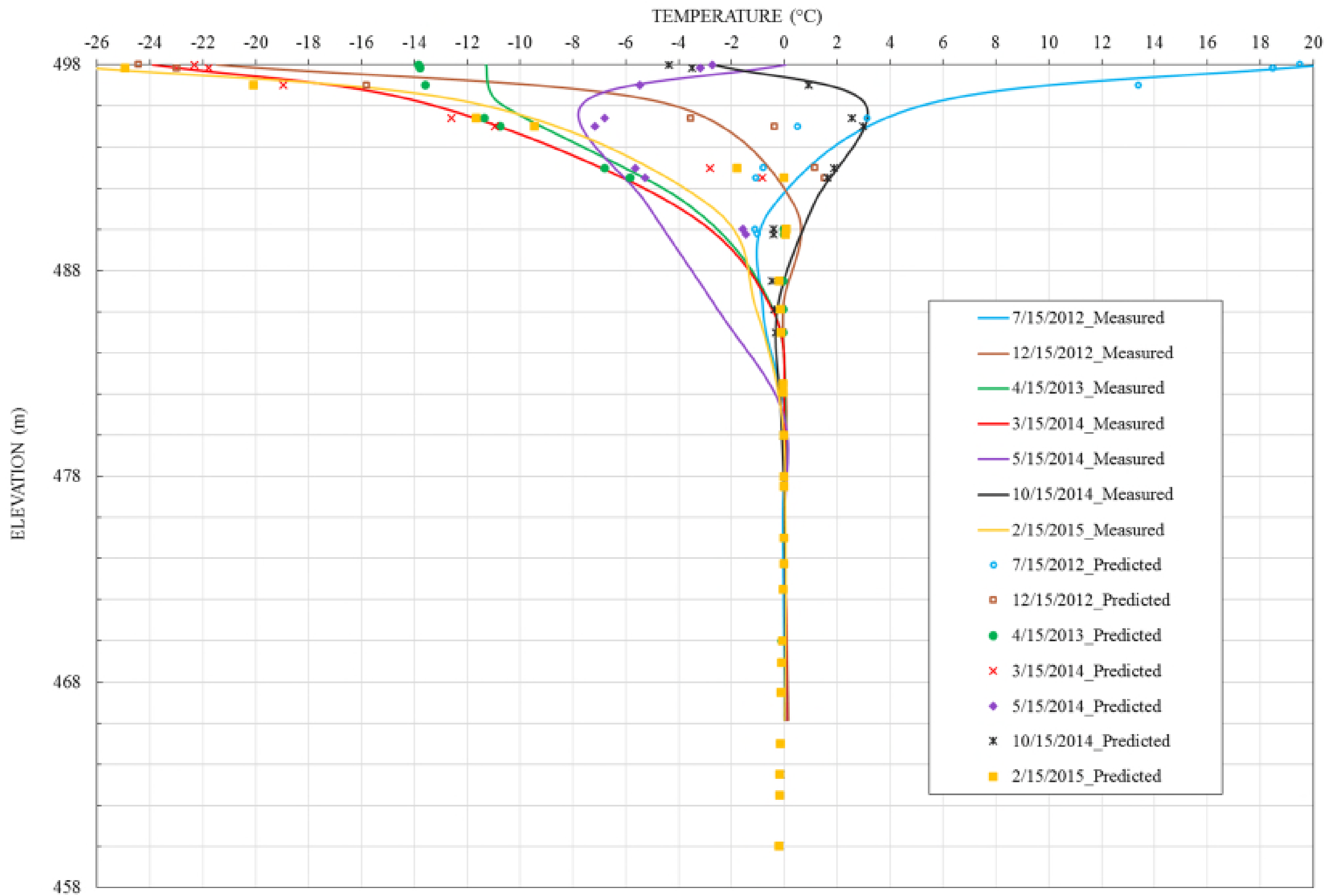
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

MEASURED TEMPERATURE PROFILES AT SELECTED DATES FOR FD5

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 8



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

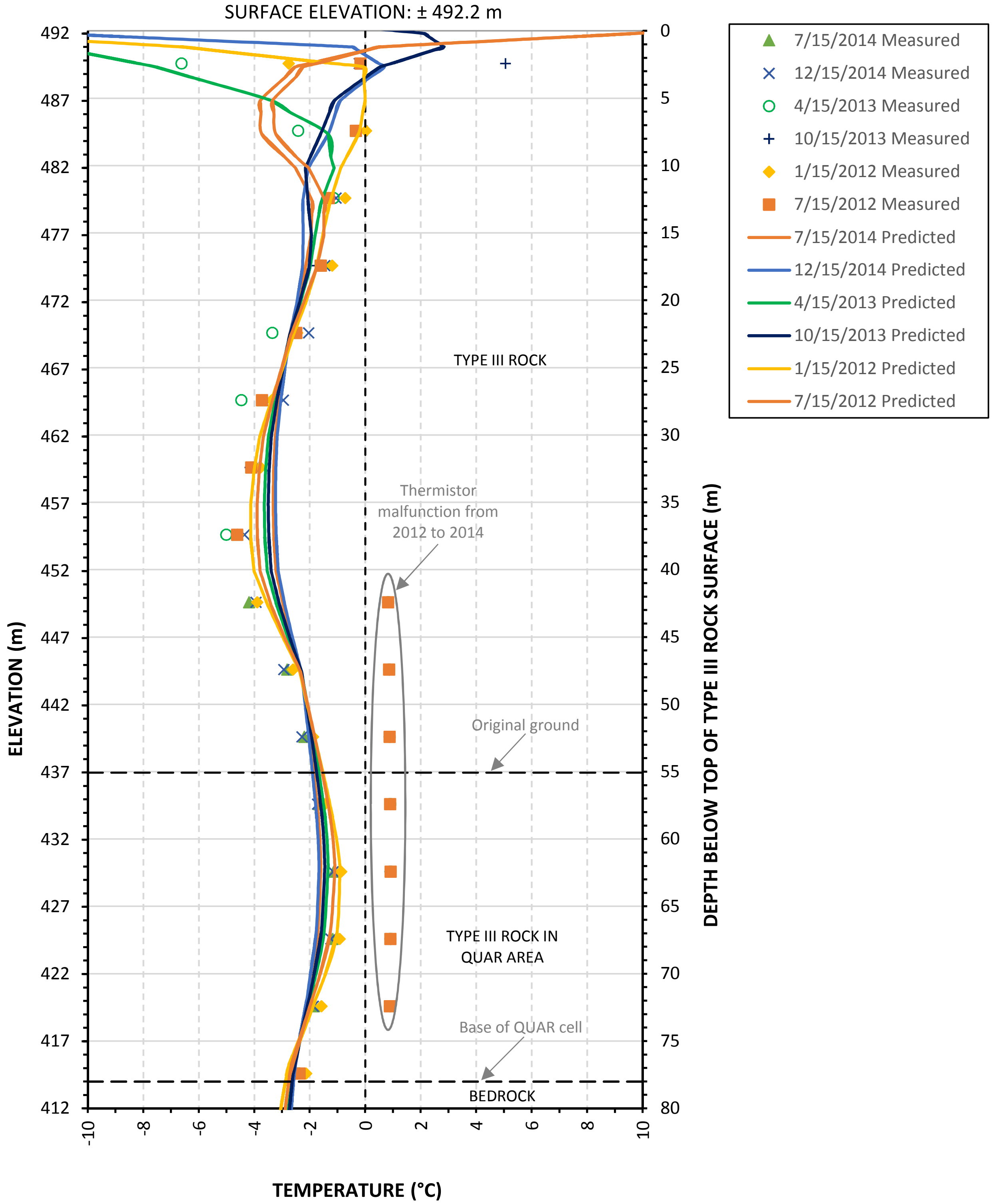
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

COMPARISON OF MEASURED AND PREDICTED TEMPERATURE AT FD1 LOCATION

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	YL	HX	HX	A

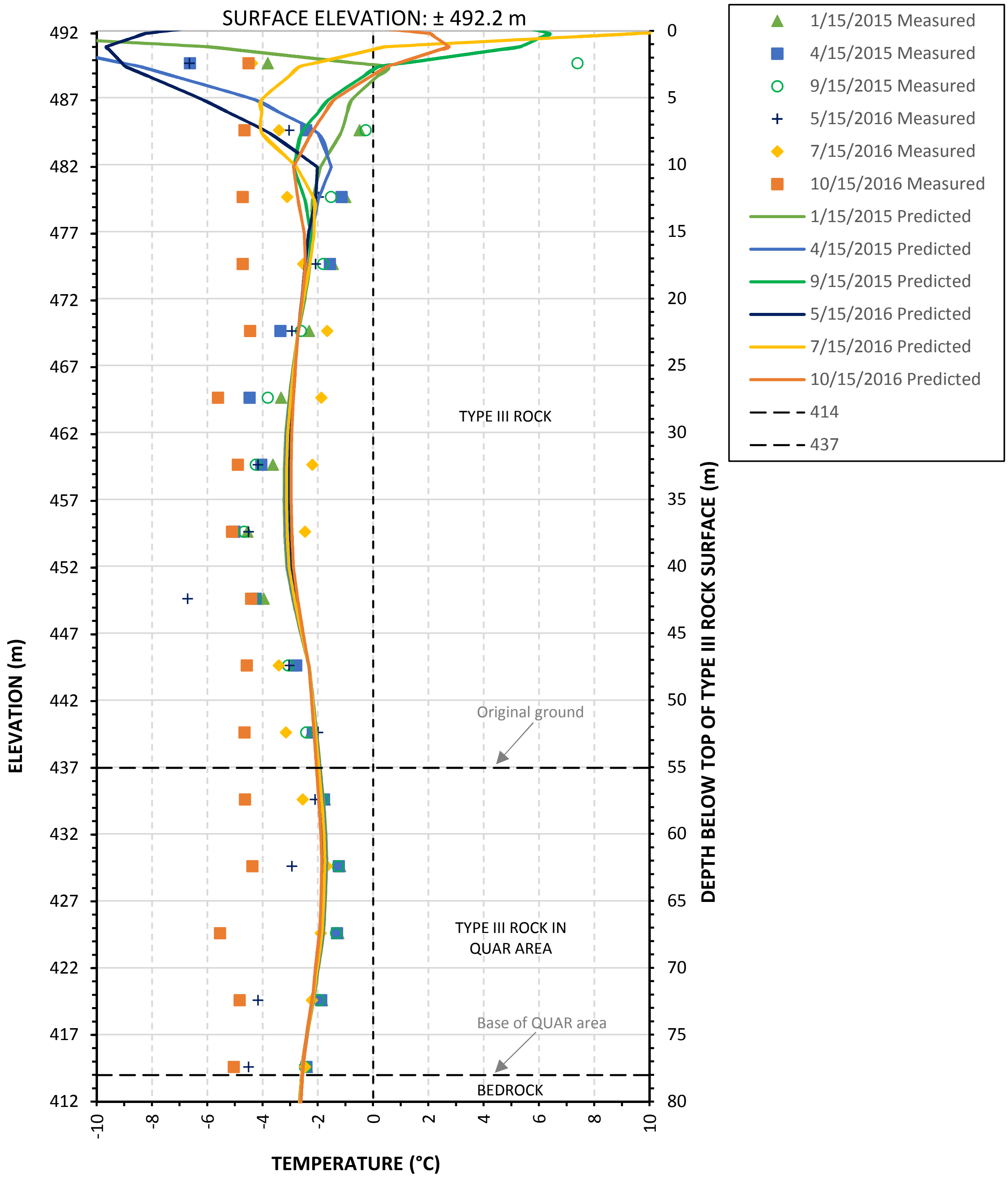
OFFICE	DATE
EDM	April 2017

Figure 9



LEGEND	NOTES		THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP
	STATUS ISSUED FOR USE	TETRA TECH	COMPARISON OF MEASURED AND PREDICTED DATA AT FD5 (2012 – 2014)

PROJECT NO.	DWN	CKD	APVD	REV	
ENG.EARC03073-01	CP	HX	HX	A	Figure 10
OFFICE	DATE				
EDM	April 2017				



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

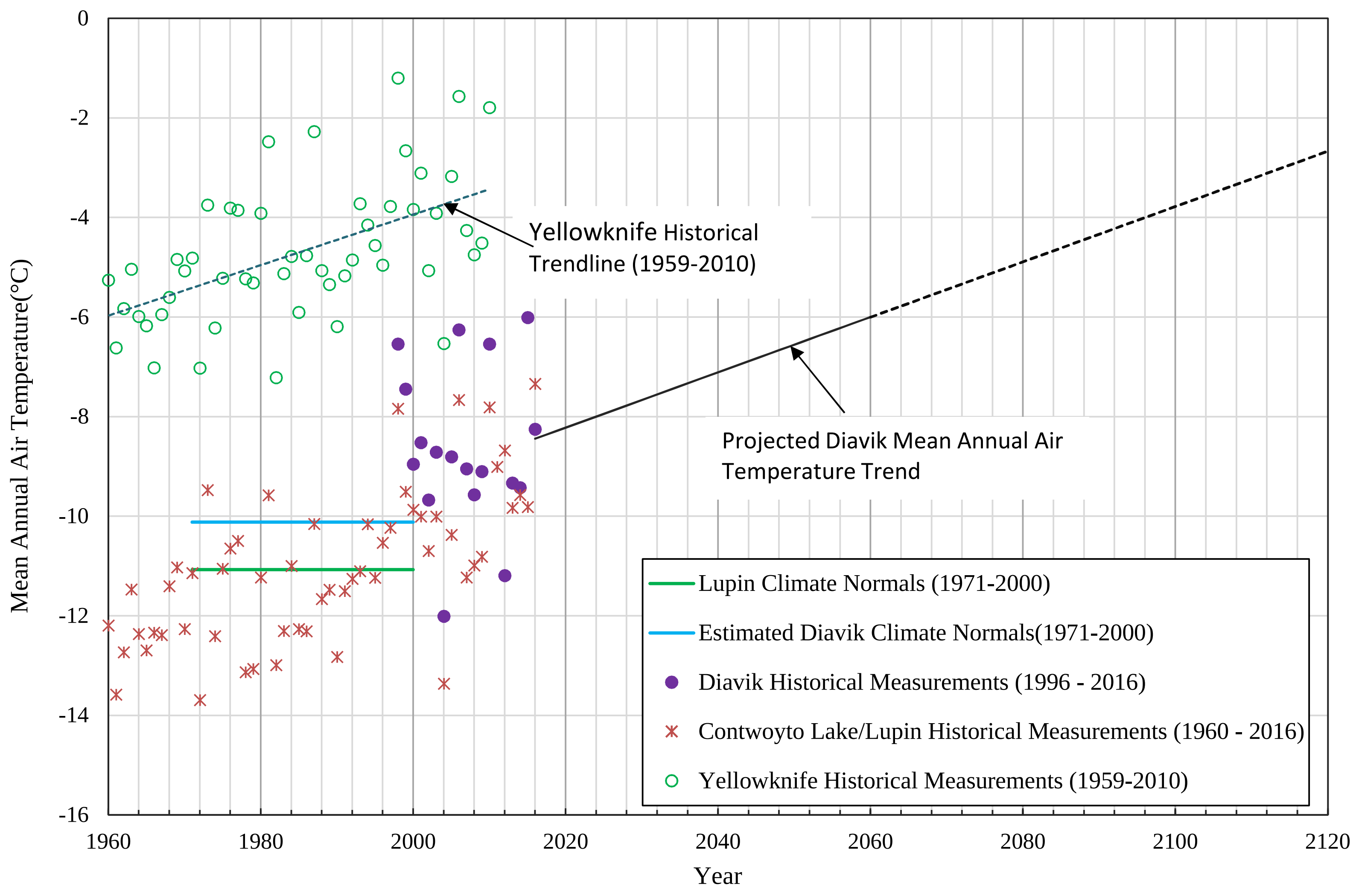
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

COMPARISON OF MEASURED AND PREDICTED DATA AT FD5 (2015 – 2016)

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 11



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

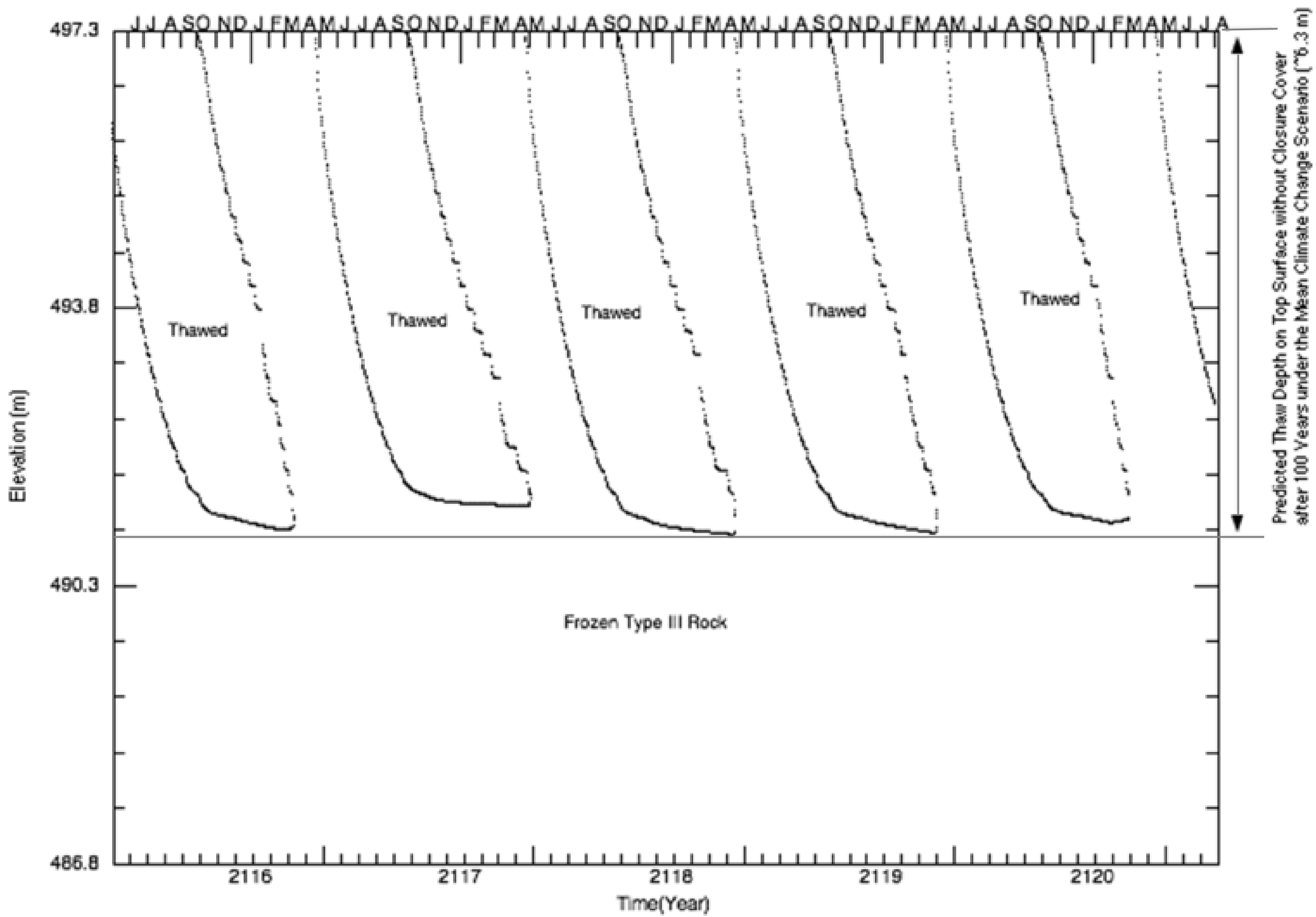
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

HISTORIAL AND PROJECTED ANNUAL AIR TEMPERATURE AT DIAVIK

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	YL	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 12



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

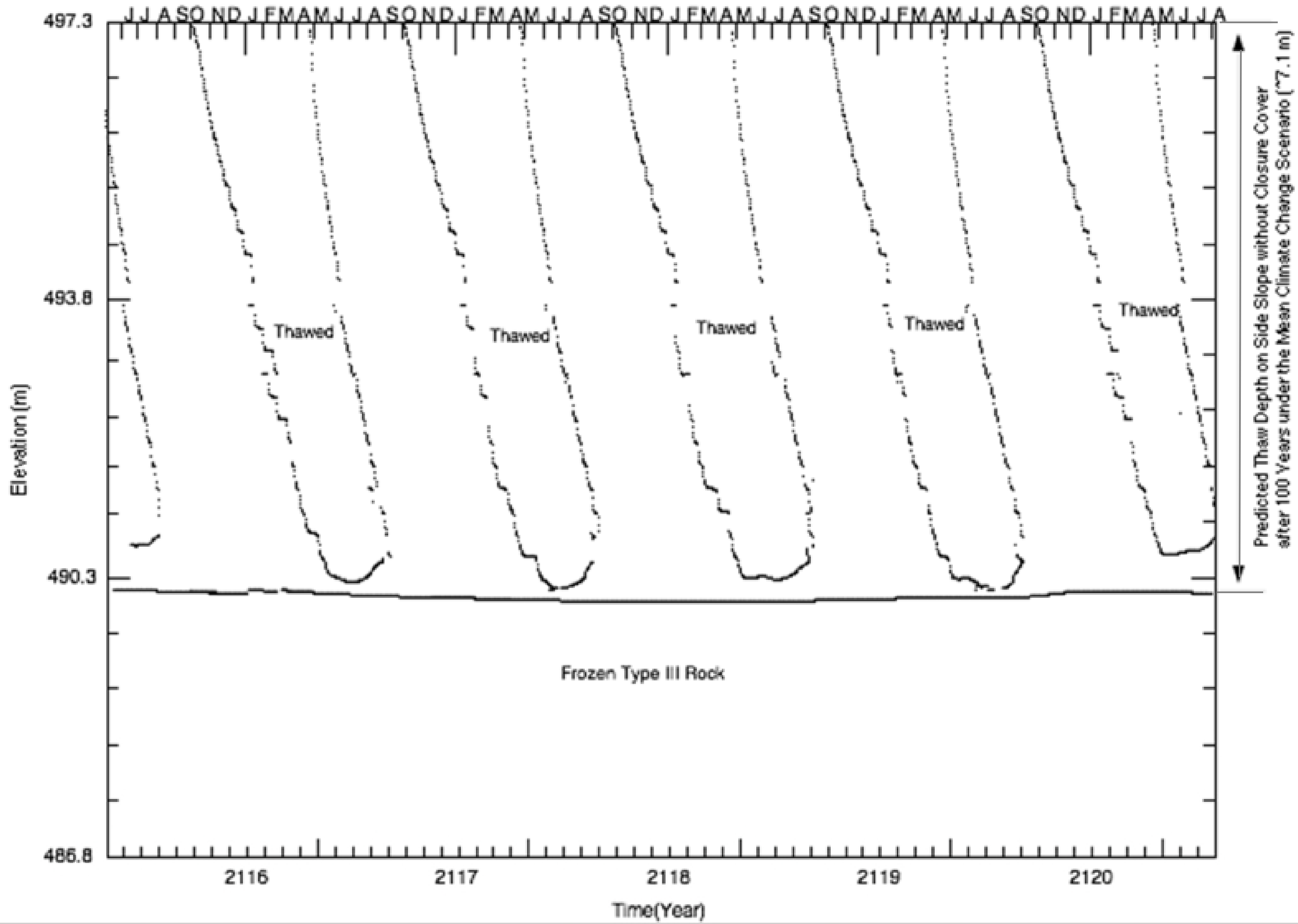
DIAVIK DIAMOND MINE PROJECT NWT, CANADA

PREDICTED MAXIMUM THAW DEPTH ON THE TOP SURFACE WITHOUT CLOSURE COVER AFTER 100 YEARS UNDER CLIMATE CHANGE SCENARIO

PROJECT NO.	DWN	CKD	APVD	REV
EARC03073-01	HX	HX		

OFFICE	DATE
EBA-EDM	April 2017

Figure 13



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

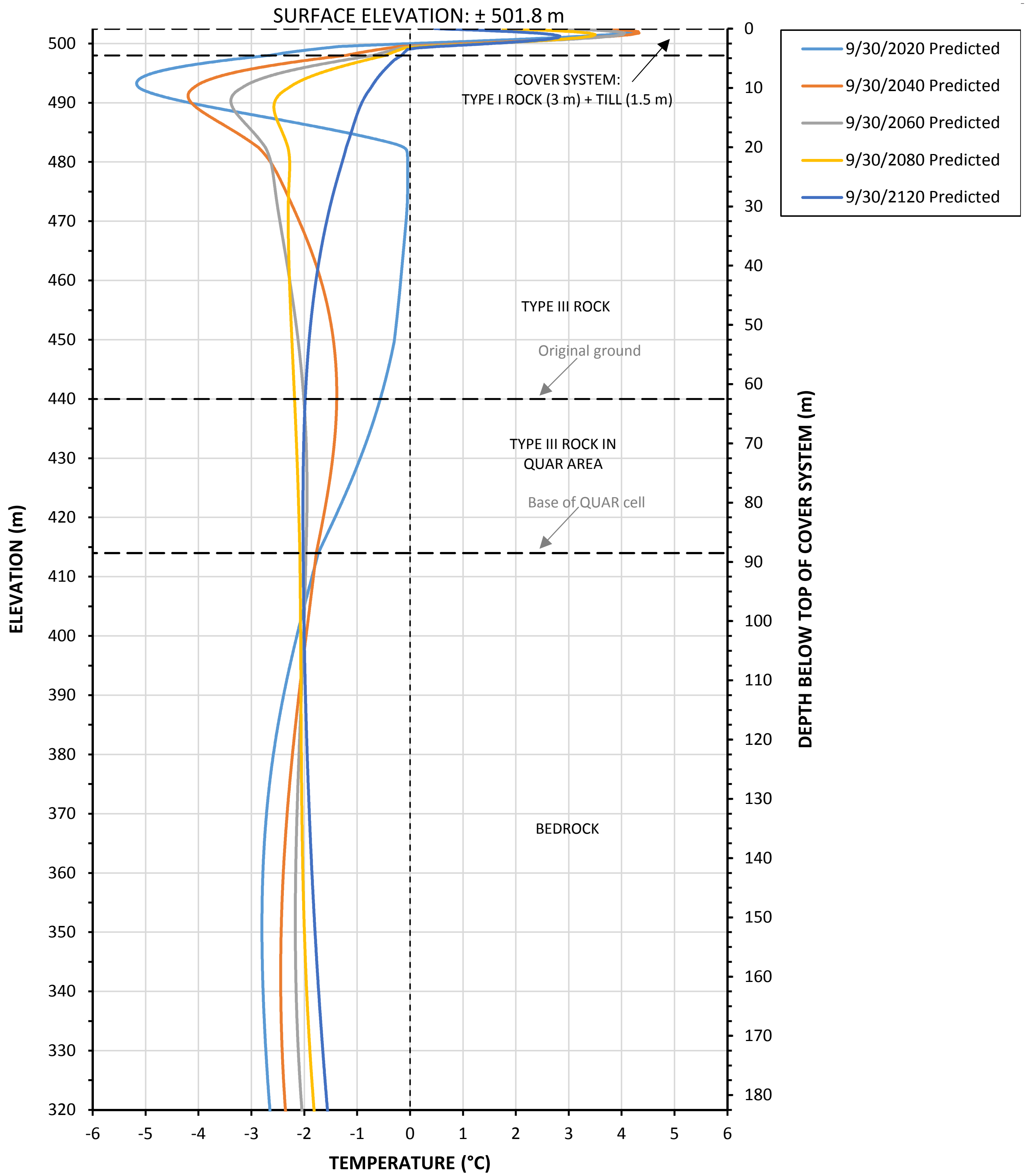
DIAVIK DIAMOND MINE PROJECT NWT, CANADA

PREDICTED MAXIMUM THAW DEPTH ON SIDE SLOPE WITHOUT CLOSURE COVER AFTER 100 YEARS UNDER CLIMATE CHANGE SCENARIO

PROJECT NO.	DWN	CKD	APVD	REV
EARC03073-01	HX	HX		

OFFICE	DATE
EBA-EDM	April 2017

Figure 14



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

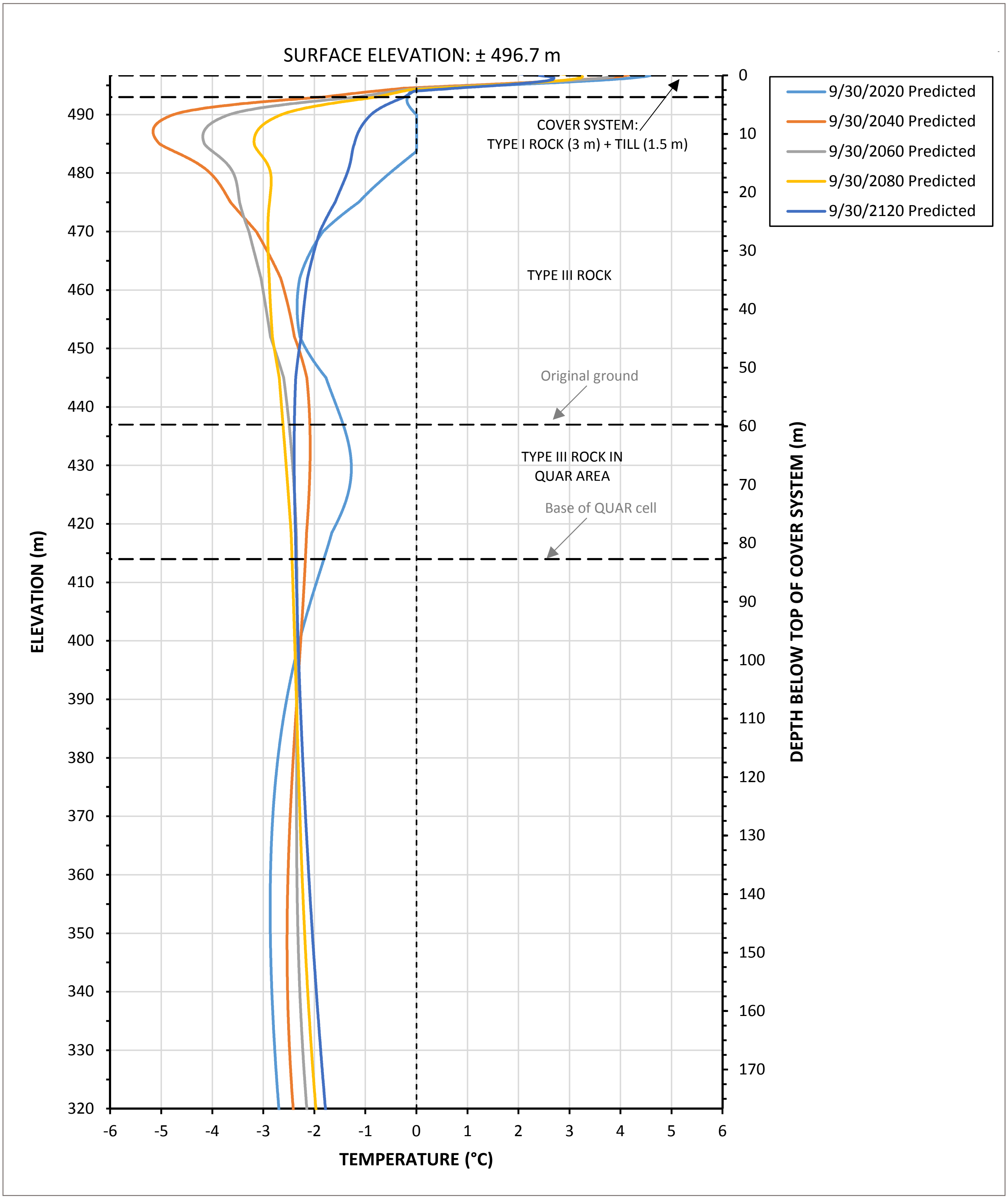
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

PREDICTED TEMPERATURE PROFILES AT SELECTED DATES AT FD1 UNDER LONG-TERM CLIMATE CHANGE

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 15



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

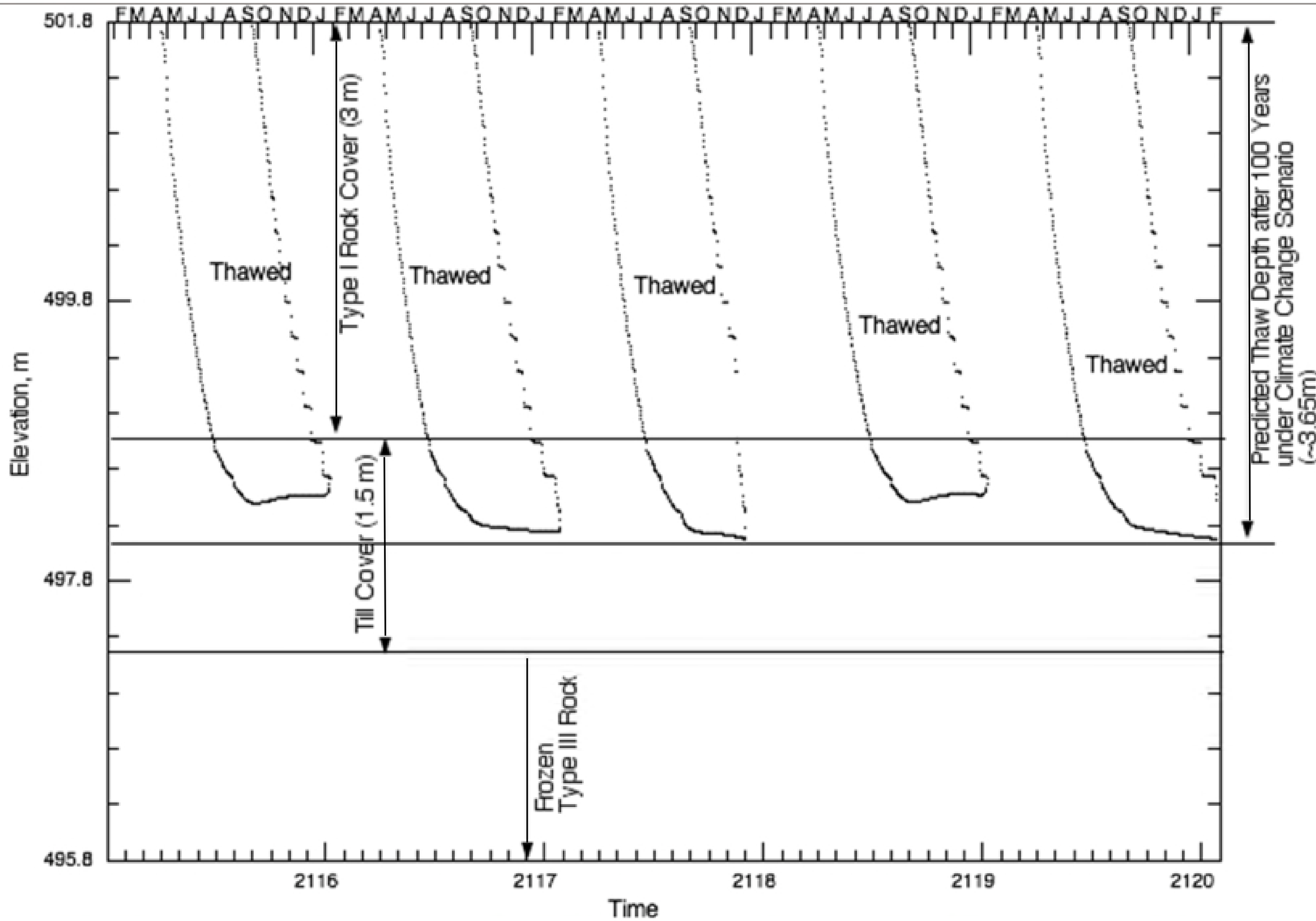
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

PREDICTED TEMPERATURE PROFILES AT SELECTED DATES AT FD5 UNDER LONG-TERM CLIMATE CHANGE

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 16



LEGEND

NOTES

STATUS
ISSUED FOR USE

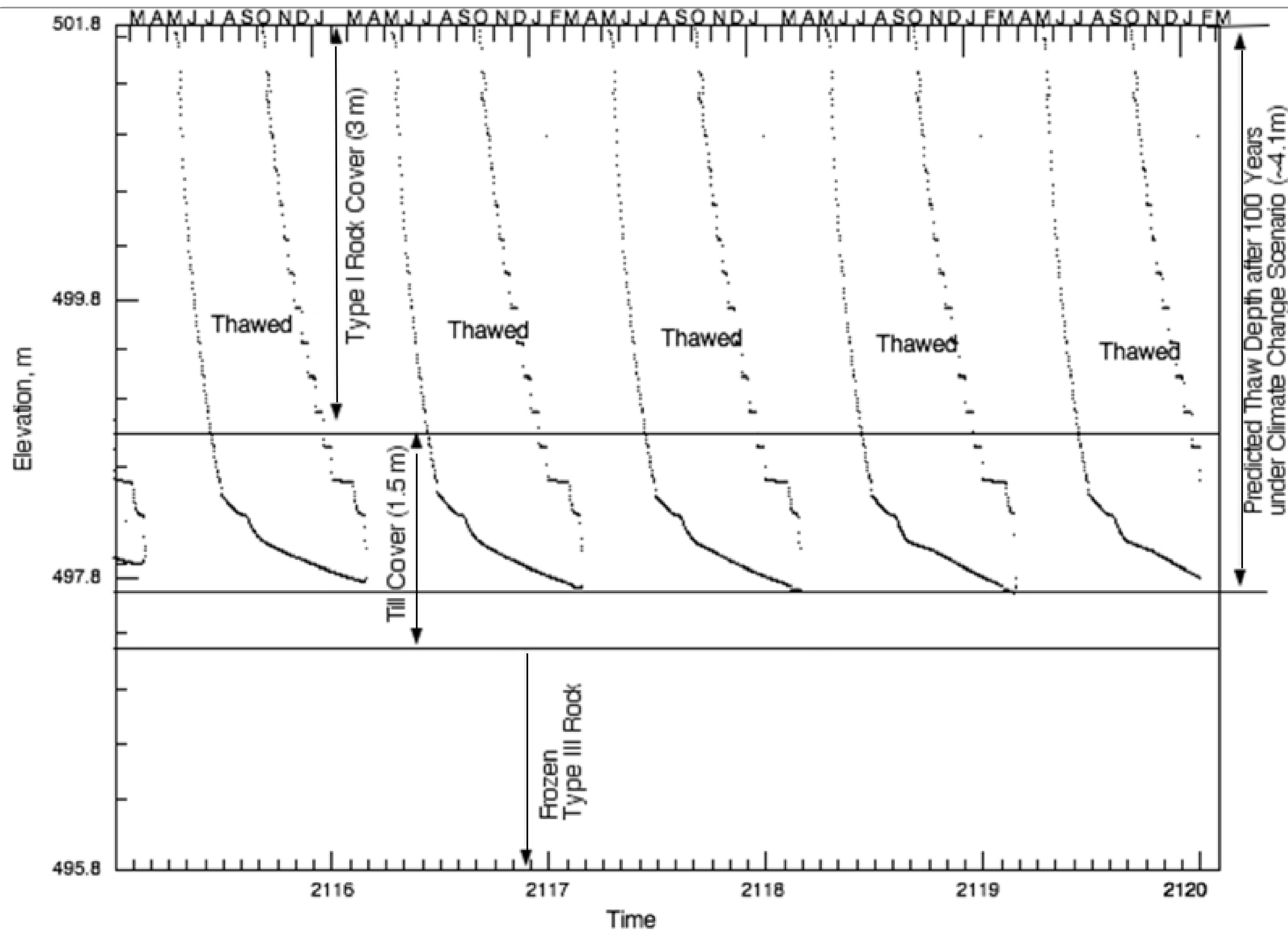
TETRA TECH

DIAVIK DIAMOND MINE PROJECT
NWT, CANADA

PREDICTED MAXIMUM THAW DEPTH ON THE TOP SURFACE AFTER 100 YEARS UNDER CLIMATE CHANGE SCENARIO

PROJECT NO.	DWN	CKD	APVD	REV
EARC03073-01	HX	HX		
OFFICE	DATE			
EBA-EDM	April 2017			

Figure 17



LEGEND

NOTES

STATUS
ISSUED FOR REVIEW

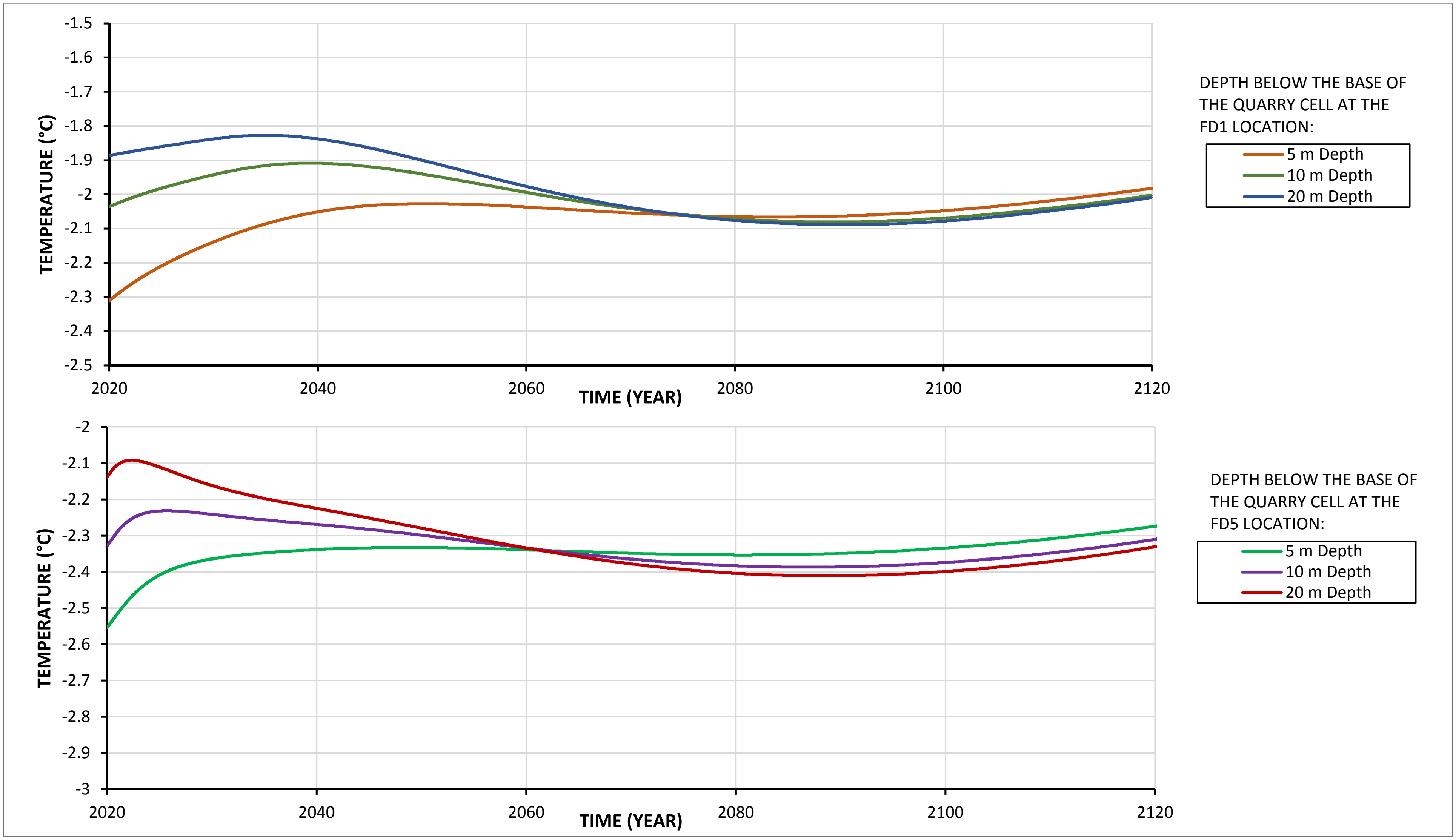
TETRA TECH

DIAVIK DIAMOND MINE PROJECT NWT, CANADA

PREDICTED MAXIMUM THAW DEPTH ON THE SIDE SLOPE AFTER 100 YEARS UNDER CLIMATE CHANGE SCENARIO

PROJECT NO.	DWN	CKD	APVD	REV
EARC03073-01	HX	HX		
OFFICE	**DATE**			
EBA-EDM	April 2017			

Figure 18



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

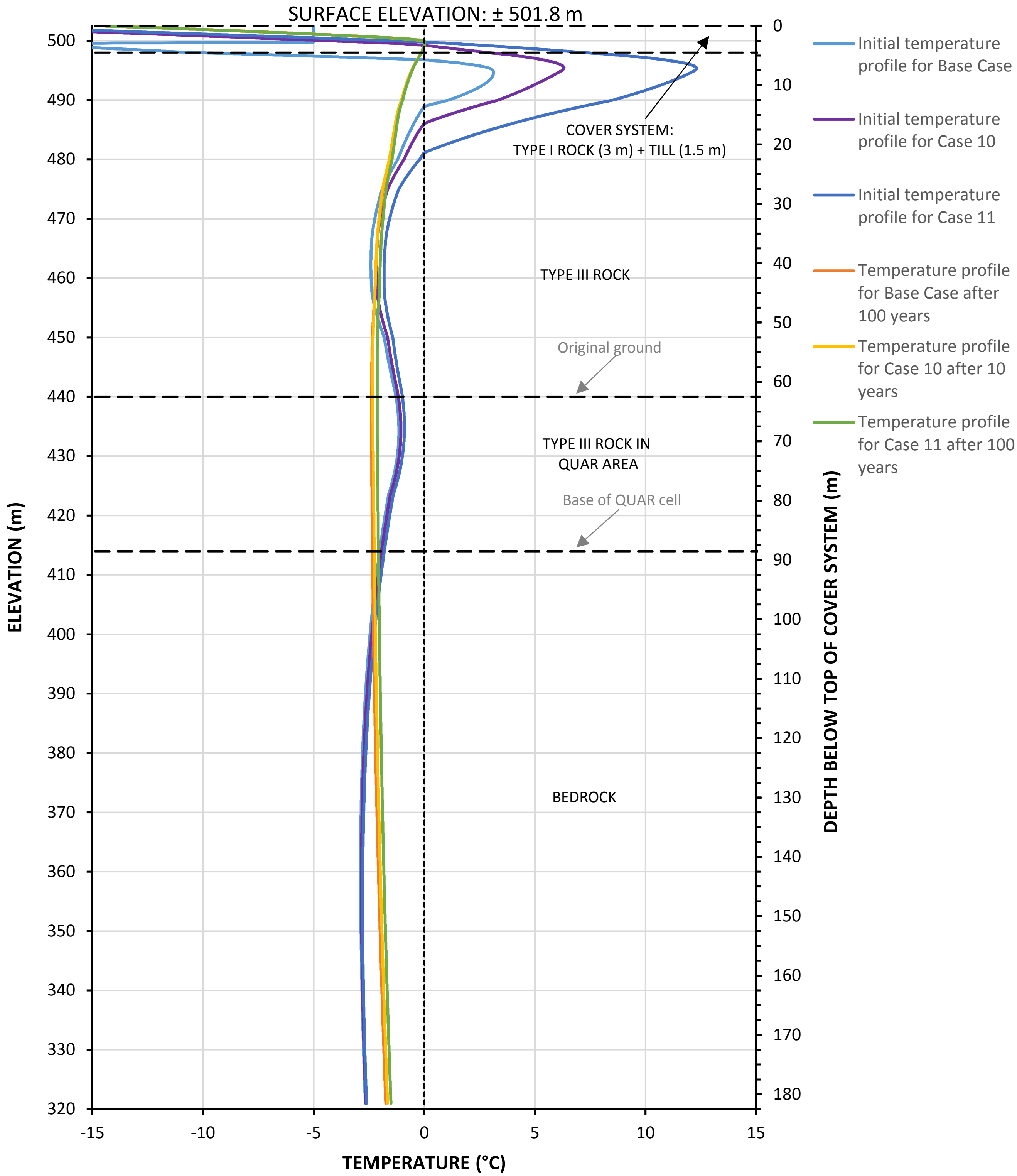
THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

LONG-TERM BEDROCK TEMPERATURE PREDICTIONS AT DEPTHS BELOW THE QUARRY CELL AT FD1 AND FD5

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 19



LEGEND

NOTES

STATUS
ISSUED FOR USE

TETRA TECH

THERMAL EVALUATION OF TYPE III ROCK CLOSURE COVER AT NCRP

PREDICTED TEMPERATURE PROFILES AT FD1 UNDER INITIAL CONDITIONS AND AFTER 100 YEARS WITH HEAT GENERATION

PROJECT NO.	DWN	CKD	APVD	REV
ENG.EARC03073-01	CP	HX	HX	A

OFFICE	DATE
EDM	April 2017

Figure 20

APPENDIX A

TETRA TECH'S GENERAL CONDITIONS

GENERAL CONDITIONS

GEOTECHNICAL REPORT

This report incorporates and is subject to these “General Conditions”.

1.1 USE OF REPORT AND OWNERSHIP

This geotechnical report pertains to a specific site, a specific development and a specific scope of work. It is not applicable to any other sites nor should it be relied upon for types of development other than that to which it refers. Any variation from the site or development would necessitate a supplementary geotechnical assessment.

This report and the recommendations contained in it are intended for the sole use of TETRA TECH’s Client. TETRA TECH does not accept any responsibility for the accuracy of any of the data, the analyses or the recommendations contained or referenced in the report when the report is used or relied upon by any party other than TETRA TECH’s Client unless otherwise authorized in writing by TETRA TECH. Any unauthorized use of the report is at the sole risk of the user.

This report is subject to copyright and shall not be reproduced either wholly or in part without the prior, written permission of TETRA TECH. Additional copies of the report, if required, may be obtained upon request.

1.2 ALTERNATE REPORT FORMAT

Where TETRA TECH submits both electronic file and hard copy versions of reports, drawings and other project-related documents and deliverables (collectively termed TETRA TECH’s instruments of professional service); only the signed and/or sealed versions shall be considered final and legally binding. The original signed and/or sealed version archived by TETRA TECH shall be deemed to be the original for the Project.

Both electronic file and hard copy versions of TETRA TECH’s instruments of professional service shall not, under any circumstances, no matter who owns or uses them, be altered by any party except TETRA TECH. TETRA TECH’s instruments of professional service will be used only and exactly as submitted by TETRA TECH.

Electronic files submitted by TETRA TECH have been prepared and submitted using specific software and hardware systems. TETRA TECH makes no representation about the compatibility of these files with the Client’s current or future software and hardware systems.

1.3 ENVIRONMENTAL AND REGULATORY ISSUES

Unless stipulated in the report, TETRA TECH has not been retained to investigate, address or consider and has not investigated, addressed or considered any environmental or regulatory issues associated with development on the subject site.

1.4 NATURE AND EXACTNESS OF SOIL AND ROCK DESCRIPTIONS

Classification and identification of soils and rocks are based upon commonly accepted systems and methods employed in professional geotechnical practice. This report contains descriptions of the systems and methods used. Where deviations from the system or method prevail, they are specifically mentioned.

Classification and identification of geological units are judgmental in nature as to both type and condition. TETRA TECH does not warrant conditions represented herein as exact, but infers accuracy only to the extent that is common in practice.

Where subsurface conditions encountered during development are different from those described in this report, qualified geotechnical personnel should revisit the site and review recommendations in light of the actual conditions encountered.

1.5 LOGS OF TESTHOLES

The testhole logs are a compilation of conditions and classification of soils and rocks as obtained from field observations and laboratory testing of selected samples. Soil and rock zones have been interpreted. Change from one geological zone to the other, indicated on the logs as a distinct line, can be, in fact, transitional. The extent of transition is interpretive. Any circumstance which requires precise definition of soil or rock zone transition elevations may require further investigation and review.

1.6 STRATIGRAPHIC AND GEOLOGICAL INFORMATION

The stratigraphic and geological information indicated on drawings contained in this report are inferred from logs of test holes and/or soil/rock exposures. Stratigraphy is known only at the locations of the test hole or exposure. Actual geology and stratigraphy between test holes and/or exposures may vary from that shown on these drawings. Natural variations in geological conditions are inherent and are a function of the historic environment. TETRA TECH does not represent the conditions illustrated as exact but recognizes that variations will exist. Where knowledge of more precise locations of geological units is necessary, additional investigation and review may be necessary.

1.7 PROTECTION OF EXPOSED GROUND

Excavation and construction operations expose geological materials to climatic elements (freeze/thaw, wet/dry) and/or mechanical disturbance which can cause severe deterioration. Unless otherwise specifically indicated in this report, the walls and floors of excavations must be protected from the elements, particularly moisture, desiccation, frost action and construction traffic.

1.8 SUPPORT OF ADJACENT GROUND AND STRUCTURES

Unless otherwise specifically advised, support of ground and structures adjacent to the anticipated construction and preservation of adjacent ground and structures from the adverse impact of construction activity is required.

1.9 INFLUENCE OF CONSTRUCTION ACTIVITY

There is a direct correlation between construction activity and structural performance of adjacent buildings and other installations. The influence of all anticipated construction activities should be considered by the contractor, owner, architect and prime engineer in consultation with a geotechnical engineer when the final design and construction techniques are known.

1.10 OBSERVATIONS DURING CONSTRUCTION

Because of the nature of geological deposits, the judgmental nature of geotechnical engineering, as well as the potential of adverse circumstances arising from construction activity, observations during site preparation, excavation and construction should be carried out by a geotechnical engineer. These observations may then serve as the basis for confirmation and/or alteration of geotechnical recommendations or design guidelines presented herein.

1.11 DRAINAGE SYSTEMS

Where temporary or permanent drainage systems are installed within or around a structure, the systems which will be installed must protect the structure from loss of ground due to internal erosion and must be designed so as to assure continued performance of the drains. Specific design detail of such systems should be developed or reviewed by the geotechnical engineer. Unless otherwise specified, it is a condition of this report that effective temporary and permanent drainage systems are required and that they must be considered in relation to project purpose and function.

1.12 BEARING CAPACITY

Design bearing capacities, loads and allowable stresses quoted in this report relate to a specific soil or rock type and condition. Construction activity and environmental circumstances can materially change the condition of soil or rock. The elevation at which a soil or rock type occurs is variable. It is a requirement of this report that structural elements be founded in and/or upon geological materials of the type and in the condition assumed. Sufficient observations should be made by qualified geotechnical personnel during construction to assure that the soil and/or rock conditions assumed in this report in fact exist at the site.

1.13 SAMPLES

TETRA TECH will retain all soil and rock samples for 30 days after this report is issued. Further storage or transfer of samples can be made at the Client’s expense upon written request, otherwise samples will be discarded.

1.14 INFORMATION PROVIDED TO TETRA TECH BY OTHERS

During the performance of the work and the preparation of the report, TETRA TECH may rely on information provided by persons other than the Client. While TETRA TECH endeavours to verify the accuracy of such information when instructed to do so by the Client, TETRA TECH accepts no responsibility for the accuracy or the reliability of such information which may affect the report.

APPENDIX B

PROJECT TEAM RESUMES

TETRA TECH

Kevin W. Jones, P.Eng.
Vice President, Arctic Development

EXPERIENCE SUMMARY

Mr. Jones is the Vice President, Arctic Development for Tetra Tech's, Arctic Engineering Group. He is responsible for the arctic engineering groups located in the Edmonton, AB, Whitehorse, YT, and Yellowknife, NT offices. He has over 32 years of experience in permafrost engineering, offshore engineering, geotechnical investigations, and the design and analysis of varied structures in arctic areas of Canada, Alaska, and Russia. His responsibilities include planning, project management, client liaison, and quality control.

RELEVANT EXPERIENCE

Mr. Jones has had significant involvement in arctic mining projects, including the following:

- Project Director for the design of many of the infrastructure components for the EKATI Diamond Mine located near Lac de Gras, NT. This has included three frozen core dams and two surface water collection systems. He has also been actively involved in the development of the interim reclamation and closure plans (ICRP) for the mine, as well as regulatory process.
- Working together with other consultants on the project team, developed feasibility level designs for the foundations of the infrastructure at the mine and port sites and the nearly 150 km long railway for the Mary River iron ore mine located on Baffin Island, NU.
- Project Director for concept level evaluations of an all-season road between Iqaluit and the mine, airstrip and site infrastructure for the proposed Chidliak Diamond Mine located on Baffin Island, NU.
- Project Director for Tetra Tech's role with Nishi-Khon/SNC-Lavalin for final design of the infrastructure for Diavik's open pit diamond mine in Lac de Gras, NT. Before the final design phase, he was responsible for developing preliminary dike designs and overseeing the original site investigations for the dikes. He directed the site investigations for all the mine site infrastructure components.
- Project Director for the development of preliminary designs for a 32 m high earth and rock fill tailings and water containment dam in discontinuous permafrost soils at the Minto Project in the Yukon.
- Project Director for concept level evaluations for infrastructure for the Kiggavik Uranium project and DO27 Diamond project, and final designs for several of the plant site components and mill upgrades at the Red Dog mine in Alaska.
- Project Engineer responsible for site investigations for the site infrastructure for the Colomac Gold Mine in the Northwest Territories. He participated in the design of the airstrip and carried out the design

EDUCATION

Diploma, Civil Engineering Technology, 1979

B.Eng., Civil Engineering, Lakehead University, Ontario

AREA OF EXPERTISE

Permafrost engineering, design, construction, and project management for foundations, dams, and mining developments in northern Canada

Site investigation, terrain evaluation, arctic onshore and offshore engineering for hydrocarbon exploration and development projects

Specialized laboratory testing, geotechnical drill sampling, and subsurface instrumentation

REGISTRATIONS/ AFFILIATIONS

Member, Association of Professional Engineers and Geoscientists of Alberta (APEGA)

Licensee, Northwest Territories and Nunavut Association of Professional Engineers and Geoscientists (NAPEG)

Member, Canadian Geotechnical Society (CGS)

Member, Geotechnical Society of Edmonton (GSE)

Past-Chair, Cold Regions Division, Canadian Geotechnical Society (CGS)

OFFICE

Edmonton, AB

YEARS OF EXPERIENCE

32

CONTACT

Kevin.Jones@tetratech.com

of the foundations for the plant site infrastructure. He also oversaw the QA/QC program during facility construction.

- Project Engineer responsible for site investigations and participation in designs for the tailings and water control dam on Garrow Lake at the Polaris Mine in Nunavut.

TETRA TECH

Hongwei Xia, Ph.D., P.Eng.
Senior Geotechnical Engineer

EXPERIENCE SUMMARY

Dr. Xia is a Geotechnical Engineer with more than 9 years of consulting experience in geotechnical and permafrost engineering through design and construction projects in Canada and Russia. His areas of technical expertise include geothermal design and evaluation, mine waste rock, tailings, water management, and associated earthwork structure design, northern mine permitting, piled and shallow foundation design in permafrost. He also gained extensive experience in numerical modelling and analytical analysis through the eleven years of university study and research.

RELEVANT EXPERIENCE

Some geotechnical projects that Dr. Xia has been involved in include:

- Lead Engineer for Thermal Foundation Design for Various Buildings for Meliadine Gold Project, Agnico Eagle Mines Ltd.
- Lead Engineer for Thermal Evaluation of Waste Rock Storage Areas at Ekati Mine, Dominion Diamond Ekati Corporation.
- Project Engineer for Gahcho Kué Diamond Mine Engineering Detailed Design, De Beers Canada Inc.
- Project Engineer for Meliadine Gold Project Engineering Detailed Design, Agnico Eagle Mines Ltd.
- Project Engineer for Thermal Evaluation of Till Cover of Pigeon Pit Waste Rock Storage Area at Ekati Mine, Dominion Diamond Ekati Corporation.
- Project Engineer for Geotechnical and Permafrost Consultant Work for Yamal LNG Processing Facilities Detail Design, Technip-JGC Consortium, Paris, FR.
- Project Engineer for Thermal Foundation Design of HP Flare Stack, Yamal-LNG Detailed Design; Technip-JGC Consortium, Paris, FR.
- Project Engineer for Thermal Foundation Design of BOG Stack, Yamal-LNG Detailed Design; JGC Corporation, Japan.
- Project Engineer for Waste and Water Management Feasibility Study for Meliadine Gold Project, Agnico-Eagle Mines Ltd.
- Project Engineer for Tailings Management Scoping Study for Meliadine Gold Project, Agnico-Eagle Mines Ltd.
- Geotechnical Engineer for Yamal LNG Third Party Design Review Project, Chicago Bridge & Iron Company, London, UK.
- Geotechnical Engineer for Prefeasibility Study for Courageous Lake Project, Seabridge Gold Inc.
- Geotechnical Engineer for Feasibility Study for Roche Bay Iron Ore Project, Advanced Explorations Inc.

EDUCATION

Ph.D., Civil Engineering, Queen's University, Kingston, ON

M.Sc., Geotechnical Engineering, Tongji University, Shanghai, China

B.Sc., Engineering Geology, China Ocean University, Qingdao, China

AREA OF EXPERTISE

Mine Rock, Tailing and Water Management and Earthwork Structure Design

Northern Mine Water Licence Permitting

Permafrost Foundation Design and Evaluation

Thermal Design and Evaluation

Slope Stability and Seepage Evaluation

Construction Monitoring and Quality Control

2D and 3D Numerical Modelling

Civil 3D and Rift Tailings Desposition Modelling

Water Managmemt Modelling via Goldsim software

REGISTRATIONS/ AFFILIATIONS

Member, Association of Professional Engineers and Geoscientists of Alberta (APEGA)

Licensee, Association of Professional Engineers and Geoscientists of Northwest Territories and Nunavut (NAPEG)

Member, North American Society for Trenchless Technology (NASTT)

OFFICE

Edmonton, AB, Canada

YEARS OF EXPERIENCE

9

CONTACT

Hongwei.Xia@tetratech.com

- Geotechnical Engineer for EIS Supplement Study and Permitting (Technical Section) for Gahcho Kue Diamond Mine, De Beers Canada Inc.
- Geotechnical Engineer for LIK Project Mine Waste Management Prefeasibility Study, JDS Energy & Mining Inc., British Columbia.
- Geotechnical Engineer for EKATI Dyke C Raise Design for BHP Billiton Diamonds Inc.
- Geotechnical Engineer for Water Management Plan for Minto Mine Project, Minto Explorations Ltd., British Columbia.
- Geotechnical Engineer for Updated Water and Tailings Management Plan for Cantung Mine, North American Tungsten Corp. Ltd.
- Geotechnical Engineer for Thermal Evaluation and Thermosyphon Foundation Design for the IBC studio, FSC Architects & Engineers, Iqaluit, NU.
- Geotechnical Engineer for Thermal Evaluation of Open Pit Infilling with Thickened Tailings for Minto Mine Project, Minto Explorations Ltd., British Columbia.
- Geotechnical Engineer for Thermal Design and Evaluation for the Parking Lots and Access Road of the Legislative Assembly in Yellowknife, NT., FSC Architects & Engineers, Iqaluit, NU.

TETRA TECH

Chantal Pawlychka, B.Sc., E.I.T.
Junior Geotechnical Engineer

EXPERIENCE SUMMARY

Ms. Pawlychka is a Junior Geotechnical Engineer in the Edmonton Arctic Group. She has been focused on Arctic-region projects including thermal modelling of waste rock storage areas, frozen core dams and original ground conditions; quality control testing; and construction project management. She has a proven track record of performing tasks to a high standard with a strong focus on time management, safety, and client satisfaction.

RELEVANT EXPERIENCE

Ekati Diamond Mine

- Thermal modeling of waste rock storage areas using Tetra Tech's GEOTHERM software. Simulate the historical construction history and external factors of the waste pile for analysis. Determine the freeze-back of waste rock piles under mean, moderate and high green-house gas emission scenarios. Evaluate seasonal permafrost thaw-depth and expected temperature gradients of storage areas.

Meliadine Gold Mine Project

- Thermal modeling of frozen core dams using Tetra Tech's GEOTHERM software. Evaluate the thaw-rate and thaw-depth of the frozen core under warming temperatures attributed by seasonal effects. Analysis under a variety of influencing factors such as fluctuating water table, air boundaries and thermal insulation cover thicknesses.
- Thermal modeling of saline water storage/transfer pond and berm using Tetra Tech's GEOTHERM software. Simulate construction phases and changing water table elevations to evaluate the storage pond under mean, moderate and high green-house gas emission scenarios and a 1 in 100 return warm year.

Coffee Gold Project

- Thermal modeling of original ground conditions using Tetra Tech's GEOTHERM software. Evaluate the duration of thaw of the permafrost rich soils and the embedded massive ice lenses under mean, moderate and high green-house gas emission scenarios. Determine the period the permafrost soil layers are under frozen, thawing and thawed condition.

Diavik Diamond Mine

- Quality control testing of materials used in dyke construction for the A21 project. Responsible for assuring that material tests meet the specifications determined by the project owner. Extensive material testing includes unconfined compressive strength tests, unconsolidated undrained triaxial tests, cracked specimen erosion tests and hydraulic conductivity tests on drilled core and cast in-lab material.

EDUCATION

B.Sc., Civil Engineering, University of Alberta, Edmonton, AB. 2015

AREA OF EXPERTISE

Thermal modeling

Geotechnical Laboratory Testing

Construction Project

Management

REGISTRATIONS/ AFFILIATIONS

E.I.T., Association of Professional Engineers and Geoscientists of Alberta (APEGA)

TRAINING/CERTIFICATIONS

Construction Safety Training System (CSTS)

Standard First Aid and CPR/AED Level C

WHMIS Certificate

Transportation of Dangerous Goods (TDG) Certificate

Defensive Driving

OFFICE

Edmonton, AB

YEARS OF EXPERIENCE

2

CONTACT

chantal.pawlychka@tetratech.com

Gahcho Kué Diamond Mine

- Geotechnical soil analyses comprising of compaction testing and particle size distributions through laboratory and field testing programs. Construction monitoring and quality assurance of water retention dykes, airstrip, storage pads, and other geotechnical related structures.

APPENDIX XII

BLANK

APPENDIX XIII

EXCERPTS FROM:

ENVIRONMENT CANADA. 2009. ENVIRONMENT CANADA CODE OF PRACTICE FOR METAL MINES. PRS, 1/MM/17 E. APRIL 2009.

AND

INAC (INDIAN AND NORTHERN AFFAIRS CANADA). 2007. *MINE SITE RECLAMATION GUIDELINES FOR THE NORTHWEST TERRITORIES*. JANUARY 2007.

Table 2A. General guidance on closure objectives relevant to waste rock and till areas from *Mine Site Reclamation Guidelines for the Northwest Territories* (INAC 2007).

Table 2B. Recommendations for decommissioning of waste rock piles from *Environment Canada Code of Practice for Metal Mines* (Environment Canada 2009).

Table 2C. Guidance for generic options for closure of waste rock and overburden areas from *Mine Site Reclamation Guidelines for the Northwest Territories* (INAC 2007).

Table 2-D. General guidance on post-closure monitoring of the waste rock and till areas from *Mine Site Reclamation Guidelines for the Northwest Territories* (INAC 2007).

Table 2A. General guidance on closure objectives relevant to wasterock and till areas from MVLWB/AANDC (2013) and (INAC 2007).

- Minimize erosion, thaw settlement, slope failure, collapse or the release of contaminants or sediment
- Build to blend in with current topography, be compatible with wildlife use, and/or meet future land use targets
- Build to minimize the overall project footprint
- Develop and implement preventative and control strategies to effectively minimize the potential for ARD and ML to occur
- Where ARD and ML are occurring as a result of mine activities, mitigate and minimize impacts to the environment
- No reliance on long-term treatment as a management tool (e.g. effluent treatment facilities are not appropriate for final reclamation but may be used as a progressive reclamation tool)
- Minimal maintenance requirements in the long-term

Table 2B. Recommendations for decommissioning of wasterock piles from *Environment Canada Code of Practice for Metal Mines* (Environment Canada 2009).

- R 524: At the end of the mine operations phase, detailed inspections and assessments of wasterock piles and tailings management facilities, particularly dams and other containment structures, should be carried out. The objective of these inspections and assessments is to evaluate the actual performance against design projections related to anticipated post-closure conditions. Factors that should be considered include:
    - the extent of deformation;
    - the rate and quality of seepage;
    - the condition of foundations and sidewalls; and
    - design loads, which may be different after mine closure.
- R 525: At the end of the mine operations phase, comprehensive risk assessment should be conducted for mine closure to:
    - evaluate the long-term risk associated with possible failure modes for wasterock piles and tailings management facilities;
    - identify possible impacts on the environment and human health and safety in the event of a failure;
    - determine parameters critical to these failure modes and possible impacts; and
    - develop and implement long-term control strategies to manage the identified risks.
- R 527: At the end of mine operations phase, plans for management of wasterock and tailings to prevent, control and treat metal leaching and acidic drainage should be re-evaluated and revised as necessary, to ensure that they are consistent with the objectives and plans for mine closure and post closure. This evaluation should consider:
    - the results of the re-evaluation of the performance of these facilities;
    - the performance of progressive reclamation to date; and
    - possible alternative technologies for closure.

- R 529: At all mines that exist in permafrost conditions, downstream slopes of tailings containment structures should be revegetated.

Table 2C. Guidance for generic options for closure of wasterock and overburden areas from MVLWB/AANDC (2013) and (INAC 2007).

- Doze down crest if required or construct toe berm to flatten overall slope
- Remove weak or unstable materials from slopes and foundations
- Off-load materials from crest of the slope
- Leave waste piles composed of durable rock “as is” at the end of mining if there is no concern for deep-seated failure or erosion, and if the end land use targets can be achieved
- Cover to control reactions and/or migration (re-slope to allow for cover placement if necessary)
- Place riprap insulation/stabilization layer
- Freeze waste into permafrost
- Place potentially acid generating rock underwater or underground if available
- Place potentially acid generating within the centre of the waste pile so it is encapsulated be permafrost if conditions permit and underwater or underground disposal are not viable options
- Construct collection system to collect contaminated runoff or leachate
- Construct diversion ditches to divert uncontaminated runoff
- Install horizontal drains or pump leachate from relief wells at the toe of the slope
- Passively treat contaminated waters where necessary, active treatment is not acceptable for the long term
- Use benign waste rock as backfill in underground mine workings, to seal portals, to fill open-pits, or for construction material such as ramps or covers
- Revegetate using indigenous species or use other biotechnical measures (use of living organisms or other biological systems for environmental management) to reduce surface erosion
- Reslope, contour and/or construct ramps to facilitate wildlife access
- Use inukshuks to deter wildlife where appropriate (guidance from local communities and Elders should be sought)
- Include records of construction drawings, as-built drawings, location of landfill sites, and potential ARD material and other contaminated materials which are contained within the rock pile in the reclamation research plan.
- Control acid water at the source, preventing contaminated water flows, and allow contaminated water to be collected and treated (this would be incorporated into water management system)
- Divert or intercept surface and groundwater from ARD source

- Install covers and seals to prevent or reduce infiltration
- Induce or maintain freezing conditions to limit the formation and discharge of leachate
- Place acid generating materials in topographic lows or depressions where they are most likely to be submerged under water under natural conditions
- Mitigate consequences of ARD by the use of passive and active treatment systems, as appropriate for in-situ conditions
- Passive treatment measures include:
    - Chemical (alkali trenches, attenuation along flow path)
    - Biological (sulphate reduction, wetlands, metal uptake in plants)
    - Physical (physical removal – filtration by plants, attenuation)
- Active treatment measures may include:
    - Chemical (Lime neutralization, adsorptive process)
    - Biological (Sulphate reduction)
    - Physical (Solid/liquid separation)

Table 2-D. General guidance on post-closure monitoring of the wasterock and till areas from MVLWB/AANDC (2013) and (INAC 2007).

• Periodically inspect areas where stabilization measures may be required • Periodic inspections by a geotechnical engineer to visually assess stability and performance of waste pile and cover(s) • Periodically inspect ditches and diversion berms • Examine ground conditions to confirm predicted permafrost conditions are being established as predicted • Check thermistor data to determine thermal conditions within waste piles to confirm predicted permafrost aggradation/encapsulation where applicable • Test water quality and measure volume from controlled discharge points of workings to confirm that drainage is performing as predicted and not adversely affecting the environment • Identify water discharge areas (including volume and quality) that were not anticipated • Inspect physical stability of the mine site to confirm that no erosion, slumping or subsidence that may expose potentially ARD/ML material to air and water are occurring • Inspect any preventative and control measures (e.g. covers) to confirm that they minimize water and/or air exposure • Confirm that predicted water quality and quantity of chemical reactions is occurring ▪ Develop monitoring locations and frequency on a site by site basis, incorporating locations where possible contaminated drainage may be generated, and where drainage may be released to the water management system or to the environment (also include downstream/down gradient locations)