Date: June 21, 2011

RE: City of Duluth Bid #11-4402
(VALE Program Bid Package)

Addendum No. 2

TO: Prospective Bidders

This Addendum forms a part of the Contract Documents and modifies the original Bidding Documents dated June 9, 2011. Acknowledge receipt of this Addendum in the space provided on the Bid Form. Failure to do so may subject the Bidder to disqualification.

Technical Specifications:

**Volume No. 3 Specification**: Modify Division 15 – Mechanical Section 15747 – GROUND HEAT EXCHANGER – Modify Sub-paragraph A.1 of Article 1.3 – SUBMITTAL to read:

1. Submittal shall utilize drilling logs and thermal conductivity test information provided from (2) on site test bores. Any other parameters that the contractor uses in determining the GHEX shall be noted.
   a. Refer to Appendix I – Boring Logs for Test VHE Installations 1 & 2.
   b. Refer to Appendix II – Formation Thermal Response Testing Results for Test VHE Installations 1 & 2.

**Volume No. 3 Specification**: Modify Division 15 – Mechanical Section 15747 – GROUND HEAT EXCHANGER – Add: Appendix II – Formation Thermal Response Testing Results for Test VHE Installations 1 & 2; attached to this addendum.

**Drawings**: Replace drawings listed below with sheets included with this Addendum No. 1

- Sheet C003 – Construction Safety Phasing Plan: Revised Pipe Routing.
- Sheet C211 – Fencing Layout Site Plan and Notes: Revised Fence Layout.
- Sheet M-100 – Overall Geothermal Site Plan: Revised Geothermal Well Field Layout and GWS & GWR Pipe Routing.

**Add new drawing listed below.**

- Sheet M-112 – Geothermal Second Floor Mechanical Plan Part A.

**Other:**

Log and location map for Geotechnical Boring No. 09-05 attached for reference.
END OF ADDENDUM NO. 2
APPENDIX II

Formation Thermal Response Testing Results

For

Test VHE Installations 1 & 2
Formation Thermal Response Testing Results

Duluth International Airport – New Terminal
Duluth, Minnesota

Prepared for

Kraus-Anderson Construction Company

Prepared by

Braun Intertec Geothermal, LLC

Professional Certification:
I hereby certify that this plan, specification or report was prepared by me or under my direct supervision and that I am a duly Licensed Professional Geologist under the laws of the State of Minnesota.

[Signature]

[Print Name]  [Signature]
[License Number: 30088]

Project: GT-11-02378
June 20, 2011
Introduction

Ground coupled heat pump HVAC systems utilize the earth as a heat source and sink by combining geothermal heat pumps with a system of buried, fluid-filled, high density polyethylene pipes. This system of closed loops provides efficient transfer of heat between the geologic formations and the fluid flowing in the pipes.

For commercial and institutional applications, vertical bore is the ground heat exchanger configuration of choice. This is due to a combination of enhanced heat exchange efficiency in saturated formations at depths greater than 50 feet, and reduced site area required for installation.

The size and cost of a vertical bore ground heat exchanger (VHE) system is highly dependent on the formation thermal properties unique to each site. Accuracy in design requires certain site-specific parameters, most importantly formation thermal conductivity, borehole thermal resistance and undisturbed ground temperature measurements. Without the data gathered and calculations documented in this report, the VHE system is likely to be disproportioned, resulting either in unnecessary first costs if oversized, or in unreliable HVAC performance if undersized.

Braun Intertec Geothermal, LLC (Braun Intertec) Formation Thermal Response Testing provides a reliable method of determining ground thermal properties and borehole thermal resistance utilizing representative borehole heat exchangers installed at the site of the future VHE system. This report provides details of the drilling, installation, data gathering, and subsequent analysis of the formation thermal response testing.

Two (2) VHEs were installed during the period June 7 to June 10, 2011 by Sam’s Well Drilling. A Braun Intertec technician performed thermal response testing for not less than 36 hours for the VHEs during the period June 13 to June 17, 2011. A map showing the site location and the location of the VHEs is attached as Figure 1. Boring logs showing the encountered geology and VHE schematics, and a copy of the Minnesota Department of Health (MDH) completion form is also attached. Grout samples were collected from each installation, Grout Sample #1 (Test VHE #2) and Grout Sample #2 (Test VHE #1). The results are reported later in this report and the laboratory reports are attached.

Drilling and installation of the VHEs was observed by a Minnesota Professional Geologist. Photographs showing the progress of the drilling and installation of the VHEs are attached.
Ground Temperature, Thermal Response Testing, and Data Collection Procedures

Based on research conducted by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE), the International Ground Source Heat Pump Association (IGSHPA) developed a standard for performing thermal conductivity tests for closed-loop geothermal ground heat exchangers.

Braun Intertec Thermal Response Testing procedures are based on the most stringent interpretation of the IGSHPA Closed-Loop/Geothermal Heat Pump Systems - Design and Installation Standards (2010). We further attempt to increase the practicality of the results by including a measurement of borehole thermal resistance as well as calculations for volumetric heat capacity. All of which improve design accuracy.

Thermal Response Testing is performed by injecting heat at a constant rate into a heat carrier fluid (water), circulating the fluid through the borehole heat exchanger, and measuring the rate of temperature change over the stated test duration. With our equipment, heating capacity and flow rate are adjustable to target a temperature development in the heat carrier fluid as similar as possible to that of the final heat pump system. Desired heating rate is 20 Watts per bore foot to target the median range of the IGSHPA Standard of 15 to 25 Watts. Desired flow rate is 3 GPM/12 Mbh to ensure turbulence and realistic fluid temperature differential. Fluid temperatures are measured and logged 60 times every hour, without significant interruption\(^1\), to maximize data convergence and reliability. Collected data is then analyzed to determine thermal conductivity, thermal diffusivity, and borehole thermal resistance. Calculation procedures and results are documented later in this report.

Braun Intertec testing apparatus includes a hydronic heater, a data logger, electrical network with reliable generation, hydronic circuit, and measuring devices for the following six parameters:

- Voltage to heating elements (x2)
- Amperage to heating elements (x2)
- Incoming fluid temperature
- Outgoing fluid temperature
- Flow rate of heat conducting fluid
- Ambient air temperature within the apparatus cabinet

A total of 12.5 kW of onboard electrical generation capacity provides portable power for all equipment, enabling dependable operation at any location at system depths up to 500 feet. Braun Intertec developed and constructed this testing apparatus in 2007 to meet or exceed ASHRAE and IGSHPA standards in effect at that time.

\(^1\) “Significant Interruption” is defined as any loss of data collection, flow, and/or heat input for any single duration of greater than 10 minutes.

**Undisturbed Ground Temperature Testing Procedure:**
The IGShPA Standard for undisturbed ground temperature measurement states that it can be obtained by either observing the temperature of the water as it returns from the U-bend to the test equipment at start up, or by direct measurement at various depths with a thermocouple probe.

Braun Intertec chooses to measure by direct insertion of a thermocouple probe into the water filled U-bend. This measurement was performed at 10-foot intervals from ground surface to the bottom of the U-bend pipe, after allowing sufficient time (3 days minimum after installation) for the grout emplaced in the bore and the water temperature in the pipe to equalize with the surrounding formations, and before connection to the thermal response testing equipment. The temperature measurements were then averaged to obtain the undisturbed ground temperature of the VHEs.

Table 1 presents the undisturbed ground temperature measurements obtained for Test VHE #1, and shows which data were excluded for calculation of average undisturbed ground temperature. The first five temperature measurements were excluded from the calculation of average undisturbed ground temperature due to seasonal influence. Temperature sensor error prevented the collection of temperature measurements from Test VHE #2. Temperature variability in the gabbro bedrock should be minimal, so the undisturbed ground temperature measured in test VHE #1 was used also for calculations with regard to Test VHE #2. The temperature profile for Test VHE #1 is presented in Figure 2, and is also shown on the attached boring log.
Table 1: Undisturbed Ground Temperature Measurements – Test VHE #1

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<th>Temperature °C</th>
<th>Temperature °F</th>
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<tr>
<td>Average</td>
<td>8.1</td>
<td>46.5</td>
<td>45.9</td>
</tr>
</tbody>
</table>
Figure 2: Temperature Profile – Test VHE #1

Average Undisturbed Ground Temperature = 45.9 °F
First 5 data points excluded

VHE Active Depth = 497.5 feet

Static Water Level = 16 feet (est.)
Control of Testing Conditions:

The importance of accurate Linear Slope calculation: Accurate measurement of temperature rate-of-change, or Linear Slope, is dependent on carefully controlled testing conditions. Flow rate, heat input, and ambient air temperature within the testing cabinet all must be maintained within close tolerances to obtain an accurate Slope for use in calculating a dependable thermal conductivity value. Braun Intertec measures its effectiveness of testing condition control by averaging the incoming and outgoing fluid temperatures \((T_{in} + T_{out})/2\), and plotting the results against a trend line of the full data set. The IGSHPA 2010 Standard states a maximum deviation of +/- 0.5 °F when comparing to the trend line of the full data set.

Method and data exclusion: Braun Intertec uses the Line Source method of data analysis (Gehlin, 1998; Mogensen, 1983; Witte, et al. 2002) as prescribed by the 2007 ASHRAE Applications Handbook. This method assumes an infinitely thin line source of heat in a continuous medium.

To allow the effect of the finite dimensions of the pipes and grouting material to become insignificant, a number of initial hours of data collected must be omitted from the thermal conductivity calculation. However, neither the IGSHPA Standard nor the ASHRAE research it is based upon, specify this value.

We utilize a calculation (see Equation 1 below) developed by Spitler, et al.\(^2\), to establish the proper point at which the average of the incoming and outgoing fluid temperatures begin to fit the linear slope trend line for the remainder of the test. At this hour, it is assumed that the borehole heat exchanger becomes essentially saturated and the heat within the fluid begins to transfer to the formation in a constant manner. Test VHEs #1 and #2 both became saturated at 10 hours.

\[
t \geq 5r_b^2 / a_{ground}
\]

Equation 1

Where,

- \(t\) Time of borehole heat saturation \(hr\)
- \(r_b\) Nominal borehole radius \(ft\)
- \(a_{ground}\) Formation thermal diffusivity \(ft^2/hr\)

\(^2\) For additional information on this procedure, please refer to In Situ Measurement of Ground Thermal Conductivity: A Dutch Perspective, ASHRAE Transactions 4521 (2002).
**Thermal Response Testing Control Quality:**
Figures 3 through 6 present the testing control effectiveness by presenting the average fluid temperature, trend line of the full data set, and the Control Parameters described above, and the resultant linear slope utilized in the calculation of formation thermal conductivity, thermal diffusivity and borehole thermal resistance, for the tests.

**Formation Thermal Response:**
To model actual operating system performance, and per ASHRAE recommendations, the fluid flow rate during testing should be sufficient to maintain a temperature differential of 6 to 12 °F, as this is the common operating range for heat pump systems. Figures 7 through 10 present the fluid temperature into and out of the ground heat exchangers and the resultant delta T for the tests.

**Heat Rate and Power Consistency:**
ASHRAE/IGSHPA recommend a heat development of 15 – 25 W (51 – 85 Btu/hr) per foot of borehole heat exchanger. Furthermore, ASHRAE/IGSHPA recommends a peak power deviation of ≤10%, and a standard deviation ≤1.5%. Braun Intertec experience has shown that power interruptions have a profound effect on the reliability of the test results and carefully control testing procedures to prevent this occurrence. Figures 11 through 14 present the heat rate and consistency of power applied for the tests.
Figure 3: Control Quality of Testing Conditions (0 to 36 hours) – Test VHE #1

Figure 4: Temperature vs. Linear Time (10 to 36 hours) – Test VHE #1
Figure 5: Control Quality of Testing Conditions (0 to 36 hours) – Test VHE #2

Figure 6: Temperature vs. Linear Time (10 to 36 hours) – Test VHE #2

Trendline Equation: $y = 3.9369x + 66.733$
Figure 7: Temperature vs. Time (0 to 36 hours) – Test VHE #1

Figure 8: Fluid Delta T vs. Time (10 to 36 hours) – Test VHE #1
Figure 9: Temperature vs. Time (0 to 36 hours) – Test VHE #2

Figure 10: Fluid Delta T vs. Time (10 to 36 hours) – Test VHE #2
Figure 11: Heat Rate (10 to 36 hours) – Test VHE #1

Figure 12: Power Consistency (10 to 36 hours) – Test VHE #1
Figure 13: Heat Rate (10 to 36 hours) – Test VHE #2

Figure 14: Power Consistency (10 to 36 hours) – Test VHE #2
Vertical Heat Exchanger Drilling, Installation and Testing Details

Test VHE #1:

Drilling results
- Drilling contractor: Sam’s Well Drilling (under Enviro-Tec, Inc.)
- MN State License No.: 2130
- Drilling start date: June 9, 2011
- Drilling end date: June 10, 2011
- Depth drilled: 500 ft
- Productivity (time to drill to stated depth): 13 hrs
- Drilling technique utilized: mud rotary / air percussion hammer
- Temporary casing installation: 6 in., 0-40 ft (see comments)
- Bore diameter: 8 ¾ in. 0-40 ft; 6 in. 48-500 ft
- Bore diameter (weighted average): 6.2 in.
- Static water level: 16 ft Estimated
- Geology: See attached boring log

Vertical heat exchanger installation
- Installation date: June 10, 2011
- Active depth of installation: 497.5 ft
- Pipe type: HDPE
- Field pressure testing specification: Passed
- Pipe diameter / SDR: 1.25 in. / 9
- Grout thermal conductivity: 0.95 Btu/(hr-ft-°F), see attached lab report
- Portland cement amount used: 7,050 lbs
- Silica sand amount used: 7,050 lbs, Unimin 4030
- Installation record filed with: MDH
- Record identification number: VL-3086 (copy attached)

Testing results
- Testing dates: June 16 – June 17, 2011
- Test duration: 36 hrs
- Ground temperature equilibration period: 6 days
- Average undisturbed ground temperature: 49.5 °F
- Average delta T: 12.2 °F
- Average flow rate: 5.0 gpm
- Estimated volumetric heat capacity: 34.1 ft²·°F
- Tested formation thermal conductivity: 1.25 Btu/(hr-ft-°F)
- Calculated formation thermal diffusivity: 0.88 ft²/day
- Tested borehole thermal resistance: 0.304 (hr-ft-°F)/Btu
Drilling and VHE installation comments:
The U-bend loop began floating out of the borehole after installation and grouting on June 10, 2011. The temporary casing could not be removed since the U-bend loop would also have been lifted out of the borehole. Since the Portland-cement based grout was curing by the end of day, the temporary casing could not be removed so it was left in place.
Test VHE #2:

Drilling results

- Drilling contractor: Sam’s Well Drilling (under Enviro-Tec, Inc.)
- MN State License No.: 2130
- Drilling start date: June 7, 2011
- Drilling end date: June 8, 2011
- Depth drilled: 500 ft
- Productivity (time to drill to stated depth): 13 hrs
- Drilling technique utilized: mud rotary / air percussion hammer
- Temporary casing installation: 6 in., 0-48 ft
- Bore diameter: 8 ¾ in. 0-48 ft; 6 in. 48-500 ft
- Bore diameter (weighted average): 6.3 in.
- Static water level: 16 ft Estimated
- Geology: See attached boring log

Vertical heat exchanger installation

- Installation date: June 9, 2011
- Active depth of installation: 498.5 ft
- Pipe type: HDPE
- Field pressure testing specification: Passed
- Pipe diameter / SDR: 1.25 in. / 9
- Grout thermal conductivity: 0.95 Btu/(hr-ft-°F), see attached lab report
- Portland cement amount used: 5,640 lbs
- Silica sand amount used: 5,640 lbs, Unimin 4030
- Installation record filed with: MDH
- Record identification number: VL-3086 (copy attached)

Testing results

- Test duration: 36 hrs
- Ground temperature equilibration period: 4 days
- Average undisturbed ground temperature: 45.9 °F
- Average delta T: 12.2 °F
- Average flow rate: 5.0 gpm
- Estimated volumetric heat capacity: 34.1 ft²°F
- Tested formation thermal conductivity: 1.23 Btu/(hr-ft-°F)
- Calculated formation thermal diffusivity: 0.87 ft²/day
- Tested borehole thermal resistance: 0.330 (hr-ft-°F)/Btu
Formation Thermal Property Calculations

Formation Thermal Conductivity:
Formation thermal conductivity can not be measured directly but must be inferred from the measurements recorded during thermal response testing. In order to do so, and in accordance with ASHRAE/IGSHPA guidelines, a heat transfer model must be adopted, such as the line source method utilized in this analysis. This method is based on Fourier’s Law of Heat Conduction. The basis of in situ thermal conductivity testing is to impose a pulse of known and fixed energy flux into the fluid contained in the VHE and to measure the resulting temperature response. The relationship between energy flux and temperature establishes the inferred thermal conductivity of a material (Spitler, et al., 2002).

In order to determine the effective thermal conductivity, the average of the incoming and outgoing fluid temperatures \((T_\text{in} + T_\text{out})/2\), was plotted against the logarithm of time after data omission (see Page 6 and Figures 4 and 6).

To solve for thermal conductivity, \(\lambda_{\text{ground}}\), the value of the slope of the lines for each test were inserted, along with the average heat injected, \(P\), and the active borehole length, \(H\), into Equation 2:

\[
\lambda_{\text{ground}} = \frac{3.413 \times P}{4 \pi H \times \text{Slope}}
\]

Equation 2

Where,

- \(\lambda_{\text{ground}}\) Formation thermal conductivity \(\text{Btu}/(\text{hr-ft} \cdot ^\circ\text{F})\)
- \(P\) Average power injected \(\text{W}\)
- \(H\) Active depth of the borehole heat exchanger \(\text{ft}\)

Test VHE #1 – Thermal conductivity calculation

Where,

- \(P = 8865.0\ \text{W}\)
- \(H = 497.5\ \text{ft}\)
- \(\text{Slope} = 3.868\)

\[
\lambda_{\text{ground}} = \frac{3.413 \times 8865.0}{4 \times 3.1415 \times 497.5 \times 3.868} = \frac{302563}{24181.1} = 1.25 \text{Btu/(hr - ft - } ^\circ\text{F)}
\]

Average heat per ft of active bore: \(17.8\ \text{W}\)
Peak power deviation: \(91.2\% - 103.7\%\)
Standard deviation: \(2.5\%\)
Test VHE #2 – Thermal conductivity calculation

Where,

- \( P = 8912.4 \text{ W} \)
- \( H = 498.5 \text{ ft} \)
- \( \text{Slope} = 3.937 \)

\[
\lambda_{\text{ground}} = \frac{3.413 \times 8912.4}{4 \times 3.1415 \times 498.5 \times 3.937} = \frac{304180}{246620} = 1.23 \text{ Btu/(hr-ft-°F)}
\]

Average heat per ft of active bore: \( 17.9 \text{ W} \)
Peak power deviation: \( 88.6\% - 103.2\% \)
Standard deviation: \( 2.4\% \)

**Formation Volumetric Heat Capacity and Thermal Diffusivity Estimation Procedure:**

While neither ASHRAE nor IGSHPA specify the manner in which thermal diffusivity shall be calculated, simply dividing calculated formation thermal conductivity by the estimated volumetric heat capacity of the formation provides this value according to the following equation:

\[
a_{\text{ground}} = \frac{\lambda_{\text{ground}}}{c_{\text{ground}}} x 24 \quad \text{Equation 3}
\]

Where,

- \( a_{\text{ground}} = \text{Thermal diffusivity} \quad \text{ft}^2/\text{day} \)
- \( c_{\text{ground}} = \text{Volumetric heat capacity} \quad \text{Btu/(ft}^3\cdot\text{°F)} \)

Volumetric heat capacity is difficult to measure directly, but can be effectively estimated by averaging the soil/rock fractions encountered, along with an estimation of the percentage of groundwater present within the formations. Using published soils data, specific heat and density values are assigned to the soil/rock fractions as follows.

**Table 2: Estimated Physical Properties of Encountered Formations – Test VHE #1**

<table>
<thead>
<tr>
<th>Formation Log</th>
<th>Depth From (ft)</th>
<th>Depth To (ft)</th>
<th>Total Porosity (%)</th>
<th>Equivalent water (ft)</th>
<th>Specific Heat (Btu/lb·°F)</th>
<th>Density (lb/ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty sand with gravel, dry</td>
<td>0</td>
<td>15</td>
<td>42</td>
<td>0.0</td>
<td>0.19</td>
<td>103</td>
</tr>
<tr>
<td>Gravel, saturated</td>
<td>15</td>
<td>40</td>
<td>33</td>
<td>8.3</td>
<td>0.19</td>
<td>126</td>
</tr>
<tr>
<td>Gabbro, moist</td>
<td>40</td>
<td>497.5</td>
<td>3</td>
<td>13.7</td>
<td>0.18</td>
<td>187</td>
</tr>
</tbody>
</table>

Dividing the estimated water content in the formations surrounding the borehole (22.0 feet) by the total depth yields a percentage of groundwater present within the formations of approximately 4%. Using
the estimated water content and the specific heat and density values assigned to water and to the formations encountered results in a nominal volumetric heat capacity calculated to be 34.1 Btu/(ft³·°F).

Thermal diffusivity for Test VHE #1 is then calculated as follows:

\[
\frac{1.25}{34.1} \times 24 = 0.88 \text{ ft}^2/\text{day}
\]

<table>
<thead>
<tr>
<th>Formation Log</th>
<th>Depth From (ft)</th>
<th>Depth To (ft)</th>
<th>Total Porosity (%)</th>
<th>Equivalent water (ft)</th>
<th>Specific Heat (Btu/lb·°F)</th>
<th>Density (lb/ft³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silty sand with gravel, dry</td>
<td>0</td>
<td>16</td>
<td>42</td>
<td>0.0</td>
<td>0.19</td>
<td>103</td>
</tr>
<tr>
<td>Silty sand with gravel, saturated</td>
<td>16</td>
<td>38</td>
<td>42</td>
<td>9.2</td>
<td>0.19</td>
<td>126</td>
</tr>
<tr>
<td>Gravel, saturated</td>
<td>38</td>
<td>48</td>
<td>33</td>
<td>3.3</td>
<td>0.19</td>
<td>126</td>
</tr>
<tr>
<td>Gabbro, moist</td>
<td>48</td>
<td>498.5</td>
<td>3</td>
<td>13.5</td>
<td>0.18</td>
<td>187</td>
</tr>
</tbody>
</table>

Dividing the estimated water content in the formations surrounding the borehole (26.0 feet) by the total depth yields a percentage of groundwater present within the formations of approximately 5%. Using the estimated water content and the specific heat and density values assigned to water and to the formations encountered results in a nominal volumetric heat capacity calculated to be 34.1 Btu/(ft³·°F).

Thermal diffusivity for Test VHE #2 is then calculated as follows:

\[
\frac{1.23}{34.1} \times 24 = 0.87 \text{ ft}^2/\text{day}
\]

**Borehole Thermal Resistance Calculation Procedure:**

Borehole thermal resistance \( R_b \) is the total resistance to heat transfer between the fluid in the pipe and the formation surrounding the borehole heat exchanger. This takes into account pipe resistance, fluid convective resistance, grout resistance, and spacing of the pipe in relation to the bore wall. Due to the inconsistency in pipe spacing, borehole thermal resistance is difficult to calculate directly without test data. This measurement is very important as it has a proportional effect on the size of the ground heat exchanger system.

Braun Intertec addresses this problem by installing representative borehole heat exchangers and applying the temperature response data, bore depth, injected heat power rate, formation thermal conductivity, formation thermal diffusivity, radius of the borehole heat exchanger, and the undisturbed ground temperature to a formula established by Gehlin (2002, Page 137) to solve for borehole thermal resistance.

Based on the line-source approximation as used by Mogensen (1983), Eskilson (1987) and Hellstrom (1991), and further simplified by Gehlin (2002), the thermal resistance, \( R_b \), between the fluid and the borehole wall can be reliably modeled using the following formula:


\[ T(t) = T_{ug} + \frac{Q}{4\pi \lambda_{ground} H} \left[ E_1 \left( \frac{r_b^2}{4a_{ground} t} \right) \right] + \frac{Q}{H} R_b \]

Equation 4

Where,

- \( T(t) \) Temperature dependent on time \( t \) °F
- \( T_{ug} \) Undisturbed ground temperature °F
- \( Q \) Average heat injected Btu/hr
- \( \lambda_{ground} \) Formation thermal conductivity Btu/(hr-ft-°F)
- \( H \) Active depth of the borehole heat exchanger ft
- \( a_{ground} \) Formation thermal diffusivity ft²/hr
- \( r_b \) Nominal borehole radius ft
- \( R_b \) Borehole thermal resistance (hr-ft-°F)/Btu

\[ E_1(x) = \sum_{n=1}^{\infty} \frac{e^{-u}}{u^n} du \]

A serial development may be used as an approximation of the exponential integral, \( E_1 \), for small values of \( x \), the normal case for thermal response tests on ground heat exchangers. The following approximation of the exponential integral is used (Gehlin, 2002 from Abramowitz and Stegun, 1964):

\[ E_1 \approx -\gamma - \ln x + A \cdot x - B \cdot x^2 + D \cdot x^3 - E \cdot x^4 + F \cdot x^5 \]

Where,

- \( A = 0.99999193 \)
- \( B = 0.24991055 \)
- \( D = 0.05519968 \)
- \( E = 0.00976004 \)
- \( F = 0.00107857 \)
- \( \gamma \) Euler’s constant = 0.5772....

For a given time \( t \), a solution for borehole thermal resistance can be obtained by assuming it to be constant over time.

\( T(t) \) is established by determining the hour in which the average temperature begins to fit the linear slope line for the remainder of the test (see Page 6 for further information), with all data prior to that point omitted from the analysis. The calculations are then averaged for every \( t \) after data omission to obtain \( R_b \). 

For additional information on this procedure, please refer to Signhild Gehlin’s Doctoral Thesis, Division of Water Resources Engineering, Department of Environmental Engineering, Lulea University of Technology (2002).
Borehole thermal resistance calculations – Test VHE #1

Where,

\[
\begin{align*}
T_{ug} &= 45.9 \quad ^{\circ}F \\
Q &= 30256 \quad \text{Btu/hr} \\
\lambda_{ground} &= 1.25 \quad \text{Btu/(hr-ft-}^{\circ}\text{F)} \\
H &= 497.5 \quad \text{ft} \\
a_{ground} &= 0.037 \quad \text{ft}^2/\text{hr} \\
r_b &= 0.26 \quad \text{ft}
\end{align*}
\]

\[
T(t) = 45.9 + \frac{30256}{4\pi*1.25*497.5} \left[ E1 \left( \frac{0.26^2}{4*0.037*t} \right) \right] + \frac{30256}{497.5} R_b
\]

The following figure presents the result of this calculation. Note: (t) was obtained every 60 seconds.

Figure 15: Borehole Thermal Resistance vs. Time (10 to 36 hours) – Test VHE #1

Trendline Equation: \( y = 0.0006x + 0.304 \)

\( R_b = 0.304 \)
Borehole thermal resistance calculations – Test VHE #2

Where,

\[ T_{ug} = 45.9 \text{ °F} \]
\[ Q = 30418 \text{ Btu/hr} \]
\[ \lambda_{ground} = 1.23 \text{ Btu/(hr-ft-°F)} \]
\[ H = 498.5 \text{ ft} \]
\[ a_{ground} = 0.036 \text{ ft}^2/\text{hr} \]
\[ r_b = 0.26 \text{ ft} \]

\[ T(t) = 45.9 + \frac{30418}{4\pi \cdot 1.23 \cdot 498.5} \left[ Ei\left(\frac{0.26^2}{4 \cdot 0.036^2 \cdot t}\right)\right] + \frac{30418}{498.5} R_b \]

The following figure presents the result of this calculation. Note: \( t \) was obtained every 60 seconds.

**Figure 16: Borehole Thermal Resistance vs. Time (10 to 36 hours) – Test VHE #2**
The following table presents a summary of the physical properties of the geologic formations and calculated results for the formation thermal property tests conducted at this site, as well as averages of the presented values.

<table>
<thead>
<tr>
<th>Test VHE</th>
<th>Active Depth (ft)</th>
<th>Undisturbed Ground Temperature (°F)</th>
<th>Formation Thermal Conductivity (Btu/(hr-ft-°F))</th>
<th>Volumetric Heat Capacity (Btu/(ft³-°F))</th>
<th>Formation Thermal Diffusivity (ft²/day)</th>
<th>Borehole Thermal Resistance ((hr-ft-°F)/Btu)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>497.5</td>
<td>45.9</td>
<td>1.25</td>
<td>34.1</td>
<td>0.88</td>
<td>0.304</td>
</tr>
<tr>
<td>2</td>
<td>498.5</td>
<td>45.9</td>
<td>1.23</td>
<td>34.1</td>
<td>0.87</td>
<td>0.330</td>
</tr>
<tr>
<td>Average</td>
<td>498.0</td>
<td>45.9</td>
<td>1.24</td>
<td>34.1</td>
<td>0.88</td>
<td>0.317</td>
</tr>
</tbody>
</table>

Conclusion

Additional ground heat exchanger development services offered by Braun Intertec include construction budgeting, design consulting, project management and construction testing/observation, and Hydrocommissioning™ of the constructed heat exchanger. Please contact us to learn more about how our specialized services help ensure cost effective project delivery and long term operational reliability.

Sincerely,

BRAUN INTERTEC GEOTHERMAL, LLC

By: S. Browne, PG
Geological Services Manager

Scott Freitag
Principal

Attachments:
  Figure 1
  Boring Logs
  MDH Vertical Heat Exchanger Record
  Grout Sample Laboratory Reports
  VHE Installation Observation Photographs
SITE LOCATION AND TEST VHE LOCATION MAP

FIG. 1

PROJECT NO: GT-11-02378
DRAWN BY: JBC
CHECKED BY: GSB
COPYRIGHT: © 2011 by Braun Intertec
Geothermal, LLC

DULUTH INTERNATIONAL AIRPORT - NEW TERMINAL
FORMATION THERMAL RESPONSE TESTING

CITY: DULUTH
STATE: MINNESOTA

ISSUE DATES:
[Blank]

PROJECT DESCRIPTION
DULUTH INTERNATIONAL AIRPORT - NEW TERMINAL
FORMATION THERMAL RESPONSE TESTING

DESCRIPTION DATE MARK

LONG TERM PARKING

NEW CELL PHONE LOT

NEW ROADWAY

PERMIT PARKING

EXISTING EMPLOYEE ACCESS ROAD

NEW RP CMN. UNDERGROUND GEOTHERMAL WATER SUPPLY AND RETURN PIPING IN A TRENCH @ 8 FT. BELOW GRADE. COORDINATE LOCATION WITH CIVIL, MECHANICAL AND ARCHITECTURAL AT THE TERMINAL BUILDING.

NOTE: OVERALL SITE PLAN FOR REFERENCE — SEE MECHANICAL DRAWING

1" = 100'

Plot Date: 20-Jun-11
File Location: Q:\ACTIVE PROJECTS\Minnesota\Duluth\Duluth Airport TC\Drawings\DULUTH SITE MAP.dwg
SILTY SAND, very dark grayish brown 10YR 3/2, fine grained, moist

SILTY SAND, strong brown 7.5YR 4/6, fine grained, with gravel

GRAVEL, with silt, strong brown 7.5YR 4/6, fine grained - possible boulder at 18'

GABBRO, grayish black N 2/0, hard

GABBRO, medium dark gray N 4/0

GABBRO, medium light gray N 6/0, to medium gray N 5/0
**LOG OF BORING: TEST VHE 1**

**DEPT IN FEET** | **SURF. ELEV.** | **USCS** | **GRAPHIC** | **TEMPERATURE (°F)** | **DESCRIPTION** | **WATER LEVELS** | **REMARKS**
--- | --- | --- | --- | --- | --- | --- | ---
180 | 1230 | Mdl | | | GABBRO, medium light gray N 6/0, to medium gray N 5/0 | |
200 | 1210 | Mdl | | | GABBRO, dark grey N 3/0, to grayish black N 2/0 | |
220 | 1190 | Mdl | | | GABBRO, grayish black N 2/0, soft seam at 205 FT | |
240 | 1170 | Mdl | | | GABBRO, grayish black N 2/0, hard | |
<table>
<thead>
<tr>
<th>DEPTH IN FEET</th>
<th>SUCE ELEV.</th>
<th>USCS GRAPHIC</th>
<th>TEMPERATURE (°F)</th>
<th>DESCRIPTION</th>
<th>WATER LEVELS</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>1070</td>
<td>GABBRO, grayish black N 2/0, hard</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>1050</td>
<td>GABBRO, medium dark gray N 4/0, to dark gray N 3/0</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>1030</td>
<td>AVERAGE UNDISTURBED GROUND TEMP = 45.5 °F</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**END OF BORING AT 500 FEET BELOW GRADE**

**COORDINATES:** LATITUDE: 46° 50.341'N; LONGITUDE: 92° 10.674'W
**COORDINATE SYSTEM:** NONE - ESTIMATED FROM GOOGLE EARTH
**SURFACE ELEVATION:** 1410 (FT-AMSL)
**BENCHMARK:** NONE
**TOTAL HOLE DEPTH:** 500 FT
**ACTIVE VHE DEPTH:** 497.5 FT

**BOREHOLE DIAMETER:** 0'-40' 8 3/4" 40'-500' 6"
**DRILLING TIME:** 6/9 START 14:24 END 18:55 @ 200' 6/10 START 06:26 END 13:43 @ 500'
**LOG DATE:** 6/20/11
**LOG OF BORING: TEST VHE 2**

**PROJECT NAME:** Duluth International Airport - New Passenger Terminal  
**PROJECT ADDRESS:** 4701 Airport Road  
**COUNTY:** Duluth, MN 55811  
**ST. LOUIS**  
**REPORT PREPARED BY:** GSS  
**PROJECT No:** GT-11-02378  
**DATE:** Drill 6/7/11 - 6/8/11, GROUT 6/9/11  
**COMPANY/METHOD:** Sams Well Drilling / Mud Rotary 0 - 48 ft, Mincon MC61 Air Percussion Hammer 48 - 500 ft

<table>
<thead>
<tr>
<th>DEPTH IN FEET</th>
<th>SILTS ELEV.</th>
<th>USCS</th>
<th>GRAPHIC</th>
<th>TEMPERATURE (°F)</th>
<th>DESCRIPTION</th>
<th>WATER LEVELS</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1392</td>
<td></td>
<td></td>
<td></td>
<td>GROUND TEMPERATURE NOT MEASURED DUE TO SENSOR ERROR</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>1372</td>
<td>SM</td>
<td></td>
<td></td>
<td>Silt, brown 10YR 3/3, fine grained, with medium gravel, angular to subrounded, dry</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1352</td>
<td>SM</td>
<td></td>
<td></td>
<td>Silt, brown 10YR 3/3, very fine grained, with trace gravel, moist</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1352</td>
<td>GP</td>
<td></td>
<td></td>
<td>Gravel, red/grey, fine to medium grained, trace wood</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1352</td>
<td>GP</td>
<td></td>
<td></td>
<td>Gravel, grey, fine to medium grained, rocky</td>
<td></td>
<td></td>
</tr>
<tr>
<td>40</td>
<td>1352</td>
<td>GP</td>
<td></td>
<td></td>
<td>Gravel, brown/grey 10YR 3/3, fine to medium grained, subrounded</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CAVE-IN AT 15' SWL=16' (ESTIMATED)**  

**DU L U TH COMPLEX (MD)  

drilling production rate: 1.3 ft/min**

**PORTLAND CEMENT/SILICA SAND (1:1)**

**Drilling Production Rate:** 1.25 ft/min  
**Drilling Production Rate:** 1.5 ft/min  
**Littel Water 100' - 120' = 1 GPM**

**W A T E R : 1 GPM**

**Drilling Production Rate:** 2.0 ft/min  
**W A T E R : 160' - 180' APPROX 8 GPM, NO EVIDENCE OF FRACTURES**

**Drill Time:** 6/7 START 09:52 END 18:17 @ 330°  
**Drill Time:** 6/8 START 07:57 END 11:38 @ 500°

**COORDINATES: LATITUDE: 46° 50.351'N; LONGITUDE: 92° 10.594'W  
COORDINATE SYSTEM: NONE - ESTIMATED FROM GOOGLE EARTH  
SURFACE ELEVATION: 1392 (FT-AMSL)  
BENCHMARK: NONE  
TOTAL HOLE DEPTH: 500 FT  
ACTIVE VHE DEPTH: 498.5 FT  
BOREHOLE DIAMETER: 3 1/2"  
48' - 500'  
DRILLING TIME:**
<table>
<thead>
<tr>
<th>Depth in Feet</th>
<th>Silt Elevation</th>
<th>USCS</th>
<th>Graphic</th>
<th>Temperature (°F)</th>
<th>Description</th>
<th>Water Levels</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>180</td>
<td>1212</td>
<td>Md1</td>
<td></td>
<td></td>
<td>GABBRO, dark gray N 3/0, thin chips of granite, hard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>1192</td>
<td>Md1</td>
<td></td>
<td></td>
<td>GABBRO, dusky green SG 3/2 pieces in primarily olive black SY 2/1 matrix, dusky green pieces 40%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td>1172</td>
<td>Md1</td>
<td></td>
<td></td>
<td>GABBRO, light olive gray SY 6/1, moderate brown SYR 4/4, medium dark gray N 4/0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>240</td>
<td>1152</td>
<td>Md1</td>
<td></td>
<td></td>
<td>GABBRO, medium dark gray N 4/0, hard</td>
<td></td>
<td></td>
</tr>
<tr>
<td>260</td>
<td>1132</td>
<td>Md1</td>
<td></td>
<td></td>
<td>GABBRO, grayish black N 2/0, with minor inclusions of dark greenish gray, SGY 4/1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>280</td>
<td>1112</td>
<td>Md1</td>
<td></td>
<td></td>
<td>GABBRO, medium light gray N 6/0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>300</td>
<td>1092</td>
<td>Md1</td>
<td></td>
<td></td>
<td>GABBRO, porphyritic (dark spots) with minor inclusions in light colored micaceous base, softer formation 295'-300'</td>
<td></td>
<td></td>
</tr>
<tr>
<td>320</td>
<td>1072</td>
<td>Md1</td>
<td></td>
<td></td>
<td>GABBRO, grayish black N 2/0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

6/7 END OF DAY: WATER LEVEL MEASURED AT 261 FT BELOW GRADE WITH 330' OPEN HOLE
6/8 START OF DAY: WATER LEVEL MEASURED AT 16 FT BELOW GRADE W/ 330' OPEN HOLE

6.0" BORE HOLE

1.25" HDPE PIPE SDR 9

PORTLAND CEMENT/SILICA SAND (1:1)

DRILLING PRODUCTION RATE: 2.0 FT/MIN
DRILLING PRODUCTION RATE: 2.0 FT/MIN
DRILLING PRODUCTION RATE: 2.2 FT/MIN
WATER: 10 GPM
DRILLING PRODUCTION RATE: 2.2 FT/MIN
DRILLING PRODUCTION RATE: 1.3 FT/MIN
DRILLING PRODUCTION RATE: 1.4 FT/MIN
DRILLING PRODUCTION RATE: 1.8 FT/MIN
DRILLING PRODUCTION RATE: 1.25 FT/MIN
WATER: 8-10 GPM
DRILLING PRODUCTION RATE: 1.0 FT/MIN

COORDINATES: LATITUDE: 46°50.351’N; LONGITUDE: 92°10.594’W
COORDINATE SYSTEM: NONE – ESTIMATED FROM GOOGLE EARTH
SURFACE ELEVATION: 1392 (FT-AMSL)
BENCHMARK: NONE
TOTAL HOLE DEPTH: 500 FT
ACTIVE VHE DEPTH: 498.5 FT

BOREHOLE DIAMETER: 0’ - 48’ 3/4”
48’ - 500’: 6”

DRILLING TIME: 6/7 START 09:52 END 18:17 @ 330’
6/8 START 07:57 END 11:58 @ 500’

LOG DATE: 6/20/11

PROJECT NAME: DULUTH INTERNATIONAL AIRPORT - NEW PASSENGER TERMINAL
PROJECT ADDRESS: 4701 Airport Road
COUNTY: Duluth, MN 55811
REPORT PREPARED BY: ST. LOUIS
PROJECT No: G58
DATE: DRILL 6/7/11 - 6/8/11, GROUT 6/9/11
COMPANY/METHOD: SAM'S WELL DRILLING / MUD ROTARY 0 - 48 FT, MINCON MC61 AIR PERCUSSION HAMMER 48 - 500 FT
<table>
<thead>
<tr>
<th>Depth (ft)</th>
<th>USCS</th>
<th>Temperature (°F)</th>
<th>Description</th>
<th>Water Levels</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>340</td>
<td>Md</td>
<td></td>
<td>GABBRO, grayish black N 2/0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>360</td>
<td>Md</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>380</td>
<td>Md</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>Md</td>
<td></td>
<td>GABBRO, medium dark gray N 4/0, to dark gray N 3/0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>420</td>
<td>Md</td>
<td></td>
<td>GABBRO, medium dark gray N 4/0, to dark gray N 3/0, with pale reddish brown 10R 5/4 (40%)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>460</td>
<td>Md</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>480</td>
<td>Md</td>
<td></td>
<td>GABBRO, grayish black N 2/0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>500</td>
<td>Md</td>
<td></td>
<td></td>
<td></td>
<td>END OF BORING AT 500 FEET BELOW GRADE</td>
</tr>
</tbody>
</table>

**Drilling Details:**
- **Production Rate:**
  - Upper Layer: 1.3 ft/min
  - Predominantly from upper layer
- **Water:**
  - 8-10 GPM, assumed
- **Additional Water:**
  - Drilling rate: 1.2 ft/min
  - Water: 400'-420' increased by 4 GPM; 12 GPM total from 200'-420'

**Notes:**
- Premade U-Bend at 498.5'
- HDPE pipe SDR 9

**Coordinates:**
- Latitude: 46° 50.351'N
- Longitude: 92° 10.594'W
- Coordinate System: None - Estimated from Google Earth
- Surface Elevation: 1392 (ft-AMSL)
- Total Hole Depth: 500 ft
- Borehole Diameter: 0' - 48' 8-3/4'
- Drilling Time: 6/7 Start 09:52, end 18:17 @ 330' 6/8 Start 07:57, end 11:38 @ 500'

**Log Date:** 6/20/11
**VERTICAL HEAT EXCHANGER RECORD**

**Vertical Heat Exchanger Location**

**County Name**: St. Louis

**Township Name**: Hermantown

**Township No.**: 50N

**Range No.**: 15

**Section No.**: 1

**Fraction**: NE 1/4 SE 1/4 SE 1/4

**Depth (completed)**: 500 ft.

**Date Work Completed**: 6-10-11

**Hole Diameter**: 8.75 in. to 50 ft.

**Pipe Diameter**: 6 inches

**Number of Bore Holes**: 22

**Capacity (Tons)**: 0

**Pipe Material**
- [ ] High Density Polyethylene
- [ ] Other

**Type of Joint**
- [ ] Butt Fusion
- [ ] Socket Fusion
- [ ] Other

**Type of Grout Used (Indicate Product Name)**
- [ ] Cement Sand from 0 to 500 ft.
- [ ] Neat Cement from _______ to _______ ft.
- [ ] Bentonite from _______ to _______ ft.
- [ ] Thermally Enhanced Bentonite from _______ to _______ ft.
- [ ] Other _______ from _______ to _______ ft.

**Type of Coolant Used (Indicate Product Name)**
- [ ] Water
- [ ] Propylene Glycol
- [ ] Other

**Pressure Test of Installed Piping**

- **Test Pressure (lbs.)**: 100
- **Test Duration (minutes)**: 60

**Contractor's Certification**

This vertical heat exchanger was constructed under my jurisdiction and this report is true to the best of my knowledge and belief.

_Euro-Tec Inc._

2130

† Business Name

† Licentse No.

1123

† Certified Representative Signature

† Certification No.

† Date

Jason Bickford

6-10-11

† Name of Driller

† Date

† Name of Heat Pump Installer (HVAC Contractor), if different (Optional)

**Remarks, Elevation, Source of Data, etc.**

12,690 ft. cement / 12,690 ft. sand

For entire project

(+) 16' to static water

Test boxes constructed for conductivity tests

Minnesota Department of Health Copy
Thermal Conductivity of Grouts Comprised of Portland Cement and Aggregate
In Accordance with ASTM D 5334

Date: 16 June, 2011

Client: Brett Cahoon
Kraus-Anderson Construction Company
3716 Oneota Street
Duluth, MN 55807-2827

Project Number: GT-11-02378

Project Description:
Thermal Conductivity Testing
Duluth IAP
4701 Grinden Drive
Duluth, MN 55811

Batch Data:
Mix Description: Portland/Silica Sand 1:1
Date/Time Sampled: 6/10/11 at 4:34 PM
Date/Time Received: 6/15/11 at 12:00 PM
Sample Location: Set #2/Test Bore #1
Samples Cast By: Braun Intertec / G. Browne
Type of Sample: 5"x5" Plastic Mold

Laboratory Data:
Batch ID: N/A
Date Tested: 6/16/2011
Average Thermal Conductivity .95 Btu / hr-ft-°F
(1.65 W / m-°C)

Remarks: Sample tested more than once to verify measurement.
The sample exceeds the minimum specified thermal conductivity.

Reviewed By:

Wayne Golembek
Concrete Lab Supervisor
Thermal Conductivity of Grouts Comprised of Portland Cement and Aggregate
In Accordance with ASTM D 5334

Date: 16 June, 2011

Client:
Brett Cahoon
Kraus-Anderson Construction Company
3716 Oneota Street
Duluth, MN 55807-2827

Project Number: GT-11-02378

Project Description:
Thermal Conductivity Testing
Duluth IAP
4701 Grinden Drive
Duluth, MN 55811

Batch Data:
Mix Description: Portland/Silica Sand 1:1
Date/Time Sampled: 6/9/11 at 12:50 PM
Date/Time Received: 6/15/11 at 12:00 PM
Sample Location: Set #1/Test Bore #2
Samples Cast By: Braun Intertec / G. Browne
Type of Sample: 5"x5" Plastic Mold

Laboratory Data:
Batch ID: N/A
Date Tested: 6/16/2011
Average Thermal Conductivity
.95 Btu / hr-ft-°F
(1.64 W / m-°C)

Remarks: Sample tested more than once to verify measurement.
The sample exceeds the minimum specified thermal conductivity.

Reviewed By:
Wayne Golemebeck
Concrete Lab Supervisor
Photo 1 – Drilling setup, Test VHE #2 (east), 06/06/11, view S
Photo 2 – Preparing to drill Test VHE #2 (east), new terminal in background, 06/07/11, view W
Photo 3 – Drill rig setup on Test VHE #2 (east), 06/07/11, view WSW
Photo 4 – Drilling Test VHE #2, water containment silt fence foreground, 06/07/11, view WSW
Photo 5 – Air percussion hammer tooling
Photo 6 – Air percussion drill bit
Photo 7 – Minor drill mud emanating from test VHE #2 drill area, 06/07/11, view W
Photo 8 – Silt fencing containing majority of drill cuttings around Test VHE #2 drill area, 06/07/11, view S
Photo 9 – Drill cuttings from Test VHE #2, 260-foot depth on right, 280-foot depth on left, 06/07/11
Photo 10 – Preparing Day 2 drilling at Test VHE #2, 06/08/11, view N
Photo 11 – Attaching 5-foot long, 1-inch diameter rebar to bottom of loop prior to insertion into Test VHE #2 bore, 06/08/11, view SSE
Photo 12 – Loading U-bend loop into Test VHE #2, 06/08/11, view SSW
Photo 13 – Tremie pipe and loop loaded into Test VHE #2, 06/09/11
Photo 14 – Grouting completed at Test VHE #2, 06/09/11, view ESE
Photo 15 – Setting up at Test VHE #1 (west), 06/09/11, view SW
Photo 16 – Mud drilling top portion of Test VHE #1 (west), 06/09/11, view W
Photo 17 – Preparing to air percussion hammer (installing tooling) at Test VHE #1, 06/09/11, view W
Photo 18 – Silt fencing installed downgradient of Test VHE #1 drill area, 06/10/11, view WSW
Photo 19 – Flowing water through U-bend loop installed in Test VHE #1, prior to grouting, 06/10/11, view NW
Photo 20 – Tremie pipe installed in Test VHE #1 bore, 06/10/11, view NW
Photo 21 – Redi-mix truck at Test VHE #1, preparing to grout, 06/10/11, view E
Photo 22 – Setting up Redi-mix to deliver grout into grout tank for grouting Test VHE #1, 06/10/11, view NNE
Photo 23 – Test VHE #1 installed and grouted, note casing remained in bore, 06/10/11, view NW
# Subsurface Test Boring Log

**AET Job No:** 07-04216.2  
**Log of Boring No:** 09-05 (p. 1 of 1)  
**Project:** Duluth International Airport Terminal; Duluth, MN

<table>
<thead>
<tr>
<th>Depth in Feet</th>
<th>Surface Elevation: Material Description</th>
<th>Geology</th>
<th>N</th>
<th>MC</th>
<th>Sample Type</th>
<th>Rec In</th>
<th>Field &amp; Laboratory Tests</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Fill, slightly organic silty sand with roots, dark brown</td>
<td>Fill</td>
<td>M</td>
<td>M</td>
<td>SU</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Fill, medium to coarse sand with gravel, brown</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Silty sand with gravel, dark brown, moist, medium dense, trace roots above about 2.5' (SM) (may be fill)</td>
<td>TILL OR FILL</td>
<td>15</td>
<td>M</td>
<td>SS</td>
<td>15</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Silty sand, a little gravel, dark brown, moist, medium dense (SM)</td>
<td></td>
<td>14</td>
<td>M</td>
<td>SS</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>TILL</td>
<td>22</td>
<td>M</td>
<td>SS</td>
<td>11</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>TILL</td>
<td>30</td>
<td>M</td>
<td>SS</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Silty sand with gravel, dark brown, moist, dense (SM)</td>
<td></td>
<td>37</td>
<td>M</td>
<td>SS</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Silty sand, a little gravel, dark brown, moist, medium dense (SM)</td>
<td></td>
<td>29</td>
<td>M</td>
<td>SS</td>
<td>17</td>
<td></td>
</tr>
</tbody>
</table>
| 9             | End of Boring at 16.0 Feet  
Borehole backfilled with auger cuttings |         |    |    |    |        |        |

**Drilling Method:** 3.25" HSA  
**Water Level Measurements**

<table>
<thead>
<tr>
<th>Depth: 0-14½'</th>
<th>Drilling Method: 3.25&quot; HSA</th>
<th>Date</th>
<th>Time</th>
<th>Sampled Depth</th>
<th>Casing Depth</th>
<th>Cave-in Depth</th>
<th>Drilling Fluid Level</th>
<th>Water Level</th>
</tr>
</thead>
<tbody>
<tr>
<td>9/15/09</td>
<td>14:57</td>
<td>16.0</td>
<td>14.5</td>
<td>15.0</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>None</td>
</tr>
<tr>
<td>9/15/09</td>
<td>15:03</td>
<td>16.0</td>
<td>None</td>
<td>12.7</td>
<td>---</td>
<td>---</td>
<td>---</td>
<td>None</td>
</tr>
</tbody>
</table>

**Boring Completed:** 9/15/09  
**Dr.:** LA  
**LQ:** TDD Rig: 51