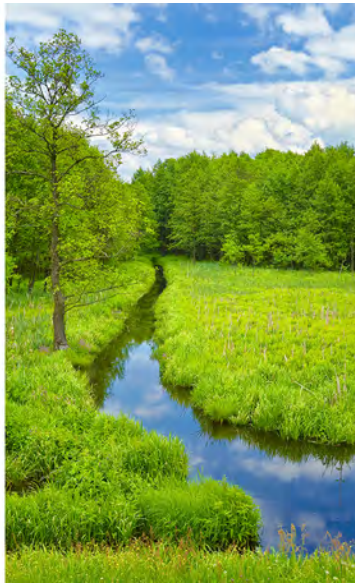


Appendix A

LNAPL Delineation, Mobility and Recoverability Study Report – Eastern LNAPL Area



LNAPL Delineation, Mobility and Recoverability Study – Eastern LNAPL Area

Former General Motors (GM) Willow Run
Powertrain
Ypsilanti, Michigan

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List of Acronyms

API	American Petroleum Institute
ASTM	American Society for Testing and Materials
bgs	Below ground surface
cm	Centimeters
cm/s	Centimeters per second
CRA	Conestoga-Rovers & Associates
ft	Feet
g/cm	Grams per centimeter
LIF	Laser induced fluorescence
LNAPL	Light non-aqueous phase liquid
PAH	Polycyclic aromatic hydrocarbons
PTS	PTS Laboratories
RACER	RACER Trust
RE	Reference Emitter
Site	Former Powertrain Willow Run
UV	Ultraviolet
UVOST	Ultra-violet optical screening tool

List of Parameters/Symbols

α	van Genuchten alpha/ α
ϕ	Total Soil Porosity
i_w	Water Hydraulic Gradient (assumed equal to oil gradient)
K_w	Hydraulic Conductivity Water (centimeters/second or feet/day)
μ_o	LNAPL Viscosity (centipoise)
N	van Genuchten N
ρ_o	LNAPL Density (grams/cubic centimeters)
S_o	LNAPL Saturation
S_w	Water Saturation
S_{wr}	Water Residual (Irreducible) Saturation

Section 1.0 Introduction

Light non-aqueous phase liquid (LNAPL) impacts resulting from historical operations have been historically identified at areas across the Former Willow Run Powertrain facility (Site). The purpose of the evaluation presented herein was to delineate and assess the potential mobility and recoverability of the LNAPL in the area known as the Eastern LNAPL Plume/Area (Study Area). The Eastern LNAPL Area was the focus of this particular evaluation due to persistent observations of significant in-well LNAPL thicknesses and the proximity of the area to the eastern property boundary. Consequently, the evaluation of the overall stability of the Eastern LNAPL Area was desirable since this area was deemed to have the greatest potential of impacting off-Site property. In addition, this evaluation was undertaken to support the most efficient and effective implementation of future LNAPL recovery efforts by identifying areas where potentially recoverable LNAPL is found. This LNAPL delineation, mobility and recoverability evaluation was conducted by Conestoga-Rovers & Associates (CRA) on behalf of the Revitalizing Auto Communities Environmental Response Trust (RACER). This report presents the methodology and results of the study as follows:

- Section 1.0 – Introduction
- Section 2.0 – Methodology
- Section 3.0 – Results
- Section 4.0 – Discussion
- Section 5.0 – Conclusions
- Section 6.0 – References

As a primer on the occurrence and behavior of LNAPL in the subsurface, the following appendices are provided that illustrate the technical fundamentals behind the methodology and interpretation of results presented herein:

- A list of common LNAPL-related terms and definitions is provided in Appendix A
- A general discussion on LNAPL release dynamics, the creation of a multi-phase fluid system (i.e., LNAPL body), LNAPL saturation/residual saturation, mobility/body stability, chemical/physical properties, etc. is provided in Appendix B
- A discussion of the analytical equations and models used to describe LNAPL occurrence, behavior and migration at the water table is presented in Appendix C.

Section 2.0 Methodology

The following field activities were conducted to complete the LNAPL delineation and mobility/recoverability evaluation:

- Utilized laser induced fluorescence (LIF) survey data to further characterize and define the lateral and vertical extents of the LNAPL impacts in the Study Area and select locations for the collection of soil core samples
- Collected relatively undisturbed soil cores to represent the overall impacted area spatially, all apparently unique LNAPL-soil type pairs, and the full range of LIF results from low to high impacts (i.e., lowest to highest LNAPL saturations)
- Collected LNAPL-groundwater sample pairs from locations across the Study Area exhibiting apparently different LNAPL types
- Submitted the soil cores for laboratory photography and physical property testing of key LNAPL mobility parameters
- Submitted the fluid samples for physical property testing related to the potential mobility and recoverability of the LNAPL

The methodology used to evaluate the LIF data, collect soil cores and complete the laboratory testing is presented below. The LIF survey data and laboratory test results are presented in Section 3.0. A discussion regarding the mobility evaluation results is presented in Section 4.0.

2.1 LIF / UVOST Survey

The LIF survey was performed by Matrix Environmental LLC of Osseo, Minnesota using the Ultra-Violet Optical Screening Tool (UVOST) system. The UVOST survey was completed with the oversight of CRA in October 2010.

The LIF technology detects LNAPL by screening for the presence of polycyclic aromatic hydrocarbons (PAHs) present in petroleum fuels during the advancement of a specialized direct-push probe. The LIF probe is equipped with a sapphire window through which a laser is directed. The laser light is adsorbed by PAH molecules in contact with the window as the probe is advanced. This addition of energy (photons) to the PAHs causes them to fluoresce as they return to ground state after excitation. A portion of the fluorescence emitted from any encountered PAHs is returned through the sapphire window and conveyed by a fiber optic cable to a detection system at the surface. The emission data from the pulsed laser light is averaged into one reading per one-second intervals and is recorded continuously. The emission data is reported as percent of the fluorescence intensity of a "reference emitter" (%RE). The %RE is quantified with reference to the fluorescence produced by a standard proprietary hydrocarbon liquid mixture used to calibrate the equipment. For example, an LIF location producing a reading of 100%RE is fluorescing at exactly the same intensity as the standard hydrocarbon mixture. Other things being equal, LIF response is proportional to the amount of aromatic hydrocarbon present. More specifically, LIF response is proportional to LNAPL saturation (i.e., percent of the pore space that is filled with LNAPL). In addition, the LIF instrumentation measures the intensities of four

different wavelengths of light produced when a given LNAPL fluoresces. The proportions of each wavelength that comprise the overall fluorescence response are unique to a given petroleum product type, allowing the real-time identification of LNAPL types in the field.

In short, an LIF survey can:

- Provide definitive delineation of LNAPL/free product impacts vertically and laterally both above and below the water table
- Identify areas of a plume with the highest mobility/recoverability potential by determining the relative intensity of impacts across the plume (i.e., a location producing an LIF response of 300%RE will generally represent a higher LNAPL saturation and greater potential for mobile and/or recoverable LNAPL than a location producing an LIF response of 100%RE)
- Provide an indication of LNAPL type

LIF survey results, by themselves, cannot:

- Specifically quantify LNAPL saturation or mobility (without follow-up targeted well installation and/or soil core testing to "calibrate" LIF responses)
- Detect dissolved or vapor phase contamination – only product phase concentrations are detected

The main features of a typical LIF result are explained in the sample output included as Appendix D.

The UVOST investigation was conducted at a total of sixty-three locations throughout the Study Area.¹ In most cases, the UVOST probe was pushed to a depth ranging from sixteen to twenty ft below ground surface (bgs).

2.2 Soil Core Sampling

CRA collected relatively undisturbed soil cores in select locations in the LNAPL-impacted soil zones based primarily on the LIF results. The results of the LIF survey and other historical Site data/observations were used to select sample locations and sample intervals to represent the range of impacts identified by the LIF survey (i.e., covering the range from highest impacts to the lowest impacts at the LNAPL body fringe). Boreholes were advanced at strategic locations using Geoprobe drilling and sampling methods. More specifically, locations were selected based on the following considerations:

- LIF response intensities

¹ This LIF mobilization complemented earlier work conducted Site-wide in January-February 2010 (see Arcadis 2010 and CRA 2011).

- LNAPL types (inferred from LIF results)
- Areal coverage of soil cores across the Study Area

Soil cores were collected from a total of thirteen locations. Once at the appropriate depth below ground surface, soil cores were collected using the Geoprobe Macrocore sampling system. Macrocore samples were collected in 2-inch diameter, 5-foot long, clear acetate liners. In general, one or two 5-foot long cores were collected from each borehole to obtain a 5 to 10-foot vertical soil profile across the LNAPL impacted zone. Upon retrieval from the ground, the cores were sealed at each end to prevent fluid loss, stored on dry ice to freeze the cores and preserve the pore fluids, and shipped to PTS Laboratories (PTS) in Santa Fe Springs, California for soil core photography and subsequent mobility testing.

2.3 Core Photography

Core photography was performed consistent with American Society for Testing and Materials International (ASTM) D5079. More specifically, frozen soil cores were cut open along the vertical length of the sample tube to enable photographs to be taken of the soil cores. Soil cores were allowed to partially thaw along the surface prior to photographing. The partial thawing was allowed to enable LNAPL, where present, to pool to the surface of the profile. Photographs were taken in both white light and ultraviolet (UV) light. The white light photographs displayed the natural state (color, texture) of the soil profile including any pooled LNAPL, where applicable. The UV photos were used to identify LNAPL by the same principal described with respect to the LIF/UVOST technology. As previously mentioned, LNAPL tends to fluoresce when exposed to UV light. For a given pairing of LNAPL and LNAPL-impacted soil type, the intensity of fluorescence is proportional to the amount of LNAPL, with higher intensities corresponding to greater LNAPL saturations. UV photos also provide qualitative information regarding the type of LNAPL. Generally speaking, lighter end petroleum compounds, such as gasoline or kerosene, tend to fluoresce white or blue; middle distillates including diesel and No. 2 fuel oil tend to fluoresce blue, yellow or gold; and heavier end compounds such as oils and coal tars tend to fluoresce red or brown.

Core photographs were provided by the laboratory to CRA to enable the identification of discrete (two tenths of a foot) intervals of maximum UV fluorescence. Select intervals were then designated for laboratory testing of mobility parameters.

2.4 Laboratory Testing

Discrete soil intervals of maximum UV fluorescence were determined qualitatively from the core photography. Core photography of the soil in the core under white light was also considered to evaluate the pore structure and gradation of the soil/rock samples in the respective sample zones for maximum

porosity. These locations in the core soil samples were selected for one or more of the following laboratory tests (with methods shown in parentheses where applicable):

- Grain size analysis (ASTM D422/D4464M)
- Soil bulk density, grain density, total and air-filled porosity, hydraulic conductivity measurements (various)
- Initial pore fluid (water and LNAPL) saturations (American Petroleum Institute [API] RP40)
- Initial and final LNAPL saturations using a water drive method (Proprietary/API RP40)
- Residual water saturation and van Genuchten parameters (ASTM D6836)

Samples of LNAPL and underlying groundwater were collected from the Site and submitted for the following analyses:

- LNAPL specific gravities, densities and viscosities at three temperatures (ASTM D1481, D445, API RP40)
- Interfacial/surface tensions for air/water, air/LNAPL and LNAPL/water pairs (ASTM D971)

Some of the key laboratory test methods are further described below.

2.4.1 LNAPL Saturation and Residual Saturation Testing

One soil core subsample per location was subjected to initial and residual LNAPL saturation testing via the Water Drive method. This test is considered to yield a LNAPL residual saturation value that is more representative of LNAPL mobility and recoverability conditions under realistic pressure gradients and drainage conditions than other available tests (i.e., 1,000 g centrifugal method or water/LNAPL drainage/imbibition capillary pressure testing). An additional subsample was selected for the determination of pore fluid saturations (i.e., initial LNAPL and water saturations) for certain locations with more than one discrete interval of comparable fluorescence. This was conducted to ensure that the zones of maximum LNAPL impacts were tested to allow a conservative evaluation of LNAPL mobility/recoverability. For each location, the discrete soil interval(s) of maximum UV fluorescence were selected for the respective testing.

LNAPL saturations in soil were determined by the laboratory using the API RP40 Method (via a Dean-Stark extraction procedure). Initial LNAPL saturations were determined either from the Pore Fluids Saturation test or the Residual Saturation by Water Drive test. Subsamples selected for the Water Drive test were additionally driven to residual LNAPL saturation by flushing the sample with multiple pore volumes of water under 25 psi confining pressure.

The potential for LNAPL mobility/recoverability was evaluated by comparing laboratory-measured initial LNAPL saturations to residual saturations. Any locations having initial LNAPL saturations that exceeded the corresponding residual LNAPL saturations were deemed to be potentially mobile, and therefore potentially recoverable.

2.4.2 Soil Grain Size Analysis

Subsamples selected from various cores were submitted to the laboratory for grain size analysis. The subsamples were selected to provide areal coverage of the Study Area and to represent the range of impacted soil types observed in the results of the core photography. Soil grain size was evaluated to confirm impacted soil types.

2.4.3 Capillary Pressure Testing

Subsamples were selected from certain soil cores and subjected to air/water drainage capillary pressure testing to determine the irreducible (residual) water saturations, hydraulic conductivities, soil bulk and grain densities, total and air-filled porosities. Curve fitting was also conducted for each of the moisture retention curves developed during the air/water capillary testing to determine the respective van Genuchten parameters and estimate the residual or irreducible water saturations. These curve fitting parameters describe the drainage characteristics of the soil and are key inputs in LNAPL analytical modeling.

2.4.4 Fluid Testing

Samples of LNAPL and underlying groundwater were collected from the Study Area and submitted for physical testing including density, viscosity and interfacial tensions. Samples were specifically collected from wells with potentially different types of LNAPL based on field observations and LIF results. The testing was completed to help identify differences in the LNAPL(s) based on the physical testing, and to provide Site-specific inputs for subsequent LNAPL analytical modeling.

2.5 LNAPL Analytical Modeling

LNAPL saturation is continuously variable across the vertical LNAPL impacted zone, both above and below the water table. In order to perform a conservative evaluation of the potential mobility and recoverability of the LNAPL, maximum LNAPL relative permeability, conductivity and saturation values can be utilized to approximate an upper limit for potential LNAPL mobility. The maximum LNAPL saturation may be obtained through calculation or a combination of field and laboratory techniques. This maximum saturation may then be used to calculate the maximum (or most conservative estimate of) LNAPL relative permeability and mobility potential (through the estimation of LNAPL velocity). A discussion of the analytical equations used to describe LNAPL occurrence, behavior and migration at the water table upon which the modeling is based is presented in Appendix C.

As stated previously, CRA selected the areas of maximum fluorescence from the core photography results, with consideration given to different LNAPL and/or impacted soil types, to determine the corresponding laboratory-measured ‘maximum’ LNAPL saturations. These ‘maximum’ LNAPL saturations were then used as the primary inputs to determine corresponding LNAPL relative permeability, conductivity, mobility and velocity values using capillary pressure principles and analytical modeling techniques consistent with API methodology. Consequently, CRA carried out the analytical modeling calculations in the most conservative/worst-case manner. Any calculated LNAPL velocity values exceeding a de minimis value of 10^{-6} centimeters per second (cm/s) (ASTM, 2007) were deemed to be potentially mobile, and therefore potentially recoverable.

CRA used the laboratory-measured ‘maximum’ LNAPL saturations and the methodology outlined in Appendix C (derived from API, 2003) to generate an assumed maximum LNAPL relative permeability value for each of the tested soil core sub-samples. CRA then used the calculated relative permeability values and other Site-specific inputs to calculate maximum LNAPL conductivity, mobility and velocity values at each soil core location. Specifically, CRA:

- Obtained assumed maximum LNAPL saturation values for each soil core from lab results
- Calculated maximum LNAPL relative permeability values using Equations 4.10 through 4.13 (Appendix C)
- Calculated maximum LNAPL conductivity values using Equations 4.7, 4.8 and 4.9 (Appendix C)
- Calculated maximum LNAPL mobility values using Equation 4.6 (Appendix C)
- Calculated maximum LNAPL velocity values using Equation 4.26 (Appendix C)

As previously mentioned, the calculation inputs were selected to provide the most conservative site-specific mobility calculations. More specifically, the calculation inputs were selected as follows:

- LNAPL Saturation (S_o): Laboratory values for each respective subsample
- Water Saturation (S_w): Laboratory values for each respective subsample
- Irreducible Water Saturation (S_{wr}): The minimum value from the laboratory-generated water retention curve fitting (i.e., from air/water drainage capillary pressure testing) that was less than each subsample’s water saturation was utilized
- van Genuchten N (N): The maximum value was utilized from all calculated values from the laboratory-generated water retention curves (i.e., from air/water drainage capillary pressure testing)
- LNAPL Density (ρ_o): Highest of the laboratory-generated values for Site LNAPL was used
- LNAPL Viscosity (μ_o): Lowest of the laboratory-generated values for Site LNAPL was used

- Total Soil Porosity (Φ): Lowest of the laboratory-generated values was used
- Hydraulic Gradient (i_w): Conservative value from historic Site data
- Hydraulic Conductivity (K_w): The maximum laboratory value generated during air/water drainage capillary pressure testing was used

Section 3.0 Results

The LIF survey, soil core photography and laboratory test results are discussed in the following sections.

3.1 LIF / UVOST Survey

A total of 63 LIF locations were completed during the East Plume LIF survey. The locations of the 63 LIF survey points are identified in Figure 3.1 (denoted as LIF-1, 2, 3...). The LIF locations completed previously during the January-February 2010 Site-wide LIF mobilization are also shown on Figure 3.1 (denoted as ARC-1, 2, 3...). The individual Study Area LIF results for each location (vertical profile graphs of relative fluorescence response against depth below ground surface) are provided as Appendix E.

The results of both LIF survey events are summarized in Table 3.1 and Figure 3.1. In general, the results indicate that three main LNAPL types are observed at the Site: a lighter kerosene-range product, a diesel-range product, and heavier oil. The LIF spectral fingerprints provide approximations of product types, and should not be assumed to be as accurate as LNAPL fingerprinting via laboratory gas chromatography. In the creation of Table 3.1 and Figure 3.1, the following were considered to be background or insignificant response scenarios:

- Locations where response levels are less than 10%RE throughout the entire vertical profile. LIF response levels in excess of 10%RE were considered significant and representative of LNAPL source material as they are above the background response range.
- Locations with shallow (0-5ft bgs) results at or greater than 10%RE but clean at water table depth. Sub-slab and other shallow vadose zone responses are assumed to be the result of concrete dust interference or LNAPL that is present below residual levels and effectively unrecoverable (i.e., interference or insignificant response).

Maximum LIF response levels varied from 11.60 – 585.50 %RE. The depths of the maximum response levels were as shallow as 2 ft bgs and as deep as 15 ft bgs. The maximum depths of LNAPL impacts were observed to fluctuate from 7 – 20 ft bgs. In order to establish the spatial distribution of the LNAPL impacts with respect to current water table elevations, the LIF results were cross-referenced with well level monitoring data. Examples of this comparison are provided in Figure 3.2. As can be seen in Figure 3.2, the majority of the LNAPL impacts are observed beneath the water table.

The positive LIF responses noted at LIF-013, -058, and -063 along the eastern property line indicate that some level of off-Site migration of LNAPL has taken place onto Willow Run Airport property. The extent of LNAPL impacts in the Study Area was not fully delineated during this survey. However, the type and magnitude of LNAPL impacts in the Study Area are now much better characterized than has been the case historically.

3.2 Core Photographs

The locations selected for soil core sampling are shown on Figure 3.3. The resulting soil core photographs are provided in Appendix F. The photos indicate that many of the sample cores contained LNAPL at varying degrees as evidenced by the UV fluorescence. CRA reviewed the photographs and identified discrete intervals of UV fluorescence and corresponding soil types for each sample location. In addition, CRA identified the zone(s) of maximum UV fluorescence for each sample location where impacts were noted. Where possible, the zones of maximum fluorescence from the core photos were then compared with the corresponding LIF data to confirm that the results from the different datasets were in general agreement. A summary of the zones/subsamples of maximum fluorescence for each location from the core photography selected for laboratory testing is provided in Table 3.2.

3.3 LNAPL Saturation and Residual Saturation

As previously noted, at least one saturation and/or residual saturation test was completed for each of the soil core locations. Pore fluid saturation tests were conducted on ten soil core subsamples. Water Drive residual saturation testing was conducted on thirteen core subsamples (i.e., one subsample per location). The LNAPL saturation and residual saturation test results are provided in Appendix G and summarized in Table 3.2.

The initial LNAPL saturation results obtained from the above testing indicate that LNAPL saturations across the body vary from 6.5% to 58.6%. With respect to the subsamples subjected to Water Drive testing, LNAPL was released from the soil during the tests at the following locations: LIF-9, LIF-25, LIF-61 and ARC-65. This indicates that LNAPL is present at these locations at saturations exceeding residual levels (i.e., potentially mobile and/or recoverable). No LNAPL was released during Water Drive testing for the remainder of the respective subsamples, indicating that the LNAPL at the majority of the tested locations is present at saturations less than residual levels (i.e., immobile and/or unrecoverable). The fraction of the in place LNAPL that is potentially recoverable for each location with LNAPL saturations exceeding residual is also estimated in Table 3.2. These estimates should be viewed as an upper limit to the potentially recoverable LNAPL as subsurface heterogeneities and the technological limitations of recovery techniques will limit how much of the potentially recoverable LNAPL can actually be recovered under field conditions.

3.4 Grain Size Analysis

The soil grain size analysis results are provided in Appendix G.

The grain size analyses indicate that the mean grain size descriptions for impacted soils were mainly fine sands, with a single sample identified as medium sand. The percentages of fine-grained material (silt/clay) were predominantly in the 5%-15% range, with a single sample in excess of 30% fines. The results indicate that although the Site soils exhibit considerable heterogeneity, the LNAPL-impacted soils are principally fine sands with 5%-15% silt/clay that have served as the preferential pathways for LNAPL movement.

3.5 Hydraulic Conductivity and Other Soil Properties/Characteristics

Laboratory-generated hydraulic conductivity values, soil bulk and grain densities, porosities, and van Genuchten curve-fitting results are provided in Appendix G.

Laboratory-generated hydraulic conductivity values for the LNAPL-impacted soil zones varied from a minimum of 4.49×10^{-3} cm/s to a maximum of 7.23×10^{-3} cm/s. Average soil bulk and grain densities were 1.63 g/cm^3 and 2.66 g/cm^3 , respectively. Total soil porosity results were in the range of 30.3% to 43.3%.

The results of the soil drainage (air/water capillary pressure test) and subsequent curve fitting identified the following:

- van Genuchten α : 1.791×10^{-2} to 2.780×10^{-2}
- van Genuchten N: 1.955 to 2.185
- Irreducible water saturation: 8.5% to 22.5%

These data were utilized as Site-specific inputs for the LNAPL mobility analytical modeling calculations discussed in Section 4.0.

3.6 Fluid Testing

LNAPL and underlying groundwater samples were collected from the following monitoring wells: CRA-204M, CRA-222M, and CRA-523R. The fluid samples were submitted for physical testing including density, viscosity and interfacial tensions. The laboratory test results are provided in Appendix G. The locations of the wells are provided on Figure 3.3.

The density and viscosity results defined the physical properties of the three distinct LNAPL types/mixtures observed in the LIF results and provided inputs for the analytical modeling discussed in the following section. A summary of the results is provided as follows:

Well ID	Density at 70°F (grams/cubic centimeter)	Viscosity at 70°F (centipoises)
CRA-523R	0.8511	10.6
CRA-204M	0.8791	98.3
CRA-222M	0.8726	51.5

3.7 Analytical Modeling

As previously outlined, CRA used the ‘maximum’ laboratory-generated LNAPL saturation values and the methodology outlined in Section 2.0 and Appendix C to calculate LNAPL relative permeability values for each soil core test location. CRA then calculated LNAPL conductivity, mobility and velocity values for each location. The model inputs and calculation results are provided in Table 3.3.

The modeling results suggest that LNAPL velocities are greater than the de minimus velocity value of 1×10^{-6} cm/s (ASTM, 2007) at the following locations: LIF-9, LIF-21, LIF-25, LIF-61 and ARC-65. This suggests that potentially mobile/recoverable LNAPL is present at these locations. The remainder of the tested locations exhibited LNAPL velocities less than the de minimus value. Therefore, this calculation methodology provides a second line of evidence that the LNAPL at these locations is effectively immobile and unrecoverable.

Section 4.0 Data Interpretation and Conclusions

The results of the LNAPL saturation and residual saturation results and analytical modeling indicate that potentially mobile/recoverable LNAPL is present in localized portions of the Study Area (see Figure 4.1). The majority of the Study Area appears to consist of LNAPL that is effectively immobile and unrecoverable according to the lines of evidence presented here. Even where LNAPL saturations are high enough to be potentially mobile and recoverable, the LNAPL is unlikely to be actually moving in the absence of sufficient LNAPL head (e.g., from an on-going release). Consequently, in the absence of an on-going release, the overall LNAPL impacts are likely to be stable (i.e., not currently migrating/expanding).

With respect to recoverability, it is likely that the fraction of the LNAPL that would be recoverable in practice is extremely limited even at locations where the preceding evaluation has indicated the presence of potentially mobile/recoverable LNAPL. This is mainly due to the fact that the laboratory

testing and analytical modeling are both conducted in ways that produce very conservative estimates of mobility/recoverability potential. It is unlikely that these theoretically recoverable fractions would be realized in the field due to LNAPL recovery technology limitations and subsurface heterogeneities. In addition, the maximum LIF responses appear to be trapped in the saturated zone (see Figure 3.2), which will exacerbate recovery efforts by necessitating significant dewatering to access the bulk of the impacted zone.

This conclusion is supported by earlier work by Arcadis (2010) that utilized different methods to conclude the following:

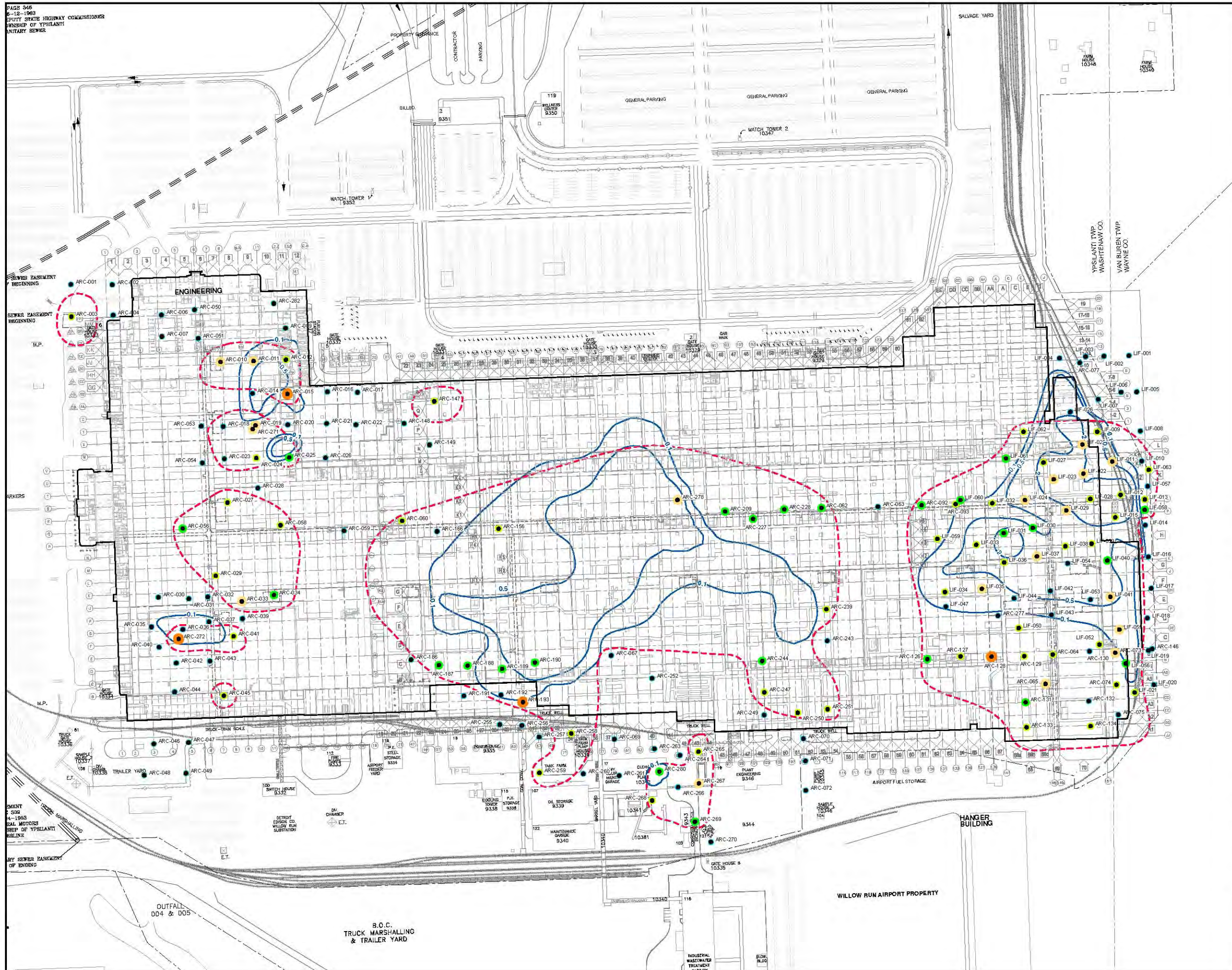
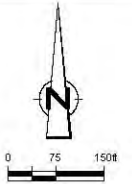
- Approximately 10% of the LNAPL at the Site is potentially recoverable. In other words, 90% of the LNAPL at the Site is likely to remain in place even after active recovery attempts.
- LNAPL baildown testing in the Study Area resulted in estimates of LNAPL transmissivity that were mainly below the recoverability threshold of 0.8 feet (ft)²/day (ITRC, 2009) at CRA-219M and CRA-041R. Estimates for CRA-131M were marginally above the recoverability threshold. This indicates that only a limited fraction of the accessible LNAPL is likely to be recoverable in this vicinity of this location.

In summary, the current and historical results indicate that the following locations in the Study Area have the greatest potential for recoverable LNAPL: LIF-9, LIF-21, CRA-131M, LIF-25, LIF-61 and ARC-65. Any future recovery efforts in the Study Area should be focused in the vicinity of these locations. However, given that the potentially recoverable fraction of the in-place LNAPL is extremely small, it is unlikely that active recovery efforts will significantly reduce the quantity of in-place LNAPL. Consequently, active LNAPL recovery in the Study Area should not be expected to have any significant environmental benefit since such a small reduction in LNAPL mass will have a negligible effect in terms of reducing source zone longevity and/or risk, and the LNAPL impacts already appear to be stable. The limited expected effectiveness of active LNAPL recovery should be considered going forward, particularly in light of the significant costs, complexities, and power consumption involved with the implementation of the planned Multi-Phase Extraction LNAPL recovery effort.

The extent of LNAPL impacts in the Study Area was not fully delineated during this survey. Further delineation/characterization work with LIF should be considered, particularly to the east where impacts extend onto the Willow Run Airport property. It is also noted that the Western and Central LNAPL areas of the Site have not been evaluated for mobility/recoverability according to a methodology comparable to what has been presented herein.

Section 5.0 References

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LEGEND

-
- PROPERTY LINE
 BUILDING
 LIF-001
 LASER-INDUCED FLOURESCENCE (LIF) BORING
 IN-WEELL LNAPL THICKNESS CONTOUR (ft.) (AUGUST 2010)
 APPROXIMATE EXTENT OF LNAPL
MAXIMUM LIF RESULT
 %RE INDICATIVE OF BACKGROUND CONDITIONS
 10 - 100 %RE
 100 - 200 %RE
 200 - 400 %RE
 400 - 600 %RE

SCALE VERIFICATION

THIS BAR MEASURES 1" ON ORIGINAL. ADJUST SCALE ACCORDINGLY.



Approved

DRAWING STATUS

Status	Date	Initial

FORMER GM POWERTRAIN WILLOW RUN
Ypsilanti, MI

LIF AND LNAPL MOBILITY STUDY

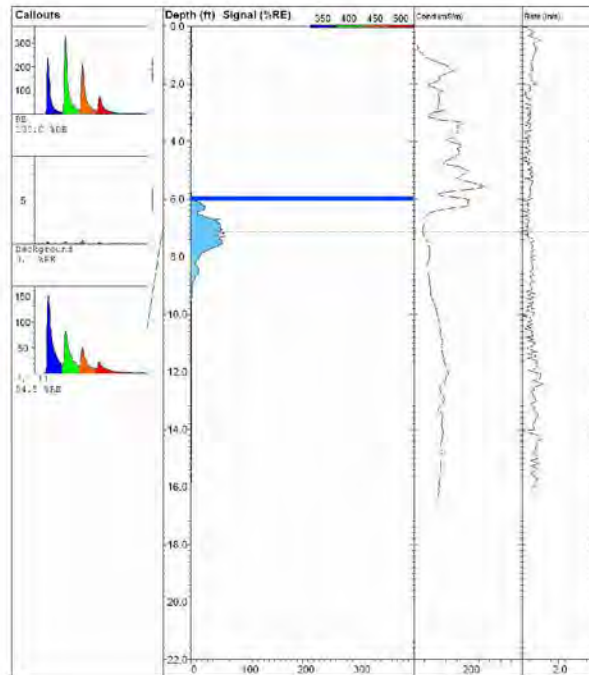
LIF SURVEY RESULTS

**CONESTOGA-ROVERS & ASSOCIATES**

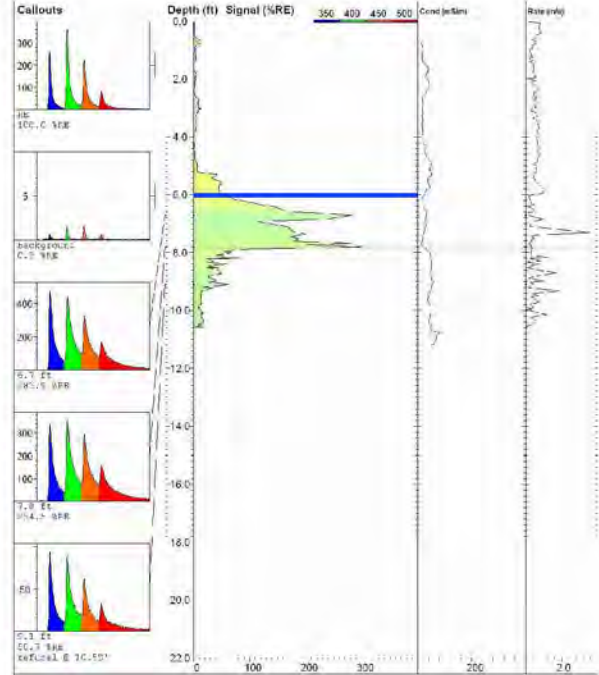
Source Reference:

Project Manager: S. ADAMOOWSKI	Reviewed By: M. ROUSSEAU	Date: JULY 2011	
Scale: 1:150	Project N°: 17358-T01	Report N°: 017	Drawing N°: FIGURE 3.1

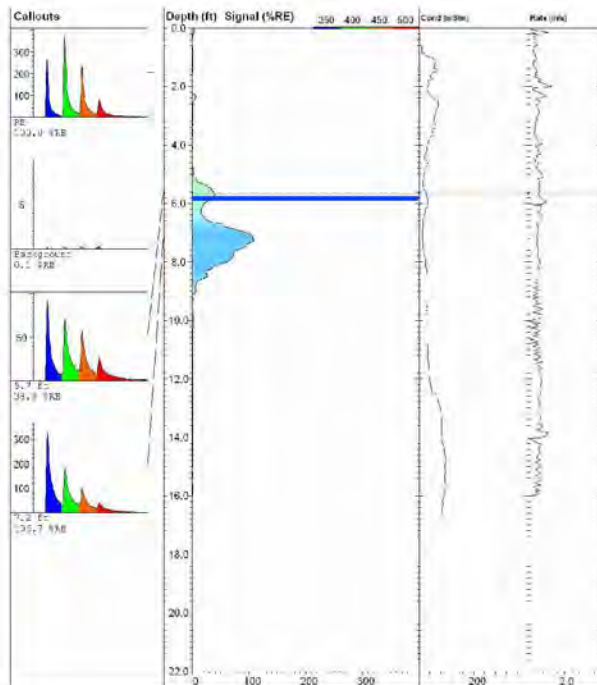
LIF-9



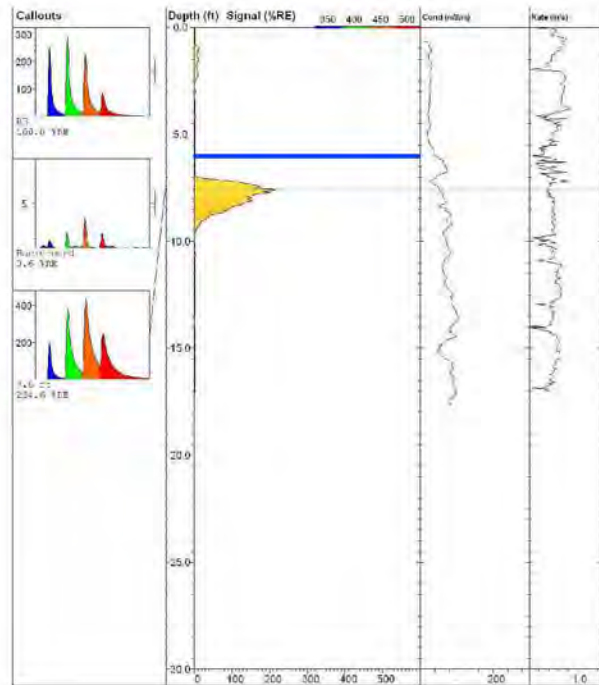
LIF-25



LIF-61



LIF-65

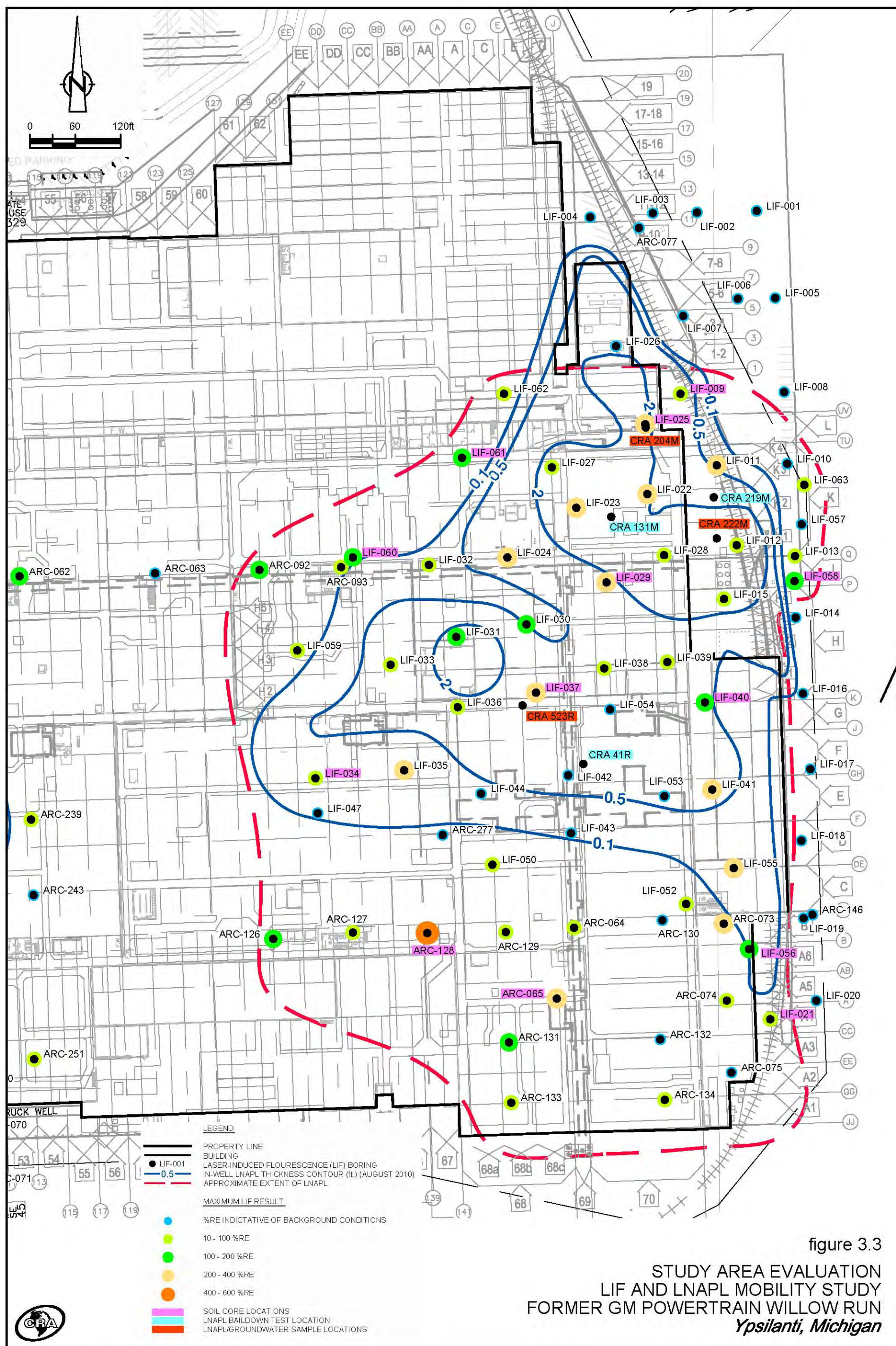
**LEGEND**

— WATER TABLE

figure 3.2

**EXAMPLE LIF OUTPUTS WITH WATER TABLE
LIF AND LNAPL MOBILITY STUDY
FORMER GM POWERTRAIN WILLOW RUN
Ypsilanti, Michigan**





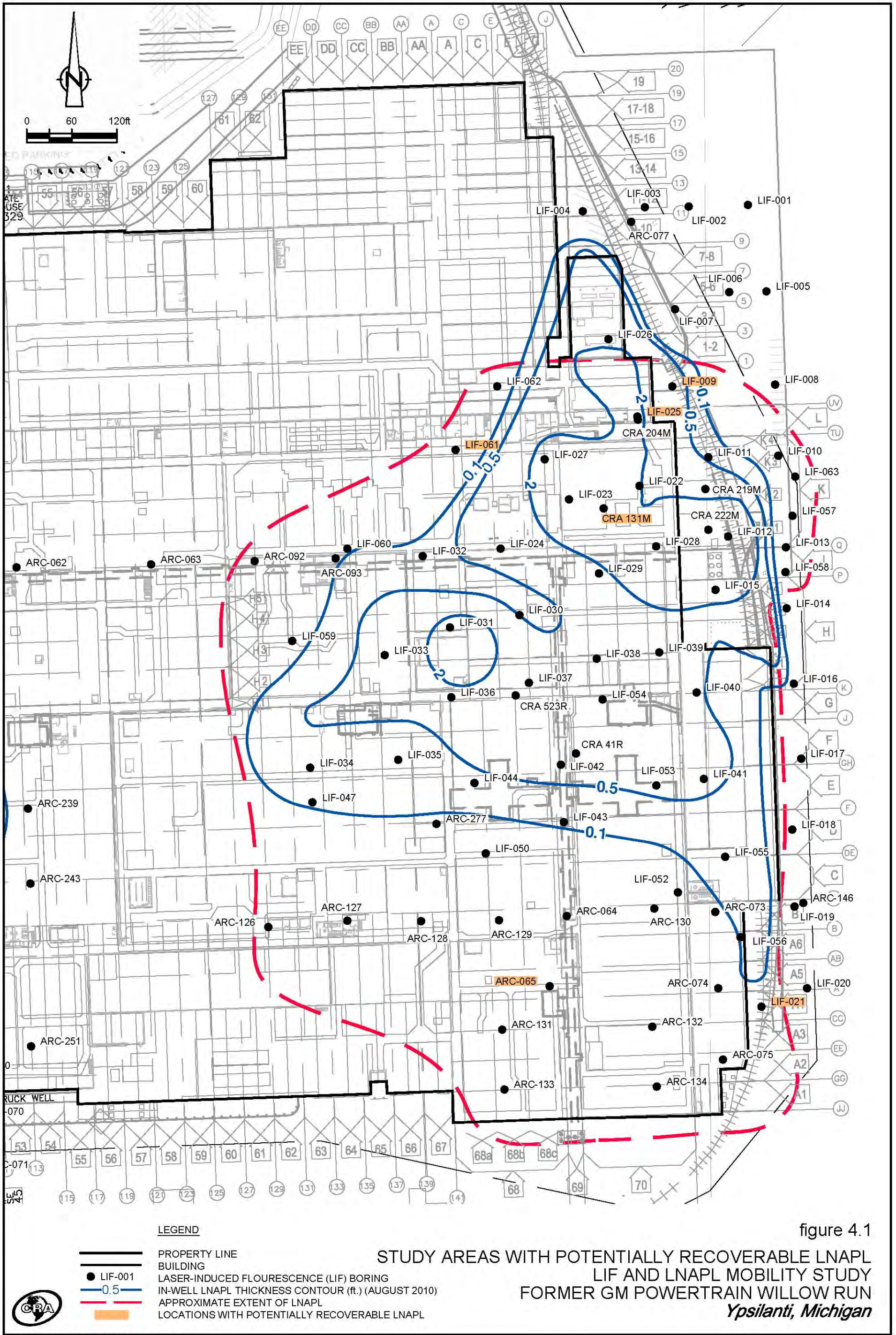


figure 4.1

STUDY AREAS WITH POTENTIALLY RECOVERABLE LNAPL
LIF AND LNAPL MOBILITY STUDY
FORMER GM POWERTRAIN WILLOW RUN
Ypsilanti, Michigan

TABLE 3.1

**SUMMARY OF LASER-INDUCED FLUORESCENCE SURVEY RESULTS AND SOIL CORE SAMPLING PROGRAM
FORMER GM POWERTRAIN WILLOW RUN
YPSILANTI, MICHIGAN**

<i>Location ID</i>	<i>LIF Total Depth (feet bgs)</i>	<i>Max LIF Result (%RE)</i>	<i>Depth of Max LIF Result (feet bgs)</i>	<i>Maximum Depth of Impacts (feet bgs)</i>	<i>Approximate LNAPL Type(s) (inferred from LIF results)</i>	<i>Soil Core Sample Interval (feet bgs, where applicable)</i>
LIF-001	16.02	--	--	--	--	--
LIF-002	16.04	--	--	--	--	--
LIF-003	16.07	--	--	--	--	--
LIF-004	16.00	--	--	--	--	--
LIF-005	16.03	--	--	--	--	--
LIF-006	16.02	--	--	--	--	--
LIF-007	16.00	--	--	--	--	--
LIF-008	16.00	--	--	--	--	--
LIF-009	16.03	63.43	7.29	9.51	kerosene-range	5-10
LIF-010	15.98	--	--	--	--	--
LIF-011	16.03	240.44	5.64	9.44	diesel-range	--
LIF-012	11.49	66.08	8.25	11.49	kerosene/diesel-ranges	--
LIF-013	20.07	--	--	--	--	--
LIF-014	16.03	--	--	--	--	--
LIF-015	16.00	84.82	6.66	11.38	diesel-range	--
LIF-016	16.03	--	--	--	--	--
LIF-017	16.09	--	--	--	--	--
LIF-018	16.03	--	--	--	--	--
LIF-019	16.09	--	--	--	--	--
LIF-020	16.07	--	--	--	--	--
LIF-021	22.03	81.49	3.40	8.41	diesel-range	2-12
LIF-022	20.20	290.33	7.56	10.80	diesel-range	--
LIF-023	19.44	236.41	8.90	11.84	diesel-range	--
LIF-024	20.03	234.49	6.48	9.48	diesel-range	--
LIF-025	10.59	303.65	7.80	10.44	diesel-range	5-10
LIF-026	4.45	--	--	--	--	--
LIF-027	5.08	--	--	--	--	--
LIF-028	20.01	48.15	6.16	6.62	diesel/heavier oil-ranges	--
LIF-029	20.01	210.10	6.50	11.30	diesel/heavier oil-ranges	1-8
LIF-030	16.01	169.53	8.51	10.19	diesel-range	--
LIF-031	17.11	166.06	3.06	9.78	diesel-range	--
LIF-032	0.96	--	--	--	--	--
LIF-033	16.17	78.73	6.40	9.04	kerosene-range	--
LIF-034	16.00	54.08	7.75	8.23	diesel-range	5-10
LIF-035	16.04	247.19	7.62	9.49	heavier oil-range	--
LIF-036	16.00	86.25	1.97	10.31	diesel-range	--
LIF-037	16.00	248.69	6.68	8.61	diesel/heavier oil-ranges	5-10
LIF-038	1.94	--	--	--	--	--
LIF-039	16.01	39.23	7.15	7.97	kerosene/diesel-ranges	--
LIF-040	15.93	199.10	5.64	7.85	diesel-range	5-10
LIF-041	16.00	258.22	6.24	7.63	diesel-range	--
LIF-042	5.21	--	--	--	--	--
LIF-043	16.02	--	--	--	--	--
LIF-044	16.00	--	--	--	--	--
LIF-047	16.00	--	--	--	--	--
LIF-050	15.98	--	--	--	--	--
LIF-052	16.02	--	--	--	--	--
LIF-053	11.14	--	--	--	--	--
LIF-054	1.48	--	--	--	--	--
LIF-055	20.00	370.02	6.99	14.16	diesel/heavier oil-ranges	4-14
LIF-056	16.00	199.62	6.78	8.96	diesel-range	--
LIF-057	16.00	--	--	--	--	--
LIF-058	20.15	111.365	4.07	4.61	diesel-range	2-7
LIF-059	16.06	28.03	6.49	6.67	kerosene/diesel-ranges	--
LIF-060	16.05	183.82	6.46	9.88	kerosene/diesel-ranges	5-10
LIF-061	16.01	108.77	7.26	8.64	kerosene-range	5-10
LIF-062	16.05	--	--	--	--	--
LIF-063	16.00	--	--	--	--	--
ARC-001	14.42	--	--	--	--	--
ARC-002	15.03	--	--	--	--	--

TABLE 3.1

**SUMMARY OF LASER-INDUCED FLUORESCENCE SURVEY RESULTS AND SOIL CORE SAMPLING PROGRAM
FORMER GM POWERTRAIN WILLOW RUN
YPSILANTI, MICHIGAN**

<i>Location ID</i>	<i>LIF Total Depth (feet bgs)</i>	<i>Max LIF Result (%RE)</i>	<i>Depth of Max LIF Result (feet bgs)</i>	<i>Maximum Depth of Impacts (feet bgs)</i>	<i>Approximate LNAPL Type(s) (inferred from LIF results)</i>	<i>Soil Core Sample Interval (feet bgs, where applicable)</i>
ARC-003	14.05	--	--	--	--	--
ARC-004	30.05	--	--	--	--	--
ARC-006	15.00	--	--	--	--	--
ARC-007	25.99	--	--	--	--	--
ARC-009	14.99	--	--	--	--	--
ARC-010	15.00	230.60	4.92	9.00	heavier oil-range	--
ARC-011	13.52	397.80	4.05	9.00	heavier oil-range	--
ARC-012	15.03	91.30	8.91	10.00	diesel-range	--
ARC-014	15.02	--	--	--	--	--
ARC-015	16.03	479.80	4.88	9.50	diesel/heavier oil-ranges	--
ARC-016	14.99	--	--	--	--	--
ARC-017	15.09	--	--	--	--	--
ARC-018	16.08	--	--	--	--	--
ARC-019	18.04	319.40	8.57	14.00	diesel-range	--
ARC-020	15.02	--	--	--	--	--
ARC-021	15.04	--	--	--	--	--
ARC-022	15.06	--	--	--	--	--
ARC-023	14.99	--	--	--	--	--
ARC-024	18.03	69.70	8.67	17.50	kerosene/diesel-ranges	--
ARC-025	15.04	141.20	7.87	15.00	kerosene/diesel-ranges	--
ARC-026	15.00	--	--	--	--	--
ARC-027	18.23	43.60	9.20	18.00	heavier oil-range	--
ARC-028	15.01	--	--	--	--	--
ARC-029	20.00	31.50	12.97	20.00	kerosene-range	--
ARC-030	15.06	--	--	--	--	--
ARC-031	15.00	--	--	--	--	--
ARC-032	18.11	--	--	--	--	--
ARC-033	22.03	367.80	10.12	14.50	diesel/heavier oil-ranges	--
ARC-034	20.00	135.30	9.42	15.00	diesel/heavier oil-ranges	--
ARC-035	16.01	--	--	--	--	--
ARC-036	18.02	--	--	--	--	--
ARC-037	7.42	--	--	--	--	--
ARC-039	16.02	--	--	--	--	--
ARC-040	18.07	--	--	--	--	--
ARC-041	18.01	--	--	--	--	--
ARC-042	3.80	--	--	--	--	--
ARC-043	15.01	--	--	--	--	--
ARC-044	15.02	--	--	--	--	--
ARC-045	16.00	--	--	--	--	--
ARC-046	15.02	--	--	--	--	--
ARC-047	15.09	--	--	--	--	--
ARC-048	10.12	--	--	--	--	--
ARC-048A	15.01	--	--	--	--	--
ARC-049	15.09	--	--	--	--	--
ARC-050	4.11	--	--	--	--	--
ARC-051	15.07	--	--	--	--	--
ARC-053	13.71	--	--	--	--	--
ARC-054	15.05	--	--	--	--	--
ARC-056	18.08	123.30	4.56	14.00	heavier oil-range	--
ARC-058	5.14	--	--	--	--	--
ARC-059	15.34	--	--	--	--	--
ARC-060	14.99	--	--	--	--	--
ARC-062	15.05	100.50	7.77	10.50	diesel/heavier oil-ranges	--
ARC-063	15.04	--	--	--	--	--
ARC-064	15.00	--	--	--	--	--
ARC-065	17.03	224.60	7.57	9.50	heavier oil-range	5-10
ARC-067	15.10	--	--	--	--	--
ARC-069	15.08	--	--	--	--	--
ARC-070	15.01	--	--	--	--	--
ARC-071	15.01	--	--	--	--	--

TABLE 3.1

**SUMMARY OF LASER-INDUCED FLUORESCENCE SURVEY RESULTS AND SOIL CORE SAMPLING PROGRAM
FORMER GM POWERTRAIN WILLOW RUN
YPSILANTI, MICHIGAN**

<i>Location ID</i>	<i>LIF Total Depth (feet bgs)</i>	<i>Max LIF Result (%RE)</i>	<i>Depth of Max LIF Result (feet bgs)</i>	<i>Maximum Depth of Impacts (feet bgs)</i>	<i>Approximate LNAPL Type(s) (inferred from LIF results)</i>	<i>Soil Core Sample Interval (feet bgs, where applicable)</i>
ARC-072	15.00	--	--	--	--	--
ARC-073	15.00	281.30	6.65	9.00	heavier oil-range	--
ARC-074	15.00	36.60	8.54	15.00	kerosene-range	--
ARC-075	15.00	--	--	--	--	--
ARC-077	15.03	--	--	--	--	--
ARC-092	15.05	--	--	--	--	--
ARC-093	15.17	77.10	6.41	15.00	diesel/heavier oil-ranges	--
ARC-126	16.01	101.00	7.90	10.00	heavier oil-range	--
ARC-127	15.04	42.30	6.05	10.00	heavier oil-range	--
ARC-128	17.00	585.50	7.62	17.00	diesel/heavier oil-ranges	5-10
ARC-129	15.01	50.20	4.98	15.00	heavier oil-range	--
ARC-130	15.05	--	--	--	--	--
ARC-131	15.07	195.40	8.03	10.00	diesel/heavier oil-ranges	--
ARC-132	15.01	--	--	--	--	--
ARC-133	16.03	--	--	--	--	--
ARC-134	15.00	--	--	--	--	--
ARC-146	16.11	--	--	--	--	--
ARC-147	15.03	--	--	--	--	--
ARC-148	15.08	--	--	--	--	--
ARC-149	15.02	--	--	--	--	--
ARC-156	15.00	39.00	7.33	15.00	kerosene-range	--
ARC-166	15.02	--	--	--	--	--
ARC-186	15.00	--	--	--	--	--
ARC-187	20.04	108.60	8.10	14.50	diesel/heavier oil-ranges	--
ARC-188	15.08	172.20	7.88	9.50	diesel/heavier oil-ranges	--
ARC-189	16.05	175.70	7.38	11.00	diesel/heavier oil-ranges	--
ARC-190	15.72	143.50	7.60	10.00	kerosene-range	--
ARC-191	15.06	--	--	--	--	--
ARC-192	15.04	--	--	--	--	--
ARC-193	16.00	420.10	8.92	11.00	diesel-range	--
ARC-209	16.15	163.90	7.17	11.00	kerosene/diesel-ranges	--
ARC-227	16.02	181.60	7.58	11.00	heavier oil-range	--
ARC-228	19.55	199.00	8.99	14.00	diesel/heavier oil-ranges	--
ARC-239	15.09	--	--	--	--	--
ARC-243	15.04	--	--	--	--	--
ARC-244	15.16	106.70	8.41	12.00	kerosene-range	--
ARC-247	15.01	28.00	8.39	15.00	kerosene-range	--
ARC-249	15.13	--	--	--	--	--
ARC-249MN	15.00	--	--	--	--	--
ARC-250	15.27	--	--	--	--	--
ARC-251	15.01	--	--	--	--	--
ARC-252	15.14	--	--	--	--	--
ARC-255	15.05	--	--	--	--	--
ARC-256	15.08	--	--	--	--	--
ARC-257	13.87	--	--	--	--	--
ARC-258	15.05	87.00	8.75	15.00	kerosene-range	--
ARC-259	15.09	29.30	15.09	15.00	heavier oil-range	--
ARC-260	15.00	--	--	--	--	--
ARC-261	15.17	--	--	--	--	--
ARC-263	15.03	--	--	--	--	--
ARC-264	15.04	--	--	--	--	--
ARC-265	15.06	52.70	10.27	15.00	diesel-range	--
ARC-266	15.00	--	--	--	--	--
ARC-267	18.00	242.50	10.87	12.50	heavier oil-range	--
ARC-268	15.00	--	--	--	--	--
ARC-269	17.00	141.00	8.93	15.00	diesel-range	--
ARC-270	15.05	--	--	--	--	--
ARC-271	19.05	256.00	8.60	14.50	diesel-range	--
ARC-272	21.99	447.40	11.39	17.00	diesel/heavier oil-ranges	--
ARC-277	14.99	--	--	--	--	--

TABLE 3.1

SUMMARY OF LASER-INDUCED FLUORESCENCE SURVEY RESULTS AND SOIL CORE SAMPLING PROGRAM
FORMER GM POWERTRAIN WILLOW RUN
YPSILANTI, MICHIGAN

Location ID	LIF Total Depth (feet bgs)	Max LIF Result (%RE)	Depth of Max LIF Result (feet bgs)	Maximum Depth of Impacts (feet bgs)	Approximate LNAPL Type(s) (inferred from LIF results)	Soil Core Sample Interval (feet bgs, where applicable)
ARC-278	15.53	348.80	7.12	10.00	diesel/heavier oil-ranges	--
ARC-280	16.03	141.50	5.95	11.50	diesel-range	--
ARC-282	15.37	--	--	--	--	--

Locations that are clean throughout the entire vertical profile (all results less than 10%RE)

Locations with shallow (0-5' bgs) results at or greater than 10%RE but clean at water table depth

TABLE 3.2

SUMMARY OF LABORATORY SOIL CORE TESTING PROGRAM AND LNAPL SATURATION RESULTS
FORMER GM POWERTRAIN WILLOW RUN
YPSILANTI, MICHIGAN

Soil Core ID	Soil Core Sample Interval (feet bgs)	Soil Core Sub-Sample Selected for Respective Tests (feet bgs)					LNAPL Saturation Results		Potentially Mobile/Recoverable Fraction (% of in place LNAPL)
		Grain Size Analysis	Pore Fluids Saturation Test	Residual Saturation by Water Drive	Air/Water Capillary Pressure Test	van Genuchten Parameters	Initial Saturation (% of pore space)	Residual Saturation (% of pore space)	
LIF-9	5-10		6.65				6.5		0.0 ^a
				5.6			48.6	37.6	22.6
LIF-21	2-12	8.5	8.3				25.7		0.0 ^a
				9.15			31.0	>31.0	0.0
LIF-25	5-10	6.2	5.9				56.1		55.4 ^b
				6.4			16.1	>16.1	0.0
LIF-29	0-10	6.1		6.3	6.1	6.1	25.0	>25.0	0.0
LIF-34	5-10	8.5		8.15			10.8	>10.8	0.0
LIF-37	5-10	6.9	7.9		6.9	6.9	10.1		0.0 ^a
				6.7			13.6	>13.6	0.0
LIF-40	5-10	7.9	6.7				17.3		0.0 ^a
				6.5			33.7	>33.7	0.0
LIF-55	4-14	7.4	10.7				7.8		0.0 ^a
				7.2			15.3	>15.3	0.0
LIF-58	2-7		2.9				6.7		0.0 ^a
				3.1			12.8	>12.8	0.0
LIF-60	5-10			8.0			11.7	>11.7	0.0
LIF-61	5-10		8.3				58.6		57.3 ^b
				8.1			42.0	12.6	70.0
Arcadis-65	5-10	8.4	8.6				10.6		0.0 ^a
				8.0			48.0	46.9	2.3
Arcadis-128	5-10	8.4	8.8		8.4	8.4	11.6		0.0 ^a
				8.2			24.2	>24.2	0.0

^aResidual saturation testing was not performed on these sub-samples. It is estimated that the LNAPL saturation level in these sub-samples is immobile and unrecoverable based on the residual LNAPL saturation values determined for the other sub-samples at these locations.

^bResidual saturation testing was not performed on these sub-samples. The reported mobility/recoverability range is estimated with reference to an assumed residual LNAPL saturation of 25%.

TABLE 3.3

LNAPL MOBILITY AND VELOCITY CALCULATIONS
FORMER GM POWERTRAIN WILLOW RUN
YPSILANTI, MICHIGAN

		LIF-9 (6.65' bgs)	LIF-9 (5.6' bgs)	LIF-21 (8.3' bgs)	LIF-21 (9.15' bgs)	LIF-25 (5.9' bgs)	LIF-25 (6.4' bgs)	LIF-29 (6.3' bgs)	LIF-34 (8.15' bgs)	LIF-37 (7.9' bgs)	LIF-37 (6.7' bgs)	LIF-40 (6.7' bgs)	LIF-40 (6.5' bgs)
Model Inputs	LNAPL Saturation (S_o)	0.065	0.486	0.257	0.310	0.561	0.161	0.250	0.108	0.101	0.136	0.173	0.337
	Water Saturation (S_w)	0.749	0.483	0.330	0.493	0.215	0.116	0.387	0.731	0.645	0.489	0.473	0.322
	Total Fluid Saturation (S_t)	0.814	0.969	0.587	0.803	0.776	0.277	0.637	0.839	0.746	0.625	0.646	0.659
	Irreducible Water Saturation (S_{wr})	0.225	0.225	0.225	0.225	0.151	0.085	0.225	0.225	0.225	0.225	0.225	0.225
	van Genuchten N (N) (1)	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185
	LNAPL Density (ρ_o) - (g/cm ³) ⁽¹⁾	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
	LNAPL Viscosity (μ_o) - (cp) ⁽¹⁾	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6
	Total Soil Porosity (Φ)	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	Hydraulic Gradient	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Hydraulic Conductivity Water (K_w) - (cm/s)	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03
Model Outputs	Model Parameter 1 (λ)	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855
	Model Parameter 2 (M)	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542
	LNAPL Relative Permeability (k_{ro}) ^{(2),(4)}	5.46E-04	2.00E-01	5.11E-03	3.33E-02	1.13E-01	1.41E-04	7.24E-03	2.55E-03	1.39E-03	1.52E-03	3.23E-03	1.63E-02
	LNAPL Conductivity (K_o) - (cm/s) ⁽⁴⁾	3.28E-07	1.20E-04	3.07E-06	2.00E-05	6.78E-05	8.43E-08	4.34E-06	1.53E-06	8.33E-07	9.14E-07	1.94E-06	9.76E-06
	LNAPL Mobility (M_o) - (cm/s) ⁽⁴⁾	1.68E-05	8.23E-04	3.98E-05	2.15E-04	4.03E-04	1.75E-06	5.79E-05	4.72E-05	2.75E-05	2.24E-05	3.74E-05	9.65E-05
	LNAPL Velocity (V_o) - (cm/s)⁽⁴⁾	8.40E-08	4.11E-06	1.99E-07	1.07E-06	2.01E-06	8.73E-09	2.89E-07	2.36E-07	1.37E-07	1.12E-07	1.87E-07	4.83E-07
	Potentially Mobile ($V_o > 10^{-6}$ cm/s)?	No	Yes	No	Yes	Yes	No	No	No	No	No	No	No

Notes:

(1) - Values taken from American Petroleum Institute (API) Interactive LNAPL Guide (Version 2.0, Release 2.0.2, August 2004) - Assessment Tools - Parameter Tables. Values selected based for diesel fuel.

(2) - LNAPL relative permeability calculation based on Burdine Equation 2.26 and Equation 2.27 in American Petroleum Institute (API) Publication Number 4729, *Models for Design of Free-Product Recovery Systems for Petroleum Hydrocarbon Liquids*, August 2003.

(3) - Blue highlighted data input values were based on Site-specific laboratory test results and/or field measurements.

(4) - Calculations based on laboratory generated LNAPL saturation values.

(5) - Irreducible Water Saturation (S_{wr}) was set equal to Water Saturation (S_w) in order to calculate potential mobility

TABLE 3.3

LNAPL MOBILITY AND VELOCITY CALCULATIONS
FORMER GM POWERTRAIN WILLOW RUN
YPSILANTI, MICHIGAN

		LIF-55 (10.7' bgs)	LIF-55 (7.2' bgs)	LIF-58 (2.9' bgs)	LIF-58 (3.1' bgs)	LIF-60 (8.0' bgs)	LIF-61 (8.3' bgs)	LIF-61 (8.1' bgs)	ARC-65 (8.6' bgs)	ARC-65 (8.0' bgs)	ARC-128 (8.8' bgs)	ARC-128 (8.2' bgs)
Model Inputs	LNAPL Saturation (S_o)	0.078	0.153	0.067	0.128	0.117	0.586	0.420	0.106	0.480	0.116	0.242
	Water Saturation (S_w)	0.638	0.781	0.579	0.655	0.800	0.106	0.563	0.618	0.323	0.614	0.529
	Total Fluid Saturation (S_t)	0.716	0.934	0.646	0.783	0.917	0.692	0.983	0.724	0.803	0.730	0.771
	Irreducible Water Saturation (S_{wr})	0.225	0.225	0.225	0.225	0.225	0.085	0.225	0.225	0.225	0.225	0.225
	van Genuchten N (N) (1)	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185	2.185
	LNAPL Density (ρ_o) - (g/cm ³) ⁽¹⁾	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88	0.88
	LNAPL Viscosity (μ_o) - (cp) ⁽¹⁾	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6	10.6
	Total Soil Porosity (Φ)	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30
	Hydraulic Gradient	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Hydraulic Conductivity Water (K_w) - (cm/s)	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03	7.23E-03
Model Outputs	Model Parameter 1 (λ)	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855	0.855
	Model Parameter 2 (M)	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542	0.542
	LNAPL Relative Permeability (k_{ro}) ^{(2),(4)}	5.81E-04	9.67E-03	2.57E-04	3.18E-03	4.33E-03	8.72E-02	1.53E-01	1.42E-03	8.63E-02	1.87E-03	1.56E-02
	LNAPL Conductivity (K_o) - (cm/s) ⁽⁴⁾	3.49E-07	5.80E-06	1.54E-07	1.91E-06	2.59E-06	5.23E-05	9.16E-05	8.51E-07	5.17E-05	1.12E-06	9.36E-06
	LNAPL Mobility (M_o) - (cm/s) ⁽⁴⁾	1.49E-05	1.26E-04	7.67E-06	4.96E-05	7.39E-05	2.97E-04	7.27E-04	2.68E-05	3.59E-04	3.23E-05	1.29E-04
	LNAPL Velocity (V_o) - (cm/s)⁽⁴⁾	7.45E-08	6.31E-07	3.83E-08	2.48E-07	3.69E-07	1.49E-06	3.63E-06	1.34E-07	1.80E-06	1.61E-07	6.45E-07
	Potentially Mobile ($V_o > 10^{-6}$ cm/s)?	No	No	No	No	No	Yes	Yes	No	Yes	No	No

Notes:

(1) - Values taken from American Petroleum Institute (API) Interactive LNAPL Guide (Version 2.0, Release 2.0.2, August 2004) - Assessment Tools - Parameter Tables. Values selected based for diesel fuel.

(2) - LNAPL relative permeability calculation based on Burdine Equation 2.26 and Equation 2.27 in American Petroleum Institute (API) Publication Number 4729, *Models for Design of Free-Product Recovery Systems for Petroleum Hydrocarbon Liquids*, August 2003.

(3) - Blue highlighted data input values were based on Site-specific laboratory test results and/or field measurements.

(4) - Calculations based on laboratory generated LNAPL saturation values.

(5) - Irreducible Water Saturation (S_{wr}) was set equal to Water Saturation (S_w) in order to calculate potential mobility

Appendix A

Common LNAPL-Related Terms and Definitions

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Section 1.0 Definitions Relating to LNAPL Mobility

Capillary Pressure: the difference between the fluid pressure in the non-wetting phase (typically LNAPL) and the pressure in the wetting phase (typically water) at a given reference point. This pressure may also be referred to as the “excess pressure”. The larger the capillary pressure, the greater the LNAPL saturation and the greater the potential for LNAPL mobility. For LNAPL movement or migration to occur, capillary pressure must exceed the resistive forces in the soil formation.

Confined Condition: a subsurface condition where pore fluids are under pressure at all reference points or elevations. In a confined condition, in-well LNAPL thickness varies directly with potentiometric surface elevation. Hence, an increase in the potentiometric surface elevation leads to an increase in in-well LNAPL thickness, and vice versa. LNAPL within the secondary porosity (fractures, fissures, seams) of fine textured soils (silts and clays) is often present in a confined condition. Confined conditions will often produce in-well LNAPL thicknesses that grossly over-represent the extent of impacts in the formation.

Effective Solubility: different than pure-phase solubility, effective solubility describes the ability of a chemical constituent from a mixture to dissolve in water in the presence of other constituents in the mixture. It is a particularly important consideration for LNAPLs that are complex petroleum mixtures. Effective solubility is a function of the mole fraction of the constituent in the mixture, and is commonly orders of magnitude less than the constituent’s corresponding pure-phase solubility. Groundwater concentrations in excess of a petroleum constituent’s effective solubility will typically indicate the presence of LNAPL in the vicinity of a monitoring well.

Interfacial Tensions: the tension or attractive forces between two fluids along the interface of contact with one another. The interfacial tension between LNAPL and water in the subsurface tends to limit the ability of LNAPL to move.

Laser-Induced Fluorescence (LIF): a real-time LNAPL delineation technology that uses ultraviolet wavelengths of light to cause polycyclic aromatic hydrocarbons (PAHs) to fluoresce. All petroleum-based LNAPLs contain PAHs, allowing the use of LIF to detect the presence of LNAPL. LIF is employed in the field using direct-push techniques to delineate LNAPL impacts in the subsurface laterally and vertically (both above and below the water table). LIF also provides an indication of the intensity of impacts across an LNAPL body and the types of LNAPL encountered.

LNAPL: light non-aqueous phase liquid. LNAPLs are immiscible fluids that are less dense than water, and may be comprised of a pure chemical or solvent, or comprised of a complex mixture of chemicals, such as petroleum-based fuels. The term “LNAPL” most often refers to immiscible petroleum mixtures/fuels (i.e., gasoline, kerosene, diesel, crude oil, etc.).

LNAPL Body: the multi-phase fluid zone of LNAPL impacts in the subsurface. An LNAPL body is comprised of three fluids: air, LNAPL and water. Generally speaking, an LNAPL body is predominantly comprised of water, with a lesser amount of LNAPL, and the least amount of air.

LNAPL Conductivity: a hydrogeological term that helps describe the ability of LNAPL to move through the subsurface. LNAPL conductivity accounts for the LNAPL relative permeability, hydraulic conductivity, and the densities and viscosities of the fluids (water and LNAPL). LNAPL conductivity is a function of and varies directly with LNAPL relative permeability. Hence, an increase in LNAPL relative permeability results in an increase in LNAPL conductivity, and vice versa.

LNAPL Migration: a description of the expansion of the perimeter of an unstable LNAPL body in some or all directions (i.e., footprint of the overall LNAPL body or body periphery is continuing to grow). All migrating LNAPL is mobile; not all mobile LNAPL is migrating. Mobile LNAPL can be present within the interior of an LNAPL body that is not migrating.

LNAPL Mobility: a description of the potential for LNAPL to move at any point within an LNAPL body. LNAPL may be mobile where the LNAPL is continuous at saturations above residual saturation. Because LNAPL residual saturation within a LNAPL body varies from the vadose zone to the saturated zone, LNAPL mobility may also vary due to fluctuations in the water table elevation. The presence of mobile LNAPL within an LNAPL body does not necessarily mean that the LNAPL body as a whole is unstable or migrating.

LNAPL Pressure Head: the LNAPL pressure conditions at any point within an LNAPL body created by the release conditions. The pressure head can result from the vertical column of LNAPL due to accumulation at or in the vicinity of the water table from a surface or near-surface source (e.g., tank), or from other pressure conditions at the time of the release (e.g., pressure conditions of a subsurface pipeline release). The greater the pressure head, the more the LNAPL will penetrate into the water table (both vertically and laterally) and spread. Once the pressure head dissipates (i.e., source of release is terminated), the LNAPL will soon after cease to migrate and achieve a stable perimeter.

LNAPL Relative Permeability: a measure of the porous medium's (soil's) ability to enable movement of LNAPL in the subsurface in the presence of water. LNAPL relative permeability is a function of and varies directly with LNAPL saturation. Hence, an increase in LNAPL saturation results in an increase in LNAPL relative permeability, and vice versa.

LNAPL Residual Saturation: the LNAPL saturation level or threshold below which LNAPL will not flow under normal hydraulic conditions. LNAPL present at saturations that are less than or equal to residual saturation levels (i.e., within the residual range) will generally be considered to be immobile and unrecoverable. Conceptually speaking, LNAPL residual saturation represents the LNAPL saturation

threshold where the LNAPL, due to its relatively low saturation, starts to break-up or become discontinuous in the form of droplets, stringers, ganglia, etc. As LNAPL saturation approaches or decreases to residual, the relative permeability of the LNAPL approaches zero, and the conductivity of the LNAPL approaches zero. The more LNAPL that initially saturates the soil pore space during a release, the higher the residual saturation will be (up to a theoretical maximum). Consequently, LNAPL residual saturation also varies continuously within an LNAPL body.

LNAPL Saturation: the percent of the soil pore space that is occupied by LNAPL. LNAPL saturation at a given point in the subsurface will be proportional to the capillary pressure at that point (i.e., the greater the capillary pressure, the greater the resulting LNAPL saturation). Because the capillary pressure varies throughout the impacted zone, the LNAPL saturation also varies accordingly. The larger the soil pore space, the greater the ability for the soil to hold LNAPL, the greater the LNAPL saturation, and vice versa.

LNAPL Stability: a description of the potential for the perimeter or footprint of an LNAPL body to move or expand over time. A LNAPL body that is moving or expanding (i.e., footprint of LNAPL body is growing) is deemed to be unstable or migrating. Conversely, a LNAPL body that is not moving or expanding with time is deemed to be stable, immobile, or non-migrating. Stable LNAPL bodies can contain localized areas of mobile LNAPL, with the overall footprint remaining unchanged over time.

LNAPL Velocity: the speed and direction at which the LNAPL can travel, based on Darcy flow principles. LNAPL velocity is based on the properties of the porous medium and fluids (water and LNAPL), pore fluid saturations, and the LNAPL gradient. LNAPL velocity only applies within the LNAPL body where there is continuous LNAPL at saturations above residual. There is no LNAPL velocity or movement within an LNAPL body where the LNAPL is not continuous and saturations are below residual. In addition, there is no LNAPL velocity or movement outside of a stable LNAPL body.

Non-Wetting Fluid: the fluid that does not preferentially coat the soil grains or particles in a multi-phase fluid system, but rather occupies the middle of the larger soil pores. In an air-water-LNAPL system (typical of an LNAPL body), both air (primarily in the unsaturated portion of the smear zone) and LNAPL (primarily in the saturated portion of the smear zone) tend to be the non-wetting fluids.

Pore Entry Displacement Pressure: the threshold pressure necessary for one fluid to enter into a porous medium occupied by another fluid, thereby displacing the fluid originally present. Pore entry displacement pressures may account for air displacing groundwater, LNAPL displacing groundwater, air displacing LNAPL, etc. In a water-saturated soil, the capillary pressure must equal or exceed the pore entry displacement pressure for the LNAPL to move and displace water.

Soil Resistive Forces: the forces that act to prevent the movement of LNAPL in a water-saturated porous medium. These forces, which are based on pore entry displacement pressure principles, account for the

contact angle or wettability of the fluids (LNAPL and water), the interfacial tension between the fluids, and the soil pore size. LNAPL movement will only occur if the capillary pressure is sufficient to overcome the soil resistive forces.

Unconfined Condition: a subsurface condition with identical or similar pressure-related fluid characteristics to an unconfined aquifer or water table condition. LNAPL within the primary porosity of granular soils (sands and gravels) in a water table/phreatic surface setting is deemed to be in an unconfined condition. In an unconfined condition, in-well LNAPL thickness varies inversely with water table elevation. Hence, an increase in the water table elevation leads to a decrease in in-well LNAPL thickness, and vice versa.

van Genuchten Parameters: curve fitting parameters that describe how water drains from a given soil in response to increasing pressure conditions. These parameters serve as critical inputs for LNAPL modeling simulations.

Wetting Fluid: the fluid that preferentially coats the soil grains or particles in a multi-phase fluid system. In an air-water-LNAPL system (typical of an LNAPL body), water typically acts as the wetting fluid while air and LNAPL act as non-wetting fluids. The wetting fluid is typically the predominant fluid present in a multi-phase fluid system.

Appendix B

General LNAPL Discussion

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Section 1.0 LNAPL Mobility and Migration

This section presents some of the basic LNAPL concepts and trends that describe the occurrence, behavior and migration of LNAPL in the subsurface. Specifically, this section addresses LNAPL behavior at the water table and includes the vertical impacted soil zone typically referred to as the smear zone. The smear zone is where potentially mobile LNAPL may reside at sites where the source(s) of the LNAPL impacts have ceased for some time (i.e., no ongoing releases). The behavior of LNAPL in the vadose or unsaturated zone (above the smear zone) is not addressed here, since LNAPL in these zones (particularly at older release sites) is often present at low saturations, and does not typically pose a potential for additional LNAPL migration at the water table.

A discussion of the analytical equations and models used to describe LNAPL occurrence, behavior and migration at the water table is presented in Appendix C.

1.1 LNAPL Release Dynamics and the Creation of a Multi-Phase Fluid System

When an LNAPL release occurs, either directly in the subsurface (for example, from a tank or pipeline) or on a permeable surface, the LNAPL, if present in sufficient quantity, will percolate vertically downward (under the influence of gravity) through the soil and eventually encounter the water table. During the downward movement, the presence of confining layers and/or other subsurface heterogeneities may result in some lateral spreading and/or perching of LNAPL before the water table is encountered. Once at the water table, the LNAPL will penetrate vertically downward and laterally (including in the upgradient direction) into the water table, displacing an amount of water proportional to the driving force of the vertical LNAPL column (or LNAPL head) created by the release. The displacement of groundwater will continue to occur only as long as sufficient downward force produced by the head or pressure from the LNAPL release remains. Once the downward force diminishes, the upward force produced by the resistance of the soil matrix and the buoyancy force resulting from the density difference between LNAPL and groundwater will prevent further downward migration. Once the release of LNAPL is terminated, the LNAPL footprint at the water table will continue to expand for a relatively short time, and eventually stop as the LNAPL head (pressure) dissipates. The LNAPL eventually ceases to expand because the driving force (pressure or head) responsible for the LNAPL migration is no longer sufficient to overcome the resistive forces necessary to displace groundwater from the soil pores (see explanation below). When the LNAPL body reaches this state, the LNAPL body is referred to as stable or non-migrating.

The concept of LNAPL penetrating vertically into the saturated zone (i.e., below the water table) during a release contradicts earlier beliefs that LNAPL only “floats” (due to it being less dense than water) like a pancake on top of the water table, filling 100% of the soil pore space within the LNAPL impacted zone (with no part penetrating the saturated zone). Recent LNAPL science and “real-world” field-based

experience shows that some LNAPL (and often times the majority of LNAPL at a given site) is commonly submerged beneath the theoretical water table surface. Further, LNAPL does not displace all groundwater from the soil pore space, but rather that portion of the groundwater that occupies the “largest” soil pore space only. Consequently, a typical LNAPL body consists of LNAPL filling much less of the soil pore space in a more highly variable distribution than what was assumed historically based on the “pancake” conceptualization. The LNAPL body at the water table is not comprised of a single fluid phase (LNAPL) but rather comprised of multiple fluids, both LNAPL and water. The top portion of the LNAPL body often includes a third fluid phase: air. Therefore, the term “LNAPL body” represents the spatial limits of LNAPL impacts, within which exists a multi-phase fluid system comprised of LNAPL, water and/or air, in proportions that will vary throughout. Generally speaking, LNAPL bodies are predominantly comprised of water, followed by a lesser amount of LNAPL, with the smallest fraction of the pore space occupied by air.

LNAPL at the water table requires pressure to move. Unlike groundwater, which typically forms a continuous system with flow velocity based on gradients, LNAPL, being a non-wetting fluid, requires pressure to force it through the soil pores to the extent required to displace the existing pore water. More specifically, the LNAPL needs sufficient capillary pressure to overcome the resistive forces in the soil to enable the continued displacement of groundwater. In a multi-phase (LNAPL/water) fluid system, capillary pressure (also referred to as excess pressure) is the difference between the pressure in the non-wetting (LNAPL) phase and the pressure in the wetting (groundwater) phase. The capillary pressure necessary to overcome the resistive forces for a non-wetting LNAPL to enter water-saturated media is called the pore entry displacement pressure (Mercer and Cohen, 1990). Once the pore entry displacement pressure is achieved, the LNAPL will continue to expand in a vertical and radial direction until there is insufficient LNAPL head or pressure to continue to displace water. The LNAPL head will typically become insufficient to displace water (and enter unimpacted pore space) shortly after the LNAPL release is terminated. Hence, soon after the LNAPL release is terminated, the LNAPL body becomes stable (i.e., overall footprint is no longer moving or expanding). Because the main mechanism for LNAPL spreading is the pressure/head resulting from the release (during the release and until the LNAPL body stabilizes), the groundwater gradient will only influence the direction of the LNAPL spreading for a defined but limited distance. Groundwater flow will not typically cause or induce any LNAPL spreading or migration once stabilization of the LNAPL body has been achieved.

The porous media flow concepts that apply to groundwater systems (Darcy flow equations, etc.) also apply to LNAPL bodies, with two distinct differences. First, LNAPL conductivity (as opposed to water or hydraulic conductivity) includes a relative permeability term, which accounts for LNAPL flowing in the presence of water, and includes density and viscosity terms for both fluids. Second, Darcy flow in an LNAPL body does not apply where the LNAPL is discontinuous/immobile. For example, Darcy flow would not apply within an LNAPL body in areas where saturations are below residual. In addition, there is no LNAPL velocity or movement outside of a stable LNAPL body.

1.2 LNAPL Saturation and Residual Saturation

LNAPL saturation is defined as the percent of the soil pore space that is occupied by LNAPL. LNAPL residual saturation is defined as the LNAPL saturation level or threshold below which LNAPL will not flow under normal hydraulic conditions found in the environment. Consequently, LNAPL that is present at saturations that are less than or equal to residual saturation is deemed to be immobile and unrecoverable. These concepts are discussed in more detail in the following subsections.

1.2.1 LNAPL Saturation

As previously discussed, LNAPL does not float on the water table like a pancake, but rather coexists with air and groundwater at varying saturations within the impacted soil zone, both above and below the water table. This is due to the fact that the saturation level of a given LNAPL at a given point in the subsurface will be proportional to the capillary pressure at that point (i.e., the greater the capillary pressure, the greater the resulting LNAPL saturation). Because the capillary pressure will vary throughout the impacted zone, the LNAPL saturation will also vary accordingly. The LNAPL saturation distribution for a given soil is predominantly determined by the grain size of the soil (USEPA, 2005a). The larger the soil pores for a given soil, the greater the capacity for the soil to hold LNAPL. Consequently, granular soils such as sands and gravels will typically have much greater LNAPL saturations than fine textured soils like silts and clays.

An idealized saturation profile used to illustrate the typical variation in LNAPL saturation above and below the theoretical water table (in a homogenous granular soil with pore fluids at vertical equilibrium) is shown in Figure 7 of Appendix C. This depiction of an LNAPL saturation profile also provides a general illustration of the multi-phase (or capillary pressure prediction) conceptualization of LNAPL behavior.

LNAPL saturations can be determined by several methods:

1. Total petroleum hydrocarbon (TPH) soil concentrations gathered in the field and analyzed in the laboratory can be converted to LNAPL saturations by the following calculation (ASTM International, 2007):

$$S_o = \frac{[TPH]}{10^6} \cdot \frac{\rho_{fb}}{\rho_o} \cdot \Theta^{-1}$$

Where: S_o = LNAPL saturation (fraction of pore space filled with LNAPL)
 $[TPH]$ = total petroleum hydrocarbon soil concentration (mg/kg)
 ρ_{fb} = soil bulk density

ρ_o = LNAPL/oil density

Θ^{-1} = total soil porosity

For example, if a soil TPH concentration of 100 mg/kg were reported by the laboratory, and assuming that the soil had a porosity of 35% and bulk density of 1.6 g/cm³, and that the suspect LNAPL had a density of 0.8 g/cm³, the equation above would convert the 100 mg/kg TPH concentration into an LNAPL saturation value of 0.0006 or 0.06 percent.

2. LNAPL-saturated soil core samples can be collected and tested at certain specialized laboratories to directly determine LNAPL saturations (e.g., Dean-Stark extraction method); and/or
3. Various tools are available from the American Petroleum Institute (API) that can be used to estimate LNAPL saturations based on in-well LNAPL thickness observations (and soil and LNAPL physical properties). These are the Charbeneau spreadsheets, the LNAPL Dissolution and Transport Screening Tool (LNAST), and, most recently, the LNAPL Distribution and Recovery Model (LDRM).

Method 3 is widely used, but generally less reliable than Methods 1 and 2 as it is primarily dependant upon in-well LNAPL thickness observations and is often used with other inputs that are not site-specific (i.e., literature values for certain soil and LNAPL properties). The lower degree of reliability is due to the fact that conditions at most environmental sites (i.e., water table fluctuations, subsurface heterogeneties, etc.) make any accurate correlation between in-well LNAPL thicknesses and the actual impacted interval in the adjacent soil formation imprecise.

LNAPL saturations are dynamic, and will tend to change over time as LNAPL initially displaces water (during vertical and lateral migration following a release), and is subsequently displaced as water refills some fraction of the pore space when the water table elevation increases (API, 2004). The average LNAPL saturation at a given location can be expected to continually decrease until such time as the LNAPL becomes sufficiently discontinuous, such that all saturations are at or below residual saturation levels.

1.2.2 LNAPL Residual Saturation

Conceptually speaking, LNAPL residual saturation represents the LNAPL saturation threshold where the LNAPL, due to its relatively low saturation, starts to break-up or become discontinuous in the form of droplets, stringers, ganglia, etc. Technically speaking, LNAPL residual saturation represents the portion of an LNAPL body that is hydraulically discontinuous and immobile under prevailing conditions (ASTM International, 2007). As LNAPL saturation approaches or decreases to residual, the relative permeability of the LNAPL approaches zero, and the conductivity of the LNAPL approaches zero. Hence, LNAPL, when present at saturations at or below residual, is considered to be immobile.

Relatively recent research suggests that LNAPL residual saturation is a function of initial LNAPL saturation (Johnston, C.D. and Adamski, M., 2005). The greater the initial saturation at any point in an LNAPL body, the greater the residual saturation at that point. This concept contradicts earlier notions that there is only one single LNAPL residual saturation value for a given LNAPL and soil type. This concept is important when determining the type of laboratory analyses to be used for determining LNAPL residual saturation (see discussion below).

LNAPL residual saturation, which is used to assess LNAPL mobility, may be characterized as a “range” of saturations less than the highest residual saturation threshold value. At any given location within the LNAPL body, if the LNAPL saturation is equal to or less than the residual saturation threshold (i.e., the upper limit of residual saturation) for that location, then the saturation is deemed to be in the “residual range” which may include any saturations above zero up to and including the residual saturation threshold. Under such conditions, the LNAPL would be deemed to be immobile.

Residual LNAPL saturations can be determined by obtaining relatively undisturbed soil and/or rock core samples from a site (maintained in a frozen state for transport to the laboratory to prevent pore fluid drainage) and subjecting them to one of several different laboratory methods:

1. Oil/water drainage/imbibition capillary pressure testing: Involves spiking (via centrifuge) a sub-sample from the soil core with LNAPL up to its maximum saturation, then forcing water through under pressure to drain as much LNAPL as possible. Whatever LNAPL is left in the core constitutes the residual LNAPL saturation.
2. Free product mobility testing via centrifuge at 1,000 times the force of gravity: Performed by taking a sub-sample from a soil core as-received (no pre-spiking with LNAPL) and spinning it in a centrifuge at 1,000 times the force of gravity (approximately equal to 40-50 psi applied to sample) for 1 hour. LNAPL remaining in the sample following the centrifuge represents the residual LNAPL saturation.
3. Water drive testing: Involves forcing multiple (typically 10-15) pore volumes of water through a soil core sub-sample under 25 psi pressure. The pore volume flushing is used to simulate the migration of groundwater through the impacted soil. The LNAPL residual saturation is represented by the LNAPL that remains in the sample following the water drive.

In terms of Method 1, recall that recent research indicates residual LNAPL saturation is a function of initial LNAPL saturation (i.e., the more LNAPL that occupies the pore space initially, the higher the residual saturation). The initial spiking of the sample with LNAPL in Method 1 may therefore produce a residual saturation result that is biased high compared with what would be representative of an unspiked sample. With Method 2, the pressure applied during the test is so exceedingly high that it is not representative of the normal hydraulic conditions at a typical environmental site. Furthermore, the elevated pressure utilized with Method 2 will often lead to the compression or collapse of the soil matrix

during the test. When this occurs, one may not be able to conclude whether any LNAPL released from the sample during the test was the result of the applied gradient or the compression of the soil matrix “squeezing” LNAPL out of the sample. In either case, the results of Method 2 are likely to produce a residual saturation result that will be biased low and non-representative of actual site conditions. Method 3 also involves an applied pressure that is likely to be higher than conditions at a typical environmental site, however, because the pressure is much lower than Method 2 and the method does not involve any pre-spiking of LNAPL as in Method 1, it is the method that is the most likely to produce representative results of the currently available techniques.

It is important to note that LNAPL residual saturation for a given LNAPL and soil type at a given location within the LNAPL body, varies greatly between the unsaturated (vadose) and saturated zones. Generally speaking, LNAPL residual saturations in the vadose zone are much lower than corresponding residual saturations in the saturated zone. This is true because of the difference in densities between an air/LNAPL pair versus a LNAPL/water pair, and the difference in interfacial tensions between an air/LNAPL pair versus a LNAPL/water pair. LNAPL in the vadose zone has a much greater ability to drain under the force of gravity and flow into a monitoring well, as opposed to LNAPL that is submerged beneath the water table. This concept is the mechanism behind the common observation of the appearance of LNAPL (or increasing LNAPL thickness) in wells during low water tables, and the absence (or decreasing LNAPL thickness) in wells during high water tables. Typical LNAPL residual saturations in the vadose and saturated zones for given soil types are as follows (ITRC, 2009c):

Soil Type	Residual Saturation (Vadose)	Residual Saturation (Saturated)
Sand	3%	25%
Sandy Loam	5%	22%
Loam	7%	18%
Silty Loam	7%	16%
Sandy Clay	7%	10%
Silty Clay	4%	6%

Note that the “saturated” residual saturation of LNAPL in a coarse grained material (sand) is much higher than the corresponding “saturated” residual saturation in a silt or clay. As previously discussed, this is due to the fact that a coarse grained soil has a much greater capacity to hold LNAPL (due to larger soil pores) than a fine textured soil. Hence, the LNAPL saturations in a coarse grained soil are typically much higher than the LNAPL saturations in a fine textured soil.

1.3 LNAPL Mobility / Stability Discussion

The mobility of LNAPL generally relates to its ability to move in a localized sense at any point within an LNAPL body. LNAPL mobility can be highly influenced by a fluctuating water table. The mobility of LNAPL is dependent on a variety of LNAPL properties (density, viscosity, interfacial tension) and soil properties (soil type(s) and drainage characteristics) and is often evaluated in terms of LNAPL saturations (at any point within an LNAPL body) and corresponding residual saturations. LNAPL saturations that exceed residual saturations are deemed to possess a potential for mobility. However, the presence of localized areas within an LNAPL body with a potential for LNAPL mobility does not necessarily indicate that the LNAPL body is unstable or migrating (ASTM International 2007, ITRC 2009a).

Seasonal water table fluctuations have a direct impact on the mobility of LNAPL. A rising and falling water table creates a “smear zone” where mobile, continuous LNAPL is spread vertically and becomes discontinuous as water and LNAPL compete for pore space. Assuming a continuous source is not present, this interaction between water and LNAPL can effectively trap LNAPL as discontinuous, immobile droplets within the soil matrix (API, 2004). Consequently, during seasonal high water tables, some or all of the LNAPL in the smear zone (in an unconfined setting) becomes submerged or trapped beneath the water table. This results in the submerged LNAPL losing much of its ability to flow through the soil matrix and/or into a monitoring well (due to a higher residual saturation in the saturated zone). In addition, LNAPL in a well can “disappear” with an increase in water table elevation. Under a rising water table condition, there will be a delay in the response of the LNAPL in the formation as buoyancy forces try to move the LNAPL upward through the resistance presented by the soil formation (Oostrom et al, 2006). This is due to the resistance to LNAPL movement provided by the soil matrix and the fact that groundwater is less viscous than LNAPL¹, and is able to move more easily through the soil than LNAPL. LNAPL in a well does not encounter the resistance to upward movement that the LNAPL in the formation does and will rise to the top of the water in the well more quickly than the LNAPL in the formation is able to rise through the soil matrix. This creates an LNAPL gradient from the well toward the formation, resulting in LNAPL flow out of the well. Conversely, during seasonal low water tables, more of the LNAPL in the smear zone becomes exposed, gaining the ability to drain from the newly unsaturated soil under gravity and flow in the soil and/or into a monitoring well (due to a lower residual saturation in the unsaturated zone). This explains the reappearance of LNAPL or increases in LNAPL thickness in wells during seasonal low water tables. Hence, the rising and lowering of the water table has a direct influence on the mobility of LNAPL within an LNAPL body, but does not necessarily create a migrating LNAPL body. Furthermore, at sites that do not have ongoing releases, changes in in-well LNAPL thickness that correlate with fluctuations in the water table elevation are more likely to be a result of the vertical redistribution of LNAPL in and out of the well (as described above), as opposed to being representative of any significant lateral mobility or migration (USEPA, 2007; ITRC 2009a).

¹ The exception is fresh gasoline, which has a viscosity that is lower than that of water. All other common LNAPL types have viscosities that are greater than water (i.e., they do not flow as easily as water).

As suggested above, LNAPL thickness in a monitoring well varies inversely with water table elevation in an unconfined setting or condition. Hence, an increase in water table elevation results in a decrease in in-well LNAPL thickness. Conversely, a decrease in water table elevation results in an increase in in-well LNAPL thickness. In a confined setting (including LNAPL present in the secondary porosity of silts, clays and possible fractured rock), in-well LNAPL thickness tends to vary directly with potentiometric surface elevation. Hence, an increase in potentiometric surface elevation results in an increase in in-well LNAPL thickness, and vice versa. Confined conditions will often produce in-well LNAPL thicknesses that grossly over-represent the extent of impacts in the formation.

LNAPL stability relates to the ability or inability of a LNAPL body to migrate (i.e., whether or not the perimeter or extent of an LNAPL body is expanding/advancing over time). If the perimeter of an LNAPL body is growing or moving over time, the body is typically referred to as migrating or unstable. If the LNAPL body remains essentially the same size and in the same location over time (i.e., same overall footprint over time), the body is referred to as stable or non-migrating. Generally speaking, the majority of all historical LNAPL bodies, where the source of the release has been terminated, will be found to be stable. LNAPL bodies are spatially self-limiting (due to the capillary pressure principles previously discussed) unless continually supplied from an on-going release (API, 2004). Typically, once the release of LNAPL stops, LNAPL in the water table region will eventually cease to move as the resistive forces in the saturated soils balance the driving forces in the LNAPL pool (API, 2002; Huntley and Beckett, 2001). The endpoint of this movement is when the LNAPL reaches field residual saturation, a condition where LNAPL relative permeability, and consequently LNAPL conductivity, is zero (API, 2002; Huntley and Beckett, 2001). Often times, the following factors combine to produce a stable plume that is not spreading or migrating (USEPA, 2005a):

- LNAPL fluid properties
- LNAPL relative permeability
- Conductivity of the porous media
- Hydraulic gradient
- Pore throat displacement entry pressure
- Fluctuating water table

For an entire LNAPL body, LNAPL can sometimes be found to be mobile near the center of the body, where LNAPL saturations are highest (in excess of residual saturation), and immobile at the outer body fringes where saturation decreases to residual. Hence, parts of the LNAPL body may exhibit some inherent mobility, whereas the overall body remains stable.

It is important to note that water table fluctuations in a stable LNAPL body may cause immobile LNAPL to become mobile and flow or drain into an immediately adjacent monitoring well. However, despite the limited LNAPL drainage and vertical redistribution or smearing, the LNAPL body will most likely continue to be stable and non-migrating. Hence, at a site with a stable LNAPL body, the disappearance of LNAPL from a monitoring well for months and/or years, followed by the reappearance of LNAPL does not necessarily mean that the LNAPL is migrating.

1.4 LNAPL Mobility / Body Stability Evaluations – Lines of Evidence

There are various lines of evidence that can be used to evaluate the mobility and stability of an LNAPL body. These lines of evidence are:

- Historical LNAPL-related data (depth to LNAPL/water levels, in-well thicknesses, stable or shrinking dissolved-phase plume associated with LNAPL body, recovery data, etc.)
- Site-specific laboratory data (TPH profiling, LNAPL saturations in soil cores, etc.)
- LNAPL modeling (analytical and/or numerical) simulations
- LNAPL dye tracer testing
- Combinations of the above

The extent to which one particular line of evidence may be needed for the LNAPL Conceptual Site Model (LCSM) is dependent on the other available lines of evidence. For example, at a site where there is little to no historical data or where the data sets are extremely sparse, there will be a stronger need for extensive site-specific laboratory data with follow-up modeling to adequately characterize LNAPL mobility and body stability issues. Conversely, at a site with an abundance of historical data covering the full range of water table fluctuations, there may be less need to engage in a comprehensive laboratory program or modeling effort to complete the LCSM.

These lines of evidence are discussed in the following subsections.

1.4.1 Historical LNAPL-Related Data

Historical LNAPL-related data often play a critical role in assessing whether LNAPL at a given site is mobile and/or stable. The most common lines of historical evidence are described below.

1.4.1.1 Spatial Distribution Of LNAPL Based on In-Well LNAPL Thicknesses and/or Other Methods

Typically, the first line of evidence for evaluating LNAPL mobility and body stability is historical data regarding the spatial distribution of the LNAPL body. Historical LNAPL spatial distribution data are typically based on “in-well” or “apparent” LNAPL thicknesses, but may also include more sophisticated

LNAPL site characterization data such as laser-induced fluorescence (LIF) results. Historical LNAPL data are the primary line of evidence when the dataset includes measurements obtained at regular intervals over an extended period, where in-well thicknesses can be assessed during both high water table and low water table conditions. Depending on the site conditions, high and low water tables may be assessed seasonally within a 12-month timeframe or may require a period of years for proper evaluation. Tidal areas may exhibit large changes in water table elevation daily. Generally speaking, if the position, orientation and size of the LNAPL body remain similar during low water table conditions over extended periods of time, the LNAPL body is likely to be stable. However, care needs to be exercised in the evaluation of in-well thickness trends as these data will not provide a valid representation of the mobility and/or stability of the LNAPL body at many environmental sites.

Monitoring well observations that may indicate the presence of mobile LNAPL include the following:

- LNAPL appearing in a well that exhibited no previous evidence of the presence of LNAPL (field soil screening, soil/groundwater analytical results, LIF results, etc.)
- The footprint or perimeter of in-well LNAPL observations appears to continue to expand in one or more directions over time (when comparing observations made during low water table conditions)
- Where unconfined conditions are present, increasing in-well LNAPL thicknesses without a corresponding site-wide drop in water table elevation

Conversely, the following well observations are likely to represent immobile LNAPL or a stable LNAPL body:

- LNAPL never appearing in a well, even though other evidence suggests its presence (field soil screening, soil/groundwater analytical results, LIF results, etc.)
- In-well thickness fluctuations corresponding directly with water table fluctuations (i.e., a drop in water table elevation of “x” feet results in an in-well LNAPL thickness increase of approximately “x” feet)
- The footprint or perimeter of in-well LNAPL observations appears to maintain approximately the same areal extent over time (when comparing observations made during low water table conditions)

Observations unrelated to monitoring wells such as seeps provide an indication that some level of LNAPL mobility exists.

1.4.1.2 Dissolved Phase Plume Data

A stable or diminishing dissolved phase plume is an indication that the LNAPL source area is stable. Hence, dissolved phase monitoring data may also be used to assess LNAPL body stability. A comprehensive groundwater monitoring program will involve examining data from multiple wells over a sufficient duration to encompass the range of seasonal/temporal variation in hydraulic conditions. Ideally, a suitable monitoring network will include source zone, up-gradient, down-gradient and cross-gradient wells (i.e., a minimum of 4-5 wells). For the purpose of evaluating trends in analyte concentrations over time in groundwater sampled from monitoring wells, two procedures are commonly used. These are: (i) the Mann-Kendall trend test (for data sets containing up to 50 percent non-detect results); and (ii) the Rank-Sum test (for data sets containing more than 50 percent non-detect results). In general, at least four rounds of data spaced relatively evenly over time will be required to obtain a statistically significant trend analysis (e.g., quarterly monitoring for one year, semi-annual monitoring for two years, etc.). The more data and the longer the monitoring period, the higher the confidence level with the results will be. As many as eight data points (i.e., monitoring events) may be required to obtain “good” results.

1.4.1.3 LNAPL Recovery Data

Performance data from LNAPL recovery efforts can provide valuable information on the potential mobility of the LNAPL. If an appropriate LNAPL recovery technique has been applied and effectively operated at a given site, a low recovery rate or the development of an asymptotic recovery rate trend over time is a strong indication that the LNAPL is (or has become) immobile (i.e., if it cannot be recovered under some type of applied hydraulic and/or pressure gradient, it isn’t likely to be moving in the absence of the applied gradient). Conversely, if sufficient quantities of LNAPL can be readily recovered, then the LNAPL likely has some mobile component.

1.4.2 Site-Specific Laboratory data

LNAPL-saturated soil cores from impacted areas within an LNAPL body may be collected and submitted for laboratory analysis of key LNAPL mobility parameters including LNAPL saturations and residual saturations. Such evaluations could include some or all of the following:

- Photographs of LNAPL-saturated undisturbed soil cores in both white light and ultraviolet light
- Soil physical property evaluation in the LNAPL saturated zones including grain size analysis and drainage characteristics (van Genuchten parameters)
- Laboratory fluid (water and LNAPL) saturation analyses to determine Site-specific saturations and/or residual saturations across the LNAPL body
- LNAPL fluid property testing for density, viscosity, and interfacial tensions

A comparison of saturation versus residual saturation values across an LNAPL body can be used to assess the mobility of the LNAPL body. In addition, the site-specific laboratory results may be incorporated into models to assess LNAPL mobility (see description below).

1.4.3 LNAPL Modeling Simulations

There are various analytical LNAPL models (e.g., LNAST, LDRM, etc., API 2007) that may be used to evaluate LNAPL mobility. These models are based on a number of assumptions including: the fluids (LNAPL and water) are in vertical equilibrium and the soil conditions are relatively homogeneous. These conditions are required for in-well LNAPL thicknesses to be considered representative of the spatial (vertical) distribution of LNAPL in the formation. Examples of situations where these conditions are not met include sites with (Johnson and Ling, 2005):

- Water table fluctuations
- Confined conditions
- Sump wells in a perched setting
- On-going LNAPL release
- Heterogeneous conditions

Although in a real world setting, there are often times when vertical equilibrium of liquids and homogeneous soil conditions do not exist, LNAPL models may still be used to generate qualitative information about LNAPL behavior. The degree to which model results are quantitatively valid and defensible will be based on actual site conditions and the accuracy of the LCSM. Where possible, the use of site-specific model inputs (as determined from field and/or laboratory testing) is preferred over the use of default literature look-up values for soil and LNAPL physical properties.

In complex geological settings, numerical (finite element or finite difference) models may be used to assess LNAPL mobility and migration. However, the resources required to adequately run these models are extensive. In addition, the complexities associated with multi-phase fluid flow (spatial discontinuities in LNAPL body, variations in LNAPL saturations, pore entry displacement pressure issues at body periphery, etc.) may limit the effectiveness of these models.

1.4.4 LNAPL Dye Tracer Testing

Single well dye tracer testing involves the use of a fluorescent dye to quantify the rate of LNAPL movement through the subsurface (Sale et al, 2007). The technique involves the addition of a hydrophobic fluorescent dye to the LNAPL in a single well. The rate of depletion of the dye is measured using a spectrometer to quantify the decrease in fluorescence (or dye concentration) over time. The

rate of depletion is used to estimate the LNAPL velocity and formation transmissivity to LNAPL. This technique has shown promise in demonstrations, but is still an area of active research and, as such, has not yet been widely adopted in the field.

1.4.5 Mobility Lines of Evidence Summary

A thorough LNAPL mobility evaluation should compare and cross reference all lines of evidence to ensure that the overall interpretation of LNAPL spatial distribution, mobility and body stability is adequate for future decision-making purposes. Any potential conflicts or conflicting information should be further evaluated and, if necessary, qualified for future reference and/or investigation. Ideally, all lines of evidence will provide a consistent depiction of the location, mobility and stability of the LNAPL. However, a weight of evidence approach may be necessary due to the complexities and limitations associated with any single evaluation technique.

Section 2.0 LNAPL Chemistry

Excepting the case of a pure solvent with a density less than water (for example, toluene), LNAPLs are predominantly petroleum-based mixtures or fuels. Petroleum-derived fuels (gasoline, kerosene, diesel, etc.) are complex mixtures of organic compounds (predominantly hydrocarbons) with varying compositions dependent upon the source of crude oil and the refining process (Thomas and Delfino, 1991). Petroleum hydrocarbons are the main components of fuels derived from crude oil. Crude oil is a mixture of paraffinic and aromatic hydrocarbons with a low percentage of sulphur and trace amounts of oxygen and nitrogen compounds. The paraffinic hydrocarbons are the most abundant compounds in crude oil. They include alkanes, which are saturated hydrocarbons with a straight carbon chain completely substituted with hydrogen atoms. The alkanes are typically very stable and unreactive as compared to their unsaturated counterparts. Crude oil contains alkanes with anywhere from one to more than 50 carbon atoms (C_1 - C_{50+}). In general, C_1 - C_4 alkanes exist as gases, while C_5 - C_{17} alkanes are liquids, and C_{18} and higher alkanes are solids at 20°C. Isoprenoids are branched chain paraffinic hydrocarbons that contain at least two methyl groups. Isoprenoids are often more volatile than the straight chain alkane compounds and make up a significant portion of fuels. Aromatic compounds include single ring structures such as benzene, toluene, ethylbenzene and xylenes (collectively referred to as the BTEX compounds) and multi-ring (polycyclic) structures such as naphthalene, phenanthrene, anthracene, fluorene, pyrene and other polycyclic aromatic hydrocarbons (PAHs). The BTEX compounds are the most abundant aromatic hydrocarbons in fuels (particularly gasoline), with smaller amounts of PAHs present (mostly the 2 and 3-ring species). All said, a typical petroleum-based LNAPL is comprised of hundreds of individual hydrocarbon compounds (straight chain and cyclic) as well as other non-hydrocarbon additives incorporated during the refining process.

Different LNAPLs behave differently based on their composition. For example, a gasoline LNAPL, which is comprised of lighter (lower carbon chain molecules) hydrocarbons than diesel or fuel oil, is more apt to partition into both the vapor phase and dissolved phase, primarily due to the presence of greater quantities of volatile and soluble BTEX compounds. Due to the chemical and toxicological properties associated with BTEX, gasoline LNAPLs tend to pose more of a vapor and dissolved phase exposure risk than heavier LNAPLs. Further, gasoline LNAPLs may also pose potential explosivity risks due to the abundance of volatile and combustible constituents in the LNAPL (and resulting vapor). In a given stratigraphy, the heavier (less volatile) petroleum products will typically exhibit a lower potential for mobility, a lower degree of recoverability, and less potential exposure issues than the lighter end/more volatile product types.

The process of identifying the type of LNAPL (and sometimes the approximate age) via a laboratory process is often referred to as LNAPL fingerprinting or LNAPL forensic testing. During this process, the laboratory generates a gas chromatograph of the LNAPL which effectively identifies the signature or pattern of carbon chain molecules in the LNAPL, starting from the lowest carbon chain (C₄) up through molecules in excess of 30 carbon atoms (>C₃₀). Various types of LNAPLs are predominantly comprised of specific ranges of hydrocarbon molecules as follows (Potter and Simmons, 1998):

- Gasoline: C₄ to C₁₂ range compounds
- Jet Fuel/Kerosene: C₆ to C₁₈ range compounds
- Diesel/No. 2 Fuel Oil: C₈ to C₂₁ range compounds
- Lube Oil: C₁₈ to >C₃₄ range compounds
- Crude Oil: C₁ to >C₃₄ range compounds

Various chromatographic markers and peak ratios are utilized to identify the type or types of LNAPL present, as well as provide an estimation of the level of degradation and/or approximate age. Laboratories may also use a boiling point evaluation to categorize the LNAPLs based on boiling point distillates.

The interpretation of laboratory fingerprinting data can be a difficult task, particularly when dealing with weathered LNAPLs or mixtures of various LNAPLs. For this reason, there is only a relatively small number of laboratories with experienced petroleum forensic chemists that specialize in LNAPL forensic testing in the United States.

2.1 Effective Solubilities from LNAPL Mixtures

Because petroleum-derived LNAPLs are comprised of hundreds of individual hydrocarbon compounds, these compounds must compete with each other when partitioning to the vapor or dissolved phases. As

a result, the ability of each compound to partition into the vapor or dissolved phase when present in a mixture is much less than what can be volatilized or dissolved from a pure solvent. For example, the solubility of benzene from a pure benzene solvent is approximately 1,760 milligrams per litre (mg/L) (API, 2004). Hence, a pure benzene solvent in contact with groundwater has the ability to yield 1,760 mg of benzene to each litre of water via dissolution. However, the effective solubility of benzene from a gasoline LNAPL ranges from approximately 25 mg/L to 40 mg/L, depending on the benzene composition in the LNAPL mixture and the degree of weathering (API, 2004). The ability for an LNAPL to yield an individual compound to groundwater via dissolution is a function of the mole fraction of the compound in the LNAPL mixture as well as the pure compound solubility. Effective solubility values for the components of various petroleum fuels are reported in the literature, or can be calculated according to Raoult's Law if site-specific LNAPL chemistry data are available (API, 2004):

$$C_i^{eq} = S_i \cdot MF_i$$

Where: C_i^{eq} = equilibrium aqueous concentration (or effective solubility) of hydrocarbon constituent i
 S_i = pure phase solubility of hydrocarbon constituent i
 MF_i = mole fraction of hydrocarbon constituent i in the LNAPL, approximately equal to the mass fraction

This is an extremely important concept when assessing dissolved phase concentrations associated with a LNAPL body. For heavier LNAPLs, such as diesel, lube oil, etc., real world experience demonstrates that dissolved phase impacts associated with these LNAPLs are often times very limited, as opposed to impacts associated with lighter LNAPLs such as gasoline.

Section 3.0 LNAPL Physical Properties

The physical properties of LNAPL that are most often measured and used for LNAPL mobility and recoverability assessment include: density, viscosity and interfacial tensions. LNAPLs, being less dense than water, have specific gravities ranging from approximately 0.73 to just less than 1.0 (i.e., the density of water). Hence, in an open water environment, LNAPLs float on top of the water (which, as previously discussed, is not the case with LNAPL in the subsurface). Density can, however, be used to help distinguish one LNAPL from another. The following density ranges can be used to help characterize an LNAPL (API, 2004):

- Gasoline: 0.68 to 0.78 grams per cubic centimeter (g/cm³)
- Diesel/No. 2 Fuel Oil: 0.80 to 0.85 g/cm³

- Lube Oil: 0.83 to 0.88 g/cm³
- Crude Oil: 0.70 to 0.98 g/cm³

Other constituents or impurities within the LNAPL mixture may also have an effect on the LNAPL density (for example, LNAPL containing chlorinated compounds).

LNAPL viscosity is used to assess the “pumpability” of the LNAPL as well as the ability of the LNAPL to flow or migrate in the subsurface. Viscosity commonly refers to a fluid’s “thickness” or resistance to flow. Consequently, the higher the LNAPL viscosity, the more resistant the LNAPL is to flow, the less likely the LNAPL will be to migrate, and the harder the LNAPL will be to recover via pumping technologies. With the exception of a gasoline LNAPL, which has a viscosity lower than water, most petroleum-based LNAPLs are more viscous than water. The viscosity of LNAPL, along with LNAPL relative permeability, is accounted for in the determination of LNAPL conductivity, and often times yields a conductivity value one to two orders of magnitude lower than the conductivity of water (i.e., hydraulic conductivity). Typical room temperature viscosity values for various LNAPLs are (API, 2004):

- Gasoline: 0.62 centipoise (cp)
- Diesel: 2.7 cp
- JP-4 Fuel: 1 cp
- Crude Oil: 60 cp

Interfacial tensions between air/water, LNAPL/water and LNAPL/air play an important part in limiting or resisting the movement of LNAPL in the subsurface. In a multiphase system, the tension between different fluids in contact with one another (interfacial tension) will limit the ability for each respective fluid to flow (as compared to the presence of a single fluid only). As previously mentioned, for an LNAPL to enter a water-saturated media, the capillary pressure must exceed the pore entry displacement pressure which in part, is determined by the interfacial tension between the LNAPL/water.

Section 4.0 Effects of Geology on LNAPL Presence/Behavior

Geology plays an extremely important role at LNAPL sites. The larger the soil pores in the primary porosity of the soil matrix, the greater the capacity for the soil to hold LNAPL, the greater the ease at which LNAPL can move, and the less pressure that is required for LNAPL to displace water and enter the pore space. Granular soils, such as sands and gravels, have large soil pores, relative to silts and clays, and can hold LNAPL at saturations upwards of 40 to 60% (LNAPL saturations in excess of 60% are not typically encountered at environmental sites). Conversely, silts and clays, which have extremely small soil pores relative to sands and gravels, will typically only allow LNAPL saturations on the order of 5 to

15%. The smaller soil pores not only limit the amount of LNAPL saturation, but also limit the flow or movement of LNAPL.

Soil porosity principles for LNAPL saturations and movement in overburden soil may also be applied to competent bedrock (i.e., bedrock that does not have secondary porosity in the form of fractures). For example, a competent sandstone will enable LNAPL to behave in a similar manner as in a sandy soil.

Secondary porosity also plays an extremely important role at LNAPL sites. Fine textured soils, such as silts and clays, are often comprised of a secondary porosity which may include macropores such as fractures, fissures, sand seams, etc. The same holds true for fractured bedrock. LNAPL movement through secondary porosity may occur at rates several orders of magnitude greater than the movement through the primary porosity. This is primarily due to the fact that the macropores generally have much larger pore sizes than the primary porosity in fine-grained soils, with a corresponding pore entry displacement pressure that is much lower. That is, LNAPL can displace water and move through macropores much more easily (and to a greater extent) than it can in the primary porosity of a fine-grained soil matrix. In addition, LNAPL that is present in macropores will be much more likely to be present under confined conditions, and consequently be more sensitive to changes in subsurface pressure conditions. This may result in LNAPL migrating much greater distances and penetrating greater depths than would be typically expected. Hence, the potential for LNAPL movement through secondary porosity must be considered when LNAPL impacts are present in fine textured soil and/or fractured bedrock.

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Appendix C

LNAPL Behavior Equations and Models

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List of Symbols/Acronyms

α	van Genuchten α
α_{ow}	Capillary Pressure Head Parameter – Oil/Water (ft ⁻¹)
α_{ao}	Capillary Pressure Head parameter – Air/Oil (ft ⁻¹)
b_o	LNAPL Thickness (ft)
ϕ	Total Soil Porosity
ϕ_{eff}	Effective Porosity (Effective Free Oil Porosity)
g	Gravitational Constant (kg m/s ²)
h	Water Pressure Head in van Genuchten Drainage Model
h_c	Critical height/head of LNAPL
i	Reference Point Along Vertical LNAPL Saturation Profile
i_w	Water Hydraulic Gradient (assumed equal to oil gradient)
k	Soil Permeability (cm ²)
k_{ro}	LNAPL Relative Permeability
k_{ro-b}	LNAPL Relative Permeability from Burdine Equation
k_{ro-m}	LNAPL Relative Permeability from Mualem Equation
K_w	Hydraulic Conductivity Water (cm/s or ft/day)
K_o	LNAPL Conductivity (cm/s)
λ	Model Fitting Parameter
μ_o	LNAPL Viscosity (cp)
μ_w	Water Viscosity (cp)
M	Model Fitting Parameter
M_o	LNAPL Mobility (cm/s or ft/day)
n	Number of Equally Spaced Points on the Z-Axis
N	van Genuchten N
ρ_o	LNAPL Density (g/cm ³)
ρ_w	Water Density (g/cm ³)
P_c	Capillary Pressure
P_D	Pore Displacement Entry Pressure

P_o	Oil/LNAPL Pressure
P_R	Resistive Soil Pressure/Force
P_w	Water Pressure
q_o	LNAPL Specific Discharge (cm/s or ft/day)
r	Radius of Curvature at Fluid Interface
σ_{aw}	Air-Water Interfacial Tension (dynes/cm)
σ_{ow}	Oil-Water Interfacial Tension (dynes/cm)
σ_{ao}	Air-Oil Interfacial Tension (dynes/cm)
S_o	LNAPL Saturation
S_{or}	LNAPL Residual Saturation
S_{ors}	LNAPL Residual Saturation – Saturated Zone
S_{orv}	LNAPL Residual Saturation – Vadose Zone
S_t	Total (LNAPL plus Water) Saturation
S_w	Water Saturation
S_{wr}	Water Residual (Irreducible) Saturation
θ	Contact Angle between Fluid Interface and Soil Particle
T_o	LNAPL Transmissivity (cm ² /s or ft ² /day)
V_o	LNAPL Specific Volume (ft ³ /ft ²)
v_o	LNAPL Velocity (cm/s or ft/day)
z	Reference Elevation on the Vertical LNAPL Saturation Profile (ft)
z_{ao}	Air-Oil Elevation (ft)
z_{aw}	Air-Water Elevation (ft)
z_{ow}	Oil-Water Elevation (ft)
z_{max}	Maximum Elevation of LNAPL (above residual saturation) in Smear Zone (ft)

Section 1.0 Introduction to LNAPL Behavior Equations / Theory

This Appendix presents some of the basic LNAPL concepts and mathematical expressions or equations that describe the occurrence, behavior and migration of LNAPL in the subsurface. Specifically, this section addresses LNAPL behavior at the water table and includes the vertical impacted soil zone typically referred to as the smear zone. The smear zone is where potentially mobile LNAPL may reside at sites where the source(s) of the LNAPL impacts have ceased for some time (i.e., no ongoing sources). The behavior of LNAPL in the vadose or unsaturated zone (above the smear zone) is not addressed here.

The analytical equations/models presented herein are based on a number of assumptions including: the fluids (LNAPL and water) are in vertical equilibrium and the soil conditions are homogeneous. These conditions are required for in-well or apparent LNAPL thicknesses to be considered representative of the spatial (vertical) distribution of LNAPL in the formation. Situations where these conditions are not met include sites with:

- Water table fluctuations
- Confined conditions
- Sump wells in a perched setting
- On-going LNAPL release(s)
- Heterogeneous conditions

Although in a real world setting, there are often times when vertical equilibrium of liquids and homogeneous soil conditions do not exist; LNAPL analytical equations and models may still be used to generate qualitative information about LNAPL behavior. The degree to which model results are quantitatively valid and defensible will be based on actual site conditions and the accuracy of the LNAPL Conceptual Site Model (LCSM). Where possible, the use of site-specific model inputs (as determined from field and/or laboratory testing) is preferred over the use of default literature look-up values.

Section 2.0 Pressure Conditions Necessary for LNAPL Movement

LNAPL requires pressure to move in the subsurface at the water table. More specifically, the capillary pressure must be sufficient to overcome the soil resistive forces to enable the displacement of groundwater from unimpacted saturated soil pores. The following sections provide a discussion regarding capillary pressure, soil resistive forces and pore entry displacement pressure. A figure illustrating the idealized relationship between LNAPL in a well versus LNAPL in a formation, based on the principles of capillary pressure and LNAPL saturation, is provided in Figure 1.

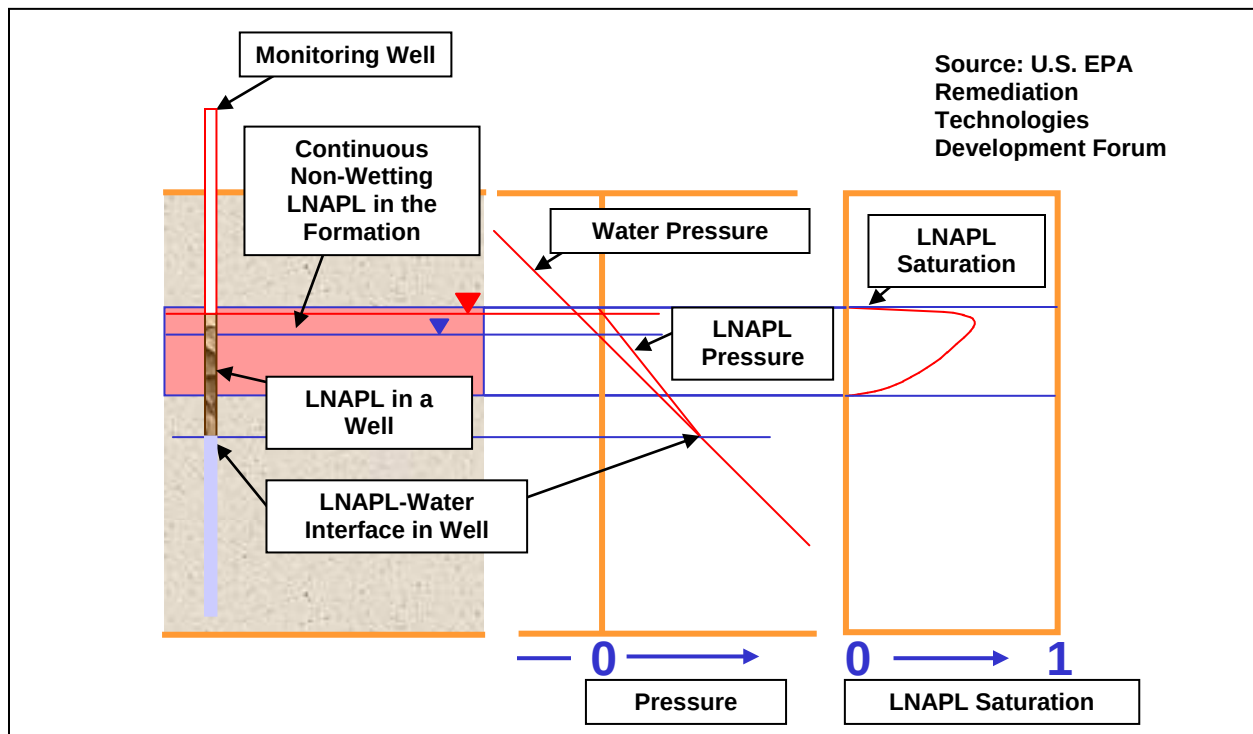


Figure 1 – Idealized Relationship Between In-Well LNAPL Thickness and Formation Thickness

2.1 Capillary Pressure

Capillary pressure, which is sometimes referred to as “excess pressure”, is defined as the difference between the fluid pressure in the non-wetting phase (typically LNAPL) and the pressure in the wetting phase (typically water) at a given reference point. The larger the capillary pressure (i.e., pressure difference between the two fluids), the greater the LNAPL saturation, and the greater the potential for LNAPL mobility. For LNAPL movement or migration to occur, LNAPL capillary pressure must exceed the resistive forces in the soil formation.

Any object submerged in a fluid is subject to a fluid pressure based on the depth of submersion beneath the top of fluid (or air/fluid interface). The greater the depth of submersion, the greater the pressure at that point. The fluid pressure is a function of the density of the fluid, the depth of submersion, and the gravitational constant. In a subsurface environment, LNAPL and water exhibit pressures depending on the depth beneath the fluid or phreatic surface. As shown in the middle panel in Figure 1, LNAPL pressure is zero at the top surface of the LNAPL, and increases in a linear manner with increasing depth below the surface. Similarly, water pressure is zero at the top surface of the water, and increase linearly with increasing depth. The prime difference, however, is that the tops of the fluid (LNAPL and water) surfaces are at different elevations, based on the density differences between the fluids. Figure 2 provides the pressure graph from Figure 1 along with the elevation or depth scale for the fluids, with the zero reference being at different locations for the LNAPL and water.

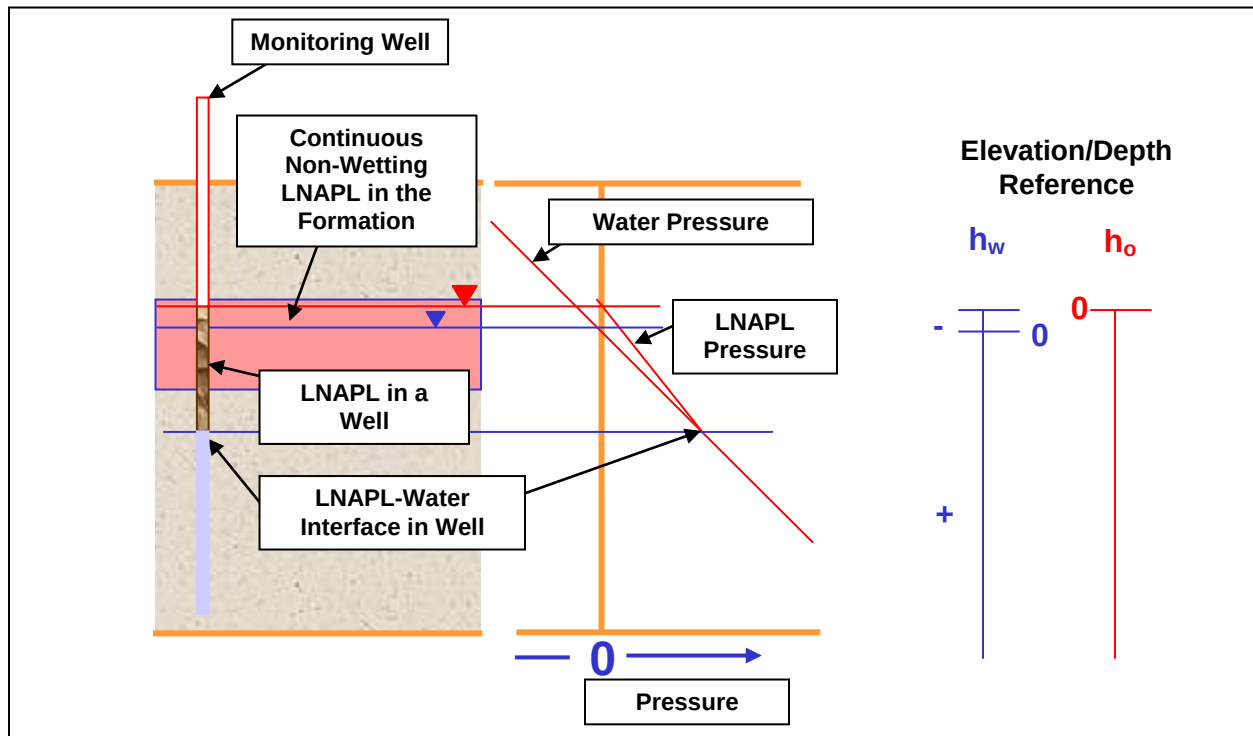


Figure 2 – Pressure Graph with Reference Elevations/Depths for LNAPL and Water

As shown above in Figure 2, the LNAPL and water pressures are equal at the elevation of the LNAPL/water interface in the adjacent monitoring well. Graphically, the capillary pressure represents the difference between the LNAPL and water pressure lines, for a given reference point or elevation/height.

As shown on the left hand panel in Figure 2, the LNAPL within the well extends below the LNAPL in the formation. This occurs because the well behaves as a large macropore, and the LNAPL at the bottom of the well lacks the necessary capillary pressure at this elevation to displace water in the adjacent formation. The degree to which the LNAPL in a well extends below the LNAPL in the formation is more pronounced in fine textured soils (silts and clays) (USEPA, 2005).

It is important to note that the water pressure line extends up into the capillary fringe, where the elevation reference becomes negative, resulting in a negative pressure or vacuum. This vacuum represents the negative pressure experienced in the water phase within the capillary fringe. Hence, the zero pressure at the surface of the LNAPL minus the negative pressure of the water in the capillary fringe, still results in a positive capillary pressure.

The capillary pressure is represented mathematically by the following equation:

$$P_C = P_o - P_w \quad (2.1)$$

Where:

P_C = Capillary pressure at reference point below fluid surface

P_o = Oil/LNAPL pressure at reference point below LNAPL surface

P_w = Water pressure at reference point below (or above) water surface

The pressure of the fluid in each fluid phase is a function of the following:

$$P = \rho gh \quad (2.2)$$

Where:

ρ = Density of the fluid

g = Gravitational constant

h = Height of fluid above reference point

Hence, capillary pressure can be expressed as:

$$P_C = (\rho_o gh) - (\rho_w gh) \quad (2.3)$$

$$P_C = (\rho_o - \rho_w)gh \quad (2.4)$$

2.2 Soil Resistive Forces

For LNAPL to enter a water-saturated porous media and displace water from the pore space, the LNAPL (and more specifically, the capillary pressure) must exert sufficient pressure to overcome the resistive forces of the soil. The resistive forces of the soil are based on the soil pore size, the interfacial tension between the LNAPL and water at the fluid interface, the curvature formed between the fluids at the fluid interface, and the contact angle between the fluid interface and soil particles. When two fluids are in contact with one another in small confines, the fluid interface forms a curvature based on the properties of the fluids. The smaller the confines, the greater the curvature of the interface. Hence, on a microscopic pore scale level, the smaller the effective soil pore size, the greater the curvature of the fluid interface, and the smaller the radius of curvature. The pressure conditions created when two fluids are present in the soil pore space can be represented by the equation (API, 2003):

$$P_R = \frac{2\sigma_{ow}}{r} \quad (2.5)$$

Where:

P_R = Resistive pressure

σ_{ow} = Oil/LNAPL-water interfacial tension

r = Effective soil pore size/radius of curvature of interface between fluids

This resistive pressure effectively works to prevent or resist the movement of one fluid in the presence of the other. As inferred from Equation 2.5, soils with very small pore sizes (i.e., silts and clays) will have fluid interfaces with very small radii of curvature resulting in very large resistive pressures working to prevent LNAPL movement. Conversely, soils with larger pore sizes will have larger radii of curvature resulting in lower resistive pressures working to prevent LNAPL movement.

At the source of a release, where LNAPL has migrated down to and penetrated vertically into the water table, the downward movement of LNAPL in the saturated zone results in the lateral displacement of water. The horizontal component of the displacement is based on the contact angle between the fluid interface and the soil particles. Figure 3 provides a conceptual drawing illustrating the primary forces and contact angles involved during the displacement of water by LNAPL.

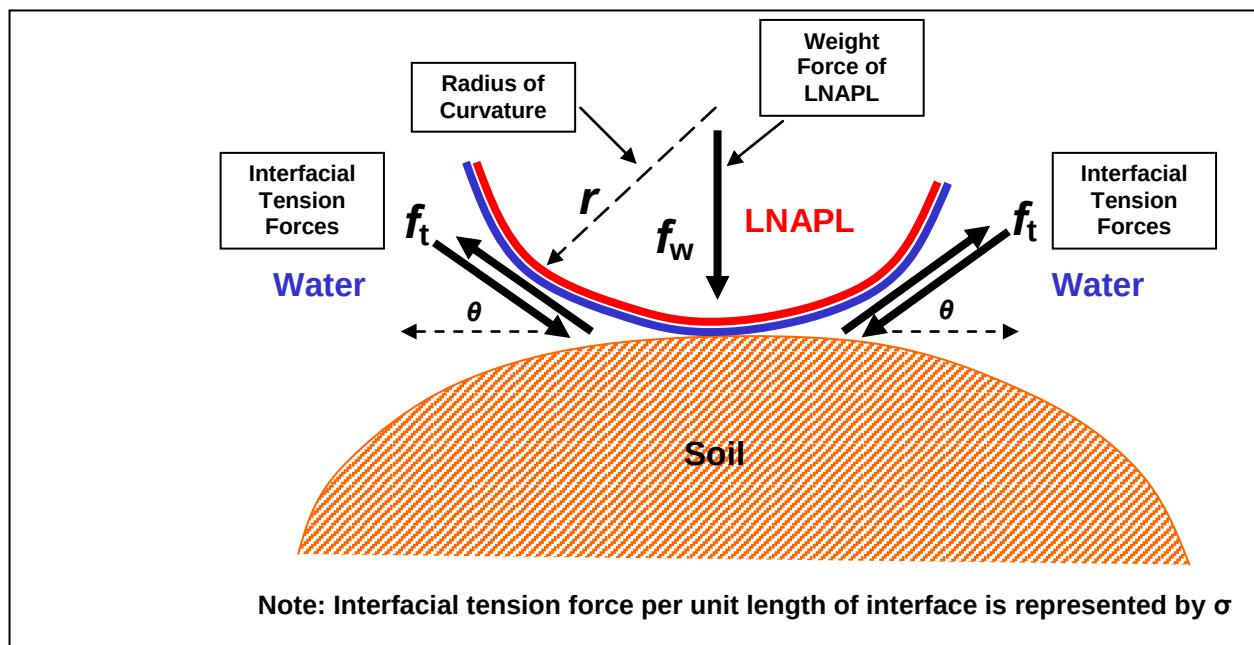


Figure 3 – Soil Resistive Forces for LNAPL Displacement of Pore Water

From Figure 3, the soil resistive force or pressure working to prevent LNAPL from displacing water can be expressed as:

$$P_R = \frac{2\sigma \cos \theta}{r} \quad (2.6)$$

Where:

- θ = Contact angle between the two fluids (based on degree of fluid wettability)
- $\cos \theta$ = Perpendicular or horizontal component of the resistive force/pressure

The doubling of the forces in the numerator is to account for the mirror image of interfacial tension forces shown in Figure 3 on both the right and left-hand sides.

The following expressions may therefore be used to summarize when LNAPL movement into a water-saturated porous medium may or may not occur:

- If $P_C > P_R$, LNAPL will displace water from soil pore
- If $P_C \leq P_R$, LNAPL will not displace water from soil pore

2.3 Pore Entry Displacement Pressure

The pore entry displacement pressure represents the specific threshold pressure necessary for one fluid to enter into a porous medium occupied by another fluid, thereby displacing the initial fluid (Mercer and Cohen, 1990). Pore entry displacement pressures may account for air displacing groundwater, LNAPL displacing groundwater, air displacing LNAPL, etc. In a water-saturated soil, the capillary pressure must equal or exceed the pore entry displacement pressure, for the LNAPL to move into the pore and displace water.

The specific capillary pressure threshold necessary for LNAPL to displace water in a water-saturated porous medium can be established by setting the capillary pressure equal to the soil resistive forces equation above as follows (API, 2007, Adamson, 1982):

$$P_C = \frac{2\sigma_{ow} \cos \theta}{r} \quad (2.7)$$

Using the conceptual drawings in Figures 1 and 2, the capillary pressure threshold necessary to displace pore water is identified in Figure 4.

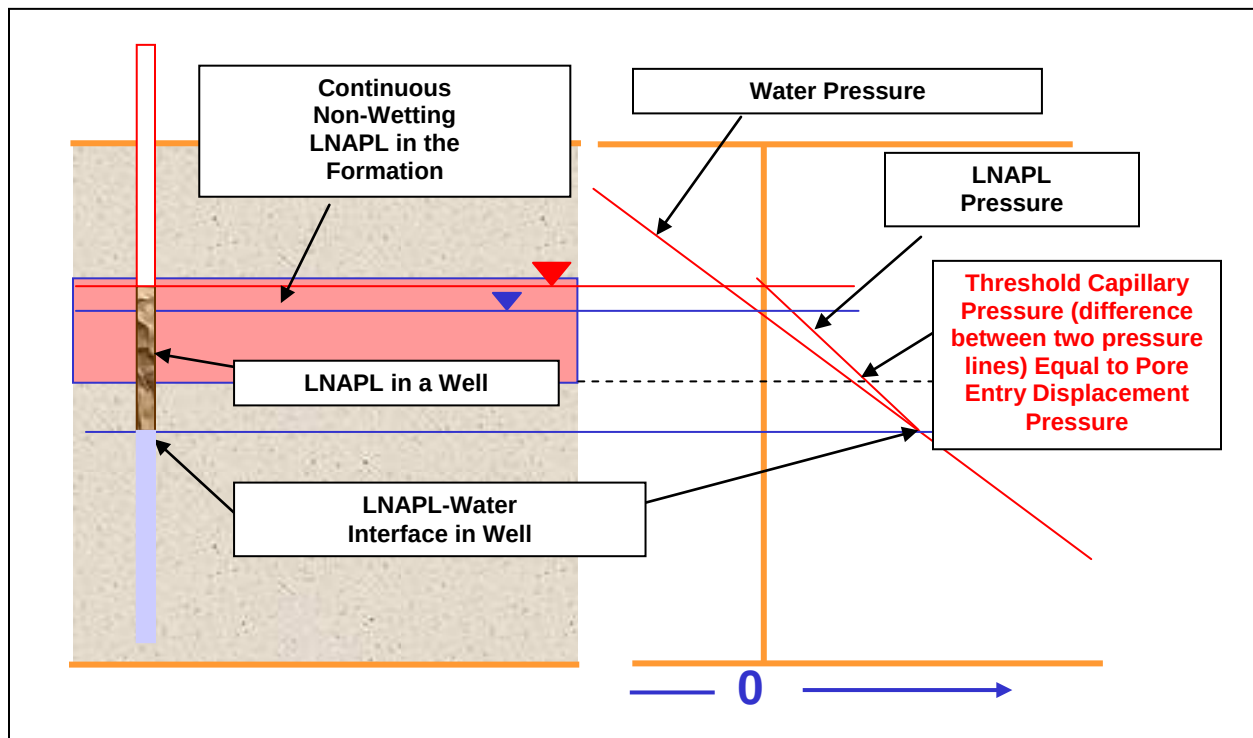


Figure 4 – Threshold Capillary Pressure Equal to Pore Entry Displacement Pressure

Although the situation illustrated in Figure 3 was for LNAPL migrating vertically into the water table, Equations 2.6 and 2.7 may also be used to assess the potential for horizontal LNAPL migration in the saturated zone at the periphery or leading edge of the LNAPL body. Further, Equations 2.6 and 2.7 may be used to determine the critical height or head of LNAPL necessary to exceed the pore entry displacement pressure and result in the displacement of groundwater.

Combining Equations 2.4 and 2.7 yields the following expression:

$$(\rho_o - \rho_w)gh = \frac{2\sigma_{ow} \cos \theta}{r} \quad (2.8)$$

Equation 2.8 can be rearranged to solve for the critical height (or head) of LNAPL necessary for displacement of water to occur, as follows:

$$h_c = \frac{2\sigma_{ow} \cos \theta}{rg|(\rho_o - \rho_w)|} \quad (2.9)$$

Where:

h_c = Critical height of LNAPL necessary to generate a capillary pressure equal to the pore entry displacement pressure, whereby LNAPL will displace water

It is important to note that the expressions used to describe capillary pressure, soil resistive forces, and the pore entry displacement pressure identified above are simplified analytical expressions used to describe LNAPL movement in an idealized situation (i.e., homogeneous soil with fluids at vertical equilibrium). This expression of critical head will often be compared to in-well LNAPL thickness data to assess the potential for LNAPL mobility. However, fluctuations in the water table elevation and heterogeneous soil conditions have a significant effect on in-well LNAPL thickness. Therefore, caution must be used when attempting to use the expressions above in relation to in-well LNAPL thickness to assess the potential for LNAPL movement or migration.

Section 3.0 Soil Drainage Characteristics

Two primary models are used to represent soil drainage characteristics with respect to LNAPL mobility. The first is the Brooks and Corey (1964) soil characteristic model which assumes that some minimum amount of threshold pressure buildup is necessary to initiate the drainage of water from a saturated soil. The threshold pressure is the pore entry displacement pressure (Mercer and Cohen, 1990) discussed in Section 2.0 as it applies to an air/water setting. The second is the van Genuchten model, which assumes that drainage or fluid displacement will occur (albeit at a minor amount) as soon as a pressure is applied by one fluid to the other. The difference between the models is shown conceptually in Figure 5.

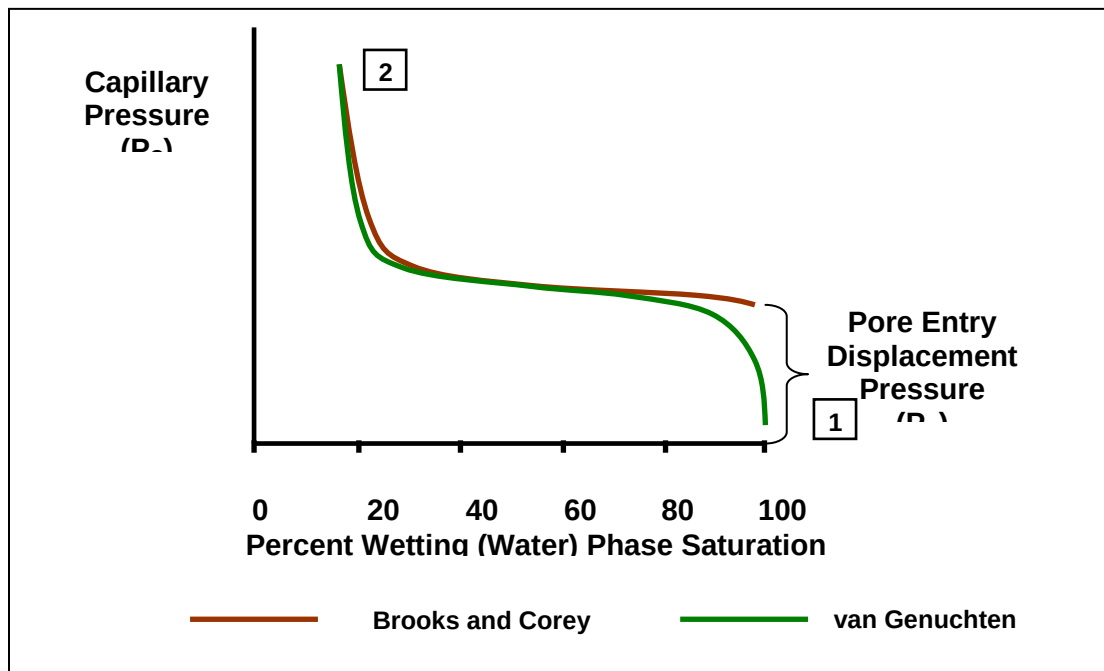


Figure 5 – Soil Drainage Characteristic Models

According to the van Genuchten (1980) model, the water saturation S_w is related to the suction pressure head h by the following expression (API, 2003):

$$S_w(h) = S_{wr} + (1 - S_{wr}) \left[\frac{1}{1 + (\alpha h)^N} \right]^M \quad (3.1)$$

Where:

- S_w = Water saturation (as percent of soil pore space)
- S_{wr} = Residual (or irreducible) water saturation
- h = Water pressure head
- α, M, N = Model or curve fitting parameters (refer to Section 4.0)

The Brooks and Corey (1964) model may be expressed as (API, 2007):

$$S_e = \left(\frac{P_D}{P_C} \right)^\lambda \quad ; \quad P_C > P_D \quad (3.2)$$

$$S_e = 1 \quad ; \quad P_C < P_D \quad (3.3)$$

Where:

- S_e = Wetting (water) phase saturation for capillary pressures greater than displacement pressure
- P_D = Displacement pressure head
- P_C = Capillary pressure head
- λ = Brooks and Corey pore size distribution parameter

Equation 3.2 can be further expressed as (API, 2001):

$$S_e = \left[\frac{S_w - S_{wr}}{1 - S_{wr}} \right] \quad (3.4)$$

The soil drainage characteristic curves in Figure 5 are based on air displacing water, and are generated in an air-water drainage capillary pressure test. Capillary pressure tests are typically conducted in a laboratory with the use of a centrifuge. For an air-water capillary pressure test, the test commences with a fully water saturated soil core (see point “1” in Figure 5). The core is placed in the centrifuge and spun at increasing speeds to induce increasing pressure conditions. As the core is spun, the water drains out of the core, under the influence of the centrifugal force/pressure, and is replaced with air. The mass of water released is recorded for each distinct pressure condition (to be added to the final water saturation at the conclusion of the test to determine water saturations at each point in the test). The test concludes when no more water drains from the core, despite increases in pressure. The remaining water at this point (see point “2” in Figure 5) is referred to as the irreducible water saturation or the residual water saturation.

As shown in Figure 5, the primary difference between the Brooks and Corey model versus the van Genuchten model occurs only at very high water saturations, with the Brooks and Corey drainage of water not commencing until the pore entry displacement pressure is obtained.

Capillary pressure tests may also be conducted for LNAPL and water as illustrated in Figure 6.

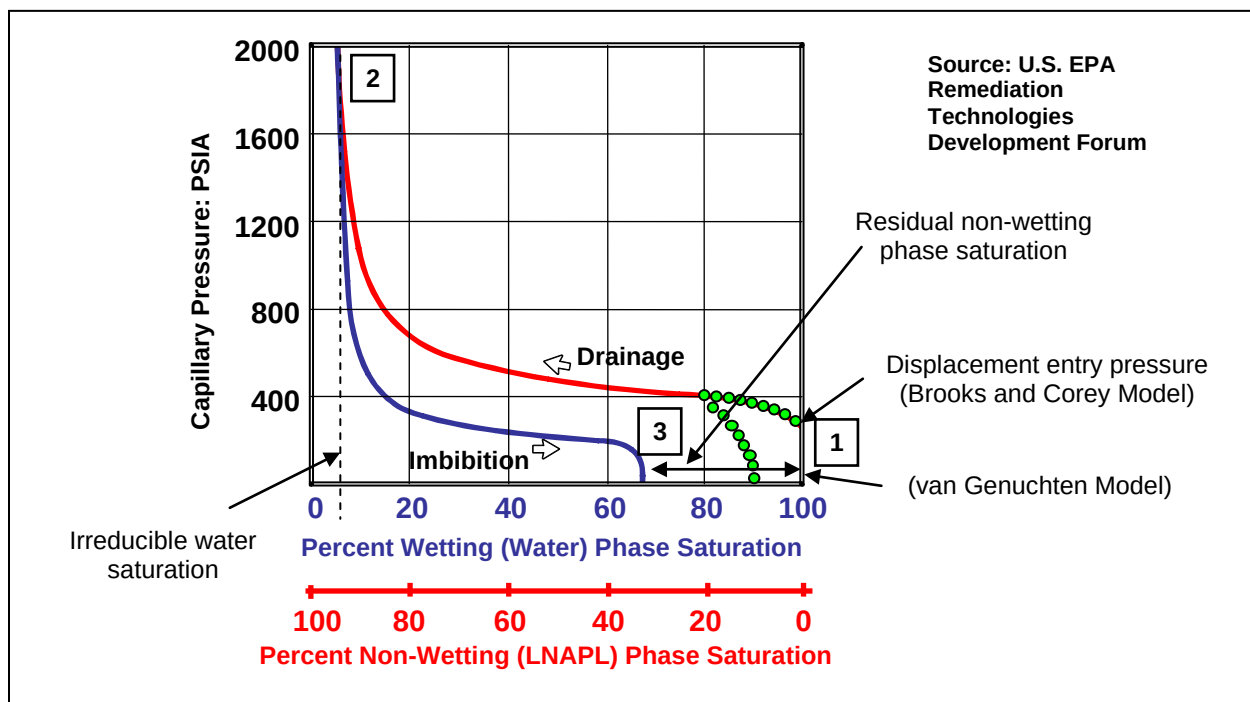


Figure 6 – Capillary Pressure Test for LNAPL-Water

As shown in Figure 6, the LNAPL-water capillary pressure test consists of three parts. The test commences with a fully water saturated soil core (again, placed in a centrifuge – see point “1”). As the core is spun, water drains from the core and is replaced by LNAPL (hence, the water and LNAPL saturation scales on the x-axis). The LNAPL displacing water is represented by the red line in Figure 6. The term “Drainage” refers to the phase of the test when the wetting fluid (water) is being drained from the core during the initial spin phase. Spinning continues until no further water drainage occurs with increased pressure (see point “2”). At this point, spinning ceases and water is reintroduced as the displacing fluid. The second spin phase results in LNAPL being drained from the core and being replaced by water, and is represented by the blue line in Figure 6. This phase of the test is referred to as “Imbibition”, which refers to the wetting fluid (water) being imbibed or reintroduced into the core. Spinning continues until no further LNAPL drainage occurs with increasing pressure. The LNAPL saturation at this point is referred to as the LNAPL residual saturation (Note: The capillary pressure test is only one method for determining the LNAPL residual saturation).

As shown in Figure 6, the Drainage curves (red line) for both the Brooks and Corey and van Genuchten model are essentially the same, except at very low LNAPL saturations. In practice, the differences in the estimates provided by the different methods will most often be negligible.

The Brooks and Corey and van Genuchten equations shown above may be used for other fluid combinations if appropriate scaling relationships for density and interfacial tensions are introduced (API,

2001, 2003, 2007). These equations, as well as the concepts discussed in Section 2.0, are used in Section 4.0 to generate expressions for LNAPL saturation (refer to right-hand panel in Figure 1) and relative permeability, which in turn are used to determine LNAPL conductivity, mobility and velocity. For additional information pertaining to capillary pressure scaling relationships, refer to API 2001, API 2003 and API 2007.

The API models provided in the LNAPL Interactive Guide (API, 2004) allow for the use of either the Brooks and Corey or van Genuchten models. However, the more recent API LDRM model (API, 2007) relies solely on the van Genuchten model. The van Genuchten model has found wide use because it provides a smooth function in predicting the vertical saturation distribution and may readily be fit to both laboratory and field data (API, 2007). However, the van Genuchten model is contrary to the fact that a positive capillary pressure is required for LNAPL to displace groundwater in previously unimpacted soil pores, which is accounted for in the Brooks and Corey model. Hence, the van Genuchten model is considered appropriate for LNAPL migration in LNAPL impacted areas, whereas the Brooks and Corey model is considered more appropriate for potential LNAPL migration into previously unimpacted soil areas (API, 2007).

Section 4.0 LNAPL Mobility and Velocity Equations

4.1 LNAPL Mobility Equations

As described in the API Interactive LNAPL Guide (API, 2004), inherent oil mobility was defined by Parker (1996) and others as the ratio of free oil transmissivity to specific oil volume at a given location. These two parameters can be measured with core analyses or estimated through baildown test analyses. The oil transmissivity is the product of the oil conductivity and the thickness of the free oil zone. The specific volume is the product of oil saturation, total porosity, and the thickness of the free oil zone. The inherent oil mobility is expressed as:

$$M_o = \frac{T_o}{V_o} \quad (4.1)$$

Where:

M_o = inherent oil mobility (ft/day)
 V_o = specific oil volume per unit area (ft³/ft²)
 T_o = oil transmissivity (ft²/day)

The specific oil volume is a function of the oil saturation along the vertical profile and is expressed as:

$$V_o = \int_{z_1}^{z_2} \phi S_o dz \quad (4.2)$$

Where:

ϕ = total porosity (dimensionless)

S_o = oil saturation (dimensionless)

z = vertical thickness of oil impacts where z_1 is typically considered to be the oil-water interface elevation and z_2 is considered to be the maximum elevation of LNAPL above the air-oil interface (ft)

Oil saturation is a function of capillary pressure (the difference between the pressure in the non-wetting phase and the pressure in the wetting phase) and varies across the vertical impacted zone in a non-linear manner as shown in Figure 7.

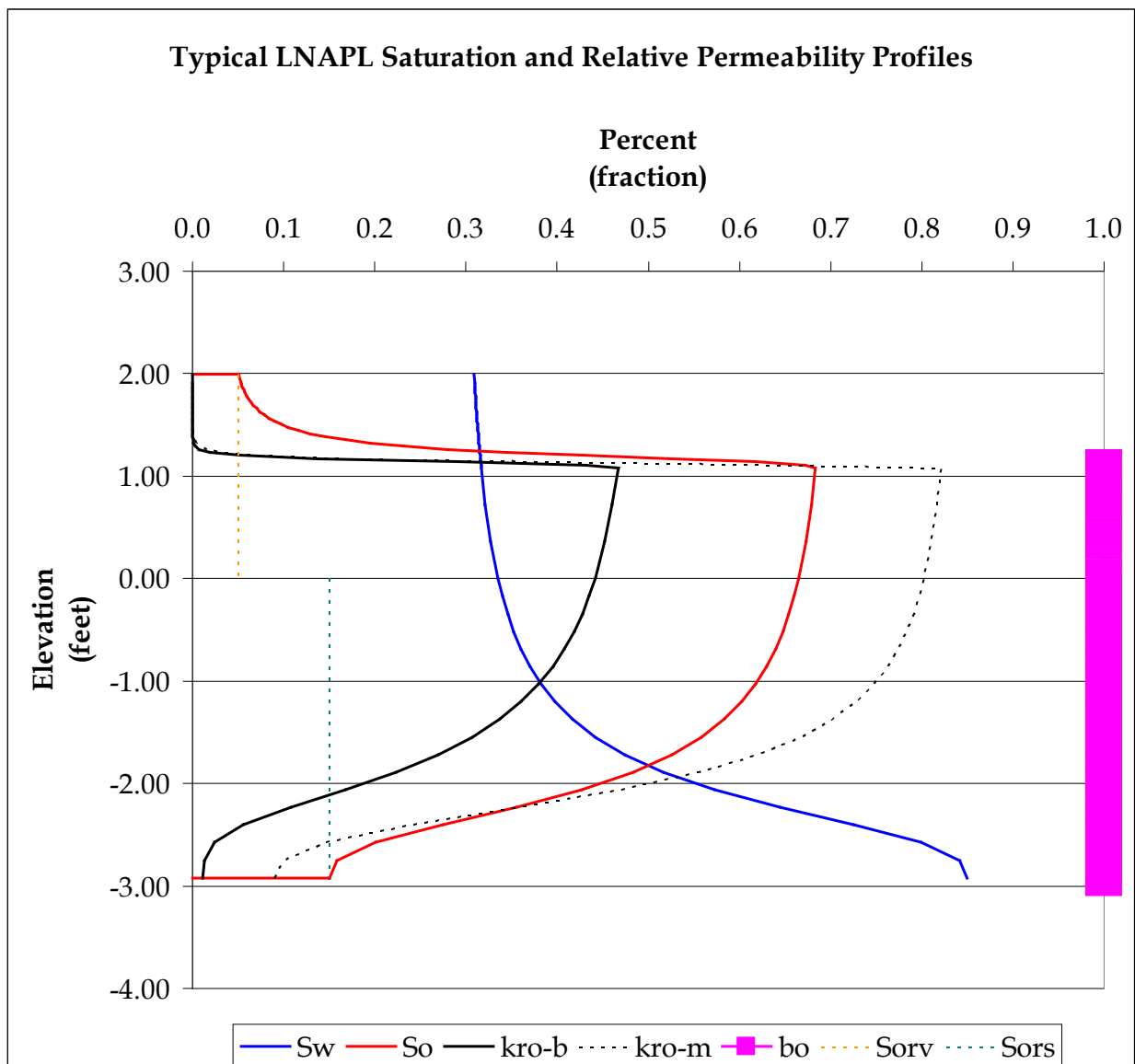


Figure 7 – Idealized LNAPL Saturation and Relative Permeability Profiles

- Sw = Water Saturation Profile
- So = Oil/LNAPL Saturation Profile
- kro-b = Oil/LNAPL Relative Permeability Profile using Burdine Calculation
- kro-m = Oil/LNAPL Relative Permeability Profile using Mualem Calculation
- bo = In-Well Oil/LNAPL Thickness
- Sorv = Oil/LNAPL Residual Saturation in the Vadose Zone
- Sors = Oil/LNAPL Residual Saturation in the Saturated Zone

Note: the “Elevation” axis is referred to as the z-axis, with the theoretical water table elevation set at 0.00 feet, and the following elevation references:

$z_{\max}/z_2$	=	Maximum Oil/LNAPL Elevation in the Capillary Fringe
z_{ow}/z_1	=	Minimum Oil/LNAPL Elevation, equivalent to the Oil/Water Elevation in Well
z_{ao}	=	Maximum Oil/LNAPL Elevation in the Well, or the Air/Oil Interface Elevation

Hence, Equation 4.2 cannot be evaluated analytically. However, a simplified expression of the specific oil volume averaged across the vertical LNAPL saturation profile can be expressed as (API, 2004):

$$\overline{V_o} = b_o \phi \overline{S_o} \quad (4.3)$$

Where:

$$\begin{aligned} \overline{V_o} &= \text{mean oil specific volume averaged across the saturation profile (ft}^3\text{/ft}^2\text{)} \\ b_o &= \text{vertical extent of LNAPL impacts (ft)} \\ \overline{S_o} &= \text{mean oil saturation averaged across the saturation profile (dimensionless)} \end{aligned}$$

The oil transmissivity is expressed as:

$$T_o = \frac{\rho_o}{\rho_w} \frac{\mu_w}{\mu_o} \int_{z_1}^{z_2} k_{ro} K_w dz \quad (4.4)$$

Where:

$$\begin{aligned} \rho_o &= \text{oil density (g/cm}^3\text{)} \\ \rho_w &= \text{water density (g/cm}^3\text{)} \\ \mu_o &= \text{oil viscosity (cp)} \\ \mu_w &= \text{water viscosity (cp)} \\ k_{ro} &= \text{oil relative permeability (dimensionless)} \\ K_w &= \text{water hydraulic conductivity (cm/s)} \end{aligned}$$

Oil relative permeability is a function of oil saturation and varies across the vertical impacted zone in a non-linear manner as shown in Figure 7. Hence, Equation 4.4 cannot be evaluated analytically. However, a simplified expression of the free oil transmissivity averaged across the vertical LNAPL saturation profile can be expressed as (API, 2004):

$$\overline{T_o} = b_o \overline{K_o} \quad (4.5)$$

Where:

$$\begin{aligned}\overline{T_o} &= \text{mean oil transmissivity averaged across the saturation profile (ft}^2\text{/day)} \\ \overline{K_o} &= \text{mean oil conductivity averaged across the saturation profile (ft/day)}\end{aligned}$$

Substituting Equations 4.3 and 4.5 into Equation 4.1 results in a simplified expression to determine inherent mobility at any location within an LNAPL body:

$$\overline{M_o} = \frac{b_o \overline{K_o}}{b_o \phi \overline{S_o}} = \frac{\overline{K_o}}{\phi \overline{S_o}} \quad (4.6)$$

Where:

$$\overline{M_o} = \text{mean inherent oil mobility (ft/day)}$$

Therefore, the mean inherent oil mobility is equivalent to the ratio of the average oil conductivity to the effective free oil porosity (API, 2004).

It is important to recognize that the inherent LNAPL mobility only defines the potential for LNAPL movement (API, 2004). Although described in terms of “length per time” (feet per day, centimeters per second), it does not explicitly define LNAPL migration. To determine the movement of a LNAPL requires defining the oil gradient in addition to inherent mobility, both of which are needed to evaluate LNAPL body stability.

Equation 4.6 is expressed as a function of “mean” or “average” saturation and oil conductivity to yield a mean mobility value. A mean value is typically used for mobility calculations because LNAPL saturation, conductivity and relative permeability vary across the vertical LNAPL impacted zone both above and below the water table. The use of mean or average values for LNAPL saturation, relative permeability and conductivity is deemed to represent the inherent mobility of LNAPL on a macro-scale or plume-scale.

The mean oil conductivity is expressed as:

$$\overline{K_o} = \frac{\rho_o}{\mu_o} \overline{k_{ro}} kg \quad (4.7)$$

Where:

$$\begin{aligned}\overline{K_o} &= \text{mean oil conductivity (ft/day)} \\ \overline{k_{ro}} &= \text{mean oil relative permeability (dimensionless)} \\ k &= \text{soil permeability (ft}^2\text{)} \\ g &= \text{gravitational constant (ft/day}^2\text{)}\end{aligned}$$

The permeability of the soil is expressed as:

$$k = \frac{K_w \mu_w}{\rho_w g} \quad (4.8)$$

Consequently, Equation 4.7 can be re-written as:

$$\overline{K_o} = \overline{k_{ro}} K_w \frac{\rho_o \mu_w}{\rho_w \mu_o} \quad (4.9)$$

The density and viscosity values for water are close to one, and therefore may be eliminated from Equation 4.9.

The relative permeability of LNAPL represents the ability of the LNAPL to flow in the presence of water. Assuming that the LNAPL residual saturation in both the vadose zone and saturated zone are zero, LNAPL relative permeability can be expressed as a function of LNAPL saturation and water saturation based on the following three phase integration of the Burdine (1953) equations and Brooks and Corey (1964) soil characteristic model (API, 2003):

$$k_{ro}(S_w, S_o) = S_o^2 \left[\left(\frac{S_t - S_{wr}}{1 - S_{wr}} \right)^{\frac{\lambda+2}{\lambda}} - \left(\frac{S_w - S_{wr}}{1 - S_{wr}} \right)^{\frac{\lambda+2}{\lambda}} \right] \quad (4.10)$$

Where:

$$\begin{aligned}S_w &= \text{water saturation (dimensionless)} \\ S_o &= \text{oil saturation (dimensionless)} \\ S_t &= \text{total saturation } (S_w + S_o) \\ \lambda &= \text{pore size distribution index (dimensionless)} \\ S_{wr} &= \text{water residual (or irreducible) saturation (dimensionless)}\end{aligned}$$

The pore distribution size index is expressed as (API, 2003):

$$\lambda = \frac{M}{1-M} (1 - 0.5^{1/M}) \quad (4.11)$$

Where:

M = model fitting parameter (dimensionless)

M is determined from the expression (API, 2003, 2007):

$$M = 1 - \frac{2}{N} \quad ; \quad N > 2 \quad \text{Burdine} \quad (4.12)$$

$$M = 1 - \frac{1}{N} \quad ; \quad N > 1 \quad \text{Mualem (see below)} \quad (4.12)$$

Where:

N = van Genuchten model fitting parameter (dimensionless)

Alternatively, LNAPL relative permeability can be expressed as a function of LNAPL saturation and water saturation based on the following three phase integration of the Mualem (1976) equation with van Genuchten's soil characteristics function (Parker et al., 1987; API, 2003):

$$k_{ro}(S_w, S_o) = S_o^{1/2} \left\{ \left[1 - \left(\frac{S_w - S_{wr}}{1 - S_{wr}} \right)^{1/M} \right]^M - \left[1 - \left(\frac{S_t - S_{wr}}{1 - S_{wr}} \right)^{1/M} \right]^M \right\}^2 \quad (4.13)$$

Equations 4.10 and 4.13 predict different distributions of LNAPL relative permeability for the same set of fluid saturation values, with Equation 4.10 generally predicting smaller values for LNAPL relative permeability. Generally speaking, the Mualem equation (Equation 4.13) is believed to better predict LNAPL relative permeability in fine-grained soils (e.g., clays), whereas the Burdine equation (Equation 4.10) is believed to better predict LNAPL relative permeability in sands (U.S. EPA, 2005).

The mean (or effective) relative permeability of the LNAPL may be calculated from:

$$\overline{k_{ro}} = \frac{1}{b_o} \int_{z_1}^{z_2} k_{ro} dz \quad (4.14)$$

Equation 4.14 cannot be evaluated analytically. However, the mean oil relative permeability may be approximated from the relative oil permeability profile (graph) by:

$$\overline{k_{ro}} = \frac{1}{n} \sum_{i=1}^n k_{roi} \quad (4.15)$$

Where:

- n = number of equally spaced points between z_1 and z_2 (on z-axis) where the oil relative permeability is read off the relative permeability graph
- k_{roi} = LNAPL relative permeability value (dimensionless) at point ' i ' on the LNAPL relative permeability profile
- i = the specific point number on the relative permeability profile

Alternatively, the mean oil relative permeability may be approximated using a piecewise linear function (Note: some computer models including the API Interactive LNAPL Guide software calculate a mean oil relative permeability value).

As shown in Figure 7, LNAPL or oil saturation varies as a function of depth across the vertical LNAPL impacted zone. Assuming vertical equilibrium of the LNAPL and water, the water saturation across the LNAPL impacted zone may be expressed as (API, 2003):

$$S_w(z) = S_{wr} + (1 - S_{wr} - S_{ors}) \left[\frac{1}{1 + (\alpha_{ow}(z - z_{ow}))^N} \right]^M \quad (4.16)$$

Where:

- S_{ors} = oil residual saturation in the saturated zone (dimensionless)
- α_{ow} = capillary pressure head parameter between LNAPL and water (1/ft)
- z_{ow} = elevation of the oil-water interface in a monitoring well (ft)

The capillary pressure head between LNAPL and water is scaled appropriately to reflect the densities and interfacial tensions of the two fluids and is expressed as (API, 2003):

$$\alpha_{ow} = \left(1 - \frac{\rho_0}{\rho_w} \right) \left(\frac{\sigma_{aw}}{\sigma_{ow}} \right) \alpha \quad (4.17)$$

Where:

σ_{aw} = air-water interfacial tension (dynes/cm)

σ_{ow} = oil-water interfacial tension (dynes/cm)

α = van Genuchten model fitting parameter (dimensionless)

The total liquid saturation (LNAPL plus water) across the LNAPL impacted zone is expressed as (API, 2003):

$$S_t(z) = S_{wr} + S_{orv} + (1 - S_{wr} - S_{orv}) \left[\frac{1}{1 + (\alpha_{ao}(z - z_{ao}))^N} \right]^M \quad (4.18)$$

Where:

S_{orv} = oil residual saturation in the vadose zone (dimensionless)

α_{ao} = capillary pressure head parameter between air and LNAPL (1/ft)

z_{ao} = elevation of the air-oil interface in a monitoring well (ft)

The capillary pressure head between air and LNAPL is scaled appropriately to reflect the densities and interfacial tensions of the two fluids and is expressed as (API, 2003):

$$\alpha_{ao} = \frac{\rho_o}{\rho_w} \left(\frac{\sigma_{aw}}{\sigma_{ao}} \right) \alpha \quad (4.19)$$

Where:

σ_{ao} = air-LNAPL interfacial tension (dynes/cm)

Hence, the LNAPL saturation is obtained from the expression (API, 2003):

$$S_o(z) = S_t(z) - S_w(z) \quad (4.20)$$

A typical LNAPL saturation profile (as determined by Equations 4.16 through 4.20), and relative permeability profile (as determined by Equations 4.10 through 4.13), corresponding to an in-well LNAPL thickness of 4.0 feet in a sandy soil, is illustrated in Figure 7.

The mean oil saturation may be calculated from:

$$\overline{S_o} = \frac{1}{b_o} \int_{z_1}^{z_2} S_o dz \quad (4.21)$$

Equation 1.21 cannot be evaluated analytically. However, the mean oil saturation may be approximated from the oil saturation profile (graph) by:

$$\overline{S_o} = \frac{1}{n} \sum_{i=1}^n S_{oi} \quad (4.22)$$

Where:

- n = number of equally spaced points between z_1 and z_2 (on z-axis) where the oil saturation is read off the oil saturation graph
- S_{oi} = LNAPL saturation value (dimensionless) at point 'i' on the LNAPL saturation profile
- i = the specific point number on the saturation profile

Alternatively, the mean oil saturation may be approximated using a piecewise linear function (Note: some computer models including the API Interactive LNAPL Guide software calculate a mean oil saturation value).

As shown in Figure 7, the LNAPL saturation varies across the LNAPL impacted zone. For the purposes of calculating LNAPL mobility, one can use "mean" or "average" values for relative permeability, conductivity and saturation to calculate (using Equation 4.6) the average LNAPL mobility across the vertical LNAPL impacted zone. Alternatively, if one determines the maximum LNAPL saturation value, either through calculation or a combination of field and laboratory techniques, then an approximate "worst-case" scenario for LNAPL mobility may be calculated using Equation 4.6.

4.2 LNAPL Specific Discharge and Velocity Equations

As previously mentioned, to determine the movement of a LNAPL requires defining the oil gradient in addition to inherent mobility, both of which are needed to evaluate LNAPL body stability. The LNAPL specific discharge is expressed as:

$$\overline{q_o} = \overline{K_o} i_o \quad (4.23)$$

Where:

$\overline{q_o}$ = mean oil specific discharge (ft/year)
 i_o = oil gradient (often assumed to be equal to the water table gradient)

The seepage velocity of the LNAPL is based on the specific discharge while correcting for the effective porosity of the formation. The seepage velocity is the potential average velocity of the LNAPL within connected or continuous pore throats and is expressed as:

$$v_o = \frac{\overline{q_o}}{\phi_{eff}} \quad (4.24)$$

Where:

v_o = oil seepage velocity (ft/year)
 ϕ_{eff} = effective porosity (dimensionless)

The effective porosity of the oil or the free oil porosity is expressed as:

$$\phi_{eff} = \phi \overline{S_o} \quad (4.25)$$

Consequently, equation 4.24 may be re-written as:

$$v_o = \frac{\overline{K_o}}{\phi \overline{S_o}} \cdot i_o \quad (4.26)$$

Which represents the inherent oil mobility (M_o) from Equation 4.6, multiplied by the LNAPL gradient.

4.3 LNAPL Immobility

LNAPL bodies are spatially self-limiting unless continually supplied from an on-going release, thus distinguishing LNAPLs from dissolved and vapor plumes that may migrate significant distances (API, 2004). Typically, once the release of free product stops, LNAPL in the water table region will eventually cease to move as the resistive forces in the saturated soils balance the driving forces in the LNAPL pool (Huntley and Beckett, 2001). The endpoint of this movement is when the LNAPL reaches field residual saturation, a condition where effective hydraulic conductivity of the LNAPL is zero (Huntley and Beckett, 2001).

The LNAPL velocity from Equation 4.26 does not account for the resistive forces impeding LNAPL movement at the body periphery (i.e., it does not recognize the fact that the Darcy flow equations for multi-phase fluid flow do not apply outside of a stable LNAPL body). This may lead to misleading calculations of LNAPL velocities that are not evident in the field.

When evaluating LNAPL velocities within the confines of a stable LNAPL body and/or at the periphery of a migrating LNAPL body, it is recommended that a lower limit to velocity potential be used as a screening value. For instance, landfill liners may have allowable seepage potentials of 1×10^{-6} cm/s (ASTM, 2005). Hence, an LNAPL velocity of 1×10^{-6} cm/s or less can be used as a *de minimis* mobility level for LNAPL (ASTM, 2007).

Section 5.0 LNAPL Specific Volume and Recoverable Volume

The specific volume of LNAPL defined by Equation 4.2 represents the area beneath (to the left of) the LNAPL saturation curve (see Figure 7) multiplied by the total soil porosity. As previously stated, Equation 4.2 cannot be evaluated analytically. However, Equation 4.3 provides an expression to solve for the mean oil specific volume (averaged across the saturation profile) as a function of mean LNAPL saturation, vertical extent of LNAPL impacts, and soil porosity. Mean LNAPL saturation can be determined graphically as defined by Equation 4.22. Once the mean LNAPL saturation is calculated, the LNAPL specific volume may be determined using Equation 4.3. Alternatively, the LNAPL specific volume may be determined graphically from the expression:

$$\overline{V}_o = (z_{\max} + |z_{ow}|) \frac{1}{n} \sum_{i=1}^n \phi S_{oi} \quad (4.27)$$

Where:

- $\overline{V}_o$ = LNAPL specific volume (ft³/ft²)
- $z_{\max}$ = z_2 , representing maximum elevation of LNAPL above the air-oil interface (ft)
- z_{ow} = elevation of LNAPL/water interface (ft)
- n = number of equally spaced points between z_1 and z_2 (on z-axis) where the oil saturation is read off the oil saturation graph
- S_{oi} = LNAPL saturation value (dimensionless) at point 'i' on the LNAPL saturation profile
- i = the specific point number on the saturation profile
- ϕ = total soil porosity

Equation 4.27 is approximately equal to the simplified expression for specific volume provided in Equation 4.3.

It is important to note that the LNAPL specific volume includes both the recoverable LNAPL (at saturations above residual saturation) and non-recoverable LNAPL (at saturations equal to or less than residual saturation). Recoverable LNAPL includes only LNAPL at saturations above residual saturation. On the LNAPL saturation profile (Figure 7), the recoverable LNAPL is represented by that portion of the area beneath (to the left of) the saturation curve and to the right of the vertical residual saturation lines (vadose and saturated). When residual saturations (vadose and saturated) are set equal to zero, the LNAPL specific volume is equal to the LNAPL recoverable volume.

LNAPL recoverable volume is equal to the LNAPL specific volume minus the volume of LNAPL at saturations less than residual. Hence, the LNAPL recoverable volume is defined by:

$$\overline{V}_r = (z_{\max} + |z_{ow}|) \frac{1}{n} \sum_{i=1}^n \phi S_{oi} - \{z_{\max} (S_{orv}) \phi + |z_{ow}| (S_{ors}) \phi\} \quad (4.28)$$

or:

$$\overline{V}_r = \overline{V}_o - \{z_{\max} (S_{orv}) \phi + |z_{ow}| (S_{ors}) \phi\}$$

Where:

$$V_r = \text{LNAPL recoverable volume (ft}^3\text{/ft}^2\text{)}$$

If the approximate dimensions of an LNAPL body are known (length and width), then the approximate total volume of LNAPL may be determined by multiplying the area of the body by the LNAPL specific volume. Similarly, the recoverable volume of LNAPL may be determined by multiplying the area of the body by the LNAPL recoverable volume. However, it is important to note that the calculations of total and recoverable LNAPL volumes are based on vertical equilibrium assumptions for the fluids and homogeneous soils (refer to Section 1.0), and may not be indicative of actual site conditions. Hence, LNAPL specific volume and recoverable volume calculations should be viewed, at best, as rough order of magnitude approximations for qualitative screening purposes.

Section 6.0 References

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Appendix D

Example LIF/UVOST Profile

UVOST Log Reference Guide

Main Plot :

Signal (total fluorescence) versus depth where signal is relative to the Reference Emitter (RE). The total area of the waveform is divided by the total area of the Reference Emitter yielding the %RE. This %RE scales with the NAPL fluorescence. The fill color is based on relative contribution of each channel's area to the total waveform area (see callout waveform). The channel-to-color relationship and corresponding wavelengths are given in the upper right corner of the main plot.

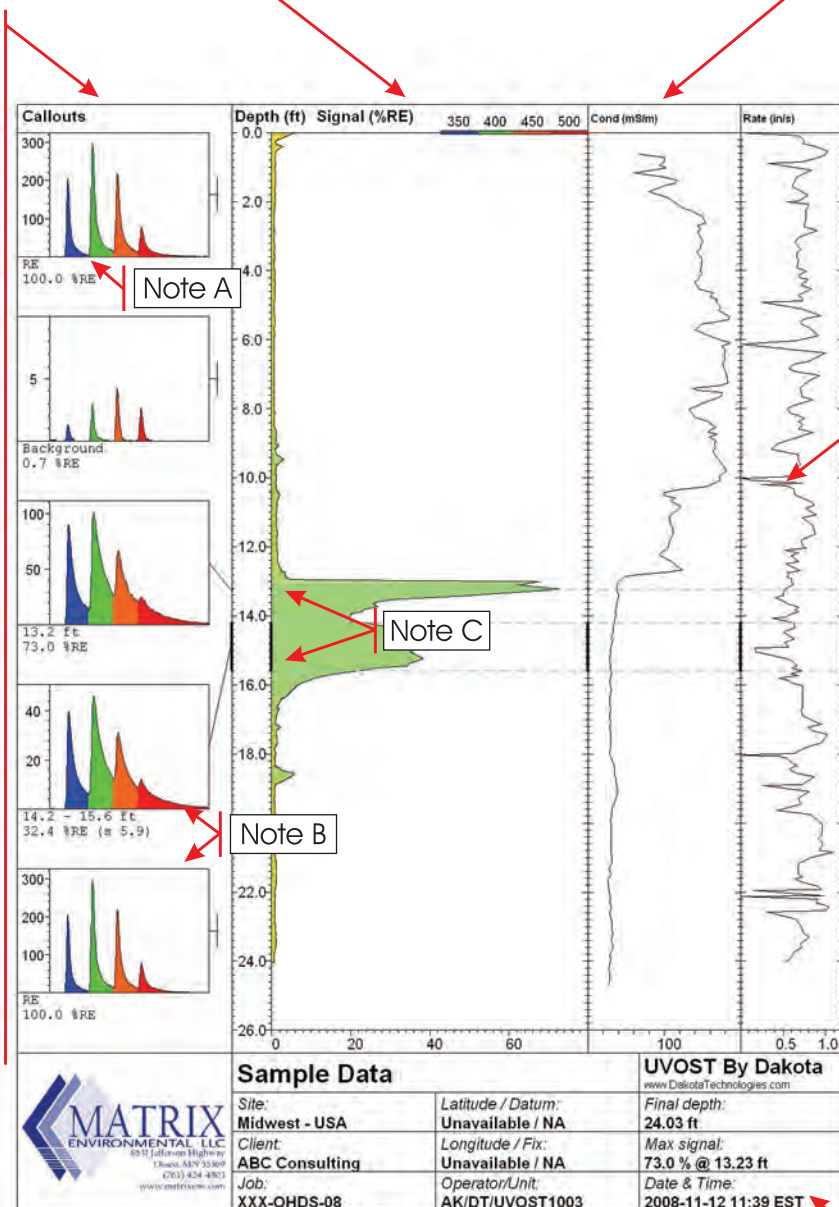
Callouts :

Waveforms from selected depths or depth ranges showing the multi-wavelength waveform for that depth.

The four peaks are due to fluorescence at four wavelengths and referred to as "channels". Each channel is assigned a color.

Various NAPLs will have a unique waveform "fingerprint" due to the relative amplitude of the four channels and/or broadening of one or more channels.

Basic waveform statistics and any operator notes are given below the callout.



Conductivity Plot :

The Electrical Conductivity (EC) of the soil can be logged simultaneously with the UVOST data. EC often provides insight into the stratigraphy. Note the drop in EC from 10 - 13 ft, indicating a shift from consolidated to unconsolidated stratigraphy. This correlates with the observed NAPL distribution.

Rate Plot :

The rate of probe advancement. ~ 0.8 in (2cm) per second is preferred.

A noticeable decrease in the rate of advancement may be indicative of difficult probing conditions (gravel, angular sands, etc.).

Notice that this log was terminated arbitrarily, not due to "refusal", which would have been indicated by a sudden rate drop at final depth.

Info Box :

Contains pertinent log info including name and location.

Note A:

Time is along the x axis. No scale is given, but it is a consistent 320ns wide.

The y axis is in mV and directly corresponds to the amount of light striking the photodetector.

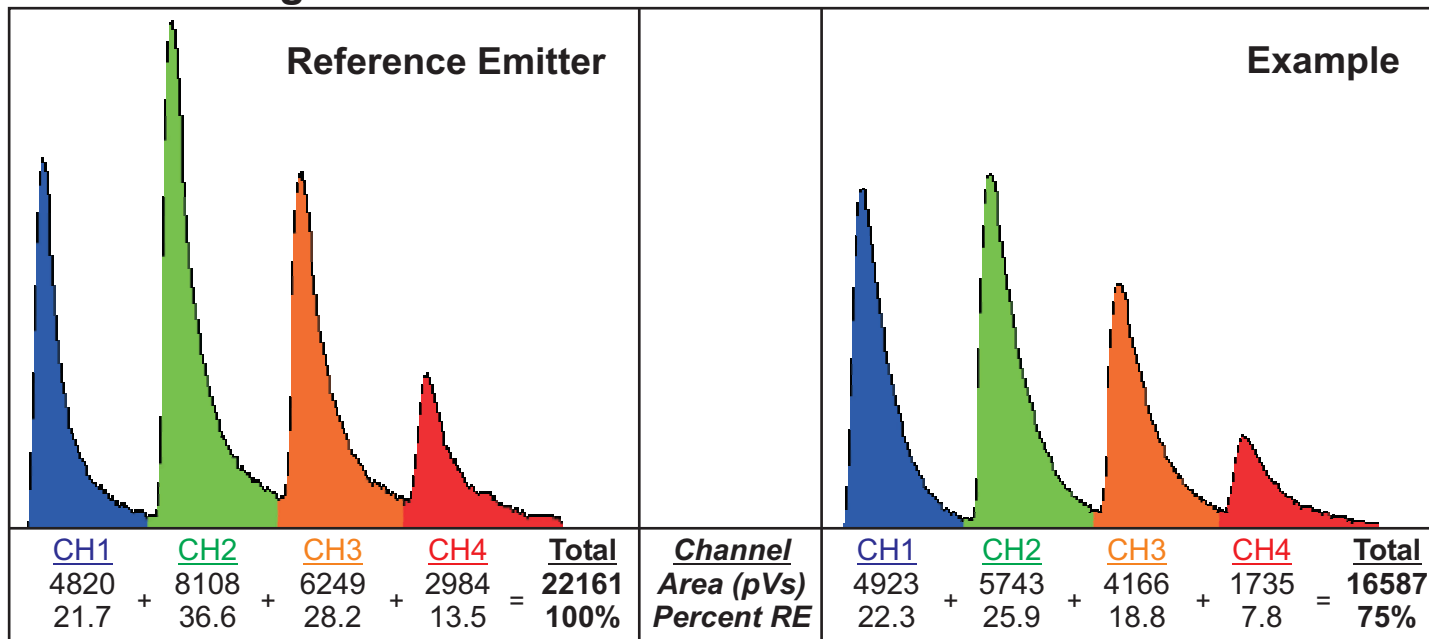
Note B :

These two waveforms are clearly different. The first is weathered diesel from the log itself while the second is the Reference Emitter (a blend of NAPLs) always taken before each log for calibration.

Note C :

Callouts can be a single depth (see 3rd callout) or a range (see 4th callout). The range is noted on the depth axis by a bold line. When the callout is a range, the average and standard deviation in %RE is given below the callout.

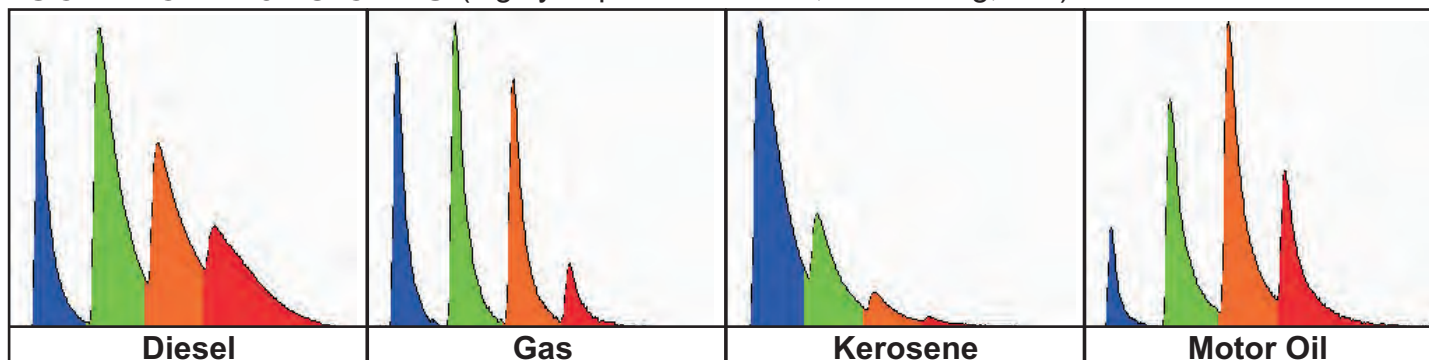
Waveform Signal Calculation



Data Files

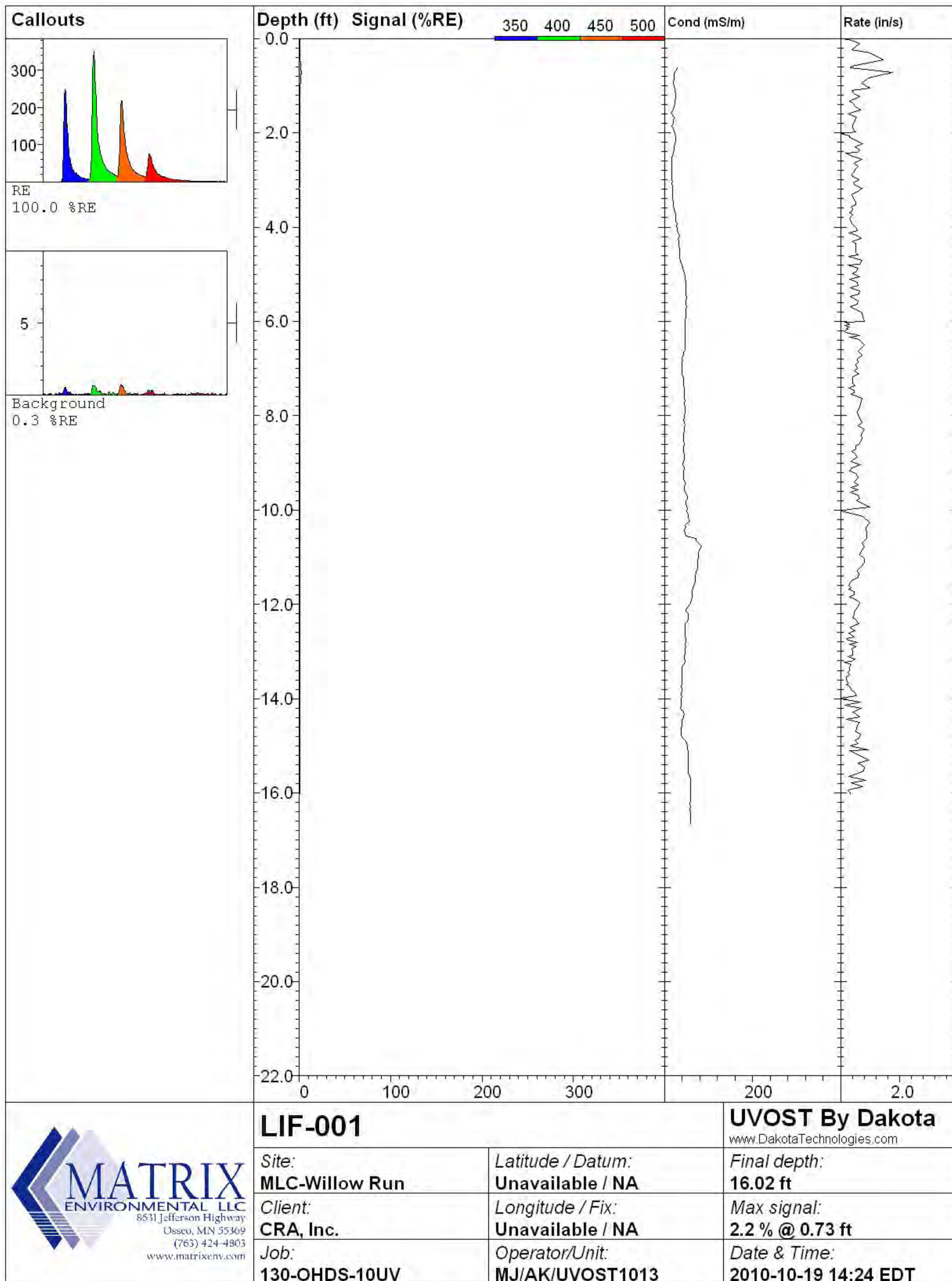
*.lif.raw.bin	Raw data file. Header is ASCII format and contains information stored when the file was initially written (e.g. date, total depth, max signal, gps, etc., and any information entered by the operator). All raw waveforms are appended to the bottom of the file in a binary format.
*.lif.plt	Stores the plot scheme history (e.g. callout depths) for associated Raw file. Transfer along with the Raw file in order to recall previous plots.
*.lif.jpg	A jpg image of the OST log including the main signal vs. depth plot, callouts, information, etc.
*.lif.dat.txt	Data export of a single Raw file. ASCII tab delimited format. No string header is provided for the columns (to make importing into other programs easier). Each row is a unique depth reading. The columns are: Depth, Total Signal (%RE), Ch1%, Ch2%, Ch3%, Ch4%, Rate, Conductivity Depth, Conductivity Signal. Summing channels 1 to 4 yields the Total Signal.
*.lif.sum.txt	A summary file for a number of Raw files. ASCII tab delimited format. The file contains a string header. The summary includes one row for each Raw file and contains information for each file including: the file name, gps coordinates, max depth, max signal, and depth at which the max signal occurred.
*.lif.log.txt	An activity log generated automatically located in the OST application directory in the 'log' subfolder. Each OST unit the computer operates will generate a separate log file per month. A log file contains much of the header information contained within each separate Raw file, including: date, total depth, max signal, etc.

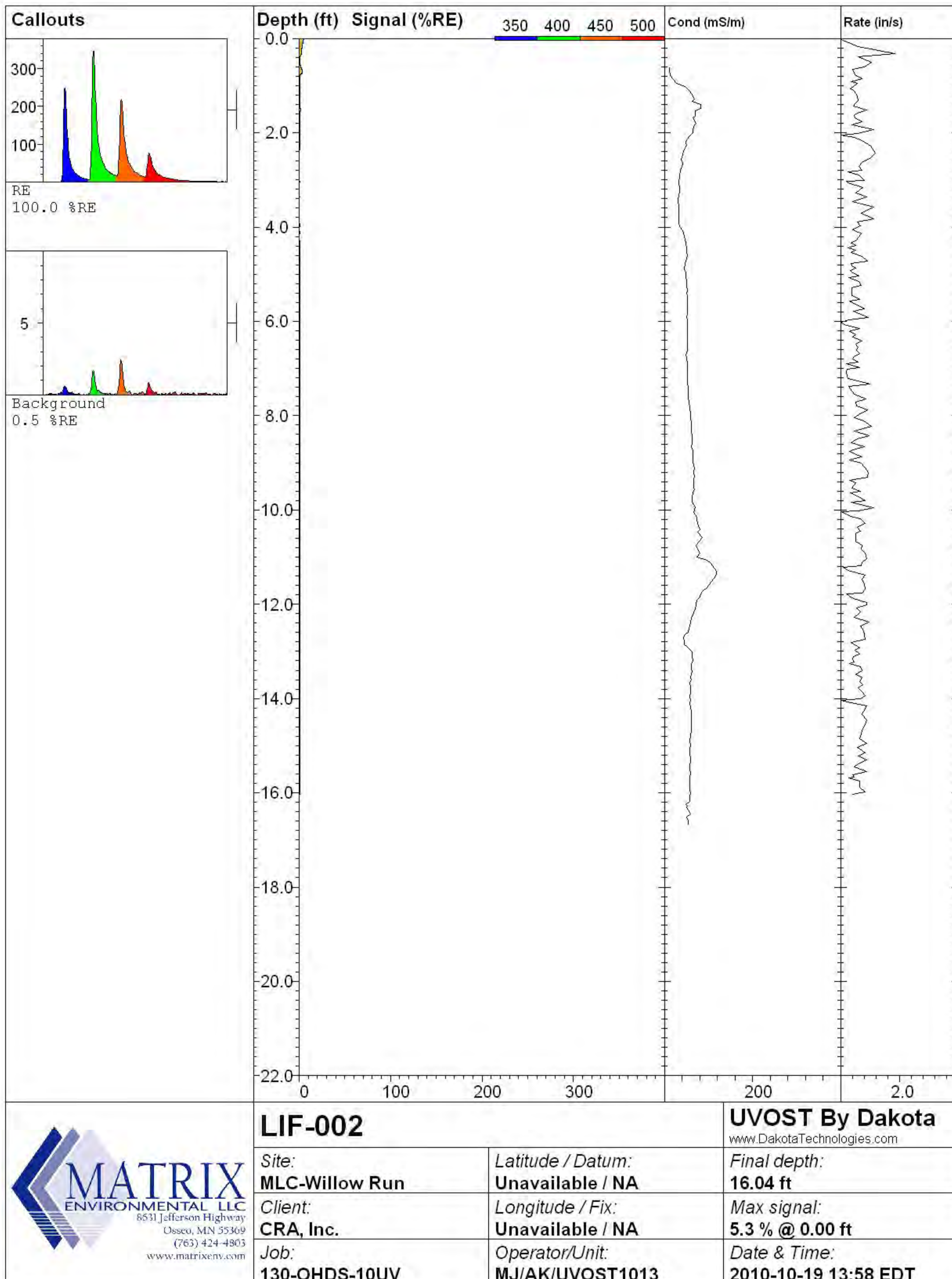
Common Waveforms (highly dependent on soil, weathering, etc.)

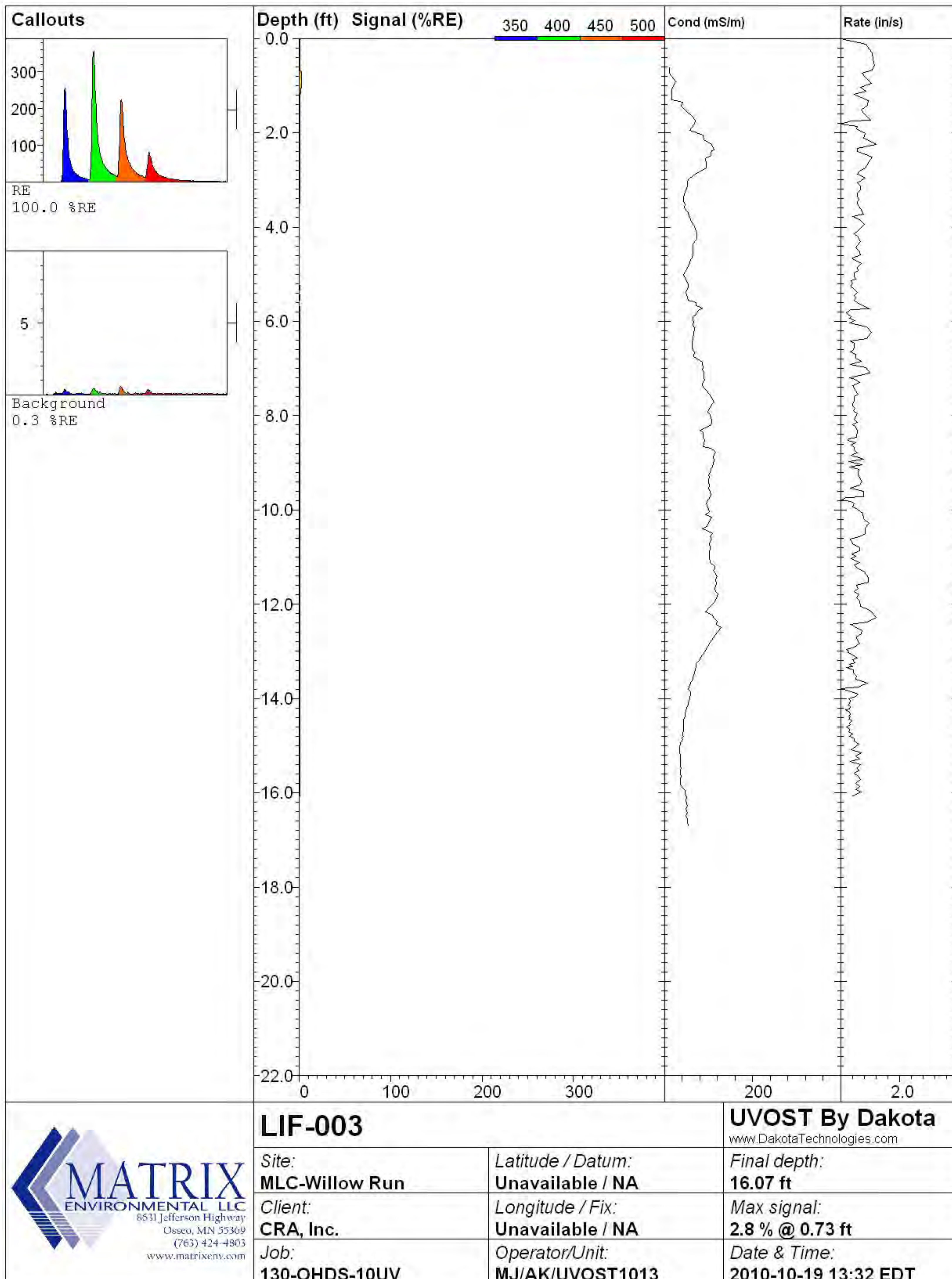


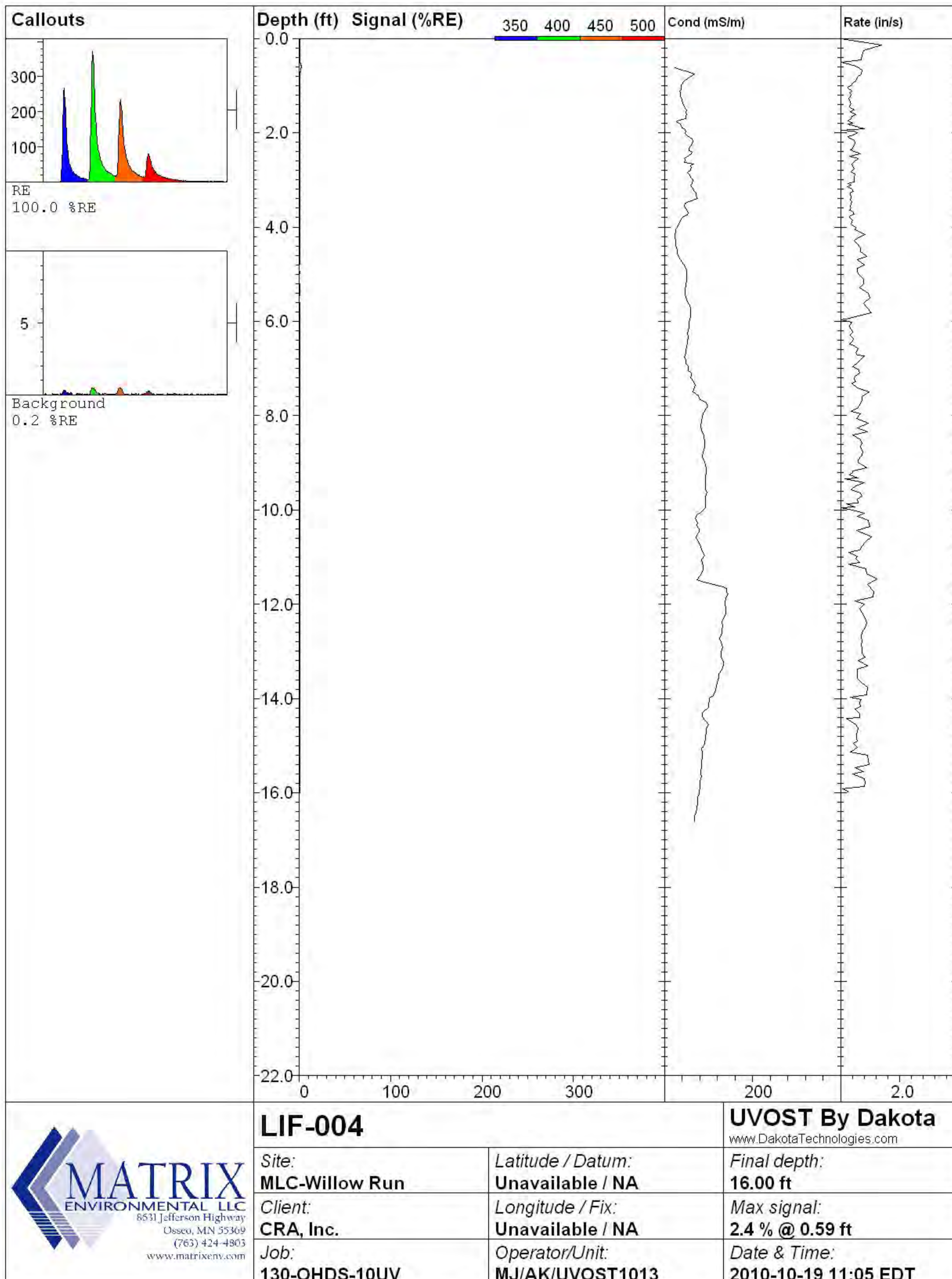
Appendix E

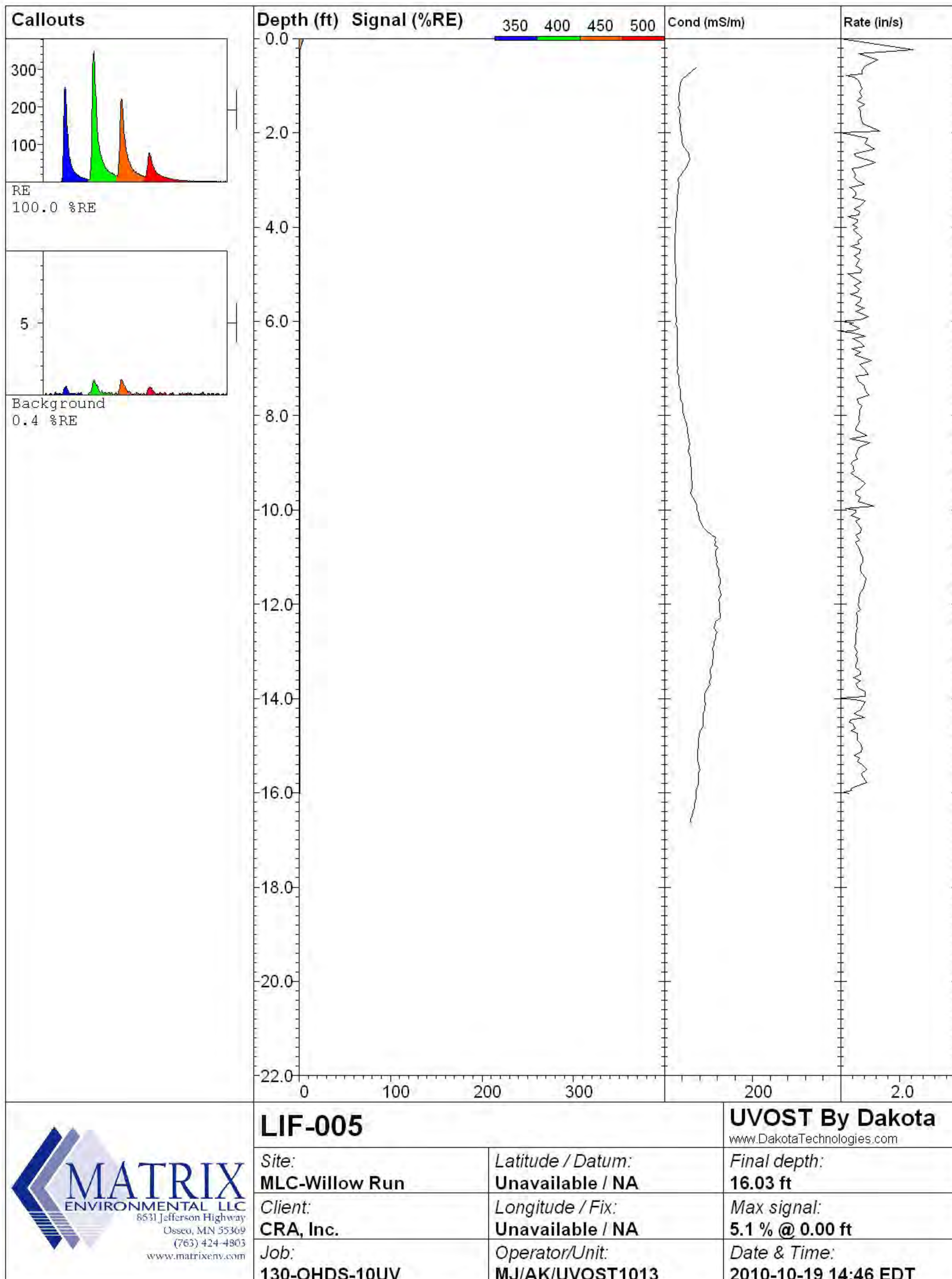
LIF/UVOST Survey Results

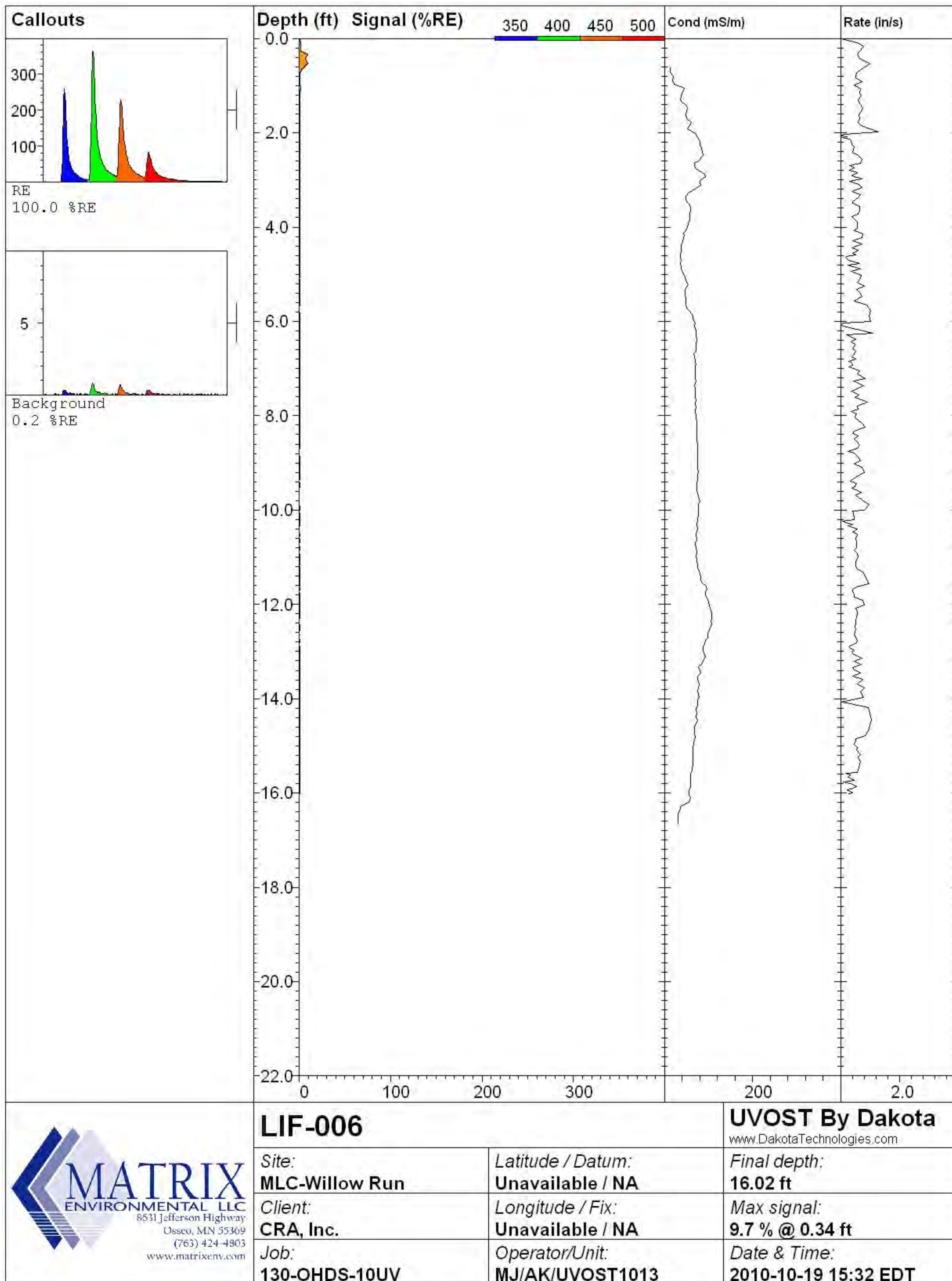


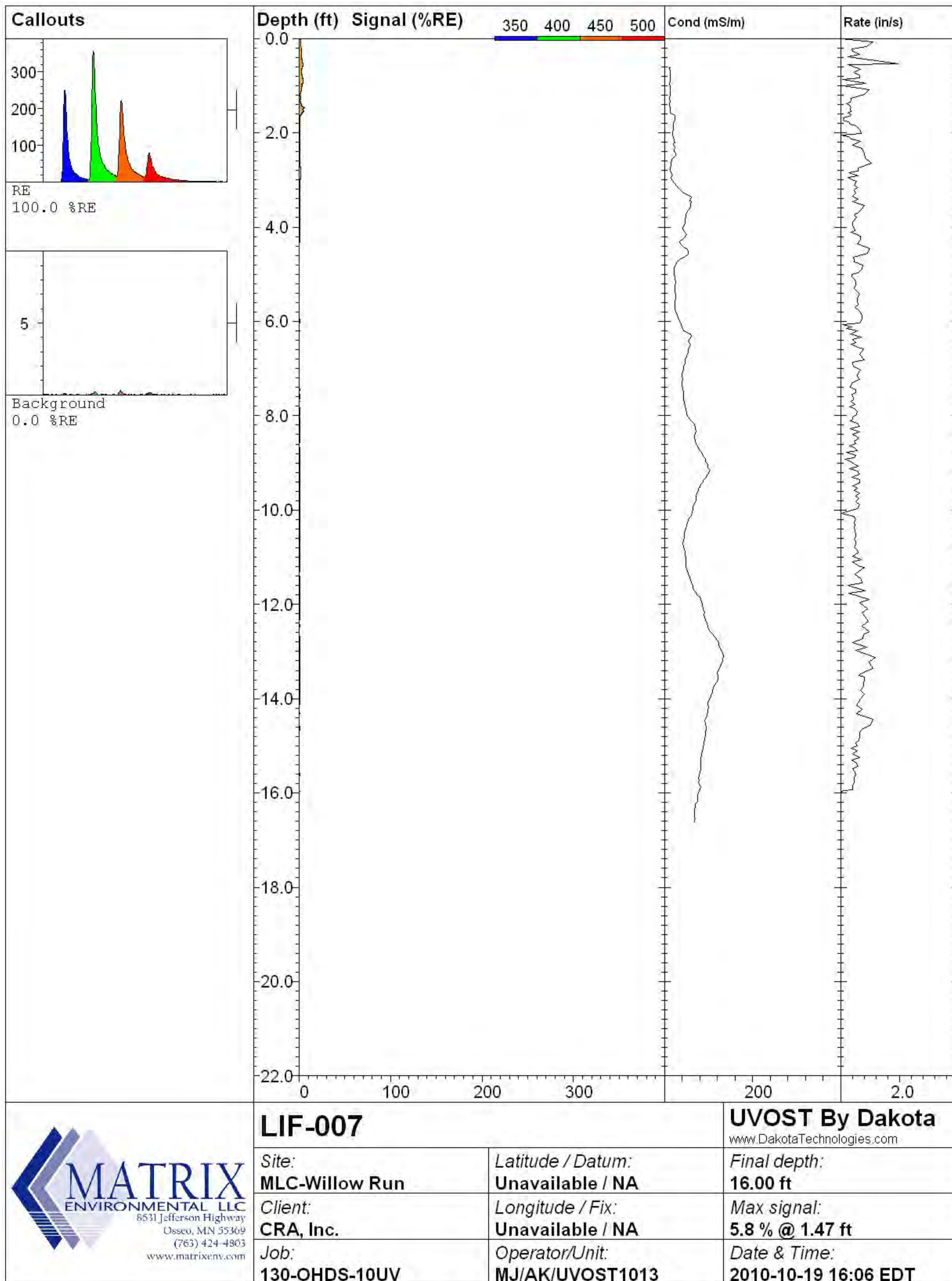


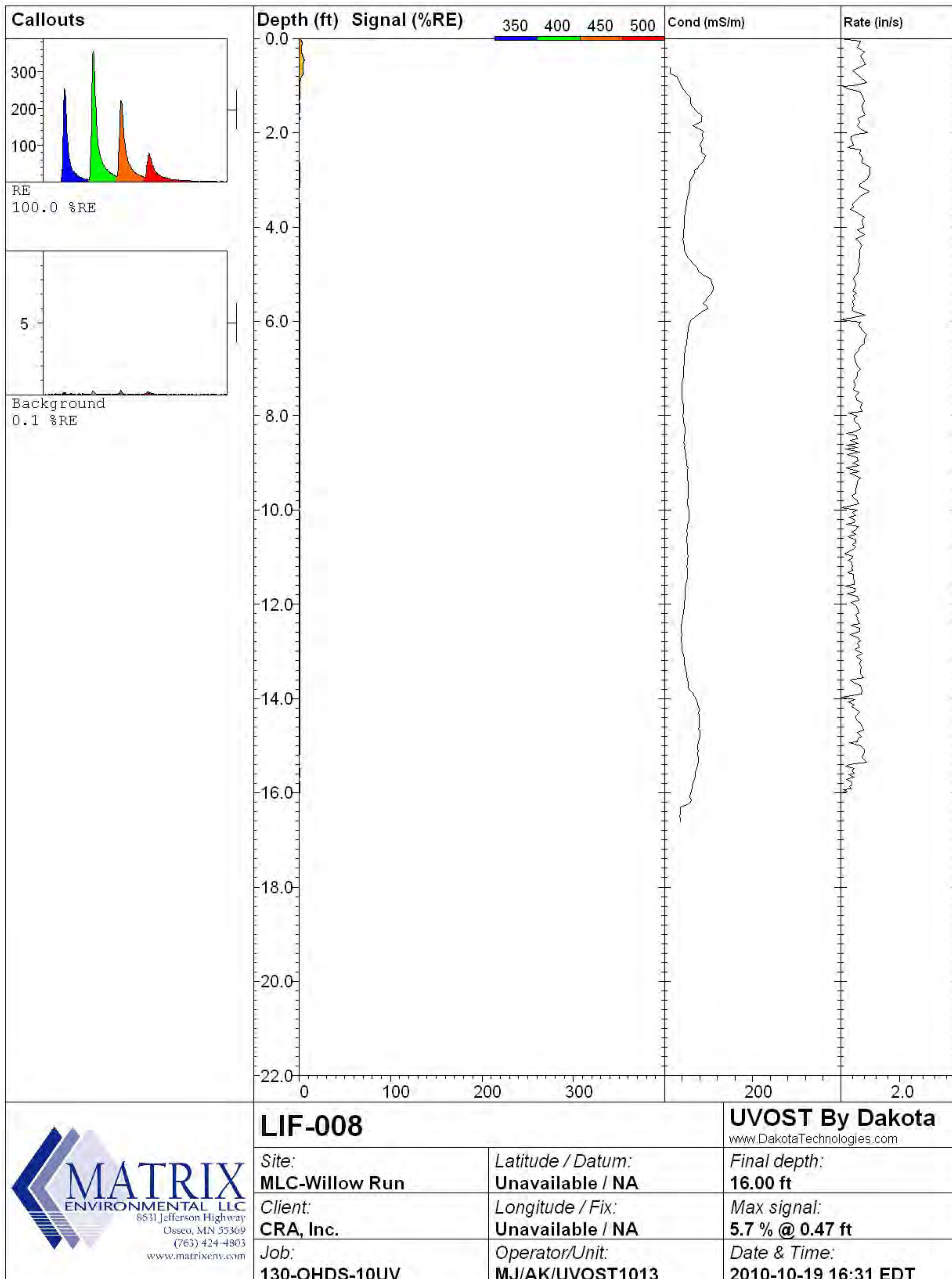


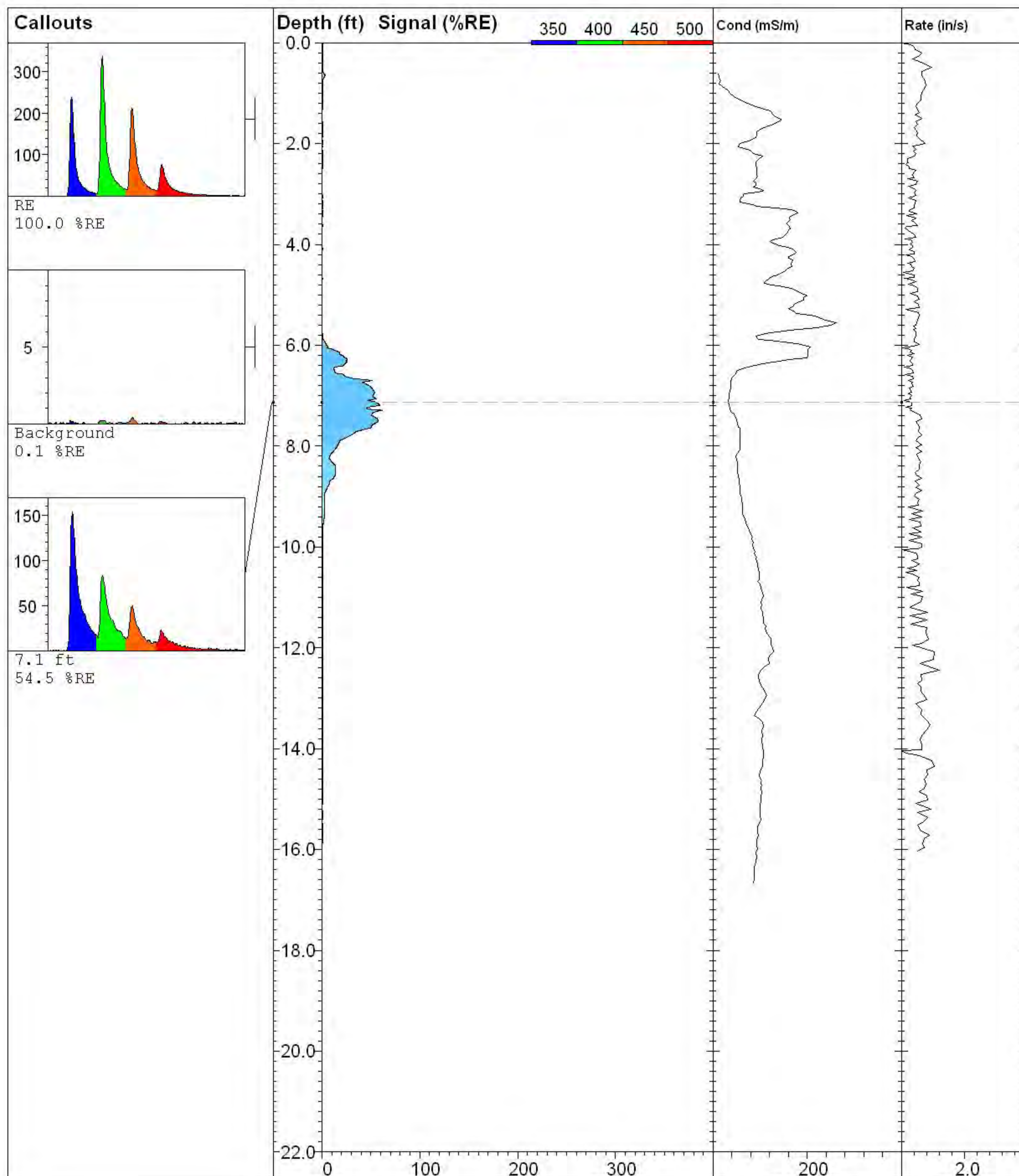












LIF-009

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.03 ft

Client:
CRA, Inc.

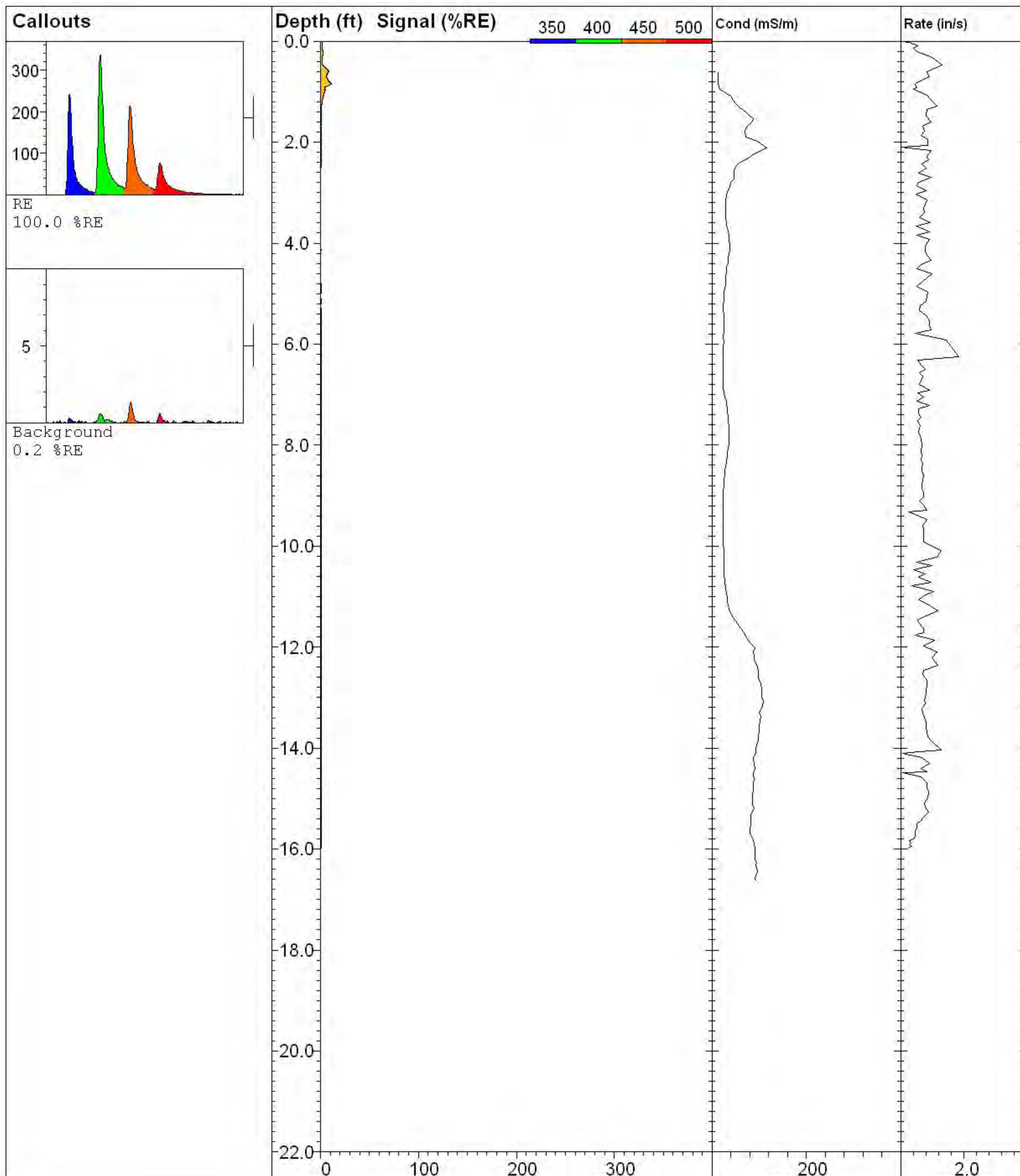
Longitude / Fix:
Unavailable / NA

Max signal:
63.4 % @ 7.29 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-20 13:29 EDT



LIF-010

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
15.98 ft

Client:
CRA, Inc.

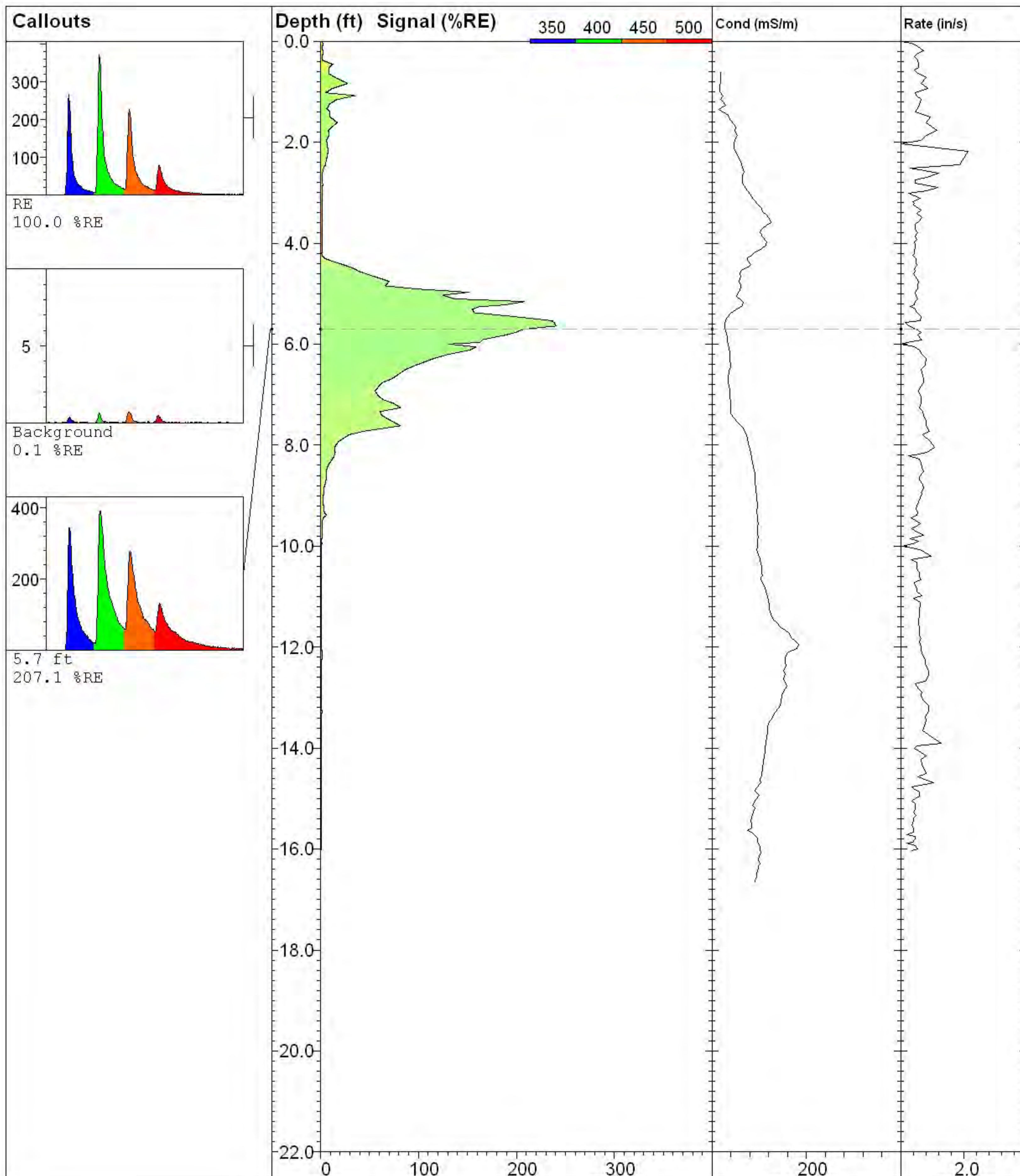
Longitude / Fix:
Unavailable / NA

Max signal:
11.1 % @ 0.85 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-20 13:58 EDT



LIF-011

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.03 ft

Client:
CRA, Inc.

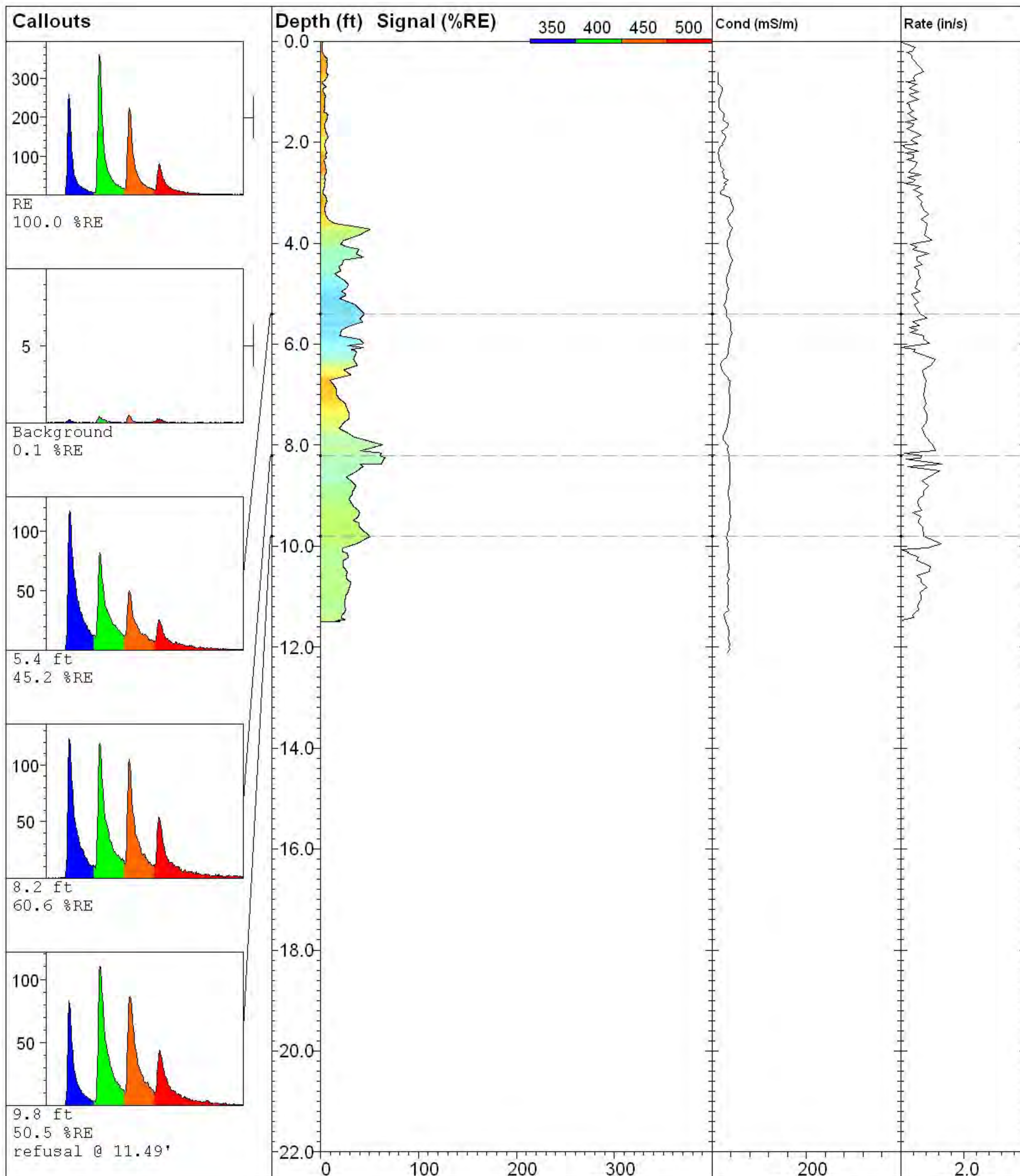
Longitude / Fix:
Unavailable / NA

Max signal:
240.4 % @ 5.64 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-18 17:02 EDT



LIF-012

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
11.49 ft

Client:
CRA, Inc.

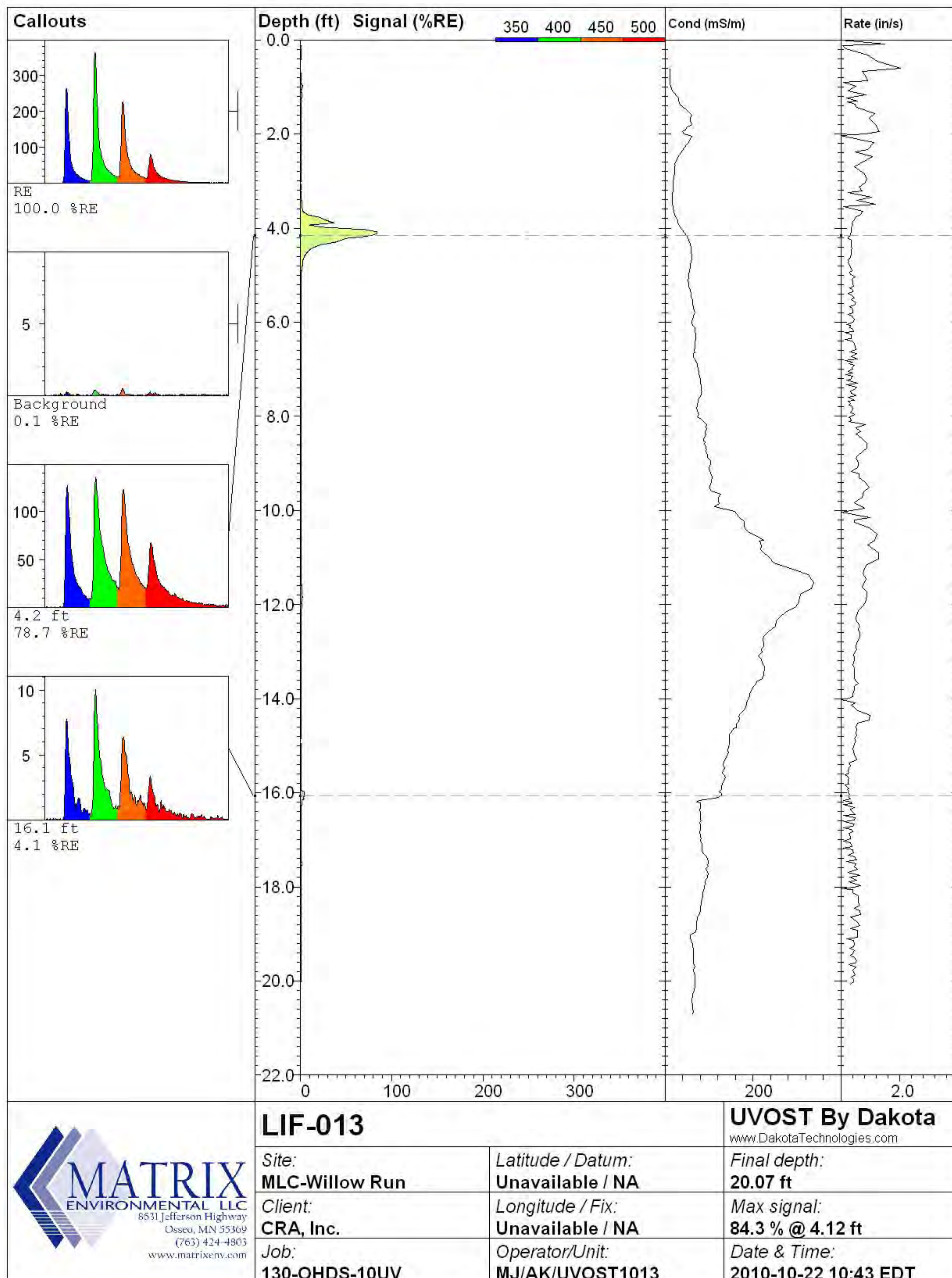
Longitude / Fix:
Unavailable / NA

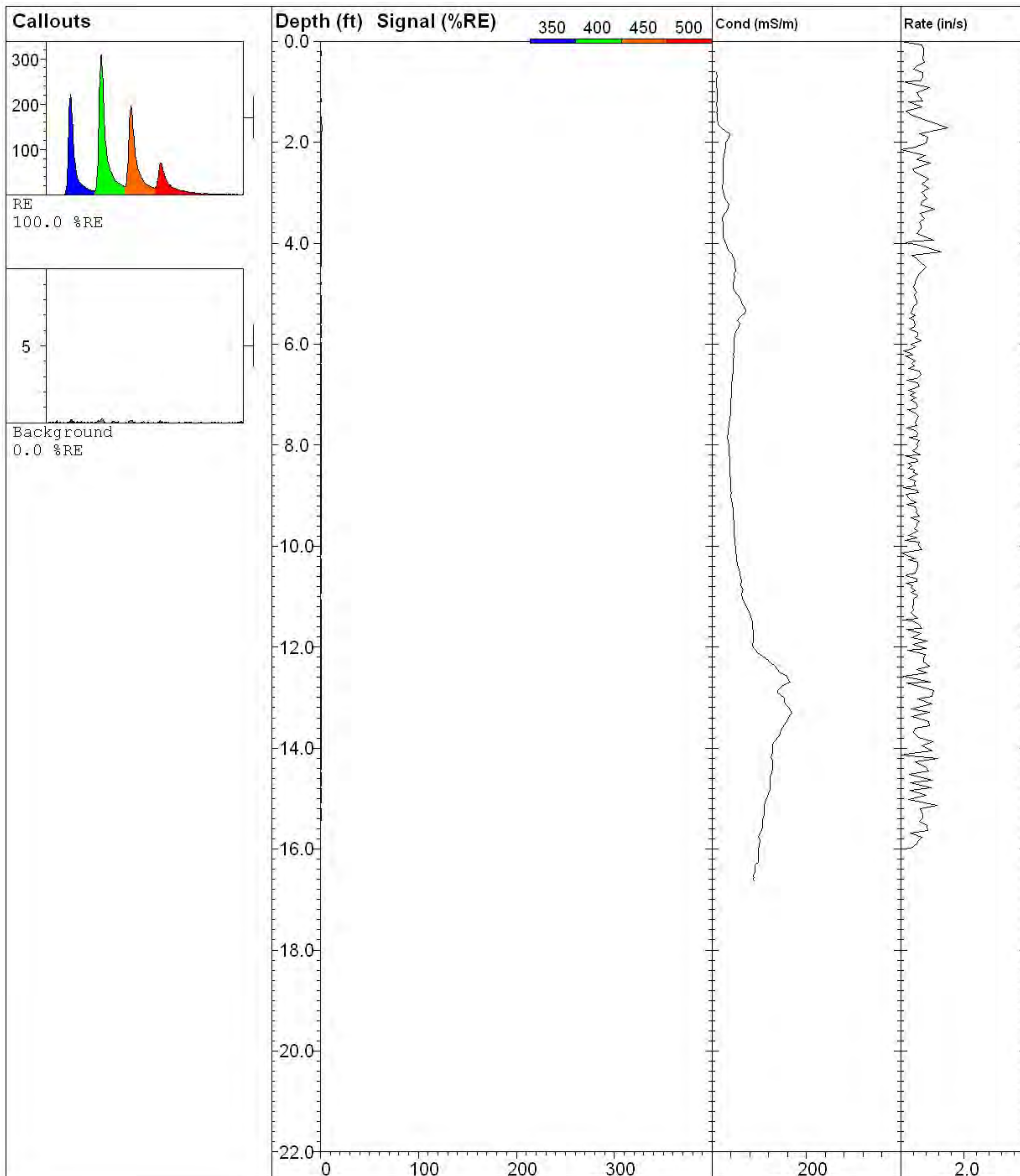
Max signal:
66.1 % @ 8.25 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-18 17:34 EDT





LIF-014

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.01 ft

Client:
CRA, Inc.

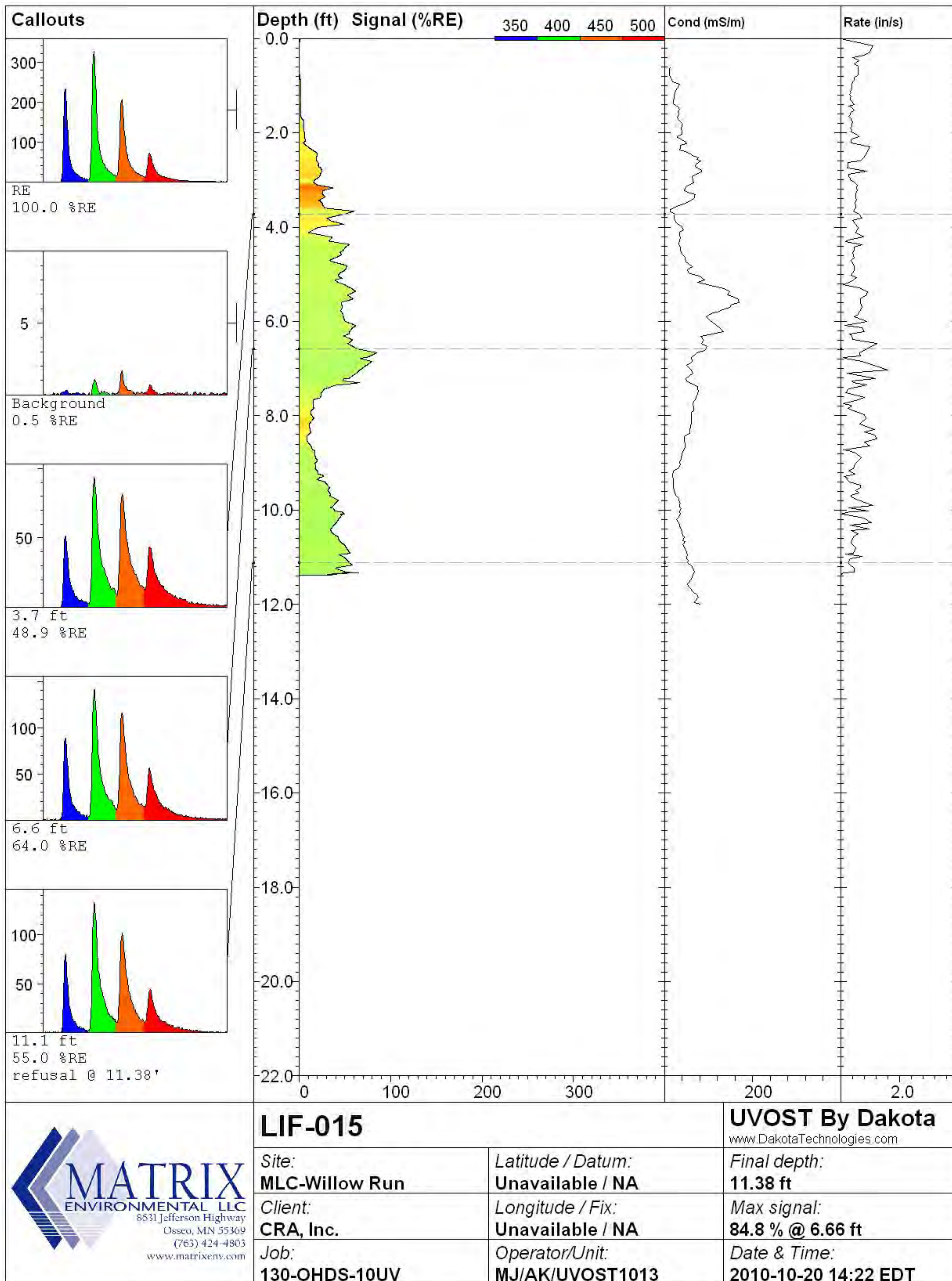
Longitude / Fix:
Unavailable / NA

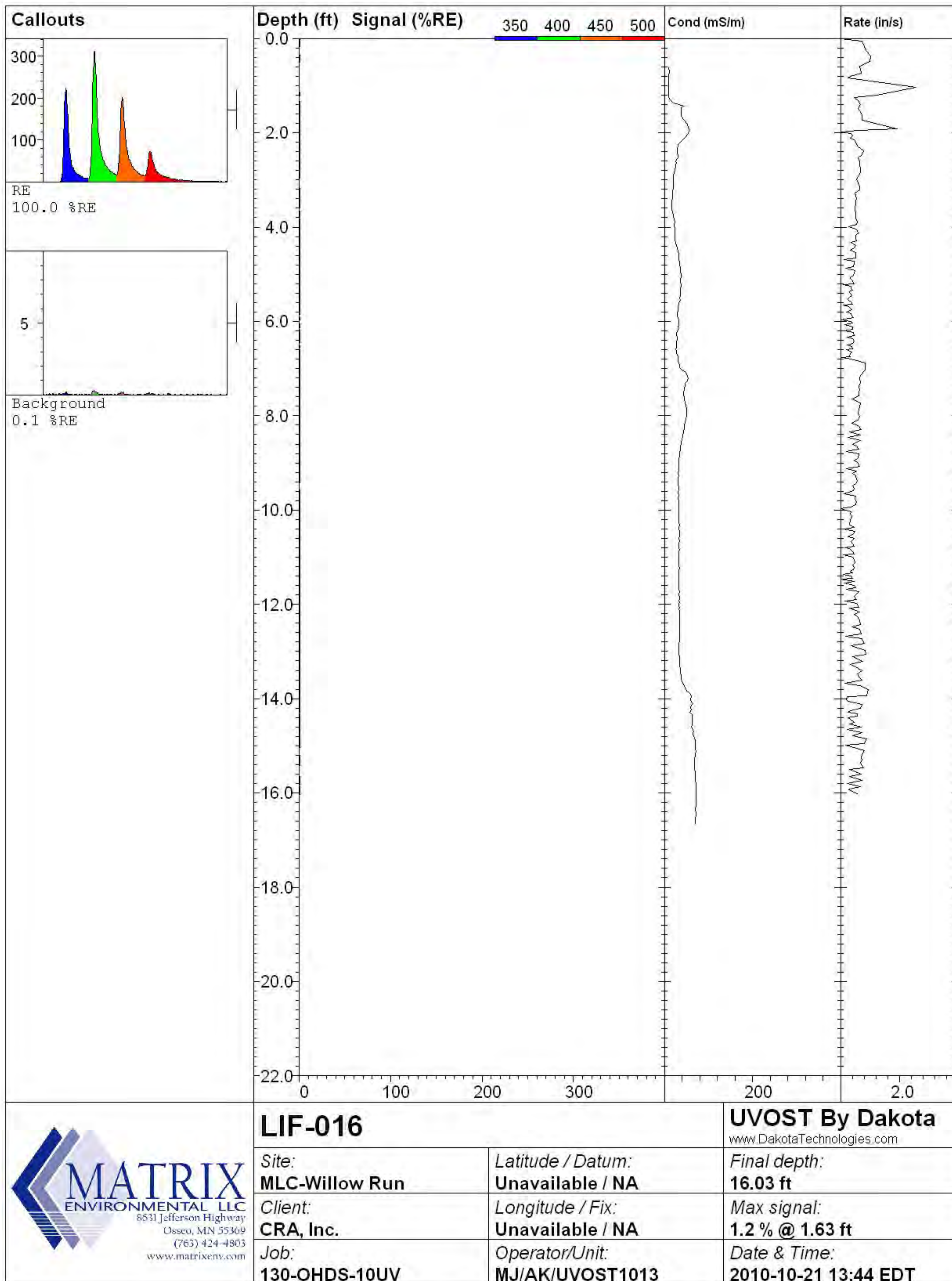
Max signal:
1.5 % @ 1.72 ft

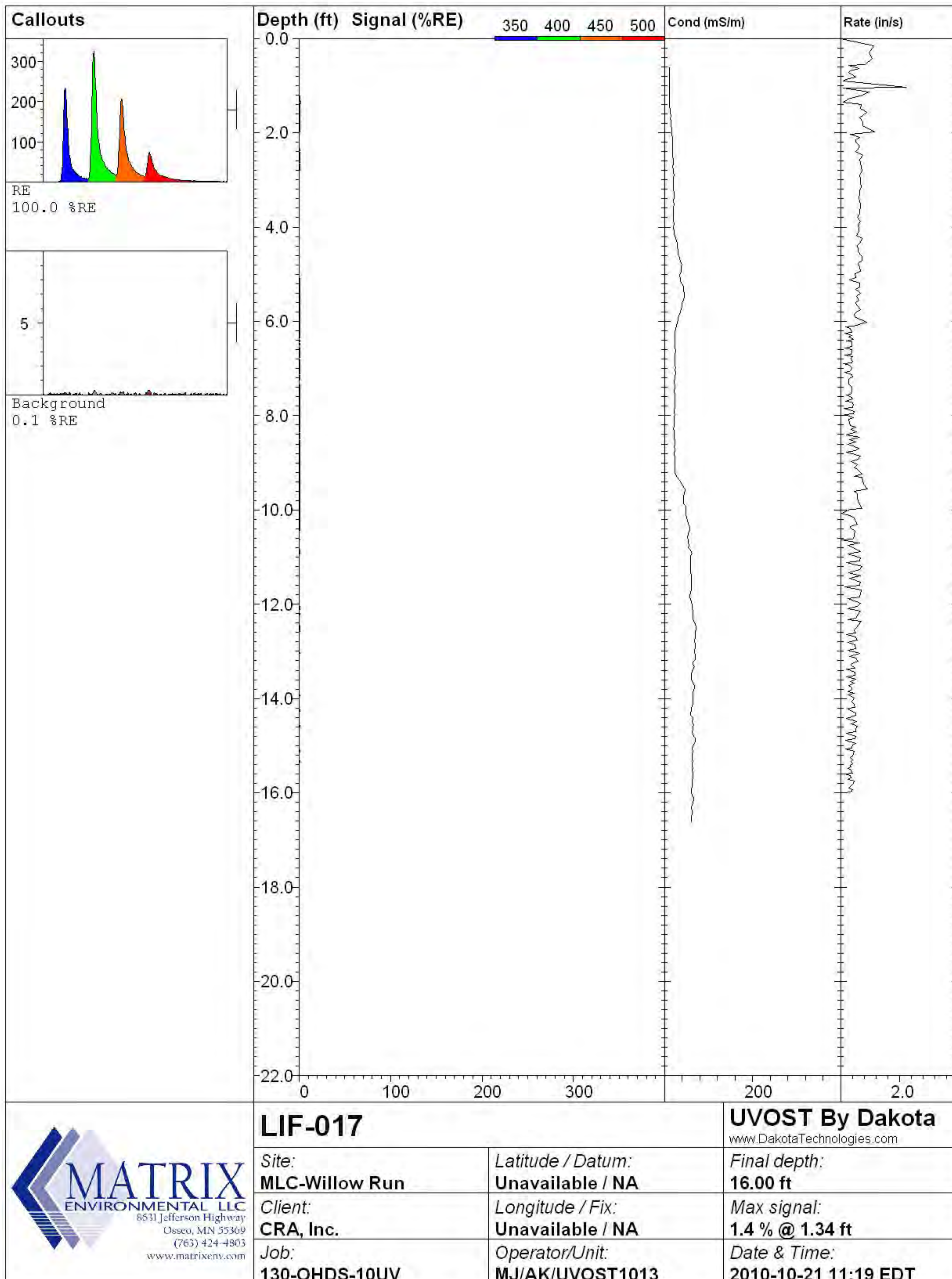
Job:
130-OHDS-10UV

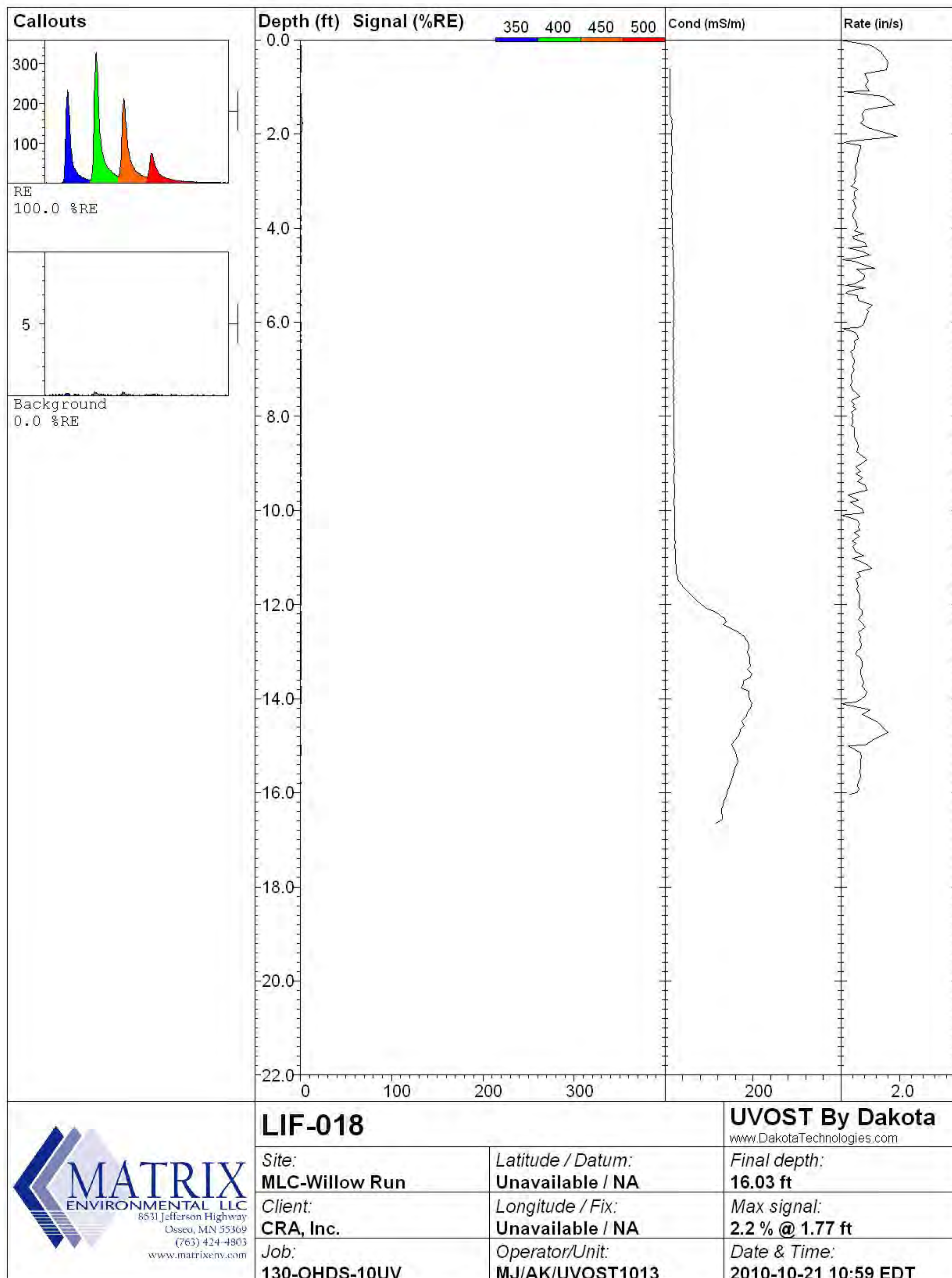
Operator/Unit:
MJ/AK/UVOST1013

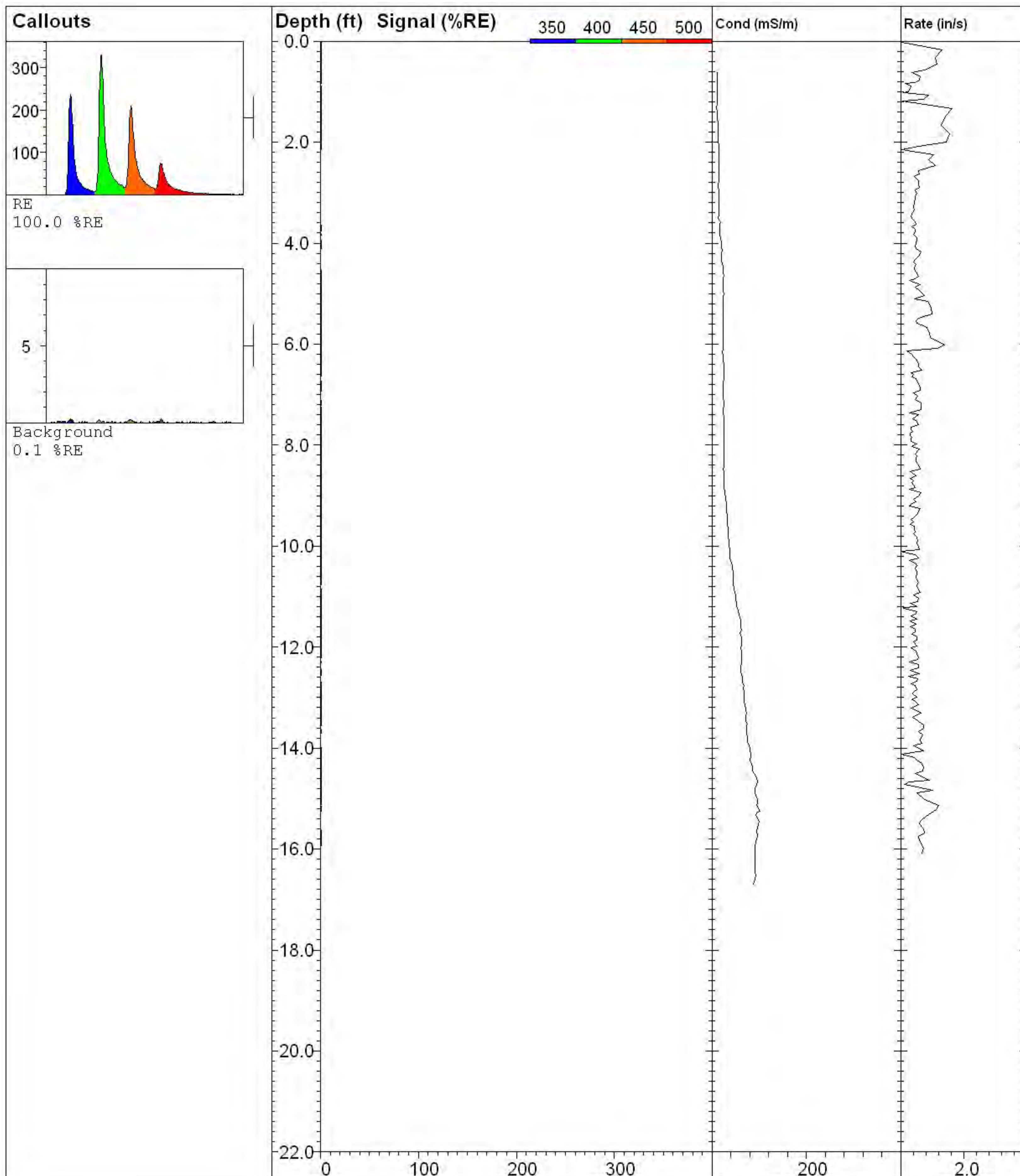
Date & Time:
2010-10-21 14:07 EDT











LIF-019

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.09 ft

Client:
CRA, Inc.

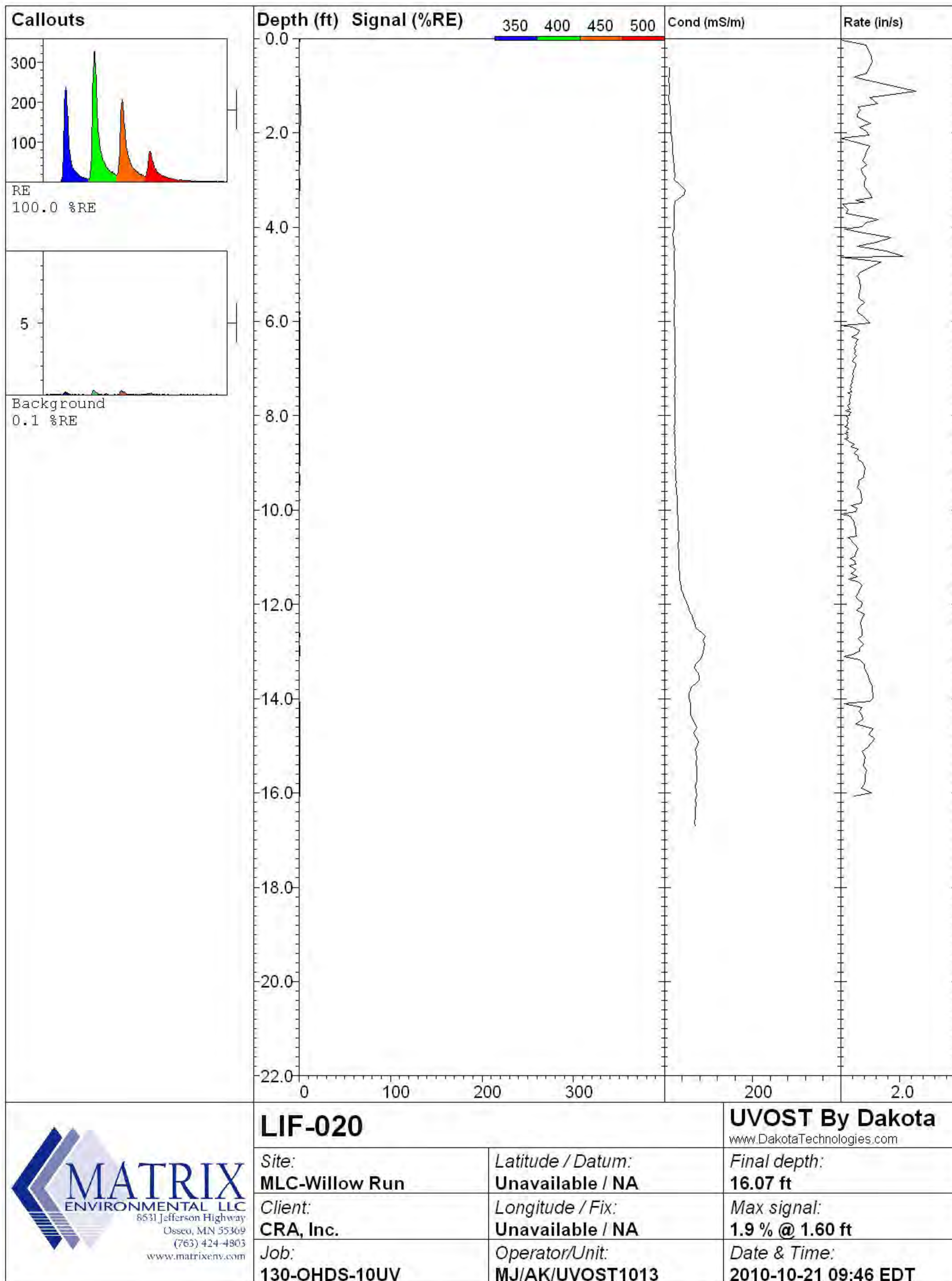
Longitude / Fix:
Unavailable / NA

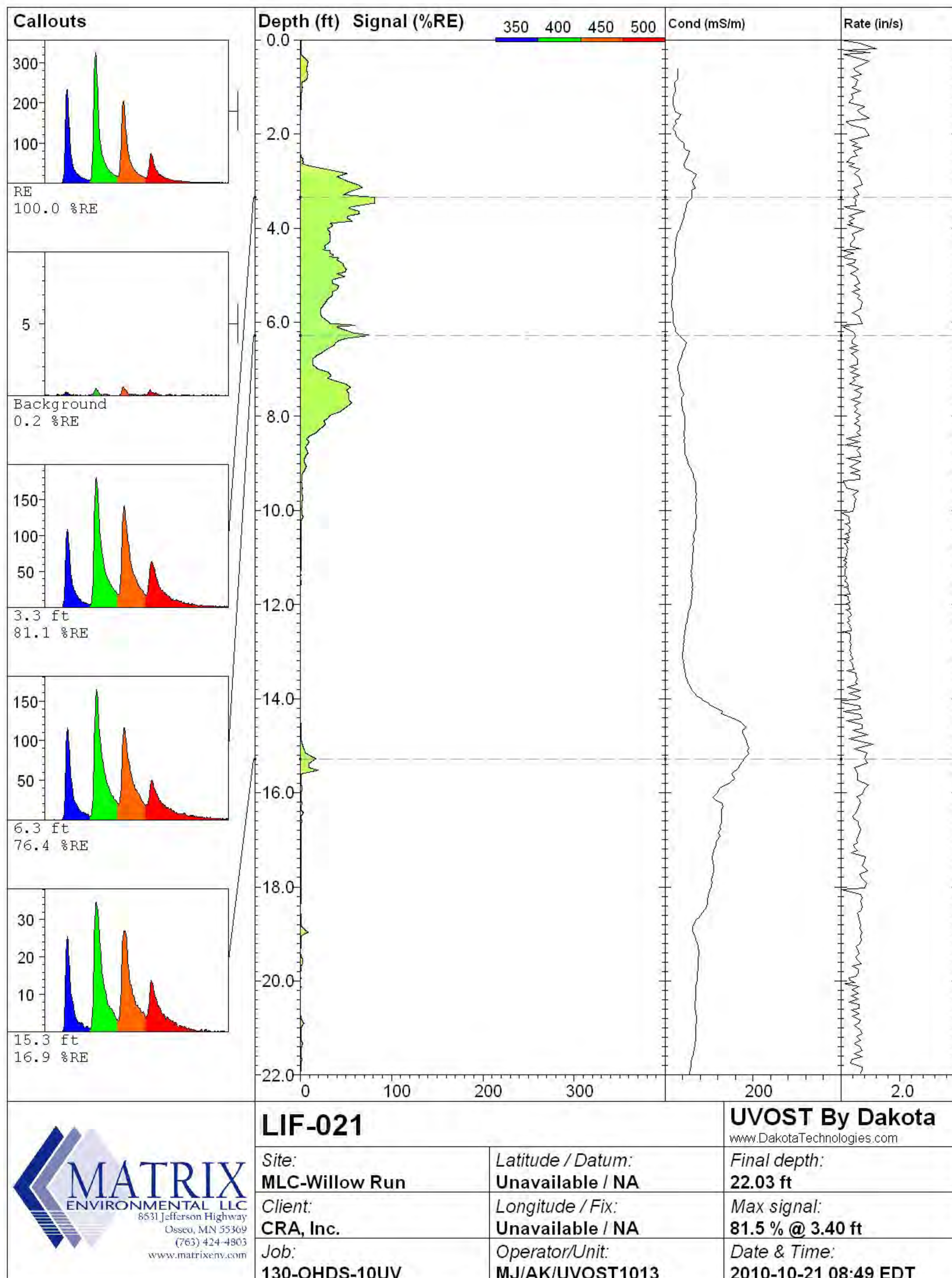
Max signal:
1.1 % @ 1.67 ft

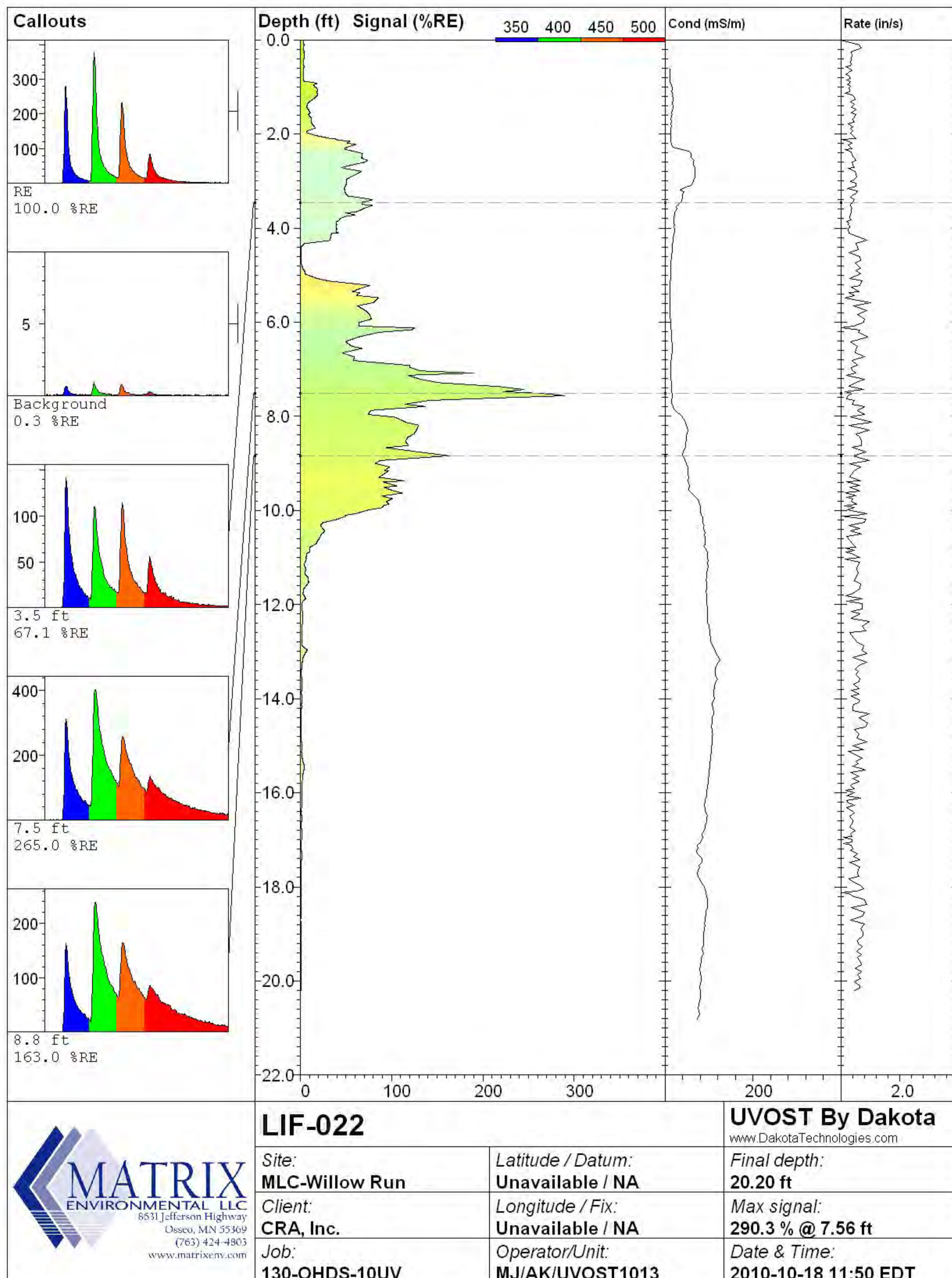
Job:
130-OHDS-10UV

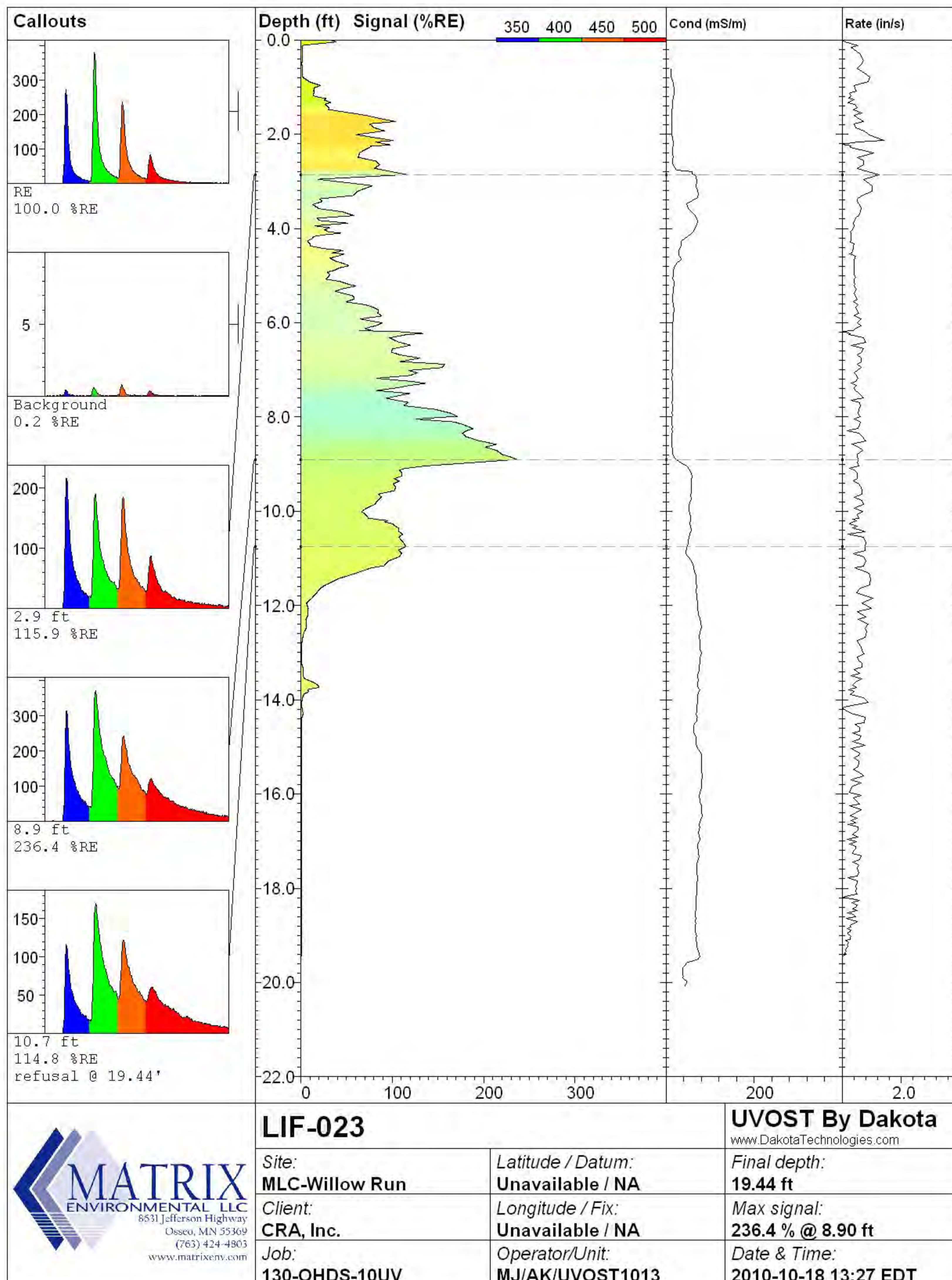
Operator/Unit:
MJ/AK/UVOST1013

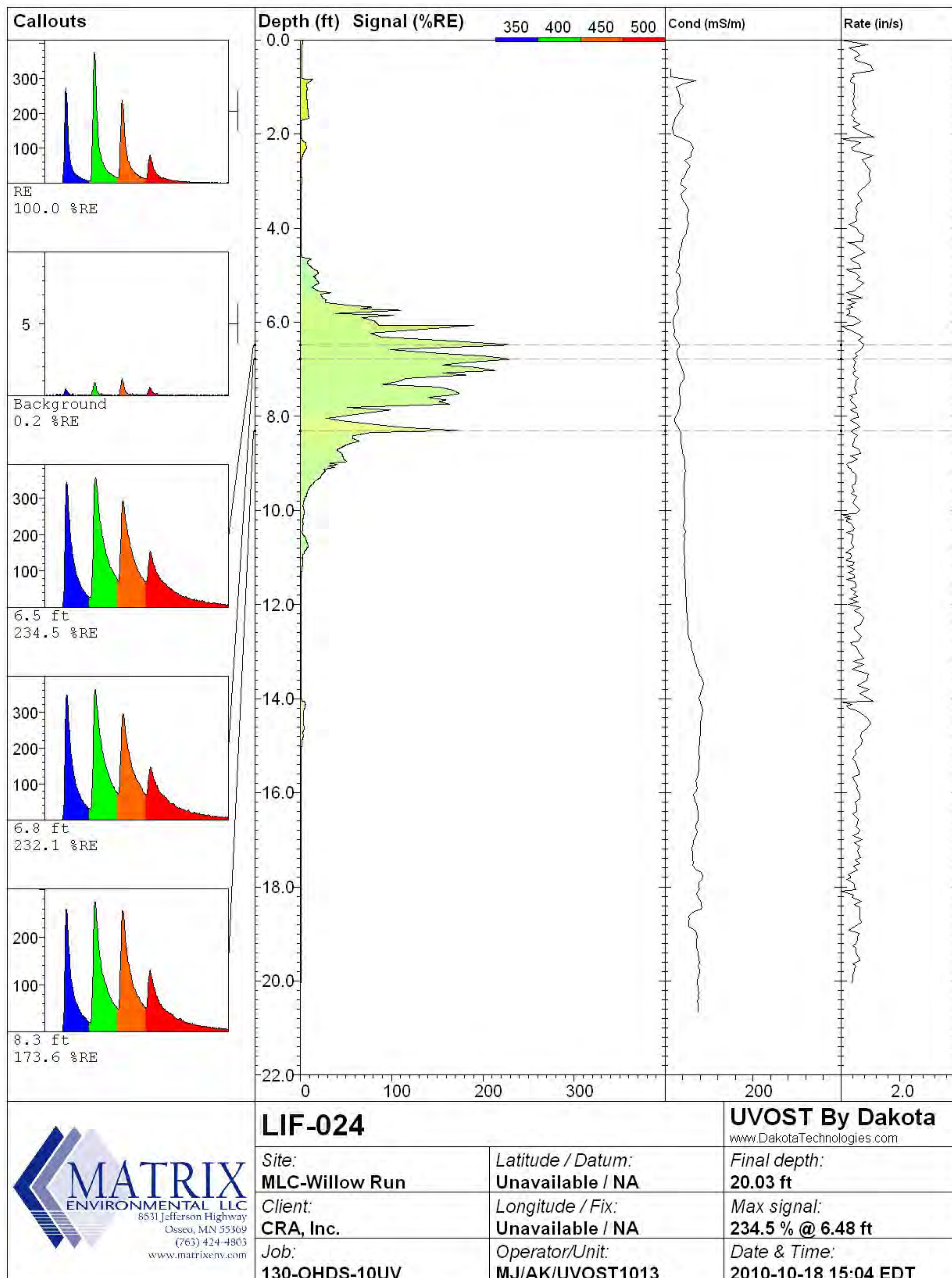
Date & Time:
2010-10-21 10:10 EDT

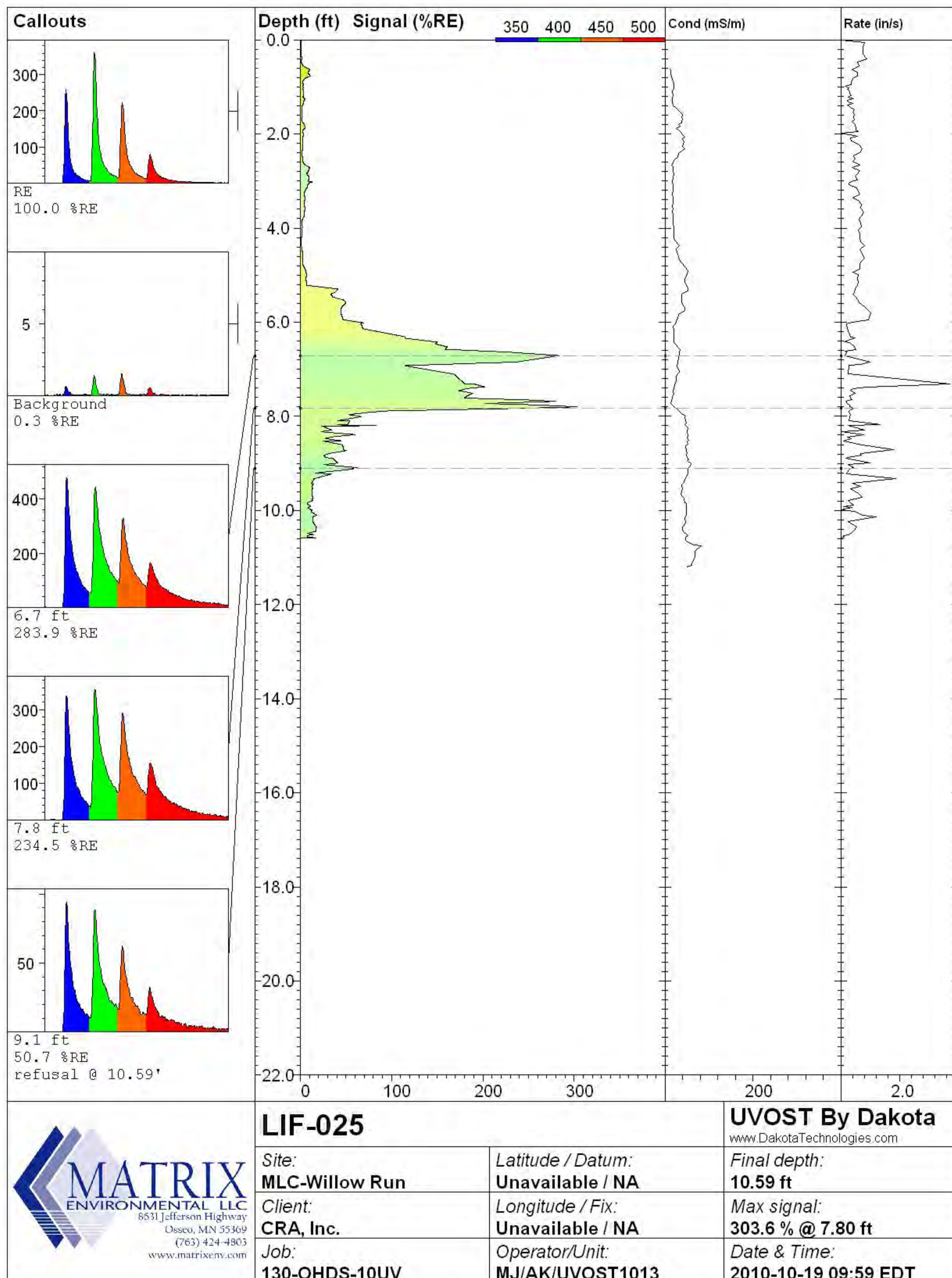


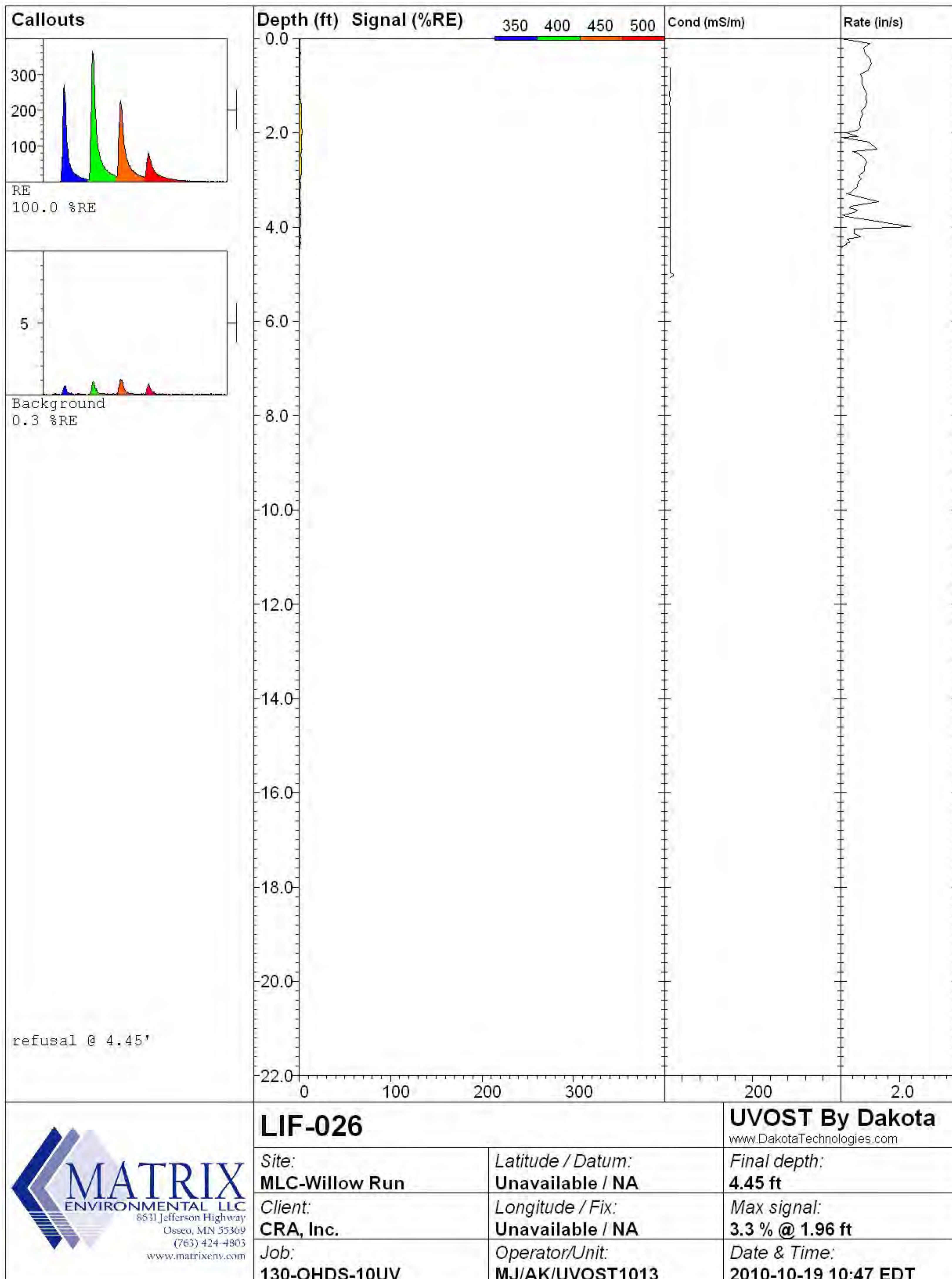


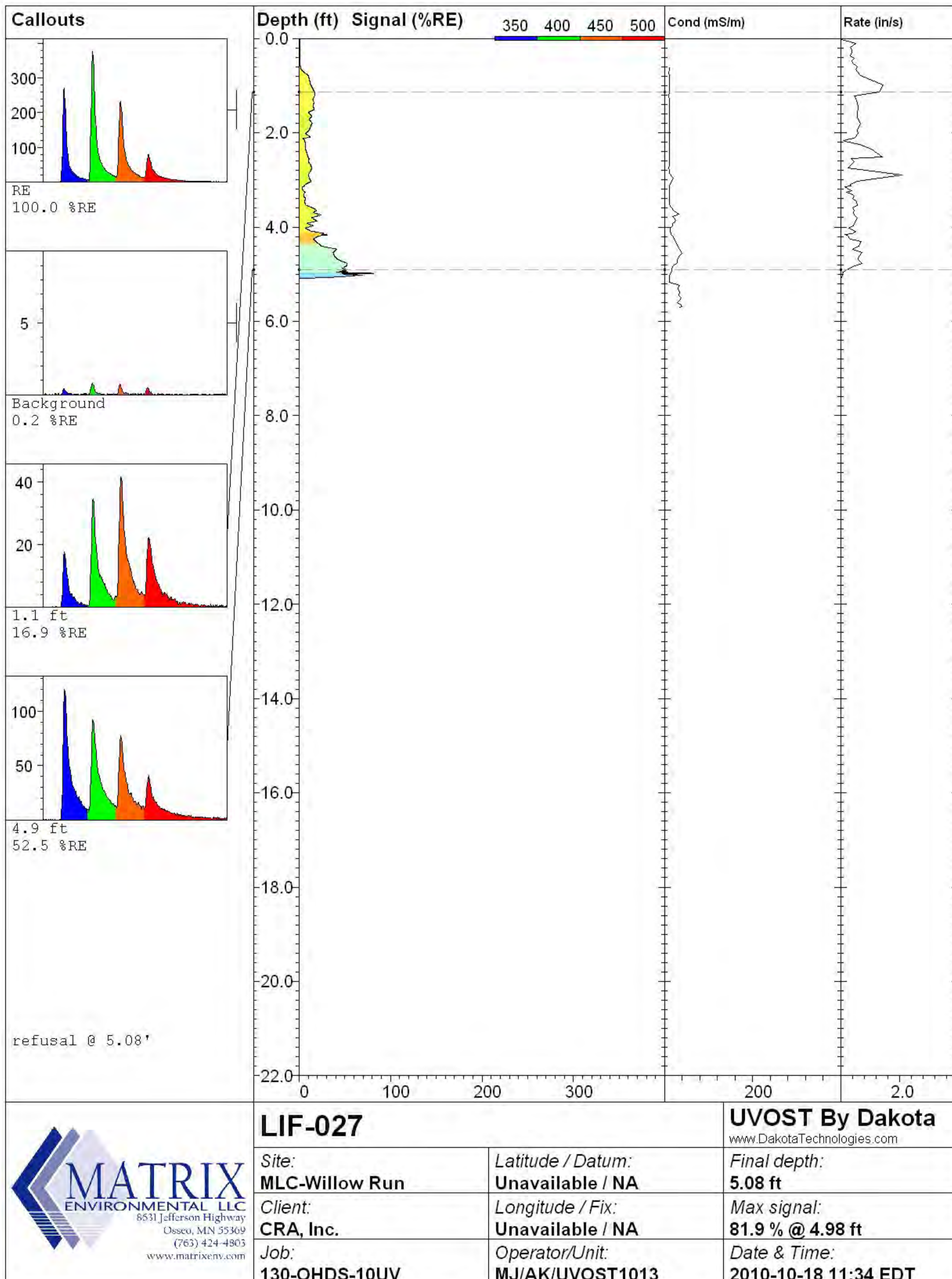


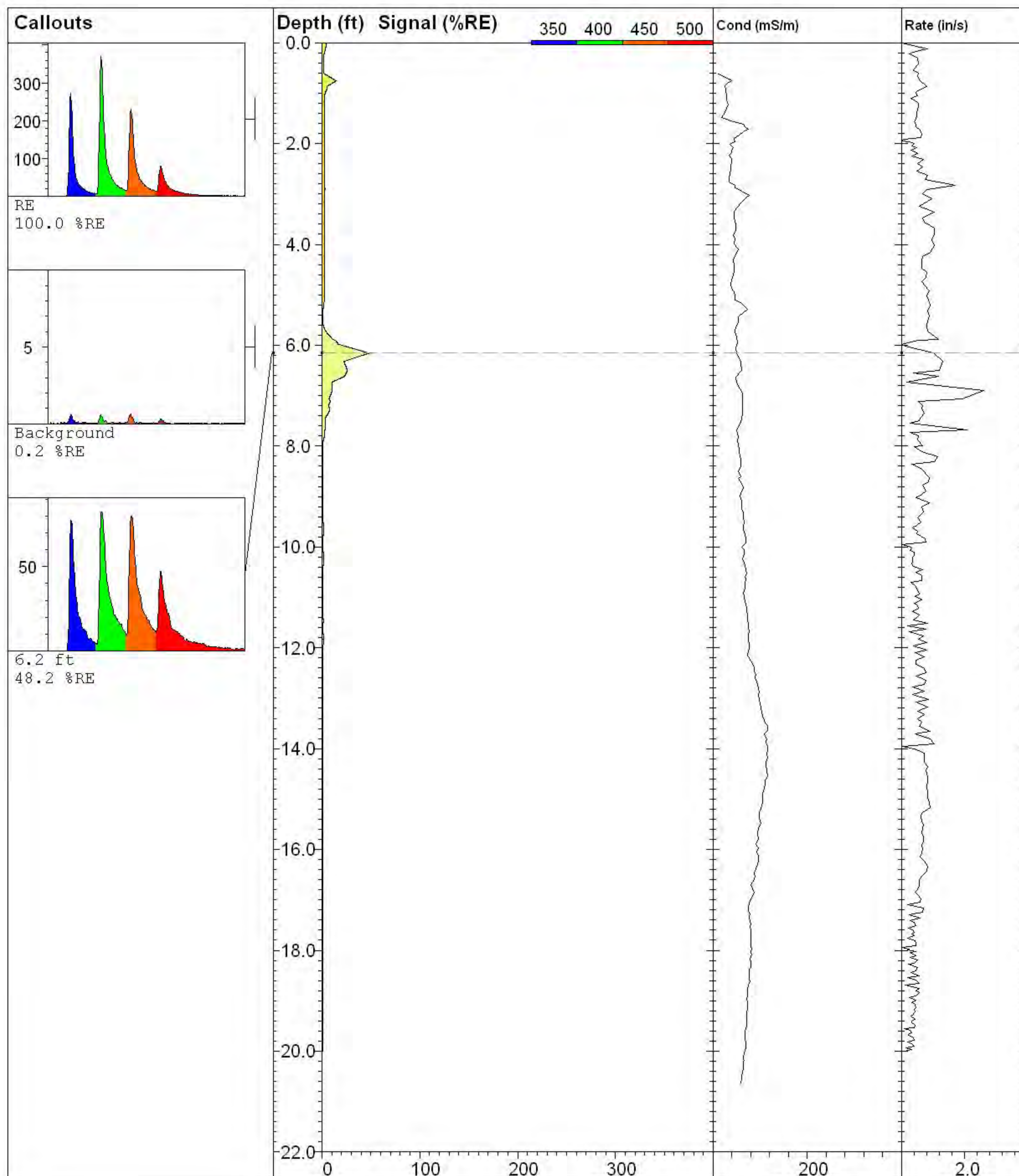












LIF-028

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
20.01 ft

Client:
CRA, Inc.

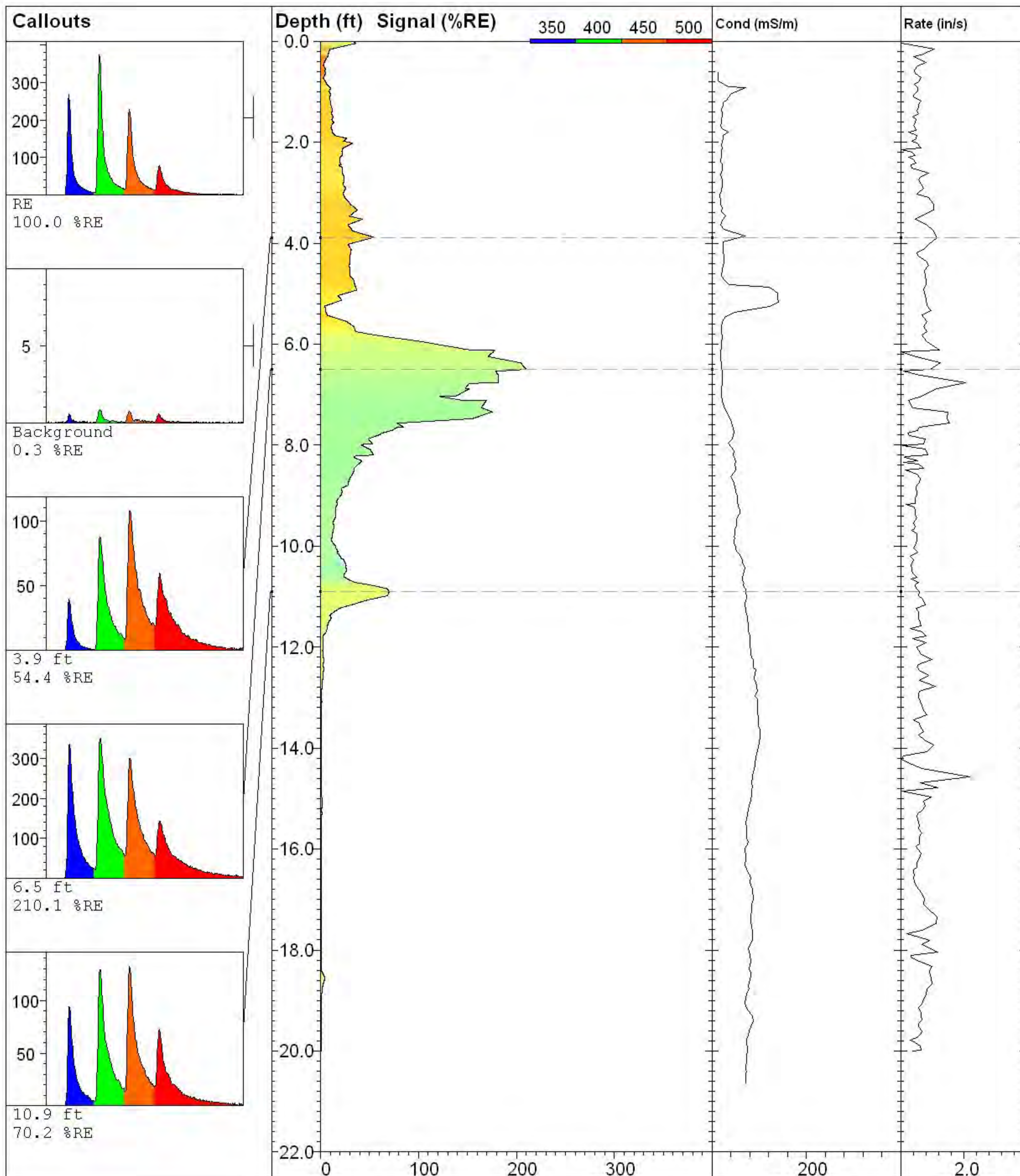
Longitude / Fix:
Unavailable / NA

Max signal:
48.2 % @ 6.16 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-18 13:56 EDT



LIF-029

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
20.01 ft

Client:
CRA, Inc.

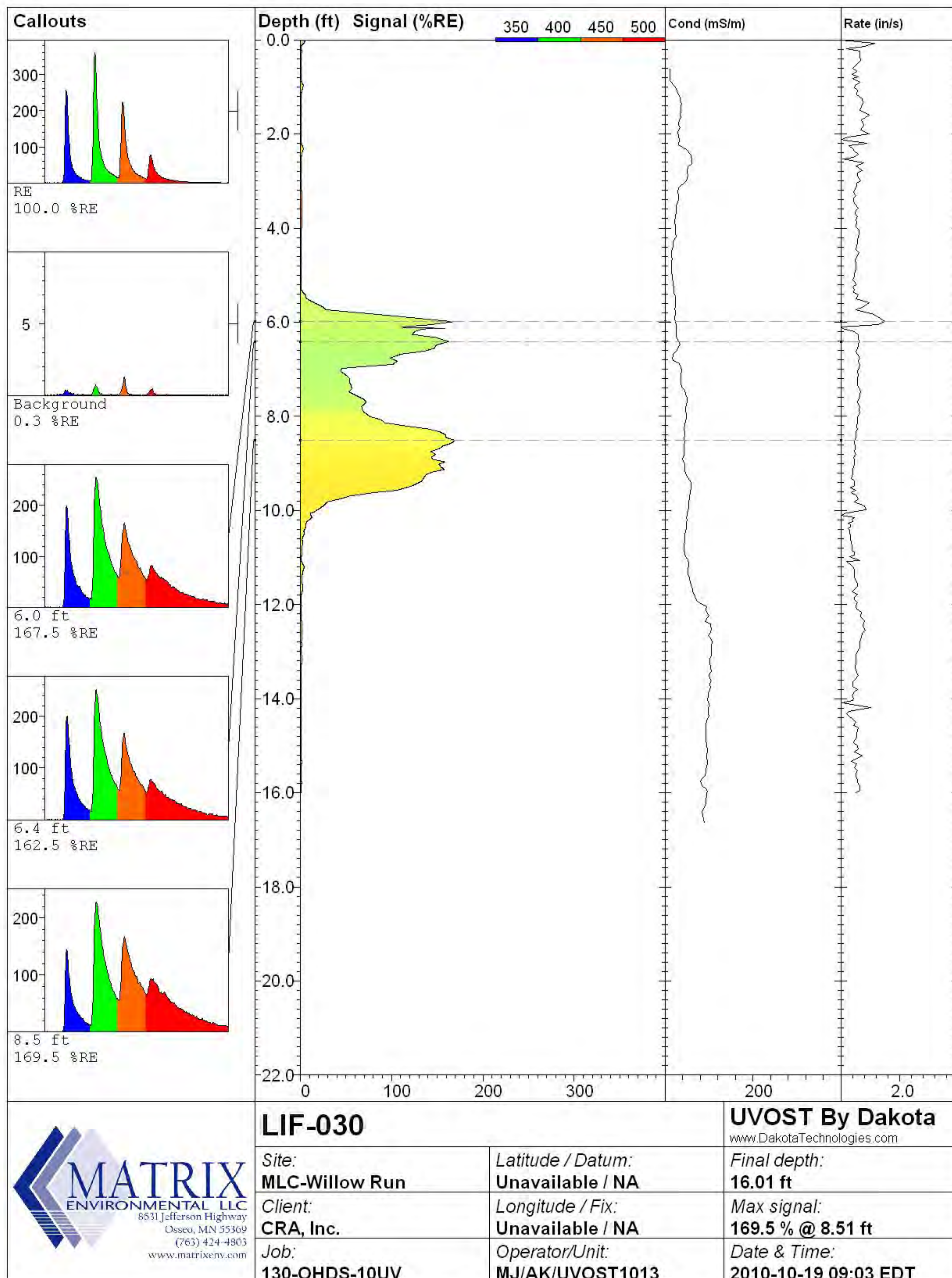
Longitude / Fix:
Unavailable / NA

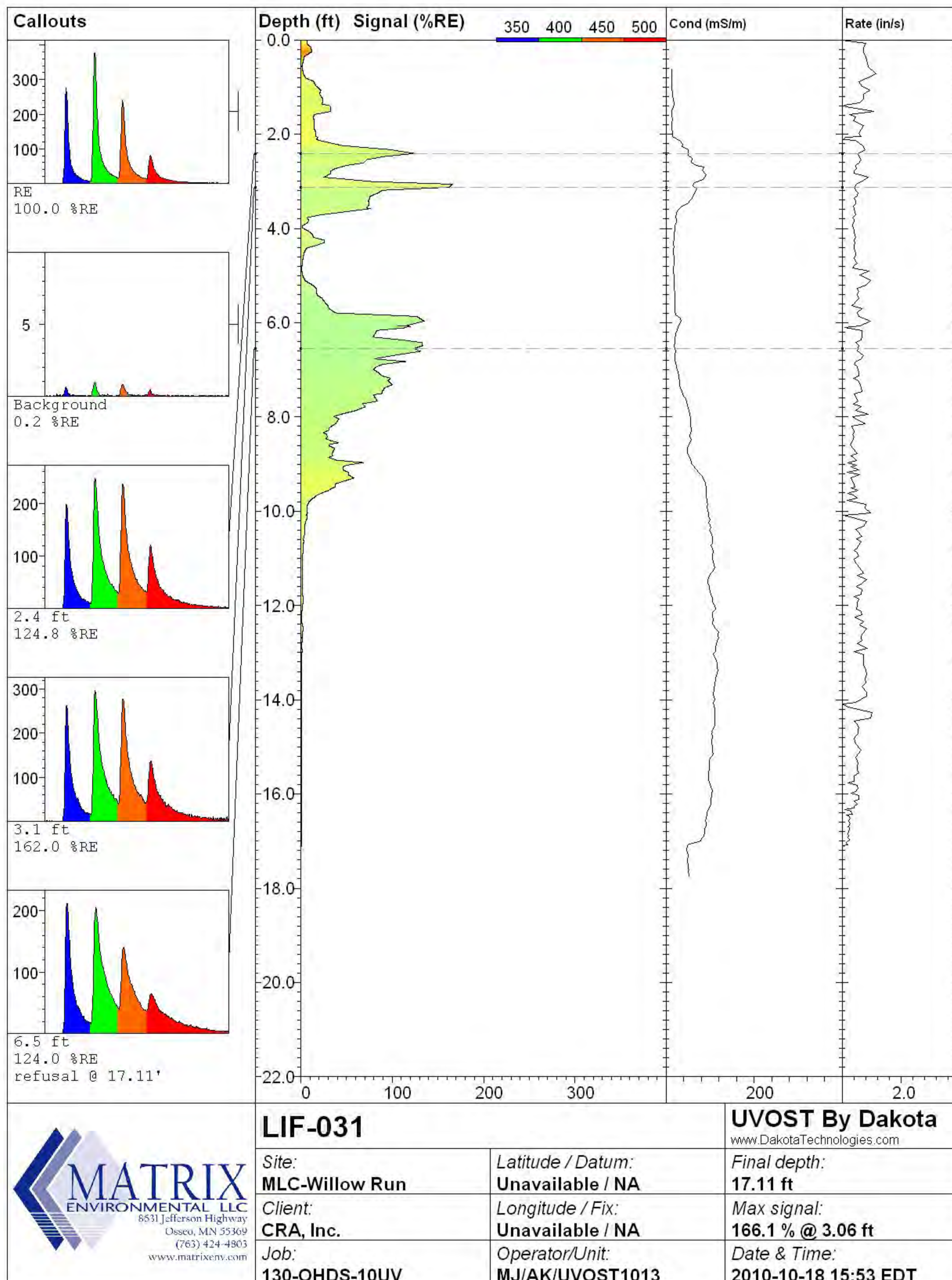
Max signal:
210.1 % @ 6.50 ft

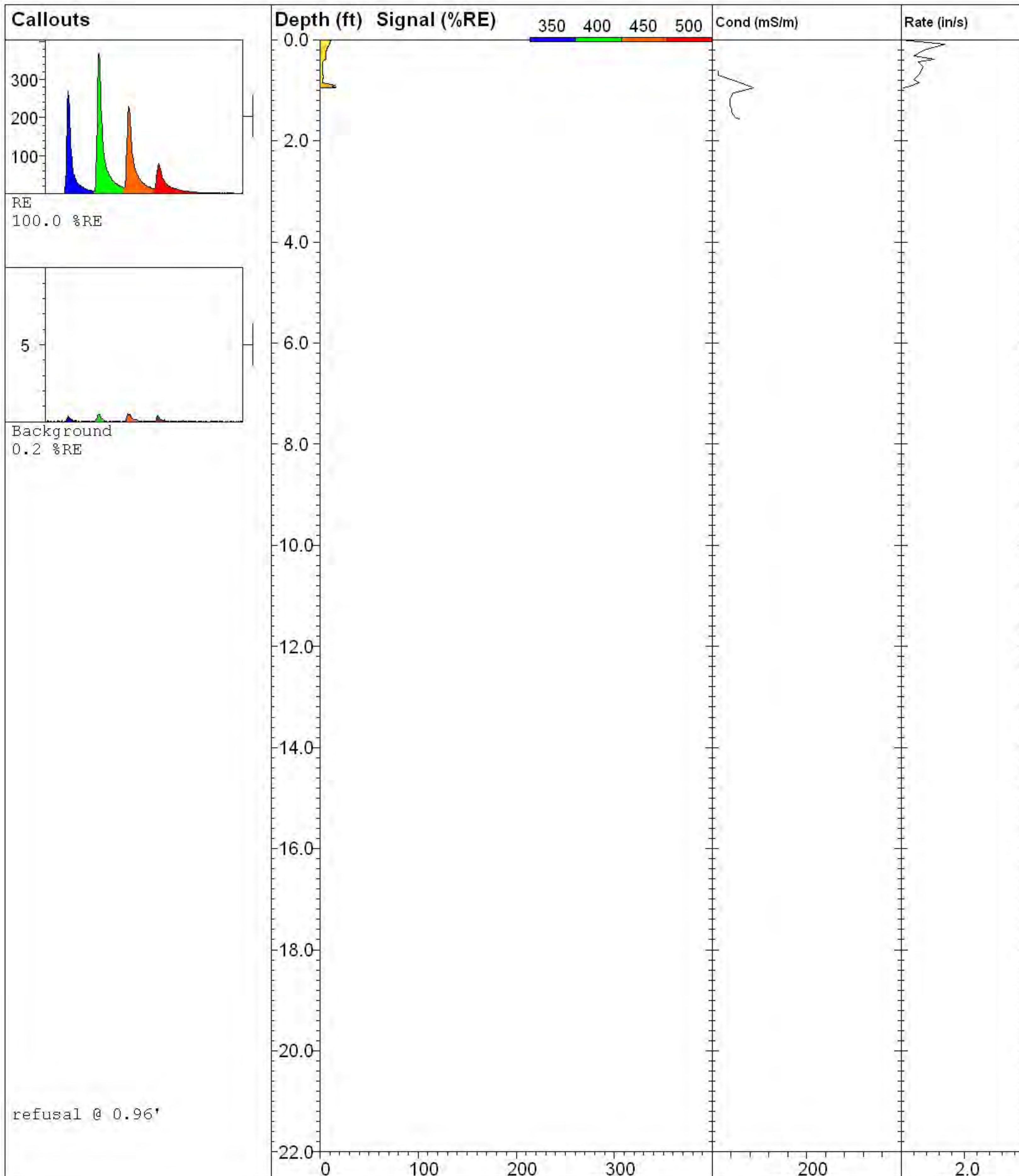
Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-18 14:30 EDT







LIF-032

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
0.96 ft

Client:
CRA, Inc.

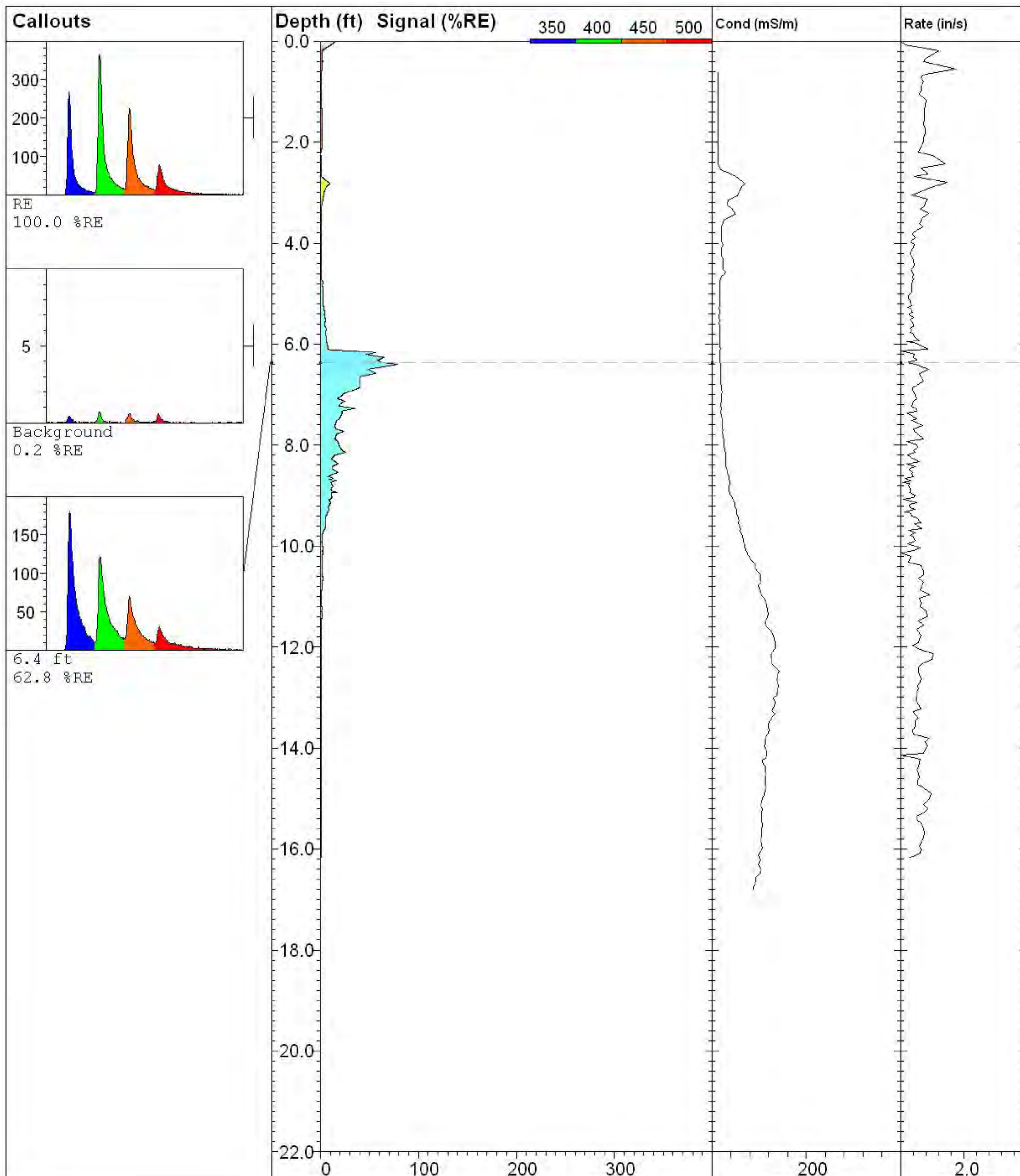
Longitude / Fix:
Unavailable / NA

Max signal:
16.9 % @ 0.94 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-18 15:30 EDT



LIF-033

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.17 ft

Client:
CRA, Inc.

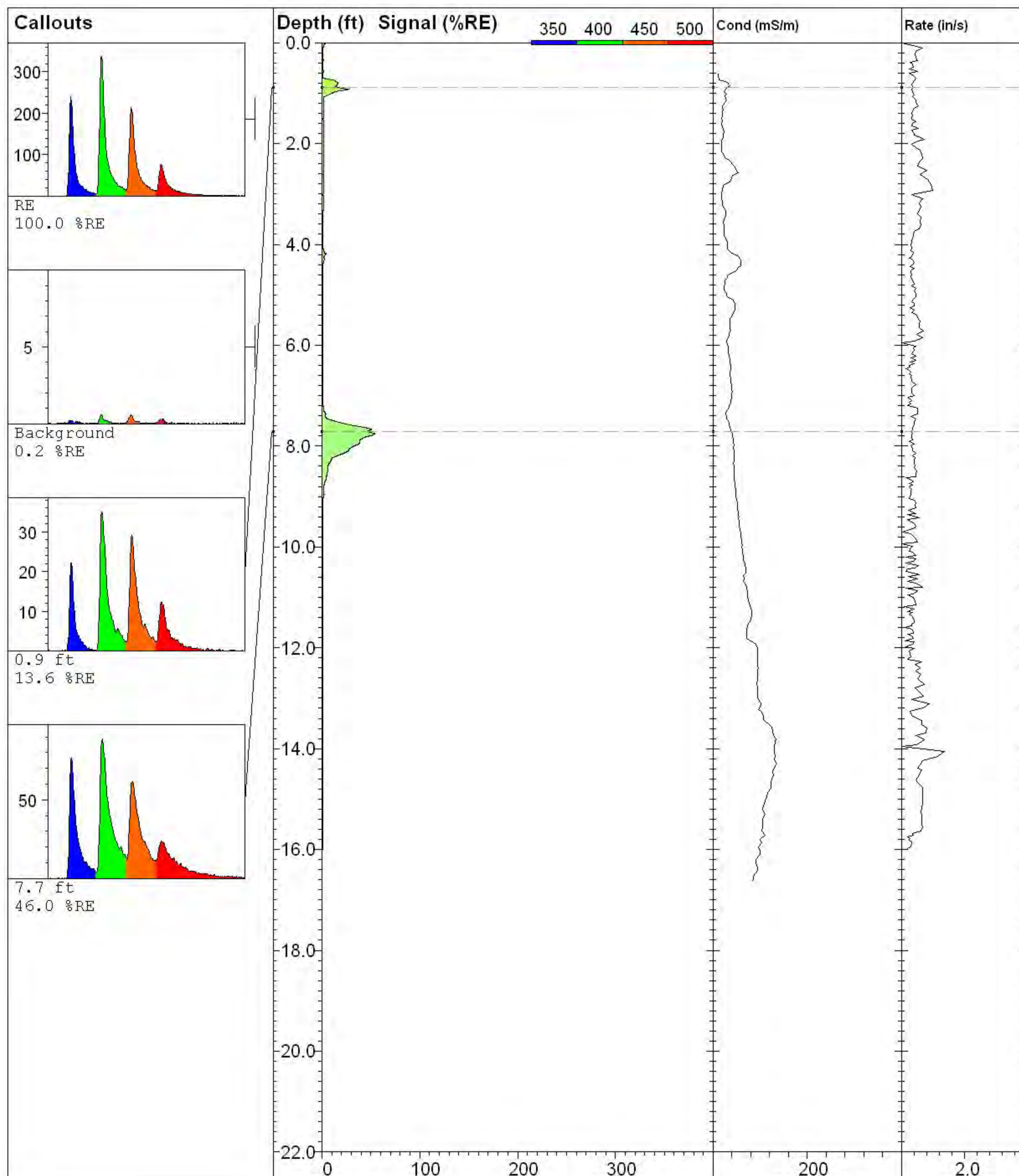
Longitude / Fix:
Unavailable / NA

Max signal:
78.7 % @ 6.40 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-18 16:21 EDT



LIF-034

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.00 ft

Client:
CRA, Inc.

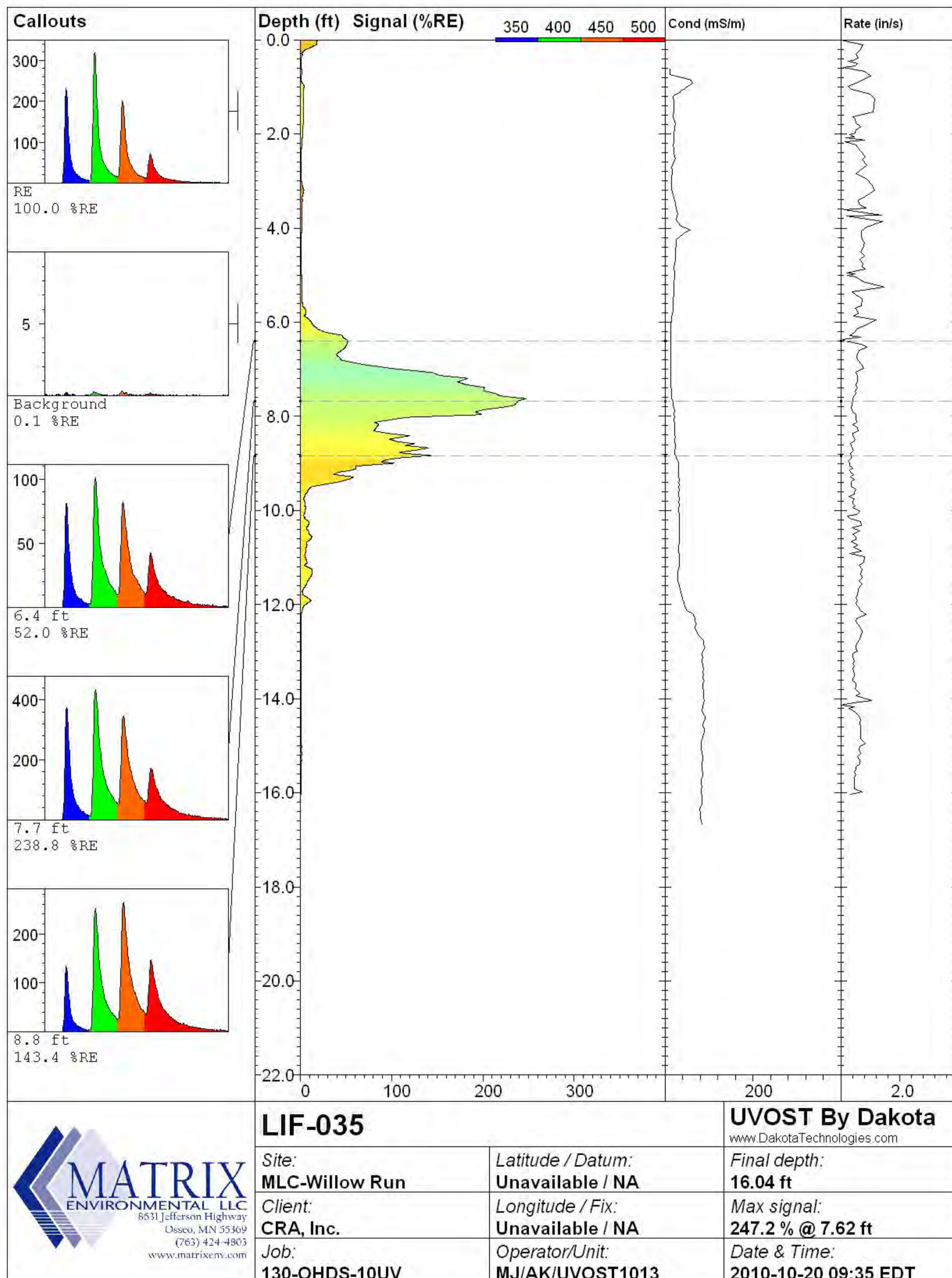
Longitude / Fix:
Unavailable / NA

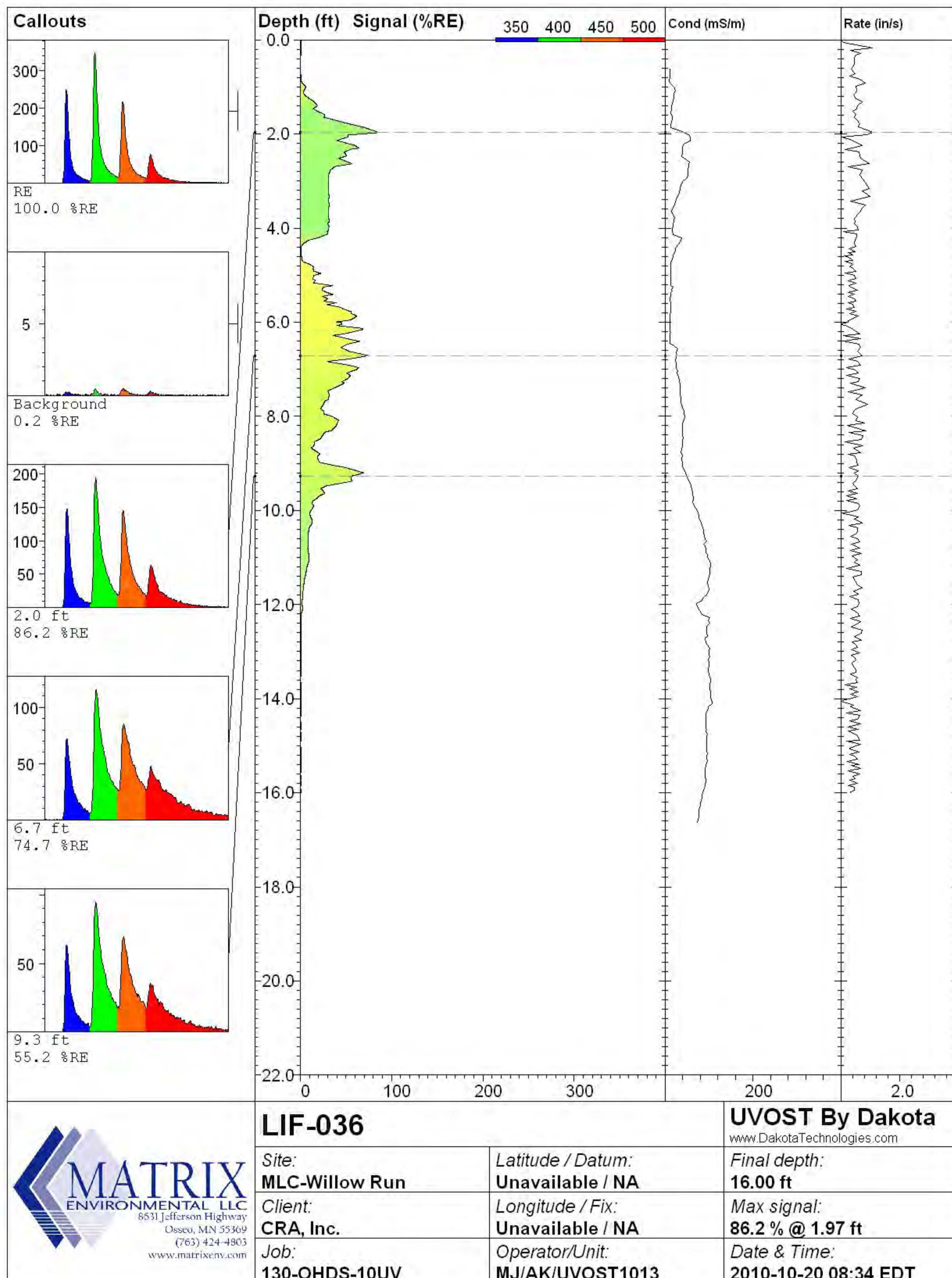
Max signal:
54.1 % @ 7.75 ft

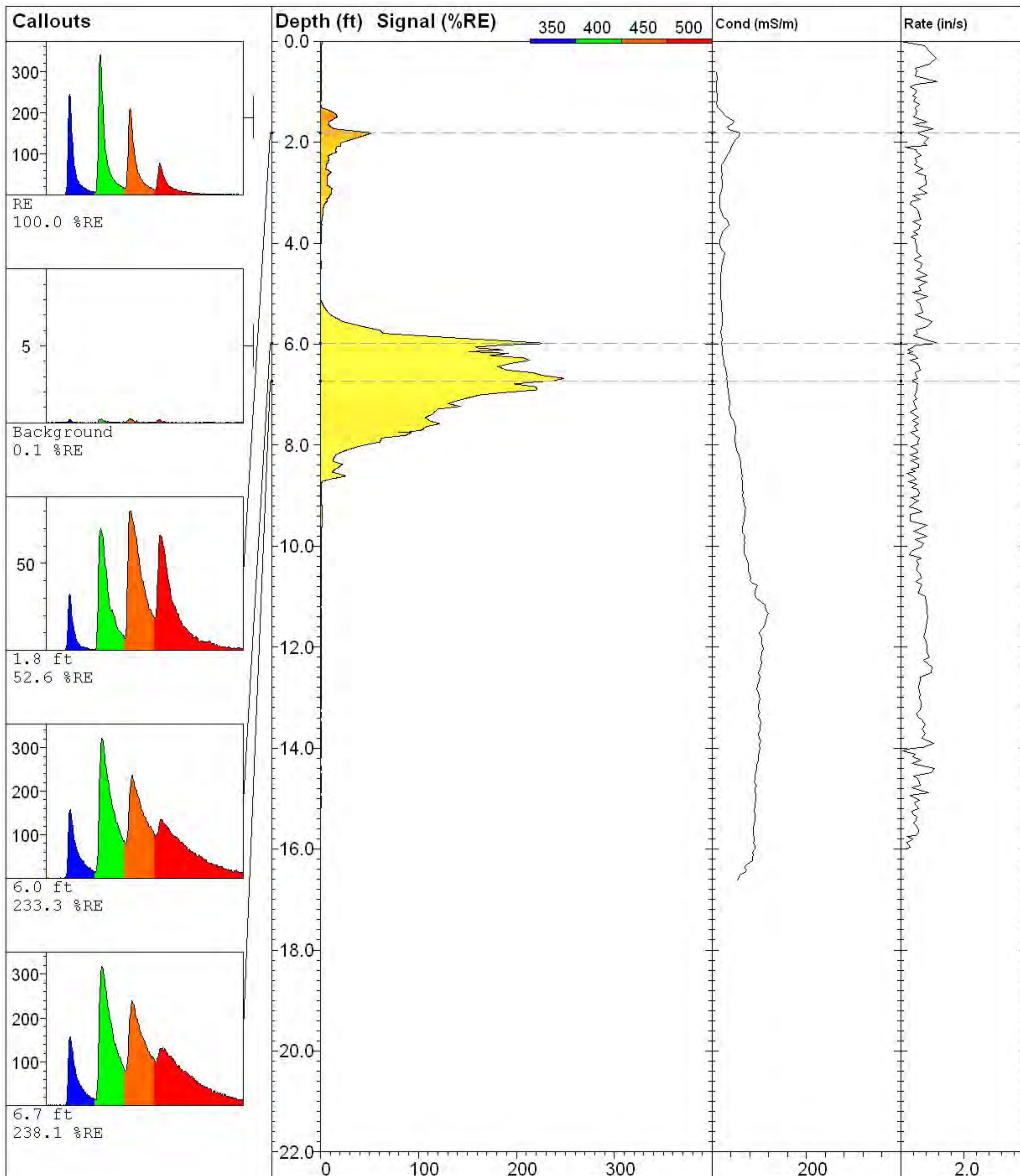
Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-20 09:57 EDT







LIF-037

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.00 ft

Client:
CRA, Inc.

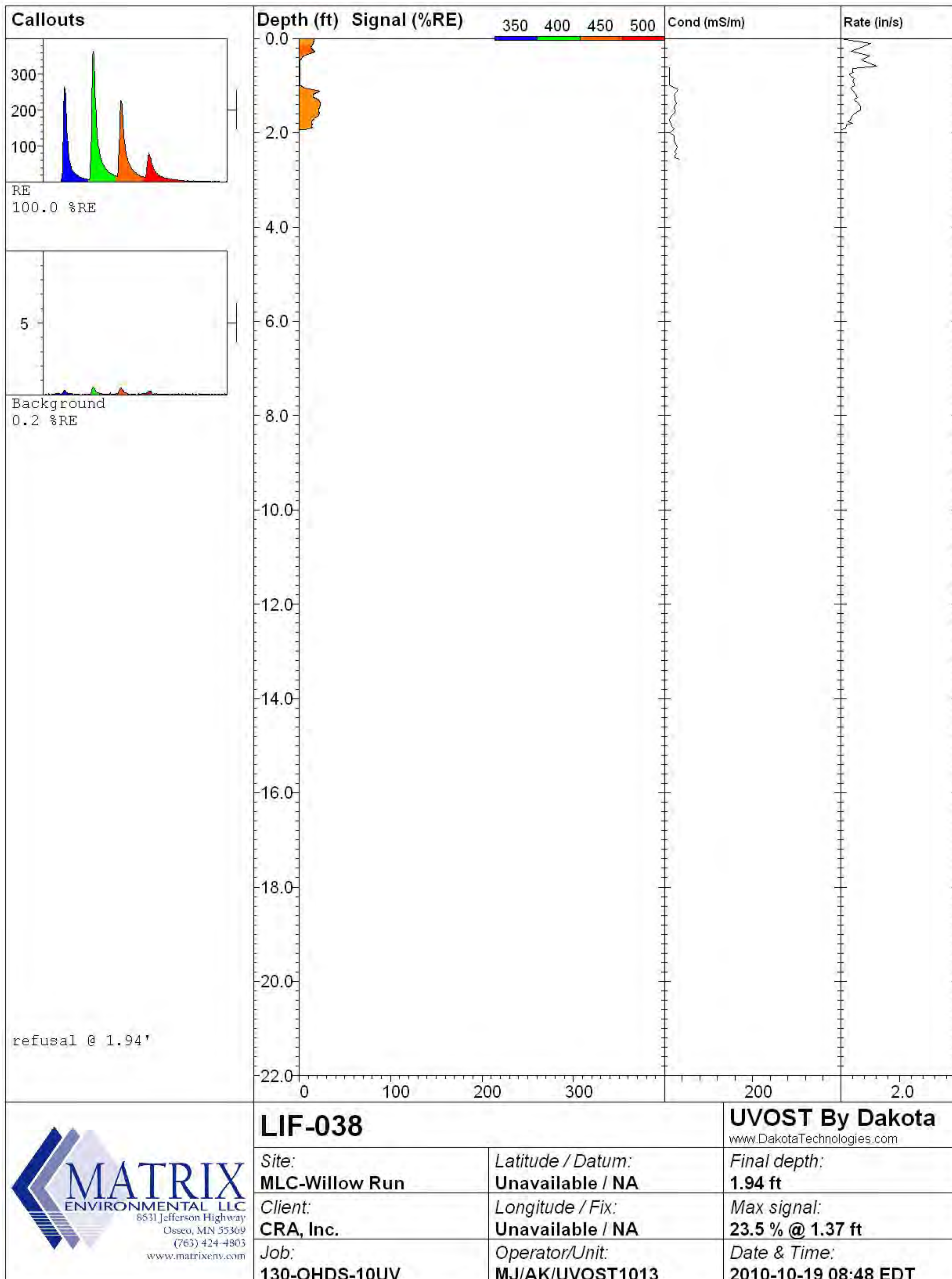
Longitude / Fix:
Unavailable / NA

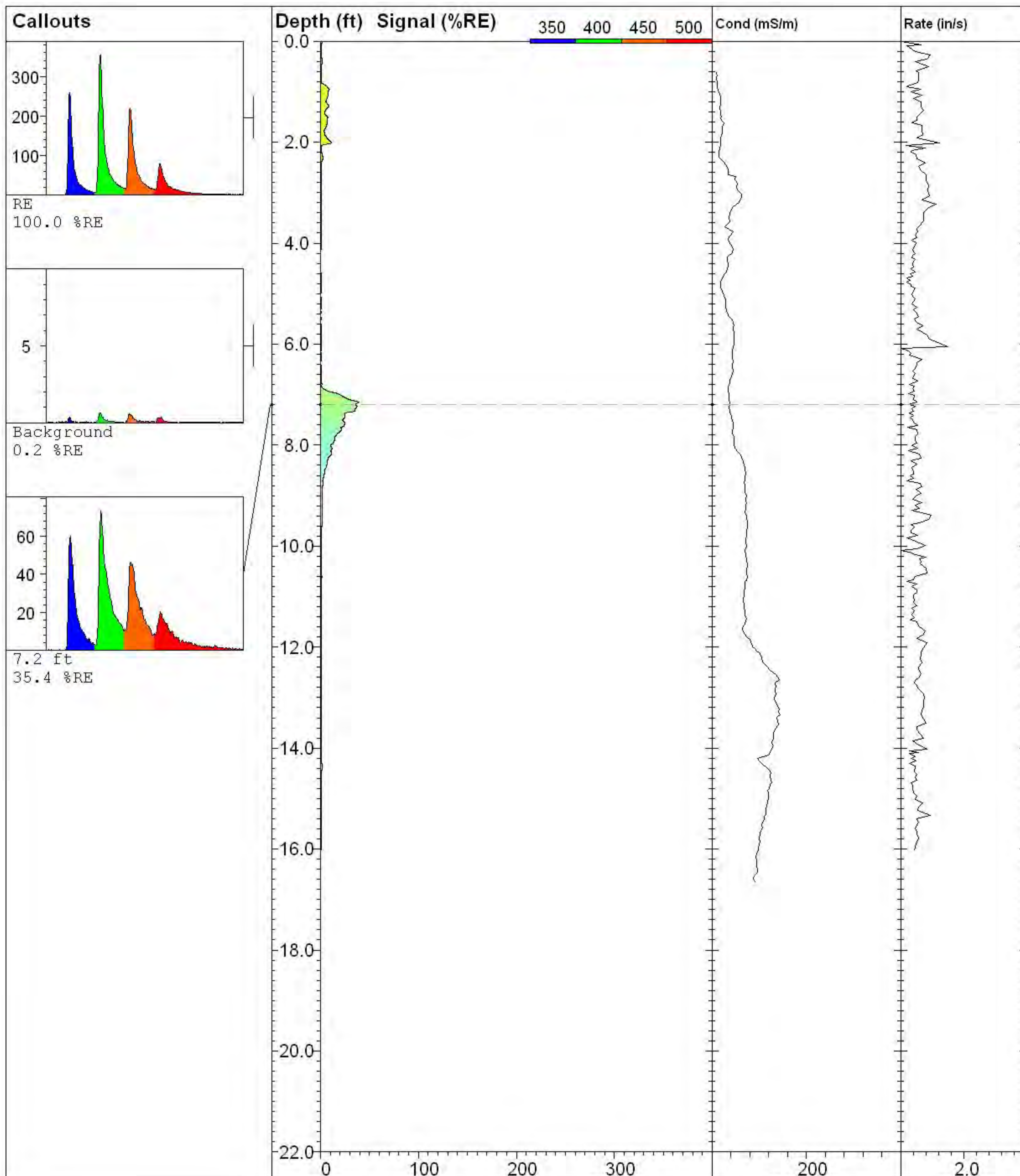
Max signal:
248.7 % @ 6.68 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-20 08:12 EDT





LIF-039

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.01 ft

Client:
CRA, Inc.

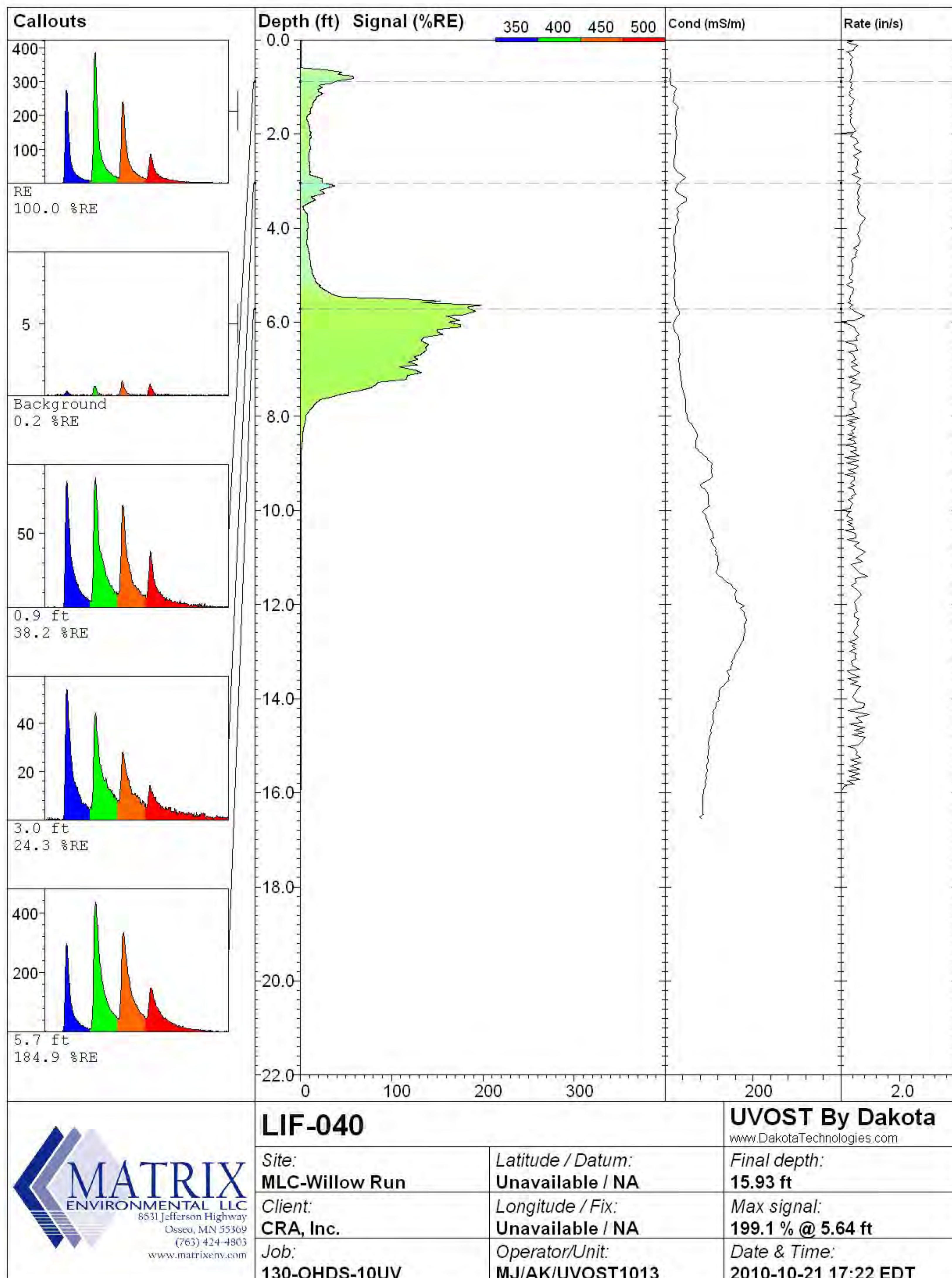
Longitude / Fix:
Unavailable / NA

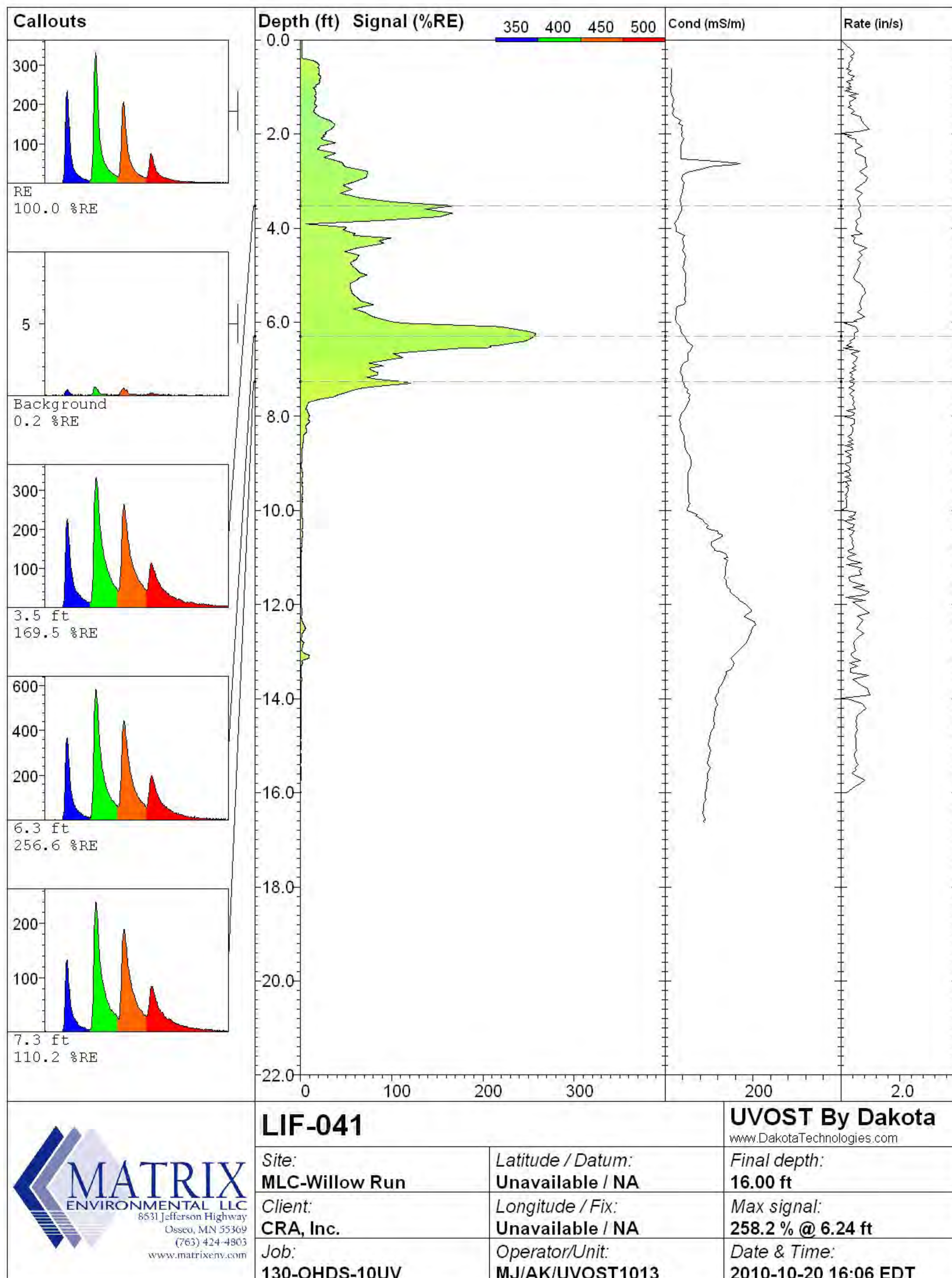
Max signal:
39.2 % @ 7.15 ft

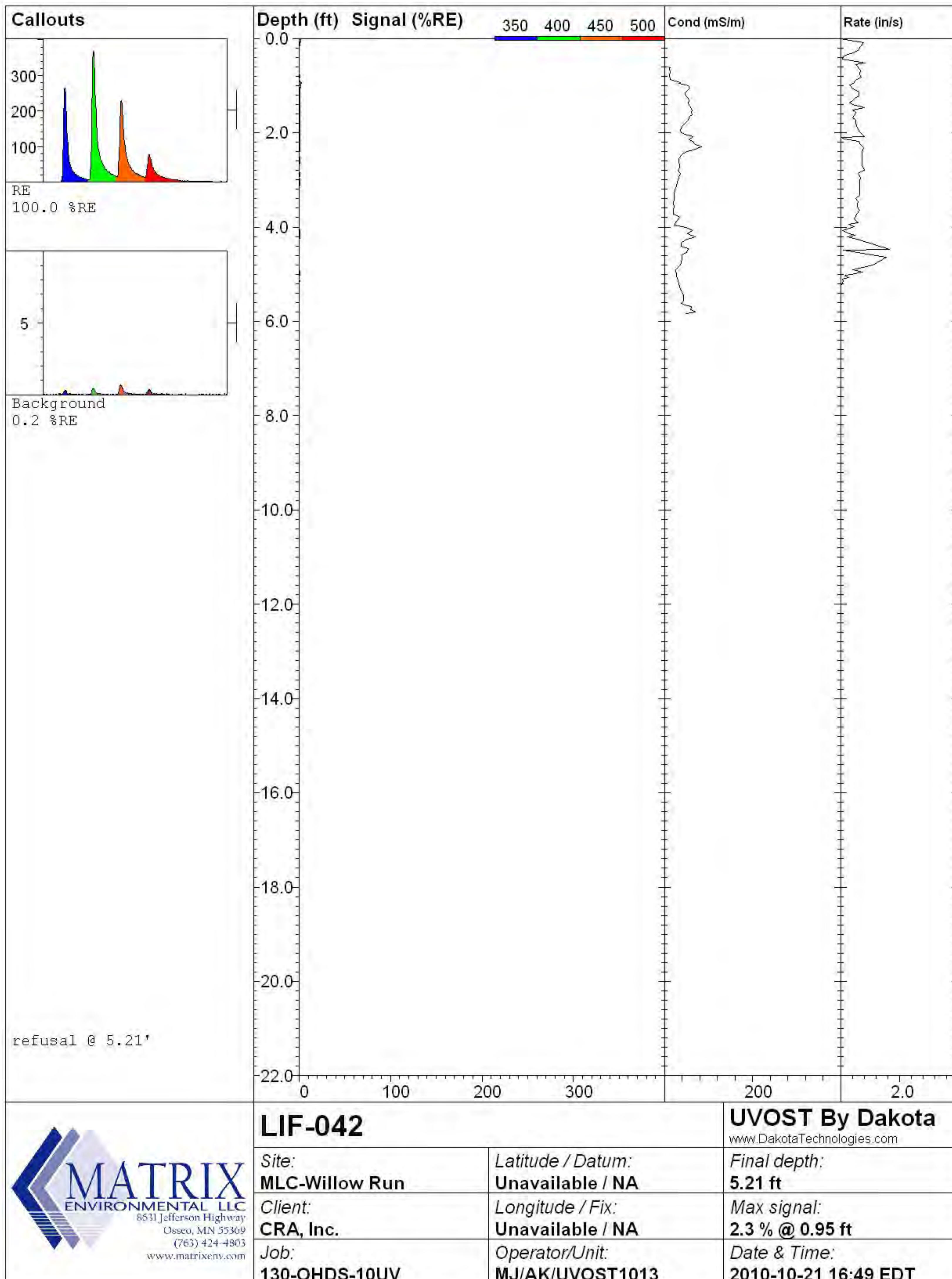
Job:
130-OHDS-10UV

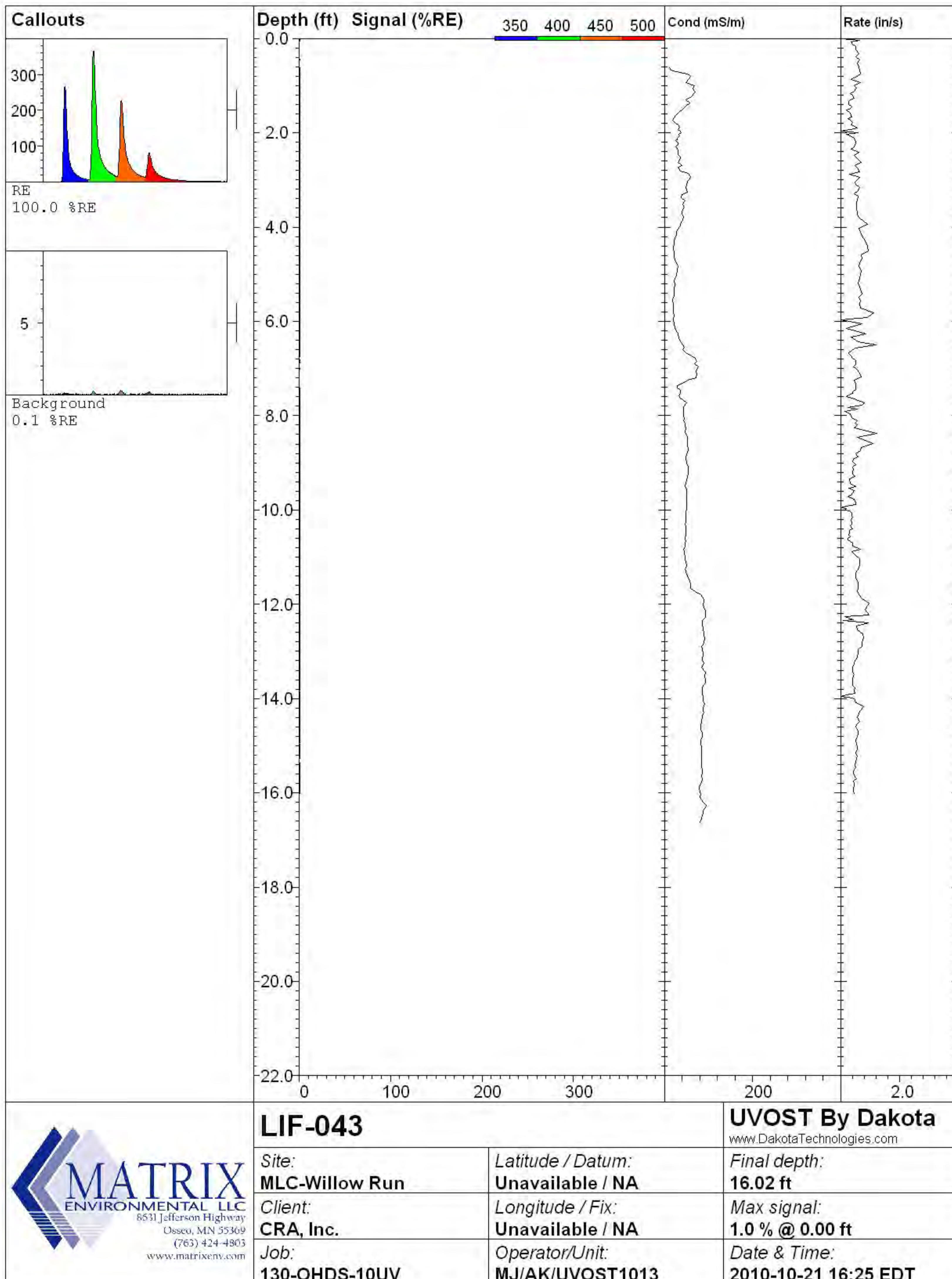
Operator/Unit:
MJ/AK/UVOST1013

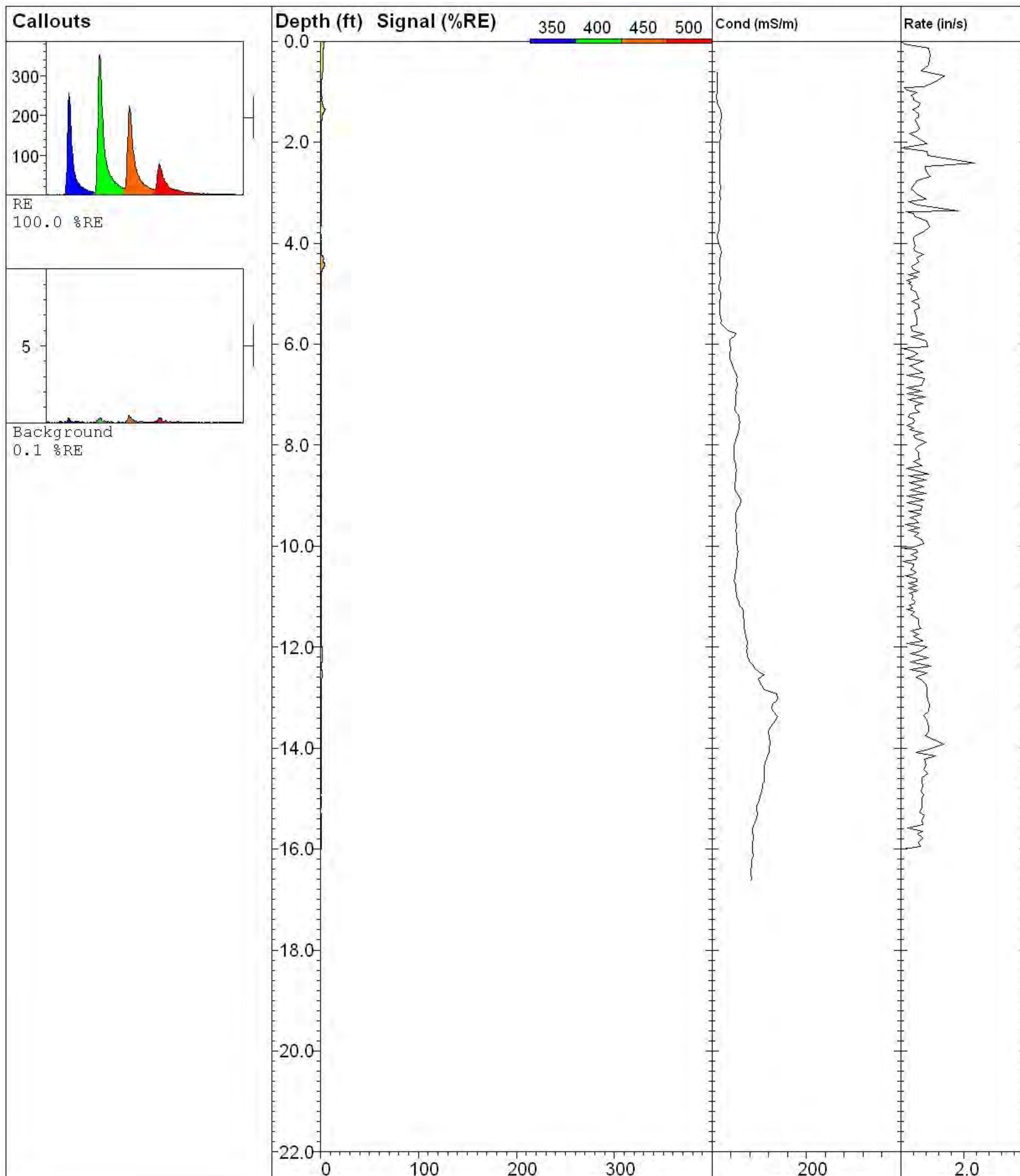
Date & Time:
2010-10-19 08:21 EDT











LIF-044

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.00 ft

Client:
CRA, Inc.

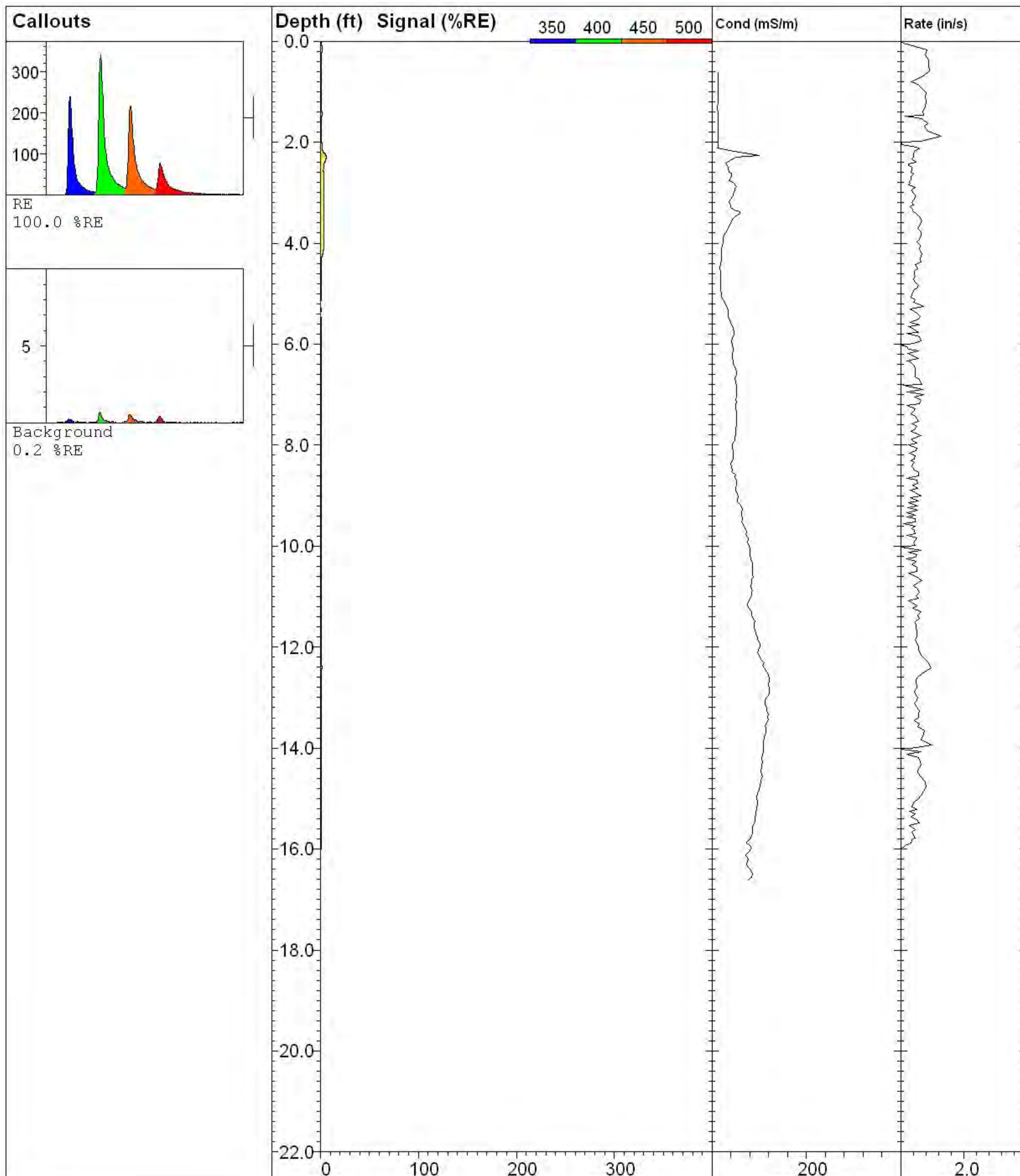
Longitude / Fix:
Unavailable / NA

Max signal:
4.8 % @ 1.36 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-20 08:58 EDT



LIF-047

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.00 ft

Client:
CRA, Inc.

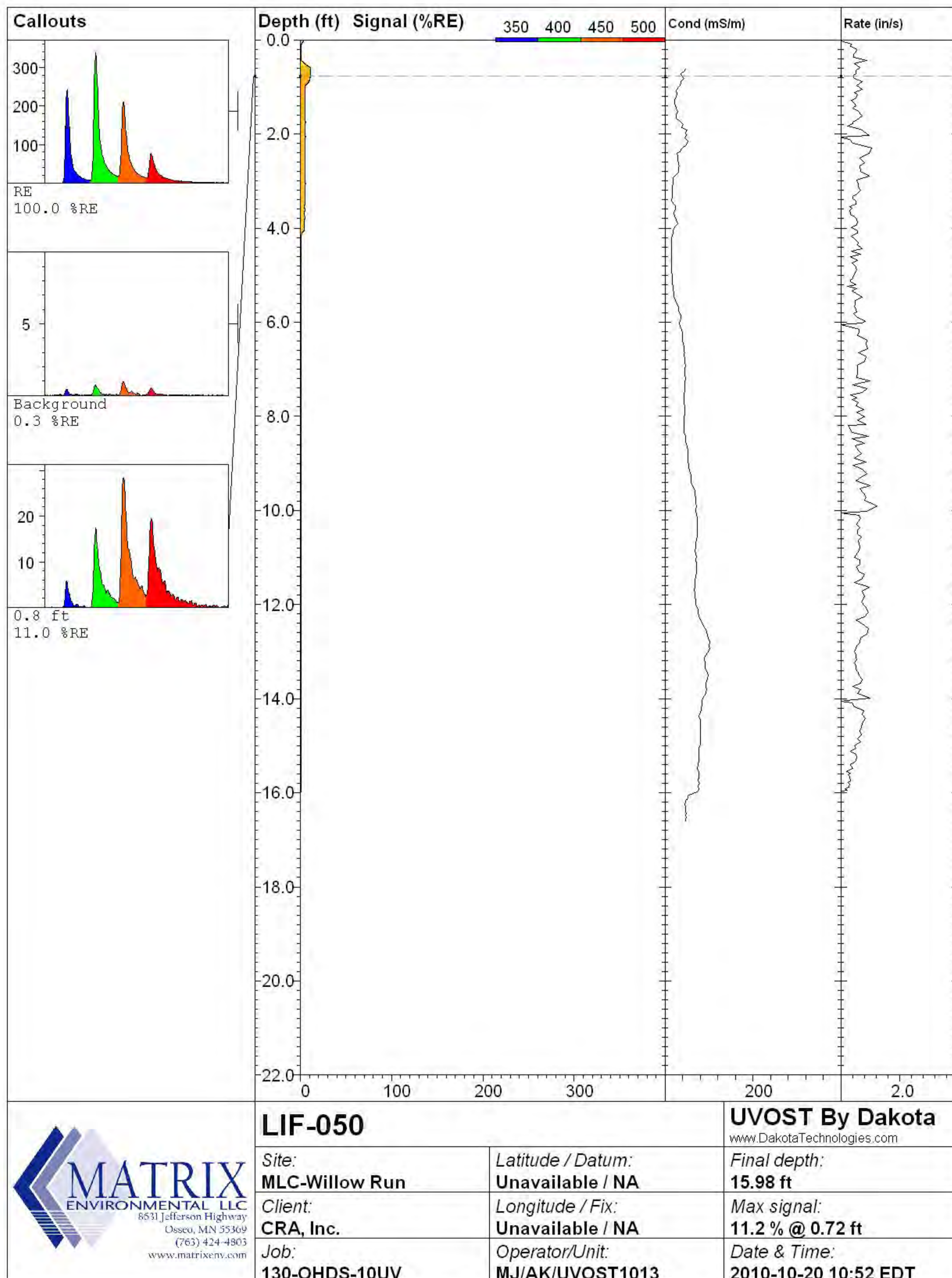
Longitude / Fix:
Unavailable / NA

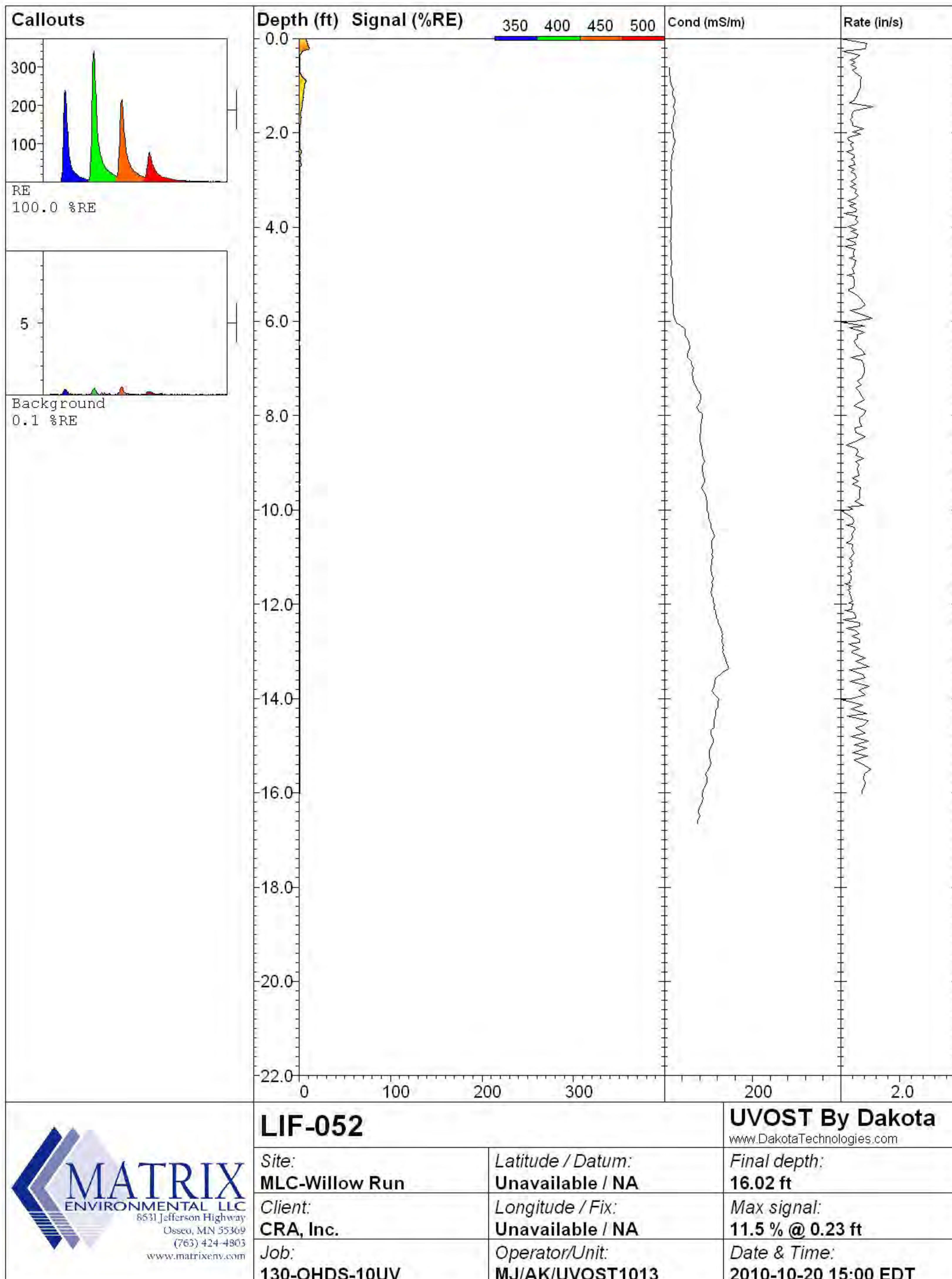
Max signal:
5.7 % @ 2.29 ft

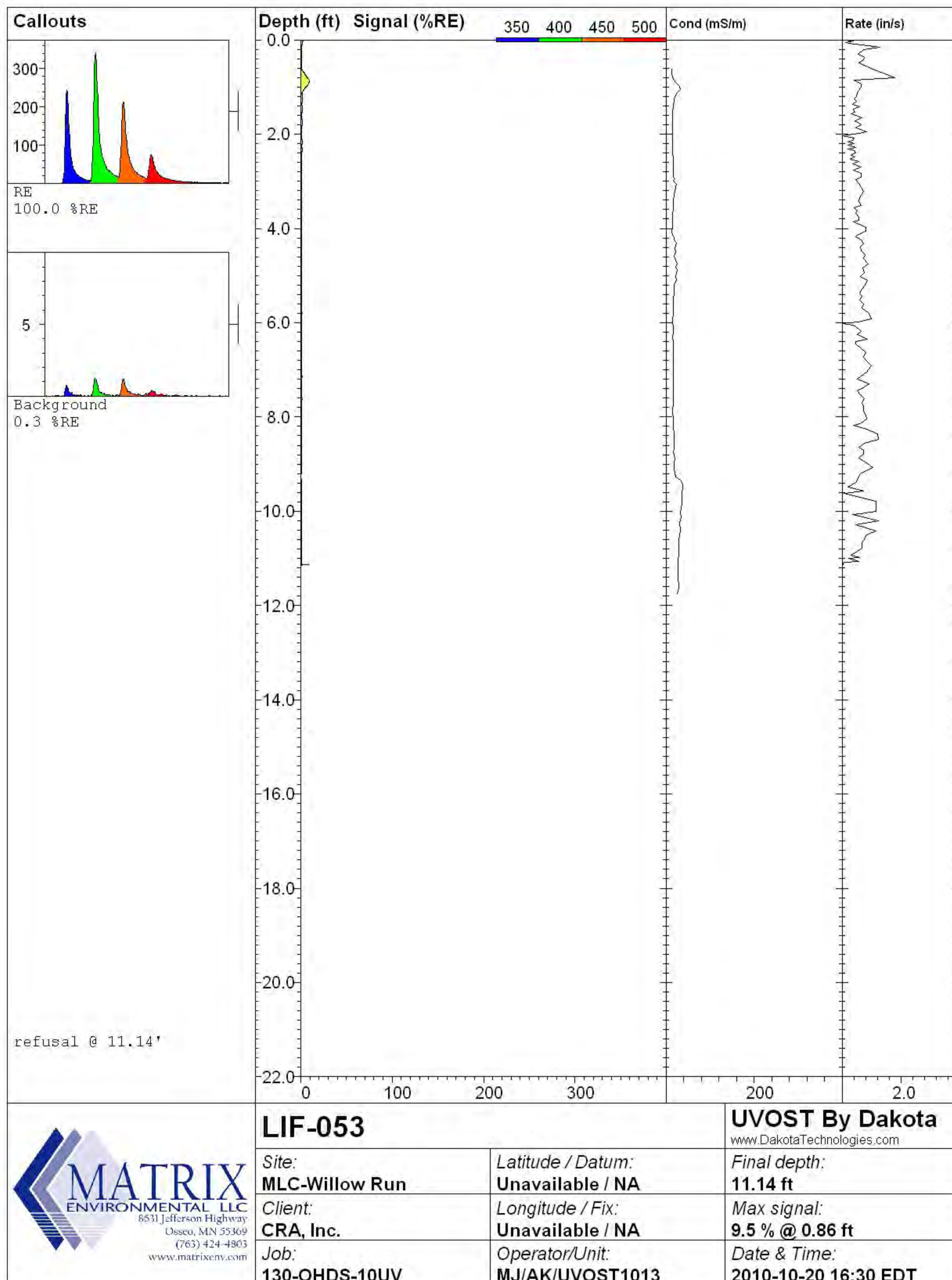
Job:
130-OHDS-10UV

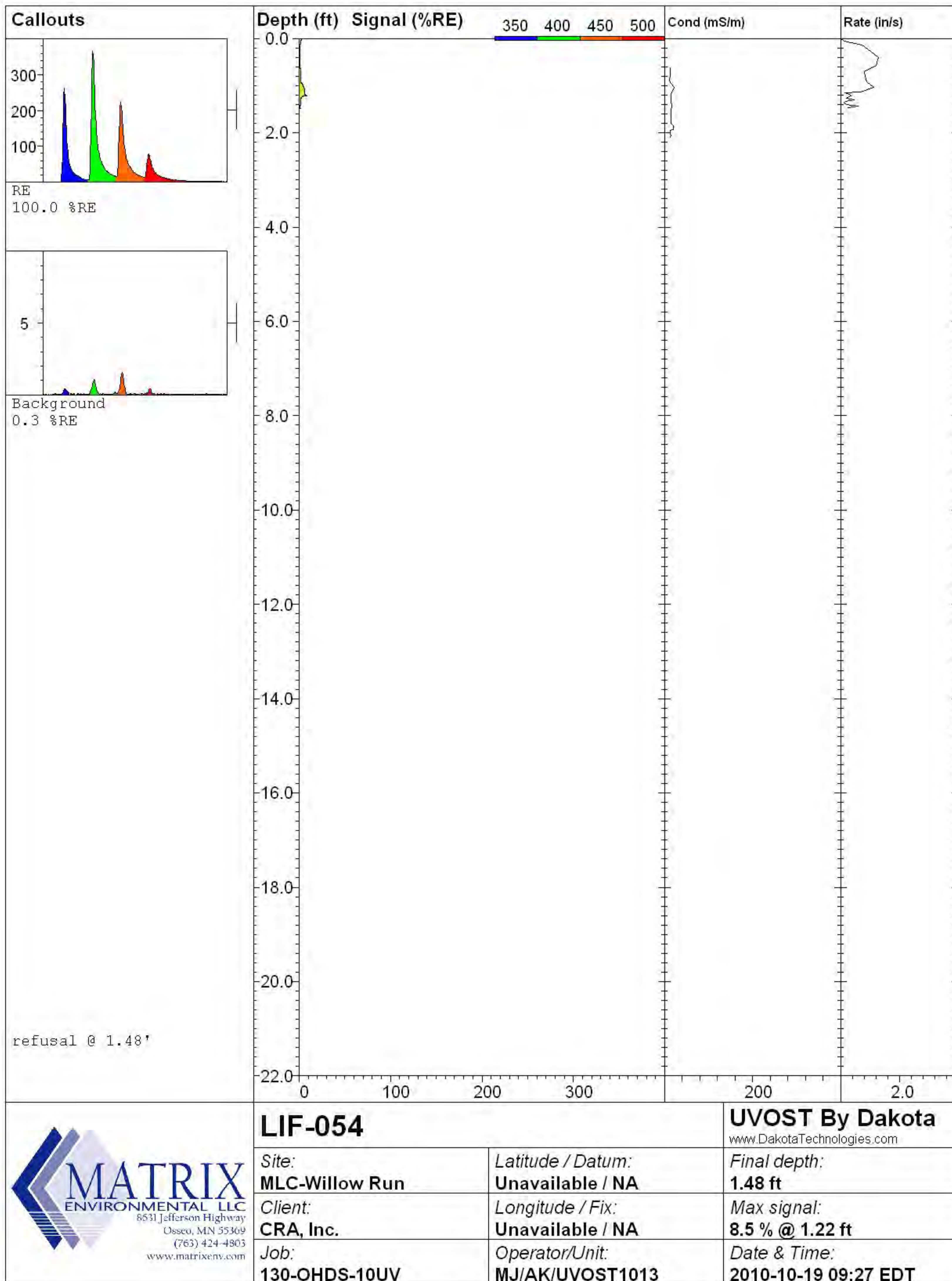
Operator/Unit:
MJ/AK/UVOST1013

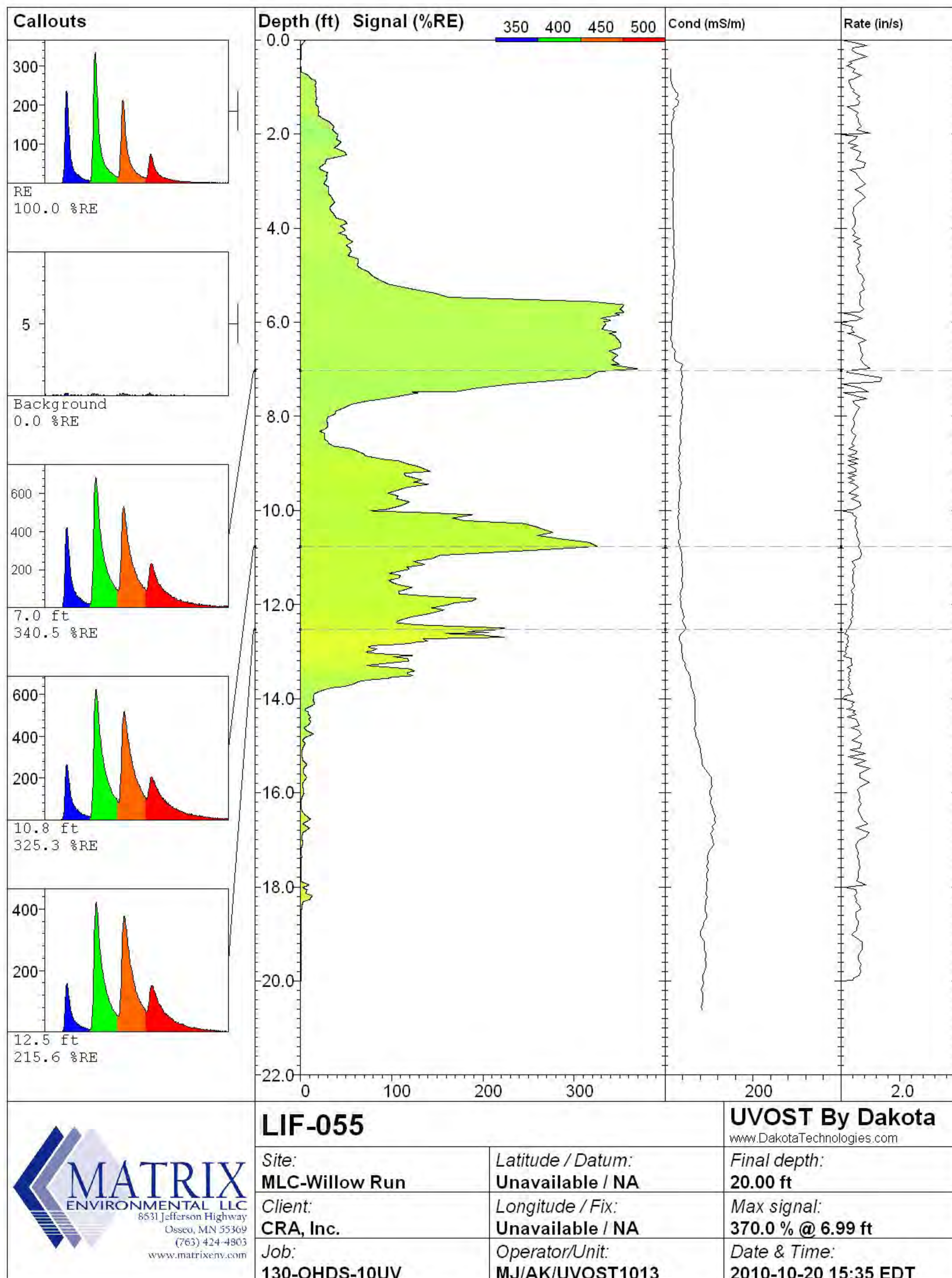
Date & Time:
2010-10-20 10:23 EDT

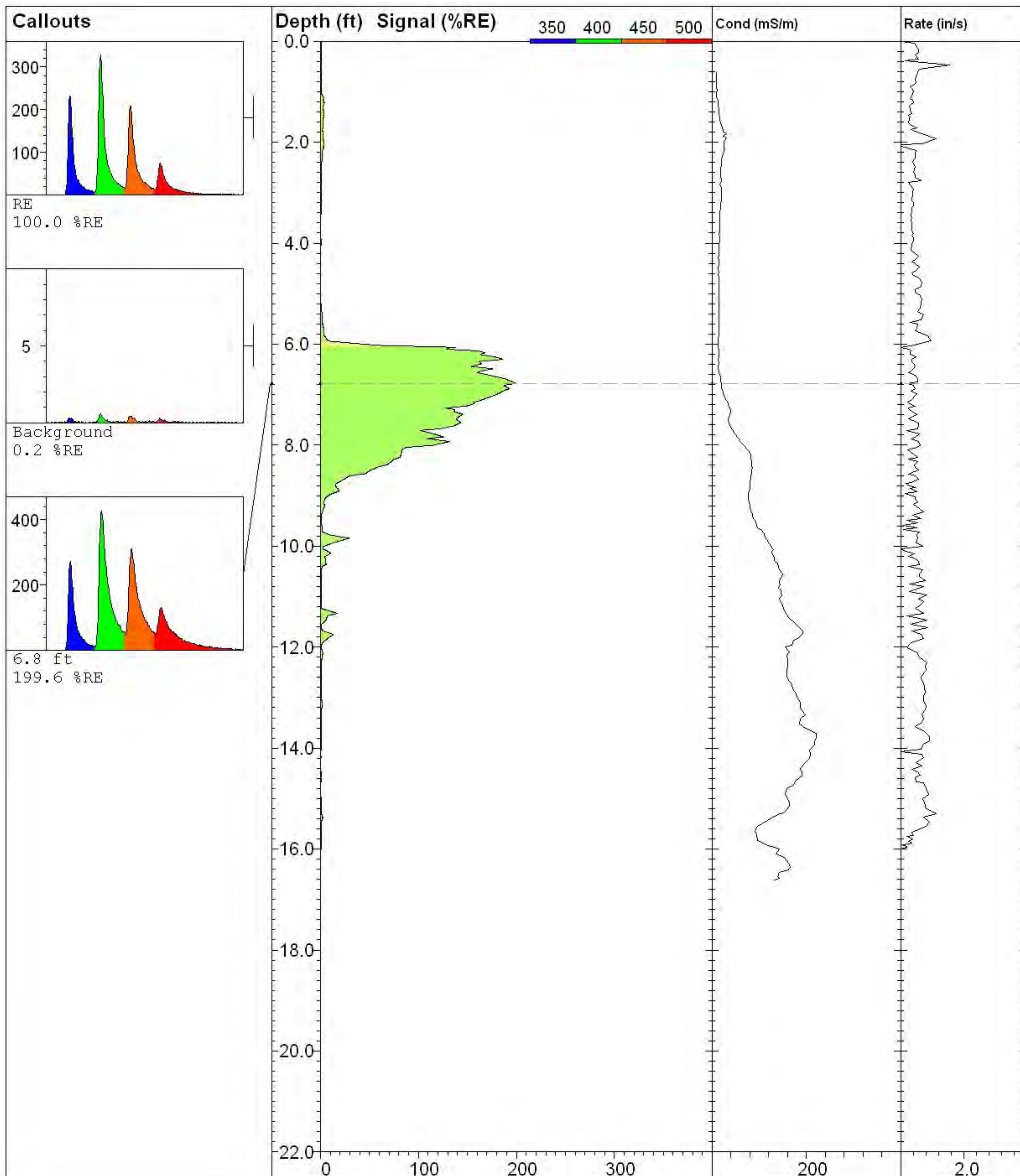












LIF-056

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.00 ft

Client:
CRA, Inc.

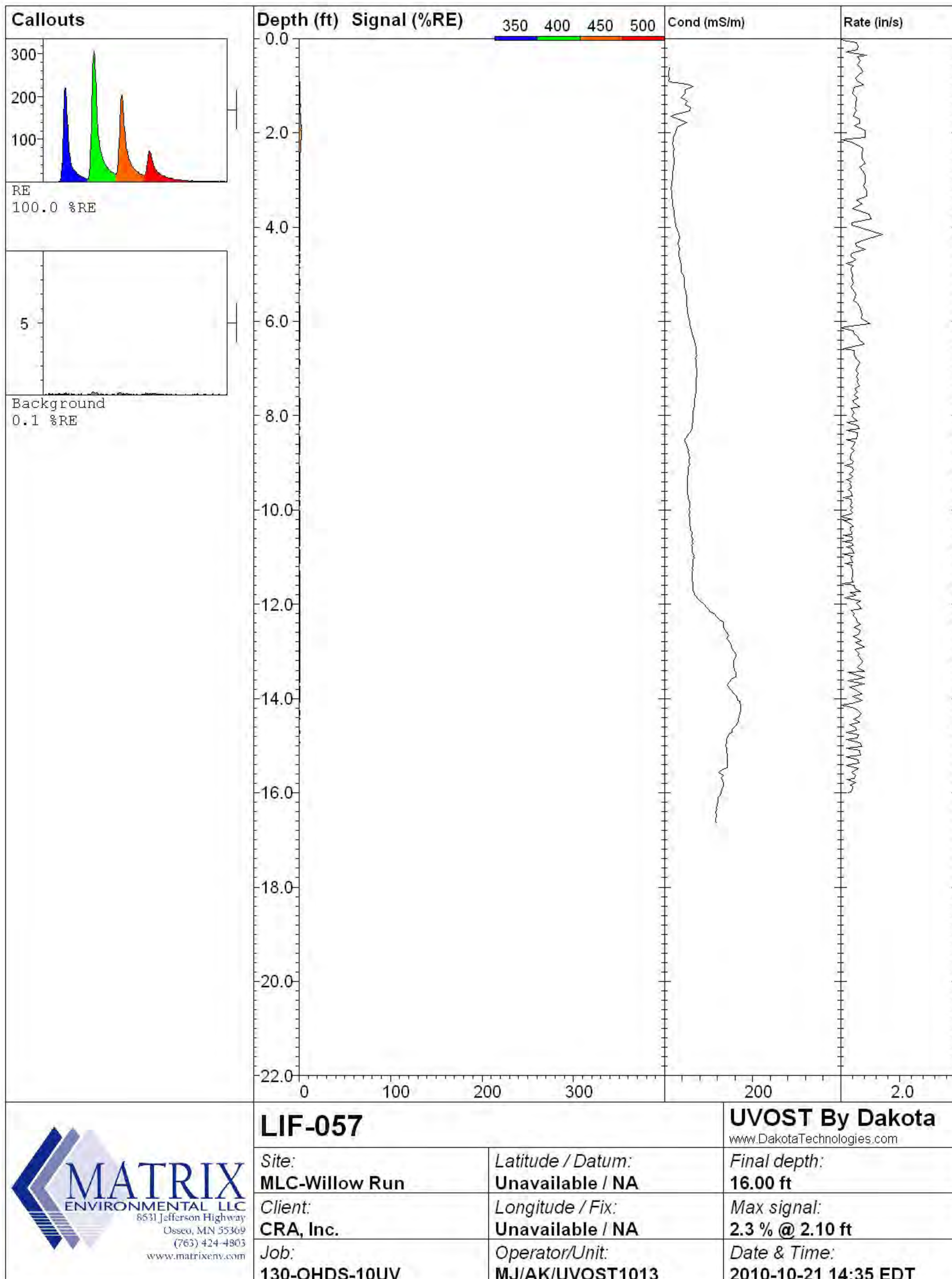
Longitude / Fix:
Unavailable / NA

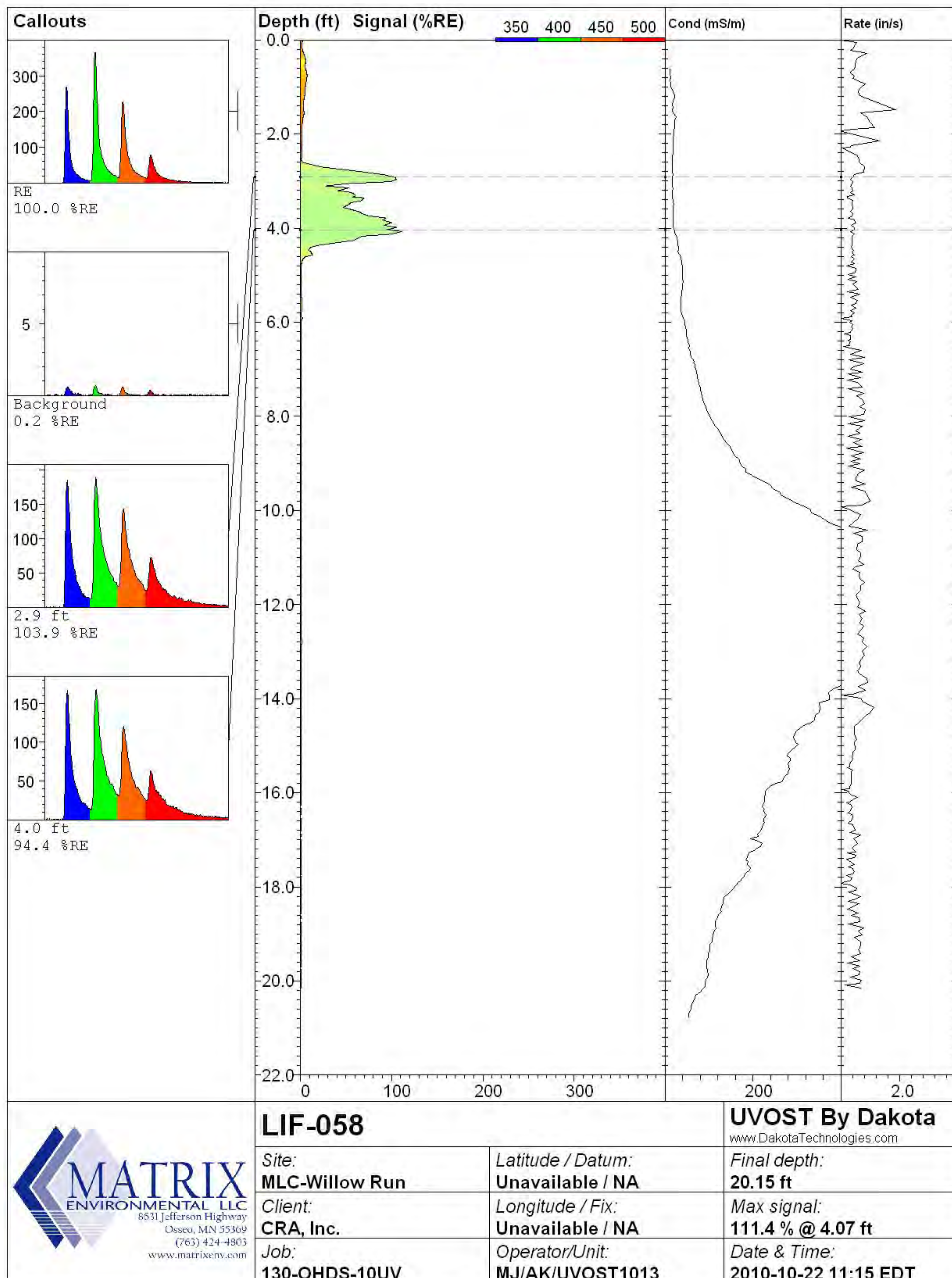
Max signal:
199.6 % @ 6.78 ft

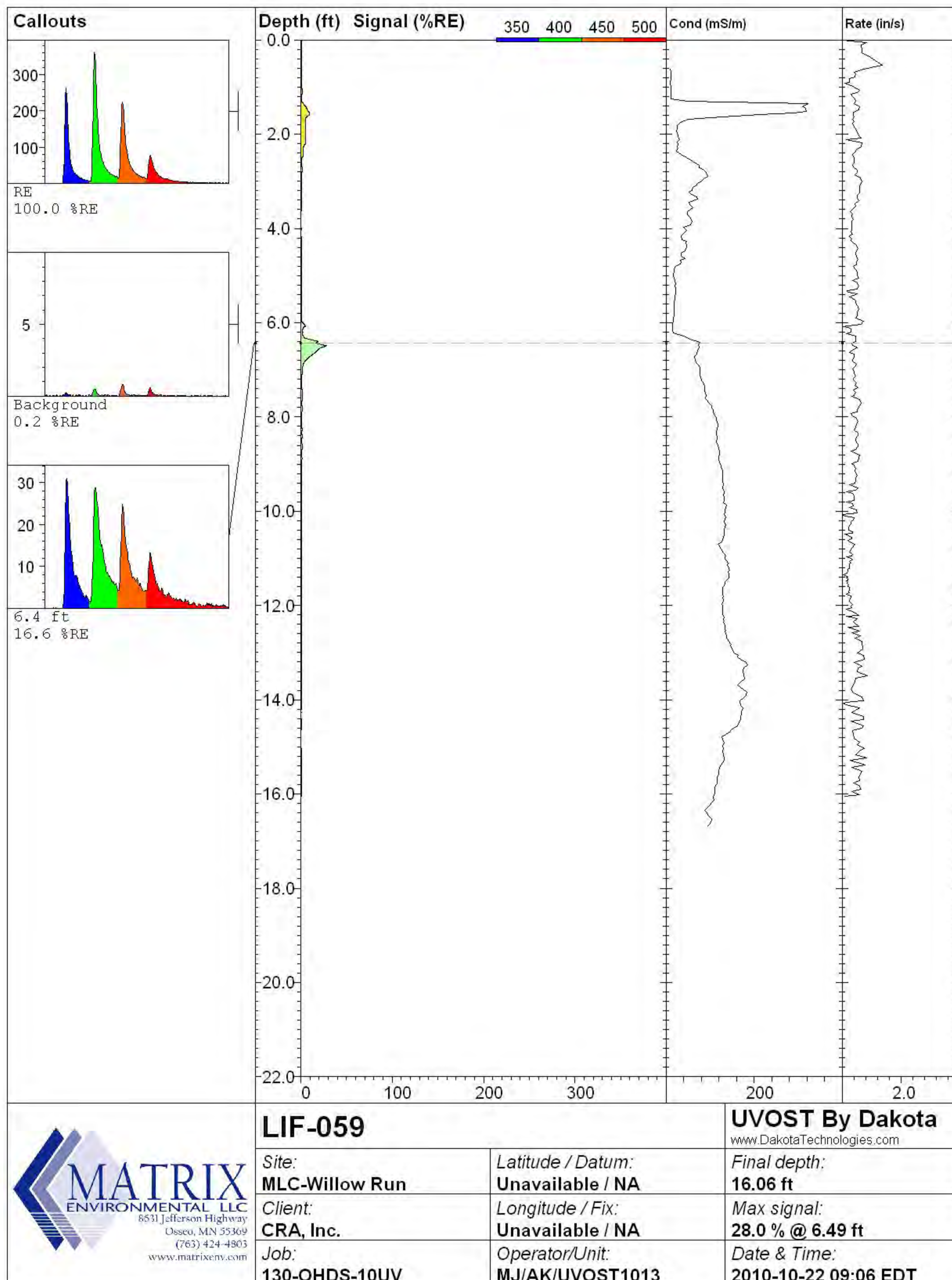
Job:
130-OHDS-10UV

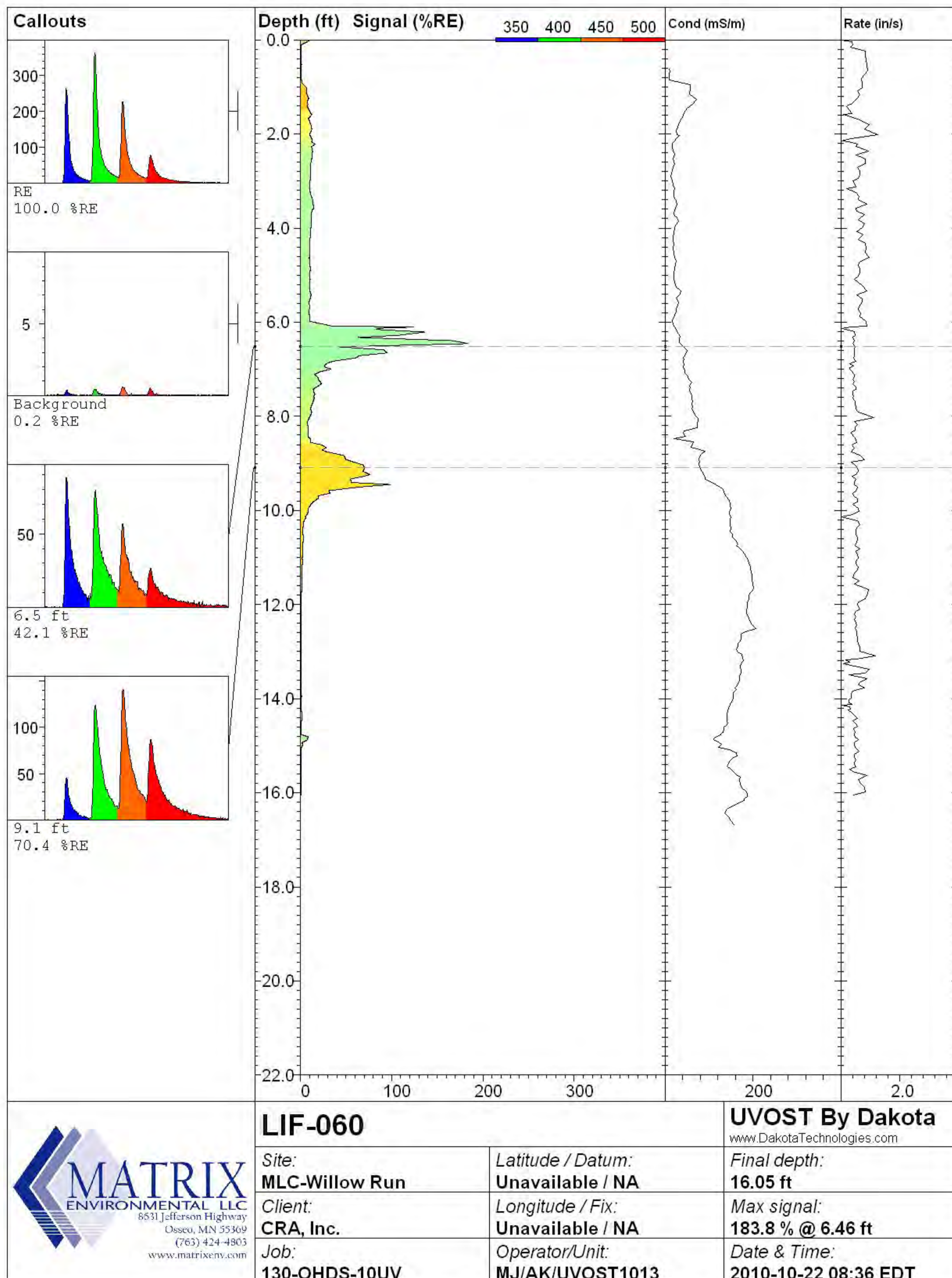
Operator/Unit:
MJ/AK/UVOST1013

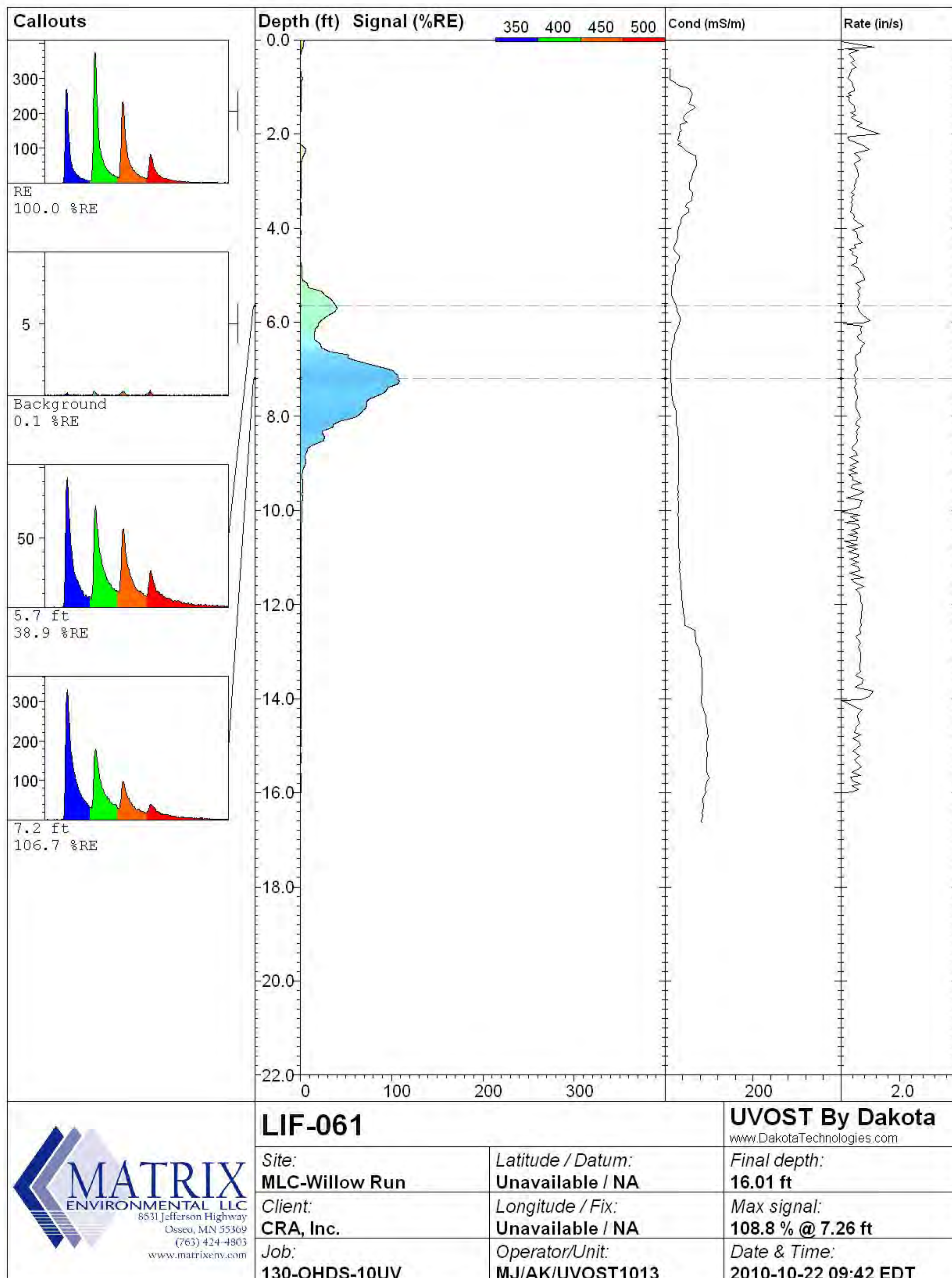
Date & Time:
2010-10-21 08:25 EDT

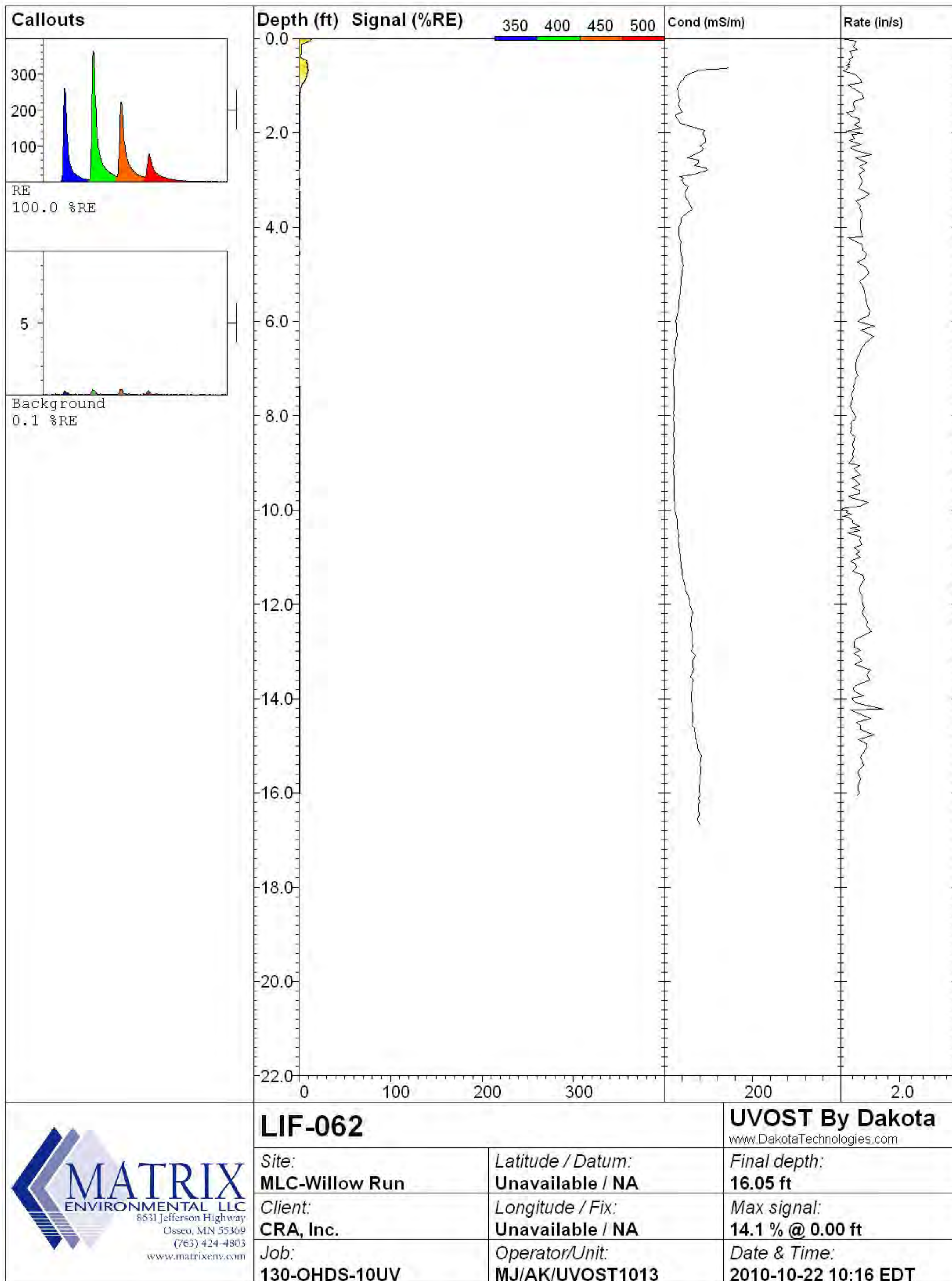


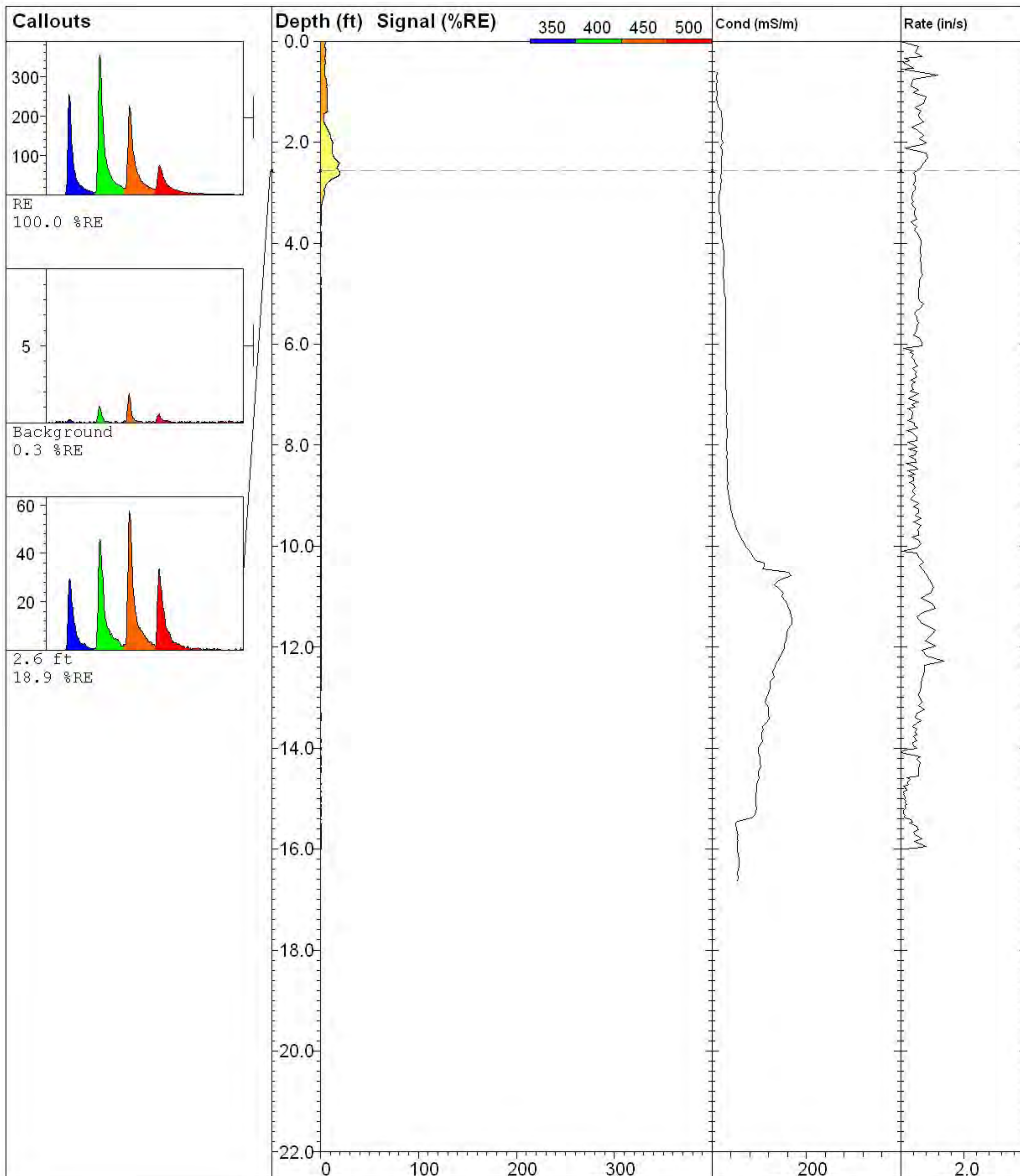












LIF-063

UVOST By Dakota

www.DakotaTechnologies.com

Site:
MLC-Willow Run

Latitude / Datum:
Unavailable / NA

Final depth:
16.00 ft

Client:
CRA, Inc.

Longitude / Fix:
Unavailable / NA

Max signal:
19.9 % @ 2.62 ft

Job:
130-OHDS-10UV

Operator/Unit:
MJ/AK/UVOST1013

Date & Time:
2010-10-22 13:59 EDT

Appendix F

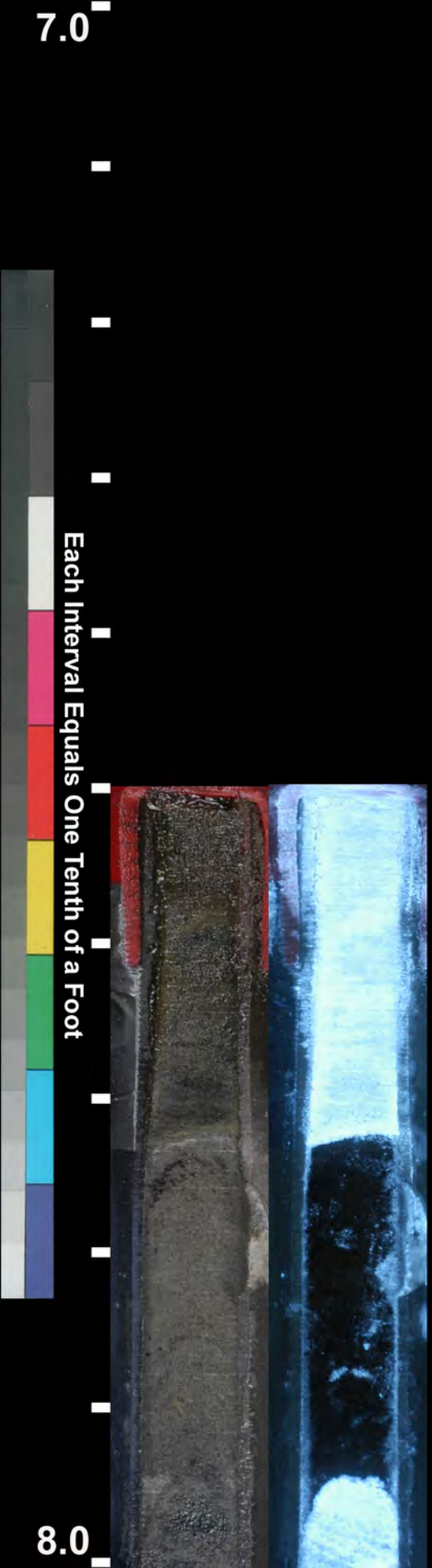
Soil Core Photographs



Project: MLC-Willow Run Boring ID: ARC-128 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: ARC-128 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: ARC-128 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: ARC-128 (5'-10')

Project No.: 17358-T01

8.0

Each Interval Equals One Tenth of a Foot

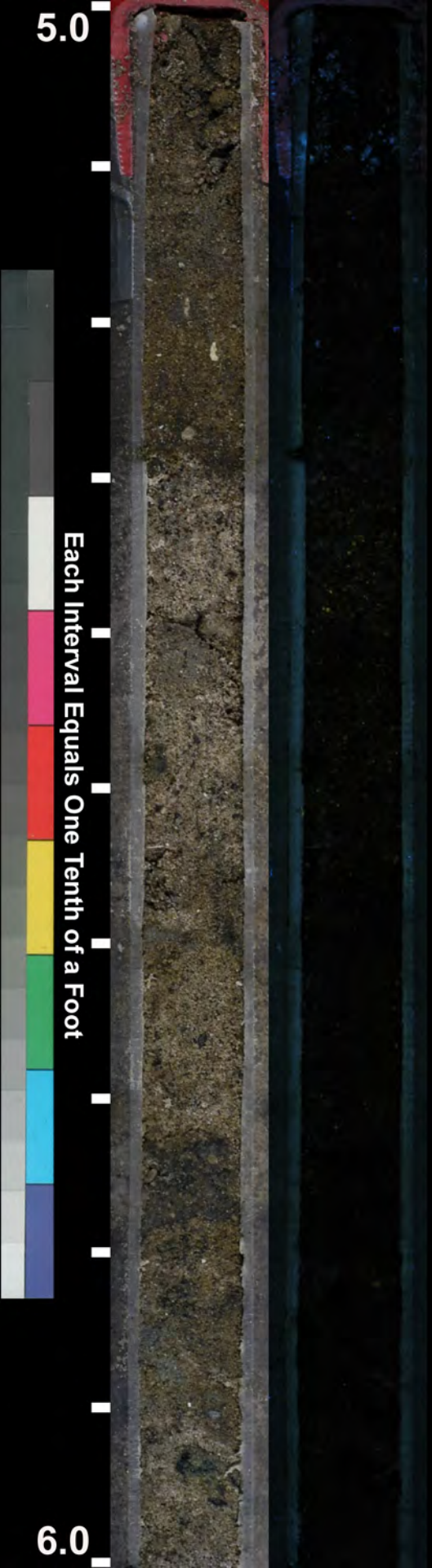
9.0

Project: MLC-Willow Run Boring ID: ARC-128 (5'-10')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: ARC-128 (5'-10')
Project No.: 17358-T01

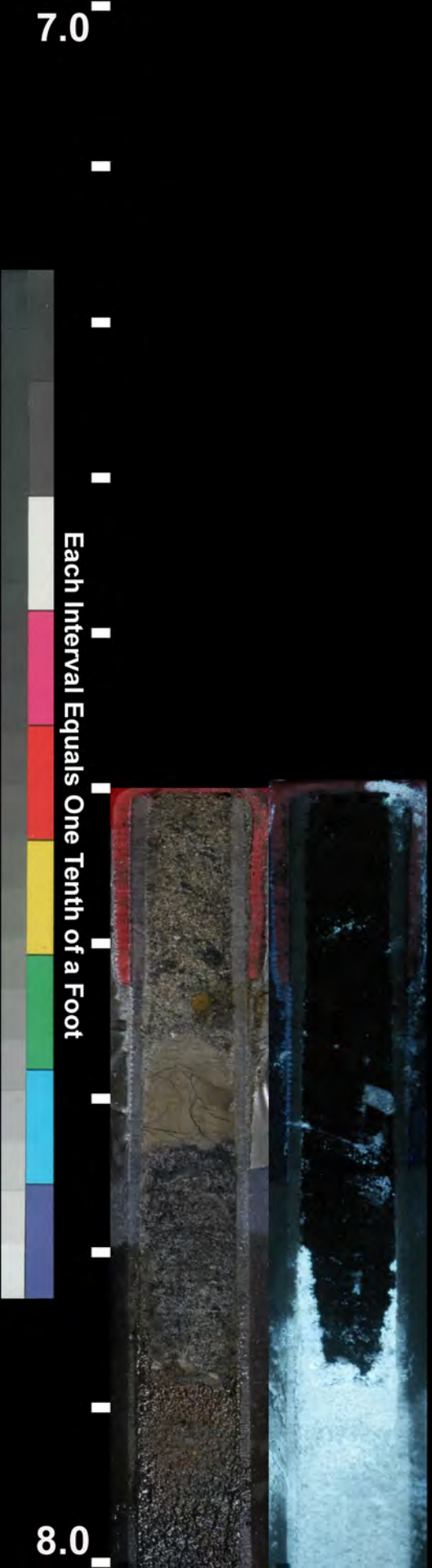


Project: MLC-Willow Run Boring ID: ARC-65 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: ARC-65 (5'-10')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: ARC-65 (5'-10')
Project No.: 17358-T01

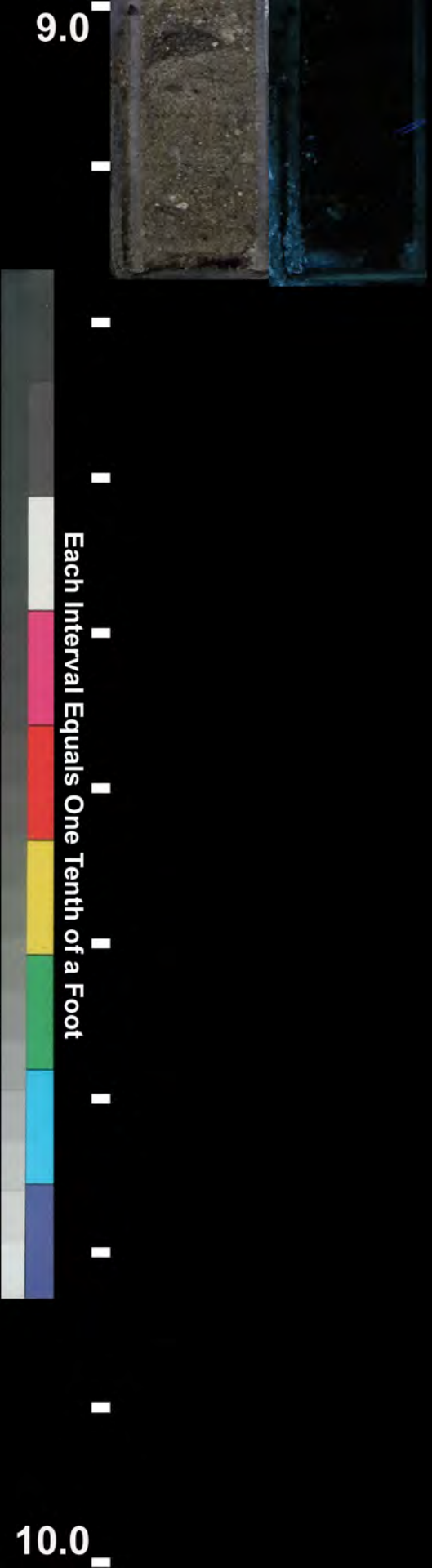
8.0

Each Interval Equals One Tenth of a Foot

9.0

Project: MLC-Willow Run Boring ID: ARC-65 (5'-10')

Project No.: 17358-T01



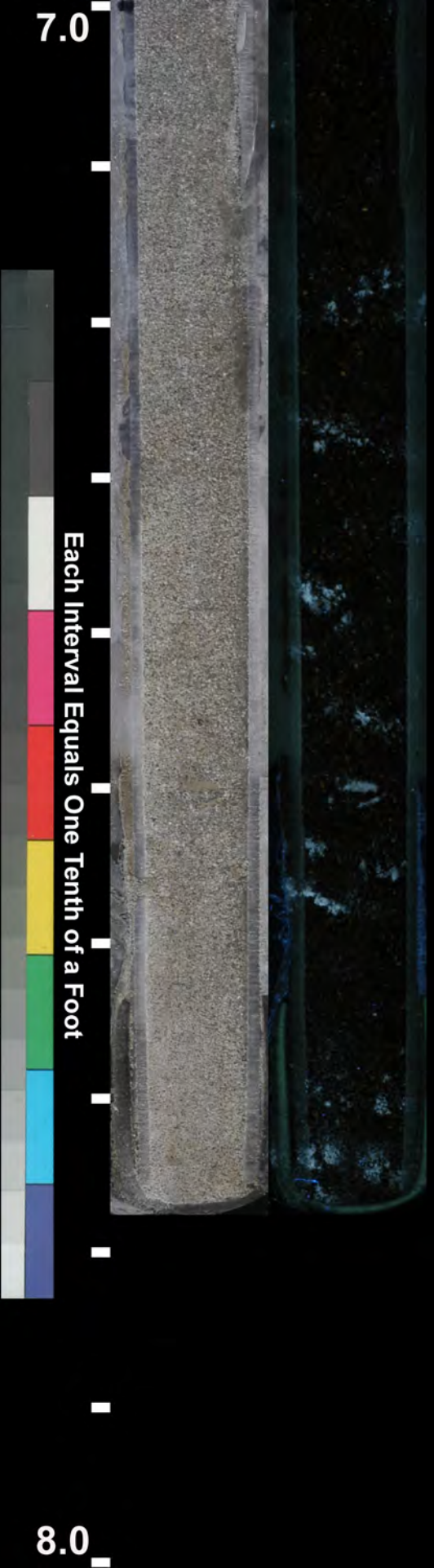
Project: MLC-Willow Run Boring ID: ARC-65 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-009 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-009 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-009 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-021 (2'-7')
Project No.: 17358-T01



3.0

Each Interval Equals One Tenth of a Foot



4.0

Project: MLC-Willow Run Boring ID: LIF-021 (2'-7')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-021 (2'-7')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-021 (2'-7')
Project No.: 17358-T01



6.0

Each Interval Equals One Tenth of a Foot



7.0

Project: MLC-Willow Run Boring ID: LIF-021 (2'-7')
Project No.: 17358-T01



Each Interval Equals One Tenth of a Foot



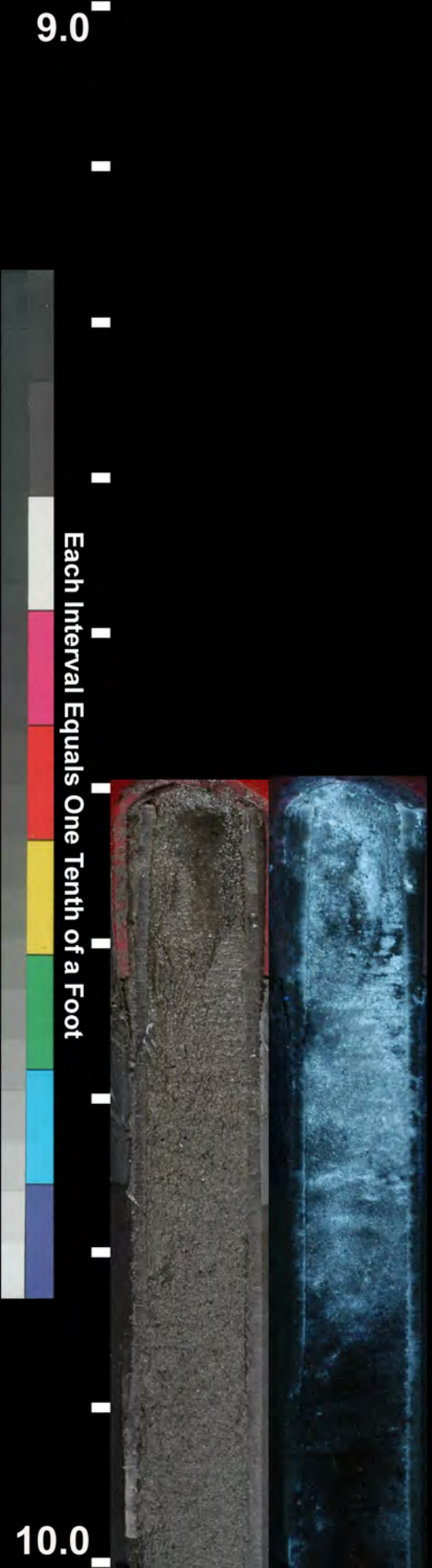
Project: MLC-Willow Run Boring ID: LIF-021 (7'-12')
Project No.: 17358-T01

7.0

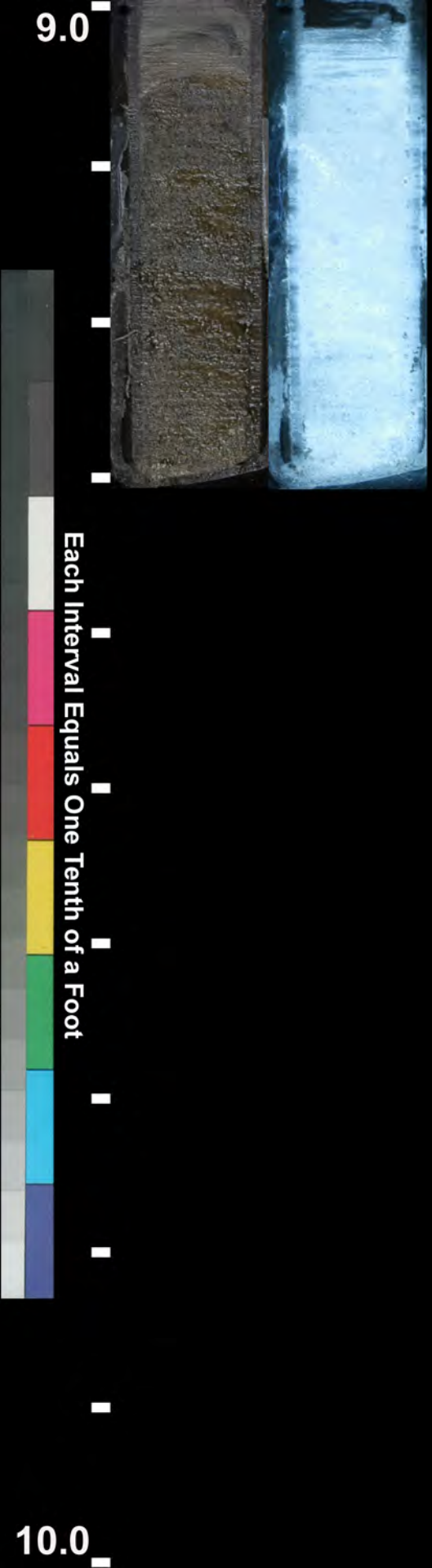
8.0



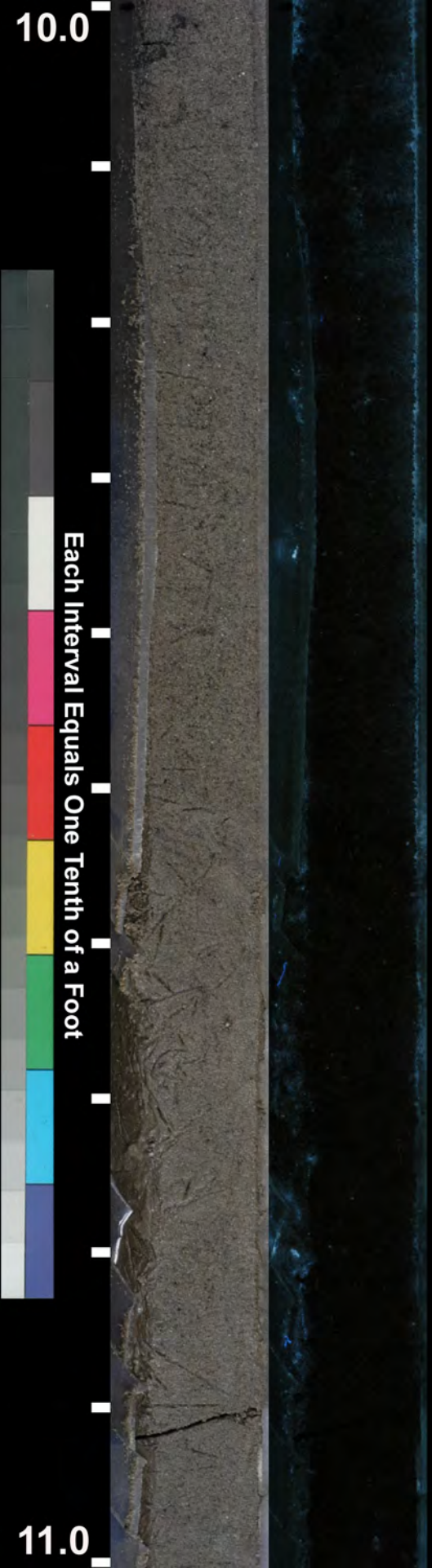
Project: MLC-Willow Run Boring ID: LIF-021 (7'-12')
Project No.: 17358-T01



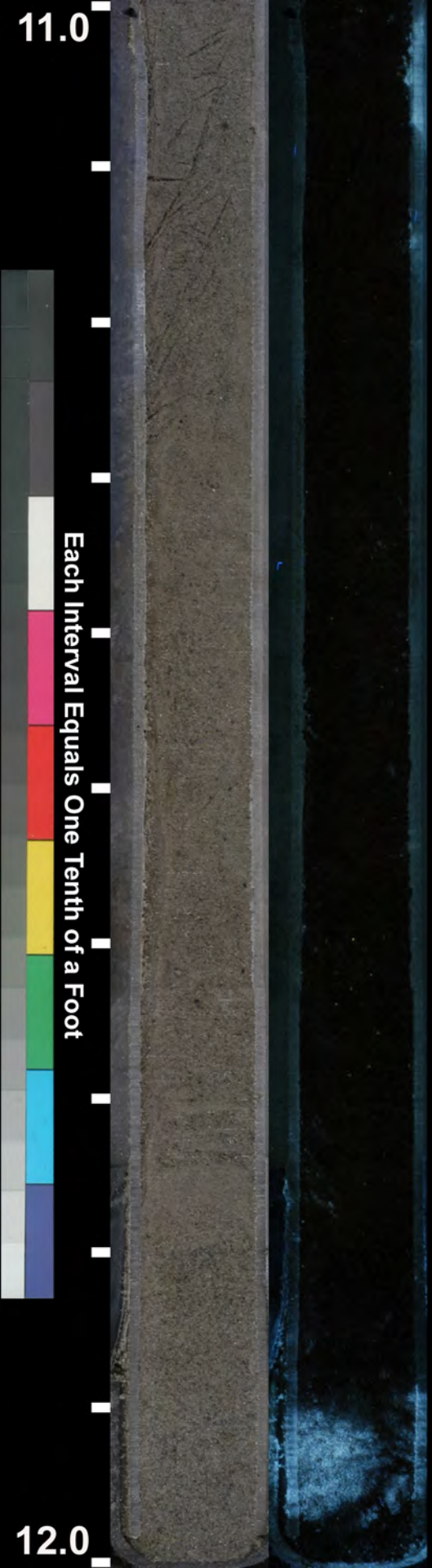
Project: MLC-Willow Run Boring ID: LIF-021 (7'-12')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-021 (2'-7')
Project No.: 17358-T01



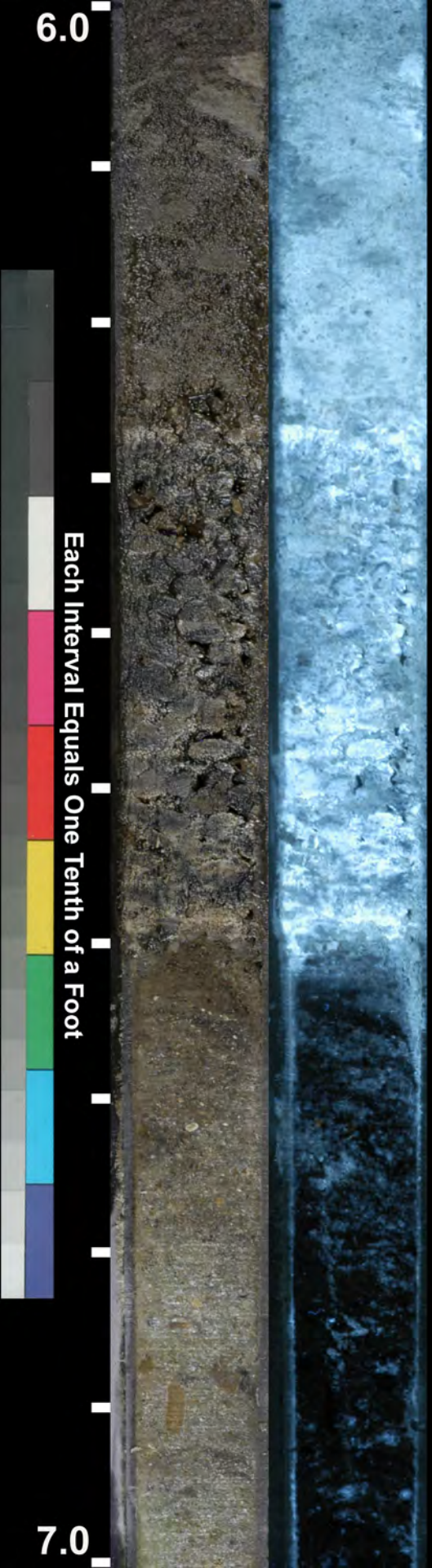
Project: MLC-Willow Run Boring ID: LIF-021 (2'-7')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-021 (7'-12')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-025 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-025 (5'-10')
Project No.: 17358-T01



7.0

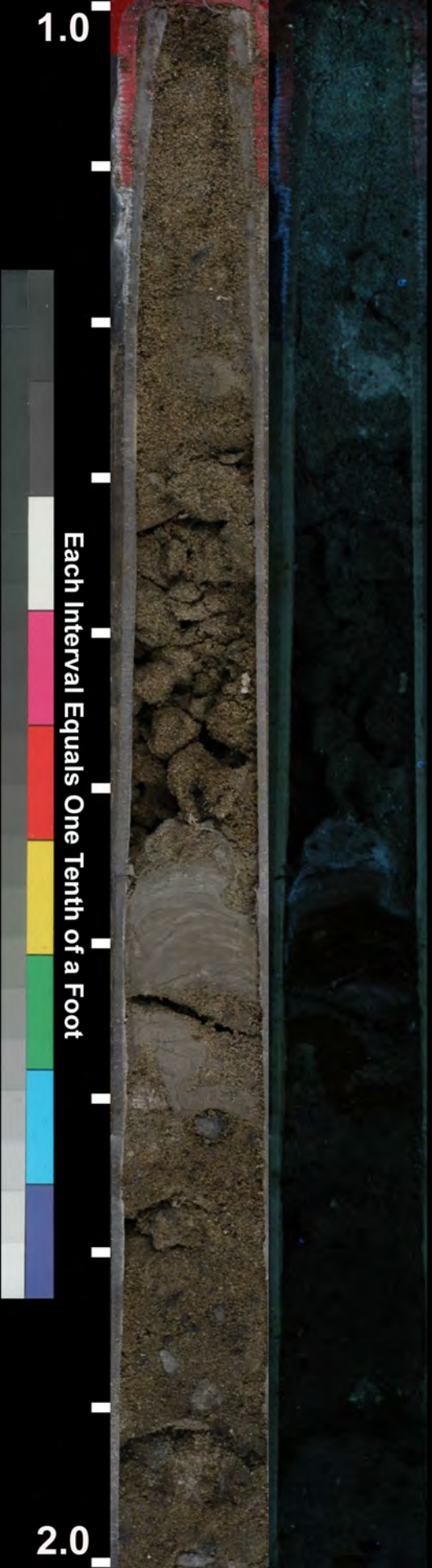
Each Interval Equals One Tenth of a Foot



8.0

Project: MLC-Willow Run Boring ID: LIF-025 (5'-10')

Project No.: 17358-T01

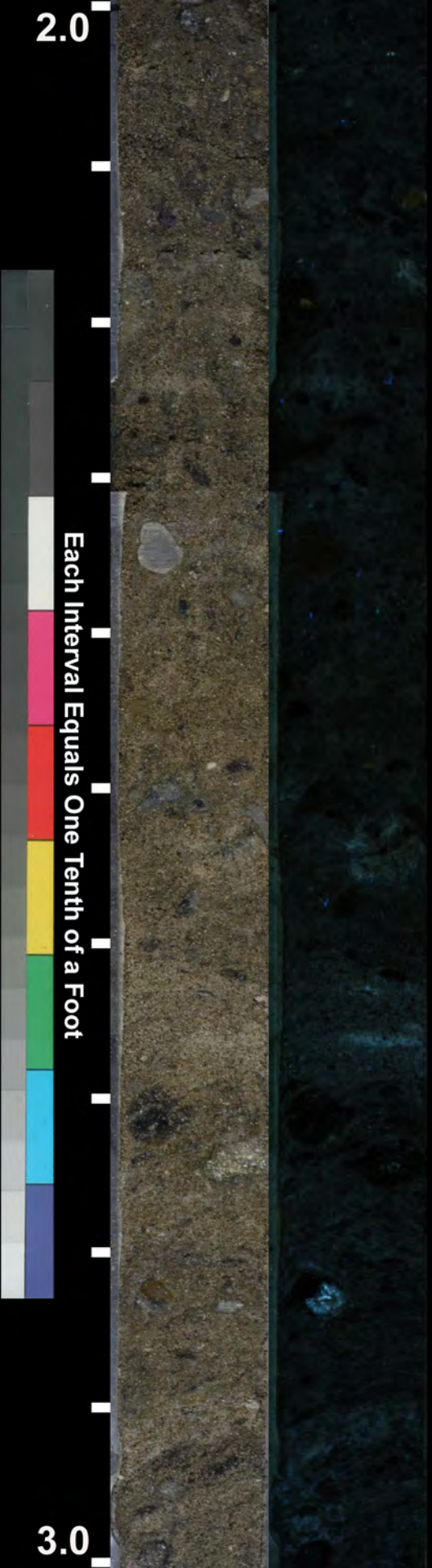


Each Interval Equals One Tenth of a Foot

Project: MLC-Willow Run Boring ID: LIF-029 (1'-5')
Project No.: 17358-T01

1.0

2.0



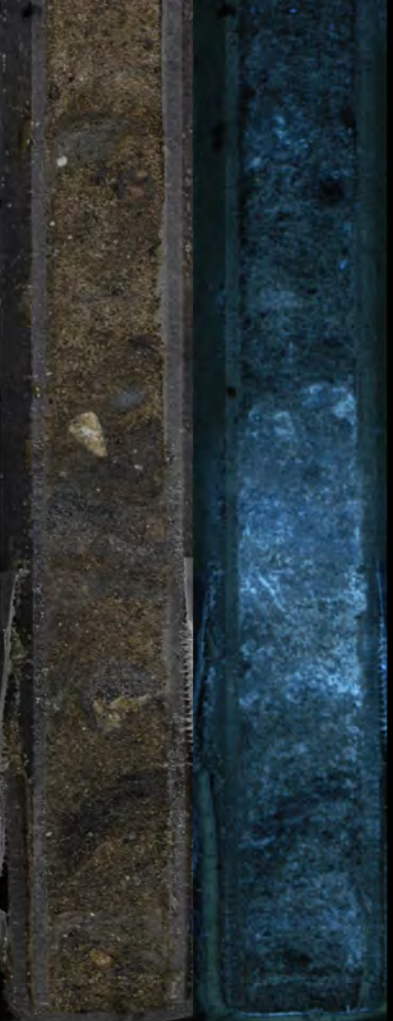
Project: MLC-Willow Run Boring ID: LIF-029 (1'-5')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-029 (1'-5')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-029 (5'-10')
Project No.: 17358-T01



6.0

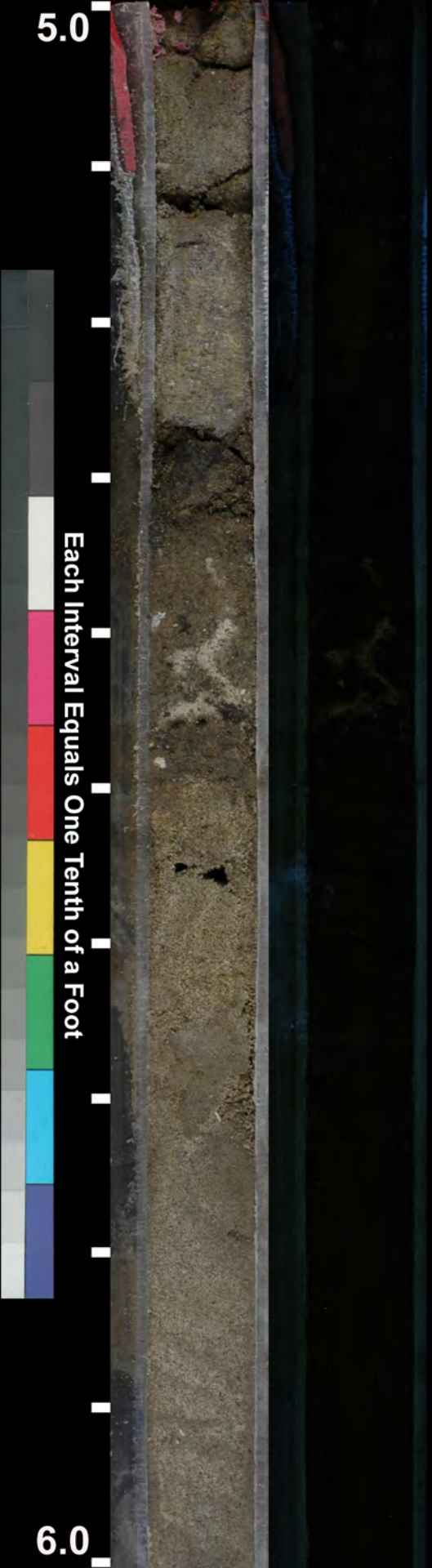
Each Interval Equals One Tenth of a Foot



7.0

Project: MLC-Willow Run Boring ID: LIF-029 (5'-10')

Project No.: 17358-T01



5.0

Each Interval Equals One Tenth of a Foot

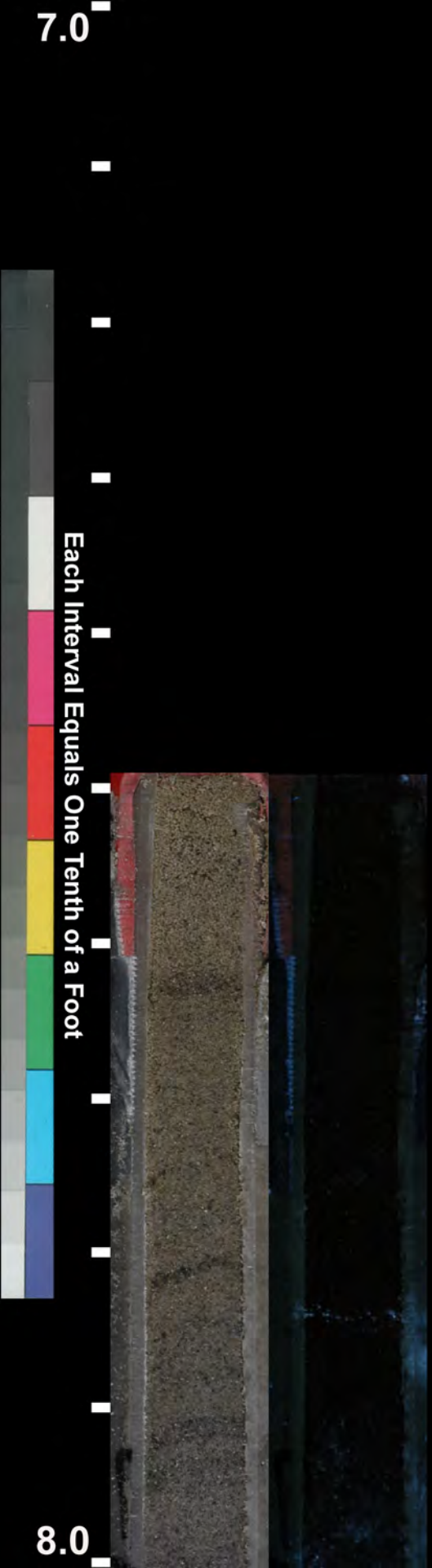
6.0

Project: MLC-Willow Run Boring ID: LIF-034 (5'-10')
Project No.: 17358-T01

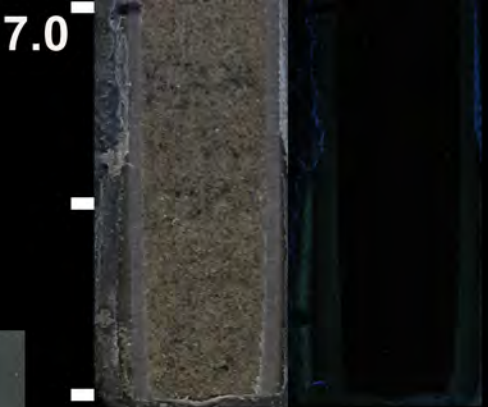


Project: MLC-Willow Run Boring ID: LIF-034 (5'-10')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-034 (5'-10')
Project No.: 17358-T01



Each Interval Equals One Tenth of a Foot



Project: MLC-Willow Run Boring ID: LIF-034 (5'-10')

Project No.: 17358-T01





Each Interval Equals One Tenth of a Foot



Project: MLC-Willow Run Boring ID: LIF-034 (5'-10')

Project No.: 17358-T01

5.0

Each Interval Equals One Tenth of a Foot

6.0

Project: MLC-Willow Run Boring ID: LIF-037 (5'-10')

Project No.: 17358-T01

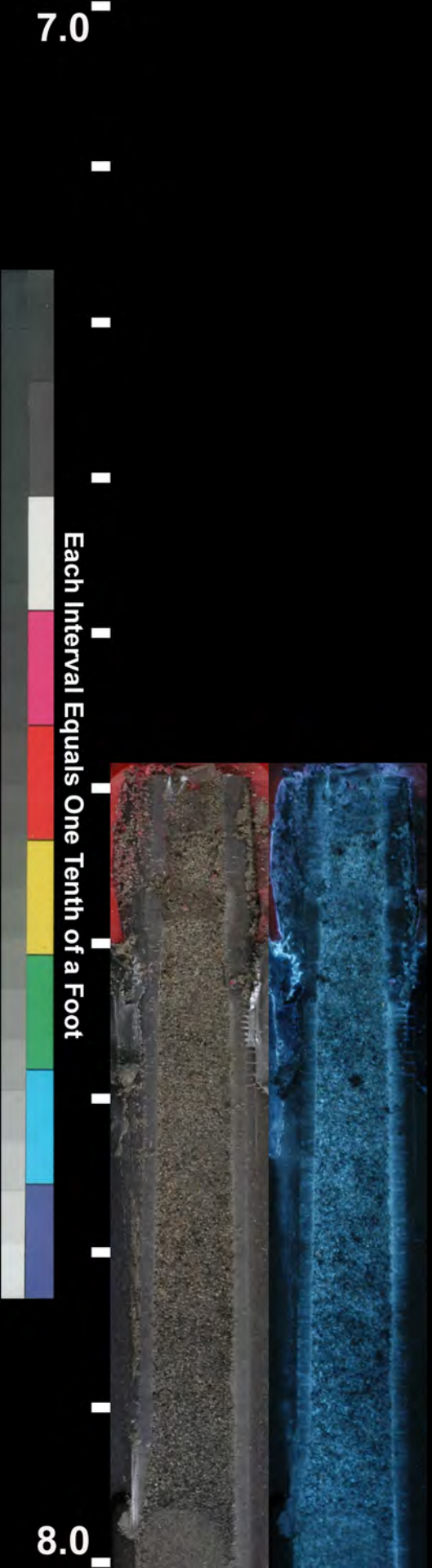
6.0

Each Interval Equals One Tenth of a Foot

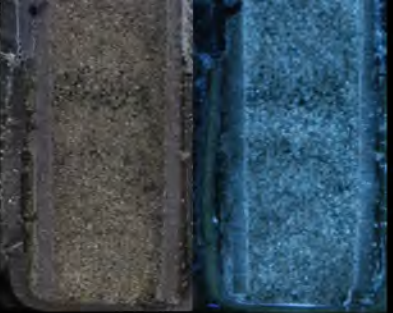
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Project: MLC-Willow Run Boring ID: LIF-037 (5'-10')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-037 (5'-10')
Project No.: 17358-T01



7.0

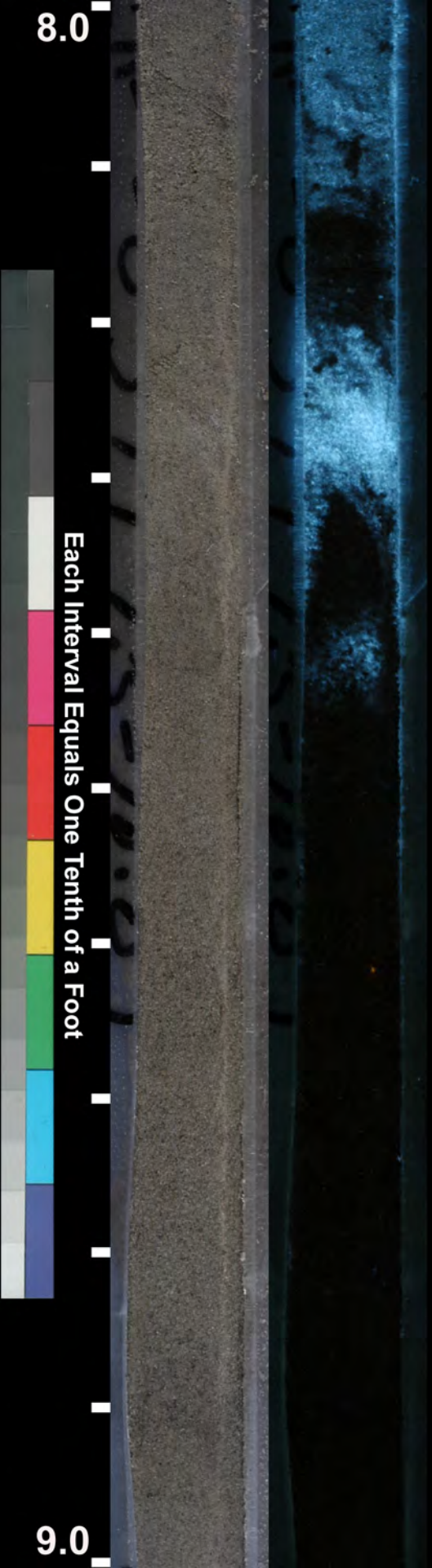
Each Interval Equals One Tenth of a Foot



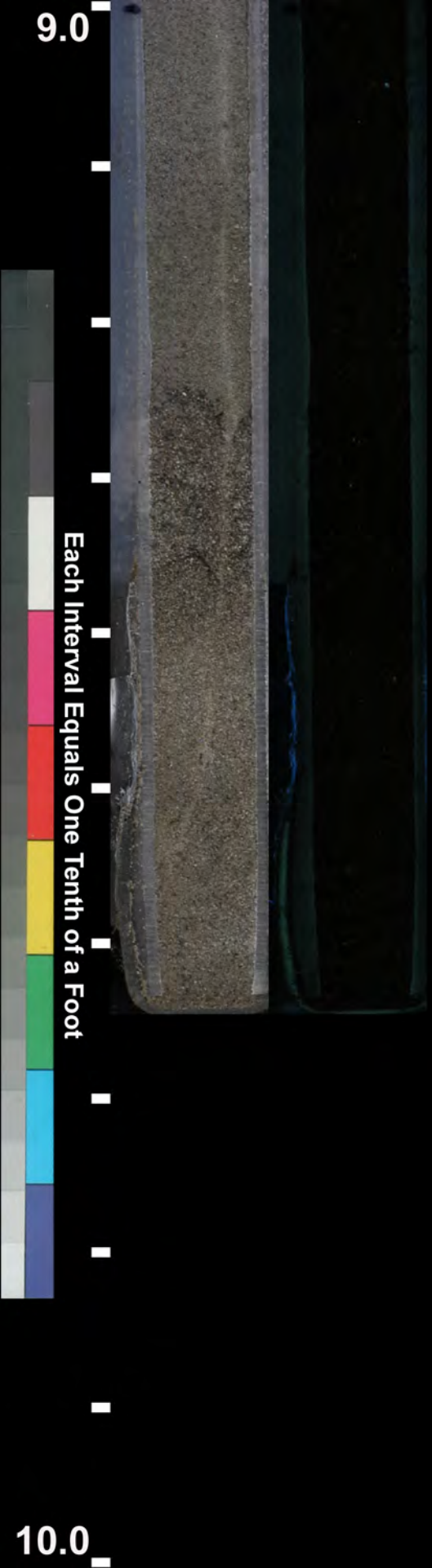
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Project: MLC-Willow Run Boring ID: LIF-037 (5'-10')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-037 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-037 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-040 (5'-10')
Project No.: 17358-T01

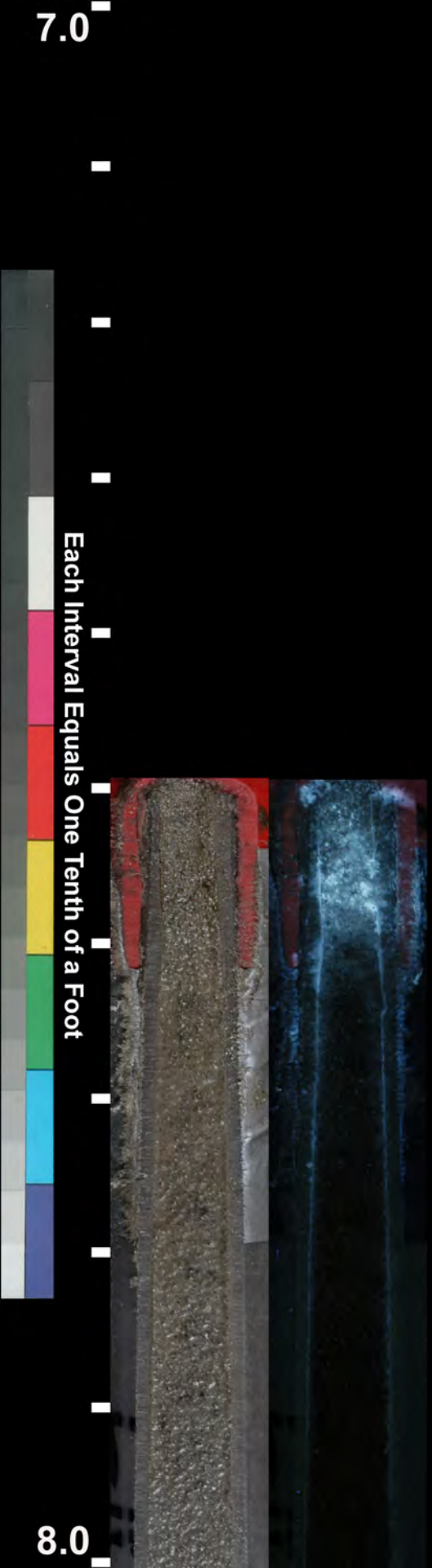
6.0

Each Interval Equals One Tenth of a Foot

7.0

Project: MLC-Willow Run Boring ID: LIF-040 (5'-10')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-040 (5'-10')
Project No.: 17358-T01



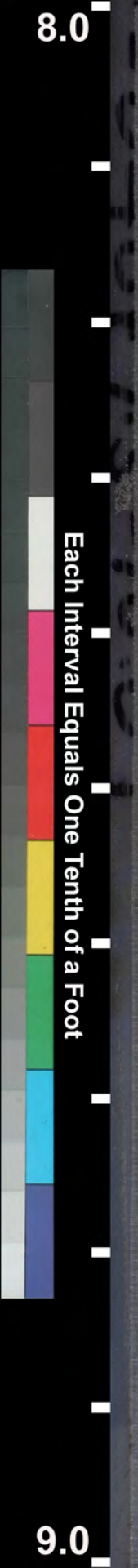
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Each Interval Equals One Tenth of a Foot



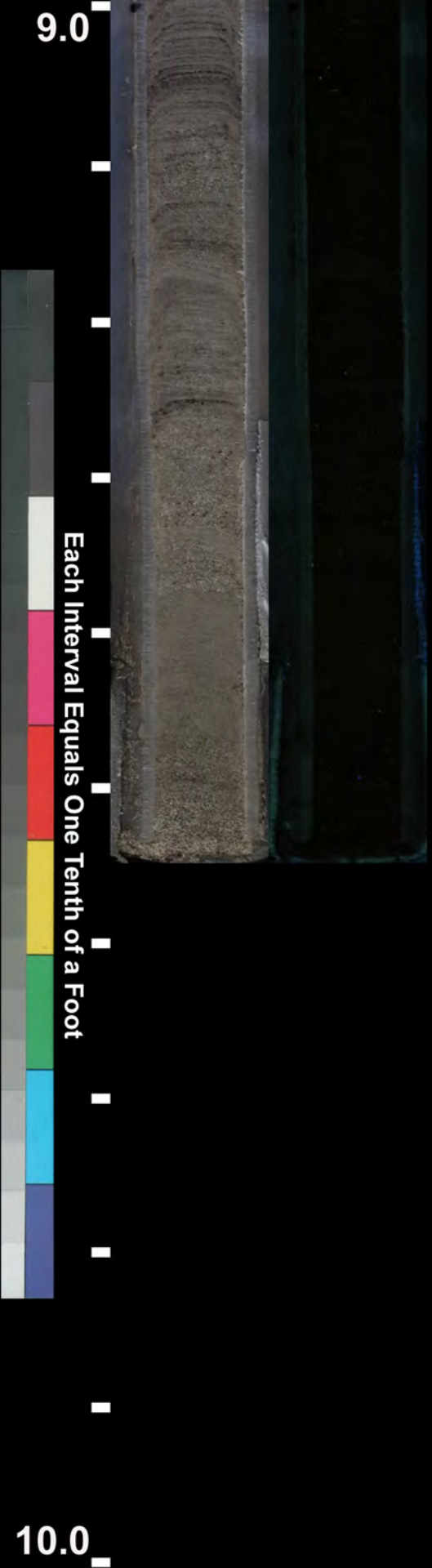
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Project No.: 17358-T01

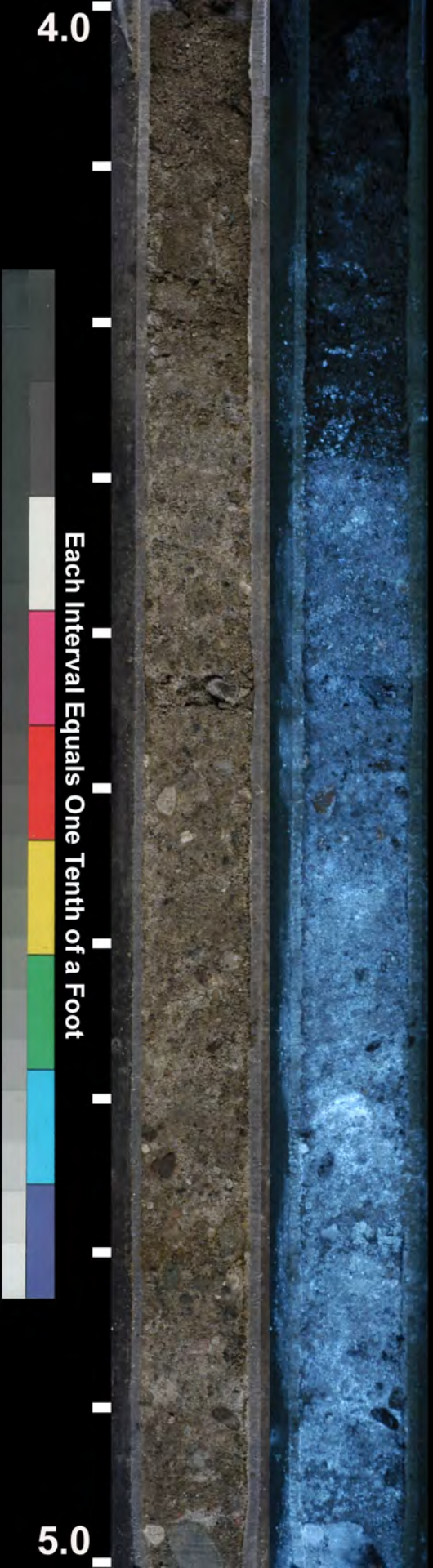


Project: MLC-Willow Run Boring ID: LIF-040 (5'-10')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-040 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-055 (4'-9')
Project No.: 17358-T01



5.0

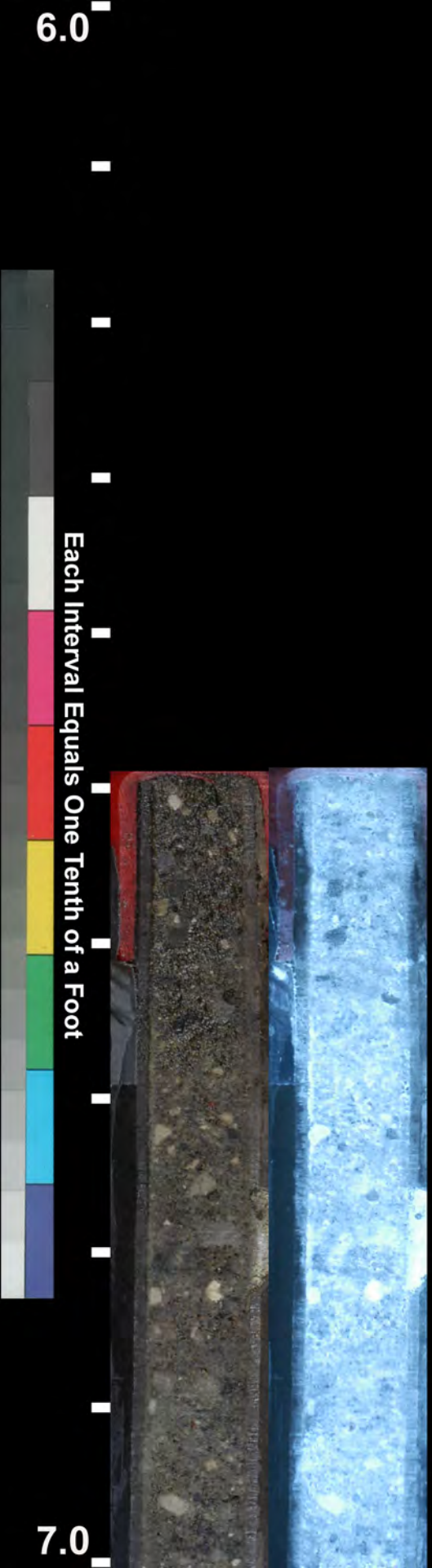
Each Interval Equals One Tenth of a Foot



6.0

Project: MLC-Willow Run Boring ID: LIF-055 (4'-9')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-055 (4'-9')
Project No.: 17358-T01

7.0

Each Interval Equals One Tenth of a Foot

8.0

Project: MLC-Willow Run Boring ID: LIF-055 (4'-9')

Project No.: 17358-T01



8.0

Each Interval Equals One Tenth of a Foot

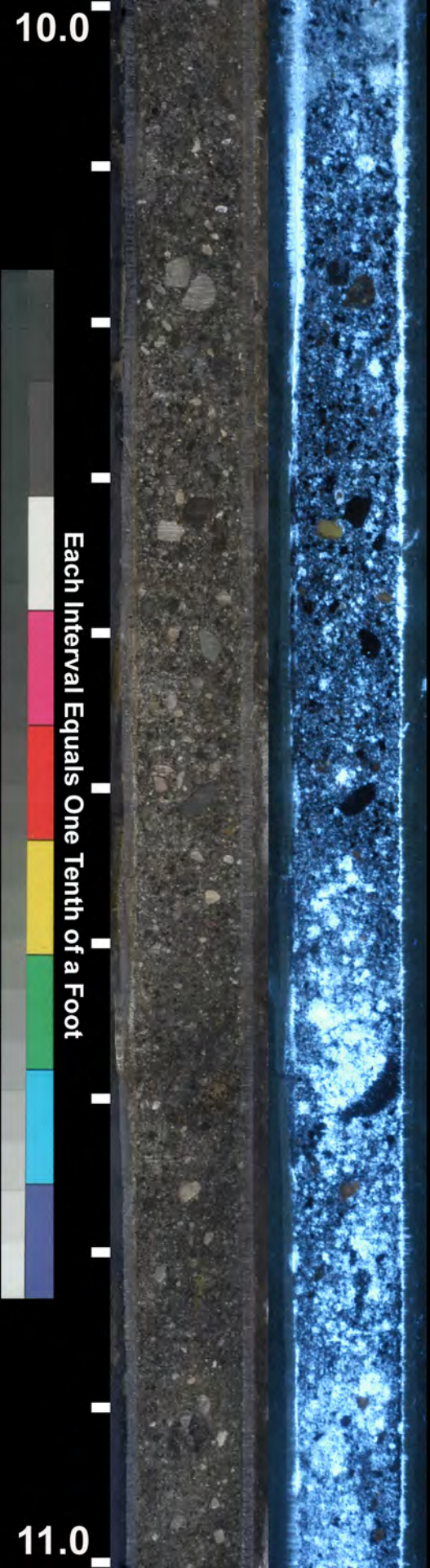


9.0

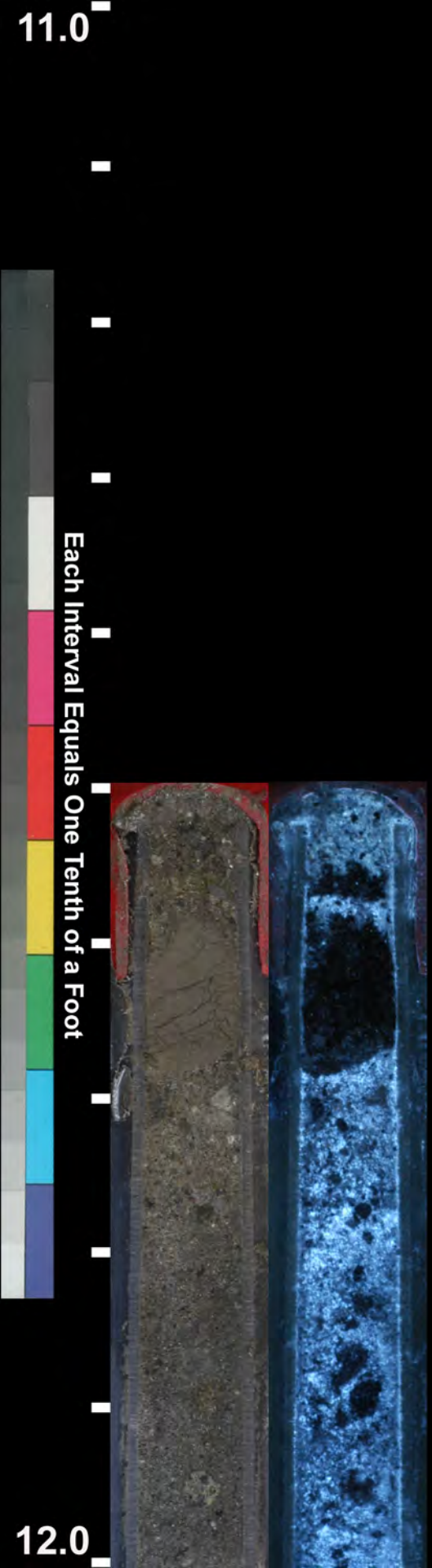
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Project No.: 17358-T01



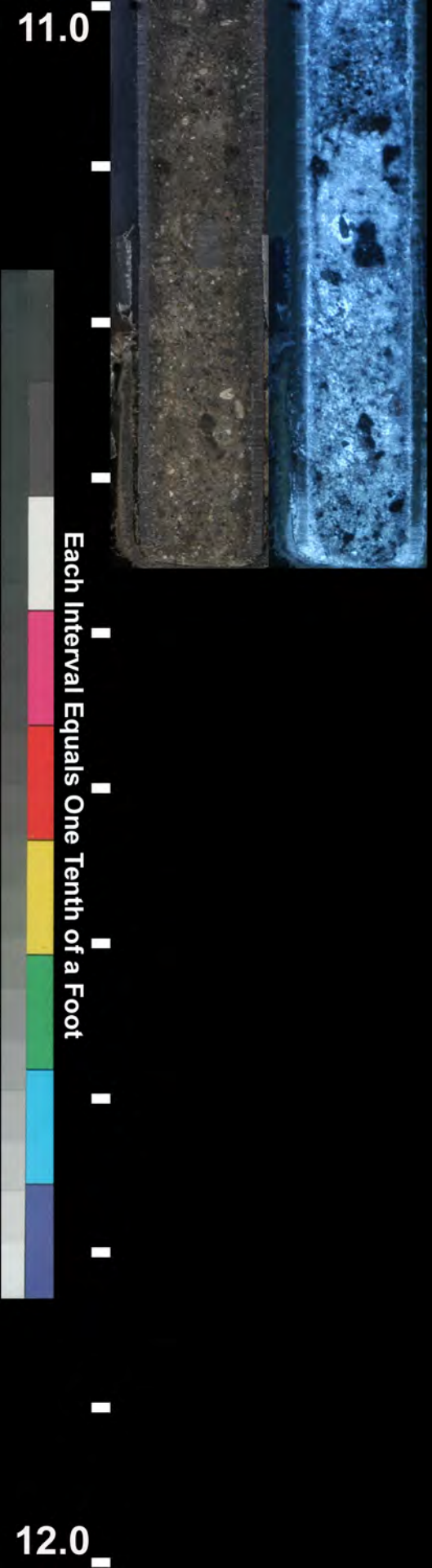
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Project No.: 17358-T01



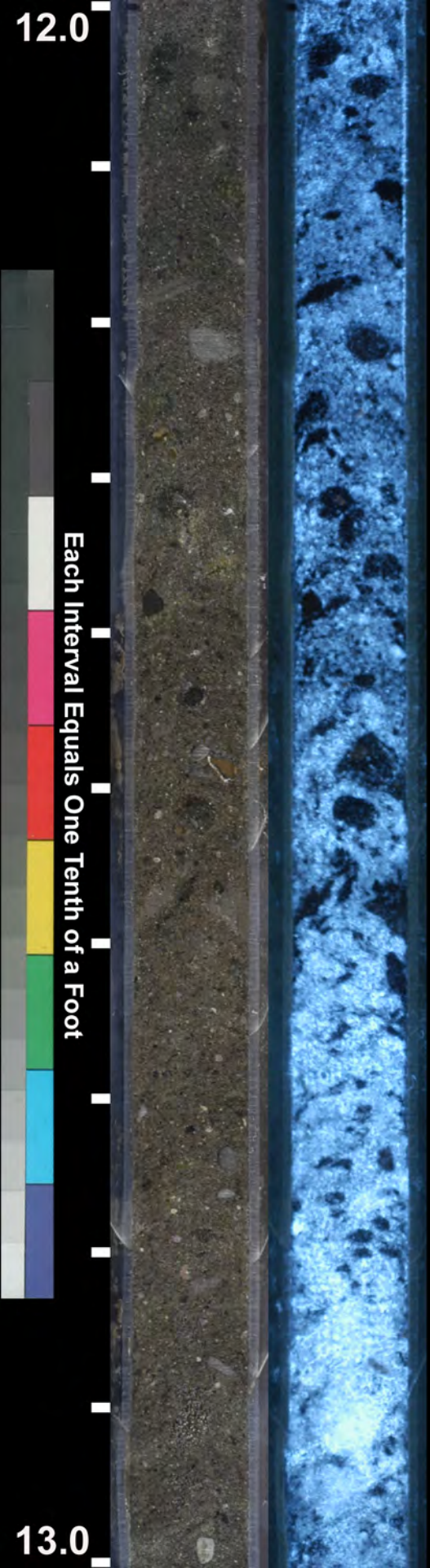
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Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-055 (9'-14')
Project No.: 17358-T01



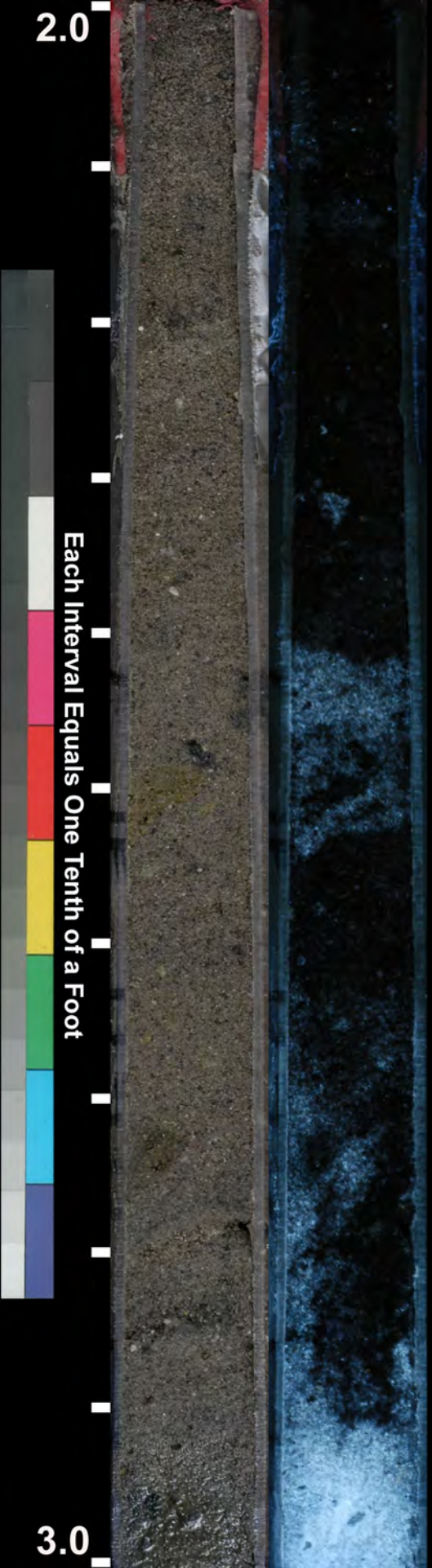
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Project No.: 17358-T01



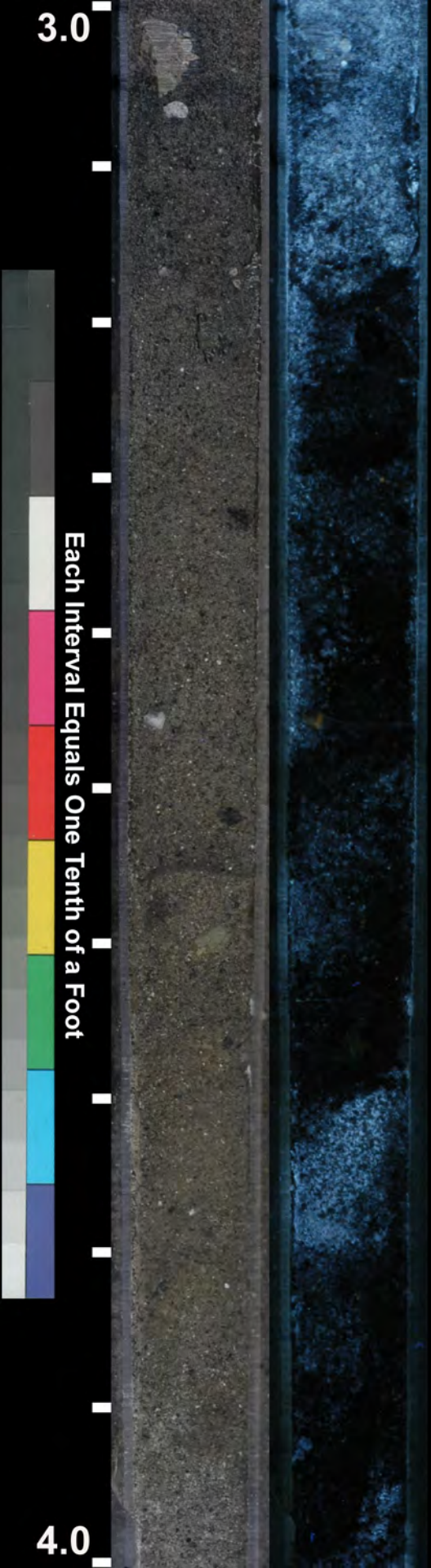
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Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-055 (9'-14')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-058 (2'-7')
Project No.: 17358-T01



3.0

Each Interval Equals One Tenth of a Foot

4.0

Project: MLC-Willow Run Boring ID: LIF-058 (2'-7')
Project No.: 17358-T01



Each Interval Equals One Tenth of a Foot

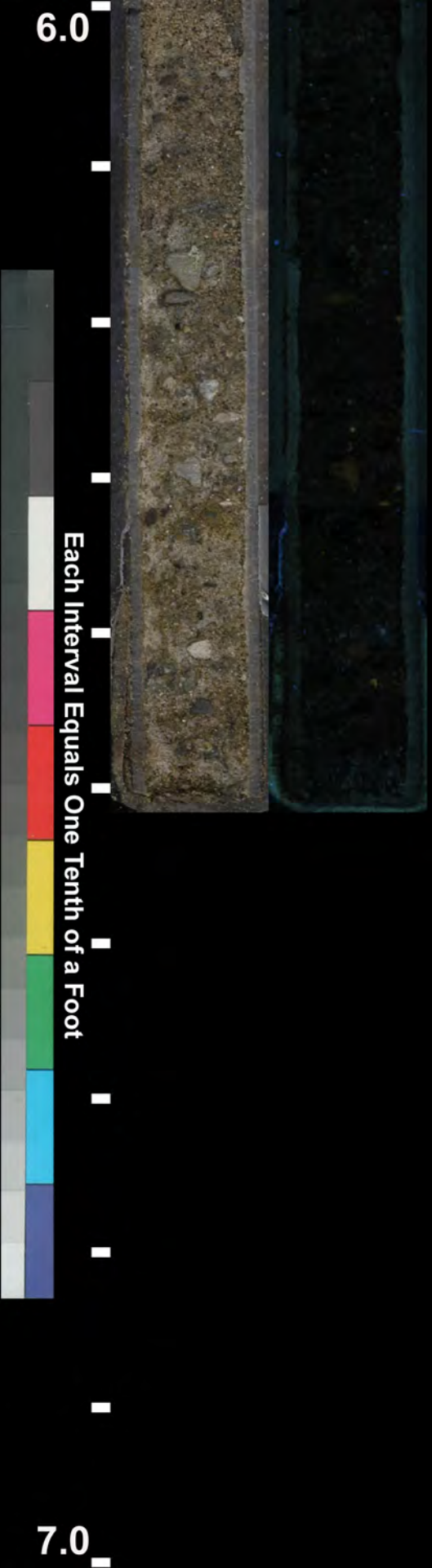


Project: MLC-Willow Run Boring ID: LIF-058 (2'-7')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-060 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-060 (5'-10')
Project No.: 17358-T01

7.0

Each Interval Equals One Tenth of a Foot

8.0

Project: MLC-Willow Run Boring ID: LIF-060 (5'-10')

Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-060 (5'-10')
Project No.: 17358-T01

5.0

Each Interval Equals One Tenth of a Foot

6.0

Project: MLC-Willow Run Boring ID: LIF-061 (5'-10')

Project No.: 17358-T01

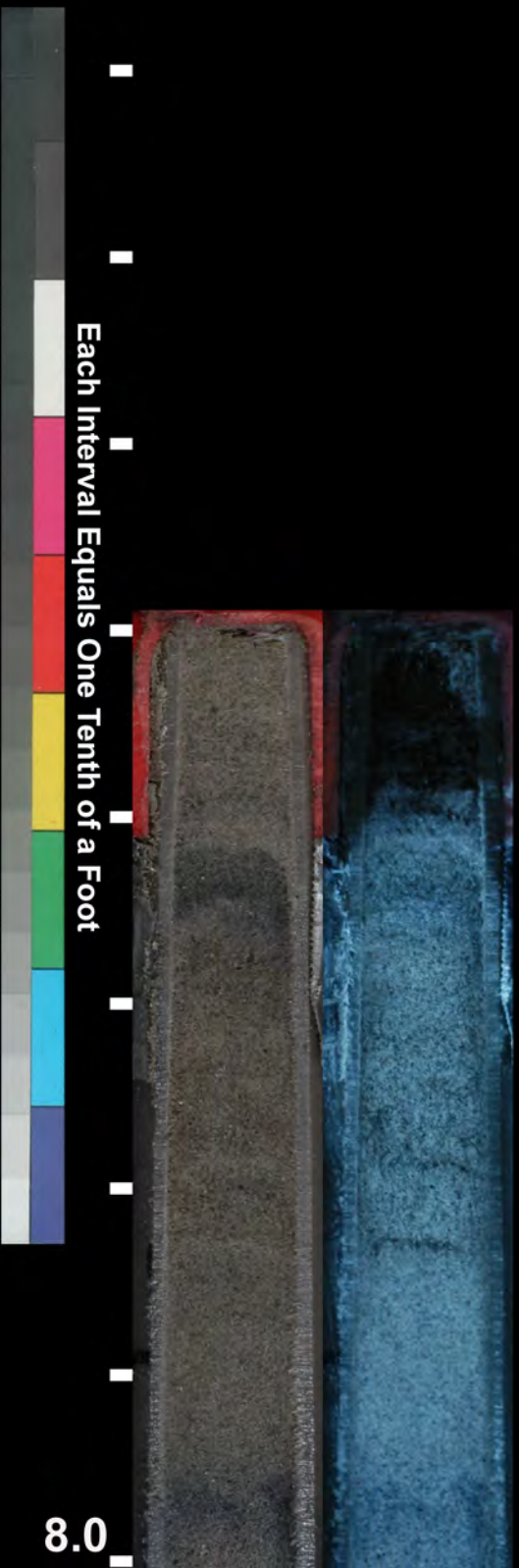


Project: MLC-Willow Run Boring ID: LIF-061 (5'-10')
Project No.: 17358-T01

7.0

Each Interval Equals One Tenth of a Foot

8.0



Project: MLC-Willow Run Boring ID: LIF-061 (5'-10')

Project No.: 17358-T01



7.0

Each Interval Equals One Tenth of a Foot

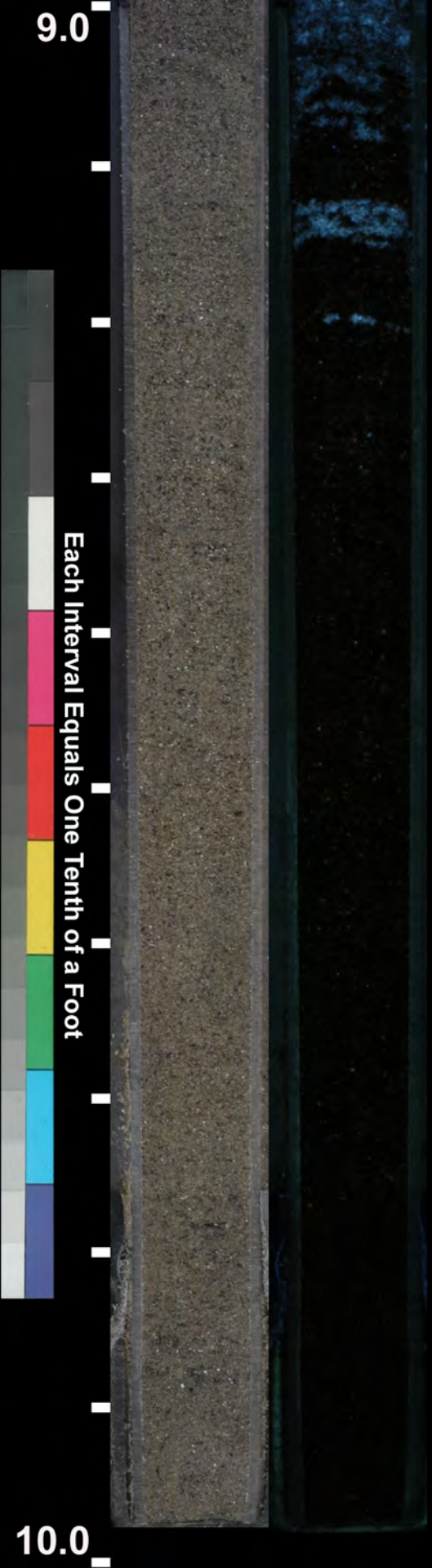


8.0

Project: MLC-Willow Run Boring ID: LIF-061 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-061 (5'-10')
Project No.: 17358-T01



Project: MLC-Willow Run Boring ID: LIF-061 (5'-10')
Project No.: 17358-T01

Appendix G

Laboratory Test Results



CONESTOGA-ROVERS & ASSOCIATES

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

PAGE 1 OF 1

Required Client Information:

Company: CRA, Inc.	Report To: M. Rousseau
Address: 14496 Sheldon Rd.	Copy To:
Suite 200	Invoice To:
Plymouth, MI 48170	P.O.:
Phone: 734-453-5123	Project Name: MLC-Willow
Fax: 734-453-5201	Project Number: 17358-T01 Run
Email:	

Laboratory: PTS Labs
Laboratory Location: Santa Fe Springs CA
Laboratory Contact: Rachel Spitz
Requested Due Date: TAT: STD
QA/QC Requirements:

ID # No D 8229

SSOW Ref. Code:
17358-T01

Sample Identification:		Valid Matrix Codes: WG Groundwater WB Borehole Water WS Surface Water SO Soil SE Sediment See Back for Additional Codes	Matrix Code	Date Collected	Time Collected	# Containers	Preservative					Other:	Analysis and Method										Remarks/Lab ID
							Unpreserved	HCl	H2SO4	HNO3	NaOH												
1.	LIF-040 (5'-10')		SD	10/28/10	1400	2	2						X										
2.	LIF-037 (5'-10')		↓	↓	1420	2	2						X										
3.	LIF-034 (5'-10')		↓	↓	1445	2	2						X										
4.	LIF-058 (2'-7')		↓	↓	1505	1	1						X										
5.	LIF-009 (5'-10')		↓	↓	1525	1	1						X										
6.																							
7.																							
8.																							
9.																							
10.																							
11.																							
12.																							
13.																							
14.																							
15.																							
TOTAL NUMBER OF CONTAINERS						22																	

SHIPMENT METHOD	NO. OF COOLERS	RELINQUISHED BY / AFFILIATION	DATE	TIME	RECEIVED BY / AFFILIATION	DATE	TIME
FED EX	1	D. Rivers / CRA	10/29/10	1200	Jed / PTS Labs	10/29/10	1450
AIRBILL NO. 8614 5009 6290							

Temp in C/F	-40°F
Received on Ice	Y/N
Sealed Cooler	Y/N
Samples Intact	Y/N

Additional Comments: Keep Cores Frozen

Sampler Name: David Rivers
Sampler Signature: DRivers Date: 10/29/10



CONESTOGA-ROVERS & ASSOCIATES

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

PAGE 1 OF 1

Required Client Information:

Company: CRA, Inc.	Report To: M. Rousseau
Address: 14496 Sheldon Rd.	Copy To:
Suite 200	Invoice To:
Plymouth, MI 48170	P.O.:
Phone: 734-453-5123	Project Name: MLC-Willow Run
Fax: 734-453-5201	Project Number: 17358-T01
Email:	

Laboratory: PTS Labs
Laboratory Location: Santa Fe Springs CA
Laboratory Contact: Rachel Spitz
Requested Due Date: TAT: STD
QA/QC Requirements:

ID # N° D 8230

SSOW Ref. Code:
17358-T01

Sample Identification:		Valid Matrix Codes: WG Groundwater WB Borehole Water WS Surface Water SO Soil SE Sediment See Back for Additional Codes	Matrix Code	Date Collected	Time Collected	# Containers	Unpreserved	Preservative					Other:	Core Photographs																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																		

SHIPMENT METHOD	NO. OF COOLERS	RELINQUISHED BY / AFFILIATION	DATE	TIME	RECEIVED BY / AFFILIATION	DATE	TIME
FED EX	21	D. Rivers / CRA	10/29/10	1800	Adel / PTS LABS	10/29/10	1450
AIRBILL NO.	86145009 6290						

Sample Condition	
Temp in °C	-40°F
Received on Ice	(Y)/N
Sealed Cooler	Y/N
Samples Intact	Y/N

Additional Comments:

Keep Cores Frozen

Sampler Name:	D. Rivers
Sampler Signature:	D. Rivers
Date:	10/29/10



CONESTOGA-ROVERS & ASSOCIATES

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

40772

PAGE 1 OF 1

Required Client Information:

Company: CRA, Inc.	Report To: <i>M. Rousseau</i>
Address: 14496 Sheldon Rd.	Copy To:
Suite 200	Invoice To:
Plymouth, MI 48170	P.O.:
Phone: 734-453-5123	Project Name: <i>MLC-Willow Run</i>
Fax: 734-453-5201	Project Number: <i>17358-T01</i>
Email:	

Laboratory: <i>PTS Laboratories</i>
Laboratory Location: <i>Santa Fe Springs, CA</i>
Laboratory Contact: <i>Rachel Spitz</i>
Requested Due Date: TAT: <i>STD</i>
QA/QC Requirements:

ID # *Nº D 7466*

SSOW Ref. Code:
17358-T01

Sample Identification:			Valid Matrix Codes: WG Groundwater WB Borehole Water WS Surface Water SO Soil SE Sediment See Back for Additional Codes	Matrix Code	Date Collected	Time Collected	# Containers	Unpreserved	Preservative					Core Photo	Remarks/Lab ID		
									HCl	H2SO4	HNO3	NaOH	Other:				
✓	LIF-025	(5'-10')	SO	10/29/10	845	1	1							X			
✓	LIF-021	(2'-7')	↓	↓	915	2	2							X			
✓	LIF-021	(7'-12')	↓	↓	920	2	2							X			
✓	LIF-055	(4'-9')	↓	↓	945	2	2							X			
✓	LIF-055	(9'-14')	↓	↓	950	2	2							X			
✓	ARC-128	(5'-10')	↓	↓	1025	2	2							X			
✓	ARC-65	(5'-10')	↓	↓	1055	2	2							X			
8.																	
9.																	
10.																	
11.																	
12.																	
13.																	
14.																	
15.																	
TOTAL NUMBER OF CONTAINERS							13										

SHIPMENT METHOD	NO. OF COOLERS	RELINQUISHED BY / AFFILIATION	DATE	TIME	RECEIVED BY / AFFILIATION	DATE	TIME
<i>FED EX</i>	<i>2</i>	<i>D. Rivers / CRA</i>	<i>10/29/10</i>	<i>1500</i>	<i>Jeffrey PTS Labs Inc</i>	<i>11/1/10</i>	<i>0834</i>
AIRBILL NO.							

Temp in °F	<i>-40°F</i>
Received on Ice	<i>Y/N</i>
Sealed Cooler	<i>Y/N</i>
Samples Intact	<i>Y/N</i>

Additional Comments: *Keep Cores Frozen*

Sampler Name:	<i>E. Varnas</i>
Sampler Signature:	<i>[Signature]</i>
Date:	<i>10-29-10</i>



CONESTOGA-ROVERS & ASSOCIATES

CHAIN-OF-CUSTODY / Analytical Request Document

The Chain-of-Custody is a LEGAL DOCUMENT. All relevant fields must be completed accurately.

#40772

PAGE 1 OF 1

Required Client Information:

Company: CRA, Inc.	Report To: Paul Wiseman / CRA
Address: 14496 Sheldon Rd.	Copy To: Laina Jordon / CRA
Suite 200	Invoice To:
Plymouth, MI 48170	P.O.:
Phone: 734-453-5123	Project Name: Powertrain willow run
Fax: 734-453-5201	Project Number: 017358
Email: pwiseman@crausd.com	

Laboratory: PTS Laboratories, Inc.
Laboratory Location: Santa Fe Springs, CA
Laboratory Contact:
Requested Due Date: _____ TAT: standard
QA/QC Requirements: _____

ID # No D 7075

SSOW Ref. Code: _____

Sample Identification:			Valid Matrix Codes: WG Groundwater WB Borehole Water WS Surface Water SO Soil SE Sediment See Back for Additional Codes	Matrix Code	Date Collected	Time Collected	# Containers	Unpreserved	Preservative					Other:	Fluid properties package																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																					

TOTAL NUMBER OF CONTAINERS

SHIPMENT METHOD	NO. OF COOLERS	RELINQUISHED BY / AFFILIATION	DATE	TIME	RECEIVED BY / AFFILIATION	DATE	TIME
FedEx	1	C-Bondy / CRA	4/19/11	1515	Asel Per PTS Labs Inc	4/21/11	1052 am
AIRBILL NO.							

Sample Condition

Temp in °C / °F	58° F
Received on Ice	Y (N)
Sealed Cooler	Y (N)
Samples Intact	Y (N)

Additional Comments: BATCH COMPLETE

Sampler Name: C-Bondy
Sampler Signature: C-Bondy
Date: 4/19/11

PTS File No: 40772
 Client: Conestoga-Rovers & Associates

SAMPLE PROPERTIES - AIR/WATER CAPILLARY PRESSURE

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01

SAMPLE ID.	DEPTH, ft.	METHODS: SAMPLE ORIENTATION (1)	API RP 40 / ASTM D2216	API RP 40		API RP 40		API RP 40
			MOISTURE CONTENT, % weight	DENSITY		POROSITY, %Vb (2)		TOTAL PORE FLUID SATURATIONS (3), % Pv
				BULK, g/cc	GRAIN, g/cc	TOTAL	AIR FILLED	
LIF-037 (5'-10')	6.9	H	15.8	1.59	2.62	39.4	14.2	63.8
LIF-029 (5'-8')	6.1	H	8.3	1.56	2.58	39.6	26.8	32.5
ARC-128 (5'-10')	8.4	H	14.7	1.65	2.58	36.1	11.8	67.3

(1) Sample Orientation: H = horizontal; V = vertical

(2) Total Porosity = all interconnected pore channels; Air Filled = pore channels not occupied by pore fluids

(3) Water = 0.9996 g/cc

Vb = Bulk Volume, cc; Pv = Pore Volume, cc; ND = Not Detected

PTS File No: 40772
 Client: Conestoga-Rovers & Associates

PERMEABILITY DATA - AIR/WATER CAPILLARY PRESSURE

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01

METHODS:			API RP 40; EPA 9100		
			25 PSI CONFINING STRESS		
SAMPLE ID.	DEPTH, ft.	SAMPLE ORIENTATION (1)	SPECIFIC PERMEABILITY TO AIR, millidarcy (2)	EFFECTIVE PERMEABILITY TO WATER, millidarcy (3)	HYDRAULIC CONDUCTIVITY, cm/s (3)
LIF-037 (5'-10')	6.9	H	8181	7461	7.23E-03
LIF-029 (5'-8')	6.1	H	7015	5857	5.64E-03
ARC-128 (5'-10')	8.4	H	8331	4640	4.49E-03

- (1) Sample Orientation: H = horizontal; V = vertical
 (2) No pore fluids in place
 (3) Permeability to water and hydraulic conductivity measured at saturated conditions

PTS File No: 40772
 Client: Conestoga-Rovers & Associates

AIR/WATER CAPILLARY PRESSURE TABULAR DATA

(ASTM D6836; Centrifugal Method: air displacing water)

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01

Capillary Pressure		Height Above Water Table, ft	Sample ID	
			LIF-037 (5'-10') at 6.9 ft.	
psi	cm water		Saturation, % pore volume	Moisture, % dry weight
0.000	0.00	0.000	100.0	21.9
0.079	5.53	0.182	100.0	21.9
0.177	12.4	0.410	99.1	21.8
0.315	22.1	0.728	93.1	20.4
0.492	34.6	1.14	74.2	16.3
0.708	49.8	1.64	60.4	13.3
0.96	67.8	2.23	49.2	10.8
1.26	88.5	2.91	39.8	8.7
1.97	138	4.55	32.9	7.2
3.32	234	7.69	26.0	5.7
5.03	354	11.7	22.5	5.0
7.87	553	18.2	19.1	4.2
17.7	1245	41.0	16.5	3.7
31.5	2213	72.8	15.7	3.5

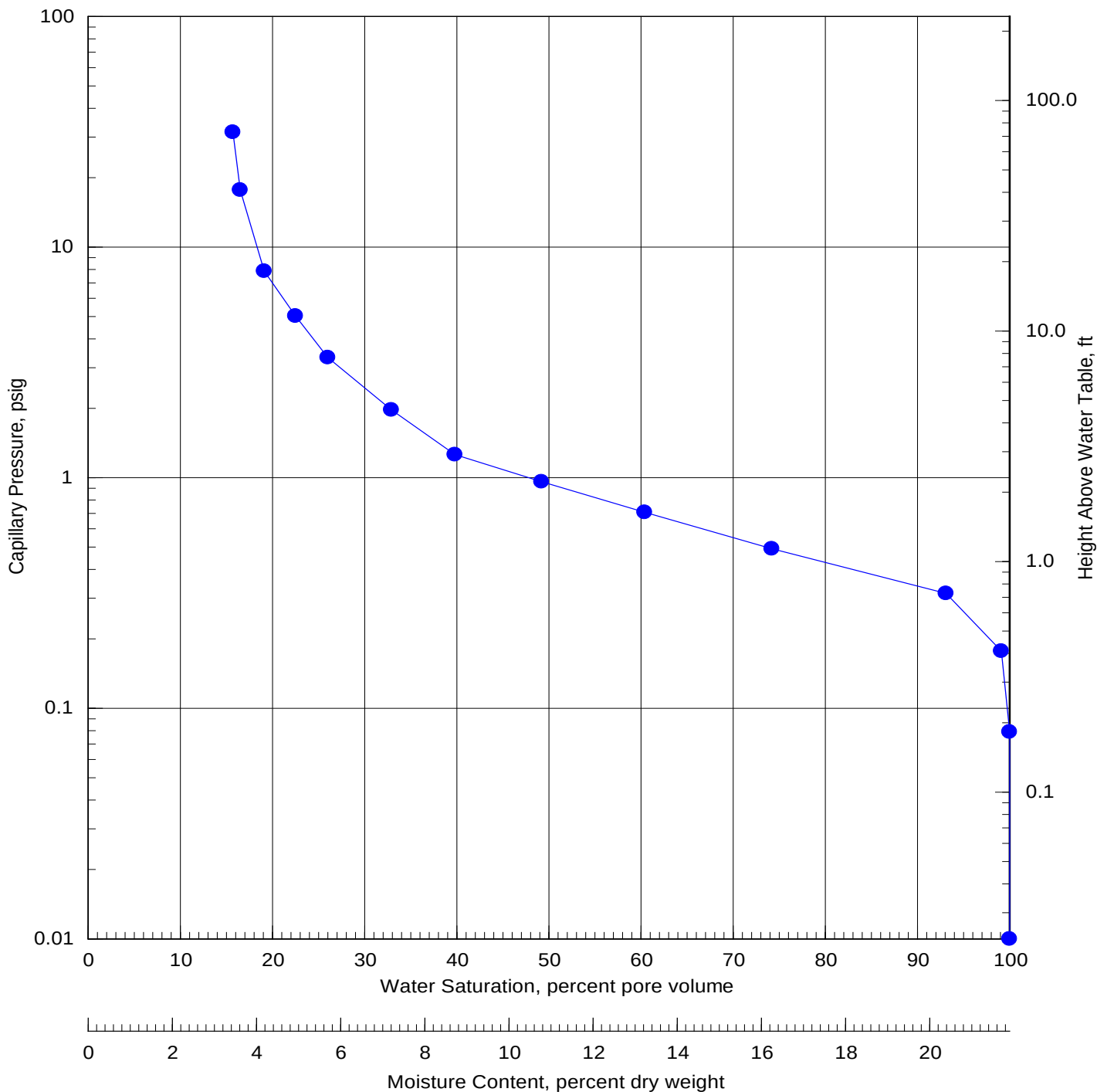


CAPILLARY PRESSURE Centrifugal Method

Air Displacing Water System - ASTM D6836

Project Name: MLC-Willow Run
Project No: 17358-T01

Sample ID: LIF-037 (5'-10')
Depth, ft: 6.9



PTS File No: 40772
 Client: Conestoga-Rovers & Associates

AIR/WATER CAPILLARY PRESSURE TABULAR DATA

(ASTM D6836; Centrifugal Method: air displacing water)

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01

Capillary Pressure		Height Above Water Table, ft	Sample ID	
			LIF-029 (5'-8') at 6.1 ft.	
psi	cm water		Saturation, % pore volume	Moisture, % dry weight
0.000	0.00	0.000	100.0	23.7
0.079	5.53	0.182	100.0	23.7
0.177	12.4	0.410	100.0	23.7
0.315	22.1	0.728	94.9	22.5
0.492	34.6	1.14	84.6	20.1
0.708	49.8	1.64	72.7	17.3
0.96	67.8	2.23	59.9	14.2
1.26	88.5	2.91	52.2	12.4
1.97	138	4.55	45.4	10.8
3.32	234	7.69	38.6	9.2
5.03	354	11.7	34.3	8.2
7.87	553	18.2	30.0	7.2
17.7	1245	41.0	25.8	6.1
31.5	2213	72.8	24.1	5.7

* NAPL produced during centrifuge testing. Volume of NAPL produced added to volume of water produced.

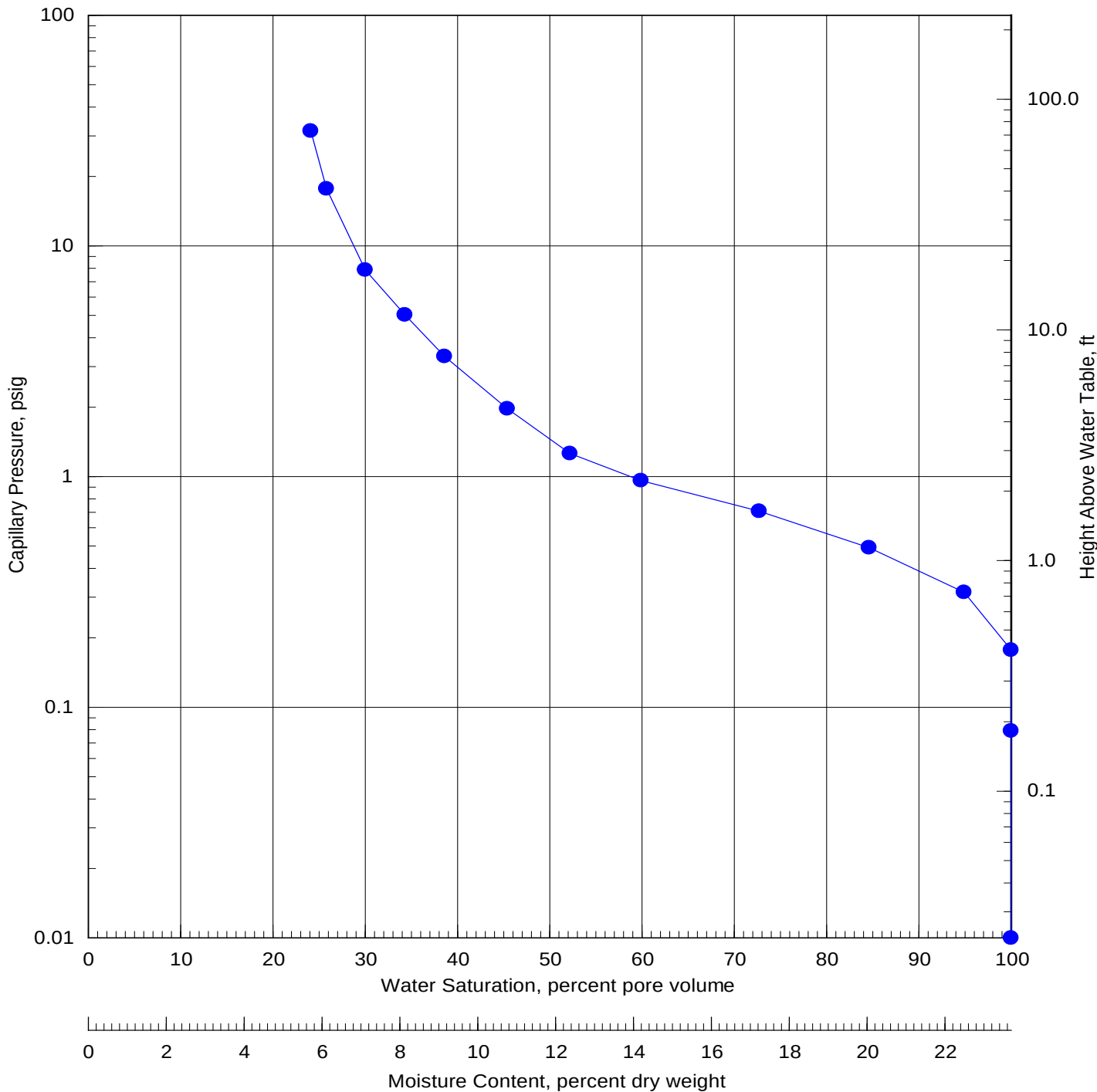


CAPILLARY PRESSURE Centrifugal Method

Air Displacing Water System - ASTM D6836

Project Name: MLC-Willow Run
Project No: 17358-T01

Sample ID: LIF-029 (5'-8')
Depth, ft: 6.1



PTS File No: 40772
 Client: Conestoga-Rovers & Associates

AIR/WATER CAPILLARY PRESSURE TABULAR DATA

(ASTM D6836; Centrifugal Method: air displacing water)

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01

Capillary Pressure		Height Above Water Table, ft	Sample ID	
			ARC-128 (5'-10') at 8.4 ft.	
psi	cm water		Saturation, % pore volume	Moisture, % dry weight
0.000	0.00	0.000	100.0	18.2
0.079	5.56	0.183	100.0	18.2
0.178	12.5	0.412	100.0	18.2
0.316	22.2	0.732	99.0	18.0
0.494	34.8	1.14	92.0	16.7
0.712	50.0	1.65	75.0	13.7
0.97	68.1	2.24	61.7	11.2
1.27	89.0	2.93	50.1	9.1
1.98	139	4.58	36.1	6.6
3.34	235	7.73	26.1	4.8
5.06	356	11.7	20.2	3.7
7.91	556	18.3	16.2	3.0
17.8	1251	41.2	11.2	2.1
31.6	2224	73.2	9.2	1.7

* NAPL produced during centrifuge testing. Volume of NAPL produced added to volume of water produced.

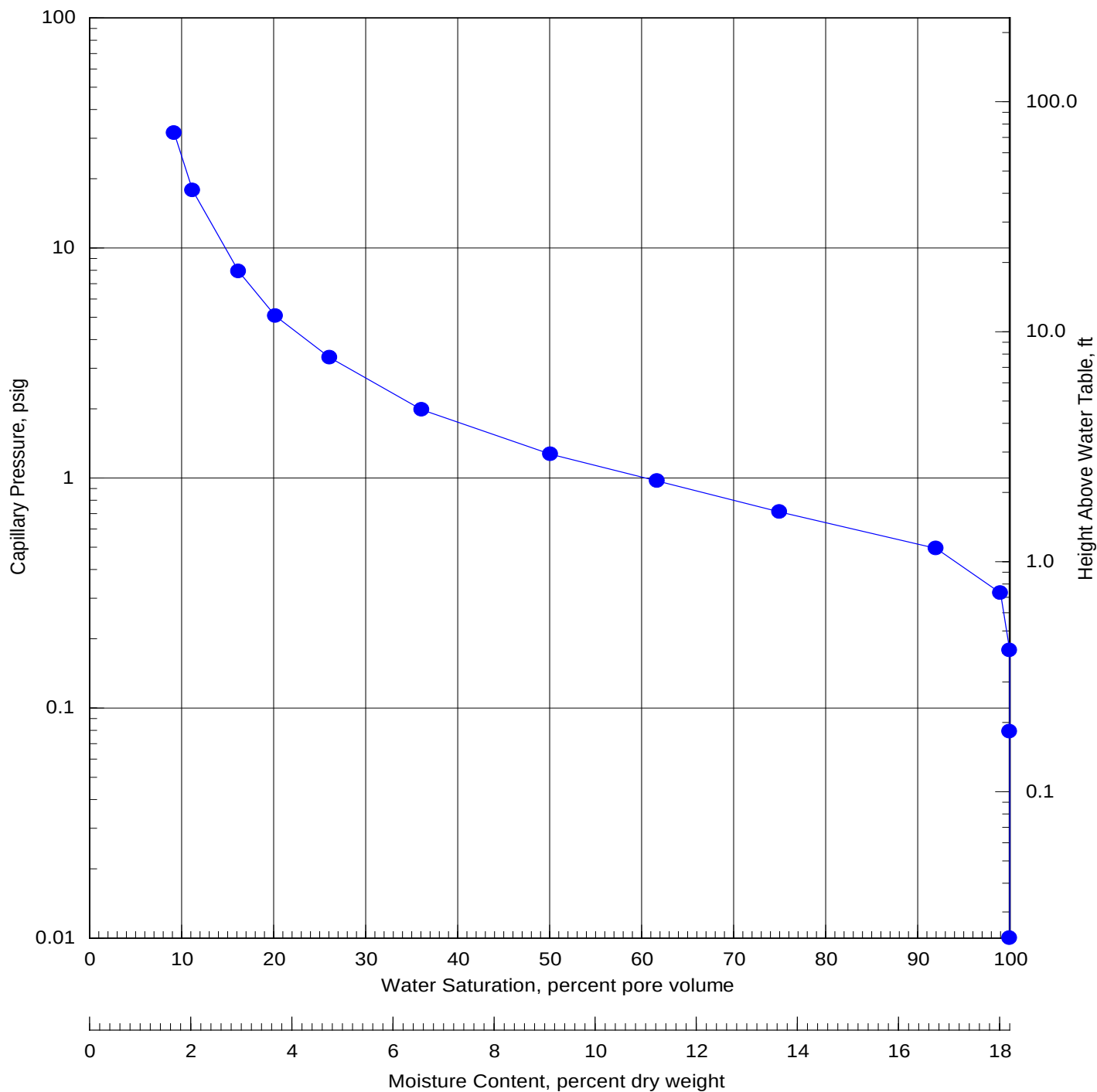


CAPILLARY PRESSURE Centrifugal Method

Air Displacing Water System - ASTM D6836

Project Name: MLC-Willow Run
Project No: 17358-T01

Sample ID: ARC-128 (5'-10')
Depth, ft: 8.4



PTS File No:40772

Client:Conestoga-Rovers & Associates

VISCOSITY, DENSITY, and SPECIFIC GRAVITY DATA

(METHODOLOGY: ASTM D445, ASTM D1481, API RP40)

PROJECT NAME:MLC-Willow Run

PROJECT NO:17358-T01

SAMPLE ID	MATRIX	TEMPERATURE, °F	SPECIFIC GRAVITY	DENSITY, g/cc	VISCOSITY	
					centistokes	centipoise
GW-17358-041911-CB-002	Water	70	1.002	1.000	1.02	1.02
		100	1.002	0.9954	0.709	0.706
		130	1.004	0.9900	0.611	0.605
LNAPL-17358-041911-CB-001	NAPL	70	0.8528	0.8511	12.4	10.6
		100	0.8446	0.8387	6.99	5.86
		130	0.8404	0.8286	4.84	4.01
GW-17358-041911-CB-004	Water	70	1.001	0.9991	1.01	1.01
		100	1.000	0.9934	0.700	0.695
		130	1.003	0.9893	0.548	0.543
LNAPL-17358-041911-CB-003	NAPL	70	0.8809	0.8791	112	98.3
		100	0.8730	0.8669	47.3	41.0
		130	0.8692	0.8570	25.1	21.5
GW-17358-041911-CB-006	Water	70	1.004	1.002	1.01	1.01
		100	1.002	0.9950	0.707	0.703
		130	1.004	0.9900	0.544	0.539
LNAPL-17358-041911-CB-005	NAPL	70	0.8744	0.8726	59.0	51.5
		100	0.8655	0.8595	25.0	21.5
		130	0.8610	0.8489	13.7	11.6

PTS File No: 40772

Client: Conestoga-Rovers & Associates

INTERFACIAL / SURFACE TENSION DATA

(METHODOLOGY: DuNuoy Method - ASTM D971)

PROJECT NAME: MLC-Willow Run

PROJECT NO: 17358-T01

PHASE PAIR		TEMPERATURE, °F	INTERFACIAL TENSION, Dynes/centimeter
SAMPLE ID / PHASE	SAMPLE ID / PHASE		
GW-17358-041911-CB-002	Air	72.9	48.6
LNAPL-17358-041911-CB-001	Air	72.1	28.0
GW-17358-041911-CB-002	LNAPL-17358-041911-CB-001	72.1	1.6
GW-17358-041911-CB-004	Air	72.3	52.0
LNAPL-17358-041911-CB-003	Air	73.2	30.2
GW-17358-041911-CB-004	LNAPL-17358-041911-CB-003	72.7	6.9
GW-17358-041911-CB-006	Air	72.9	55.1
LNAPL-17358-041911-CB-005	Air	72.7	29.7
GW-17358-041911-CB-006	LNAPL-17358-041911-CB-005	72.7	4.2

QUALITY CONTROL DATA

PHASE PAIR: DIWATER / AIR

TEMPERATURE, °F: 72.3

IFT, MEASURED: 72.2

IFT, PUBLISHED: 72.4

RPD: -0.26

PARTICLE SIZE SUMMARY

(METHODOLOGY: ASTM D422/D4464M)

PROJECT NAME: MLC-Willow Run
PROJECT NO: 17358-T01

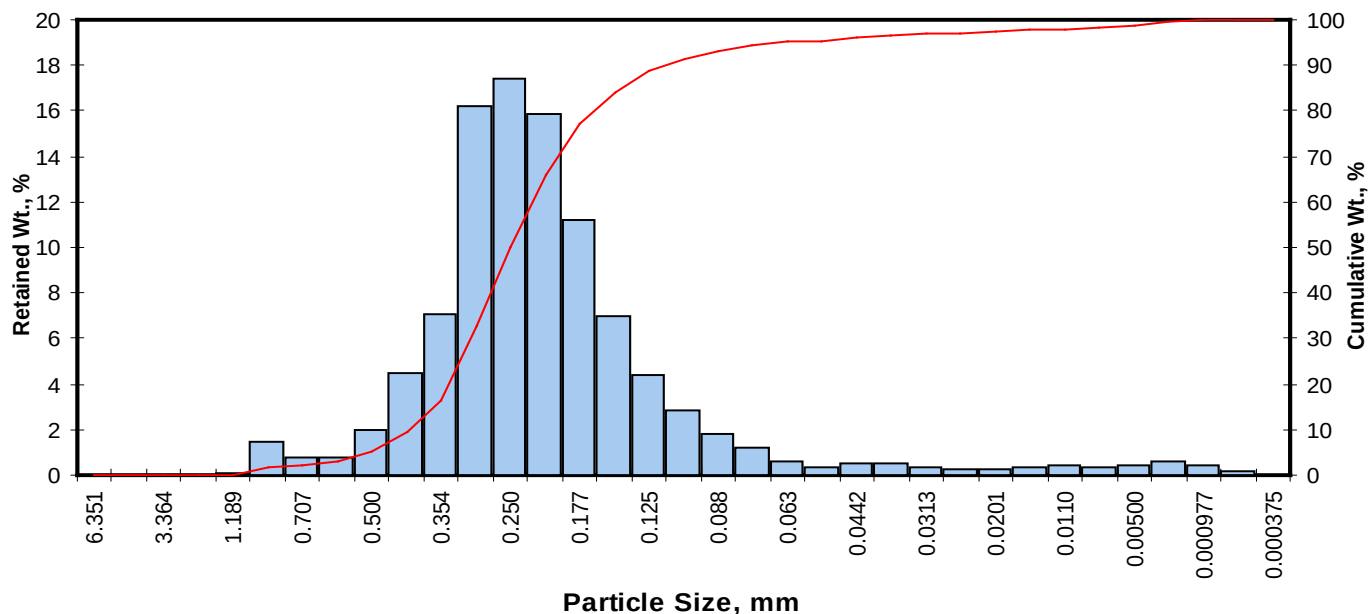
Sample ID	Depth, ft.	Mean Grain Size Description (1)	Median Grain Size mm	Particle Size Distribution, wt. percent						Silt & Clay
				Gravel	Sand Size			Silt	Clay	
					Coarse	Medium	Fine			
LIF-040 (5'-10')	7.9	Fine sand	0.250	0.00	0.00	9.55	84.96	4.28	1.21	5.49
LIF-037 (5'-10')	6.9	Fine sand	0.234	0.00	0.00	4.92	86.55	7.48	1.05	8.53
LIF-034 (5'-10')	8.5	Fine sand	0.215	0.00	0.00	6.43	87.77	4.66	1.14	5.80
LIF-029 (5'-8')	6.1	Fine sand	0.232	0.00	0.00	21.13	62.14	14.76	1.96	16.72
LIF-025 (5'-10')	6.2	Fine sand	0.275	0.00	0.00	20.14	68.59	9.50	1.76	11.26
LIF-021 (7'-12')	8.5	Fine sand	0.130	0.00	0.00	1.61	83.25	14.02	1.12	15.14
LIF-055 (4'-9')	7.4	Medium sand	0.500	4.48	7.10	44.58	37.49	(2)	(2)	6.36
ARC-128 (5'-10')	8.4	Fine sand	0.277	0.00	0.00	18.94	74.12	5.90	1.04	6.94
ARC-65 (5'-10')	8.4	Fine sand	0.236	0.00	0.00	29.23	37.60	21.40	11.78	33.17

(1) Based on Mean from Trask

Client: Conestoga-Rovers & Associates
Project: MLC-Willow Run
Project No: 17358-T01

PTS File No: 40772
Sample ID: LIF-040 (5'-10')
Depth, ft: 7.9

Grv	Sand Size			Silt	Clay
	crs	medium	fine		



Particle Size, mm

Opening		Phi of Screen	U.S. No.	Sample Weight, grams	Increment Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.2500	6.351	-2.67	1/4	0.00	0.00	0.00
0.1873	4.757	-2.25	4	0.00	0.00	0.00
0.1324	3.364	-1.75	6	0.00	0.00	0.00
0.0787	2.000	-1.00	10	0.00	0.00	0.00
0.0468	1.189	-0.25	16	0.08	0.08	0.08
0.0331	0.841	0.25	20	1.45	1.45	1.53
0.0278	0.707	0.50	25	0.74	0.74	2.27
0.0234	0.595	0.75	30	0.80	0.80	3.07
0.0197	0.500	1.00	35	1.98	1.98	5.05
0.0166	0.420	1.25	40	4.50	4.50	9.55
0.0139	0.354	1.50	45	7.03	7.03	16.58
0.0117	0.297	1.75	50	16.20	16.20	32.78
0.0098	0.250	2.00	60	17.40	17.40	50.18
0.0083	0.210	2.25	70	15.90	15.90	66.08
0.0070	0.177	2.50	80	11.20	11.20	77.28
0.0059	0.149	2.75	100	6.94	6.94	84.22
0.0049	0.125	3.00	120	4.41	4.41	88.63
0.0041	0.105	3.25	140	2.81	2.81	91.44
0.0035	0.088	3.50	170	1.84	1.84	93.28
0.0029	0.074	3.75	200	1.23	1.23	94.51
0.0025	0.063	4.00	230	0.61	0.61	95.12
0.0021	0.053	4.25	270	0.34	0.34	95.46
0.00174	0.0442	4.50	325	0.50	0.50	95.96
0.00146	0.0372	4.75	400	0.51	0.51	96.47
0.00123	0.0313	5.00	450	0.31	0.31	96.78
0.000986	0.0250	5.32	500	0.24	0.24	97.02
0.000790	0.0201	5.64	635	0.28	0.28	97.30
0.000615	0.0156	6.00		0.33	0.33	97.63
0.000435	0.0110	6.50		0.40	0.40	98.03
0.000308	0.00781	7.00		0.35	0.35	98.38
0.000197	0.00500	7.65		0.41	0.41	98.79
0.000077	0.00195	9.00		0.64	0.64	99.43
0.000038	0.000977	10.00		0.40	0.40	99.83
0.000019	0.000488	11.00		0.17	0.17	100.00
0.000015	0.000375	11.38		0.00	0.00	100.00
TOTALS				100.00	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	0.99	0.0198	0.502
10	1.27	0.0164	0.416
16	1.48	0.0141	0.359
25	1.63	0.0127	0.323
40	1.85	0.0109	0.277
50	2.00	0.0099	0.250
60	2.15	0.0088	0.225
75	2.45	0.0072	0.183
84	2.74	0.0059	0.149
90	3.12	0.0045	0.115
95	3.95	0.0025	0.065

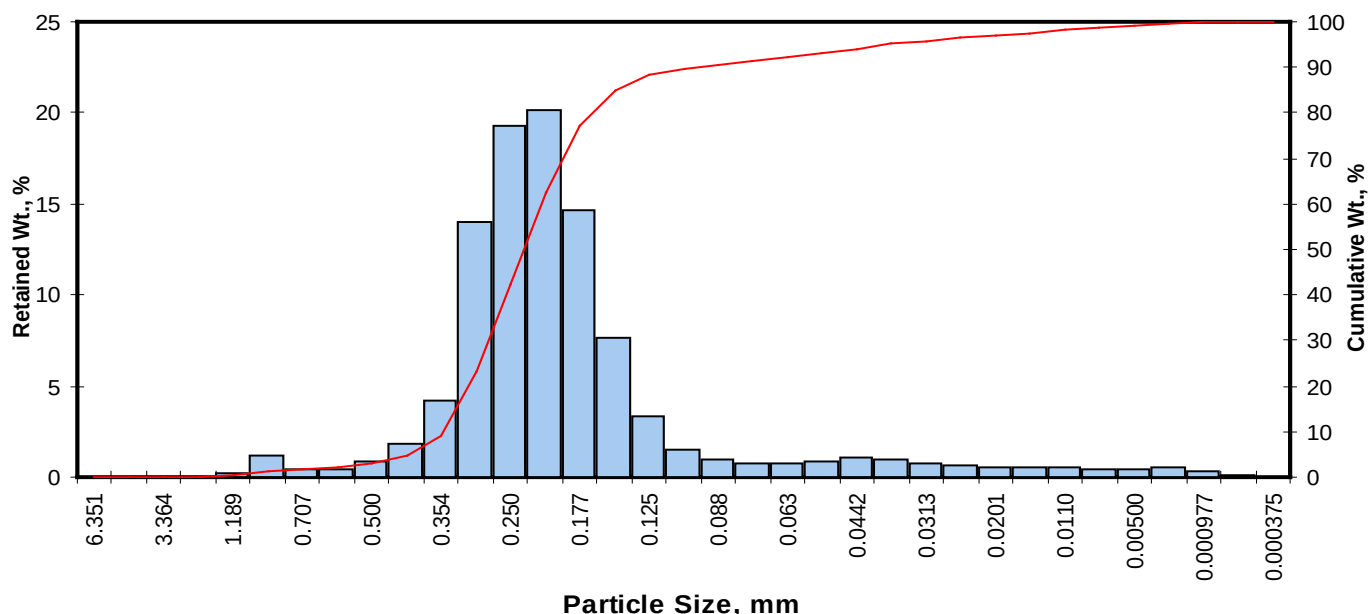
Measure	Trask	Inman	Folk-Ward
Median, phi	2.00	2.00	2.00
Median, in.	0.0099	0.0099	0.0099
Median, mm	0.250	0.250	0.250
Mean, phi	1.98	2.11	2.07
Mean, in.	0.0100	0.0091	0.0094
Mean, mm	0.253	0.232	0.238
Sorting	1.328	0.631	0.764
Skewness	0.971	0.180	0.250
Kurtosis	0.233	1.342	1.479
Grain Size Description (ASTM-USCS Scale)		Fine sand (based on Mean from Trask)	

Description	Retained on Sieve #	Weight Percent
Gravel	4	0.00
Coarse Sand	10	0.00
Medium Sand	40	9.55
Fine Sand	200	84.96
Silt	>0.005 mm	4.28
Clay	<0.005 mm	1.21
Total		100

Client: Conestoga-Rovers & Associates
Project: MLC-Willow Run
Project No: 17358-T01

PTS File No: 40772
Sample ID: LIF-037 (5'-10')
Depth, ft: 6.9

Grv	Sand Size			Silt	Clay
	crs	medium	fine		



Opening		Phi of Screen	U.S. No.	Sample Weight, grams	Increment Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.2500	6.351	-2.67	1/4	0.00	0.00	0.00
0.1873	4.757	-2.25	4	0.00	0.00	0.00
0.1324	3.364	-1.75	6	0.00	0.00	0.00
0.0787	2.000	-1.00	10	0.00	0.00	0.00
0.0468	1.189	-0.25	16	0.26	0.26	0.26
0.0331	0.841	0.25	20	1.14	1.14	1.40
0.0278	0.707	0.50	25	0.46	0.46	1.86
0.0234	0.595	0.75	30	0.46	0.46	2.32
0.0197	0.500	1.00	35	0.81	0.81	3.13
0.0166	0.420	1.25	40	1.79	1.79	4.92
0.0139	0.354	1.50	45	4.16	4.16	9.08
0.0117	0.297	1.75	50	14.00	14.00	23.08
0.0098	0.250	2.00	60	19.30	19.30	42.38
0.0083	0.210	2.25	70	20.10	20.10	62.49
0.0070	0.177	2.50	80	14.70	14.70	77.19
0.0059	0.149	2.75	100	7.67	7.67	84.86
0.0049	0.125	3.00	120	3.37	3.37	88.23
0.0041	0.105	3.25	140	1.53	1.53	89.76
0.0035	0.088	3.50	170	0.93	0.93	90.69
0.0029	0.074	3.75	200	0.78	0.78	91.47
0.0025	0.063	4.00	230	0.75	0.75	92.22
0.0021	0.053	4.25	270	0.85	0.85	93.07
0.00174	0.0442	4.50	325	1.06	1.06	94.13
0.00146	0.0372	4.75	400	1.01	1.01	95.14
0.00123	0.0313	5.00	450	0.76	0.76	95.90
0.000986	0.0250	5.32	500	0.66	0.66	96.56
0.000790	0.0201	5.64	635	0.52	0.52	97.08
0.000615	0.0156	6.00		0.50	0.50	97.58
0.000435	0.0110	6.50		0.55	0.55	98.13
0.000308	0.00781	7.00		0.42	0.42	98.55
0.000197	0.00500	7.65		0.40	0.40	98.95
0.000077	0.00195	9.00		0.52	0.52	99.47
0.000038	0.000977	10.00		0.37	0.37	99.84
0.000019	0.000488	11.00		0.16	0.16	100.00
0.000015	0.000375	11.38		0.00	0.00	100.00
TOTALS				100.00	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	1.25	0.0165	0.419
10	1.52	0.0138	0.350
16	1.62	0.0128	0.325
25	1.77	0.0115	0.292
40	1.97	0.0101	0.255
50	2.09	0.0092	0.234
60	2.22	0.0085	0.215
75	2.46	0.0071	0.181
84	2.72	0.0060	0.152
90	3.31	0.0040	0.100
95	4.72	0.0015	0.038

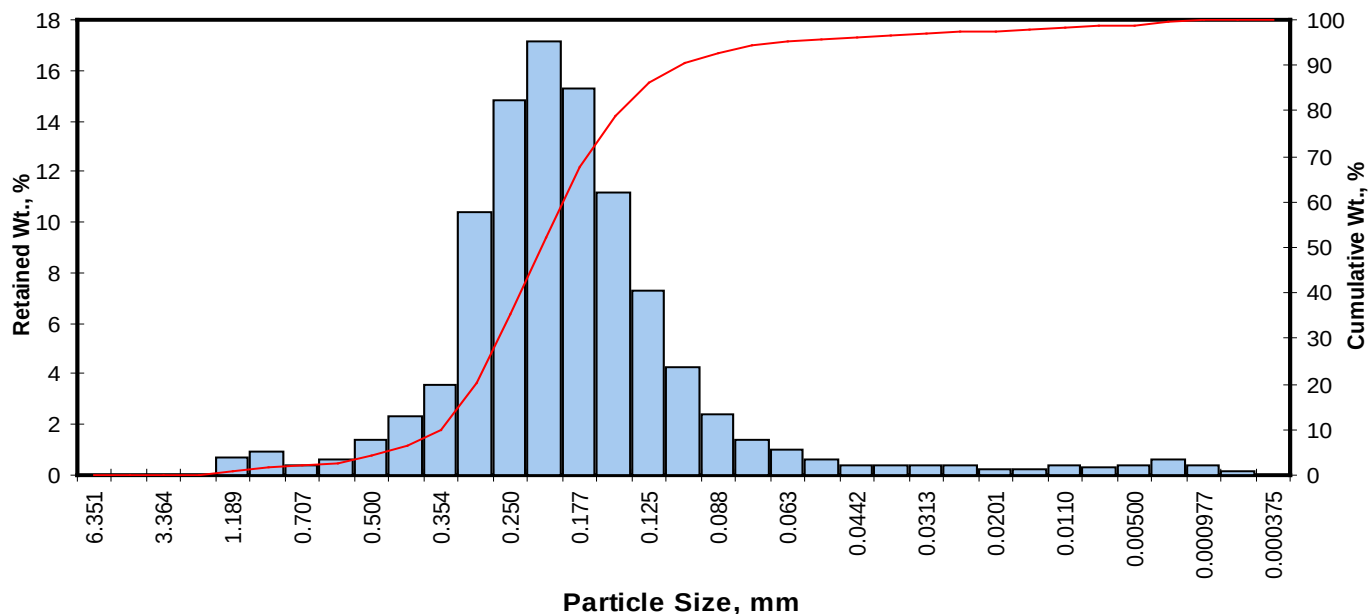
Measure	Trask	Inman	Folk-Ward
Median, phi	2.09	2.09	2.09
Median, in.	0.0092	0.0092	0.0092
Median, mm	0.234	0.234	0.234
Mean, phi	2.08	2.17	2.15
Mean, in.	0.0093	0.0087	0.0089
Mean, mm	0.237	0.222	0.226
Sorting	1.269	0.549	0.799
Skewness	0.983	0.142	0.328
Kurtosis	0.223	2.150	2.062
Grain Size Description (ASTM-USCS Scale)		Fine sand (based on Mean from Trask)	

Description	Retained on Sieve #	Weight Percent
Gravel	4	0.00
Coarse Sand	10	0.00
Medium Sand	40	4.92
Fine Sand	200	86.55
Silt	>0.005 mm	7.48
Clay	<0.005 mm	1.05
Total		100

Client: Conestoga-Rovers & Associates
Project: MLC-Willow Run
Project No: 17358-T01

PTS File No: 40772
Sample ID: LIF-034 (5'-10')
Depth, ft: 8.5

Grv	Sand Size			Silt	Clay
	crs	medium	fine		



Opening		Phi of Screen	U.S. No.	Sample Weight, grams	Increment Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.2500	6.351	-2.67	1/4	0.00	0.00	0.00
0.1873	4.757	-2.25	4	0.00	0.00	0.00
0.1324	3.364	-1.75	6	0.00	0.00	0.00
0.0787	2.000	-1.00	10	0.00	0.00	0.00
0.0468	1.189	-0.25	16	0.71	0.71	0.71
0.0331	0.841	0.25	20	0.96	0.96	1.67
0.0278	0.707	0.50	25	0.40	0.40	2.07
0.0234	0.595	0.75	30	0.62	0.62	2.69
0.0197	0.500	1.00	35	1.42	1.42	4.11
0.0166	0.420	1.25	40	2.31	2.31	6.43
0.0139	0.354	1.50	45	3.53	3.53	9.96
0.0117	0.297	1.75	50	10.40	10.41	20.37
0.0098	0.250	2.00	60	14.80	14.81	35.18
0.0083	0.210	2.25	70	17.10	17.11	52.29
0.0070	0.177	2.50	80	15.30	15.31	67.60
0.0059	0.149	2.75	100	11.20	11.21	78.81
0.0049	0.125	3.00	120	7.28	7.29	86.10
0.0041	0.105	3.25	140	4.28	4.28	90.38
0.0035	0.088	3.50	170	2.38	2.38	92.76
0.0029	0.074	3.75	200	1.43	1.43	94.20
0.0025	0.063	4.00	230	0.97	0.97	95.17
0.0021	0.053	4.25	270	0.61	0.61	95.78
0.00174	0.0442	4.50	325	0.42	0.42	96.20
0.00146	0.0372	4.75	400	0.39	0.39	96.59
0.00123	0.0313	5.00	450	0.35	0.35	96.94
0.000986	0.0250	5.32	500	0.35	0.35	97.29
0.000790	0.0201	5.64	635	0.27	0.27	97.56
0.000615	0.0156	6.00		0.27	0.27	97.83
0.000435	0.0110	6.50		0.35	0.35	98.18
0.000308	0.00781	7.00		0.32	0.32	98.50
0.000197	0.00500	7.65		0.36	0.36	98.86
0.000077	0.00195	9.00		0.59	0.59	99.45
0.000038	0.000977	10.00		0.39	0.39	99.84
0.000019	0.000488	11.00		0.16	0.16	100.00
0.000015	0.000375	11.38		0.00	0.00	100.00
TOTALS				99.90	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	1.10	0.0184	0.468
10	1.50	0.0139	0.353
16	1.65	0.0126	0.320
25	1.83	0.0111	0.282
40	2.07	0.0094	0.238
50	2.22	0.0085	0.215
60	2.38	0.0076	0.193
75	2.66	0.0062	0.158
84	2.93	0.0052	0.131
90	3.23	0.0042	0.107
95	3.96	0.0025	0.064

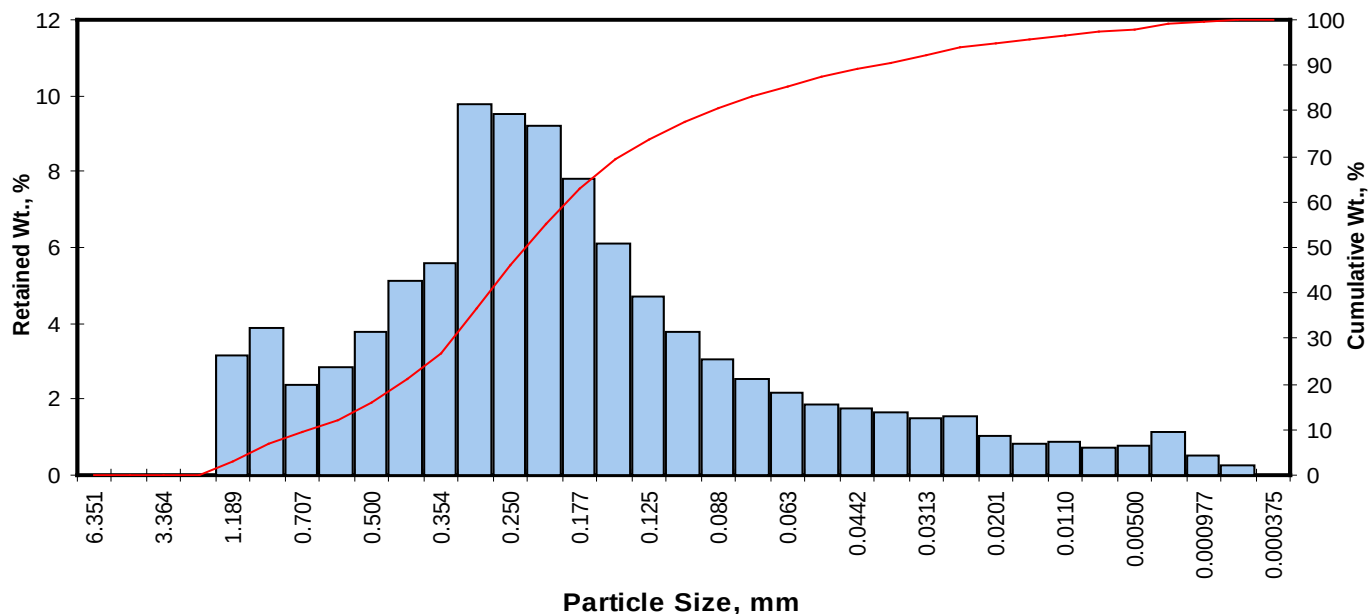
Measure	Trask	Inman	Folk-Ward
Median, phi	2.22	2.22	2.22
Median, in.	0.0085	0.0085	0.0085
Median, mm	0.215	0.215	0.215
Mean, phi	2.19	2.29	2.26
Mean, in.	0.0086	0.0081	0.0082
Mean, mm	0.220	0.205	0.208
Sorting	1.336	0.641	0.754
Skewness	0.979	0.109	0.163
Kurtosis	0.251	1.230	1.401
Grain Size Description (ASTM-USCS Scale)		Fine sand (based on Mean from Trask)	

Description	Retained on Sieve #	Weight Percent
Gravel	4	0.00
Coarse Sand	10	0.00
Medium Sand	40	6.43
Fine Sand	200	87.77
Silt	>0.005 mm	4.66
Clay	<0.005 mm	1.14
Total		100

Client: Conestoga-Rovers & Associates
Project: MLC-Willow Run
Project No: 17358-T01

PTS File No: 40772
Sample ID: LIF-029 (5'-8')
Depth, ft: 6.1

Grv	Sand Size			Silt	Clay
	crs	medium	fine		



Opening		Phi of Screen	U.S. No.	Sample Weight, grams	Increment Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.2500	6.351	-2.67	1/4	0.00	0.00	0.00
0.1873	4.757	-2.25	4	0.00	0.00	0.00
0.1324	3.364	-1.75	6	0.00	0.00	0.00
0.0787	2.000	-1.00	10	0.00	0.00	0.00
0.0468	1.189	-0.25	16	3.13	3.13	3.13
0.0331	0.841	0.25	20	3.89	3.89	7.02
0.0278	0.707	0.50	25	2.38	2.38	9.40
0.0234	0.595	0.75	30	2.84	2.84	12.24
0.0197	0.500	1.00	35	3.77	3.77	16.01
0.0166	0.420	1.25	40	5.12	5.12	21.13
0.0139	0.354	1.50	45	5.59	5.59	26.72
0.0117	0.297	1.75	50	9.80	9.80	36.52
0.0098	0.250	2.00	60	9.53	9.53	46.05
0.0083	0.210	2.25	70	9.23	9.23	55.28
0.0070	0.177	2.50	80	7.81	7.81	63.09
0.0059	0.149	2.75	100	6.09	6.09	69.18
0.0049	0.125	3.00	120	4.73	4.73	73.92
0.0041	0.105	3.25	140	3.75	3.75	77.67
0.0035	0.088	3.50	170	3.06	3.06	80.73
0.0029	0.074	3.75	200	2.55	2.55	83.28
0.0025	0.063	4.00	230	2.15	2.15	85.43
0.0021	0.053	4.25	270	1.86	1.86	87.29
0.00174	0.0442	4.50	325	1.74	1.74	89.03
0.00146	0.0372	4.75	400	1.68	1.68	90.71
0.00123	0.0313	5.00	450	1.52	1.52	92.23
0.000986	0.0250	5.32	500	1.54	1.54	93.77
0.000790	0.0201	5.64	635	1.06	1.06	94.83
0.000615	0.0156	6.00		0.84	0.84	95.67
0.000435	0.0110	6.50		0.89	0.89	96.56
0.000308	0.00781	7.00		0.72	0.72	97.28
0.000197	0.00500	7.65		0.76	0.76	98.04
0.000077	0.00195	9.00		1.15	1.15	99.19
0.000038	0.000977	10.00		0.54	0.54	99.73
0.000019	0.000488	11.00		0.25	0.25	99.98
0.000015	0.000375	11.38		0.02	0.02	100.00
TOTALS				100.00	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	-0.01	0.0396	1.007
10	0.55	0.0268	0.682
16	1.00	0.0197	0.500
25	1.42	0.0147	0.373
40	1.84	0.0110	0.279
50	2.11	0.0091	0.232
60	2.40	0.0075	0.189
75	3.07	0.0047	0.119
84	3.83	0.0028	0.070
90	4.64	0.0016	0.040
95	5.71	0.0007	0.019

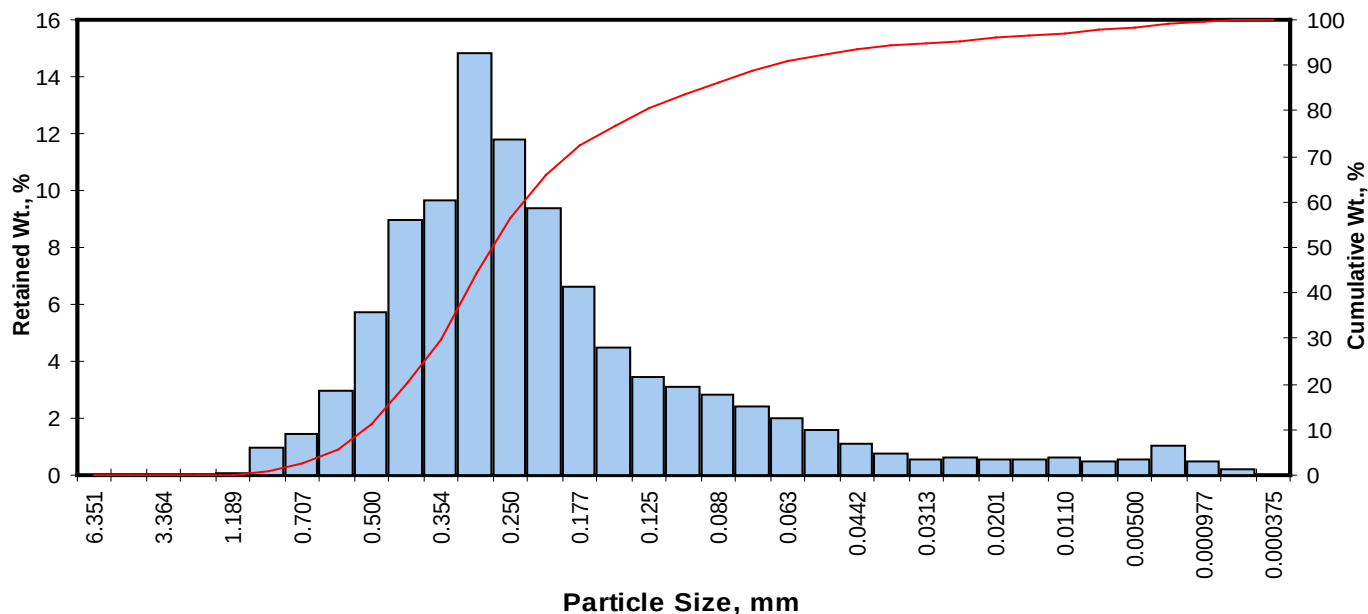
Measure	Trask	Inman	Folk-Ward
Median, phi	2.11	2.11	2.11
Median, in.	0.0091	0.0091	0.0091
Median, mm	0.232	0.232	0.232
Mean, phi	2.02	2.42	2.31
Mean, in.	0.0097	0.0074	0.0079
Mean, mm	0.246	0.187	0.201
Sorting	1.771	1.417	1.576
Skewness	0.907	0.219	0.240
Kurtosis	0.198	1.019	1.422
Grain Size Description (ASTM-USCS Scale)		Fine sand (based on Mean from Trask)	

Description	Retained on Sieve #	Weight Percent
Gravel	4	0.00
Coarse Sand	10	0.00
Medium Sand	40	21.13
Fine Sand	200	62.14
Silt	>0.005 mm	14.76
Clay	<0.005 mm	1.96
Total		100

Client: Conestoga-Rovers & Associates
Project: MLC-Willow Run
Project No: 17358-T01

PTS File No: 40772
Sample ID: LIF-025 (5'-10')
Depth, ft: 6.2

Grv	Sand Size			Silt	Clay
	crs	medium	fine		



Opening		Phi of Screen	U.S. No.	Sample Weight, grams	Increment Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.2500	6.351	-2.67	1/4	0.00	0.00	0.00
0.1873	4.757	-2.25	4	0.00	0.00	0.00
0.1324	3.364	-1.75	6	0.00	0.00	0.00
0.0787	2.000	-1.00	10	0.00	0.00	0.00
0.0468	1.189	-0.25	16	0.06	0.06	0.06
0.0331	0.841	0.25	20	0.97	0.97	1.03
0.0278	0.707	0.50	25	1.47	1.47	2.50
0.0234	0.595	0.75	30	2.99	2.99	5.49
0.0197	0.500	1.00	35	5.70	5.70	11.19
0.0166	0.420	1.25	40	8.95	8.95	20.14
0.0139	0.354	1.50	45	9.63	9.63	29.78
0.0117	0.297	1.75	50	14.80	14.80	44.58
0.0098	0.250	2.00	60	11.80	11.80	56.39
0.0083	0.210	2.25	70	9.41	9.41	65.80
0.0070	0.177	2.50	80	6.62	6.62	72.42
0.0059	0.149	2.75	100	4.50	4.50	76.92
0.0049	0.125	3.00	120	3.48	3.48	80.40
0.0041	0.105	3.25	140	3.08	3.08	83.48
0.0035	0.088	3.50	170	2.81	2.81	86.29
0.0029	0.074	3.75	200	2.44	2.44	88.74
0.0025	0.063	4.00	230	2.02	2.02	90.76
0.0021	0.053	4.25	270	1.57	1.57	92.33
0.00174	0.0442	4.50	325	1.11	1.11	93.44
0.00146	0.0372	4.75	400	0.75	0.75	94.19
0.00123	0.0313	5.00	450	0.57	0.57	94.76
0.000986	0.0250	5.32	500	0.64	0.64	95.40
0.000790	0.0201	5.64	635	0.58	0.58	95.98
0.000615	0.0156	6.00		0.55	0.55	96.53
0.000435	0.0110	6.50		0.62	0.62	97.15
0.000308	0.00781	7.00		0.51	0.51	97.66
0.000197	0.00500	7.65		0.58	0.58	98.24
0.000077	0.00195	9.00		1.01	1.01	99.25
0.000038	0.000977	10.00		0.50	0.50	99.75
0.000019	0.000488	11.00		0.23	0.23	99.98
0.000015	0.000375	11.38		0.02	0.02	100.00
TOTALS				100.00	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	0.71	0.0241	0.612
10	0.95	0.0204	0.518
16	1.13	0.0179	0.456
25	1.38	0.0152	0.385
40	1.67	0.0123	0.314
50	1.86	0.0108	0.275
60	2.10	0.0092	0.234
75	2.64	0.0063	0.160
84	3.30	0.0040	0.102
90	3.91	0.0026	0.067
95	5.12	0.0011	0.029

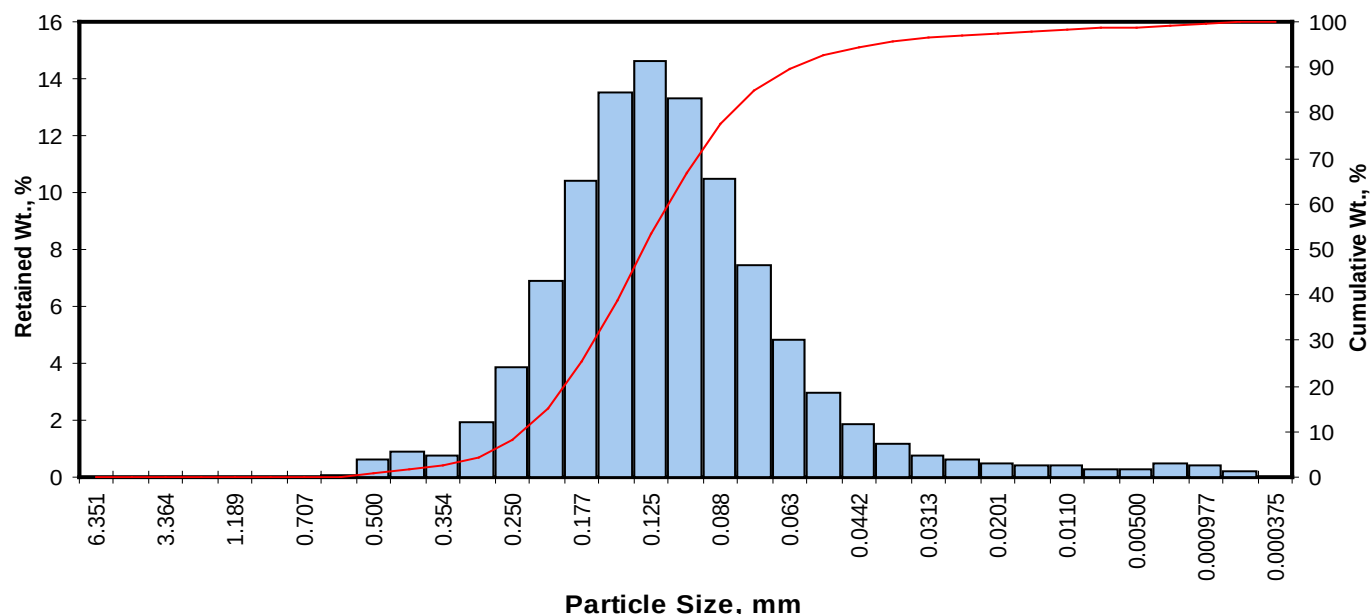
Measure	Trask	Inman	Folk-Ward
Median, phi	1.86	1.86	1.86
Median, in.	0.0108	0.0108	0.0108
Median, mm	0.275	0.275	0.275
Mean, phi	1.87	2.22	2.10
Mean, in.	0.0107	0.0085	0.0092
Mean, mm	0.273	0.215	0.234
Sorting	1.551	1.081	1.209
Skewness	0.904	0.324	0.400
Kurtosis	0.249	1.041	1.427
Grain Size Description (ASTM-USCS Scale)		Fine sand (based on Mean from Trask)	

Description	Retained on Sieve #	Weight Percent
Gravel	4	0.00
Coarse Sand	10	0.00
Medium Sand	40	20.14
Fine Sand	200	68.59
Silt	>0.005 mm	9.50
Clay	<0.005 mm	1.76
Total		100

Client: Conestoga-Rovers & Associates
Project: MLC-Willow Run
Project No: 17358-T01

PTS File No: 40772
Sample ID: LIF-021 (7'-12')
Depth, ft: 8.5

Grv	Sand Size			Silt	Clay
	crs	medium	fine		



Particle Size, mm

Opening		Phi of Screen	U.S. No.	Sample Weight, grams	Increment Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.2500	6.351	-2.67	1/4	0.00	0.00	0.00
0.1873	4.757	-2.25	4	0.00	0.00	0.00
0.1324	3.364	-1.75	6	0.00	0.00	0.00
0.0787	2.000	-1.00	10	0.00	0.00	0.00
0.0468	1.189	-0.25	16	0.00	0.00	0.00
0.0331	0.841	0.25	20	0.00	0.00	0.00
0.0278	0.707	0.50	25	0.00	0.00	0.00
0.0234	0.595	0.75	30	0.07	0.07	0.07
0.0197	0.500	1.00	35	0.64	0.64	0.71
0.0166	0.420	1.25	40	0.90	0.90	1.61
0.0139	0.354	1.50	45	0.77	0.77	2.38
0.0117	0.297	1.75	50	1.96	1.96	4.34
0.0098	0.250	2.00	60	3.85	3.85	8.19
0.0083	0.210	2.25	70	6.91	6.91	15.10
0.0070	0.177	2.50	80	10.40	10.40	25.50
0.0059	0.149	2.75	100	13.50	13.50	39.00
0.0049	0.125	3.00	120	14.60	14.60	53.61
0.0041	0.105	3.25	140	13.30	13.30	66.91
0.0035	0.088	3.50	170	10.50	10.50	77.41
0.0029	0.074	3.75	200	7.45	7.45	84.86
0.0025	0.063	4.00	230	4.82	4.82	89.68
0.0021	0.053	4.25	270	2.98	2.98	92.66
0.00174	0.0442	4.50	325	1.83	1.83	94.49
0.00146	0.0372	4.75	400	1.15	1.15	95.64
0.00123	0.0313	5.00	450	0.74	0.74	96.38
0.000986	0.0250	5.32	500	0.65	0.65	97.03
0.000790	0.0201	5.64	635	0.49	0.49	97.52
0.000615	0.0156	6.00		0.41	0.41	97.93
0.000435	0.0110	6.50		0.41	0.41	98.34
0.000308	0.00781	7.00		0.29	0.29	98.63
0.000197	0.00500	7.65		0.25	0.25	98.88
0.000077	0.00195	9.00		0.45	0.45	99.33
0.000038	0.000977	10.00		0.43	0.43	99.76
0.000019	0.000488	11.00		0.22	0.22	99.98
0.000015	0.000375	11.38		0.02	0.02	100.00
TOTALS				100.00	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	1.79	0.0114	0.289
10	2.07	0.0094	0.239
16	2.27	0.0082	0.207
25	2.49	0.0070	0.178
40	2.77	0.0058	0.147
50	2.94	0.0051	0.130
60	3.12	0.0045	0.115
75	3.44	0.0036	0.092
84	3.72	0.0030	0.076
90	4.03	0.0024	0.061
95	4.61	0.0016	0.041

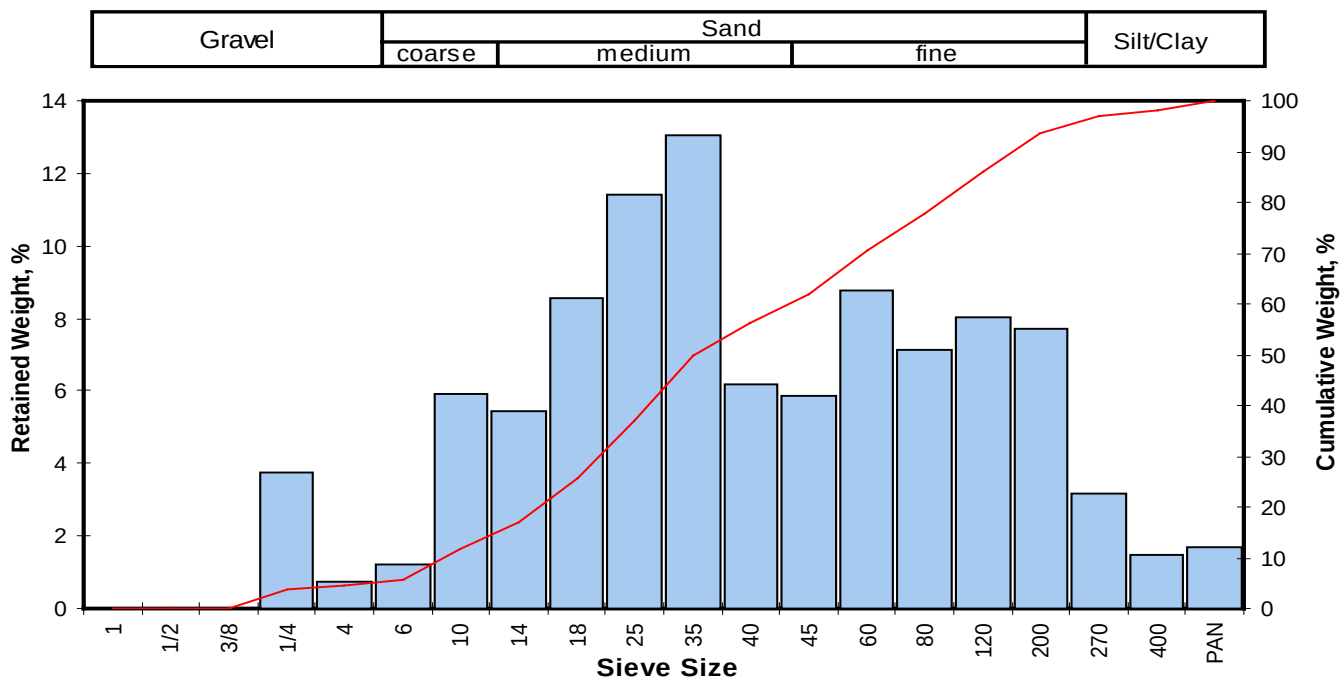
Measure	Trask	Inman	Folk-Ward
Median, phi	2.94	2.94	2.94
Median, in.	0.0051	0.0051	0.0051
Median, mm	0.130	0.130	0.130
Mean, phi	2.89	3.00	2.98
Mean, in.	0.0053	0.0049	0.0050
Mean, mm	0.135	0.125	0.127
Sorting	1.392	0.725	0.789
Skewness	0.981	0.080	0.134
Kurtosis	0.243	0.944	1.209

Grain Size Description	Fine sand
(ASTM-USCS Scale)	(based on Mean from Trask)

Description	Retained on Sieve #	Weight Percent
Gravel	4	0.00
Coarse Sand	10	0.00
Medium Sand	40	1.61
Fine Sand	200	83.25
Silt	>0.005 mm	14.02
Clay	<0.005 mm	1.12
Total		100

Client: Conestoga-Rovers & Associates
 Project: MLC-Willow Run
 Project No: 17358-T01

PTS File No: 40772
 Sample ID: LIF-055 (4'-9')
 Depth, ft: 7.4



Opening		Phi of Screen	U.S. Sieve No.	Sample Weight grams	Incremental Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.9844	25.002	-4.64	1	0.00	0.00	0.00
0.4922	12.501	-3.64	1/2	0.00	0.00	0.00
0.3740	9.500	-3.25	3/8	0.00	0.00	0.00
0.2500	6.351	-2.67	1/4	1.31	3.73	3.73
0.1873	4.757	-2.25	4	0.26	0.74	4.48
0.1324	3.364	-1.75	6	0.42	1.20	5.67
0.0787	2.000	-1.00	10	2.07	5.90	11.57
0.0557	1.414	-0.50	14	1.90	5.42	16.99
0.0394	1.000	0.00	18	3.00	8.55	25.54
0.0278	0.707	0.50	25	4.01	11.43	36.97
0.0197	0.500	1.00	35	4.57	13.03	50.00
0.0166	0.420	1.25	40	2.16	6.16	56.16
0.0139	0.354	1.50	45	2.05	5.84	62.00
0.0098	0.250	2.00	60	3.07	8.75	70.75
0.0070	0.177	2.50	80	2.51	7.16	77.91
0.0049	0.125	3.00	120	2.82	8.04	85.95
0.0029	0.074	3.75	200	2.70	7.70	93.64
0.0021	0.053	4.25	270	1.11	3.16	96.81
0.0015	0.037	4.75	400	0.52	1.48	98.29
			PAN	0.60	1.71	100.00
TOTALS				35.08	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	-2.03	0.1609	4.087
10	-1.20	0.0904	2.297
16	-0.59	0.0593	1.507
25	-0.03	0.0402	1.022
40	0.62	0.0257	0.652
50	1.00	0.0197	0.500
60	1.41	0.0148	0.375
75	2.30	0.0080	0.204
84	2.88	0.0054	0.136
90	3.40	0.0037	0.095
95	3.96	0.0025	0.064

Measure	Trask	Inman	Folk-Ward
Median, phi	1.00	1.00	1.00
Median, in.	0.0197	0.0197	0.0197
Median, mm	0.500	0.500	0.500
Mean, phi	0.71	1.14	1.10
Mean, in.	0.0241	0.0178	0.0184
Mean, mm	0.613	0.453	0.468
Sorting	2.241	1.735	1.776
Skewness	0.912	0.083	0.036
Kurtosis	0.186	0.728	1.055

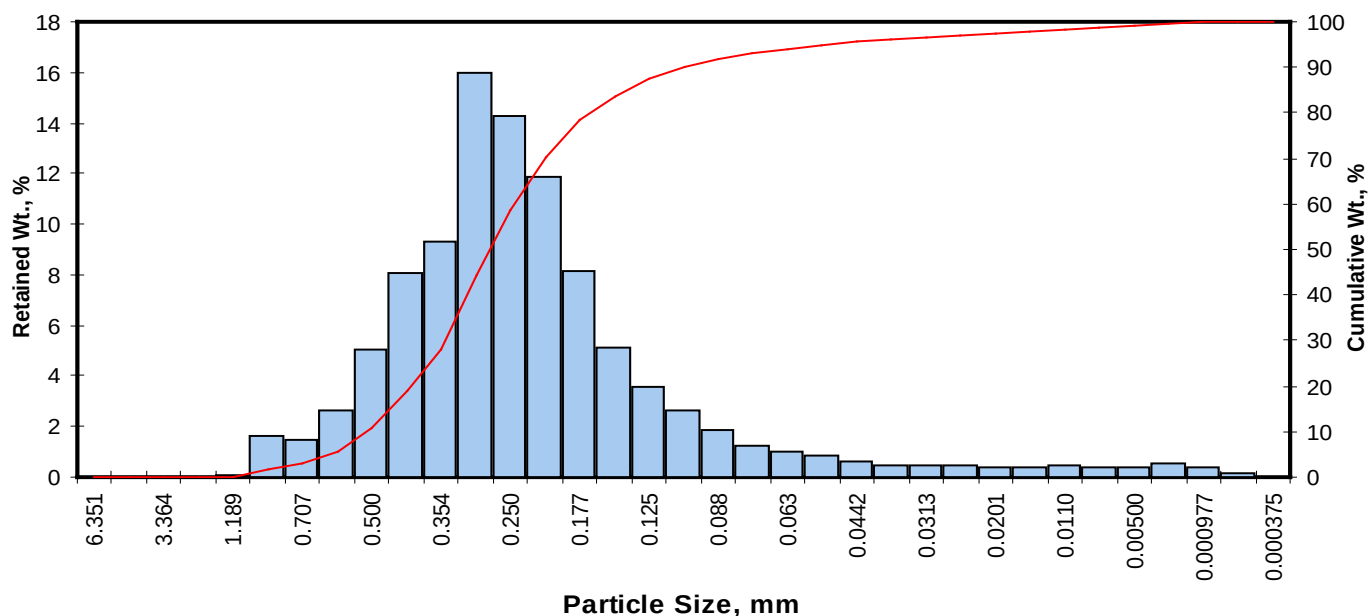
Grain Size Description (ASTM-USCS Scale)	Medium sand (based on Mean from Trask)

Description	Retained on Sieve #	Weight Percent
Gravel	4	4.48
Coarse Sand	10	7.10
Medium Sand	40	44.58
Fine Sand	200	37.49
Silt/Clay	<200	6.36
Total		100

Client: Conestoga-Rovers & Associates
Project: MLC-Willow Run
Project No: 17358-T01

PTS File No: 40772
Sample ID: ARC-128 (5'-10')
Depth, ft: 8.4

Grv	Sand Size			Silt	Clay
	crs	medium	fine		



Opening		Phi of Screen	U.S. No.	Sample Weight, grams	Increment Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.2500	6.351	-2.67	1/4	0.00	0.00	0.00
0.1873	4.757	-2.25	4	0.00	0.00	0.00
0.1324	3.364	-1.75	6	0.00	0.00	0.00
0.0787	2.000	-1.00	10	0.00	0.00	0.00
0.0468	1.189	-0.25	16	0.08	0.08	0.08
0.0331	0.841	0.25	20	1.62	1.62	1.70
0.0278	0.707	0.50	25	1.46	1.46	3.16
0.0234	0.595	0.75	30	2.62	2.62	5.78
0.0197	0.500	1.00	35	5.07	5.07	10.85
0.0166	0.420	1.25	40	8.10	8.10	18.94
0.0139	0.354	1.50	45	9.29	9.29	28.23
0.0117	0.297	1.75	50	16.00	16.00	44.23
0.0098	0.250	2.00	60	14.30	14.30	58.52
0.0083	0.210	2.25	70	11.90	11.90	70.42
0.0070	0.177	2.50	80	8.15	8.15	78.57
0.0059	0.149	2.75	100	5.15	5.15	83.71
0.0049	0.125	3.00	120	3.59	3.59	87.30
0.0041	0.105	3.25	140	2.67	2.67	89.97
0.0035	0.088	3.50	170	1.84	1.84	91.81
0.0029	0.074	3.75	200	1.25	1.25	93.06
0.0025	0.063	4.00	230	1.04	1.04	94.10
0.0021	0.053	4.25	270	0.87	0.87	94.97
0.00174	0.0442	4.50	325	0.60	0.60	95.57
0.00146	0.0372	4.75	400	0.47	0.47	96.04
0.00123	0.0313	5.00	450	0.43	0.43	96.47
0.000986	0.0250	5.32	500	0.49	0.49	96.96
0.000790	0.0201	5.64	635	0.40	0.40	97.36
0.000615	0.0156	6.00		0.38	0.38	97.74
0.000435	0.0110	6.50		0.46	0.46	98.20
0.000308	0.00781	7.00		0.38	0.38	98.58
0.000197	0.00500	7.65		0.38	0.38	98.96
0.000077	0.00195	9.00		0.55	0.55	99.51
0.000038	0.000977	10.00		0.35	0.35	99.86
0.000019	0.000488	11.00		0.14	0.14	100.00
0.000015	0.000375	11.38		0.00	0.00	100.00
TOTALS				100.00	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	0.68	0.0246	0.626
10	0.96	0.0203	0.515
16	1.16	0.0176	0.448
25	1.41	0.0148	0.376
40	1.68	0.0123	0.311
50	1.85	0.0109	0.277
60	2.03	0.0096	0.245
75	2.39	0.0075	0.191
84	2.77	0.0058	0.147
90	3.25	0.0041	0.105
95	4.26	0.0021	0.052

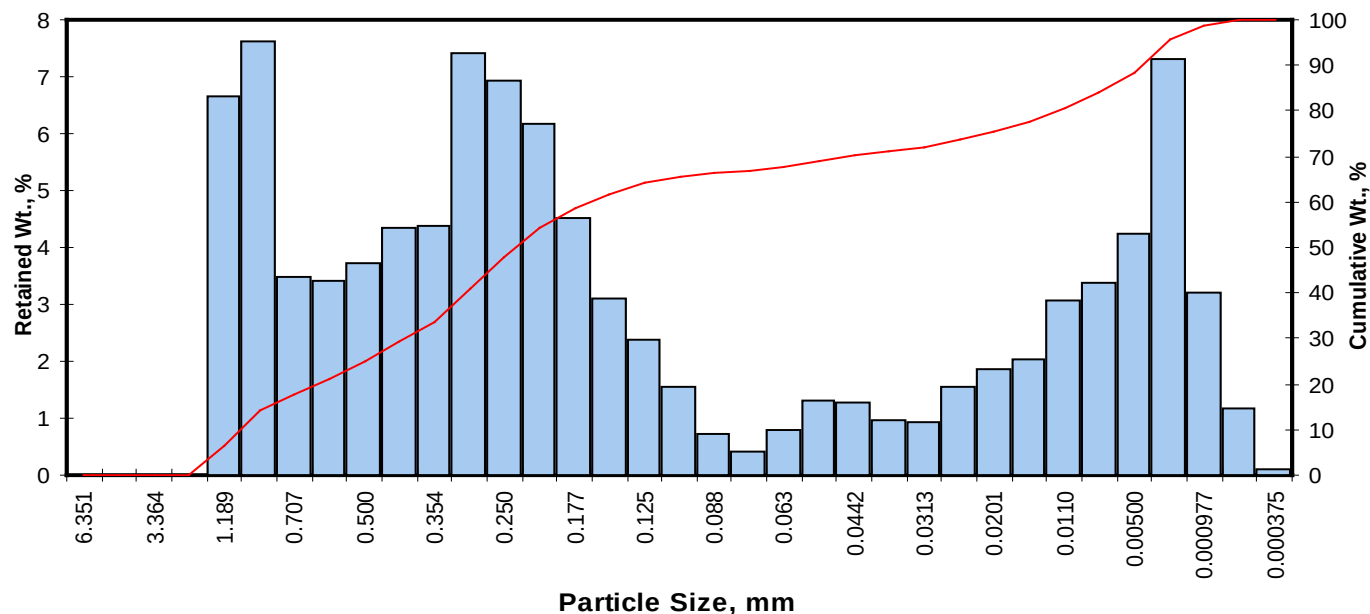
Measure	Trask	Inman	Folk-Ward
Median, phi	1.85	1.85	1.85
Median, in.	0.0109	0.0109	0.0109
Median, mm	0.277	0.277	0.277
Mean, phi	1.82	1.96	1.93
Mean, in.	0.0111	0.0101	0.0104
Mean, mm	0.283	0.256	0.263
Sorting	1.403	0.805	0.946
Skewness	0.965	0.141	0.243
Kurtosis	0.225	1.226	1.503
Grain Size Description (ASTM-USCS Scale)		Fine sand (based on Mean from Trask)	

Description	Retained on Sieve #	Weight Percent
Gravel	4	0.00
Coarse Sand	10	0.00
Medium Sand	40	18.94
Fine Sand	200	74.12
Silt	>0.005 mm	5.90
Clay	<0.005 mm	1.04
Total		100

Client: Conestoga-Rovers & Associates
Project: MLC-Willow Run
Project No: 17358-T01

PTS File No: 40772
Sample ID: ARC-65 (5'-10')
Depth, ft: 8.4

Grv	Sand Size			Silt	Clay
	crs	medium	fine		



Opening		Phi of Screen	U.S. No.	Sample Weight, grams	Increment Weight, percent	Cumulative Weight, percent
Inches	Millimeters					
0.2500	6.351	-2.67	1/4	0.00	0.00	0.00
0.1873	4.757	-2.25	4	0.00	0.00	0.00
0.1324	3.364	-1.75	6	0.00	0.00	0.00
0.0787	2.000	-1.00	10	0.00	0.00	0.00
0.0468	1.189	-0.25	16	6.65	6.65	6.65
0.0331	0.841	0.25	20	7.61	7.61	14.26
0.0278	0.707	0.50	25	3.48	3.48	17.74
0.0234	0.595	0.75	30	3.43	3.43	21.17
0.0197	0.500	1.00	35	3.71	3.71	24.88
0.0166	0.420	1.25	40	4.35	4.35	29.23
0.0139	0.354	1.50	45	4.39	4.39	33.62
0.0117	0.297	1.75	50	7.41	7.41	41.03
0.0098	0.250	2.00	60	6.94	6.94	47.97
0.0083	0.210	2.25	70	6.17	6.17	54.14
0.0070	0.177	2.50	80	4.51	4.51	58.65
0.0059	0.149	2.75	100	3.12	3.12	61.77
0.0049	0.125	3.00	120	2.37	2.37	64.14
0.0041	0.105	3.25	140	1.56	1.56	65.70
0.0035	0.088	3.50	170	0.71	0.71	66.41
0.0029	0.074	3.75	200	0.42	0.42	66.83
0.0025	0.063	4.00	230	0.79	0.79	67.62
0.0021	0.053	4.25	270	1.31	1.31	68.93
0.00174	0.0442	4.50	325	1.28	1.28	70.21
0.00146	0.0372	4.75	400	0.96	0.96	71.17
0.00123	0.0313	5.00	450	0.92	0.92	72.08
0.000986	0.0250	5.32	500	1.55	1.55	73.63
0.000790	0.0201	5.64	635	1.87	1.87	75.50
0.000615	0.0156	6.00		2.04	2.04	77.54
0.000435	0.0110	6.50		3.08	3.08	80.62
0.000308	0.00781	7.00		3.37	3.37	83.99
0.000197	0.00500	7.65		4.23	4.23	88.22
0.000077	0.00195	9.00		7.30	7.30	95.52
0.000038	0.000977	10.00		3.20	3.20	98.72
0.000019	0.000488	11.00		1.18	1.18	99.90
0.000015	0.000375	11.38		0.10	0.10	100.00
TOTALS				100.00	100.00	100.00

Cumulative Weight Percent greater than			
Weight percent	Phi Value	Particle Size	
		Inches	Millimeters
5	-0.44	0.0533	1.353
10	-0.03	0.0402	1.021
16	0.38	0.0304	0.771
25	1.01	0.0196	0.498
40	1.72	0.0120	0.305
50	2.08	0.0093	0.236
60	2.61	0.0065	0.164
75	5.55	0.0008	0.021
84	7.00	0.0003	0.008
90	7.97	0.0002	0.004
95	8.90	0.0001	0.002

Measure	Trask	Inman	Folk-Ward
Median, phi	2.08	2.08	2.08
Median, in.	0.0093	0.0093	0.0093
Median, mm	0.236	0.236	0.236
Mean, phi	1.95	3.69	3.15
Mean, in.	0.0102	0.0031	0.0044
Mean, mm	0.259	0.078	0.112
Sorting	4.834	3.313	3.071
Skewness	0.436	0.485	0.473
Kurtosis	0.234	0.409	0.842
Grain Size Description		Fine sand	
(ASTM-USCS Scale)		(based on Mean from Trask)	

Description	Retained on Sieve #	Weight Percent
Gravel	4	0.00
Coarse Sand	10	0.00
Medium Sand	40	29.23
Fine Sand	200	37.60
Silt	>0.005 mm	21.40
Clay	<0.005 mm	11.78
Total		100

PTS File No: 40772
Client: Conestoga-Rovers & Associates

PHYSICAL PROPERTIES DATA - PORE FLUID SATURATIONS

PROJECT NAME: MLC-Willow Run
PROJECT NO: 17358-T01

SAMPLE ID.	DEPTH, ft.	METHODS: SAMPLE ORIENTATION (1)	API RP 40 / ASTM D2216	API RP 40		API RP 40		API RP 40	
			MOISTURE CONTENT, % weight	DENSITY		POROSITY, %Vb (2)		PORE FLUID SATURATIONS, % Pv (3)	
				BULK, g/cc	GRAIN, g/cc	TOTAL	AIR FILLED	WATER	NAPL
LIF-040 (5'-10')	6.7	V	14.7	1.63	2.66	38.5	13.6	47.3	17.3
LIF-037 (5'-10')	7.9	V	16.3	1.67	2.67	37.4	9.5	64.5	10.1
LIF-058 (2'-7')	2.9	V	17.0	1.55	2.65	41.5	14.7	57.9	6.7
LIF-009 (5'-10')	6.65	V	19.6	1.62	2.67	39.4	7.3	74.9	6.5
LIF-061 (5'-10')	8.3	V	14.0	1.65	2.66	37.9	11.7	10.6	58.6
LIF-025 (5'-10')	5.9	V	19.9	1.52	2.68	43.3	9.7	21.5	56.1
LIF-021 (7'-12')	8.3	V	14.5	1.57	2.68	41.3	17.1	33.0	25.7
LIF-055 (9'-14')	10.7	V	16.0	1.67	2.69	37.9	10.8	63.8	7.8
ARC-128 (5'-10')	8.8	V	16.7	1.64	2.66	38.4	10.4	61.4	11.6
ARC-65 (5'-10')	8.6	V	15.2	1.70	2.68	36.5	10.1	61.8	10.6

(1) Sample Orientation: H = horizontal; V = vertical

(2) Total Porosity = all interconnected pore channels; Air Filled = pore channels not occupied by pore fluids

PHYSICAL PROPERTIES DATA - PORE FLUID SATURATIONS

PROJECT NAME: MLC-Willow Run
PROJECT NO: 17358-T01

		METHODS:		API RP 40 / ASTM D2216	API RP 40		API RP 40		API RP 40	
SAMPLE ID.	DEPTH, ft.	SAMPLE ORIENTATION (1)	MOISTURE CONTENT, % weight		DENSITY		POROSITY, %Vb (2)		PORE FLUID SATURATIONS, % Pv (3)	
					BULK, g/cc	GRAIN, g/cc	TOTAL	AIR FILLED	WATER	NAPL

(3) Water = 0.9996 g/cc, Hydrocarbon = 0.8600 g/cc
Vb = Bulk Volume, cc; Pv = Pore Volume, cc; ND = Not Detected

PTS File No: 40772
 Client: Conestoga-Rovers & Associates

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ENDPOINT SATURATION WATER DRIVE TEST: INITIAL AND RESIDUAL SATURATIONS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01

METHODS:			API RP 40		API RP 40	ASTM D425M, DEAN-STARK			
SAMPLE ID.	DEPTH, ft.	SAMPLE ORIENTATION (1)	DENSITY		TOTAL POROSITY, %Vb	PORE FLUID SATURATIONS, % Pv			
			BULK, g/cc	GRAIN, g/cc		Initial Fluid Saturations		After Waterflood Test	
						WATER (Swi) SATURATION	NAPL (Soi) SATURATION	WATER (Srw) SATURATION	NAPL (Sor) SATURATION
LIF-040 (5'-10')	6.5	V	1.70	2.68	36.7	32.2	33.7	53.5	33.7
	NOTE:	No visible LNAPL produced; 13.4 pore volumes of water injected. Produced water clear with faint hydrocarbon odor.							
LIF-037 (5'-10')	6.7	V	1.61	2.70	40.3	48.9	13.6	54.1	13.6
	NOTE:	No visible LNAPL produced; 10.9 pore volumes of water injected. Produced water clear with faint hydrocarbon odor.							
LIF-034 (5'-10')	8.15	V	1.65	2.70	38.9	73.1	10.8	80.5	10.8
	NOTE:	No visible LNAPL produced; 11.8 pore volumes of water injected. Produced water clear with faint hydrocarbon odor.							
LIF-058 (2'-7')	3.1	V	1.60	2.68	40.1	65.5	12.8	65.5	12.8
	NOTE:	No visible LNAPL produced; 10.8 pore volumes of water injected. Produced water cloudy with faint hydrocarbon odor. Sample compressed slightly from confining pressure.							
LIF-009 (5'-10')	5.6	V	1.67	2.66	37.2	48.3	48.6	57.0	37.6
	NOTE:	Cloudy light brown LNAPL produced; 99.2 pore volumes of water injected. Produced water clear with faint hydrocarbon odor.							
LIF-029 (5'-8')	6.3	V	1.61	2.63	38.9	38.7	25.0	66.4	25.0
	NOTE:	No visible LNAPL produced; 15.7 pore volumes of water injected. Produced water clear with faint hydrocarbon odor.							
LIF-060 (5'-10')	8.0	V	1.83	2.63	30.3	80.0	11.7	82.4	11.7
	NOTE:	No visible LNAPL produced; 13.9 pore volumes of water injected. Produced water yellow tint with moderate hydrocarbon odor.							

Water drives conducted at 25 psi confining pressure and 70°F. Laboratory fresh water (tap) used as injection fluid.

N/A = Not Analyzed. Vb = Bulk Volume, Pv = Pore Volume. (1) H = horizontal, V = vertical

Soi = Initial NAPL Saturation as received prior to water flooding, Swi = Initial Water Saturation as received prior to waterflooding

PTS File No: 40772
Client: Conestoga-Rovers & Associates

REPORT REVISED 20110630

PTS Laboratories

ENDPOINT SATURATION WATER DRIVE TEST: INITIAL AND RESIDUAL SATURATIONS

PROJECT NAME: MLC-Willow Run
PROJECT NO: 17358-T01

		METHODS:		API RP 40		API RP 40		ASTM D425M, DEAN-STARK			
								PORE FLUID SATURATIONS, % Pv			
SAMPLE ID.	DEPTH, ft.	SAMPLE ORIENTATION (1)	DENSITY		TOTAL POROSITY, %Vb	Initial Fluid Saturations		After Waterflood Test			
			BULK, g/cc	GRAIN, g/cc		WATER (Swi) SATURATION	NAPL (Soi) SATURATION	WATER (Srw) SATURATION	NAPL (Sor) SATURATION		

Sor = Residual NAPL Saturation after waterflooding, Srw = Residual Water Saturation after waterflooding

Water = 0.9996 g/cc, NAPL = 0.8600 g/cc.

PTS File No: 40772
 Client: Conestoga-Rovers & Associates

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PTS Laboratories

ENDPOINT SATURATION WATER DRIVE TEST: INITIAL AND RESIDUAL SATURATIONS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01

		METHODS:	API RP 40		API RP 40	ASTM D425M, DEAN-STARK			
SAMPLE ID.	DEPTH, ft.	SAMPLE ORIENTATION (1)	DENSITY		TOTAL POROSITY, %Vb	PORE FLUID SATURATIONS, % Pv			
			BULK, g/cc	GRAIN, g/cc		Initial Fluid Saturations		After Waterflood Test	
						WATER (Swi) SATURATION	NAPL (Soi) SATURATION	WATER (Srw) SATURATION	NAPL (Sor) SATURATION
LIF-061 (5'-10')	8.1	V	1.56	2.64	41.1	56.3	42.0	56.3	12.6
	NOTE:	Light brown LNAPL produced; 47.0 pore volumes of water injected. Produced water clear with faint hydrocarbon odor. Sample compressed slightly from confining pressure.							
LIF-025 (5'-10')	6.4	V	1.72	2.71	36.5	11.6	16.1	21.1	16.1
	NOTE:	No visible LNAPL produced; 12.5 pore volumes of water injected. Produced water clear with faint hydrocarbon odor.							
LIF-021 (7'-12')	9.15	V	1.64	2.66	38.2	49.3	31.0	58.3	31.0
	NOTE:	No visible LNAPL produced; 11.8 pore volumes of water injected. Produced water clear with no hydrocarbon odor.							
LIF-055 (4'-9')	7.2	V	1.89	2.70	30.0	78.1	15.3	78.1	15.3
	NOTE:	No visible LNAPL produced; 0.8 pore volumes of water injected. Produced water clear with no hydrocarbon odor. Testing discontinued due to low permeability. Sample compressed slightly from confining pressure.							
ARC-128 (5'-10')	8.2	V	1.67	2.65	37.1	52.9	24.2	53.9	24.2
	NOTE:	No visible LNAPL produced; 13.1 pore volumes of water injected. Produced water clear with faint hydrocarbon odor.							
ARC-65 (5'-10')	8.0	V	1.75	2.66	34.2	32.3	48.0	58.8	46.9
	NOTE:	Dark brown LNAPL produced; 20.2 pore volumes of water injected. Produced water cloudy with no hydrocarbon odor.							

Water drives conducted at 25 psi confining pressure and 70°F. Laboratory fresh water (tap) used as injection fluid.

N/A = Not Analyzed. Vb = Bulk Volume, Pv = Pore Volume. (1) H = horizontal, V = vertical

Soi = Initial NAPL Saturation as received prior to water flooding, Swi = Initial Water Saturation as received prior to waterflooding

PTS File No: 40772
Client: Conestoga-Rovers & Associates

REPORT REVISED 20110630

PTS Laboratories

ENDPOINT SATURATION WATER DRIVE TEST: INITIAL AND RESIDUAL SATURATIONS

PROJECT NAME: MLC-Willow Run
PROJECT NO: 17358-T01

		METHODS:		API RP 40		API RP 40		ASTM D425M, DEAN-STARK			
								PORE FLUID SATURATIONS, % Pv			
SAMPLE ID.	DEPTH, ft.	SAMPLE ORIENTATION (1)	DENSITY		TOTAL POROSITY, %Vb	Initial Fluid Saturations		After Waterflood Test			
			BULK, g/cc	GRAIN, g/cc		WATER (Swi) SATURATION	NAPL (Soi) SATURATION	WATER (Srw) SATURATION	NAPL (Sor) SATURATION		

Sor = Residual NAPL Saturation after waterflooding, Srw = Residual Water Saturation after waterflooding

Water = 0.9996 g/cc, NAPL = 0.8600 g/cc.

TABLE 1

**SOIL MOISTURE RETENTION CURVE FITTING FOR QUANTIFYING
 THE HYDRAULIC FUNCTIONS OF UNSATURATED SOILS**

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: ARC-128 (5'-10') at 8.4

van Genuchten Parameters

alpha (1/cm)	1.791E-02
n	2.185
residual water	0.085
total water	1.017
m	0.542
Water Perm (mD)	4650
Air Perm (mD)	8350
R ²	0.99540

Notes: alpha, n, and residual saturation are capillary parameters defined by the following equation (van Genuchten, 1980), with $m = 1-1/n$, S = water saturation, and h = capillary head (cm):

$$S_r + [(S_s - S_r) / (1 + (\alpha h)^n)^m]$$

Laboratory Measured Data

Capillary Head (cm)	ARC-128 (5'-10') at 8.4 Volumetric Moisture	Predicted Moisture by Curve Fit	RPD (%)
0.00	1.000	1.017	0.87%
5.56	1.000	1.014	0.71%
12.51	1.000	0.999	0.06%
22.24	0.990	0.956	1.74%
34.75	0.920	0.876	2.47%
50.05	0.750	0.766	0.99%
68.12	0.617	0.647	2.39%
88.97	0.501	0.539	3.67%
139.02	0.361	0.380	2.55%
234.94	0.261	0.251	2.04%
355.89	0.202	0.188	3.52%
556.08	0.162	0.146	5.10%
2224.30	0.092	0.097	2.66%

TABLE 2

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: ARC-128 (5'-10') at 8.4

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
0.001	1.017	4.64E+03	2.25E-13
0.02	1.017	4.64E+03	7.19E-09
0.04	1.017	4.64E+03	7.92E-08
0.05	1.017	4.64E+03	1.72E-07
0.08	1.017	4.64E+03	8.73E-07
0.09	1.017	4.64E+03	1.31E-06
1	1.017	4.56E+03	5.49E-03
1.2	1.017	4.54E+03	1.03E-02
1.3	1.017	4.53E+03	1.36E-02
1.5	1.017	4.51E+03	2.23E-02
2	1.017	4.46E+03	6.04E-02
3	1.017	4.35E+03	2.46E-01
5	1.015	4.12E+03	1.43E+00
7	1.012	3.87E+03	4.56E+00
9	1.008	3.63E+03	1.08E+01
11	1.003	3.38E+03	2.12E+01
15	0.990	2.89E+03	5.98E+01
20	0.968	2.34E+03	1.51E+02
25	0.940	1.85E+03	3.00E+02
30	0.909	1.45E+03	5.10E+02
35	0.874	1.13E+03	7.74E+02
40	0.838	8.67E+02	1.08E+03
45	0.802	6.66E+02	1.42E+03
50	0.766	5.12E+02	1.78E+03
60	0.698	3.05E+02	2.50E+03
70	0.636	1.85E+02	3.18E+03
75	0.608	1.45E+02	3.49E+03
80	0.582	1.15E+02	3.79E+03
85	0.557	9.16E+01	4.07E+03
90	0.535	7.34E+01	4.32E+03
95	0.513	5.93E+01	4.56E+03
100	0.494	4.82E+01	4.78E+03
120	0.428	2.24E+01	5.50E+03
140	0.378	1.13E+01	6.02E+03
160	0.339	6.17E+00	6.41E+03
180	0.309	3.57E+00	6.70E+03
200	0.284	2.18E+00	6.93E+03
220	0.264	1.38E+00	7.10E+03

TABLE 2

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: ARC-128 (5'-10') at 8.4

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
240	0.247	9.12E-01	7.25E+03
260	0.233	6.20E-01	7.36E+03
280	0.221	4.33E-01	7.46E+03
300	0.210	3.10E-01	7.54E+03
320	0.201	2.26E-01	7.61E+03
340	0.193	1.68E-01	7.67E+03
360	0.187	1.27E-01	7.72E+03
380	0.180	9.77E-02	7.77E+03
400	0.175	7.60E-02	7.81E+03
420	0.170	5.98E-02	7.84E+03
440	0.165	4.75E-02	7.87E+03
460	0.161	3.82E-02	7.90E+03
480	0.157	3.10E-02	7.92E+03
500	0.154	2.53E-02	7.94E+03
550	0.147	1.58E-02	7.99E+03
600	0.141	1.03E-02	8.03E+03
650	0.136	6.94E-03	8.06E+03
700	0.131	4.81E-03	8.09E+03
750	0.128	3.42E-03	8.11E+03
800	0.125	2.48E-03	8.13E+03
850	0.122	1.84E-03	8.14E+03
900	0.120	1.39E-03	8.15E+03
950	0.117	1.06E-03	8.17E+03
1000	0.115	8.22E-04	8.18E+03
1050	0.114	6.46E-04	8.19E+03
1100	0.112	5.13E-04	8.19E+03
1150	0.111	4.11E-04	8.20E+03
1200	0.110	3.33E-04	8.21E+03
1250	0.108	2.72E-04	8.22E+03
1300	0.107	2.24E-04	8.22E+03
1350	0.106	1.86E-04	8.23E+03
1400	0.105	1.55E-04	8.23E+03
1450	0.105	1.30E-04	8.24E+03
1500	0.104	1.10E-04	8.24E+03
1550	0.103	9.36E-05	8.24E+03
1600	0.102	8.00E-05	8.25E+03
1650	0.102	6.86E-05	8.25E+03
1700	0.101	5.92E-05	8.25E+03

TABLE 2

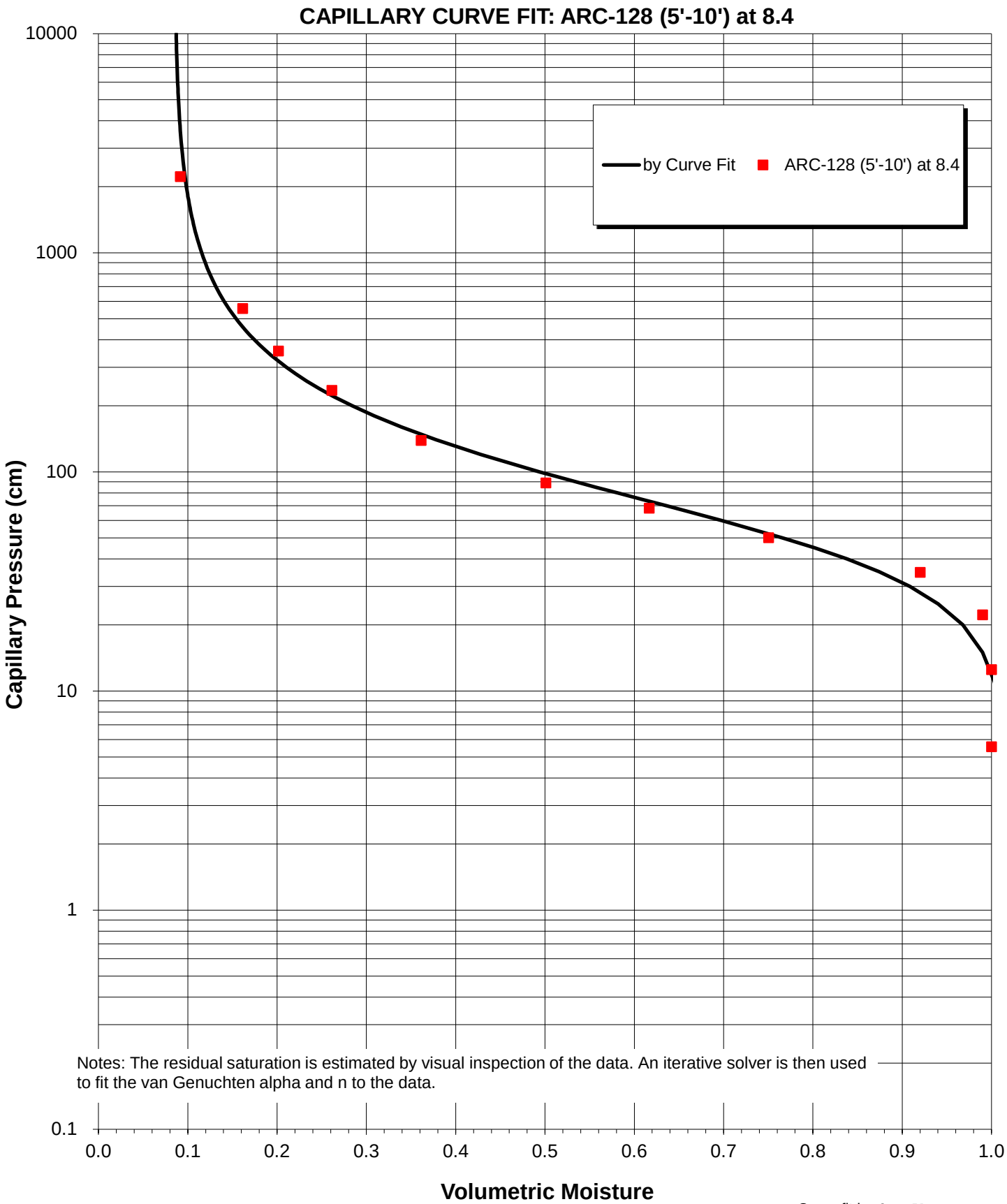
FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: ARC-128 (5'-10') at 8.4

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
1750	0.101	5.13E-05	8.26E+03
1800	0.100	4.46E-05	8.26E+03
1850	0.100	3.89E-05	8.26E+03
1900	0.099	3.41E-05	8.26E+03
1950	0.099	3.00E-05	8.26E+03
2000	0.098	2.64E-05	8.27E+03
2200	0.097	1.65E-05	8.27E+03
2400	0.096	1.07E-05	8.28E+03
2600	0.095	7.19E-06	8.28E+03
2800	0.094	4.98E-06	8.29E+03
3000	0.093	3.54E-06	8.29E+03
3200	0.093	2.57E-06	8.30E+03
3400	0.092	1.90E-06	8.30E+03
3600	0.092	1.43E-06	8.30E+03
3800	0.091	1.09E-06	8.30E+03
4000	0.091	8.48E-07	8.30E+03
4200	0.091	6.66E-07	8.31E+03
4400	0.090	5.29E-07	8.31E+03
4600	0.090	4.24E-07	8.31E+03
4800	0.090	3.43E-07	8.31E+03
5000	0.090	2.80E-07	8.31E+03
5200	0.089	2.31E-07	8.31E+03
5400	0.089	1.91E-07	8.31E+03
5600	0.089	1.60E-07	8.31E+03
5800	0.089	1.34E-07	8.31E+03
6000	0.089	1.13E-07	8.31E+03
6500	0.088	7.63E-08	8.32E+03
7000	0.088	5.28E-08	8.32E+03
7500	0.088	3.75E-08	8.32E+03
8000	0.088	2.72E-08	8.32E+03
8500	0.087	2.01E-08	8.32E+03
9000	0.087	1.52E-08	8.32E+03
9500	0.087	1.16E-08	8.32E+03
10000	0.087	8.99E-09	8.32E+03

PTS File No: 40772
Client: Conestoga-Rovers & Associates



CAPILLARY CURVE FIT: ARC-128 (5'-10') at 8.4

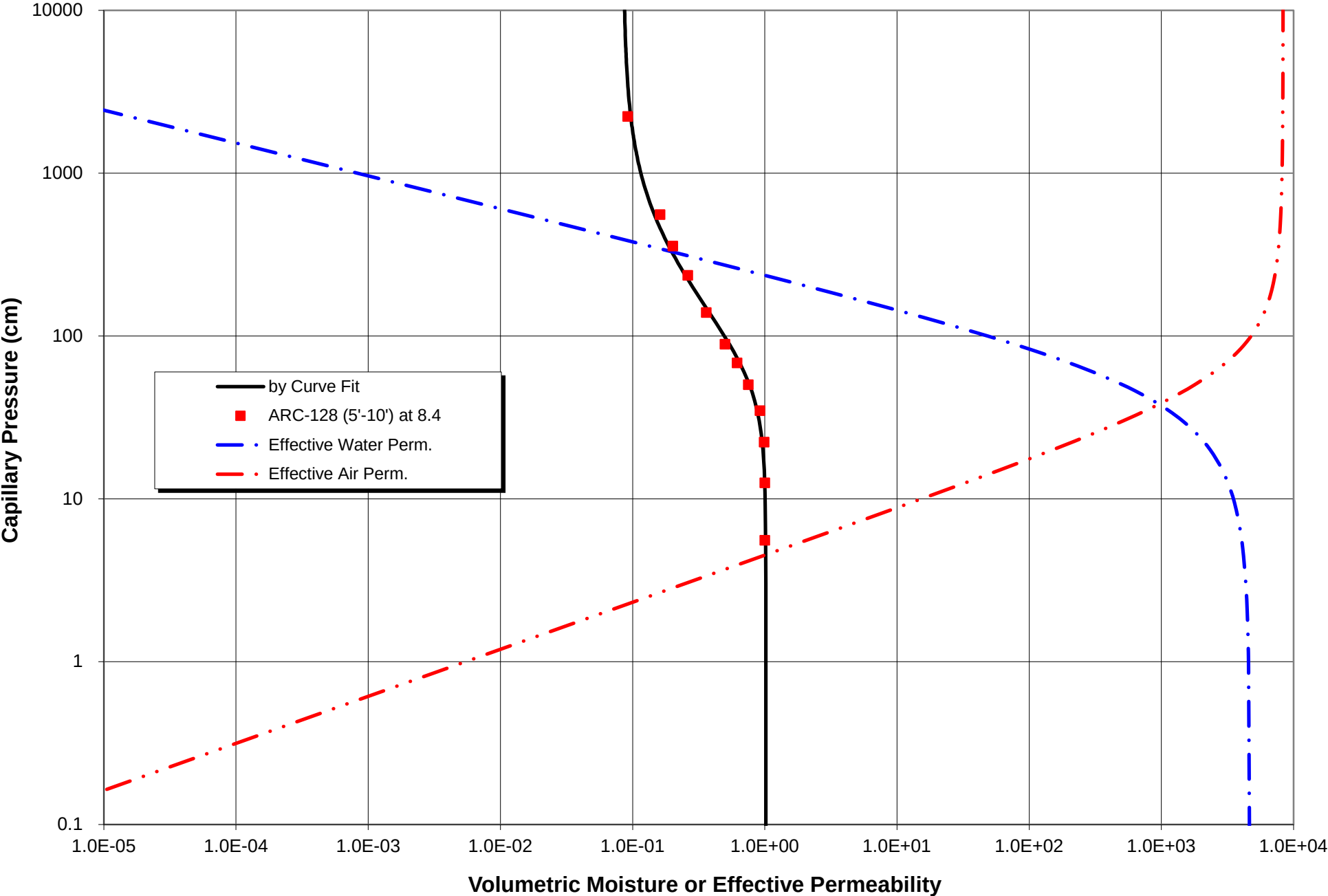


TABLE 1

**SOIL MOISTURE RETENTION CURVE FITTING FOR QUANTIFYING
 THE HYDRAULIC FUNCTIONS OF UNSATURATED SOILS**

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: LIF-029 (5'-8') at 6.1 ft.

van Genuchten Parameters

alpha (1/cm)	2.480E-02
n	1.955
residual water	0.225
total water	1.017
m	0.488
Water Perm (mD)	5850
Air Perm (mD)	7000
R ²	0.99466

Notes: alpha, n, and residual saturation are capillary parameters defined by the following equation (van Genuchten, 1980), with $m = 1-1/n$, S = water saturation, and h = capillary head (cm):

$$S_r + [(S_s - S_r) / (1 + (\alpha h)^n)^m]$$

Laboratory Measured Data

Capillary Head (cm)	LIF-029 (5'-8') at 6.1 ft. Volumetric Moisture	Predicted Moisture by Curve Fit	RPD (%)
0.00	1.000	1.017	0.83%
5.53	1.000	1.009	0.44%
12.45	1.000	0.981	0.98%
22.13	0.949	0.919	1.59%
34.57	0.846	0.829	1.04%
49.78	0.727	0.730	0.21%
67.76	0.599	0.640	3.28%
88.50	0.522	0.565	3.92%
138.28	0.454	0.459	0.55%
233.70	0.386	0.371	2.00%
354.01	0.343	0.324	2.89%
553.14	0.300	0.290	1.80%
1244.56	0.258	0.255	0.54%
2212.55	0.241	0.242	0.34%

TABLE 2

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: LIF-029 (5'-8') at 6.1 ft.

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
0.001	1.017	5.86E+03	2.47E-10
0.02	1.017	5.85E+03	1.41E-06
0.04	1.017	5.84E+03	1.04E-05
0.05	1.017	5.84E+03	1.98E-05
0.08	1.017	5.83E+03	7.71E-05
0.09	1.017	5.82E+03	1.08E-04
1	1.016	5.52E+03	1.13E-01
1.2	1.016	5.45E+03	1.92E-01
1.3	1.016	5.42E+03	2.41E-01
1.5	1.016	5.36E+03	3.65E-01
2	1.016	5.21E+03	8.36E-01
3	1.014	4.91E+03	2.68E+00
5	1.010	4.36E+03	1.16E+01
7	1.004	3.86E+03	2.99E+01
9	0.997	3.40E+03	6.02E+01
11	0.988	2.99E+03	1.04E+02
15	0.966	2.29E+03	2.35E+02
20	0.934	1.63E+03	4.77E+02
25	0.898	1.15E+03	7.87E+02
30	0.862	8.13E+02	1.14E+03
35	0.826	5.79E+02	1.51E+03
40	0.791	4.17E+02	1.89E+03
45	0.759	3.03E+02	2.25E+03
50	0.729	2.23E+02	2.58E+03
60	0.675	1.26E+02	3.18E+03
70	0.630	7.44E+01	3.68E+03
75	0.610	5.82E+01	3.90E+03
80	0.592	4.61E+01	4.09E+03
85	0.576	3.68E+01	4.27E+03
90	0.560	2.97E+01	4.43E+03
95	0.546	2.41E+01	4.57E+03
100	0.533	1.98E+01	4.71E+03
120	0.490	9.61E+00	5.13E+03
140	0.456	5.13E+00	5.44E+03
160	0.431	2.95E+00	5.66E+03
180	0.410	1.80E+00	5.84E+03
200	0.393	1.15E+00	5.97E+03
220	0.379	7.68E-01	6.08E+03

TABLE 2

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: LIF-029 (5'-8') at 6.1 ft.

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
240	0.367	5.29E-01	6.17E+03
260	0.357	3.75E-01	6.24E+03
280	0.348	2.73E-01	6.31E+03
300	0.340	2.03E-01	6.36E+03
320	0.334	1.53E-01	6.41E+03
340	0.328	1.18E-01	6.45E+03
360	0.322	9.20E-02	6.48E+03
380	0.317	7.27E-02	6.51E+03
400	0.313	5.82E-02	6.54E+03
420	0.309	4.70E-02	6.57E+03
440	0.305	3.84E-02	6.59E+03
460	0.302	3.17E-02	6.61E+03
480	0.299	2.63E-02	6.63E+03
500	0.296	2.20E-02	6.64E+03
550	0.290	1.45E-02	6.68E+03
600	0.285	9.93E-03	6.71E+03
650	0.281	7.00E-03	6.74E+03
700	0.277	5.06E-03	6.76E+03
750	0.273	3.74E-03	6.77E+03
800	0.271	2.82E-03	6.79E+03
850	0.268	2.16E-03	6.80E+03
900	0.266	1.68E-03	6.82E+03
950	0.264	1.33E-03	6.83E+03
1000	0.262	1.06E-03	6.84E+03
1050	0.260	8.57E-04	6.85E+03
1100	0.259	6.99E-04	6.85E+03
1150	0.257	5.75E-04	6.86E+03
1200	0.256	4.77E-04	6.87E+03
1250	0.255	3.99E-04	6.87E+03
1300	0.254	3.36E-04	6.88E+03
1350	0.253	2.85E-04	6.88E+03
1400	0.252	2.43E-04	6.89E+03
1450	0.251	2.08E-04	6.89E+03
1500	0.250	1.79E-04	6.90E+03
1550	0.249	1.55E-04	6.90E+03
1600	0.249	1.35E-04	6.90E+03
1650	0.248	1.18E-04	6.91E+03
1700	0.247	1.04E-04	6.91E+03

TABLE 2

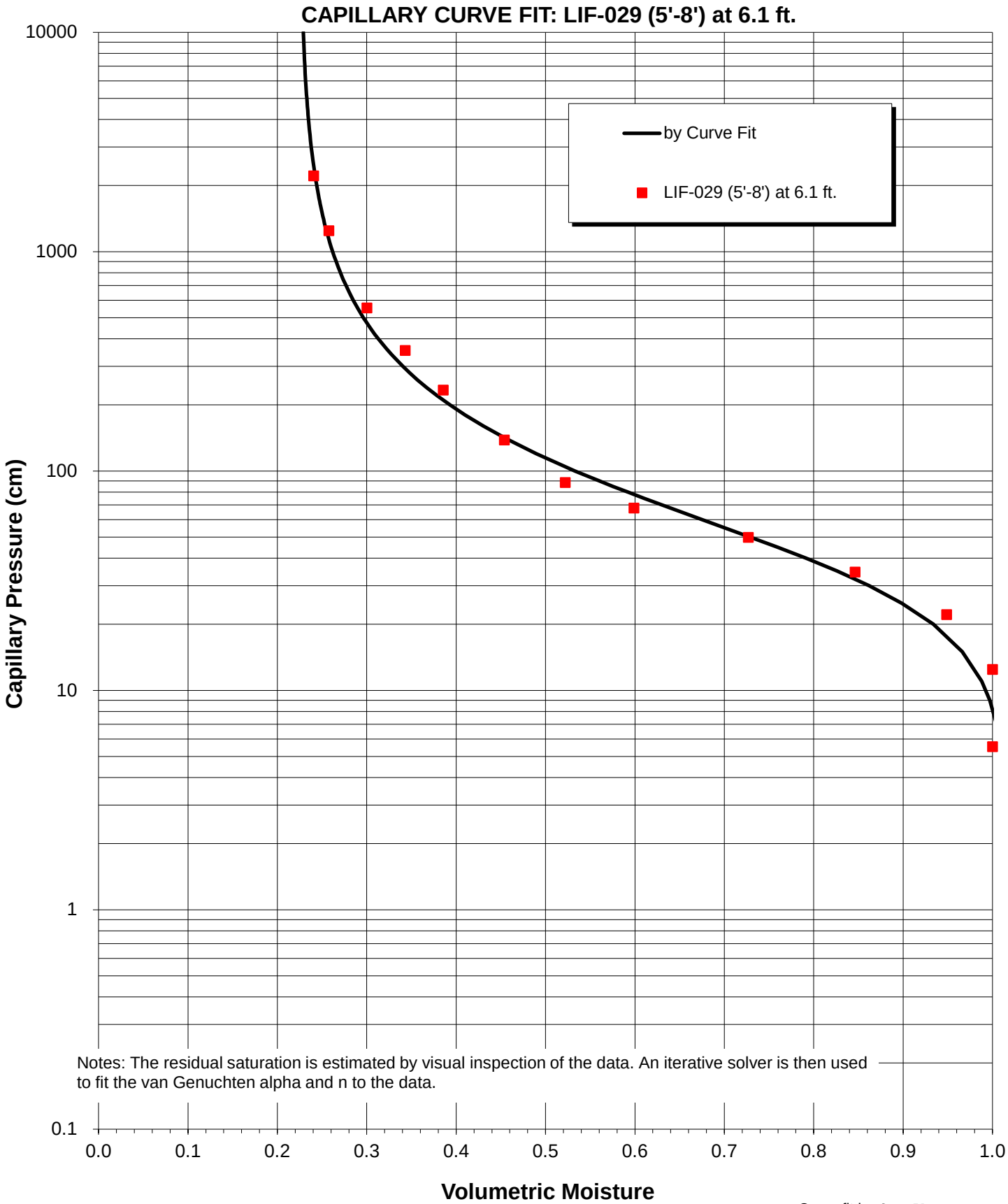
FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: LIF-029 (5'-8') at 6.1 ft.

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
1750	0.247	9.13E-05	6.91E+03
1800	0.246	8.07E-05	6.92E+03
1850	0.245	7.15E-05	6.92E+03
1900	0.245	6.37E-05	6.92E+03
1950	0.244	5.68E-05	6.92E+03
2000	0.244	5.08E-05	6.93E+03
2200	0.242	3.35E-05	6.93E+03
2400	0.241	2.28E-05	6.94E+03
2600	0.240	1.61E-05	6.95E+03
2800	0.239	1.16E-05	6.95E+03
3000	0.238	8.58E-06	6.96E+03
3200	0.237	6.47E-06	6.96E+03
3400	0.236	4.96E-06	6.96E+03
3600	0.236	3.86E-06	6.97E+03
3800	0.235	3.04E-06	6.97E+03
4000	0.235	2.43E-06	6.97E+03
4200	0.234	1.96E-06	6.97E+03
4400	0.234	1.60E-06	6.97E+03
4600	0.234	1.32E-06	6.98E+03
4800	0.233	1.09E-06	6.98E+03
5000	0.233	9.13E-07	6.98E+03
5200	0.233	7.69E-07	6.98E+03
5400	0.232	6.51E-07	6.98E+03
5600	0.232	5.55E-07	6.98E+03
5800	0.232	4.76E-07	6.98E+03
6000	0.232	4.10E-07	6.98E+03
6500	0.231	2.89E-07	6.99E+03
7000	0.231	2.09E-07	6.99E+03
7500	0.230	1.54E-07	6.99E+03
8000	0.230	1.16E-07	6.99E+03
8500	0.230	8.90E-08	6.99E+03
9000	0.230	6.93E-08	6.99E+03
9500	0.229	5.46E-08	7.00E+03
10000	0.229	4.36E-08	7.00E+03

PTS File No: 40772
Client: Conestoga-Rovers & Associates



CAPILLARY CURVE FIT: LIF-029 (5'-8') at 6.1 ft.

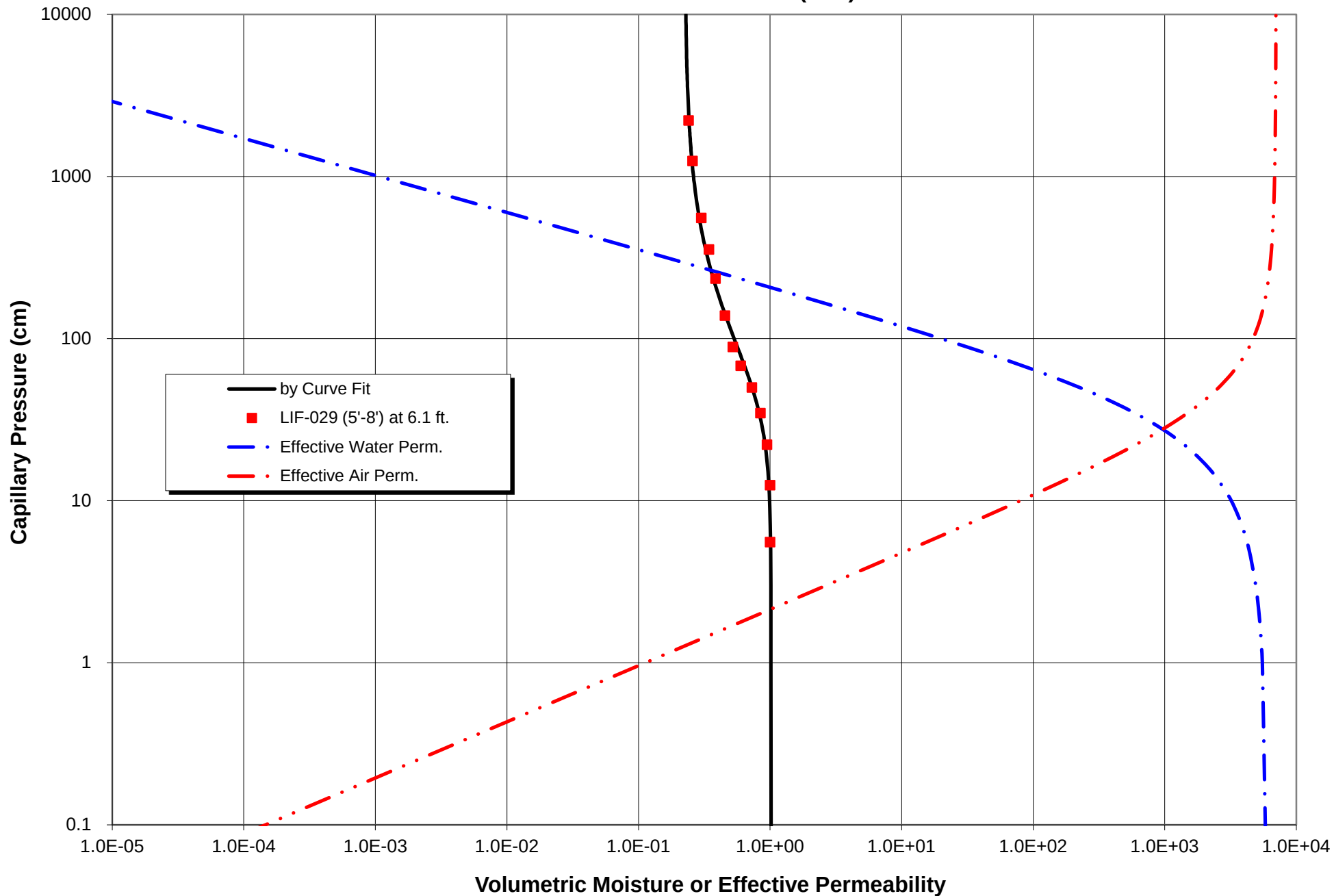


TABLE 1

**SOIL MOISTURE RETENTION CURVE FITTING FOR QUANTIFYING
 THE HYDRAULIC FUNCTIONS OF UNSATURATED SOILS**

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: LIF-037 (5'-10') at 6.9 ft.

van Genuchten Parameters

alpha (1/cm)	2.780E-02
n	2.131
residual water	0.151
total water	1.017
m	0.531
Water Perm (mD)	7450
Air Perm (mD)	8200
R ²	0.99551

Notes: alpha, n, and residual saturation are capillary parameters defined by the following equation (van Genuchten, 1980), with $m = 1-1/n$, S = water saturation, and h = capillary head (cm):

$$S_r + [(S_s - S_r) / (1 + (\alpha h)^n)^m]$$

Laboratory Measured Data

Capillary Head (cm)	LIF-037 (5'-10') at 6.9 ft. Volumetric Moisture	Predicted Moisture by Curve Fit	RPD (%)
0.00	1.000	1.017	0.82%
5.53	1.000	1.008	0.40%
12.45	0.991	0.972	0.98%
22.13	0.931	0.888	2.39%
34.57	0.742	0.763	1.43%
49.78	0.604	0.634	2.43%
67.76	0.492	0.525	3.24%
88.50	0.398	0.442	5.26%
138.28	0.329	0.334	0.84%
233.70	0.260	0.254	1.10%
354.01	0.225	0.216	2.16%
553.14	0.191	0.190	0.20%
1244.56	0.165	0.167	0.45%
2212.55	0.157	0.159	0.82%

TABLE 2

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: LIF-037 (5'-10') at 6.9 ft.

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
0.001	1.017	7.46E+03	4.12E-12
0.02	1.017	7.46E+03	8.80E-08
0.04	1.016	7.45E+03	8.83E-07
0.05	1.016	7.45E+03	1.86E-06
0.08	1.016	7.45E+03	8.87E-06
0.09	1.016	7.44E+03	1.31E-05
1	1.016	7.20E+03	3.96E-02
1.2	1.016	7.14E+03	7.26E-02
1.3	1.016	7.11E+03	9.47E-02
1.5	1.016	7.05E+03	1.52E-01
2	1.016	6.90E+03	3.96E-01
3	1.014	6.58E+03	1.52E+00
5	1.010	5.93E+03	8.21E+00
7	1.003	5.29E+03	2.46E+01
9	0.993	4.67E+03	5.51E+01
11	0.982	4.10E+03	1.03E+02
15	0.953	3.09E+03	2.63E+02
20	0.908	2.11E+03	5.87E+02
25	0.859	1.42E+03	1.03E+03
30	0.808	9.46E+02	1.53E+03
35	0.759	6.35E+02	2.07E+03
40	0.713	4.30E+02	2.60E+03
45	0.671	2.95E+02	3.10E+03
50	0.633	2.06E+02	3.55E+03
60	0.567	1.05E+02	4.33E+03
70	0.514	5.71E+01	4.95E+03
75	0.492	4.30E+01	5.21E+03
80	0.472	3.28E+01	5.43E+03
85	0.453	2.53E+01	5.64E+03
90	0.437	1.98E+01	5.82E+03
95	0.422	1.56E+01	5.98E+03
100	0.408	1.24E+01	6.12E+03
120	0.364	5.48E+00	6.57E+03
140	0.332	2.70E+00	6.87E+03
160	0.308	1.45E+00	7.09E+03
180	0.289	8.35E-01	7.25E+03
200	0.274	5.08E-01	7.38E+03
220	0.261	3.23E-01	7.47E+03

TABLE 2

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: LIF-037 (5'-10') at 6.9 ft.

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
240	0.251	2.14E-01	7.55E+03
260	0.243	1.46E-01	7.62E+03
280	0.235	1.02E-01	7.67E+03
300	0.229	7.37E-02	7.71E+03
320	0.224	5.41E-02	7.75E+03
340	0.219	4.04E-02	7.78E+03
360	0.215	3.07E-02	7.81E+03
380	0.211	2.37E-02	7.84E+03
400	0.208	1.85E-02	7.86E+03
420	0.205	1.47E-02	7.88E+03
440	0.202	1.17E-02	7.90E+03
460	0.199	9.46E-03	7.91E+03
480	0.197	7.71E-03	7.93E+03
500	0.195	6.34E-03	7.94E+03
550	0.191	4.00E-03	7.97E+03
600	0.187	2.63E-03	7.99E+03
650	0.184	1.79E-03	8.01E+03
700	0.181	1.25E-03	8.02E+03
750	0.179	8.98E-04	8.04E+03
800	0.177	6.58E-04	8.05E+03
850	0.175	4.91E-04	8.06E+03
900	0.174	3.73E-04	8.06E+03
950	0.172	2.87E-04	8.07E+03
1000	0.171	2.24E-04	8.08E+03
1050	0.170	1.77E-04	8.08E+03
1100	0.169	1.42E-04	8.09E+03
1150	0.168	1.14E-04	8.09E+03
1200	0.167	9.31E-05	8.10E+03
1250	0.167	7.64E-05	8.10E+03
1300	0.166	6.32E-05	8.11E+03
1350	0.165	5.27E-05	8.11E+03
1400	0.165	4.42E-05	8.11E+03
1450	0.164	3.73E-05	8.12E+03
1500	0.164	3.17E-05	8.12E+03
1550	0.163	2.71E-05	8.12E+03
1600	0.163	2.32E-05	8.12E+03
1650	0.162	2.00E-05	8.12E+03
1700	0.162	1.73E-05	8.13E+03

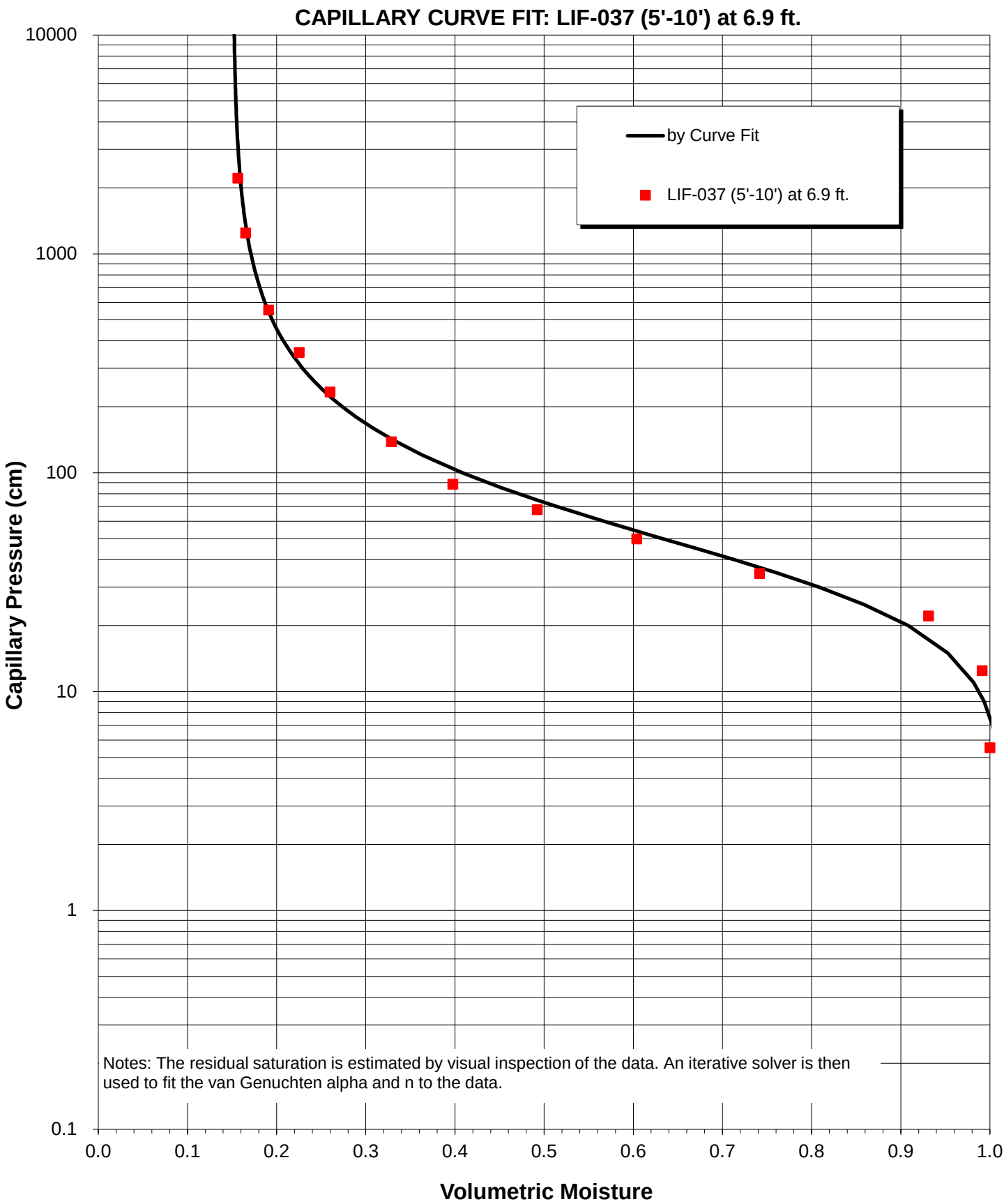
TABLE 2

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

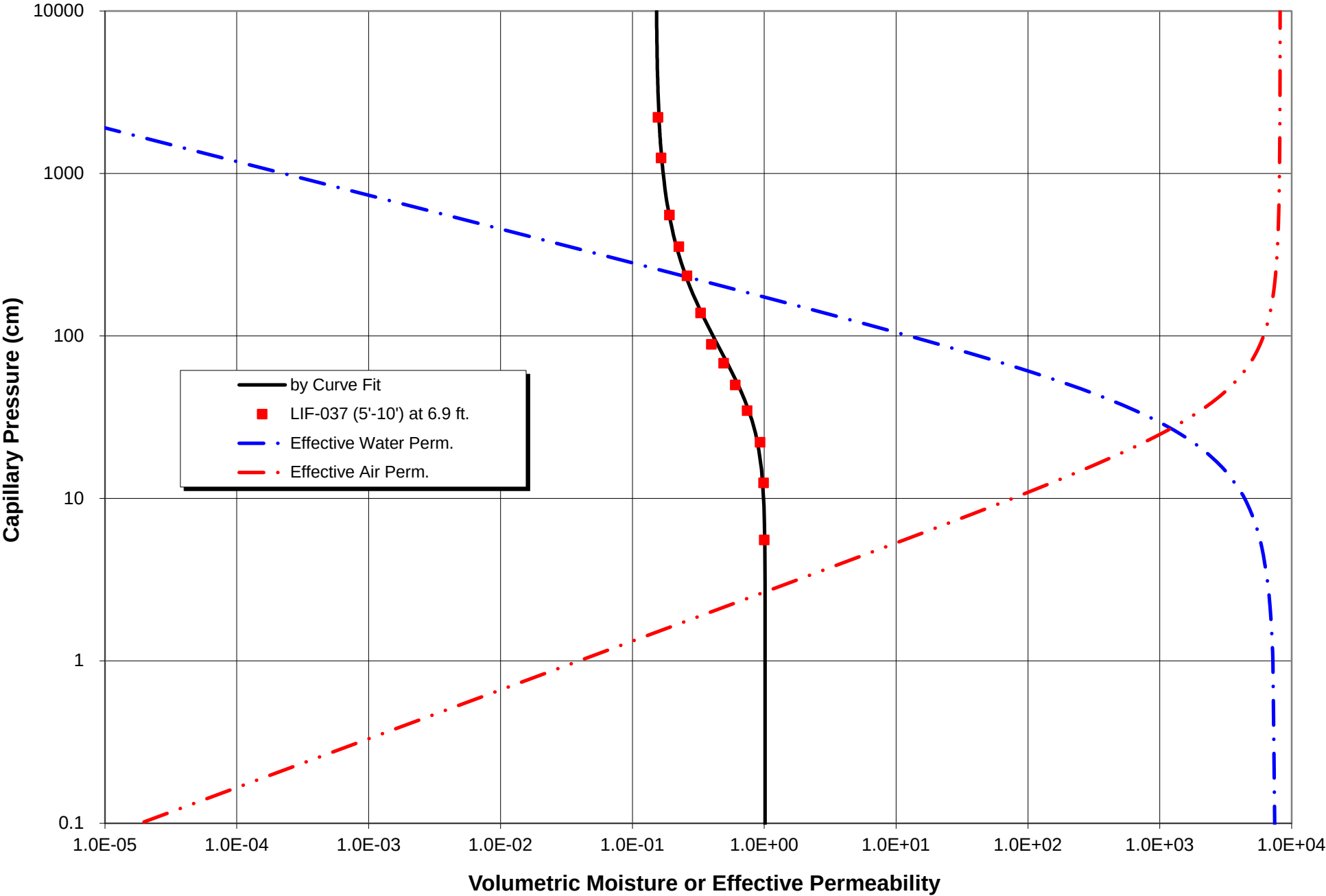
PROJECT NAME: MLC-Willow Run
 PROJECT NO: 17358-T01
 SAMPLE ID: LIF-037 (5'-10') at 6.9 ft.

FUNCTIONAL RELATIONSHIPS BASED ON DERIVED CAPILLARY PARAMETERS

Capillary Head (cm)	(van Genuchten, 1980) Volumetric Moisture	(Mualem, 1976) Effective Water Perm.	(Mualem, 1976) Effective Air Perm.
1750	0.162	1.51E-05	8.13E+03
1800	0.161	1.31E-05	8.13E+03
1850	0.161	1.15E-05	8.13E+03
1900	0.161	1.01E-05	8.13E+03
1950	0.160	8.94E-06	8.13E+03
2000	0.160	7.91E-06	8.14E+03
2200	0.159	4.99E-06	8.14E+03
2400	0.158	3.28E-06	8.14E+03
2600	0.158	2.23E-06	8.15E+03
2800	0.157	1.56E-06	8.15E+03
3000	0.157	1.12E-06	8.15E+03
3200	0.156	8.18E-07	8.15E+03
3400	0.156	6.10E-07	8.16E+03
3600	0.156	4.63E-07	8.16E+03
3800	0.155	3.57E-07	8.16E+03
4000	0.155	2.79E-07	8.16E+03
4200	0.155	2.20E-07	8.16E+03
4400	0.155	1.76E-07	8.16E+03
4600	0.155	1.42E-07	8.16E+03
4800	0.154	1.16E-07	8.16E+03
5000	0.154	9.49E-08	8.17E+03
5200	0.154	7.85E-08	8.17E+03
5400	0.154	6.54E-08	8.17E+03
5600	0.154	5.49E-08	8.17E+03
5800	0.154	4.63E-08	8.17E+03
6000	0.154	3.93E-08	8.17E+03
6500	0.153	2.67E-08	8.17E+03
7000	0.153	1.87E-08	8.17E+03
7500	0.153	1.34E-08	8.17E+03
8000	0.153	9.81E-09	8.17E+03
8500	0.153	7.32E-09	8.17E+03
9000	0.153	5.56E-09	8.17E+03
9500	0.153	4.28E-09	8.17E+03
10000	0.152	3.34E-09	8.17E+03



CAPILLARY CURVE FIT: LIF-037 (5'-10') at 6.9 ft.



Appendix B

Common LNAPL-Related Terms and Definitions

Table of Contents**Page**

Section 1.0	Definitions Relating to LNAPL Mobility	1

Section 1.0 Definitions Relating to LNAPL Mobility

Capillary Pressure: the difference between the fluid pressure in the non-wetting phase (typically LNAPL) and the pressure in the wetting phase (typically water) at a given reference point. This pressure may also be referred to as the “excess pressure”. The larger the capillary pressure, the greater the LNAPL saturation and the greater the potential for LNAPL mobility. For LNAPL movement or migration to occur, capillary pressure must exceed the resistive forces in the soil formation.

Confined Condition: a subsurface condition where pore fluids are under pressure at all reference points or elevations. In a confined condition, in-well LNAPL thickness varies directly with potentiometric surface elevation. Hence, an increase in the potentiometric surface elevation leads to an increase in in-well LNAPL thickness, and vice versa. LNAPL within the secondary porosity (fractures, fissures, seams) of fine textured soils (silts and clays) is often present in a confined condition. Confined conditions will often produce in-well LNAPL thicknesses that grossly over-represent the extent of impacts in the formation.

Effective Solubility: different than pure-phase solubility, effective solubility describes the ability of a chemical constituent from a mixture to dissolve in water in the presence of other constituents in the mixture. It is a particularly important consideration for LNAPLs that are complex petroleum mixtures. Effective solubility is a function of the mole fraction of the constituent in the mixture, and is commonly orders of magnitude less than the constituent’s corresponding pure-phase solubility. Groundwater concentrations in excess of a petroleum constituent’s effective solubility will typically indicate the presence of LNAPL in the vicinity of a monitoring well.

Interfacial Tensions: the tension or attractive forces between two fluids along the interface of contact with one another. The interfacial tension between LNAPL and water in the subsurface tends to limit the ability of LNAPL to move.

Laser-Induced Fluorescence (LIF): a real-time LNAPL delineation technology that uses ultraviolet wavelengths of light to cause polycyclic aromatic hydrocarbons (PAHs) to fluoresce. All petroleum-based LNAPLs contain PAHs, allowing the use of LIF to detect the presence of LNAPL. LIF is employed in the field using direct-push techniques to delineate LNAPL impacts in the subsurface laterally and vertically (both above and below the water table). LIF also provides an indication of the intensity of impacts across an LNAPL body and the types of LNAPL encountered.

LNAPL: light non-aqueous phase liquid. LNAPLs are immiscible fluids that are less dense than water, and may be comprised of a pure chemical or solvent, or comprised of a complex mixture of chemicals, such as petroleum-based fuels. The term “LNAPL” most often refers to immiscible petroleum mixtures/fuels (i.e., gasoline, kerosene, diesel, crude oil, etc.).

LNAPL Body: the multi-phase fluid zone of LNAPL impacts in the subsurface. An LNAPL body is comprised of three fluids: air, LNAPL and water. Generally speaking, an LNAPL body is predominantly comprised of water, with a lesser amount of LNAPL, and the least amount of air.

LNAPL Conductivity: a hydrogeological term that helps describe the ability of LNAPL to move through the subsurface. LNAPL conductivity accounts for the LNAPL relative permeability, hydraulic conductivity, and the densities and viscosities of the fluids (water and LNAPL). LNAPL conductivity is a function of and varies directly with LNAPL relative permeability. Hence, an increase in LNAPL relative permeability results in an increase in LNAPL conductivity, and vice versa.

LNAPL Migration: a description of the expansion of the perimeter of an unstable LNAPL body in some or all directions (i.e., footprint of the overall LNAPL body or body periphery is continuing to grow). All migrating LNAPL is mobile; not all mobile LNAPL is migrating. Mobile LNAPL can be present within the interior of an LNAPL body that is not migrating.

LNAPL Mobility: a description of the potential for LNAPL to move at any point within an LNAPL body. LNAPL may be mobile where the LNAPL is continuous at saturations above residual saturation. Because LNAPL residual saturation within a LNAPL body varies from the vadose zone to the saturated zone, LNAPL mobility may also vary due to fluctuations in the water table elevation. The presence of mobile LNAPL within an LNAPL body does not necessarily mean that the LNAPL body as a whole is unstable or migrating.

LNAPL Pressure Head: the LNAPL pressure conditions at any point within an LNAPL body created by the release conditions. The pressure head can result from the vertical column of LNAPL due to accumulation at or in the vicinity of the water table from a surface or near-surface source (e.g., tank), or from other pressure conditions at the time of the release (e.g., pressure conditions of a subsurface pipeline release). The greater the pressure head, the more the LNAPL will penetrate into the water table (both vertically and laterally) and spread. Once the pressure head dissipates (i.e., source of release is terminated), the LNAPL will soon after cease to migrate and achieve a stable perimeter.

LNAPL Relative Permeability: a measure of the porous medium's (soil's) ability to enable movement of LNAPL in the subsurface in the presence of water. LNAPL relative permeability is a function of and varies directly with LNAPL saturation. Hence, an increase in LNAPL saturation results in an increase in LNAPL relative permeability, and vice versa.

LNAPL Residual Saturation: the LNAPL saturation level or threshold below which LNAPL will not flow under normal hydraulic conditions. LNAPL present at saturations that are less than or equal to residual saturation levels (i.e., within the residual range) will generally be considered to be immobile and unrecoverable. Conceptually speaking, LNAPL residual saturation represents the LNAPL saturation threshold where the LNAPL, due to its relatively low saturation, starts to break-up or become

discontinuous in the form of droplets, stringers, ganglia, etc. As LNAPL saturation approaches or decreases to residual, the relative permeability of the LNAPL approaches zero, and the conductivity of the LNAPL approaches zero. The more LNAPL that initially saturates the soil pore space during a release, the higher the residual saturation will be (up to a theoretical maximum). Consequently, LNAPL residual saturation also varies continuously within an LNAPL body.

LNAPL Saturation: the percent of the soil pore space that is occupied by LNAPL. LNAPL saturation at a given point in the subsurface will be proportional to the capillary pressure at that point (i.e., the greater the capillary pressure, the greater the resulting LNAPL saturation). Because the capillary pressure varies throughout the impacted zone, the LNAPL saturation also varies accordingly. The larger the soil pore space, the greater the ability for the soil to hold LNAPL, the greater the LNAPL saturation, and vice versa.

LNAPL Stability: a description of the potential for the perimeter or footprint of an LNAPL body to move or expand over time. A LNAPL body that is moving or expanding (i.e., footprint of LNAPL body is growing) is deemed to be unstable or migrating. Conversely, a LNAPL body that is not moving or expanding with time is deemed to be stable, immobile, or non-migrating. Stable LNAPL bodies can contain localized areas of mobile LNAPL, with the overall footprint remaining unchanged over time.

LNAPL Velocity: the speed and direction at which the LNAPL can travel, based on Darcy flow principles. LNAPL velocity is based on the properties of the porous medium and fluids (water and LNAPL), pore fluid saturations, and the LNAPL gradient. LNAPL velocity only applies within the LNAPL body where there is continuous LNAPL at saturations above residual. There is no LNAPL velocity or movement within an LNAPL body where the LNAPL is not continuous and saturations are below residual. In addition, there is no LNAPL velocity or movement outside of a stable LNAPL body.

Non-Wetting Fluid: the fluid that does not preferentially coat the soil grains or particles in a multi-phase fluid system, but rather occupies the middle of the larger soil pores. In an air-water-LNAPL system (typical of an LNAPL body), both air (primarily in the unsaturated portion of the smear zone) and LNAPL (primarily in the saturated portion of the smear zone) tend to be the non-wetting fluids.

Pore Entry Displacement Pressure: the threshold pressure necessary for one fluid to enter into a porous medium occupied by another fluid, thereby displacing the fluid originally present. Pore entry displacement pressures may account for air displacing groundwater, LNAPL displacing groundwater, air displacing LNAPL, etc. In a water-saturated soil, the capillary pressure must equal or exceed the pore entry displacement pressure for the LNAPL to move and displace water.

Soil Resistive Forces: the forces that act to prevent the movement of LNAPL in a water-saturated porous medium. These forces, which are based on pore entry displacement pressure principles, account for the contact angle or wettability of the fluids (LNAPL and water), the interfacial tension between the fluids,

and the soil pore size. LNAPL movement will only occur if the capillary pressure is sufficient to overcome the soil resistive forces.

Unconfined Condition: a subsurface condition with identical or similar pressure-related fluid characteristics to an unconfined aquifer or water table condition. LNAPL within the primary porosity of granular soils (sands and gravels) in a water table/phreatic surface setting is deemed to be in an unconfined condition. In an unconfined condition, in-well LNAPL thickness varies inversely with water table elevation. Hence, an increase in the water table elevation leads to a decrease in in-well LNAPL thickness, and vice versa.

van Genuchten Parameters: curve fitting parameters that describe how water drains from a given soil in response to increasing pressure conditions. These parameters serve as critical inputs for LNAPL modeling simulations.

Wetting Fluid: the fluid that preferentially coats the soil grains or particles in a multi-phase fluid system. In an air-water-LNAPL system (typical of an LNAPL body), water typically acts as the wetting fluid while air and LNAPL act as non-wetting fluids. The wetting fluid is typically the predominant fluid present in a multi-phase fluid system.

Appendix C

General LNAPL Discussion

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Section 1.0 LNAPL Mobility and Migration

This section presents some of the basic LNAPL concepts and trends that describe the occurrence, behavior and migration of LNAPL in the subsurface. Specifically, this section addresses LNAPL behavior at the water table and includes the vertical impacted soil zone typically referred to as the smear zone. The smear zone is where potentially mobile LNAPL may reside at sites where the source(s) of the LNAPL impacts have ceased for some time (i.e., no ongoing releases). The behavior of LNAPL in the vadose or unsaturated zone (above the smear zone) is not addressed here, since LNAPL in these zones (particularly at older release sites) is often present at low saturations, and does not typically pose a potential for additional LNAPL migration at the water table.

1.1 LNAPL Release Dynamics and the Creation of a Multi-Phase Fluid System

When an LNAPL release occurs, either directly in the subsurface (for example, from a tank or pipeline) or on a permeable surface, the LNAPL, if present in sufficient quantity, will percolate vertically downward (under the influence of gravity) through the soil and eventually encounter the water table. During the downward movement, the presence of confining layers and/or other subsurface heterogeneities may result in some lateral spreading and/or perching of LNAPL before the water table is encountered. Once at the water table, the LNAPL will penetrate vertically downward and laterally (including in the upgradient direction) into the water table, displacing an amount of water proportional to the driving force of the vertical LNAPL column (or LNAPL head) created by the release. The displacement of groundwater will continue to occur only as long as sufficient downward force produced by the head or pressure from the LNAPL release remains. Once the downward force diminishes, the upward force produced by the resistance of the soil matrix and the buoyancy force resulting from the density difference between LNAPL and groundwater will prevent further downward migration. Once the release of LNAPL is terminated, the LNAPL footprint at the water table will continue to expand for a relatively short time, and eventually stop as the LNAPL head (pressure) dissipates. The LNAPL eventually ceases to expand because the driving force (pressure or head) responsible for the LNAPL migration is no longer sufficient to overcome the resistive forces necessary to displace groundwater from the soil pores (see explanation below). When the LNAPL body reaches this state, the LNAPL body is referred to as stable or non-migrating.

The concept of LNAPL penetrating vertically into the saturated zone (i.e., below the water table) during a release contradicts earlier beliefs that LNAPL only “floats” (due to it being less dense than water) like a pancake on top of the water table, filling 100% of the soil pore space within the LNAPL impacted zone (with no part penetrating the saturated zone). Recent LNAPL science and “real-world” field-based experience shows that some LNAPL (and often times the majority of LNAPL at a given site) is commonly submerged beneath the theoretical water table surface. Further, LNAPL does not displace all groundwater from the soil pore space, but rather that portion of the groundwater that occupies the “largest” soil pore space only. Consequently, a typical LNAPL body consists of LNAPL filling much less of

the soil pore space in a more highly variable distribution than what was assumed historically based on the “pancake” conceptualization. The LNAPL body at the water table is not comprised of a single fluid phase (LNAPL) but rather comprised of multiple fluids, both LNAPL and water. The top portion of the LNAPL body often includes a third fluid phase: air. Therefore, the term “LNAPL body” represents the spatial limits of LNAPL impacts, within which exists a multi-phase fluid system comprised of LNAPL, water and/or air, in proportions that will vary throughout. Generally speaking, LNAPL bodies are predominantly comprised of water, followed by a lesser amount of LNAPL, with the smallest fraction of the pore space occupied by air.

LNAPL at the water table requires pressure to move. Unlike groundwater, which typically forms a continuous system with flow velocity based on gradients, LNAPL, being a non-wetting fluid, requires pressure to force it through the soil pores to the extent required to displace the existing pore water. More specifically, the LNAPL needs sufficient capillary pressure to overcome the resistive forces in the soil to enable the continued displacement of groundwater. In a multi-phase (LNAPL/water) fluid system, capillary pressure (also referred to as excess pressure) is the difference between the pressure in the non-wetting (LNAPL) phase and the pressure in the wetting (groundwater) phase. The capillary pressure necessary to overcome the resistive forces for a non-wetting LNAPL to enter water-saturated media is called the pore entry displacement pressure (Mercer and Cohen, 1990). Once the pore entry displacement pressure is achieved, the LNAPL will continue to expand in a vertical and radial direction until there is insufficient LNAPL head or pressure to continue to displace water. The LNAPL head will typically become insufficient to displace water (and enter unimpacted pore space) shortly after the LNAPL release is terminated. Hence, soon after the LNAPL release is terminated, the LNAPL body becomes stable (i.e., overall footprint is no longer moving or expanding). Because the main mechanism for LNAPL spreading is the pressure/head resulting from the release (during the release and until the LNAPL body stabilizes), the groundwater gradient will only influence the direction of the LNAPL spreading for a defined but limited distance. Groundwater flow will not typically cause or induce any LNAPL spreading or migration once stabilization of the LNAPL body has been achieved.

The porous media flow concepts that apply to groundwater systems (Darcy flow equations, etc.) also apply to LNAPL bodies, with two distinct differences. First, LNAPL conductivity (as opposed to water or hydraulic conductivity) includes a relative permeability term, which accounts for LNAPL flowing in the presence of water, and includes density and viscosity terms for both fluids. Second, Darcy flow in an LNAPL body does not apply where the LNAPL is discontinuous/immobile. For example, Darcy flow would not apply within an LNAPL body in areas where saturations are below residual. In addition, there is no LNAPL velocity or movement outside of a stable LNAPL body.

1.2 LNAPL Saturation and Residual Saturation

LNAPL saturation is defined as the percent of the soil pore space that is occupied by LNAPL. LNAPL residual saturation is defined as the LNAPL saturation level or threshold below which LNAPL will not flow

under normal hydraulic conditions found in the environment. Consequently, LNAPL that is present at saturations that are less than or equal to residual saturation is deemed to be immobile and unrecoverable. These concepts are discussed in more detail in the following subsections.

1.2.1 LNAPL Saturation

As previously discussed, LNAPL does not float on the water table like a pancake, but rather coexists with air and groundwater at varying saturations within the impacted soil zone, both above and below the water table. This is due to the fact that the saturation level of a given LNAPL at a given point in the subsurface will be proportional to the capillary pressure at that point (i.e., the greater the capillary pressure, the greater the resulting LNAPL saturation). Because the capillary pressure will vary throughout the impacted zone, the LNAPL saturation will also vary accordingly. The LNAPL saturation distribution for a given soil is predominantly determined by the grain size of the soil (USEPA, 2005a). The larger the soil pores for a given soil, the greater the capacity for the soil to hold LNAPL. Consequently, granular soils such as sands and gravels will typically have much greater LNAPL saturations than fine textured soils like silts and clays.

LNAPL saturations can be determined by several methods:

1. Total petroleum hydrocarbon (TPH) soil concentrations gathered in the field and analyzed in the laboratory can be converted to LNAPL saturations by the following calculation (ASTM International, 2007):

$$S_o = \frac{[TPH]}{10^6} \cdot \frac{\rho_{fb}}{\rho_o} \cdot \Theta^{-1}$$

Where: S_o = LNAPL saturation (fraction of pore space filled with LNAPL)
 $[TPH]$ = total petroleum hydrocarbon soil concentration (mg/kg)
 ρ_{fb} = soil bulk density
 ρ_o = LNAPL/oil density
 Θ^{-1} = total soil porosity

For example, if a soil TPH concentration of 100 mg/kg were reported by the laboratory, and assuming that the soil had a porosity of 35% and bulk density of 1.6 g/cm³, and that the suspect LNAPL had a density of 0.8 g/cm³, the equation above would convert the 100 mg/kg TPH concentration into an LNAPL saturation value of 0.0006 or 0.06 percent.

2. LNAPL-saturated soil core samples can be collected and tested at certain specialized laboratories to directly determine LNAPL saturations (e.g., Dean-Stark extraction method); and/or

3. Various tools are available from the American Petroleum Institute (API) that can be used to estimate LNAPL saturations based on in-well LNAPL thickness observations (and soil and LNAPL physical properties). These are the Charbeneau spreadsheets, the LNAPL Dissolution and Transport Screening Tool (LNAST), and, most recently, the LNAPL Distribution and Recovery Model (LDRM).

Method 3 is widely used, but generally less reliable than Methods 1 and 2 as it is primarily dependant upon in-well LNAPL thickness observations and is often used with other inputs that are not site-specific (i.e., literature values for certain soil and LNAPL properties). The lower degree of reliability is due to the fact that conditions at most environmental sites (i.e., water table fluctuations, subsurface heterogeneties, etc.) make any accurate correlation between in-well LNAPL thicknesses and the actual impacted interval in the adjacent soil formation imprecise.

LNAPL saturations are dynamic, and will tend to change over time as LNAPL initially displaces water (during vertical and lateral migration following a release), and is subsequently displaced as water refills some fraction of the pore space when the water table elevation increases (API, 2004). The average LNAPL saturation at a given location can be expected to continually decrease until such time as the LNAPL becomes sufficiently discontinuous, such that all saturations are at or below residual saturation levels.

1.2.2 LNAPL Residual Saturation

Conceptually speaking, LNAPL residual saturation represents the LNAPL saturation threshold where the LNAPL, due to its relatively low saturation, starts to break-up or become discontinuous in the form of droplets, stringers, ganglia, etc. Technically speaking, LNAPL residual saturation represents the portion of an LNAPL body that is hydraulically discontinuous and immobile under prevailing conditions (ASTM International, 2007). As LNAPL saturation approaches or decreases to residual, the relative permeability of the LNAPL approaches zero, and the conductivity of the LNAPL approaches zero. Hence, LNAPL, when present at saturations at or below residual, is considered to be immobile.

Relatively recent research suggests that LNAPL residual saturation is a function of initial LNAPL saturation (Johnston, C.D. and Adamski, M., 2005). The greater the initial saturation at any point in an LNAPL body, the greater the residual saturation at that point. This concept contradicts earlier notions that there is only one single LNAPL residual saturation value for a given LNAPL and soil type. This concept is important when determining the type of laboratory analyses to be used for determining LNAPL residual saturation (see discussion below).

LNAPL residual saturation, which is used to assess LNAPL mobility, may be characterized as a “range” of saturations less than the highest residual saturation threshold value. At any given location within the LNAPL body, if the LNAPL saturation is equal to or less than the residual saturation threshold (i.e., the upper limit of residual saturation) for that location, then the saturation is deemed to be in the “residual

range” which may include any saturations above zero up to and including the residual saturation threshold. Under such conditions, the LNAPL would be deemed to be immobile.

Residual LNAPL saturations can be determined by obtaining relatively undisturbed soil and/or rock core samples from a site (maintained in a frozen state for transport to the laboratory to prevent pore fluid drainage) and subjecting them to one of several different laboratory methods:

1. Oil/water drainage/imbibition capillary pressure testing: Involves spiking (via centrifuge) a sub-sample from the soil core with LNAPL up to its maximum saturation, then forcing water through under pressure to drain as much LNAPL as possible. Whatever LNAPL is left in the core constitutes the residual LNAPL saturation.
2. Free product mobility testing via centrifuge at 1,000 times the force of gravity: Performed by taking a sub-sample from a soil core as-received (no pre-spiking with LNAPL) and spinning it in a centrifuge at 1,000 times the force of gravity (approximately equal to 40-50 psi applied to sample) for 1 hour. LNAPL remaining in the sample following the centrifuge represents the residual LNAPL saturation.
3. Water drive testing: Involves forcing multiple (typically 10-15) pore volumes of water through a soil core sub-sample under 25 psi pressure. The pore volume flushing is used to simulate the migration of groundwater through the impacted soil. The LNAPL residual saturation is represented by the LNAPL that remains in the sample following the water drive.

In terms of Method 1, recall that recent research indicates residual LNAPL saturation is a function of initial LNAPL saturation (i.e., the more LNAPL that occupies the pore space initially, the higher the residual saturation). The initial spiking of the sample with LNAPL in Method 1 may therefore produce a residual saturation result that is biased high compared with what would be representative of an unspiked sample. With Method 2, the pressure applied during the test is so exceedingly high that it is not representative of the normal hydraulic conditions at a typical environmental site. Furthermore, the elevated pressure utilized with Method 2 will often lead to the compression or collapse of the soil matrix during the test. When this occurs, one may not be able to conclude whether any LNAPL released from the sample during the test was the result of the applied gradient or the compression of the soil matrix “squeezing” LNAPL out of the sample. In either case, the results of Method 2 are likely to produce a residual saturation result that will be biased low and non-representative of actual site conditions. Method 3 also involves an applied pressure that is likely to be higher than conditions at a typical environmental site, however, because the pressure is much lower than Method 2 and the method does not involve any pre-spiking of LNAPL as in Method 1, it is the method that is the most likely to produce representative results of the currently available techniques.

It is important to note that LNAPL residual saturation for a given LNAPL and soil type at a given location within the LNAPL body, varies greatly between the unsaturated (vadose) and saturated zones. Generally speaking, LNAPL residual saturations in the vadose zone are much lower than corresponding residual

saturations in the saturated zone. This is true because of the difference in densities between an air/LNAPL pair versus a LNAPL/water pair, and the difference in interfacial tensions between an air/LNAPL pair versus a LNAPL/water pair. LNAPL in the vadose zone has a much greater ability to drain under the force of gravity and flow into a monitoring well, as opposed to LNAPL that is submerged beneath the water table. This concept is the mechanism behind the common observation of the appearance of LNAPL (or increasing LNAPL thickness) in wells during low water tables, and the absence (or decreasing LNAPL thickness) in wells during high water tables. Typical LNAPL residual saturations in the vadose and saturated zones for given soil types are as follows (ITRC, 2009c):

Soil Type	Residual Saturation (Vadose)	Residual Saturation (Saturated)
Sand	3%	25%
Sandy Loam	5%	22%
Loam	7%	18%
Silty Loam	7%	16%
Sandy Clay	7%	10%
Silty Clay	4%	6%

Note that the “saturated” residual saturation of LNAPL in a coarse grained material (sand) is much higher than the corresponding “saturated” residual saturation in a silt or clay. As previously discussed, this is due to the fact that a coarse grained soil has a much greater capacity to hold LNAPL (due to larger soil pores) than a fine textured soil. Hence, the LNAPL saturations in a coarse grained soil are typically much higher than the LNAPL saturations in a fine textured soil.

1.3 LNAPL Mobility / Stability Discussion

The mobility of LNAPL generally relates to its ability to move in a localized sense at any point within an LNAPL body. LNAPL mobility can be highly influenced by a fluctuating water table. The mobility of LNAPL is dependent on a variety of LNAPL properties (density, viscosity, interfacial tension) and soil properties (soil type(s) and drainage characteristics) and is often evaluated in terms of LNAPL saturations (at any point within an LNAPL body) and corresponding residual saturations. LNAPL saturations that exceed residual saturations are deemed to possess a potential for mobility. However, the presence of localized areas within an LNAPL body with a potential for LNAPL mobility does not necessarily indicate that the LNAPL body is unstable or migrating (ASTM International 2007, ITRC 2009a).

Seasonal water table fluctuations have a direct impact on the mobility of LNAPL. A rising and falling water table creates a “smear zone” where mobile, continuous LNAPL is spread vertically and becomes discontinuous as water and LNAPL compete for pore space. Assuming a continuous source is not present, this interaction between water and LNAPL can effectively trap LNAPL as discontinuous, immobile droplets within the soil matrix (API, 2004). Consequently, during seasonal high water tables,

some or all of the LNAPL in the smear zone (in an unconfined setting) becomes submerged or trapped beneath the water table. This results in the submerged LNAPL losing much of its ability to flow through the soil matrix and/or into a monitoring well (due to a higher residual saturation in the saturated zone). In addition, LNAPL in a well can “disappear” with an increase in water table elevation. Under a rising water table condition, there will be a delay in the response of the LNAPL in the formation as buoyancy forces try to move the LNAPL upward through the resistance presented by the soil formation (Oostrom et al, 2006). This is due to the resistance to LNAPL movement provided by the soil matrix and the fact that groundwater is less viscous than LNAPL¹, and is able to move more easily through the soil than LNAPL. LNAPL in a well does not encounter the resistance to upward movement that the LNAPL in the formation does and will rise to the top of the water in the well more quickly than the LNAPL in the formation is able to rise through the soil matrix. This creates an LNAPL gradient from the well toward the formation, resulting in LNAPL flow out of the well. Conversely, during seasonal low water tables, more of the LNAPL in the smear zone becomes exposed, gaining the ability to drain from the newly unsaturated soil under gravity and flow in the soil and/or into a monitoring well (due to a lower residual saturation in the unsaturated zone). This explains the reappearance of LNAPL or increases in LNAPL thickness in wells during seasonal low water tables. Hence, the rising and lowering of the water table has a direct influence on the mobility of LNAPL within an LNAPL body, but does not necessarily create a migrating LNAPL body. Furthermore, at sites that do not have ongoing releases, changes in in-well LNAPL thickness that correlate with fluctuations in the water table elevation are more likely to be a result of the vertical redistribution of LNAPL in and out of the well (as described above), as opposed to being representative of any significant lateral mobility or migration (USEPA, 2007; ITRC 2009a).

As suggested above, LNAPL thickness in a monitoring well varies inversely with water table elevation in an unconfined setting or condition. Hence, an increase in water table elevation results in a decrease in in-well LNAPL thickness. Conversely, a decrease in water table elevation results in an increase in in-well LNAPL thickness. In a confined setting (including LNAPL present in the secondary porosity of silts, clays and possible fractured rock), in-well LNAPL thickness tends to vary directly with potentiometric surface elevation. Hence, an increase in potentiometric surface elevation results in an increase in in-well LNAPL thickness, and vice versa. Confined conditions will often produce in-well LNAPL thicknesses that grossly over-represent the extent of impacts in the formation.

LNAPL stability relates to the ability or inability of a LNAPL body to migrate (i.e., whether or not the perimeter or extent of an LNAPL body is expanding/advancing over time). If the perimeter of an LNAPL body is growing or moving over time, the body is typically referred to as migrating or unstable. If the LNAPL body remains essentially the same size and in the same location over time (i.e., same overall footprint over time), the body is referred to as stable or non-migrating. Generally speaking, the majority of all historical LNAPL bodies, where the source of the release has been terminated, will be found to be

¹ The exception is fresh gasoline, which has a viscosity that is lower than that of water. All other common LNAPL types have viscosities that are greater than water (i.e., they do not flow as easily as water).

stable. LNAPL bodies are spatially self-limiting (due to the capillary pressure principles previously discussed) unless continually supplied from an on-going release (API, 2004). Typically, once the release of LNAPL stops, LNAPL in the water table region will eventually cease to move as the resistive forces in the saturated soils balance the driving forces in the LNAPL pool (API, 2002; Huntley and Beckett, 2001). The endpoint of this movement is when the LNAPL reaches field residual saturation, a condition where LNAPL relative permeability, and consequently LNAPL conductivity, is zero (API, 2002; Huntley and Beckett, 2001). Often times, the following factors combine to produce a stable plume that is not spreading or migrating (USEPA, 2005a):

- LNAPL fluid properties
- LNAPL relative permeability
- Conductivity of the porous media
- Hydraulic gradient
- Pore throat displacement entry pressure
- Fluctuating water table

For an entire LNAPL body, LNAPL can sometimes be found to be mobile near the center of the body, where LNAPL saturations are highest (in excess of residual saturation), and immobile at the outer body fringes where saturation decreases to residual. Hence, parts of the LNAPL body may exhibit some inherent mobility, whereas the overall body remains stable.

It is important to note that water table fluctuations in a stable LNAPL body may cause immobile LNAPL to become mobile and flow or drain into an immediately adjacent monitoring well. However, despite the limited LNAPL drainage and vertical redistribution or smearing, the LNAPL body will most likely continue to be stable and non-migrating. Hence, at a site with a stable LNAPL body, the disappearance of LNAPL from a monitoring well for months and/or years, followed by the reappearance of LNAPL does not necessarily mean that the LNAPL is migrating.

1.4 LNAPL Mobility / Body Stability Evaluations – Lines of Evidence

There are various lines of evidence that can be used to evaluate the mobility and stability of an LNAPL body. These lines of evidence are:

- Historical LNAPL-related data (depth to LNAPL/water levels, in-well thicknesses, stable or shrinking dissolved-phase plume associated with LNAPL body, recovery data, etc.)
- Site-specific laboratory data (TPH profiling, LNAPL saturations in soil cores, etc.)
- LNAPL modeling (analytical and/or numerical) simulations
- LNAPL dye tracer testing

- Combinations of the above

The extent to which one particular line of evidence may be needed for the LNAPL Conceptual Site Model (LCSM) is dependent on the other available lines of evidence. For example, at a site where there is little to no historical data or where the data sets are extremely sparse, there will be a stronger need for extensive site-specific laboratory data with follow-up modeling to adequately characterize LNAPL mobility and body stability issues. Conversely, at a site with an abundance of historical data covering the full range of water table fluctuations, there may be less need to engage in a comprehensive laboratory program or modeling effort to complete the LCSM.

These lines of evidence are discussed in the following subsections.

1.4.1 Historical LNAPL-Related Data

Historical LNAPL-related data often play a critical role in assessing whether LNAPL at a given site is mobile and/or stable. The most common lines of historical evidence are described below.

1.4.1.1 Spatial Distribution of LNAPL Based on In-Well LNAPL Thicknesses and/or Other Methods

Typically, the first line of evidence for evaluating LNAPL mobility and body stability is historical data regarding the spatial distribution of the LNAPL body. Historical LNAPL spatial distribution data are typically based on “in-well” or “apparent” LNAPL thicknesses, but may also include more sophisticated LNAPL site characterization data such as laser-induced fluorescence (LIF) results. Historical LNAPL data are the primary line of evidence when the dataset includes measurements obtained at regular intervals over an extended period, where in-well thicknesses can be assessed during both high water table and low water table conditions. Depending on the site conditions, high and low water tables may be assessed seasonally within a 12-month timeframe or may require a period of years for proper evaluation. Tidal areas may exhibit large changes in water table elevation daily. Generally speaking, if the position, orientation and size of the LNAPL body remain similar during low water table conditions over extended periods of time, the LNAPL body is likely to be stable. However, care needs to be exercised in the evaluation of in-well thickness trends as these data will not provide a valid representation of the mobility and/or stability of the LNAPL body at many environmental sites.

Monitoring well observations that may indicate the presence of mobile LNAPL include the following:

- LNAPL appearing in a well that exhibited no previous evidence of the presence of LNAPL (field soil screening, soil/groundwater analytical results, LIF results, etc.)
- The footprint or perimeter of in-well LNAPL observations appears to continue to expand in one or more directions over time (when comparing observations made during low water table conditions)

- Where unconfined conditions are present, increasing in-well LNAPL thicknesses without a corresponding site-wide drop in water table elevation

Conversely, the following well observations are likely to represent immobile LNAPL or a stable LNAPL body:

- LNAPL never appearing in a well, even though other evidence suggests its presence (field soil screening, soil/groundwater analytical results, LIF results, etc.)
- In-well thickness fluctuations corresponding directly with water table fluctuations (i.e., a drop in water table elevation of “x” feet results in an in-well LNAPL thickness increase of approximately “x” feet)
- The footprint or perimeter of in-well LNAPL observations appears to maintain approximately the same areal extent over time (when comparing observations made during low water table conditions)

Observations unrelated to monitoring wells such as seeps provide an indication that some level of LNAPL mobility exists.

1.4.1.2 Dissolved Phase Plume Data

A stable or diminishing dissolved phase plume is an indication that the LNAPL source area is stable. Hence, dissolved phase monitoring data may also be used to assess LNAPL body stability. A comprehensive groundwater monitoring program will involve examining data from multiple wells over a sufficient duration to encompass the range of seasonal/temporal variation in hydraulic conditions. Ideally, a suitable monitoring network will include source zone, up-gradient, down-gradient and cross-gradient wells (i.e., a minimum of 4-5 wells). For the purpose of evaluating trends in analyte concentrations over time in groundwater sampled from monitoring wells, two procedures are commonly used. These are: (i) the Mann-Kendall trend test (for data sets containing up to 50 percent non-detect results); and (ii) the Rank-Sum test (for data sets containing more than 50 percent non-detect results). In general, at least four rounds of data spaced relatively evenly over time will be required to obtain a statistically significant trend analysis (e.g., quarterly monitoring for one year, semi-annual monitoring for two years, etc.). The more data and the longer the monitoring period, the higher the confidence level with the results will be. As many as eight data points (i.e., monitoring events) may be required to obtain “good” results.

1.4.1.3 LNAPL Recovery Data

Performance data from LNAPL recovery efforts can provide valuable information on the potential mobility of the LNAPL. If an appropriate LNAPL recovery technique has been applied and effectively

operated at a given site, a low recovery rate or the development of an asymptotic recovery rate trend over time is a strong indication that the LNAPL is (or has become) immobile (i.e., if it cannot be recovered under some type of applied hydraulic and/or pressure gradient, it isn't likely to be moving in the absence of the applied gradient). Conversely, if sufficient quantities of LNAPL can be readily recovered, then the LNAPL likely has some mobile component.

1.4.2 Site-Specific Laboratory Data

LNAPL-saturated soil cores from impacted areas within an LNAPL body may be collected and submitted for laboratory analysis of key LNAPL mobility parameters including LNAPL saturations and residual saturations. Such evaluations could include some or all of the following:

- Photographs of LNAPL-saturated undisturbed soil cores in both white light and ultraviolet light
- Soil physical property evaluation in the LNAPL saturated zones including grain size analysis and drainage characteristics (van Genuchten parameters)
- Laboratory fluid (water and LNAPL) saturation analyses to determine Site-specific saturations and/or residual saturations across the LNAPL body
- LNAPL fluid property testing for density, viscosity, and interfacial tensions

A comparison of saturation versus residual saturation values across an LNAPL body can be used to assess the mobility of the LNAPL body. In addition, the site-specific laboratory results may be incorporated into models to assess LNAPL mobility (see description below).

1.4.3 LNAPL Modeling Simulations

There are various analytical LNAPL models (e.g., LNAST, LDRM, etc., API 2007) that may be used to evaluate LNAPL mobility. These models are based on a number of assumptions including: the fluids (LNAPL and water) are in vertical equilibrium and the soil conditions are relatively homogeneous. These conditions are required for in-well LNAPL thicknesses to be considered representative of the spatial (vertical) distribution of LNAPL in the formation. Examples of situations where these conditions are not met include sites with (Johnson and Ling, 2005):

- Water table fluctuations
- Confined conditions
- Sump wells in a perched setting
- On-going LNAPL release
- Heterogeneous conditions

Although in a real world setting, there are often times when vertical equilibrium of liquids and homogeneous soil conditions do not exist, LNAPL models may still be used to generate qualitative information about LNAPL behavior. The degree to which model results are quantitatively valid and defensible will be based on actual site conditions and the accuracy of the LCSM. Where possible, the use of site-specific model inputs (as determined from field and/or laboratory testing) is preferred over the use of default literature look-up values for soil and LNAPL physical properties.

In complex geological settings, numerical (finite element or finite difference) models may be used to assess LNAPL mobility and migration. However, the resources required to adequately run these models are extensive. In addition, the complexities associated with multi-phase fluid flow (spatial discontinuities in LNAPL body, variations in LNAPL saturations, pore entry displacement pressure issues at body periphery, etc.) may limit the effectiveness of these models.

1.4.4 LNAPL Dye Tracer Testing

Single well dye tracer testing involves the use of a fluorescent dye to quantify the rate of LNAPL movement through the subsurface (Sale et al, 2007). The technique involves the addition of a hydrophobic fluorescent dye to the LNAPL in a single well. The rate of depletion of the dye is measured using a spectrometer to quantify the decrease in fluorescence (or dye concentration) over time. The rate of depletion is used to estimate the LNAPL velocity and formation transmissivity to LNAPL. This technique has shown promise in demonstrations, but is still an area of active research and, as such, has not yet been widely adopted in the field.

1.4.5 Mobility Lines of Evidence Summary

A thorough LNAPL mobility evaluation should compare and cross reference all lines of evidence to ensure that the overall interpretation of LNAPL spatial distribution, mobility and body stability is adequate for future decision-making purposes. Any potential conflicts or conflicting information should be further evaluated and, if necessary, qualified for future reference and/or investigation. Ideally, all lines of evidence will provide a consistent depiction of the location, mobility and stability of the LNAPL. However, a weight of evidence approach may be necessary due to the complexities and limitations associated with any single evaluation technique.

Section 2.0 LNAPL Chemistry

Excepting the case of a pure solvent with a density less than water (for example, toluene), LNAPLs are predominantly petroleum-based mixtures or fuels. Petroleum-derived fuels (gasoline, kerosene, diesel, etc.) are complex mixtures of organic compounds (predominantly hydrocarbons) with varying compositions dependent upon the source of crude oil and the refining process (Thomas and Delfino, 1991). Petroleum hydrocarbons are the main components of fuels derived from crude oil. Crude oil is a

mixture of paraffinic and aromatic hydrocarbons with a low percentage of sulphur and trace amounts of oxygen and nitrogen compounds. The paraffinic hydrocarbons are the most abundant compounds in crude oil. They include alkanes, which are saturated hydrocarbons with a straight carbon chain completely substituted with hydrogen atoms. The alkanes are typically very stable and unreactive as compared to their unsaturated counterparts. Crude oil contains alkanes with anywhere from one to more than 50 carbon atoms (C_1 - C_{50+}). In general, C_1 - C_4 alkanes exist as gases, while C_5 - C_{17} alkanes are liquids, and C_{18} and higher alkanes are solids at 20°C. Isoprenoids are branched chain paraffinic hydrocarbons that contain at least two methyl groups. Isoprenoids are often more volatile than the straight chain alkane compounds and make up a significant portion of fuels. Aromatic compounds include single ring structures such as benzene, toluene, ethylbenzene and xylenes (collectively referred to as the BTEX compounds) and multi-ring (polycyclic) structures such as naphthalene, phenanthrene, anthracene, fluorene, pyrene and other polycyclic aromatic hydrocarbons (PAHs). The BTEX compounds are the most abundant aromatic hydrocarbons in fuels (particularly gasoline), with smaller amounts of PAHs present (mostly the 2 and 3-ring species). All said, a typical petroleum-based LNAPL is comprised of hundreds of individual hydrocarbon compounds (straight chain and cyclic) as well as other non-hydrocarbon additives incorporated during the refining process.

Different LNAPLs behave differently based on their composition. For example, a gasoline LNAPL, which is comprised of lighter (lower carbon chain molecules) hydrocarbons than diesel or fuel oil, is more apt to partition into both the vapor phase and dissolved phase, primarily due to the presence of greater quantities of volatile and soluble BTEX compounds. Due to the chemical and toxicological properties associated with BTEX, gasoline LNAPLs tend to pose more of a vapor and dissolved phase exposure risk than heavier LNAPLs. Further, gasoline LNAPLs may also pose potential explosivity risks due to the abundance of volatile and combustible constituents in the LNAPL (and resulting vapor). In a given stratigraphy, the heavier (less volatile) petroleum products will typically exhibit a lower potential for mobility, a lower degree of recoverability, and less potential exposure issues than the lighter end/more volatile product types.

The process of identifying the type of LNAPL (and sometimes the approximate age) via a laboratory process is often referred to as LNAPL fingerprinting or LNAPL forensic testing. During this process, the laboratory generates a gas chromatograph of the LNAPL which effectively identifies the signature or pattern of carbon chain molecules in the LNAPL, starting from the lowest carbon chain (C_4) up through molecules in excess of 30 carbon atoms ($>C_{30}$). Various types of LNAPLs are predominantly comprised of specific ranges of hydrocarbon molecules as follows (Potter and Simmons, 1998):

- Gasoline: C_4 to C_{12} range compounds
- Jet Fuel/Kerosene: C_6 to C_{18} range compounds
- Diesel/No. 2 Fuel Oil: C_8 to C_{21} range compounds
- Lube Oil: C_{18} to $>C_{34}$ range compounds

- Crude Oil: C₁ to >C₃₄ range compounds

Various chromatographic markers and peak ratios are utilized to identify the type or types of LNAPL present, as well as provide an estimation of the level of degradation and/or approximate age. Laboratories may also use a boiling point evaluation to categorize the LNAPLs based on boiling point distillates.

The interpretation of laboratory fingerprinting data can be a difficult task, particularly when dealing with weathered LNAPLs or mixtures of various LNAPLs. For this reason, there is only a relatively small number of laboratories with experienced petroleum forensic chemists that specialize in LNAPL forensic testing in the United States.

2.1 Effective Solubilities from LNAPL Mixtures

Because petroleum-derived LNAPLs are comprised of hundreds of individual hydrocarbon compounds, these compounds must compete with each other when partitioning to the vapor or dissolved phases. As a result, the ability of each compound to partition into the vapor or dissolved phase when present in a mixture is much less than what can be volatilized or dissolved from a pure solvent. For example, the solubility of benzene from a pure benzene solvent is approximately 1,760 milligrams per litre (mg/L) (API, 2004). Hence, a pure benzene solvent in contact with groundwater has the ability to yield 1,760 mg of benzene to each litre of water via dissolution. However, the effective solubility of benzene from a gasoline LNAPL ranges from approximately 25 mg/L to 40 mg/L, depending on the benzene composition in the LNAPL mixture and the degree of weathering (API, 2004). The ability for an LNAPL to yield an individual compound to groundwater via dissolution is a function of the mole fraction of the compound in the LNAPL mixture as well as the pure compound solubility. Effective solubility values for the components of various petroleum fuels are reported in the literature, or can be calculated according to Raoult's Law if site-specific LNAPL chemistry data are available (API, 2004):

$$C_i^{eq} = S_i \cdot MF_i$$

Where: C_i^{eq} = equilibrium aqueous concentration (or effective solubility) of hydrocarbon constituent i
 S_i = pure phase solubility of hydrocarbon constituent i
 MF_i = mole fraction of hydrocarbon constituent i in the LNAPL, approximately equal to the mass fraction

This is an extremely important concept when assessing dissolved phase concentrations associated with a LNAPL body. For heavier LNAPLs, such as diesel, lube oil, etc., real world experience demonstrates that

dissolved phase impacts associated with these LNAPLs are often times very limited, as opposed to impacts associated with lighter LNAPLs such as gasoline.

Section 3.0 LNAPL Physical Properties

The physical properties of LNAPL that are most often measured and used for LNAPL mobility and recoverability assessment include: density, viscosity and interfacial tensions. LNAPLs, being less dense than water, have specific gravities ranging from approximately 0.73 to just less than 1.0 (i.e., the density of water). Hence, in an open water environment, LNAPLs float on top of the water (which, as previously discussed, is not the case with LNAPL in the subsurface). Density can, however, be used to help distinguish one LNAPL from another. The following density ranges can be used to help characterize an LNAPL (API, 2004):

- Gasoline: 0.68 to 0.78 grams per cubic centimeter (g/cm^3)
- Diesel/No. 2 Fuel Oil: 0.80 to 0.85 g/cm^3
- Lube Oil: 0.83 to 0.88 g/cm^3
- Crude Oil: 0.70 to 0.98 g/cm^3

Other constituents or impurities within the LNAPL mixture may also have an effect on the LNAPL density (for example, LNAPL containing chlorinated compounds).

LNAPL viscosity is used to assess the “pumpability” of the LNAPL as well as the ability of the LNAPL to flow or migrate in the subsurface. Viscosity commonly refers to a fluid’s “thickness” or resistance to flow. Consequently, the higher the LNAPL viscosity, the more resistant the LNAPL is to flow, the less likely the LNAPL will be to migrate, and the harder the LNAPL will be to recover via pumping technologies. With the exception of a gasoline LNAPL, which has a viscosity lower than water, most petroleum-based LNAPLs are more viscous than water. The viscosity of LNAPL, along with LNAPL relative permeability, is accounted for in the determination of LNAPL conductivity, and often times yields a conductivity value one to two orders of magnitude lower than the conductivity of water (i.e., hydraulic conductivity). Typical room temperature viscosity values for various LNAPLs are (API, 2004):

- Gasoline: 0.62 centipoise (cp)
- Diesel: 2.7 cp
- JP-4 Fuel: 1 cp
- Crude Oil: 60 cp

Interfacial tensions between air/water, LNAPL/water and LNAPL/air play an important part in limiting or resisting the movement of LNAPL in the subsurface. In a multiphase system, the tension between different fluids in contact with one another (interfacial tension) will limit the ability for each respective fluid to flow (as compared to the presence of a single fluid only). As previously mentioned, for an LNAPL to enter a water-saturated media, the capillary pressure must exceed the pore entry displacement pressure which in part, is determined by the interfacial tension between the LNAPL/water.

Section 4.0 Effects of Geology on LNAPL Presence/Behavior

Geology plays an extremely important role at LNAPL sites. The larger the soil pores in the primary porosity of the soil matrix, the greater the capacity for the soil to hold LNAPL, the greater the ease at which LNAPL can move, and the less pressure that is required for LNAPL to displace water and enter the pore space. Granular soils, such as sands and gravels, have large soil pores, relative to silts and clays, and can hold LNAPL at saturations upwards of 40 to 60% (LNAPL saturations in excess of 60% are not typically encountered at environmental sites). Conversely, silts and clays, which have extremely small soil pores relative to sands and gravels, will typically only allow LNAPL saturations on the order of 5 to 15%. The smaller soil pores not only limit the amount of LNAPL saturation, but also limit the flow or movement of LNAPL.

Soil porosity principles for LNAPL saturations and movement in overburden soil may also be applied to competent bedrock (i.e., bedrock that does not have secondary porosity in the form of fractures). For example, a competent sandstone will enable LNAPL to behave in a similar manner as in a sandy soil.

Secondary porosity also plays an extremely important role at LNAPL sites. Fine textured soils, such as silts and clays, are often comprised of a secondary porosity which may include macropores such as fractures, fissures, sand seams, etc. The same holds true for fractured bedrock. LNAPL movement through secondary porosity may occur at rates several orders of magnitude greater than the movement through the primary porosity. This is primarily due to the fact that the macropores generally have much larger pore sizes than the primary porosity in fine-grained soils, with a corresponding pore entry displacement pressure that is much lower. That is, LNAPL can displace water and move through macropores much more easily (and to a greater extent) than it can in the primary porosity of a fine-grained soil matrix. In addition, LNAPL that is present in macropores will be much more likely to be present under confined conditions, and consequently be more sensitive to changes in subsurface pressure conditions. This may result in LNAPL migrating much greater distances and penetrating greater depths than would be typically expected. Hence, the potential for LNAPL movement through secondary porosity must be considered when LNAPL impacts are present in fine textured soil and/or fractured bedrock.

Section 5.0 References

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Appendix D

Example LIF/UVOST Profile

UVOST Log Reference Guide

Main Plot :

Signal (total fluorescence) versus depth where signal is relative to the Reference Emitter (RE). The total area of the waveform is divided by the total area of the Reference Emitter yielding the %RE. This %RE scales with the NAPL fluorescence. The fill color is based on relative contribution of each channel's area to the total waveform area (see callout waveform). The channel-to-color relationship and corresponding wavelengths are given in the upper right corner of the main plot.

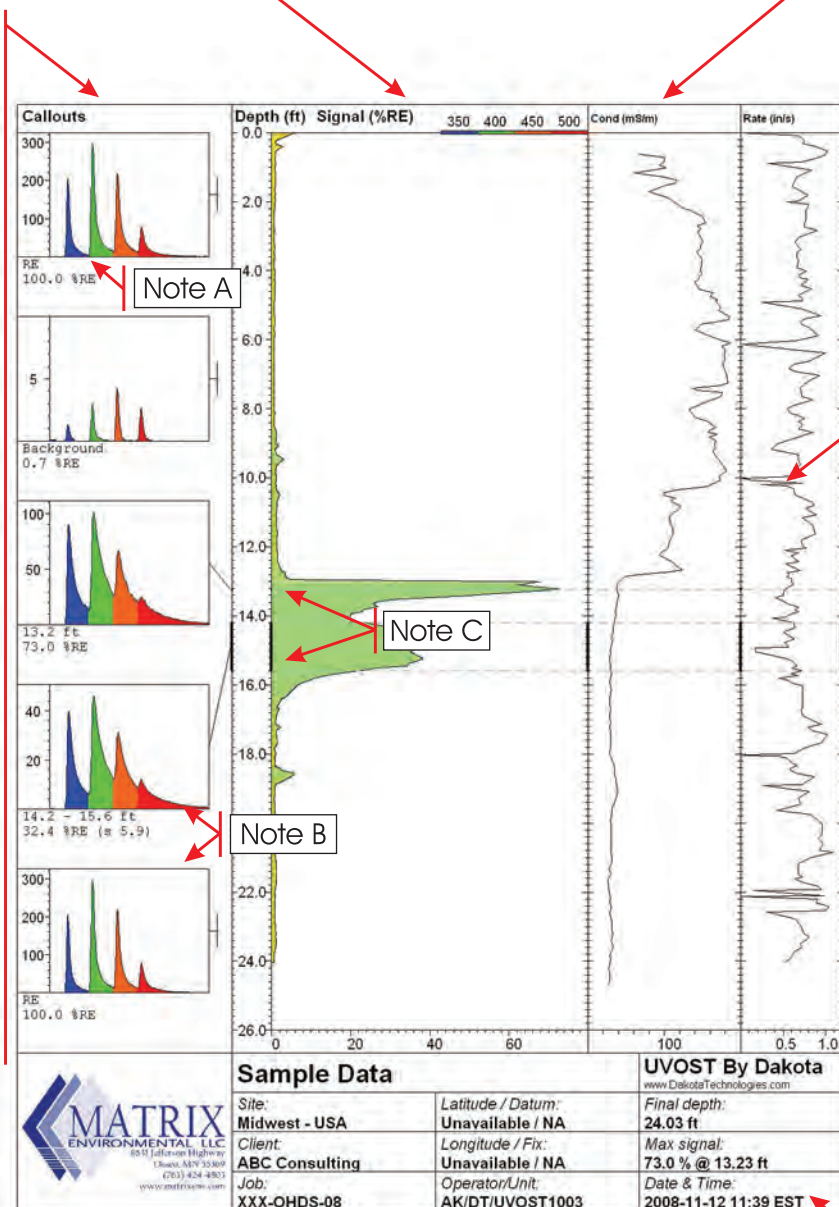
Callouts :

Waveforms from selected depths or depth ranges showing the multi-wavelength waveform for that depth.

The four peaks are due to fluorescence at four wavelengths and referred to as "channels". Each channel is assigned a color.

Various NAPLs will have a unique waveform "fingerprint" due to the relative amplitude of the four channels and/or broadening of one or more channels.

Basic waveform statistics and any operator notes are given below the callout.



Conductivity Plot :

The Electrical Conductivity (EC) of the soil can be logged simultaneously with the UVOST data. EC often provides insight into the stratigraphy. Note the drop in EC from 10 - 13 ft, indicating a shift from consolidated to unconsolidated stratigraphy. This correlates with the observed NAPL distribution.

Rate Plot :

The rate of probe advancement. ~ 0.8 in (2cm) per second is preferred.

A noticeable decrease in the rate of advancement may be indicative of difficult probing conditions (gravel, angular sands, etc.).

Notice that this log was terminated arbitrarily, not due to "refusal", which would have been indicated by a sudden rate drop at final depth.

Info Box :

Contains pertinent log info including name and location.

Note A:

Time is along the x axis. No scale is given, but it is a consistent 320ns wide. The y axis is in mV and directly corresponds to the amount of light striking the photodetector.

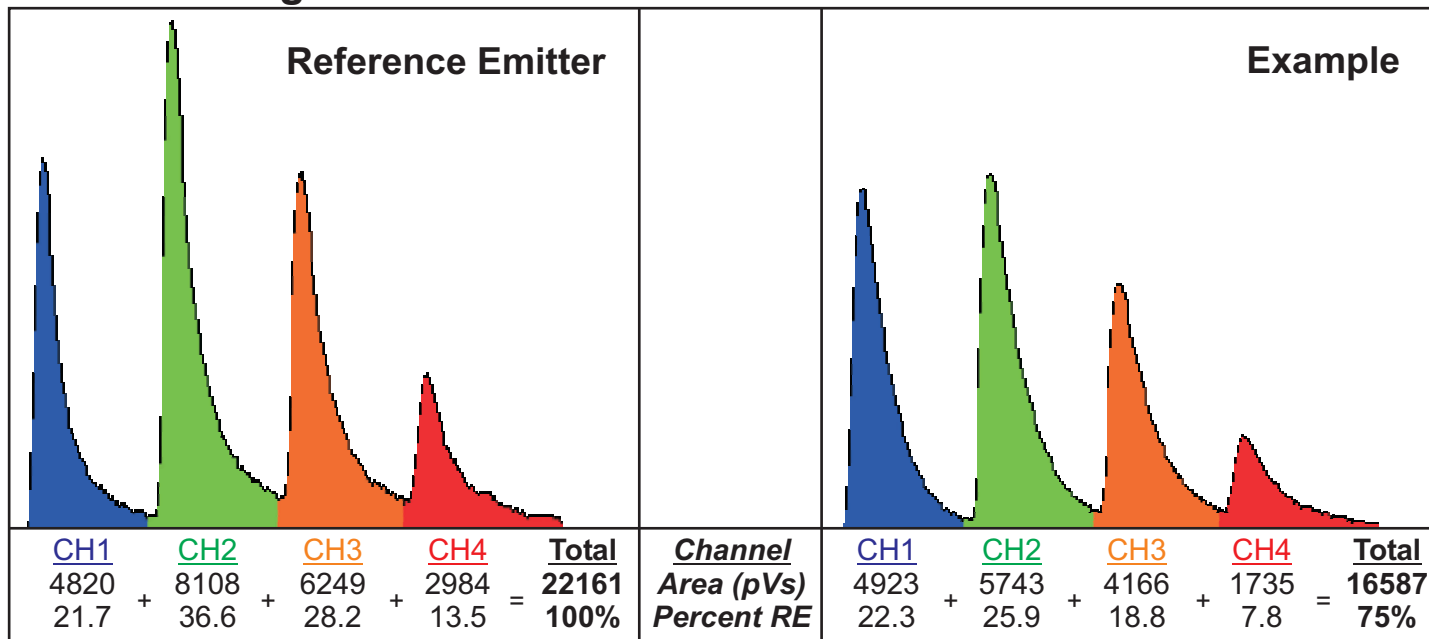
Note B :

These two waveforms are clearly different. The first is weathered diesel from the log itself while the second is the Reference Emitter (a blend of NAPLs) always taken before each log for calibration.

Note C :

Callouts can be a single depth (see 3rd callout) or a range (see 4th callout). The range is noted on the depth axis by a bold line. When the callout is a range, the average and standard deviation in %RE is given below the callout.

Waveform Signal Calculation



Data Files

*.lif.raw.bin	Raw data file. Header is ASCII format and contains information stored when the file was initially written (e.g. date, total depth, max signal, gps, etc., and any information entered by the operator). All raw waveforms are appended to the bottom of the file in a binary format.
*.lif.plt	Stores the plot scheme history (e.g. callout depths) for associated Raw file. Transfer along with the Raw file in order to recall previous plots.
*.lif.jpg	A jpg image of the OST log including the main signal vs. depth plot, callouts, information, etc.
*.lif.dat.txt	Data export of a single Raw file. ASCII tab delimited format. No string header is provided for the columns (to make importing into other programs easier). Each row is a unique depth reading. The columns are: Depth, Total Signal (%RE), Ch1%, Ch2%, Ch3%, Ch4%, Rate, Conductivity Depth, Conductivity Signal. Summing channels 1 to 4 yields the Total Signal.
*.lif.sum.txt	A summary file for a number of Raw files. ASCII tab delimited format. The file contains a string header. The summary includes one row for each Raw file and contains information for each file including: the file name, gps coordinates, max depth, max signal, and depth at which the max signal occurred.
*.lif.log.txt	An activity log generated automatically located in the OST application directory in the 'log' subfolder. Each OST unit the computer operates will generate a separate log file per month. A log file contains much of the header information contained within each separate Raw file, including: date, total depth, max signal, etc.

Common Waveforms (highly dependent on soil, weathering, etc.)

