

**USE OF LIF FOR REAL-TIME *IN-SITU*
MIXED NAPL SOURCE ZONE DETECTION**

By

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ABSTRACT

The Site Characterization and Analysis Cone Penetrometer System (SCAPS), equipped with real-time fluorophore detection capabilities, was used to delineate subsurface contaminant releases in an area where plating shop wastes were temporarily stored. Records indicated that various non-aqueous phase liquids (NAPLs) were released at the site. The investigators advanced the SCAPS Laser Induced Fluorescence (LIF) sensor to depths beneath the water table of the principal water-bearing zone. The water table was located approximately 6 ft. (1.8 meters) below ground surface (bgs) across the site. Fluorescence attributed to fuel compounds commingled with chlorinated solvents was observed at depths ranging from 4.0 to 11.5 ft. (1.2 to 3.5 meters) bgs. Fluorescence attributed to naturally occurring organic materials (by process of elimination and spectral characteristics) commingled with chlorinated solvent constituents was observed at depths ranging from approximately 13 to 40 ft. (4.0 to 12.2 meters) bgs. Fluorescence responses from compounds confirmed to be commingled with chlorinated solvents indicates that the SCAPS fluorophore detection system is capable of indirectly delineating vadose zone and subaqueous chlorinated solvents and other dense non-aqueous phase liquids (DNAPLs) at contaminant release sites. This confirmation effort represents the first documented account of the successful application of LIF to identify a mixed DNAPL/LNAPL source zone.

INTRODUCTION

Contamination from the use of fuels and chlorinated solvents is one of the most pressing environmental problems. Remediation of sites contaminated by non-aqueous phase liquids (NAPLs) is an environmental challenge with global implications. Many of these compounds are toxic, volatile, mutagenic, teratogenic, fat soluble, and only slightly soluble in water. Several NAPL compounds are considered hazardous at extremely low concentrations (Verschueren, 1983). For example, the California State Maximum Contaminant Level (MCL) for vinyl chloride is 0.5 parts per billion or ppb (California Code of Regulations, 1986). Provided there is sufficient opportunity to completely dissolve, fifteen gallons (56.8 liters) of trichloroethylene (TCE) can impact an area 1000 meters in length, 100 meters in width, and 20 meters in depth with an average ground water concentration of 100 ppb (Schwille, 1985). Some of these compounds are also more dense than water and therefore can migrate to depths below the capillary fringe and water table. Once below the water table, these contaminants can exist as a dissolved plume or as an undissolved separate non-aqueous free phase. NAPLs which become disconnected in the pore spaces are often referred to as residual and are present as micro-globules, or “ganglia”, which are believed to be distributed in a heterogeneous manner, leading to significant NAPL source zone detection challenges (Pankow and Cherry, 1996; Keller et. al, 1997; Keller et. al, 1999).

Long-term treatment of dissolved phase chlorinated constituents using pump-and-treat and in-situ methods is common remediation practice (Fenton, 1894; Howard et. al., 1991; Haag and Yao, 1992; Gillham, 1993; Gillham, et. al., 1993; Star and Cherry, 1994;

Matheson and Tratnyek, 1994; Wilson, 1995; U.S. EPA, 1995; Chappelle, et. al., 1996). These approaches can be extremely costly (multi-million dollar ventures in many cases). When the goal is restoration to background conditions, or even drinking water criteria, clean-up of groundwater contamination by organic chemicals is often not possible (Pankow and Cherry, 1996). Dissolved phase treatment approaches deal with the symptom rather than the problem, because the sources of dissolved constituents are the NAPLs. As dissolved compounds are removed via cleanup activities or natural flushing of clean water past the source zone, NAPL constituents partition into the aqueous phase. Thus, in order to adequately address the contamination problem, the NAPL source needs to be identified, thoroughly characterized in three dimensions, and completely removed or isolated from the ground water resource.

At present, detection of Dense Non-Aqueous Phase Liquids (DNAPLs) is difficult. Conventional DNAPL site characterization techniques include extrapolation of soil gas survey results and coincidental soil and ground water sampling. These techniques have advantages and disadvantages (Kram, 1998). Feenstra et. al. (1996) note that conventional monitoring and sampling techniques “rarely provide the level of detail needed to provide a reliable picture of the nature and extent of solvent DNAPL below the water table”. Broholm et. al. (1999) show that it may be possible to map DNAPL source zones by characterizing aqueous phase concentrations exceeding 10 percent of the effective solubility of the individual components in the portion of the plume directly downgradient of the source. While their efforts appear promising, their studies were performed under very controlled conditions using large amounts of data, typically beyond the budget of most site characterization projects. Broholm et. al. (1999) concede that “even with

detailed groundwater monitoring, it was not possible to determine the small-scale distribution of the DNAPL source.” Powers et al. (1997) use multivariate analyses of principal components to identify and interpret chemical signatures of ground water containing dissolved VOCs. Their method is qualitative. However, this approach can assist with determination of spatial and temporal distribution of NAPL sources.

Mariner et al. (1997) use an algorithm (NAPLANAL) to estimate NAPL saturations from soil sample chemical analyses even when only one organic compound is identified. When more than one organic compound is identified, NAPL density can also be estimated. This can be successfully applied to determine whether a confirmation soil sample contains NAPL. However, it is not as useful as a stand-alone method for determining the spatial and temporal distribution of NAPL sources, since it is a destructive method by nature, and sampling location selections must generally be based on prior subsurface information (i.e., dissolved VOC concentrations, soil gas concentrations, and barriers to vertical NAPL migration). Researchers have used NAPLANAL and partition interwell tracer tests (PITTs) to estimate spatial distribution and volume of NAPL in the subsurface (Jin et al., 1995; Dwarakanath et al., 1999). However, the PITT method setup locations must be based on previously collected subsurface data. Therefore, initial efforts to identify and locate the NAPL and define the hydrologic flow regime are required. The sequence for this approach would be to screen for source zones, confirm DNAPL presence (via chemical confirmation supported by NAPLANAL), and setup and implementation of the PITT in the most appropriate locations. The PITT has also been successfully applied to conduct remediation performance assessments (Jin *et al.*, 1995; Dwarakanath *et al.*, 1999). While researchers pursue geophysical methods of detection,

the ability to detect DNAPLs using these techniques is still elusive (Pankow and Cherry, 1996; Sinclair and Kram, 1998).

Research incorporating Raman spectroscopy into a direct detection probe has shown promise, however, interferences caused by fluorescence of naturally occurring organic materials and commingled fuel compounds have presented challenges at many sites. Therefore, successes of Raman spectroscopy can often be attributed to indirect DNAPL detection based on fluorescence of commingled fluorophores. Another promising method uses a membrane interface probe, which incorporates a heating element, polymer membrane, and detector system into a direct-push apparatus (Christy, 1998).

In addition to initial source zone characterization, there is a need to verify the success of DNAPL source zone remediation methods, several of which are currently under development. Three dimensional geospatial assessment techniques are required to evaluate performance. Therefore, the need to identify DNAPL zones located beneath the water table is critical to evaluation of the success of these methods and to permit site remediation.

Our approach to locating chlorinated DNAPLs using Laser Induced Fluorescence (LIF) is based on the fact that given their excellent solvent properties, chlorinated solvents are commonly used to remove petroleum compounds from surfaces in industrial applications. In addition, environmental releases of chlorinated solvents are often associated with oils and greases entrained during degreasing operations. For instance, TCE is often used to clean oil soaked metal parts. Also, unlined fire fighter training facilities located on industrial properties are often suspected sources of chlorinated solvent and fuel releases to the environment, since the training activities utilize mixed wastes.

The Site Characterization and Analysis Cone Penetrometer System (SCAPS) utilizes soil classification and LIF technologies to evaluate environmental conditions at sites where NAPL contaminants are suspected. The current configuration allows for direct real-time detection of aromatic petroleum compounds (Lieberman *et. al.*, 1991). In addition, naturally occurring organic materials, such as humic and fulvic acids, will also fluoresce. While SCAPS is not presently capable of directly detecting non-fluorescing DNAPLs such as alkyl chlorinated solvents, the mono- and polyaromatic hydrocarbon constituents that SCAPS can detect are highly miscible with chlorinated NAPLs and can become commingled with these materials. For instance, TCE is often used to clean oil soaked metal parts. SCAPS is thus capable of detecting many of the polyaromatic compounds in the mixed DNAPL waste fluid (Keller and Kram, 1998).

Since petroleum hydrocarbons are miscible with chlorinated solvents, detection of aromatic hydrocarbons located at depths beneath the water table can assist with the delineation of chlorinated DNAPLs at sites where both contaminants are present. Chlorinated DNAPLs can carry commingled petroleum products to depths beneath the water table as they migrate through the soil column. There is no phase separation at the water table between lighter and denser than water NAPL constituents, since the fluorescing aromatic compounds are entrained by the DNAPL. Detection of the commingled aromatics can therefore potentially lead to indirect chlorinated DNAPL detection. While this method is based on indirect detection, vertical resolution and continuous depth-related data afforded by the SCAPS LIF system allow for rapid, highly focused confirmation efforts.

In November 1995, the authors used the LIF detector to locate petroleum products which had reached levels below the current site water table at a fire fighter training facility located in the Central Valley of California. Samples collected from the target zone consisted of dissolved chlorinated contaminant constituents commingled with petroleum products identified with LIF (Kram, 1998). These findings suggested that fluorescence detection probes may be useful for indirectly detecting mixed NAPLs in contaminated areas.

This paper describes follow-up studies, conducted at a site along San Francisco Bay, California, in early December of 1996, to further evaluate the significance of the results observed at the Central Valley site work in November 1995.

METHOD DESCRIPTION

SCAPS is an innovative field screening technology used for rapidly characterizing soil types and detecting and delineating the presence and extent of subsurface contaminants. Data can be used for strategic placement of ground water monitoring wells, estimating plume and aquifer property spatial characteristics, designing monitoring and remediation wells, determining ideal locations for collecting discrete soil, water, and vapor samples, determining ground water flow directions and rates, and evaluating performance of remediation systems. SCAPS is part of the Tri-Service (Army, Navy, Air Force) Environmental Quality Strategic Plan Program.

The cone penetrometer is a device used for hydraulically pushing a small diameter (approximately 35.7-mm (1.4 inches) per ASTM D-3441 specifications) instrumented

probe and steel support rods into soils. The conventional cone tip is equipped with transducers for measuring point penetration resistance and sleeve friction. An empirical relationship between these physical strength measurements and soil type is used to derive soil classification for the layers penetrated (Robertson and Campanella, 1988). A fiber optic based LIF chemical detection system has been incorporated into the SCAPS penetrometer system to allow for real-time, *in-situ* subsurface plume delineation (Lieberman *et. al.*, 1991).

Although new probes and systems are currently being developed for a variety of constituents and properties, the LIF system referred to in this report is briefly described below. Ultraviolet light (337 nm wavelength) from a pulsed nitrogen laser with a 0.8 nanoseconds pulse width and a pulse energy of 1.4 millijoules is sent through a 500 micron diameter, 100 meter long, silica clad optical fiber connected to a sapphire window mounted flush with the outside of the penetrometer rod, 60 centimeters above the probe tip. A second fiber is used to collect the stimulated fluorescent emission from the soil in contact with the sapphire window, and return it to the detector system at the surface. Detailed system descriptions can be found in Lieberman *et. al.* (1991).

The 337 nm nitrogen laser system is best suited for detecting petroleum, oils, and lubricants (POLs) which contain sufficient concentrations of three-ring polycyclic aromatic hydrocarbons. Fuels which fall into this category include diesel, kerosene, some jet fuels, creosote, automotive lubricants and heating oils. Depending on the soil type, fuel type, and other site conditions (fuel history, mineralogy, available substrate surface area, moisture content, etc.), detection limits of approximately 100 mg/kg (total petroleum hydrocarbon) have been achieved with this system. Only contaminants at the

grain/window interface can be detected, since the depth of optical penetration is apparently only a monolayer phenomenon (Apitz *et al.*, 1992). Other fuels (e.g. gasoline) may be detected using SCAPS with the 337 nm laser, but generally at higher soil saturations. Grass, humic and fulvic acids, organic debris, and calcium carbonate also respond to the 337-nm laser/detector system, although with very different distributions of fluorescent wavelengths and relative intensities. Confirmation samples (from discrete depth intervals) are generally collected to distinguish between potential false positives due to background materials and actual POLs.

At the current site, soil confirmation samples were collected using a Mostap soil sampling cone penetrometer attachment. Inner liners were immersed in methanol, sealed, labeled, and sent to a conventional laboratory for analysis. Methanol immersion helps reduce the potential loss of volatile constituents during handling and transport. Samples were analyzed following EPA methods 8240 and 8270.

SITE DESCRIPTION

The site investigated is located on Alameda Island, in Alameda County, California. The island is located along the eastern side of San Francisco Bay (Figure 1). The site covers approximately 18.5 acres. Since 1942, a plating shop and machine shop had been used for cleaning, reworking, and manufacturing metal parts, tool maintenance, and plating and painting operations. Processes included degreasing, caustic and acid etching, metal stripping and cleaning, and chrome, nickel, silver, cadmium and copper plating.

The main areas of concern include the plating shop within the building (which presented high VOC concentrations in ground water samples), an underground storage

tank east of the building adjacent to a flagpole (where highest ground water VOC concentrations had been identified), and just east of the building and south of the flagpole where above-ground tanks are currently found. The area adjacent to the above-ground tanks is believed to have been where wastes from the plating shop were temporarily disposed and stored in a pit. The wastes were allowed to accumulate and then were siphoned off for disposal in portable tanks. The pit may have been lined with concrete. However, wastes are believed to have leaked into the ground water. No boring or well data were available for the waste pit area of concern.

GEOLOGY/HYDROLOGY

A generalized lithologic profile is presented in Figure 2. Most of the area in the vicinity of the site was constructed over artificial fill material dredged from San Francisco Bay, the Seaplane Lagoon, and Oakland Channel over the course of 75 years beginning in 1900. The hydraulically placed fill was dominated by silty sand to sand, with clay and/or gravel in some places. Wood, concrete, and metal debris have also been identified in the fill materials. The fill extends up to 40 ft. thick in the western portion of the base and thins to less than 15 ft. thick towards the east. The Bay Sediment is the youngest (Holocene) of the naturally occurring formations, and consists of Bay Sand and Bay Mud. These sediments were deposited in an estuarine environment with channels eroded into underlying sediments. The Bay Mud resides directly beneath the fill material at the site. This section consists of gray (with green or blue hues) clay to clayey silt containing minor shell materials. The Bay Sand is comprised of lenses of fine to medium-grained gray sand or sandy silt, which reside within the Bay Mud areas. Collectively, this Bay Sediment

designation can be as thick as 130 ft. just beneath the northern part of the site. Bay sediments are thin or absent in the southeastern part of the base. The Bay Mud is generally considered a barrier to vertical migration of NAPLs.

Groundwater is typically encountered between 5 to 8 ft. (1.5 to 2.4 m) below ground surface (bgs) along much of the site and vicinity. Flow is generally to the west and southwest. Two continuous aquifers underlie the site. The first water bearing zone occurs in the dredge fill, about 5 or 6 ft. (1.5 to 1.8 m) deep at the site. The deeper aquifer is found in the Lower Pleistocene sediments. Both aquifers are influenced by tidal fluctuations and are characterized by water problems associated with nitrates, saltwater intrusion, and naturally occurring mercury contamination from the bedrock formation. As a result, no groundwater is presently used as a water supply on the island.

PROJECT DESCRIPTION

The project goal was to confirm the observations from the tests conducted at NCS Stockton in 1995 in an effort to determine whether the SCAPS LIF system is capable of indirectly detecting chlorinated DNAPLs by detecting commingled fluorophores. The criterion for determining successful DNAPL detection is that soil samples collected (at locations where the LIF probe indicates the presence of high levels of fluorophores beneath the water table) exhibit organic compound concentrations exceed a concentration suggestive of NAPL presence based on the NAPLANAL model described in Mariner *et al.*, (1997). In addition, fluorophores must be present in these soil samples, mixed with chlorinated solvents.

During a brief investigation in early December, 1996, a total of four SCAPS laser induced fluorescence/soil classification probe pushes were performed and four soil samples were recovered. The push locations are presented in Figure 3. The four pushes were conducted to depths ranging from 44 to 48 ft. (13 to 15 m). Soil samples collected adjacent to push depths demonstrating relatively high fluorescence responses were analyzed.

RESULTS

Specific push logs are presented in Figures 4 through 7 (push IR-01, IR-02, IR-03, and IR-04, respectively). The SCAPS logs were partitioned into columns representing Cone Pressure (Q_c , also known as Cone Penetration Resistance or Cone Bearing), Sleeve Friction (Q_s), Soil Classification based on cone pressure and sleeve friction readings, Wavelength at Peak, and Raw Fluorescence Peak Intensity. Although not displayed here, a value N , known as the standard penetration value, relates the cone pressure (bars) to the dynamic shear modulus (bars) and shear strength of soils, and is used to discriminate between soils of differing textures. This N value is based on empirical tests using various soil types (Robertson *et al.*, 1983; Lunne *et al.*, 1986; and Robertson and Campanella, 1988). The peak wavelength value refers to the wavelength corresponding to the maximum fluorescence intensity over the observed spectral range for each depth. The logs can be used to locate fluorescence anomalies and corresponding soil types.

Figure 8 displays a superimposition of the soil classification data and LIF information for push IR-02. Table 1 presents the soil classification chart (after Robertson and Campanella, 1988) used to interpret the soil classification logs presented in Figures 4

through 7. Table 2 presents selected analytical results for the soil samples recovered. The sample label convention is to list the push number first, followed by the depth in feet below ground surface (ft bgs).

As can be seen in the SCAPS push logs, an elevated fluorescence response occurred from approximately 33 to 36 ft. (10 to 11 m) for Push 1. This signal corresponded to a zone classified as an interbedded clay to sandy silt. For Push 2, an extremely high fluorescence response occurred from 3 to 11 ft. (1.0 to 3.4 m), and then another lower response was seen at about 31 ft. (9.5 m). The shallow response area occurred in a sand to silty sand located above a clay zone. The deeper response was located in an interbedded clay to silty sand zone. For the shallow responses (between 3 and 11 ft. , 1.0 to 3.4 m) a peak wavelength shift was observed. This can often be attributed to fuel compounds dominating the fluorescence signal.

Push 3 demonstrated a very high fluorescent signal between 7 and 10 ft. (2.1 to 3 m), in a sandy to silty sand just above a clay, and then another relatively elevated response between 14 and 35 ft. (4.3 to 11 m) in an interbedded clay to silt. As with the shallow signals from Push 2, a peak wavelength shift corresponding to the shallow zones of fluorescence was observed.

Push 4 exhibited a very high response between 7 and 9 ft. (2.1 to 2.7 m), in a sandy to silty sand just above a clay, and then another relatively elevated response between 14 and 36 ft. bgs (4.3 to 11 m), in an interbedded clay to silt). Once again, the peak wavelength shift was observed for the shallower zones of fluorescence.

Soil samples collected adjacent to the fluorescent regions of Push 2 indicated high concentrations of fuel and chlorinated solvent constituents at the shallow depths just

above 10 ft. (3.0 m) bgs (Table 2). For example, at 8.2 ft. (2.5 m), TCE concentrations of approximately 2600 mg/kg and naphthalene (an excellent fluorophore) concentrations of 39 mg/kg were measured. A soil sample was collected from the deeper regions (approximately 30 ft. (9.2 m) bgs) where elevated concentrations of 1,1,1-trichloroethane (250 µg/kg) and trichloroethene (510 µg/kg) were detected (**ANY**

FLUOROPHORES IN THIS LOWER SAMPLE?)

The shallower (between the water table and 10 ft. (3.0 m) bgs) fluorescent signals in the push logs correspond to areas of elevated fuel and chlorinated hydrocarbon concentration. Mathematical analyses using NAPLANAL were conducted to evaluate the potential for NAPL presence based on constituents detected in samples IR5-02-8.2 and IR5-02-9.3. According to NAPLANAL, NAPL saturations of 1.5% and 0.9%, each with a NAPL density of approximately 1.4 kg/l, are present in samples IR5-01-8.2 and IR5-02-9.3, respectively. These shallower zones also contain significant levels of fuel compounds that readily respond to the LIF technique (e.g., naphthalene). This is supported by the spectral shifts observed in the shallow fluorescing regions, indicating a change in fluorophore composition. Background peak wavelength fluorescence (presumably due to naturally occurring organic materials and/or certain mineralogical responses) is typically found in the range of 475nm to approximately 550nm. Peak wavelength fluorescence due to fuel hydrocarbons typically ranges from 425nm to approximately 460nm. In addition, naphthalene occurs at concentrations ranging from 0.017 to 0.023 kg naphthalene per liter of NAPL according to NAPLANAL. It is interesting to note that the shallow fluorescent zones which contained NAPLs are bounded by an underlying clay layer. This is consistent

with observations at other sites where clays have acted as vertical migration barriers to chlorinated solvent transport (Pankow and Cherry, 1996).

Deeper fluorescing zones (e.g., Push IR-01, 34.5 ft. (10.5 m) bgs) may be due to concentration of naturally occurring organic fluorophores by the chlorinated solvents as they migrate through the soil column. Keller and Kram (1998) have been able to detect these natural fluorophores dissolved in chlorinated solvents. This is also supported by the observation that there is no peak wavelength shift attributed to the deeper elevated fluorescence signals, which would suggest petroleum hydrocarbon presence. In addition, chemical analyses did not reveal the presence of fuel fluorophore constituents. Analytical results indicate that elevated concentrations of 1,1,1-Trichloroethane (110 to 250 $\mu\text{g}/\text{kg}$) and TCE (510 $\mu\text{g}/\text{kg}$, IR-02, 30.8 ft. (9.39 m) bgs) are present in these deeper zones. However, these concentrations are not necessarily indicative of NAPL. NAPLANAL results for these samples suggest that NAPL is not present. It is still possible that the fluorescence detected by the LIF system was due to elevated concentrations of naturally occurring fluorophores commingled with chlorinated solvents. Field sampling logistics (e.g., spatial difference between push location for the LIF probe and the sampling probe, lack of sampling and handling protocol for purposes of identifying microglobules, etc.) may account for the apparent discrepancy. On a related note, orientation of NAPL migration pathway configurations with respect to the probe window and soil sampling tools may explain the relatively low levels of dissolved constituents (relative to saturation values) at this depth. It is also possible that fluorescence in these deeper zones represent false positives. It is interesting to note that the deeper target zone fluorescent signals for IR-01 and IR-02 are just above fine-grained layers as characterized by the SCAPS load

cell soil profile system. It is also interesting to note that there are several fine-grained zones stratigraphically located between the two fluorescent zones. Although it is unknown whether these zones are horizontally continuous, this observation suggests that vertical penetration of NAPLs and dissolved chlorinated constituents is possible in this type of hydrogeologic setting.

DISCUSSION AND CONCLUSIONS

The results indicate that fluorescing compounds can be identified beneath the water table using LIF techniques. Since fuel and other petroleum constituents can be commingled with chlorinated solvents, they can be carried to depths beneath the water table. The LIF technique is not capable of directly locating chlorinated DNAPL compounds released to the environment, but commingled fluorophores (selected fuel compounds, naturally occurring organic compounds, lubrication oil constituents, etc.) can act as indicators for delineating chlorinated DNAPL source zones.

In summary, this effort confirms earlier studies about the potential to use LIF techniques to indirectly locate DNAPL source zones by detecting commingled fluorophores below the site water table (Kram, 1996; Kram, 1998). Subsequent plume delineation efforts using LIF, a video microscope probe (GeoVis), a direct sampling ion trap mass spectrometer linked to a membrane interface probe, and confirmation soil samples at this site further support the findings in this study (Lieberman, et. al., 1998; Heron, et. al., 1998). Results from this effort led to the first successful visible identification of NAPL (commingled fuel and chlorinated solvents) *in-situ* using the GeoVis (Lieberman, et. al., 1998), evaluation of a three-dimensional seismic reflection

method for locating NAPL sources (Sinclair and Kram, 1998), and ultimate design of a successful steam-enhanced DNAPL removal system (completed in August, 1999).

Additional studies currently under way will be required to determine the extent and limitations of the method.

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Figures:

Figure 1. Vicinity map.

Figure 2. Generalized lithologic profile beneath the site.

Figure 3. Site map showing push locations.

Figure 4. SCAPS push log for Push IR-01.

Figure 5. SCAPS push log for Push IR-02.

Figure 6. SCAPS push log for Push IR-03.

Figure 7. SCAPS push log for Push IR-04.

Figure 8. Superimposition of soil type and LIF data for Push IR-02. Depths are presented in ft. below surface. The wireline represents relative fluorescence intensity.

Table 1: Cone Penetrometer Test Soil Classification Chart (after Robertson and Campanella, 1988). Q_c refers to cone pressure (bar). N is a standard penetration value (blows/ft) used to relate cone pressure to the soil type.

Zone	Q_c/N	Soil Behavior Type
1	2	sensitive fine grained
2	1	organic material
3	1	clay
4	1.5	silty clay to clay
5	2	clayey silt to silty clay
6	2.5	sandy silt to clayey silt
7	3	silty sand to sandy silt
8	4	sand to silty sand
9	5	sand
10	6	gravelly sand to sand
11	1	very stiff fine grained*
12	2	sand to clayey sand*

* Overconsolidated or cemented

Table 2: Soil sampling confirmation results. D indicates sample was diluted for reporting.

Sample I.D.	Selected Analytes	Concentration (mg/kg)	Reporting Limit
IR5-01-34.5	1,1,1-Trichloroethane	0.11	0.04
IR5-02-8.2	1,1,1-Trichloroethane	630 D	230
	1,1-Dichloroethane	24	5
	1,1-Dichloroethene	23	5
	1,2-Dichlororbenzene	5	5
	Ethylbenzene	9	5
	Tetrachloroethene (PCE)	74	5
	Toluene	67	5
	Trichloroethene (TCE)	2,600 D	230
	Trichlorotrifluoroethane	850 D	230
	Xylene (total)	75	10
	2-Methylnaphthalene	14	3.7
	bis(2-Ethylhexyl)phthalate	80	3.7
	Naphthalene	39	3.7
	IR5-02-9.3	1,1,1-Trichloroethane	400 D
1,1-Dichloroethane		13	4
1,1-Dichloroethene		16	4
Ethylbenzene		10	4
Tetrachloroethene (PCE)		42	4
Toluene		60	4
Trichloroethene (TCE)		1500 D	185
Trichlorotrifluoroethane		970 D	185
Xylene (total)		81	8
2-Methylnaphthalene		12	2.3
bis(2-Ethylhexyl)phthalate		174	2.3
Fluorene		2	2.3
Naphthalene		35	2.3
IR5-02-30.8		1,1,1-Trichloroethane	0.25
	Trichloroethene (TCE)	0.51	0.03

Figure 2. Generalized lithologic profile beneath the site.

