Innovative Technology
Summary Report

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Internal Reflection Sensor for the Cone Penetrometer

Industry Programs
Subsurface Contaminants Focus Area

Prepared for
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Office of Science and Technology

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INNOVATIVE TECHNOLOGY
Summary Report

Internal Reflection Sensor for the Cone Penetrometer

Tech ID 1723

Industry Programs
Subsurface Contaminants Focus Area

Demonstrated at
Savannah River Site
M-Area Basin
Aiken, South Carolina

INNOVATIVE TECHNOLOGY
Summary Report

Purpose of this document

Innovative Technology Summary Reports are designed to provide potential users with the information they need to quickly determine whether a technology would apply to a particular environmental management problem. They are also designed for readers who may recommend that a technology be considered by prospective users.

Each report describes a technology, system, or process that has been developed and tested with funding from DOE's Office of Science and Technology (OST). A report presents the full range of problems that a technology, system, or process will address and its advantages to the DOE cleanup in terms of system performance, cost, and cleanup effectiveness. Most reports include comparisons to baseline technologies as well as other competing technologies. Information about commercial availability and technology readiness for implementation is also included. Innovative Technology Summary Reports are intended to provide summary information. References for more detailed information are provided in an appendix.

Efforts have been made to provide key data describing the performance, cost, and regulatory acceptance of the technology. If this information was not available at the time of publication, the omission is noted.

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under "Publications."

TABLE OF CONTENTS

APPENDICES

SECTION 1
SUMMARY

Technology Summary

Problem

Locating Dense Non-Aqueous Phase Liquids (DNAPLs) in the subsurface is a challenging task. DNAPLs have low solubility in water and often exist as “free phase” contaminants. Because DNAPLs have a greater density than water, they sink in an aquifer and often migrate through cracks and fissures in the subsurface to form small, isolated “pools” of contamination. These DNAPL pools can contaminate a large volume of groundwater as they slowly dissolve over time.

Solution

EIC Laboratories, Inc. (EIC) has developed a rugged, inexpensive sensor that can be deployed by cone penetrometer technology (CPT), for real-time, *in situ* detection of DNAPLs. A photograph of the sensor module and internal components is presented in Figure 1.

How It Works

The heart of EIC’s Internal Reflection Sensor (IRS) is the internal reflection element. This element is positioned in the wall of the penetrometer cone so that its sensing face is in contact with the soil or groundwater as the cone is pushed into the ground. When DNAPL is not present at the sensing face, laser light is fully reflected within the element and is detected in the sensor head. However, when DNAPLs come into contact with the sensing face, the internally reflected light is diminished. This results in a decrease in the signal output by the detector: a positive indication of DNAPL presence. Because the response from the detector is continuously measured at the surface by a voltmeter or computer, DNAPLs can be detected instantaneously.

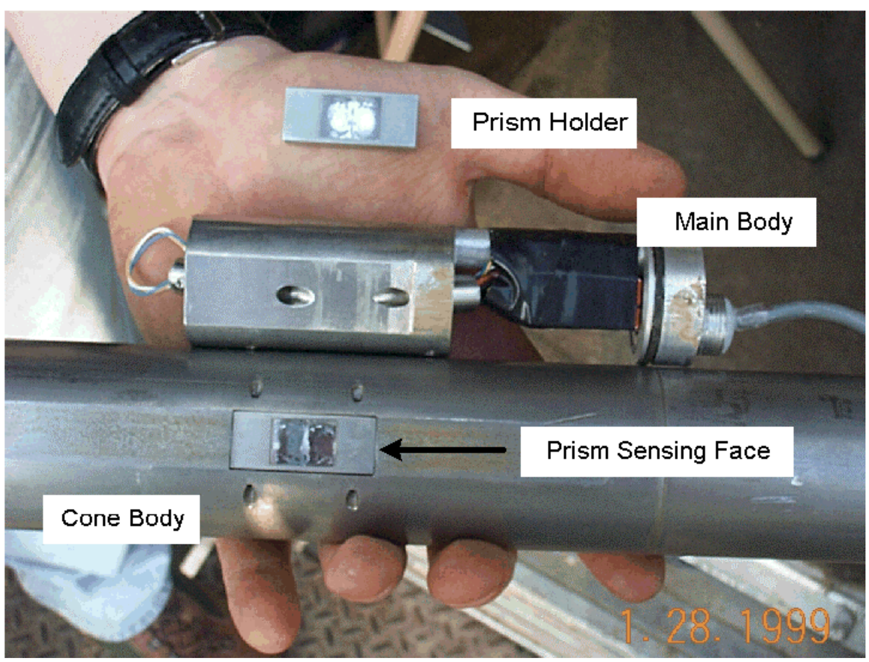

Figure 1. Components of IRS Module.

The IRS probe has the ability to detect both Dense-NAPLS and Light-NAPLs (LNAPLs). This report will primarily focus on detection and delineation of DNAPLs because this is the area with the greatest challenges and technology gaps.

An important feature of the device is that it responds only to NAPL contaminants, without interference from dissolved-phase chemicals, natural soil components, or groundwater. The sensor operates in both the vadose and saturated zones.

Advantages Over Baseline

The baseline method for the detection and delineation of subsurface DNAPLs is installing soil borings and collecting split-spoon samples. If groundwater has been impacted, selected boreholes are often completed into monitoring wells for long-term groundwater monitoring. Conventional drilling methods, such as hollow stem auger, cable-tool, or mud-rotary are typically utilized to access the subsurface. Confirmation of DNAPL presence is typically accomplished by laboratory analysis.

The CPT-deployed IRS can quickly and cost effectively screen a great number of locations for the presence of DNAPL with real-time results. Information gained from the CPT-deployed IRS system can be used to map DNAPL contamination, select the optimum location of monitoring wells, and devise remediation schemes. The CPT-deployed IRS can minimize installing soil borings and split-spoon sampling for the delineation of DNAPLs under appropriate conditions and has many advantages over baselines technologies. Advantages include:

- Real-time, *in situ*, continuous DNAPL detection;
- Lower cost;
- Minimum disturbance to the subsurface; and
- Decreased investigation derived waste (IDW): there are no drill cuttings.

Potential Markets

Since NAPL contamination is a common problem at industrial sites, the potential market for the CPT deployed IRS is significant. The CPT-deployed IRS is particularly marketable in the arena of DNAPL detection because baseline methods are slow, and costly. The technology can also be used for the detection of LNAPLs, such as gasoline, diesel fuel and other fuel oils at leaking Underground Storage Tank (UST) sites.

Demonstration Summary

The IRS was demonstrated at the Savannah River Site (SRS), M-Area Seepage Basin in Aiken, South Carolina, and at Sage Dry Cleaners, a former commercial site in Jacksonville, Florida. The M-Area Seepage Basin is contaminated with tetrachloroethylene (PCE) and trichloroethylene (TCE) and the subsurface geology is primarily sand and clay. The Sage site is contaminated with PCE and the subsurface geology at the Sage site is primarily sand. A total of four successful pushes were completed during the demonstrations; two of the pushes at SRS were to depths greater than 100 ft. DNAPL layers were successfully detected at both sites. Though the demonstration results were promising, some technical problems were also identified that need to be addressed before the technology is commercially ready.

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at www.em.doe.gov/ost under “Publications.” The Technology Management System (TMS), also available through the OST Web site, provides information about OST programs, technologies, and problems. The Tech ID for Internal Reflection Sensor for the Cone Penetrometer is 1723.

SECTION 2
TECHNOLOGY DESCRIPTION

Technology Summary

The CPT-deployed IRS is capable of providing *in situ*, continuous, and real-time detection of DNAPLs as the sensor is advanced through the subsurface. Discussions of internal reflection spectroscopy, CPT, and the integration of these two technologies are provided in the following paragraphs.

Internal Reflection Spectroscopy

Internal reflection spectroscopy is a relatively simple optical technique well suited for the detection of DNAPLs in soil and groundwater. The technique is based on changes in internal reflectivity of a light ray with changes in the medium at the sensing face of the prism. The heart of the sensor is the internal reflection element. This element is positioned in the wall of the penetrometer cone so that its sensing face is in contact with the soil or groundwater as the cone is pushed into the ground. When NAPL is not present at the sensing face, laser light is fully reflected within the element and is detected in the sensor head. However, when NAPLs come into contact with the sensing face, the internally reflected light is diminished. This results in a decrease in the signal output by the detector: a positive indication of NAPL presence. Because the response from the detector is continuously measured at the surface by a voltmeter or computer, NAPLs can be detected instantaneously.

The primary element of the IRS is a prism or similar element whose internal reflectivity changes based on the refractive index of the medium against its sensing face. Figure 2(A) shows a light ray being internally reflected in a prism. The condition for internal reflection is established by the refractive indexes of the prism (n_1) and the outside medium (n_2). Figure 2(B) demonstrates how internal reflection is lost when a light ray strikes the sensing face of the prism at an angle less than the critical angle. For a light ray to be reflected it must strike the sensing face at an angle greater than the critical angle ($\mathbf{q}_c$) defined by the following equation:

$$\mathbf{q}_c = \sin^{-1}(n_2/n_1)$$

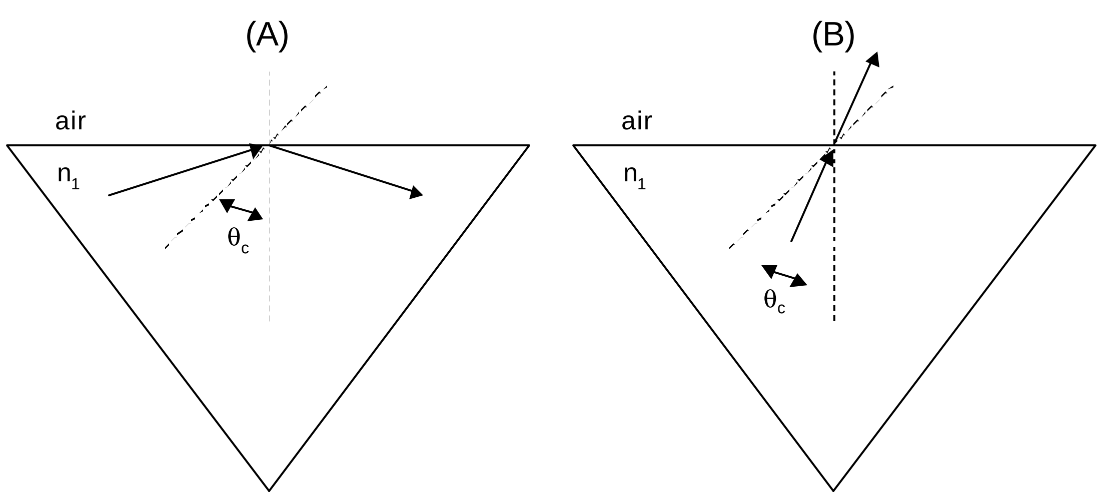

Figure 2. Paths of two light rays with different angles of incidence in silica prism with air at sensing face.

The equation above indicates that the critical angle for internal reflection depends on the sample refractive index, n_2. This simple relationship can be used for NAPL detection as shown in Figure 3 for a fused silica prism ($n_1 = 1.4584$) and a light ray striking the sensing face at 60°. When air ($n_2 = 100$) is the outside medium, $\mathbf{q}_c = 43°$,the light is internally reflected. However, when chloroform ($n_2 = 1.4460$) contacts the sensing face, the critical angle becomes 82°. The light ray, striking the interface at less than 82°, is no longer internally reflected - an instantaneous event easily detected as a decrease in internally reflected light.

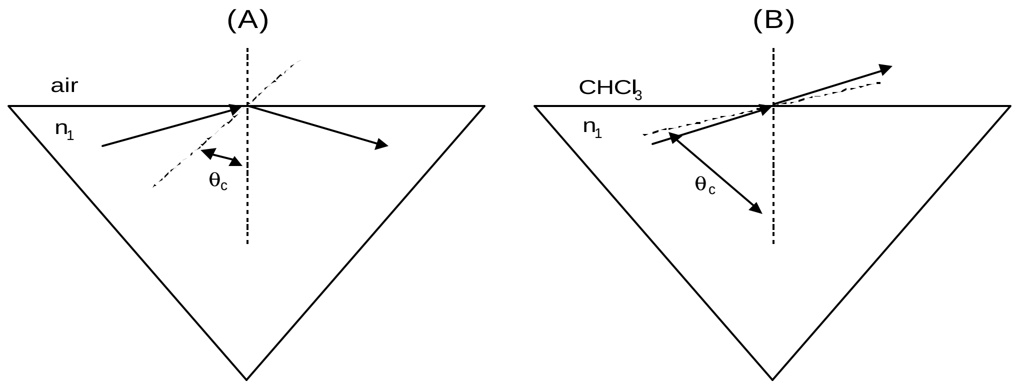

Figure 3. Paths of a light ray with air (A) and chloroform (B) at the sensing face.

To test the IRS principal, the response of the system was evaluated with 23 "pure" NAPL samples, selected to cover a wide range of refractive indexes (n_D). Table 1 contains the results. As expected, the internal reflectance decreased with increasing refractive index. All of the compounds with the exception of acetone, gave a strong easily measured response. A lower percent reflectivity corresponds to a greater decrease in voltage measured by a photodiode detector, which is a stronger measurable response.

Table 1. "Pure" NAPL test results

NAPL	nD	Starting mV	Final mV	ÎmV	% Reflectivity
Tap Water	1.333	311	311	0	100
Acetone	1.359	311	311	0	100
Icooctane	1.392	310	138	172	44.5
1-Butanol	1.397	310	108	202	34.8
Amyl Acetate	1.400	310	105	205	33.9
3- Methyl-1 Butanol	1.404	310	100	210	32.3
Decane	1.409	310	81	229	26.1
Cyclohexane	1.424	311	57	254	18.3
N, N-Dimethlyformamide	1.427	311	55	256	17.7
Dimethyl Adipate	1.428	310	55	255	17.7
Ethylene Glycol	1.429	309	50	259	16.2
Cyclohexanone	1.448	311	38	273	12.2
Carbon Tetrachloride	1.459	310	47	263	15.2
A-Pinene	1.465	310	39	271	12.6
Limonene	1.471	309	29	280	9.4
Glycerol	1.474	311	27	284	8.7
Dibutylphthalate	1.490	310	21	289	6.8
ASE 30 Motor Oil	1.495	310	21	289	6.8
Toluene	1.497	310	19	291	6.1
Tetrachloroethylene	1.506	310	26	284	8.4
Pyridine	1.507	310	20	290	6.5
Benzaldehyde	1.544	310	10	300	3.2
Aniline	1.583	309	4	305	1.3

Notes: mV = milli-volts, ÎmV = change in voltage

Cone Penetrometer Technology

CPT is a subsurface investigation tool that utilizes direct push technology to penetrate the subsurface. CPT typically consists of an enclosed 20-40 ton truck equipped with vertical hydraulic rams that are used to force a 1.75 inch-diameter, sensor probe into the ground. The CPT truck houses electronic signal processing equipment, and computer systems for data acquisition, processing, and storage. CPT serves as a platform for various sensor technologies for geotechnical, hydrogeological, and chemical characterization of the subsurface. CPT has proven to be a valuable tool in the environmental field and continues to gain value as new sensors are developed for specific measurements and characterizations. CPT does have limitations and is not applicable to all subsurface conditions. CPT is well suited to compacted sands and clays, but may experience difficulty in gravely soils where large cobbles and boulders are present. The technology can not penetrate cemented layers or rock strata.

Description of Integrated CPT-Deployed IRS

EIC has integrated IRS technology with CPT in a system consisting of the following primary components:

- 40-ton CPT Truck;
- Down-hole IRS module designed for CPT (dimensions: 13 in.-long by 1.75 in.-diameter);
- Low power micro-laser source, sapphire prism, and photodiode detector all housed in down-hole sensor; and
- Laptop computer with customized software for data acquisition and display.

A schematic of the IRS down-hole sensor module is shown in Figure 4. The outer housing of the module is constructed of hardened steel and all internal pieces are manufactured of stainless steel. Key sensing elements include a micro-laser source, sapphire prism, and photodiode detector. The micro-laser is a low power device (< 120 mA@5V, battery compatible) and the photodiode requires no power for operation. The micro-laser beam establishes the sensing area at 10 mm^2, which provides high spatial resolution when the sensor performs measurements in the subsurface. Only four electrical conductors, two for laser power and two for detector signal, are needed for the device. Each optical element is pre-assembled into a mount that can then be securely inserted, yet can be easily removed from the housing if replacement is necessary. The housing also contains a 0.25-in. diameter channel through which a standard cone penetrometer cable can pass. The IRS has no moving parts in the system. For preliminary field testing, both ends of the housing were threaded for compatibility with Applied Research Associates' (ARA's) cone penetrometer rods.

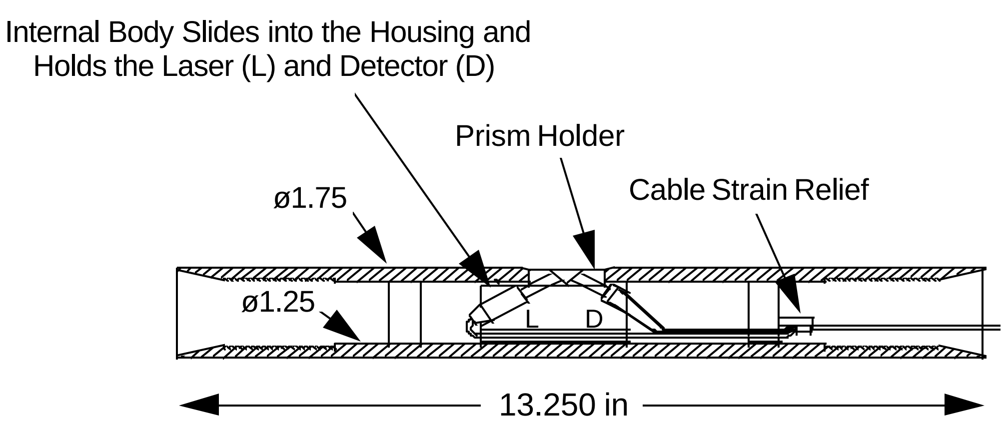

Figure 4. Schematic of IRS Probe

System Operation

Operation of the CPT-deployed IRS is relatively simple: as the IRS probe is pushed through the subsurface, it continually monitors the soil adjacent to the sensing face based on the internal reflection principal. A continuous signal is sent from the IRS to the surface where it is displayed on computer screen and electronically logged. The output from the IRS is a plot of voltage versus time. A positive detection of NAPL is indicated by a sudden decrease in measured voltage from the photodiode detector, due to a decrease in internally reflected light. After the sensor has passed through the NAPL region, the measured voltage will return to a baseline level.

The sensing face of the IRS probe is “cleaned” by the frictional forces of the compacted soil as the sensor is pushed through the subsurface. The frictional forces of the soil minimize vertical smearing of NAPL over the depth of the push. Therefore, the IRS has the ability to discretely determine the thickness of thin layers of NAPL.

The IRS does not add significant time or effort to operation of the CPT. The system does not require special calibration and operators need only minimal training to operate the IRS. Interpretation of the output data does require experienced personnel at this time, but with continued development, data interpretation should be simplified.

The operational parameters for the IRS provided below:

- Detects NAPL contamination in the vadose zone and saturated zone
- Provides real-time *in situ* detection
- Detects thin layers of NAPL
- Does not detect dissolved phase contaminants
- Does not differentiate NAPL type

The operational parameters for the CPT provided below

- Dependent on subsurface geologic conditions to assure penetration to the desired depths
- Highly effective in sandy and clayey soils, and has also demonstrated success penetrating cobbles and gravel at Hanford
- Does have difficulty at sites where large cobbles and boulders exist
- Has been applied at sites as deep as 300 ft, but is generally applied to depths up to 150 ft (U.S. Department of Energy 1996)
- Has the capability of grouting the hole as the rods are retracted

SECTION 3
PERFORMANCE

Demonstration Plan

The IRS was field-tested on three separate occasions using the DOE cone penetrometer truck; twice at the SRS in Aiken, SC and once at Sage Dry Cleaners, a former commercial site, in Jacksonville, Florida. Both sites are known to have subsurface DNAPL contamination. The objective of the demonstrations was to utilize the CPT-deployed IRS probe to positively identify the presence of DNAPL in the subsurface, and in real time. To verify the results of the IRS probe, a CPT Raman sensor was co-deployed with the IRS probe at the SRS site. Validation of the results at the Sage site was based on information from previous site investigations.

Savannah River Site

The first two demonstrations of the IRS were conducted at SRS using the DOE cone penetrometer truck in February and June of 1998. The demonstration test site was the M-Area Seepage Basin. The basin has a history as the disposal site of several million kilograms of waste solvents in the 1950s. These solvents, primarily PCE and TCE, were used in vapor degreasing operations. This site is well characterized with respect to both geology and extent of contamination. The subsurface geology is primarily sand and clay. Two successful pushes where completed at the M-Area Seepage Basin to depths greater than 100 ft.

Sage Dry Cleaners, Jacksonville, FL

A third demonstration of the IRS was performed at a commercial site in Jacksonville, Florida. This site, known as Sage Dry Cleaners, was once a commercial dry cleaning site and later used as a gas station. The site is well characterized and heavily contaminated with PCE. The subsurface geology is primarily sand. The demonstration at the Sage Dry Cleaners consisted of two pushes in one day and was accomplished in cooperation with ARA, the operator of the DOE cone penetrometer truck.

Results

Savannah River Site

During the first field test of the IRS in February, no useful data was obtained. A problem was encountered with water entering the sensor and damaging the internal electronics. As a result, the IRS was redesigned and a more liquid tight IRS was built.

The second field demonstration at SRS was accomplished in cooperation with Fugro Technologies, the company that operated the DOE cone penetrometer truck at that time. Three pushes were installed over two days. This demonstration was cut short when the threads of the IRS section failed as the cone penetrometer hit a large obstruction and encountered refusal.

The results generated from the first push conducted at the M-area Seepage Basin are presented in Figures 5 and 6. Figure 5 is a plot of voltage versus time over the entire 115-ft depth of the first push. During this push a positive NAPL response was detected at 3500 seconds, which correlated to a depth of approximately 100 feet. Figure 6 presents an expanded view of the positive response. A true positive response from the IRS can be seen as a rapid drop in voltage and will have a generally square profile. The square profile is evident in Figure 6. The rapid drop in voltage quickly recovered as the chemical was wiped away from the sensing face of the prism. The increases within the response are due to the contaminated soil contacting the sensing face until the cone passes through the contaminated area. The Raman sensor confirmed this positive response by detecting PCE at the same depth.

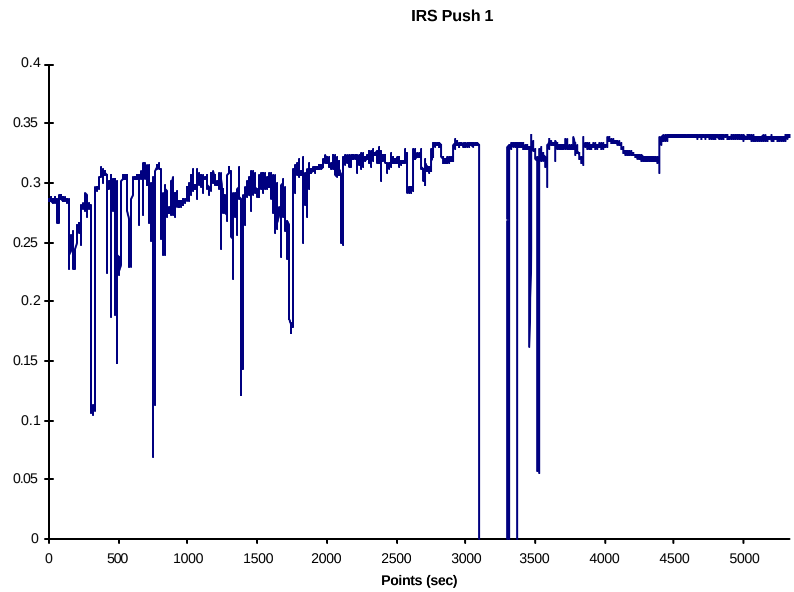

Figure 5. Result of Push 1 at SRS (volts vs. time)

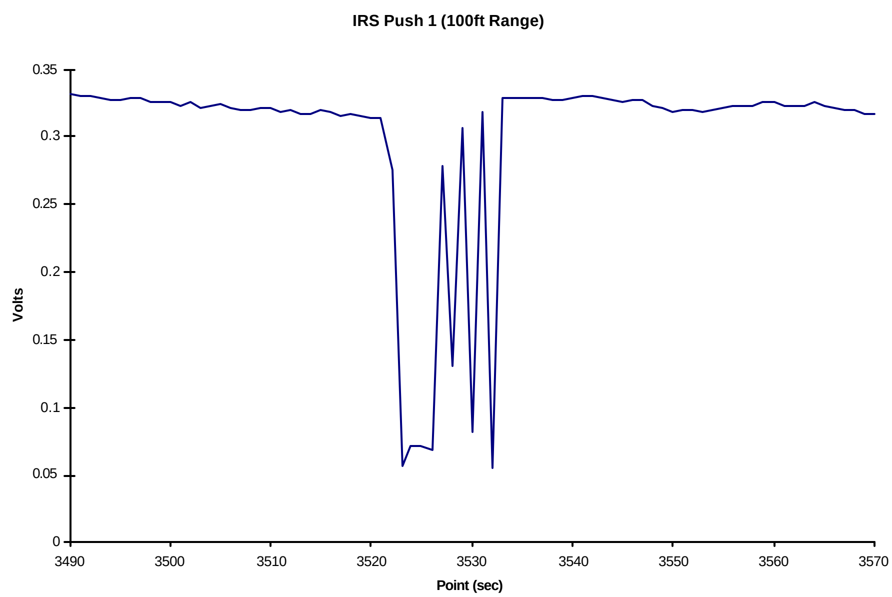

Figure 6. Enlarged view of positive response during Push 1 (volts vs. time).

Gradual or erratic voltage drops that do not fit the square profile described above are most likely false responses caused by deflection of the sensor under heavy stress. High stress causes the sensor to flex, resulting in a slight misalignment of the laser and detector, which causes the overall voltage to decrease. High levels of stress on the cone rods are also detectable from within the CPT truck. The truck usually bounces and reacts to the stresses of the cone penetrometer being pushed through hard soil or past obstructions. A typical false response that is due to stress is observed at 1500 -1800 seconds in Figure 5.

The second push at SRS, shown in Figures 7 and 8, again showed a positive NAPL response at approximately 100 ft. The overall profile of the data in Figure 7 (decreasing voltage) is due to stress on the cone penetrometer throughout the entire push. Though the voltage gradually decreases due to stress, a positive response at 2750 seconds (approximately 100 ft) is still detectable. The temporary increase in voltage at approximately 1800 seconds was probably due to a temporary relief in the stress on the cone. The positive response at 100 ft was also confirmed with the Raman sensor as PCE.

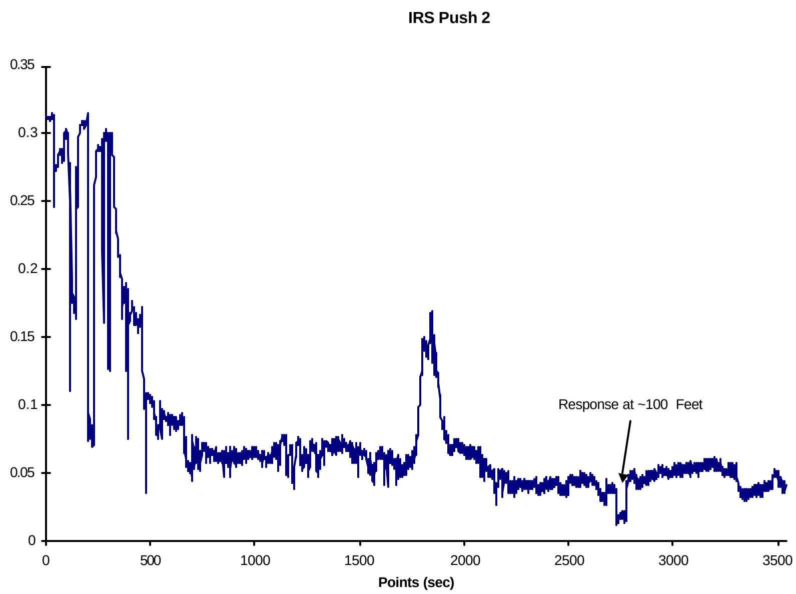

Figure 7. Results of Push 2 at SRS (volts vs. time)

Figure 8 shows, in detail, the response at 100 feet. The graph depicts what a true positive response should look like. The voltage decreases as soon as the sensing face of the prism come into contact with any chemical having a higher index of refraction than water. The voltage drop continues until the sensing face is wiped clean.

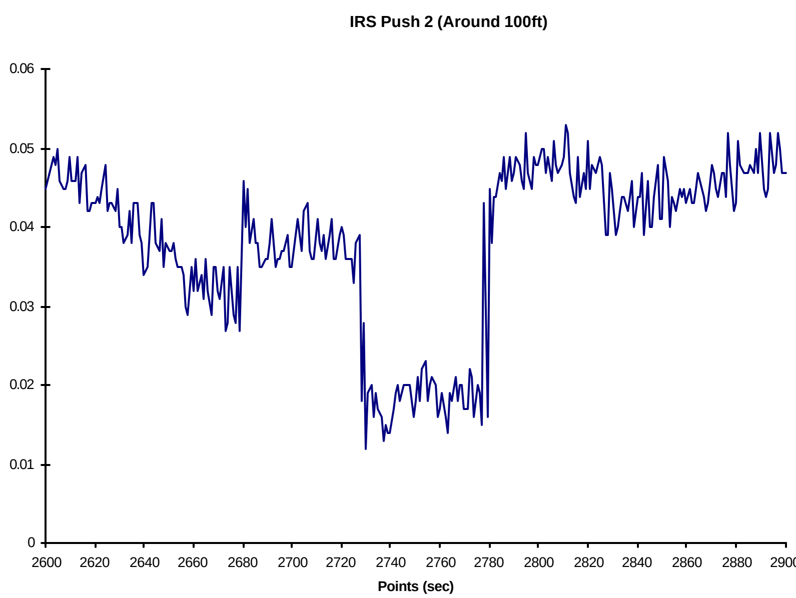

Figure 8. Enlarged view of positive response during Push 2 at SRS (volts vs. time).

Sage Dry Cleaners, Jacksonville FL

Two pushes were performed in one day at the Sage site, unfortunately, both pushes ended with laser failure: at approximately 18 ft and 22 ft respectively. The cause for the laser failure in the first push was back reflection of laser light into the laser source, which is detrimental to the laser. The laser failure on the second push was due to a plug that came loose from the laser's power source. The Raman Sensor was not co-deployed with the IRS at the Sage site; therefore, the only verification of the IRS response is historical site data.

The results of the first push at the Sage site are presented in Figure 9. The laser power ultimately failed at a depth of 18 ft, but some useful data was gained prior to laser failure. A true positive response occurred at approximately 14 feet, as indicated on Figure 9. The response was weak, probably due to the contaminate being mixed with water. The ground morphology at the site is sandy with water throughout.

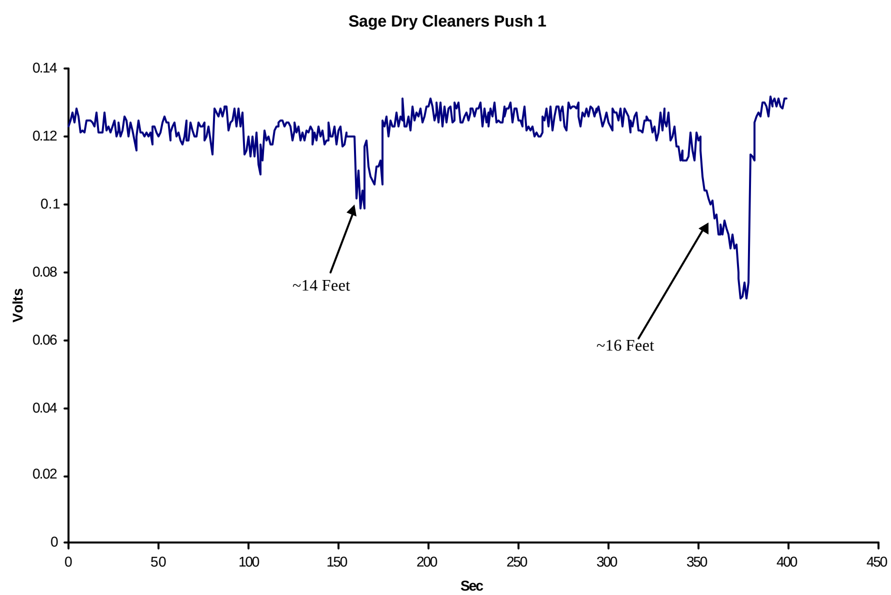

Figure 9. Results from Push 1 at Sage Site (volts vs. time).

The positive response at 14 ft has the typical square profile associated with a true positive response. It is difficult to determine whether the voltage drop at 16 ft is a true positive response or a false response due to stress on the cone penetrometer. The initial drop is abrupt, like a true positive response, but then decreases slowly. The cause of voltage drop at 16 ft was most likely stress.

The second push at the Sage site is depicted in Figure 10. Unfortunately, the laser failed after approximately 22 feet. The response at 20 feet is a true positive response, and corresponds to historical data as to the depth of most contamination. The response at 18 feet was due to stress on the cone penetrometer.

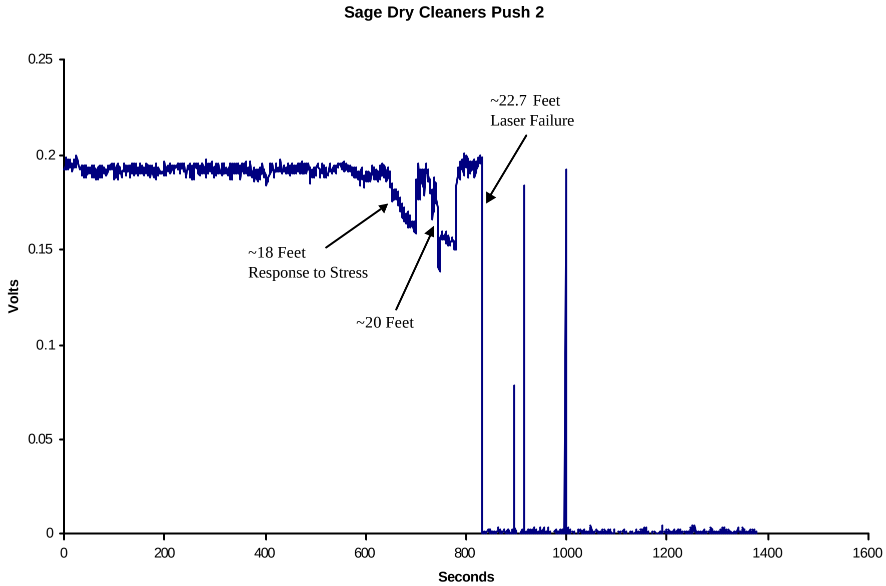

Figure 10. Results from Push 2 at Sage Site (volts vs. time).

Summary of Results

The results from demonstration of the IRS provided valuable information about the capabilities and shortcomings of the prototype sensor. The IRS responded positively to the presence of DNAPL in a manner that could be utilized to detect DNAPLs. Though the IRS responded positively to the presence of DNAPL, extraneous responses were also observed that complicated the interpretation of results. The extraneous responses were attributed to flexure of the sensor resulting in a decrease in reflected light. In some cases it is difficult to definitively determine whether the probe is responding positively to DNAPL or responding falsely due to flexing of the sensor. The problem, related to the probe flexing under stress, should be correctable by design modifications to give the sensor additional strength and rigidity.

SECTION 4
TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Technology Applicability

The IRS is applicable to locating DNAPLs in subsurface soils that are accessible by CPT. The instrument has great value as an initial screening tool at sites where DNAPLs are likely to be present. As the first tool in a subsurface investigation, the IRS could be used to screen many points over a large area for the presence of DNAPL. Valuable geologic information (e.g. lithology and stratigraphy) could also be gained from standard CPT sensors and instrumentation. The real-time results can be utilized to direct field activities. Ultimately, a more accurate picture of DNAPL contamination will result from investigation of a great number of data points. Further, the possibility of “missing” thin zones of DNAPL will be minimized. The IRS for CPT can also be used as a screening tool to determine the optimum location of monitoring wells for long-term groundwater monitoring.

The CPT-deployed IRS can also be utilized after an initial site investigation has been performed to further delineate DNAPL contamination. Often a site investigation will conclude that DNAPL is present in the subsurface, but the exact location and extent of the contamination is often not clearly defined. Accurate delineation of DNAPL is crucial to design effective remediation systems. Therefore, the IRS can also be valuable at a site that has been previously investigated, but where the investigation failed to accurately delineate DNAPL.

Competing Technologies

Baseline Technologies

The baseline technology utilized for characterization of the subsurface with respect to DNAPL contamination is installation of soil borings and collection of split-spoon samples. Bore holes may be converted into monitoring wells for long-term groundwater monitoring. Soil borings and monitoring wells are commonly installed using conventional rotary and auger drilling methods, and the soil samples are typically transferred to an off-site laboratory for analysis of DNAPL constituents.

Soil samples are typically collected by split-spoon sampling. Split-spoon samples can be screened with an organic vapor analyzer (OVA) and visually inspected to determine if DNAPL is present. Laboratory analysis may be performed to confirm the DNAPL presence and chemical constituents. Split-spoon sampling is also utilized to assess subsurface geologic conditions that affect the migration of DNAPL.

If groundwater has been impacted, monitoring wells are typically installed as a long-term means for monitoring groundwater contamination. Regulators typically require a minimum of three to four monitoring wells at sites where groundwater has potentially been impacted.

Advantages Over Baseline

The CPT-deployed IRS has many advantages over installing soil borings and split-spoon sampling.

- CPT is less expensive than conventional rotary and auger drilling
- CPT is faster than split-spoon sampling using conventional drilling techniques
- The technology provides real-time indication of the presence and location of DNAPLs via computer display

- Real-time results can be used immediately in the field to direct investigation and expedite characterization

- *In situ* analysis minimizes the human exposure to hazardous contaminants

- CPT provides minimal disturbance of the subsurface, as no drilling fluids are used and the hole diameters are small (less than 2 in.); this also minimizes migration of contaminants from shallower to deeper horizons during pushes

- CPT does not create drill cuttings

- The hole created by CPT can be grouted as the probe is removed

Strengths of Baseline Technology:

- Conventional rotary and auger drilling techniques are rugged and applicable to all types of subsurface geology

- Laboratory sample analysis provides quantitative results including chemical constituency

- Quantitative laboratory analysis of soil and groundwater is reliable, legally defensible, and often required by regulatory agencies

Other Competing Technologies

Due to the great need for sensor technologies that detect DNAPL, the DOE has funded the development of several technologies to this end. The following innovative technologies are available at various stages of development and demonstration:

- Raman Sensor for CPT

- Laser Induced Flourescence for CPT

- CPT-Enhanced Spectral Gamma Probe

- Differential Partitioning Gas Tracer Tests

- Small-Scale Alcohol Micro Injection/Extraction Test

- Hydrophobic Sorbent on Flexible Membranes

- Tomographic Site Characterization using CPT, electrical resistance tomography (ERT), and ground penetrating radar (GPR)

Patents/Commercialization/Sponsor

Research and development on the IRS by EIC Laboratories, Inc. was sponsored by the U.S. Department of Energy's National Energy Technology Laboratory (NETL). Demonstration of the technology was performed at SRS in conjunction with Fugro and ARA, both contracted operators of the DOE Cone Penetrometer truck. Westinghouse Savannah River Company was also involved with the SRS demonstration through a program funded by the Office of Science and Technology (OST) for evaluation of CPT sensors and deployment support.

EIC Laboratories is an R&D corporation that has a successful track record developing technologies in various areas for commercial applications and intends to commercialize the IRS. EIC currently has no patent rights on the IRS technology

SECTION 5
COST

Methodology

The cost information for the IRS probe presented here is based on data provided by EIC Laboratories, Inc. and is based on the demonstration of the technology at SRS and Sage Dry Cleaners. The costs for the baseline technology are based on costs reported in a Cost Analysis of DNAPL Characterization Tools (MSE Technology Application Inc, 1999) which is based on costs specific to SRS. Other cost information was obtained from published cost data from R.S. Means, Inc. (ECHOS 1998). The 1998 costs are indexed to June 1999 at a rate of 2.0 percent based on Engineering News Record's construction cost index (Engineering News Record, 1999).

The goal of the cost analysis is to compare the cost associated with the CPT-deployed IRS probe and the baseline technology. The baseline technology to which the CPT-deployed IRS probe will be compared is installation of soil borings and collection of split-spoon samples by hollow stem auger drilling.

Cost Analysis

CPT-Deployed IRS Costs

The cost for the CPT-deployed IRS are based on the following assumptions:

- The capital cost of the IRS system is $10,000 based on the prototype unit and includes the sensor, and related computer hardware and software

- To calculate a daily cost for the IRS system, the capital cost was distributed over a 1-year useful life and a utilization rate of 130 days/year (50% utilization)

- Costs are based on Safety Level D work conditions

- The push rate of CPT-deployed IRS is 400 ft/day (4 pushes of 100 ft each)

- CPT rods will be decontaminated as they are retracted from the ground and one 55-gallon drum of hazardous liquid will be generated for the 4 holes

The primary costs associated with the CPT-deployed IRS are presented in Table 2. The costs are calculated based on installing 4 pushes to a depth of 100 ft each in one work day.

As presented in Table 2 the average cost to install a 100 ft push using CPT-deployed IRS is $1,567, which translates to a cost per foot of $15.67. The low overall cost of CPT-deployed IRS is made possible by the low cost of IRS system itself ($10,000), the relatively high speed and low cost of CPT, and the small amount of waste produced. A primary factor that could result in a higher cost is difficult subsurface conditions that can result in push rates slower than 400 ft/day.

Table 2. Costs for IRS (based on 4 pushes to 100 ft).

Description	Qty	Units	Unit Cost($)	Price($)
IRS system	1	day	77	77
CPT	400	ft	7.25	2,900
Disposal of decontamination fluids[1]	1	drums	215	215
Grout hole	400	ft	2.50	1,000
Stand by time	1.5	hr	321	482
Decontamination	1	hr	175	175
Per-diem (2 person-crew)	1	day	165	165
			Sub-total:	5,014
Engineering (10%), G&A Overhead (10%), Fee (5%), Total = 25%				1,253
			Total:	6,267
			Average cost per 100 ft push	1,567
			Average cost per foot	15.67

[1]Based on landfill disposal of (1) 55-gallon drum of liquid/sludge requiring stabilization
Note: Mobilization cost of $2,500 for CPT rig is not included in calculations above

Baseline Costs

The baseline technology for which costs are presented is installation of soil borings to collect split-spoon samples. The costs provided for the baseline are based on the following assumptions:

- Hollow-stem auger drill rig will be utilized to drill an 8 in. outside diameter borehole
- Split-spoon samples will be collected at 5 ft intervals
- Split-spoon samples will be visually inspected for DNAPL and will be screened with an OVA
- One soil sample will be analyzed per split-spoon at an analytical laboratory for VOC's (Method SW 5030/SW8240) on a standard turn-around time
- Drill cuttings will be generated at a rate of one 55-gallon drum per 17 ft of borehole (6 drums per 100 ft borehole)
- Drill cuttings will be disposed at a landfill as a hazardous solid waste
- Soil borings will be grouted closed after sampling
- Two soil borings can be installed to 100 ft with split-spoon sampling each work day

The primary costs associated with installing soil boring to collect split-spoon samples are presented in Table 3 below. The costs are calculated based on installing 4 borings to a depth of 100 ft each in two working days.

Table 3. Costs for soil borings (based on 4 borings to 100 ft).

Description	Qty	Units	Unit Cost ($)	Price ($)
Hollow-stem auger (8 in. diameter)	400	ft	10.00	4,000
Split-spoon sampling	400	ft	20.00	8,000
Organic vapor analyzer rental	2	days	132	264
Volatile organic analysis-solid (SW5030/SW8240)	80	ea	144	11,520
Disposal of drill cuttings	24	drum	266	6,384
Disposal of decontamination fluids	2	drums	215	430
Grout borehole	400	ft	3	1,200
Standby labor	3	hr	170	170
Decontamination labor	1	hr	100	100
Per-diem for 3 person crew	2	days	248	496
			Sub-total:	32,564
Engineering (10%), G&A Overhead (10%), Fee (5%), Total: 25%				8,141
			Total:	40,705
			Average cost per 100 ft soil boring	10,176
			Average cost per foot	101.76

Note: Mobilization cost of $2,000 for drill rig and crew is not included in calculation above

As presented in Table 2, the average cost to install one soil boring to a depth of 100 ft to collect split-spoon samples is $10,176, which translates to a cost per foot of $101.76. The relatively high cost of installing soil borings can be attributed to the slow, labor intensive nature of the technology.

Factors that could affect the overall cost of hollow-stem auger drilling are the type and concentration of the contaminants present, which affects the disposal costs. Disposal costs can be in excess of $585 per drum if incineration is required (R.S. Means 1998). In the cost comparison presented above, a cost of $266 per 55-gallon drum of solid waste and $215/drum for liquid wastes was used. Drilling an 8-inch borehole results in approximately one 55-gallon drum of drill cuttings per 17 feet of drilling (nearly 6 drums per 100 ft). The only waste generated from CPT is rinse water from decontaminating the probe rods as they are retracted from the ground.

Cost Conclusions

Based on the cost data presented in Tables 2 and 3, it is evident that CPT-deployed IRS is less costly than soil boring/split-spoon sampling. On a unit cost basis, installing a soil boring and collecting split-spoon samples is approximately $102 per foot compared to $16 per foot for the CPT-deployed IRS. The cost to install soil borings and collect split-spoon samples is 6 times greater than the cost of pushing the IRS probe to an equal depth using CPT. Because CPT-deployed IRS technology is less expensive than soil borings, a greater number of CPT pushes can be performed for an equivalent cost, and ultimately a more comprehensive investigation can be performed.

To further compare the costs of the CPT-deployed IRS and the baseline, a calculation was performed to determine how many CPT pushes and soil borings can be installed to a depth of 100 ft for equivalent costs (ranging from $50,000 - $300,000). This number was calculated by taking the desired cost (e.g. $50,000), subtracting the mobilization/demobilization cost, then dividing by the average cost for a 100 ft installation (presented in Tables 2 and 3). The resulting number was rounded to the nearest integer. Results of these calculations are presented in Table 4 and represented graphically in Figure 11.

Table 4. Number of CPT pushes/soil borings vs. cost.

	Number of CPT Pushes or Soil Borings Installed for Given Cost					
Cost (thousands):	**$50**	**$100**	**$150**	**$200**	**$250**	**$300**
IRS	30	62	94	126	158	190
Soil borings	5	10	15	19	24	29

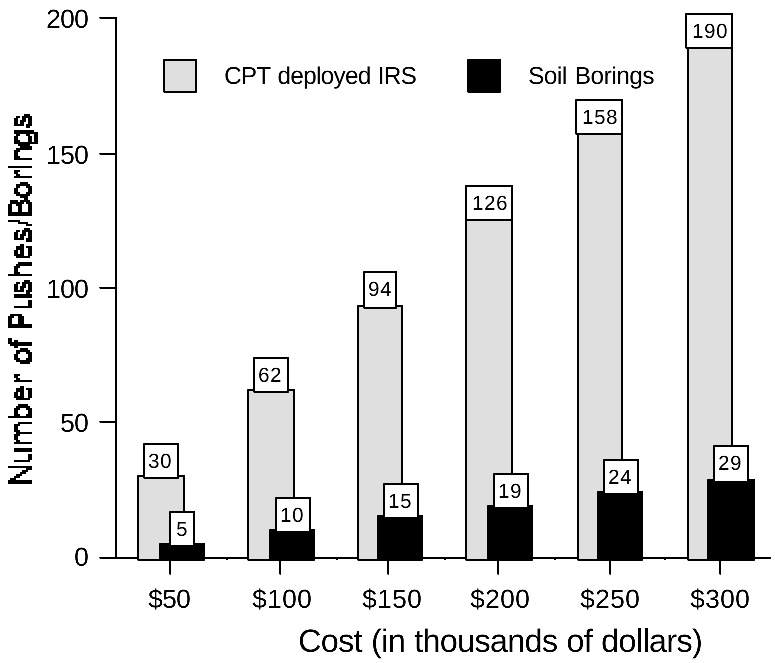

Figure 11. Number of CPT Pushes/soil borings versus cost.

Based on information presented in Figure 11, for $50,000, only 5 soil borings could be installed, but 30 pushes could be installed using CPT-deployed IRS for the same cost. At the higher end of the scale, a budget of $300,000 would allow 29 soil borings to be installed, while for the same cost, 190 pushes could be installed with CPT-deployed IRS. The CPT-deployed IRS will allow a greater number of locations to be investigated, thus providing more detailed delineation of DNAPL, while minimizing the potential for “missing” DNAPL zones.

Use of CPT-deployed IRS can also result in direct cost savings. For example, it would cost $200,000 to install 19 soil borings to 100 ft. Using CPT-deployed IRS, spending $100,000 (half of the cost of the baseline) would allow 62 pushes to be installed. This may be adequate to meet the objectives of a site investigation at particular site. This would still allow more characterization data to be gathered concerning DNAPL location at a lower cost.

SECTION 6
OCCUPATIONAL SAFETY AND HEALTH

Comparison with Baseline and Alternative Technologies

The baseline method for subsurface characterization of DNAPL is conventional drilling followed by collection of soil and groundwater samples for laboratory analysis. The CPT deployed IRS has many occupational safety and health benefits compared to the baseline. Because the IRS collects measurements *in situ*, it minimizes worker exposure to hazardous contaminants during sample collection, transport, and analysis. Further, CPT does not generate contaminated drill cuttings or drilling fluids that must be handled by workers. CPT is also much safer than rotary drilling in terms of the physical hazards associated with moving parts on drill rig. CPT utilizes a hydraulic ram to force the rods into the subsurface and has few moving parts compared to conventional drill rigs.

Required Safety and Health Measures

The IRS probe for CPT does not require extraordinary safety and health measures compared to other CPT sensors. The micro-laser used to create the beam of light is a low power device (< 120 mA@5V, battery compatible) is considered a class 1 laser as packaged in the sensor and is considered harmless. If the laser is removed from the sensor, it is considered a class 3B laser, which can cause eye and skin damage from direct, momentary intrabeam exposure. Should the sensor require maintenance, personnel trained regarding the safety precautions for this type of laser are required. Standard safety practices for CPT operations should be followed to address the mechanical and electrical hazards associated with the components of the CPT rig. Operations at sites contaminated hazardous or radiological contaminants should be performed in accordance with approved Site Health and Safety Plans.

SECTION 7
REGULATORY AND POLICY ISSUES

Regulatory Considerations

- Results gained through use of the IRS probe do not take the place of analysis by a certified analytical laboratory with regard to meeting local, state, or federal regulatory requirements. The CPT-deployed IRS is meant to be a field screening tool to aid in the efficiency and accuracy of site characterization. Confirmation samples would be required by regulators to document site characterization.

- Conventional drilling/sampling activities create investigation derived wastes such as drilling fluids, cuttings, and equipment decontamination fluids that must be handled according to applicable local, state, and federal. CPT generates minimal waste (decontamination fluid only).

- No special permits are required for the operation of a CPT. Regulatory approval is typically handled as in standard drilling where a drilling plan is submitted to the appropriate regulatory agency for their approval prior to initiation of field activities.

Risks, Benefits, Environmental and Community Issues

Environmental Impact

Environmental impacts of CPT are generally less than with conventional drilling

- No drill cutting or drilling fluids are produced during operation

- CPT is minimally intrusive and does not mobilize contamination: holes are smaller in diameter than most drill rods, and can be grouted during retraction of the CPT rods

- The entire system can be decontaminated at the surface with a minimal amount of fluid

Socioeconomic Impacts and Community Perception

- Utilization of the CPT-deployed IRS will have a minimal impact on the labor force and the economy of the region

- The general public has limited familiarity with CPT or IRS technologies, but would be expected to support it as an improvement over baseline technology as it is less intrusive than conventional drilling

SECTION 8
LESSONS LEARNED

Implementation Considerations

Prior to implementation, the end user should consider the capabilities and limitations of the IRS for CPT. The IRS is capable of providing a positive or negative indication of DNAPL presence, *in situ*, and in real time. The low cost and high speed of the IRS for CPT allow a great number of areas to be investigated in a cost-effective manner. This capability is valuable for locating and mapping hard to find DNAPLs in the field. Limitations of the IRS are discussed below.

Technology Limitations and Needs for Future Development

- The IRS does not differentiate between different NAPL types or speciate constituents
- The IRS does not detect dissolved phase contamination
- CPT is highly effective in sandy and clayey soils, but is not applicable at sites where cemented layers, large boulders, and rock exists
- The ability of CPT to reach desired depths is dependent on subsurface geologic conditions

Needs for Future Development

The results from the demonstrations were positive overall, but areas for improvement exist that need to be addressed through design modifications with additional testing with verification:

- Demonstration results showed that the IRS exhibited extraneous false responses. These false responses are attributed to stress on the IRS module that causes the module to flex. In its current state, the IRS probe components such as the prism, laser, detector, and probe main body, are held in place with setscrews. The setscrews allow repairs to be made to the system, such as changing the laser. To eliminate flexing, the components need to be held in place in a more rigid manner which may be provided through welding or brazing. In particular, the IRS probe main body and the prism hold needs to be attached permanently into the cone section for the IRS. With this modification, the IRS cone section would gain strength, but loose ease of maintenance and would essentially be a disposable unit.
- Additional testing of the IRS with validation by another cone penetrometer sensor such as the Raman or laser induced fluorescence (LIF) sensor should be performed. This can be accomplished by using the IRS in tandem with a Raman or LIF sensor during a cone penetrometer push to validate the response. Although this was performed in some of the cone penetrometer pushes at SRS, additional validation pushes and more controlled validation experiments are still needed to provide defensible data.
- The durability and ruggedness of the IRS requires improvement. The IRS experienced technical problems of some type during all three demonstrations. Most of the technical problems were addressed with design modifications. For the IRS to be widely accepted as a characterization tool, its field ruggedness and dependability must be proven.
- The IRS software needs to be modified so the results are automatically correlated to depth. Currently, the IRS logs voltage versus time, and the CPT software logs depth independently of the IRS.

APPENDIX A
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APPENDIX B
ACRONYMS AND ABBREVIATIONS

ARA	Applied Research Associates
CPT	Cone Penetrometer Technology
DNAPL	Dense Non Aqueous Phase Liquid
DOE	Department of Energy
ERT	Electric Resistance Tomography
GPR	Ground Penetrating Radar
IDW	Investigation Derived Waste
IRS	Internal Reflection Sensor
LIF	Laser Induced Flourescense
LNAPL	Light Non Aqueous Phase Liquid
MSE	Mountain States Environmental
NETL	National Energy Technology Center
OVA	Organic Vapor Analyzer
PCE	Perchloroethylene
SRS	Savannah River Site
TCE	Trichloroethylene
TMS	Technology Management System
UST	Underground Storage Tank