Innovative Technology
Summary Report

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Fiber Optic/Cone Penetrometer System for Subsurface Heavy Metals Detection

Subsurface Contaminants Focus Area
and Industry Programs

Prepared for
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INNOVATIVE TECHNOLOGY
Summary Report

Fiber Optic/Cone Penetrometer System for Subsurface Heavy Metals Detection

OST/TMS ID 319

Subsurface Contaminants Focus Area
and Industry Programs

Demonstrated at
Sandia National Laboratory
Chemical Waste Landfill
Albuquerque, New Mexico

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 http://ost.em.doe.gov under "Publications."

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SUMMARY

Technology Summary

Problem

Heavy metals contamination of surface and subsurface soil exists at numerous DOE sites. Characterization of the subsurface for heavy metals is expensive and time consuming. The present method of drilling, sampling, and laboratory analysis offers high sensitivity, but the time and cost associated with such methods often are limiting factors. Thus, there is a need for a fast, cost-effective, *in situ* system for subsurface characterization for metals contamination.

Solution

An integrated Laser Induced Breakdown Spectroscopy (LIBS) and Cone Penetrometer Technology (CPT) system has been developed to analyze the heavy-metals content of the subsurface soils *in situ* and with rapid results (currently less than 24 hours). A schematic of the subsurface heavy metal detection system is provided in Figure 1. This site characterization tool will use CPT to deploy an optical fiber chemical sensor which is based on LIBS technology.

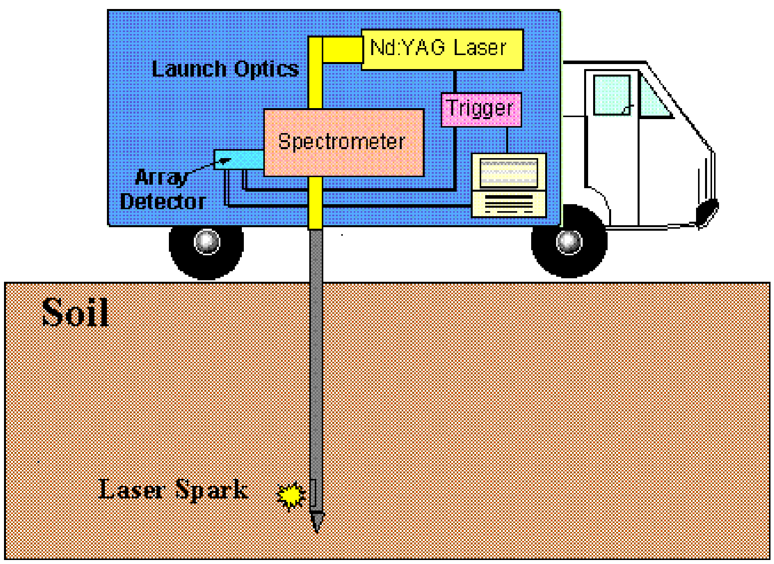

Figure 1. Subsurface Heavy Metal Detection System.

The LIBS system can also be deployed in a stand-alone system (without CPT) to analyze surficial soil samples or grab samples. Surficial soil can be analyzed *in situ* using a back-pack or cart-mounted system, and grab samples can be analyzed on-site using a portable system housed in a van or office trailer. The stand-alone LIBS system is addressed in Section 4: Technology Applicability.

How It Works

The CPT-deployed, LIBS based system utilizes a high energy laser pulse, delivered by a Nd:YAG (Neodymium: Yttrium Aluminum Garnet) Laser, operating at 1.06 µm. The soil will absorb the laser energy and heat rapidly to an electronically excited plasma. When the excitation energy is removed, the excited electrons drop to lower energy levels with the emission of characteristic photons. The plasma emission spectrum from the sample is observed via an optical fiber. Elemental analysis is conducted by observation of the wavelength and intensities of the emission lines, which will depend upon the type and amount of material present within the plasma. This technique has shown to be an effective method for the quantitative analysis of contaminants in soils.

Advantages Over Baseline

The baseline method is sample collection by conventional drilling, followed by analysis at an off-site laboratory. The baseline method, though reliable and accurate, is slow and expensive. Typically, cost limits the number of samples collected and analyzed, thus reducing the overall accuracy of the site characterization.

The CPT/LIBS system offers both time and cost savings over the baseline technology. Rapid results can be utilized to optimize sampling methodology. The current system can produce quantitative results in less than 24-hours, and with future software advances results could be made available in minutes. The baseline method of sending samples to an off-site laboratory requires a more lengthy chain of custody, and typically, weeks pass before results are available. Often the characterization activities have concluded before the first analytical result is obtained and, in many instances, the analytical results indicate that additional samples are required.

- The CPT/LIBS System for Subsurface Heavy Metals Detection has the following advantages:
  - Rapid, in-situ analysis allows for on-site identification of the location and concentration of heavy metal contamination
  - Continuous measurements over the depth of a penetration
  - Rapid analysis: a single position can be analyzed in less than a minute
  - Low cost, high production rate
  - Minimal intrusion, and minimal waste generation
  - In situ analysis minimizes worker exposure to potentially hazardous samples

Potential Markets

Forty-one percent of the sites on the National Priority List report metals contamination, with lead (Pb) and chromium (Cr) being most often cited for a wide variety of industries (Saggese, 1999). Due to the wide spread presence of metals contamination within the DOE complex and at public and private sector sites, the market for this technology is significant.

Demonstration Summary

The CPT/LIBS System for Subsurface Heavy Metals Detection was succesfully demonstrated at the Chemical Waste Landfill (CWL) at Sandia National Labs (SNL) outside of Albuquerque, New Mexico. The demonstration of the CPT/LIBS system focused on measurement of chromium as a function of depth. The CPT/LIBS results correlated well with data collected from past soil borings installed in the test location.

Science and Engineering Associates, Inc. (SEA) also successfully field tested two stand-alone LIBS instruments developed by Los Alamos National Laboratories (LANL): a backpack-mounted system for *in situ* analysis of surficial soils and a van-housed system for field analysis of ex situ soil samples. This field test was conducted at a Formerly Utilized Sites Remedial Action Program (FUSRAP) site in Luckey, Ohio to evaluate the beryllium concentration in surficial soils.

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Other

All published Innovative Technology Summary Reports are available on the OST Web site at http://em-50.em.doe.gov under "Publications." The Technology Management System, also available through the OST Web site, provides information about OST programs, technologies, and problems. The OST Reference # for Fiber Optic/Cone Penetrometer System for Subsurface Heavy Metal Detection is 0319.

SECTION 2

TECHNOLOGY DESCRIPTION

Overall Process Definition

The CPT/LIBS System for subsurface heavy metals detection is an innovative technology that combines the technologies of LIBS, CPT, and fiber optics. LIBS is a chemical analysis technique that has proven to be an effective method for the quantitative analysis of contaminated soils. CPT is a proven, direct-push, subsurface investigation tool, that has been widely utilized for collecting *in situ* measurements such as tip resistance, electrical resistivity, pH, and temperature. Fiber optics are utilized to transfer light information from a subsurface point of measurement to a detection device at the surface. Integration of the fiber optic sensor with the CPT results in a system that will enable *in situ*, low cost, high resolution, rapid, subsurface characterization of numerous heavy metal soil contaminants simultaneously. A basic fiber optic LIBS system is shown in Figure 2.

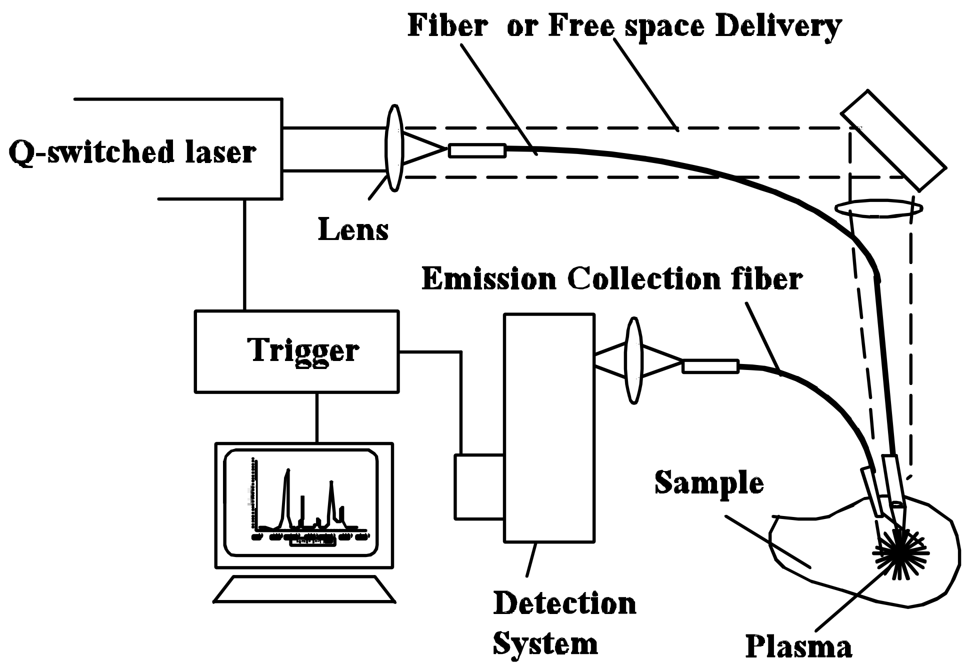


Figure 2. A typical laser induced spectroscopy (LIBS) system.

LIBS

In this LIBS based system, a high energy laser pulse, typically a Nd:YAG operating at 1.06 µm, is delivered to the subsurface soil via a CPT. The soil will absorb the laser energy and heat rapidly to become an electronically excited plasma. When the excitation energy is removed, the excited electrons drop to lower energy levels with the emission of characteristic photons. The plasma emission spectrum from the sample is observed via an optical fiber. Elemental analysis is conducted by observation of the wavelength and intensities of the emission lines, which will depend upon the type and amount of material present within the plasma. The characteristics of the emitted spectra (i.e. location and intensity of peaks) will depend upon the composition of the sample, the characteristics of the spark (temperature, volume) and the detection parameters. Figure 3 depicts the type of data which is obtained by direct observation of a plasma for a soil with metals contamination (note: the intensity is given in arbitrary(arb) units).

The spectral lines indicated can be attributed to specific elements, and the intensities can be correlated to the concentration of the elements in the sample. This technique has shown to be an effective method for the quantitative analysis of contaminants in soils. LIBS instrumentation can be made quite compact and only requires optical access to a material, thus enabling remote access to be conducted.

Using LIBS technology, it will be possible to determine rapidly both the concentration and location of elemental species at the waste site. LIBS technology has been used for the evaluation of numerous elements, including many of environmental concern, such as; lead (Pb), cadmium (Cd), copper (Cu), zinc (Zn), chromium (Cr), iron (Fe), manganese (Mn), beryllium (Be), uranium (U), zirconium (Zr), arsenic (As) and silver (Ag).

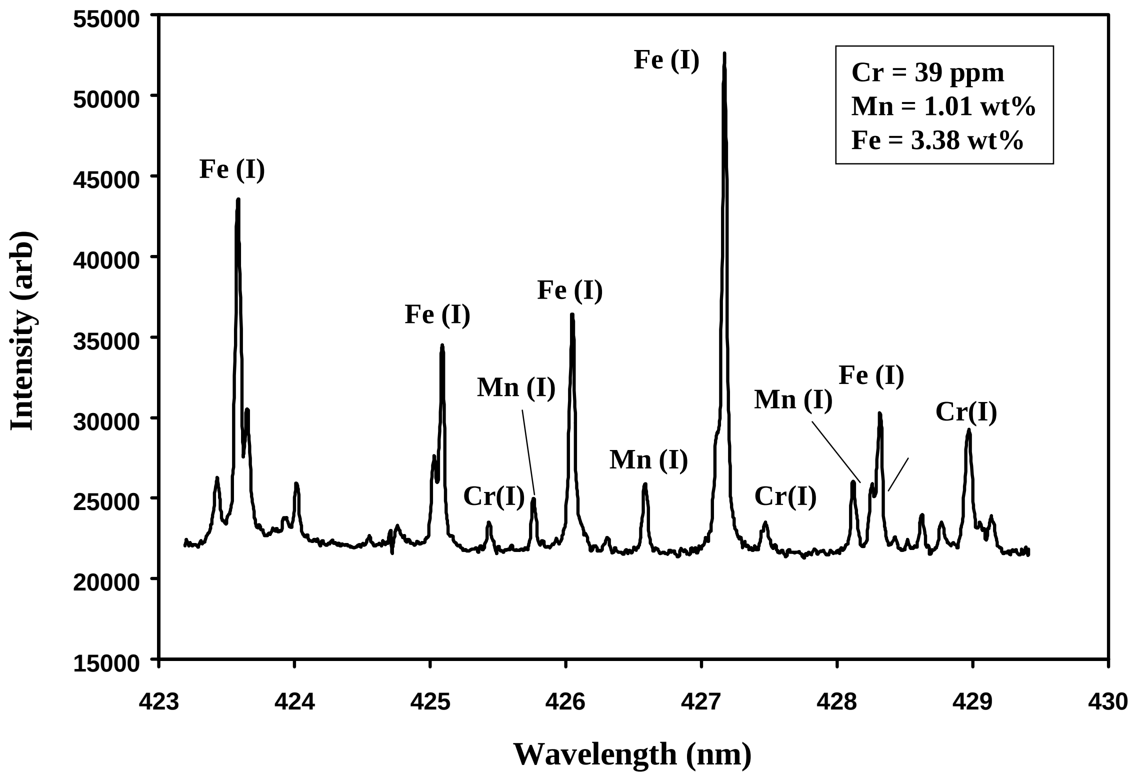


Figure 3. Example of LIBS spectra for Cr spectral range.

Cone Penetrometer Technology (CPT)

CPT is a subsurface characterization tool that utilizes a small diameter (approximately 2 inches) probe that is hydraulically pushed into the ground to collect various measurements. CPT typically consists of an enclosed 20-40 ton truck equipped with vertical hydraulic rams that force the sensor probe into the ground, electronic signal processing equipment, and computer equipment for data management. CPT serves as a platform for various technologies that are used for geotechnical, hydrogeological, and chemical characterization of the subsurface. CPT is gaining value in the environmental field as new sensors are developed for specific measurements and characterizations (i.e. detection of heavy metals).

CPT does not replace sampling and analysis for site characterization, but provides a tool for rapid field screening during initial site characterization. CPT does have limitations and is not applicable to all subsurface conditions. This direct-push technology is well suited to compacted sands and clays, but may experience difficulty in gravely soils where large cobbles are present. CPT does not have the capability to penetrate rock strata.

Fiber Optics

The optical fiber consists of a light guiding core and a light retaining cladding which surrounds the core. In the CPT/LIBS system, fiber optics are used in the return of emission spectra from the subsurface to the detection system at the surface. SEA initially intended to utilize fiber optics to deliver the laser spark to the subsurface, but ultimately opted to use a free space waveguide delivery method due to feasibility and cost issues with fiber optic delivery.

Description of Integrated System

The primary components of this technology are the CPT Rig and the LIBS system. SEA's LIBS system is a "bolt-on" accessory to CPT and can be set up in a CPT rig in less than 8 hours. The major subsystems of the integrated CPT/LIBS system are described below:

- Laser Source: a Continuum Surelite I Nd:YAG Q-switched laser with a maximum energy of 450 mJ/pulse house in a rugged container for protection during shipping

- Laser Delivery: Laser delivery to the subsurface soil is accomplished using a copper-lined hollow waveguide (similar to copper water pipe). The laser beam is initially transferred from the laser source, to the down-hole entry point by an articulated arm made up of hollow waveguide and mirrored knuckles as shown in Figure 4. The laser is then delivered down-hole to the sensor probe through successive 3-foot sections of hollow waveguide constructed of copper-lined, stainless steel tubing.

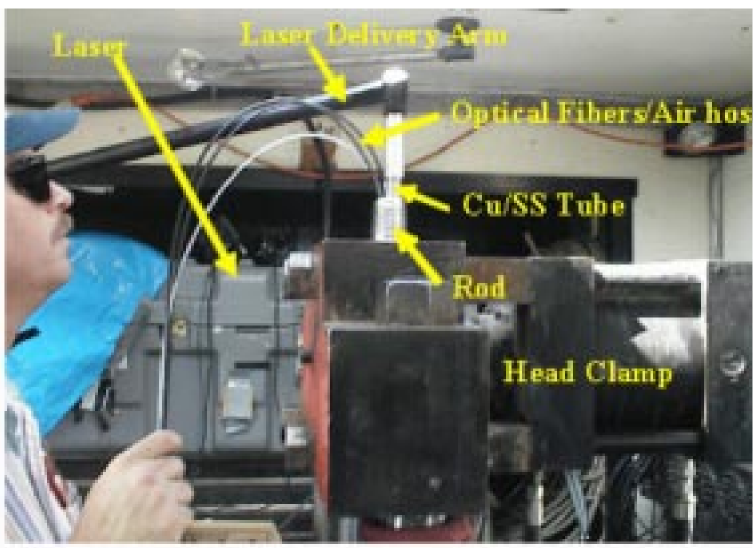
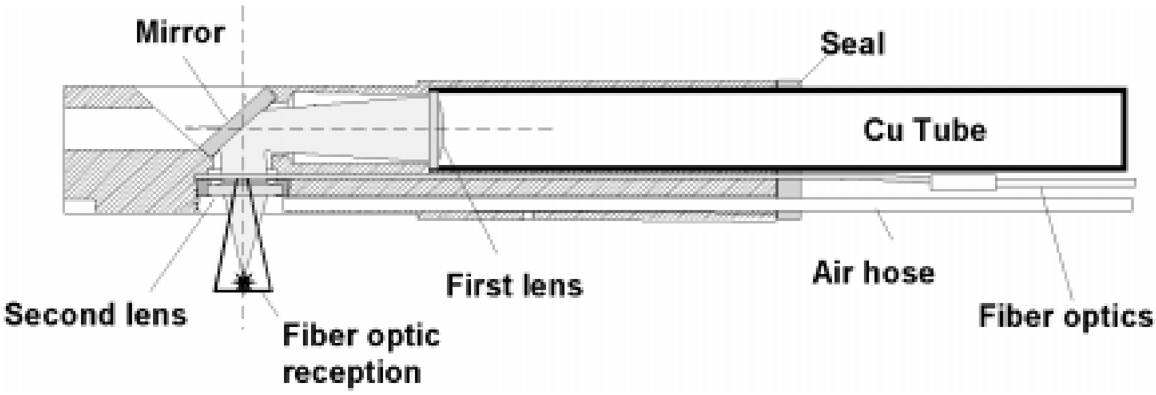


Figure 4. Laser delivery arm.

- Sensor Probe and Housing: The sensor probe is one of the most critical system components. This is where the laser spark is delivered to the soil and the emission spectra is observed. An illustration of the sensor probe is provided in Figure 5. The sensor probe contains lenses that focus the laser, a mirror to redirect the laser 90°toward the soil, two optical fibers portals to observe the emission spectra, and an air line to blow dust from the lens. The sensor probe is fitted with a sacrificial sleeve to protect the optical equipment during deployment. When the CPT is pushed to the maximum desired depth, the CPT sensor is retracted approximately one foot and the protective sleeve is left in the bottom of the hole. Measurements are collected, as the sensor is retracted upward.

- Emission Spectra Return: The emission spectra is viewed by two optical fibers located adjacent to the probe lens. Each optical fiber collects and transfers the emission spectra to the spectrometer and detector inside the CPT truck.



. Schematic of LIBS sensor probe.

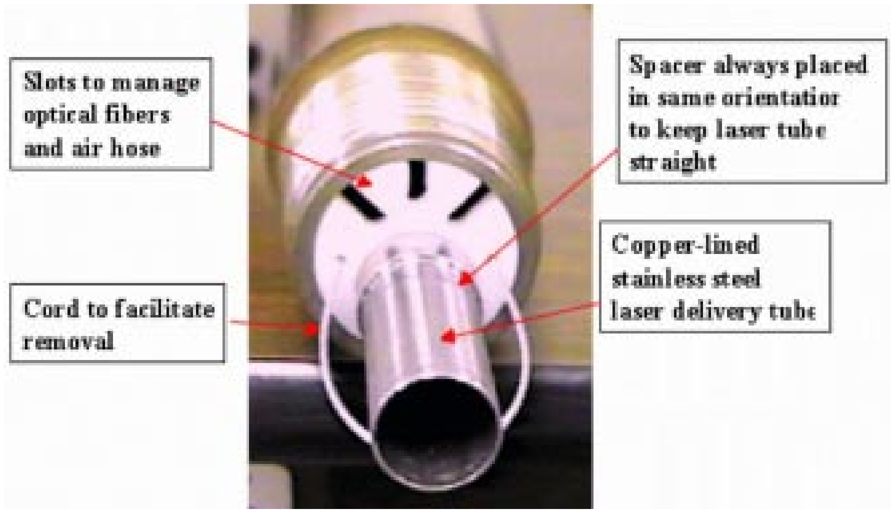
- Spectrometer: The spectrometer utilized was an Acton Research 0.75 meter spectrometer, which is capable of characterizing a number of different elements. The spectrometer has the following capabilities: angstrom to sub-angstrom wavelength resolution; readily integrated to a computer system; turret-style gratings for simplified alteration of central wavelength and range; all functions are software controllable and easily integrated with the array detector.

- Photodiode Array Detector: A time-gated detector is utilized to remove the continuum emission components that “mask” the elemental emissions during the early stages of the spark. The detector is also capable of simultaneous multi-channel analysis, so that a range of wavelengths can be detected for each spark. The detector is manufactured by Princeton Instruments.

- Data Reduction: A Dolch field rugged computer system is employed to operate the detection system and acquire data.

System Operation

Deployment of the LIBS probe is accomplished similarly to other CPT instruments. The LIBS probe is mounted to the tip of a 4-foot long CPT rod section and hydraulically forced into the subsurface. As one section of CPT rod is pushed into the subsurface, another section is added, and the process is repeated. The CPT rods are stored in a rack adjacent to the hydraulic ram with continuous fiber-optic cable and air hose “pre-threaded” through the hollow center of the rod. As the probe is advanced into the subsurface, lengths of rod are added until the desired depth is reached or refusal is experienced. A diagram of the cross section of a CPT rod, showing the hollow wave guide, fiber optics, air hose, and guide channel is presented as Figure 6.



. Cross-section of CPT rod.

When the probe has been pushed to the depth of analysis, or refusal, the following process is conducted to obtain data:

- The penetrometer is raised at least a foot to remove the sacrificial sleeve
- The articulated arm is attached to the down-hole, hollow waveguide
- The depth of the penetration is recorded
- To start the data acquisition process, the penetrometer operator and the LIBS operator simultaneously initiate the rod retraction and laser pulsing. The laser is initiated by a trigger switch, which starts the following process:
    - The laser is activated by the laser power supply at a 10Hz repetition rate
    - At each firing of the laser, the laser power supply sends a trigger pulse to the detector electronics
    - The detector electronics activate the detector at the appropriate time. The light collection by the detector is typically delayed several microseconds after the trigger pulse, then it is activated for about 30 microseconds. This scheme will neglect the continuum light generated at the beginning of the spark.
    - The spark is generated and the emitted light is detected by the optical fibers and delivered to the spectrometer
    - The spectrometer separates the light into a range of wavelengths and transfers the light to the array detector
    - The spectroscopic data is sent back from the detector directly to the system control computer via the I/O line
    - This continues until the penetrometer retraction has reached the end of a rod
    - The LIBS operator and the CPT operator simultaneously stop the retraction and data collection
    - The spectral data is transferred to the data analysis computer via a network link; this allows for data analysis during subsequent data collection

Calibration

Calibration is performed to determine the empirical relationship between the analyte peak intensity and the actual analyte concentration in the sample. Calibration standards are prepared by adding known amounts of analyte to a representative soil sample. The standards are analyzed using both standard laboratory techniques and the LIBS system. Typically three of four standards are used to develop the calibration curve. A multivariate data analysis technique was developed to improve the calibration procedure. The multivariate technique assessed data quality, removes low quality data, thus minimizing misleading results. At the present time, a limitation of the calibration procedure is that the soil used for the calibration must be representative of the soil analyzed by the CPT/LIBS system. Therefore, there must be a knowledge of the soil type prior to effective LIBS analysis.

The current CPT/LIBS system goes through a two step process to quantitatively determine contaminant concentration. First the LIBS spectra is collected via CPT, then the spectra is converted to a concentration using the calibration data and the multivariate analysis technique. Currently, this process takes less than 24-hours to produce contaminant concentrations, but with software advances this process could be shortened to minutes. The LIBS spectra, including peak height, can be viewed in real-time, but the contaminant concentrations are not available until the calibration/analysis procedure has been completed. Collecting calibration samples before the CPT penetrations are installed, combined with more sophisticated software would allow for real-time, quantitative results (i.e. minutes).

SECTION 3

PERFORMANCE

Demonstration Plan

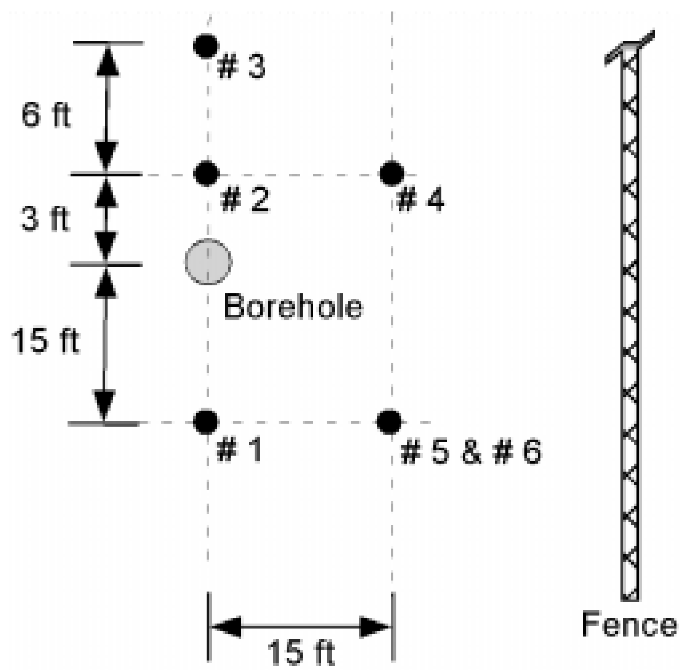
The CPT/LIBS System for Subsurface Heavy Metals Detection was demonstrated at the Sandia National Labs (SNL) outside of Albuquerque, New Mexico. The SNL facilities are within the boundaries of Kirtland Air Force Base and include a Chemical Waste Landfill (CWL) that was created in 1962 to accept waste from SNL facilities. The CPT/LIBS system was demonstrated at the 60s Pit within Tech Area III of the CWL. The test area is known to have chromium contamination based on past subsurface investigations. The demonstration of the CPT/LIBS system focused on measurement of chromium as a function of depth. The CPT/LIBS results were compared to the data collected from past soil borings installed near the test location.

The demonstration at SNL was the first field deployment of an improved CPT/LIBS probe design. The improved probe design was the result of a series of design modifications made after three field tests at non-contaminated sites in Vermont and New Mexico. Therefore, the purpose of the demonstration at SNL was to not only demonstrate the effectiveness of the CPT/LIBS system for the subsurface characterization of chromium, but as a first field test of the improved probe design.

Results

During the three-day Sandia demonstration, the CPT rig was mobilized to the site, fitted with the LIBS hardware, six penetrations were installed and calibration sampling was performed. A diagram indicating the locations of the six CPT penetrations and the previously installed borehole, is provided in Figure 7. The depth of the CPT penetrations ranged from a minimum of 4.75 ft to a maximum depth of 15.5 ft

Past subsurface investigations of the CWL identified chromium contamination at concentrations up to 6,000 ppm, at depths of 5 to 30 ft below ground surface. Figure 8 illustrates the chromium concentrations with respect to depth based on previous borehole analysis. The "1994 borehole" was located in the demonstration area, approximately 3 ft from the closest CPT/LIBS installation.



. Location of CPT penetrations with respect to past soil boring.

The system performed well during the demonstration. LIBS data was collected during six CPT penetrations. The only persistent problem experienced was fouling of the sensor's lens due to dust. Fouling of the lens due to dust was reported in two of the six penetrations. Penetrometer refusal was experienced on four of the six penetrations at depths ranging from 8.8 to 15.5 ft.

Site specific calibration was accomplished by collecting a soil sample from the test location and spiking the sample with different chromium levels using chromic acid. After the soil was spiked, a portion was evaluated utilizing standard laboratory techniques and a portion was evaluated with the LIBS system in the lab with the same parameters that where used in the field. The calibration data fell on a line of 1:1 slope, therefore it could be accurately used to predict the unknown concentration of chromium in the Sandia soil. Calibration is required to convert the field data, which is collected in terms of Cr peak height, into Cr concentration.

The results from Penetration 2 provide the best means of comparing the LIBS results to the actual concentration because Penetration 2 was located only 3 ft from the 1994 borehole. The CPT/LIBS results for Penetration 2 are presented in Figures 9 and 10. Figure 9 is a example of the LIBS spectra from Penetration 2 compared to the spectra from a chrome standard (a chrome-plated washer). Figure 10 presents that quantitative chromium concentration with respect to depth. The chromium detection limit for the LIBS system was approximately 25-50 ppm. The system does not differentiate between chromium III and chromium VI. The results from the LIBS system compared positively with the historical data. Based on the results from penetration #2, it is apparent that there is a chromium rich layer of contamination, with concentrations as high as 1,200 ppm at about 8 ft below ground surface. The borehole investigation indicated that chromium was present at concentration of approximately 2,000 ppm at 10 ft below ground surface. Penetration 2 was ended at 8.8 ft due to penetrometer refusal, so the peak concentration of 6,000 ppm exhibited in Figure 8 at a depth of approximately 30 ft was not evaluated using the CPT/LIBS system. The subsurface condition that resulted in penetrometer refusal is not known.

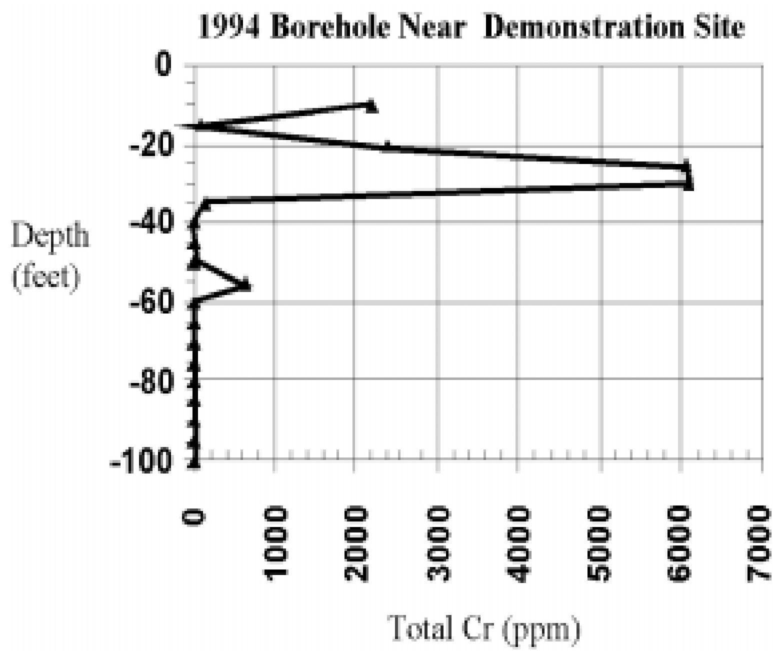


Figure 8. Chromium concentration as a function of depth for a borehole in the demonstration area.

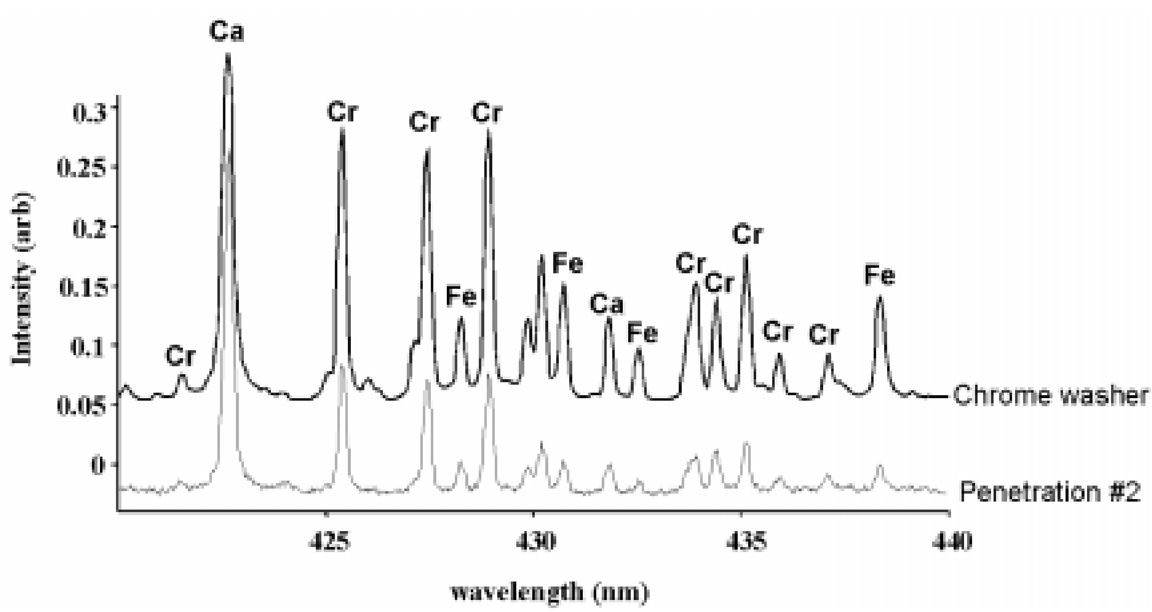


Figure 9. Example of LIBS emission spectra from Penetration 2, compared to a chrome standard.

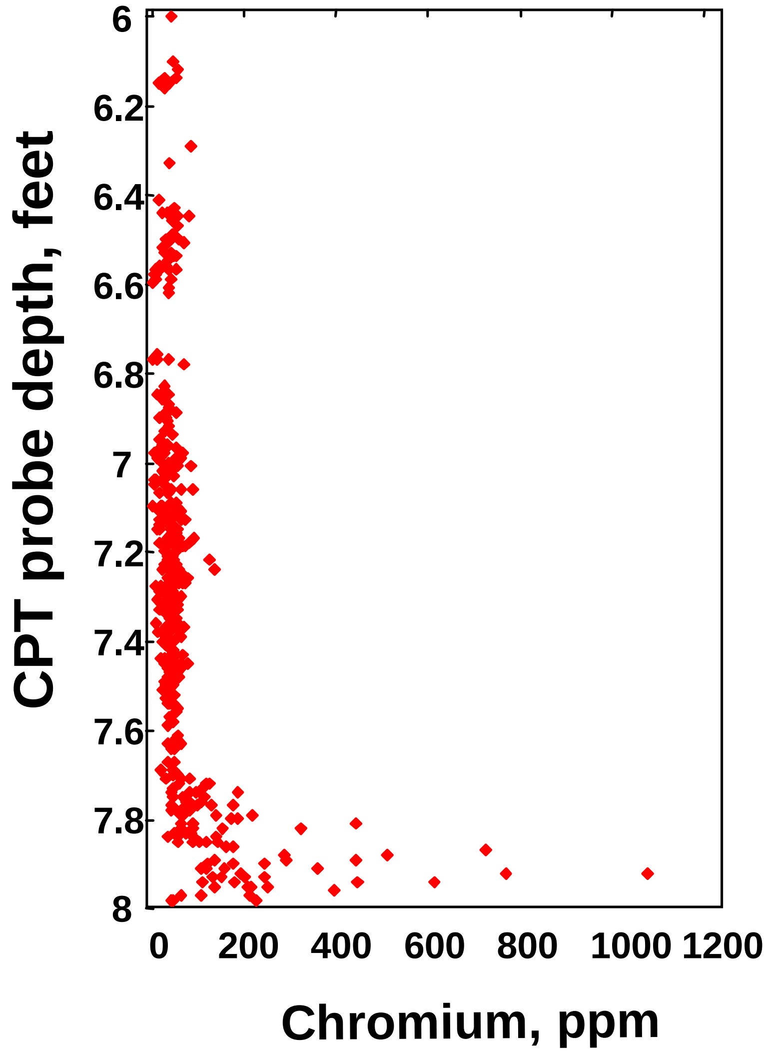


Figure 10. Chromium concentration with respect to depth for penetration 2.

Conclusions

The CPT/LIBS system successfully collected *in situ* measurements of chromium concentration with respect to depth for six CPT penetrations at Sandia's CWL. With regard to accuracy, the CPT/LIBS results generally correlated with the results from a previous soil boring. A more specific assessment of the system's accuracy during this demonstration was not performed. Due to penetrometer refusal, the maximum depth analyzed was 15.5 ft The productivity of the system was approximately three - 30 ft penetrations per day. An unresolved problem was fouling of the sensor's lens resulting from the reaction between the laser and dust on the lens.

SECTION 4

TECHNOLOGY APPLICABILITY AND ALTERNATIVES

Competing Technologies

Baseline Technologies

The baseline method used to characterize subsurface soils for metals is laboratory analysis of samples obtained by conventional drilling and core sampling. Laboratory analysis, though typically accurate and reliable, is slow and expensive. Typically, cost limits the number of samples analyzed, thus reducing the overall accuracy of the site characterization.

Other Competing Technologies

X-ray fluorescence (XRF) analyzers provide rapid quantitative analysis of metals in soils. This technology operates on the principle of energy dispersive x-ray fluorescence spectroscopy where the characteristic energy components of the excited x-ray spectrum are analyzed directly by an energy proportional response in an x-ray detector. Energy dispersion affords a highly efficient, full spectrum measurement which enables the use of low excitation energy sources (such as radioisotopes), and compact battery-powered, field portable electronics. XRF has been applied to field use for both *in situ* and ex situ measurement of metals in soils. XRF analyzers do not respond well to chromium and the field detection limits may be 5 to 10 times greater that conventional laboratory methods.

Development of a CPT-deployed XRF has been hindered by the large size of the detector, which cannot be made compact enough for CPT systems. XRF has difficulties operating effectively when in contact with an aqueous medium.

Technology Applicability

The LIBS/CPT system is applicable to the quantitative analysis of the following elements of environmental concern under the following conditions:

- Pb, Cd, Cu, Zn, Cr, Fe, Mn, Be, U, Zr, As, and Ag
- system determines *in situ* concentration in soil in the vadose zone
- continuous analysis is performed over the depth of a penetration
- a representative soil sample is required for calibration
- CPT is applicable to compacted sand and clay soils
- CPT has difficulty at sites where large boulders, cemented layers and rock strata exist

Other Potential Applications

The LIBS technology can also be utilized as a stand-alone system (without CPT) for field analysis of contaminated soils. Los Alamos National Laboratory (LANL) has developed two prototype LIBS systems: a system called TRACER (Transportable Remote Analyzer for Characterization and Environmental Remediation) that can be housed in a van or trailer, and a LIBS Backpack system. The TRACER system, shown in Figure 11, is designed to analyze grab samples in the field and uses a larger laser compared to the backpack system. The LIBS backpack System, as shown in Figure 12, utilizes a hand-held probe for the *in situ* measurement heavy metals concentration of surficial soils. The backpack hardware can also be deployed in a field-transportable cart.

SEA successfully field tested the prototype LIBS systems to evaluate the beryllium-contaminated surficial soils at a Formerly Utilized Sites Remedial Action Program (FUSRAP) site in Luckey, Ohio. The goal of the deployment was to integrate the LIBS sensor in the ongoing site characterization and provide near-real time data to support the characterization /remediation activities. The six-week field effort, generated a high density surface contour plot of beryllium concentration over a 40 acre site. During this field effort, 568 measurements were conducted with the Backpack unit and 829 measurements where performed with the TRACER unit. The results were reported to the customer within 24 hours. This was the first full-scale field deployment of the portable LIBS instruments and the LIBS data were used successfully for decision making and planning during the site characterization. The results of the demonstration at the Luckey, Ohio site are presented in greater detail in Saggese et. al. 1998.

Figure 11. Portable LIBS TRACER system.

Figure 12. LIBS backpack instrument.

Patents/Commercialization/Sponsor

Patents

SEA currently has no patents on the subject system.

Commercialization

SEA has commercialized a portable LIBS analysis system under the trade name of SPARK-I.D.™. This portable LIBS system is marketed for field analyisis of grab samples and is capable of elemental identification, soil analysis, metal sorting, air analysis, and environmental characterization.

Sponsors

SEA's effort was funded by Industry Programs through the Federal Energy Technology Center (FETC) under contract DE-AR21-95MC32089. Demonstration support for the CPT/LIBS system was provided by Hanford and Sandia National Laboratories. SEA's subcontractors include Applied Research Associates (ARA) and LANL. Contributions were also made by the University of North Dakota - Energy and Environmental Research Center (UND-EERC) under a DOE cooperative agreement. SEA's testing of LANL's prototype LIBS at the Luckey, Ohio FUSRAP site was funded by the DOE Oak Ridge FUSRAP Program and FETC. While on-site, SEA worked under the auspices of Bechtel National Inc. (BNI) and Science Applications International Corporation (SAIC).

SECTION 5

COST

Methodology

The cost analysis of the CPT/LIBS system for subsurface heavy metals detection is based on comparison of the subject system to the baseline. The baseline method is installation of soil borings, collection of core samples, and off-site laboratory analysis.

The cost analysis will include a breakdown of the cost components associated with each technology and the conditions on which the costs are based. A cost comparison that applies each of the technologies to a hypothetical site investigation scenario will be performed to quantify the cost advantages of the CPT/LIBS system. A discussion of cost advantages of the CPT/LIBS System compared to the baseline will be included.

The cost data for the CPT/LIBS is based on information supplied by SEA and the demonstration of the system at Sandia's Chemical Waste Landfill. Cost data for the baseline technology was acquired from representatives of SNL. Other cost data was taken from R.S. Means Environmental Remediation Cost Data (ECHOS, 1998).

Cost Analysis

The cost analysis will compare the CPT/LIBS system to baseline for subsurface characterization of chromium. The comparison is based on installing 3 CPT penetrations or 3 soil borings to a depth of 30 ft and the following assumptions:

CPT/LIBS System

The costs for the CPT/LIBS system are based on the following assumptions:

- The capital cost of an operational LIBS system is projected to be $70,000 per unit and includes the sensor, and related computer hardware and software (the cost of the prototype unit was $150,000)
- The daily cost of the LIBS system was determined to be $280/day. To calculate a daily cost, the capital cost ($70,000) was amortized over a 2-year useful life of the system at a real rate of 2.6% (Office of Management and Budget, 1992) and a utilization rate of 130 days/year (50% utilization).
- Site-specific calibration of the LIBS system requires 10 analytical samples and 24 man-hours of labor
- Set-up of the LIBS equipment in a CPT rig requires 8 man-hours of labor
- The CPT rig and crew will be subcontracted based on a daily rate, 2 additional LIBS operators will be required
- Costs are based on Safety Level C work conditions
- The push rate of CPT-deployed system LIBS is 90 ft/day (3 pushes to 30 ft each) based on the demonstration at Sandia
- CPT rods will be decontaminated as they are retracted from the ground and one 55-gallon drum of non-hazardous liquid will be generated per day

- Disposal costs do not consider costs for waste handling, storage, and transportation

The primary costs associated with the CPT/LIBS system are presented in Table 1. The costs are calculated based on installing 3 pushes to a depth of 30 ft each in one work day.

Table 1 - Costs for CPT/LIBS System (Based on 3 pushes to 30 ft)

Description	Qty	Units	Unit Cost	Total Cost
LIBS system	1	day	$280	$280
LIBS system set-up	8	man-hrs.	$75	$600
Mobilization/Demobilization of CPT Rig	1	each	$2,805	$2,805
CPT rig (includes equipment and labor)	1	day	$2,673	$2,673
LIBS operation	16	man-hrs.	$75	$1,200
Calibration (sampling + labor)	1	ea	$2,780	$2,780
Consumable Supplies	1	day	$250	$250
Disposal of decontamination fluids	1	drum	$150	$150
Sub-Total:				$10,738
General and Administrative Overhead (10%), Fee (5%), Total = 15%				$1,611
Total:				$12,349
Average Cost per 30 ft				$4,116
Average Cost per Foot				$137

Baseline Costs:

The baseline technology is installation of soil borings and continuous core samples. The costs provided for the baseline are based on the following assumptions:

- Costs are based on utilization of a hollow-stem auger drill rig to drill an 4.25-inch borehole
- Continuous core sampler will be utilized over the entire depth of the soil boring
- One sample will be collected every 2 ft for analysis at an off-site laboratory for RCRA Metals (Mercury, Chromium, Selenium, Cadmium, Silver, Lead, Arsenic, and Barium) on a 48-hour rush basis at a 100% surcharge.
- Drill cuttings will be generated at a rate of approximately one 55-gallon drum per 60 ft of 4.5-inch diameter borehole (approximately one-half drum per 30 ft)
- Drill cuttings will be disposed at a landfill as a hazardous solid (costs for waste handling, storage, and transportation are not included)
- Three soil borings to a depth of 30 ft with sampling can be performed in approximately 8 hours
- Costs are based on Safety Level C work conditions

The primary costs associated with installing soil boring to collect split-spoon samples are presented in Table 2 below. The costs are calculated based on installing 3 borings to a depth of 30 ft each.

Table 2 - Costs for Soil Boring and Split-spoon Sampling (Based on 3 borings to 30 ft)

Description	Qty	Units	Unit Cost	Price
Drill Rig Mobilization/Demobilization	1	ea	$ 3,000.00	$ 3,000
Drill Rig Operation (3 man crew)	8	hrs	$ 160.00	$ 1,280
Hollow Stem Auger Drilling (4.25 in. dia)	90	ft	$ 16.00	$ 1,440
Continuous Core Sampler (1.5 in. dia.)	90	ft	$ 25.00	$ 2,250
Laboratory Analysis (RCRA Metals)	45	ea	$ 214.00	$ 9,630
Disposal of Drill Cuttings	2	drums	$ 140.00	$ 280
Decontamination (labor)	1	hrs	$ 160.00	$ 160
Disposal of Decontamination Fluids	3	drums	$ 150.00	$ 450
			Sub-Total:	$15,490
General and Administrative Overhead (10%), Fee (5%), Total = 15%				$2,324
			Total:	$17,814
			Average Cost per 30 ft	$5,938
			Average Cost per Foot	$198

Cost Conclusions

As presented in Table 1, the cost to install a CPT push to 30 ft with LIBS analysis is $4,109 based on the given assumptions. This translates to an average cost of $137/ft. In comparison, the average cost to install one soil boring to a depth of 30 ft, collect continuous core samples, and have the samples analyzed at a laboratory is $5,938, which works out to a cost of $198/ft. Therefore, there is a significant potential cost savings from the use of the CPT/LIBS system compared to the baseline technology. The cost for CPT/LIBS analysis under the given conditions is approximately 30 percent less than the cost of the baseline.

The technologies being compared have different capabilities, therefore a direct comparison based solely on cost is limited. Specific difference that should be noted include:

- The baseline scenario assumes that a soil sample is collected at 2 ft intervals for analysis, the CPT/LIBS system provides continual analysis over the depth of the CPT penetration. Therefore, the CPT/LIBS system provides a greater number of data points.

- The baseline scenario includes laboratory analysis for RCRA metals based on a 48-hour turn-around time. The LIBS analysis is for chromium only, (but could be used for several different metals) with results available in 24 hours. With software advances, quantitative LIBS results could be available in minutes.

SECTION 6

REGULATORY AND POLICY ISSUES

Regulatory Considerations

- Results gained through the CPT/LIBS system do not take the place of analysis by a certified analytical laboratory with regard to meeting local, state, or federal regulatory requirements.

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

- No special permits are required for the operation of a cone penetrometer. 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.

Safety, Risks, Benefits, and Community Reaction

Worker Safety

- Being an *in situ* sensor, the CPT/LIBS System for Subsurface Heavy Metals Detection will provide safer site characterization by minimizing the exposure of on-site and laboratory personnel to high concentrations of contaminants during sample collection, transport and analysis.

- The CPT does not have rotary parts like many conventional drilling methods, thus reducing the potential for worker injuries associated with rotary drilling.

Community Safety

- The LIBS/CPT system is a monitoring technology; therefore, there is little potential that community safety will be adversely impacted from its operation.

- CPT is less intrusive than traditional drilling techniques; no drill cuttings or drilling fluids are produced during operations, reducing the potential exposure to the surrounding community.

Environmental Impact

- Environmental impacts of the CPT are generally less than with conventional drilling. CPT is minimally intrusive and holes are smaller in diameter than most drill rods.

- Because LIBS is performed *in situ*, there is no primary or secondary waste generated from analysis (i.e. the sample itself, preparation chemicals, liquids, or filters).

Socioeconomic Impacts and Community Perception

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

SECTION 7

LESSONS LEARNED

Implementation Considerations

When considering implementation of the CPT/LIBS system, the following should be considered:

- The system is applicable to characterization of the vadose zone
- Site geology must be amendable to CPT (i.e. compacted sand and clay)

Technology Limitations

Limitations of LIBS Technology

One of the shortcoming of the LIBS system is the calibration/data analysis procedure which requires a knowledge of soil type prior to effective LIBS analysis. If the soil encountered during *in situ* sampling differs significantly from the calibration soil, the results could be affected. Soil moisture also plays a similar role; if the soil being analyzed has a different moisture content from the calibration soil, the results could be affected.

Limitations of CPT

Though CPT deployment has many advantages, it does have some limitations compared to conventional drilling. CPT is dependent on appropriate geologic conditions to assure penetration to the required depths. This limitation was evident during the demonstration at Sandia, where refusal was encountered at relatively shallow depths.

Limitations of Fiber Optic Technology

Initially, fiber optics were to be used for laser delivery and return of the emission spectra. Fiber optics were ultimately not used for laser delivery for the following reasons:

- Laser energy delivery of 75mJ/pulse limited field application
- Fiber optics are susceptible to laser damage
- High cost
- Stringent requirements to launch laser into fiber
- Fiber optics difficult to replace in the field

Limitation of Integrated LIBS and CPT

A persistent problem with the integrated system was fouling of the sensor's lens due to the reaction between the laser and dust on the lens. An air flow system was designed to keep dust off of the lens, but this system may actually make the problem worse. During one of the penetrations at Sandia the air system was not used and fouling did not occur.

Needs for Future Development

The Sandia demonstration was the first field test of a new probe/sensor design. System improvements will occur as more field deployments are conducted. Areas for future development are listed below:

- Document system accuracy through data validation
- Reduce overall complexity, size, and weight of the system
- Increase system ruggedness and dependability
- Develop software for real time quantitative results

Technology Selection Considerations

The technology is relatively new and coordination with regulators may be needed prior to field use to ensure acceptance of results.

APPENDIX A

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