DNAPL Characterization Methods and Approaches, Part 2: Cost Comparisons

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Abstract

Contamination from the use of chlorinated solvents, often classified as dense nonaqueous phase liquids (DNAPLs) when in an undissolved state, pose environmental threats to ground water resources worldwide. DNAPL site characterization method performance comparisons are presented in a companion paper (Kram et al. 2001). This study compares the costs for implementing various characterization approaches using synthetic unit model scenarios (UMSs), each with particular physical characteristics. Unit costs and assumptions related to labor, equipment, and consumables are applied to determine costs associated with each approach for various UMSs. In general, the direct-push sensor systems provide cost-effective characterization information in soils that are penetrable with relatively shallow (less than 10 to 15 m) water tables. For sites with impenetrable lithology using direct-push techniques, the Ribbon NAPL Sampler Flexible Liner Underground Technologies Everting (FLUTe) membrane appears to be the most cost-effective approach. For all scenarios studied, partitioning interwell tracer tests (PITTs) are the most expensive approach due to the extensive pre- and post-PITT requirements. However, the PITT is capable of providing useful additional information, such as approximate DNAPL saturation, which is not generally available from any of the other approaches included in this comparison.

Introduction

Part I of this study (Kram et al. 2001) described and compared many of the best methods currently used to detect and delineate dense nonaqueous phase liquids (DNAPL) contaminant source zones. The objective of this paper is to compare site characterization approaches based on known site characteristics, method performance capabilities, and method costs. A cost comparison is generated using several synthetic scenarios, each exhibiting particular physical characteristics. Although cost-comparison studies have been conducted in the past by federal agencies (e.g., Federal Remediation Technologies Roundtable [Field Analysis Technologies Matrix], and the U.S. Environmental Protection Agency [Hazardous Waste Cleanup Information]), a method comparative analysis that includes unit costs for several model scenarios has not yet been performed. In general, costs associated with characterization activities are generated for a specific site, and competitive methods are not usually directly compared under identical conditions. At sites where several methods have been compared side by side, bias becomes an important issue due to the heterogeneity of the soils and distribution of DNAPL, leading to inconsistent comparison conditions.

A distinction between specific "methods" and site management "approaches" is used in this cost analysis. An approach indicated by a method descriptor (e.g., "soil gas survey" or "surface geophysics") implies

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Table 1
Synthetic Unit Model Scenarios (UMSs) and Predetermined Parameters

Unit Model Scenario	Map Area	Depth to Ground Water/ Depth of Resolution	Soil Type	Volume of DNAPL
1	50 ft (15.2 m) radius	15 ft/100 ft (4.6 m/30.5 m)	Alluvial, medium to fine grained	264 gal (1000 L)
2	50 ft (15.2 m) radius	15 ft/100 ft (4.6 m/30.5 m)	Gravel or bedrock or deposits	264 gal (1000 L)
3	50 ft (15.2 m) radius	15 ft/100 ft (4.6 m/30.5 m)	Karst	264 gal (1000 L)

that the approach includes the method as part of the overall characterization effort. Selected candidate methods are grouped into sets of approaches that represent site management options for achieving cost-effective DNAPL source zone characterization and lead toward effective remedial design. Approach comparisons based on the level of chemical and hydrogeologic resolution, associated costs, and the need for additional data requirements are generated to assist with selection of appropriate site remediation management options.

As described in Part I, environmental characterization efforts for contaminated sites typically evolve through a series of stages. To reiterate, no information is initially available. We refer to this stage as t_0. At t_1, some preliminary (generally nonintrusive) information, such as data typically contained in a preliminary site assessment, becomes available. At t_2, data-collection activities related to subsurface characterization are sufficient to initiate design of a remediation system. At t_3, the site is considered remediated and monitoring is established to determine whether there is further risk. At t_4, monitoring ceases and regulatory closure is achieved, thereby requiring no further action. The approaches discussed in this paper comprise multiple methods applied in a logical sequence with the goal of reaching stage t_2.

Methods

Comparable cost and performance data for DNAPL site characterization methods and approaches are limited. Rarely are several methods compared to each other on a systematic basis at the same site. Typically, when data are available for a particular approach or method, it is compared to a set of confirmation data collected and analyzed using standardized field laboratory methods. The data-collection locations for confirmation samples are typically dictated by previous results; e.g., when one uses a field screening technique, confirmation samples are collected from locations identified as polluted or clean based on the field screening method results. Because each method and approach varies in terms of spatial resolution and completeness with respect to requirements for remedial design, corresponding confirmation approaches will also vary. Due to the lack of comparable cost data, the lack of resources for conducting method comparisons in the field under various scenarios, and the differences associated with confirmation approaches anticipated for particular methods, the authors evaluated various DNAPL site-characterization methods and approaches using synthetic site scenarios. Three "unit model scenarios" (UMSs) were used to compare the selected site characterization techniques and approaches.

Descriptions of the three UMSs and specific parameters are presented in Table 1. Although the scenarios are not comprehensive, they provide a general framework for technology evaluation and selection. The scenarios each represent sites with relatively shallow water tables. Cost estimates can be adjusted by normalizing (e.g., based on depth, area, or estimated contaminant volume) or by adjusting the assumptions presented for each approach (Appendix I). For instance, each UMS consisted of volumes of approximately 785,400 ft^3 (22,250 m^3). The "depth of resolution" values refer to the maximum depth of characterization required. For an equal volume with a 1 acre (43,560 ft^2 or 4047 m^2) footprint at the surface, the "depth of resolution" would be approximately 18 ft (5.5 m). As described in Table 1, we consider the following:

- A depth of resolution of 100 ft (30.5 m) for each UMS
- All releases initiated at the same time and within 10 years of the initial investigation
- NAPL penetrated the subsurface to depths beyond the water table
- DNAPL is distributed heterogeneously within the UMS volume, with the majority located between approximately 65 to 75 ft (19.9 and 22.9 m) below ground surface (identified using the screening and confirmation efforts)
- Depth to ground water, depth of resolution, and volume of DNAPL released are identical for each UMS.

Therefore, the main cost differences between the approaches were due to differences in soil type, which have an effect on the potential for data or sample accessibility and resolution due to lithologic properties (competence, penetrability, acoustic or electromagnetic signal transmission, etc.).

Descriptions of DNAPL Site Characterization Techniques

The techniques compared in this paper were described in Part I (of the study). The techniques were selected because they have been used at several sites to identify DNAPL source zones and have demonstrated potential for successful DNAPL source zone delineation, either directly or indirectly. Some of the methods have been extensively tested (e.g., sample collection and analysis, soil gas surveys, seismic surveys, and other geophysical surveys), while other techniques are considered relatively new (e.g., FLUTe, ultraviolet fluorescence using a cone penetrometer, and precision injection extraction). The reader is referred to Table 1 of Part I (of this study) for descriptions of the positive and negative attributes and pertinent references associated with each of these characterization options. Several additional approaches are commercially available or emerging, but are not discussed here.

Table 2
Generic Cost Estimates for Approach Line Item Components

Item	Cost ($)	Per Unit
Drill rig	10 (UMS 1, UMS 2)	foot
Drill rig	20 (UMS 3)	foot
Push rig	3500	day
Sampling	20	sample
Grouting	3	foot
Mobilization-demobilization	1000	day
Per diem ($100pp/day)	300	day
Standby labor	170	hour
Decontamination labor	100	hour
Drilling waste disposal	40	cubic foot
Laboratory chemical analyses	150	sample
Laboratory physical analyses	200	sample
Drilling waste disposal (sed)	40	cubic foot
Drilling waste disposal (water)	10	cubic foot
Per diem	100	person-day
Reporting	2000–5000	report

Cost Analysis

To generate a useful cost comparison, several cost and approach assumptions were required (Appendix I). Each approach was compared to a common baseline approach, which consists of sample collection from the surface and from consecutive discrete 5 ft (1.5 m) depth intervals. We do not mean to imply that a 5 ft (1.5 m) level of resolution is valid for all sites; rather we consider this a typical sampling increment. Although commonly used, the likelihood of detecting DNAPL ganglia and microglobules using this type of approach is very low. In addition, if not careful, penetration of zones containing free-phase DNAPL using the baseline approach could lead to vertical migration of contaminants to deeper zones, exacerbating the problems associated with the release. Appendix II presents cost estimates and an estimate of savings based on comparisons with baseline approaches. A negative savings value indicates that the approach is more costly than the baseline approach. Where possible, references to previous studies were incorporated into the cost analyses for each scenario.

It is important to recognize that each method (or approach component) presents specific advantages and disadvantages and that, due to the nature of each method and the sequence with which it can be applied in the overall site-characterization process, direct comparisons involve some uncertainty. A project manager who knows little about the location of DNAPL at a site yet is interested in the most cost-effective approach must consider each candidate method in the proper context within the characterization process. Comparison of discrete characterization methods in isolation tends to bias the cost estimate, thereby rendering the comparison fallible. In an attempt to maximize the value of the comparison, each method is evaluated in a manner consistent with the niche fulfilled (as described in more detail for each approach). A distinction between specific methods and site management approaches is employed. Therefore, the approaches described include not only the specific methods of interest, but also confirmation methods and preliminary characterization efforts.

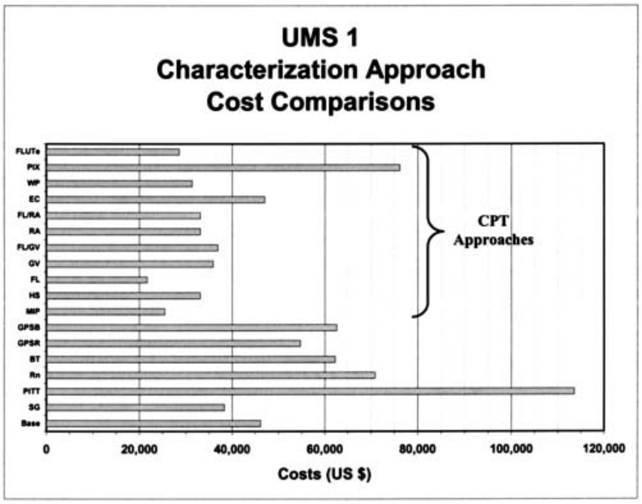

Figure 1. Costs for each DNAPL characterization approach using Unit Model Scenario 1. (Base = baseline; PITT = partition interwell tracer test; Rn = radon flux survey; BT = solute back-track; GPSR = surface geophysical; GPSB = subsurface geophysical; SG = soil gas survey; MIP = membrane interface probe; HS = hydrosparge; FL = fluorescence probe; GV = GeoVis probe; FL/GV = fluorescence probe with GeoVis; RA = Raman probe; FL/RA = fluorescence with Raman probe; EC = electrochemical sensor probe; WP = Waterloo Profiler; PIX = precision injection-extraction; FLUTe = Flexible Liner Underground Technologies Everting membrane; CPT = cone penetrometer testing).

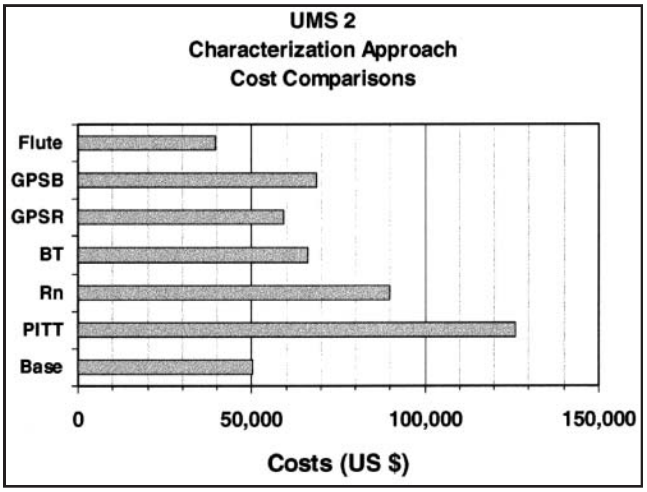

Figure 2. Costs for each applicable approach using Unit Model Scenario 2.

Because several approaches consist of similar activities, it is important to use consistent cost estimates for common line items. Table 2 lists cost estimates for generic line item approach components. For each scenario and approach, it is assumed that a zone of DNAPL is present at a depth ranging from 65 to 75 ft (19.9 to 22.9 m), and that residual contaminants exist in the vadose zone between the point of release and entry into the water table.

The following comparisons present a starting point for evaluating strategies for site-specific characterization. Figures 1, 2, and 3 summarize the cost comparisons for

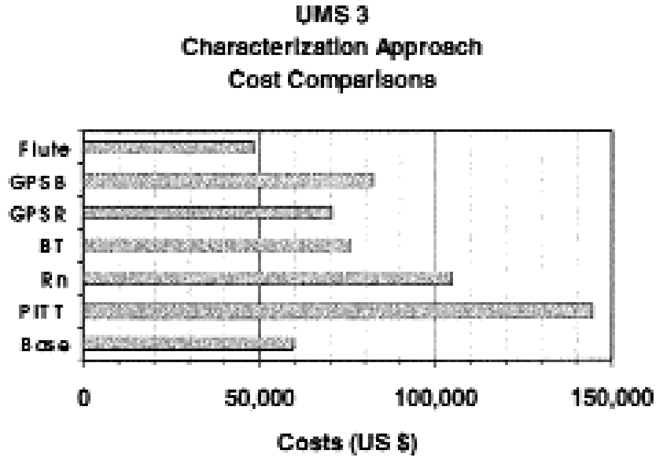

Figure 3. Costs for each applicable approach using Unit Model Scenario 3.

UMS 1 through 3, respectively. In most cases, a strategy can be adjusted or modified, leading to costs that differ from those derived in this paper.

Baseline Approach

Samples are typically collected from consecutive depth intervals using conventional drilling equipment and are analyzed using U.S. EPA–approved methods for identifying volatile organic constituents (VOCs). Rapid field evaluations, such as shake-tests, use of an ultraviolet (UV) lamp, addition of Sudan IV, and observations of drill cutting fluids, soils, and vapors (e.g., head space analyses) are also incorporated into this baseline. We assume that soil sampling from five locations will be conducted to depths of 100 ft (30.5 m) below grade, at 5 ft (1.5 m) intervals. Therefore, 21 samples per hole, for a total of 105 samples, would be collected for each UMS. Samples exhibiting high concentrations would be further analyzed for grain size distribution and permeability.

Cost differences between each scenario are attributed to time requirements based on drilling difficulties. For UMS 1, we assume that the project requires three days to complete plus one day each to mobilize and demobilize. We can also assume that there will be one hour of standby each day, one hour to decontaminate the equipment used each day, and each workday consists of 10 hours. The total anticipated cost for UMS 1 is $46,160 for this effort.

For UMS 2, we use the same assumptions as for UMS 1, except that we assume that the project requires five days to complete (given that additional time will be required to drill through resistant materials) plus one day each to mobilize and demobilize. The total anticipated cost for UMS 2 is $50,300 for this effort.

For UMS 3, we use the same assumptions as for UMS 1, except that we assume that the costs for drilling will be $20/ft (0.3 m) and that the project requires seven days to complete (given that additional time is required to drill through competent materials) plus one day each to mobilize and demobilize. The total anticipated cost for UMS 3 is $59,440 for this effort.

Soil Gas Surveys

It is assumed that a 5-by-5 grid of pushes (20 ft [6.1 m]) apart in north and south directions) to depths of 15 ft (4.6 m) is required to characterize the potential DNAPL source zone based on vadose zone soil pore vapor chemistry. Soil gas samples are to be collected with a Geo-Probe-type system every 3 vertical ft. For the 25 pushes, 125 soil gas samples will be analyzed over four field days. Two additional confirmation sampling pushes, collecting three soil samples each to 20 ft (6.1 m), will be included in the investigation. Assuming that a "hot spot" is identified in the vadose zone, an additional confirmation sampling effort consisting of two soil borings will be conducted to depths of 100 ft (30.5 m) below grade, collecting samples at 5 ft (1.5 m) intervals with a conventional drill rig over the course of three days. Therefore, 21 samples per hole, for a total of 42 samples, would be collected and analyzed. Samples exhibiting high concentrations would be further analyzed for grain size distribution and permeability. It is assumed that only UMS 1 is feasible using this approach, as penetration through gravels and consolidated units is prohibitive. Well installation efforts require four days. The total anticipated cost is presented in Appendix II.

Partitioning Interwell Tracer Tests

While the partitioning interwell tracer test (PITT) method affords useful data related to DNAPL volume present, it serves as perhaps the second or third characterization phase in an approach aimed at getting to the t_2 design level. A PITT requires several preliminary steps that include:

- Location of the NAPL source
- Soil sampling
- Conventional laboratory analyses
- Laboratory tests to evaluate initial residual saturation levels in soil samples
- Laboratory tests to select candidate tracers and determine corresponding partition coefficients via column studies (often but not always a requirement)
- Aquifer testing to determine hydraulic data specific to the aquifer volume to be tested (e.g., sustainable injection and extraction rates and calibration data for a design model)
- A conservative interwell tracer test using bromide and/or chloride
- Flow and design modeling of the site.

In addition, several injection, extraction, and monitoring wells must be installed prior to running the PITT. For sites made up of large source zones, several PITTs may be conducted.

For this assessment, we assume that preliminary field screening, confirmation, and well installation efforts are conducted using methods and associated costs described in this paper. Details include the following:

- Field screening includes use of the FLUTe membrane to 100 ft (30.5 m) depth at five locations.
- Confirmation includes collection and analysis of six samples from two locations to a total depth of 75 ft (22.9 m).
- Wells will be emplaced in a configuration similar to

that described in Meinardus et al. (1998) and screened at depths approximately 65 to 75 ft (19.8 to 22.9 m) beneath the water table.

- Four injection wells (three for tracer introduction and one for hydraulic control), three extraction wells (for tracer recovery), and one interwell monitoring point will be installed.
- Water extracted for hydraulic control and sample collection will be treated with granular activated carbon (GAC).

Due to the amount of data processing required, reporting requirements will be more extensive, and therefore more expensive, than for the baseline approach. Further details and cost summaries are provided in Appendix I and II, respectively.

A significant portion of the total cost ($9000) is due to treatment and disposal of liquid wastes generated during aquifer control. In addition, use of conventional laboratory methods to analyze tracer concentrations during the PITT can increase anticipated expenses depending on tracers used and frequency of sampling. Use of a field analytical system could significantly reduce analytical costs. Several PITTs have been conducted using only one injection well and one extraction well. This approach would cost less to conduct than the example provided. However, the savings may represent only a small percentage of the total, because costs are dominated by the preliminary site characterization efforts, which would probably not differ greatly for the single versus multiple extraction options. Information derived from the PITT approach provides additional remediation design information, as residual NAPL volume can be estimated.

Radon Flux Rates

As with the PITT approach, several assumptions are required to adequately assess the radon flux rate approach. In practice, samples for Rn-222 measurements can be obtained using conventional water sampling approaches from installed wells (Semprini et al. 1998), use of direct-push discrete ground water sampling equipment, and from multiple depth-discrete sampling equipment such as the Waterloo Profiler®. For this exercise, it is assumed that several wells are required for evaluating the distribution of Rn-222 levels at a DNAPL site. Several preliminary steps are required, including a field screening technique (such as the soil gas survey method), confirmation soil sampling and analyses, installation of wells in appropriate locations, and aquifer testing to determine hydraulic data specific to the aquifer being tested. For UMS 1, UMS 2, and UMS 3 the following assumptions are made:

- Field screening approach includes use of the FLUTe membrane to 100 ft (30.5 m) depth at five locations.
- Confirmation includes collection and analysis of six samples from two locations to a total depth of 75 ft (22.9 m).
- Five wells will be installed to 75 ft (22.9 m) with screens installed from 65 to 75 ft (19.8 to 22.9 m) beneath the water table.

Due to the amount of data processing involved, reporting requirements are more extensive, and therefore more expensive, than for the baseline approach. However, because hydraulic control (and corresponding level of data processing detail) will generally not be required, the report will be less expensive than the PITT report. Rn-222 flux information may assist with remediation design, because residual NAPL volume estimates can be derived. Further details and cost summaries are provided in Appendix I and II, respectively.

Back-Tracking Using Dissolved Concentrations in Wells

It is assumed that soil samples are collected during installation at the same frequency specified in the baseline approach. In addition, well installation costs are incurred at rates presented later. Because well screens are to be installed over the entire saturated thickness, packers will be necessary for isolating specific sampling depths. A potentially cost-effective alternative is to use clusters or nests of direct-push wells, screened at selected discrete depth ranges for UMS 1. In addition, the Waterloo Profiler or FLUTe multilevel sampler can be a cost-effective alternative for UMS 1. For this section, we are assuming that the wells are emplaced using conventional drilling techniques.

For UMS 1, we incur the same expenses presented in the baseline soil sampling and analysis approach, with the exception that grouting requirements will be replaced by well installation costs (five 10 cm (4 in) diameter wells), and seven days will be required (plus one day each for mobilization and demobilization) for the soil sampling and well installation efforts. An aquifer test (not included here) is generally conducted to identify hydraulic conductivity, transmissivity, and aquifer storage properties. However, because the screened zone is very long (approximately 85 ft [26 m]) for each well, it may not be practical to attribute one averaged value to each of these parameters.

UMS 2 requires approximately seven days for the well installation efforts. UMS 3 requires approximately nine days for the well installation efforts. These costs include only one round of water sampling. Subsequent sampling rounds run approximately $8250 per round for the analytical costs ($7500) and labor ($750). Information gained from this investigation may be useful for site remediation. To obtain useful information, wells must be placed in the appropriate locations adjacent to NAPL sources. Although not considered here, a more appropriate (and costlier in the short-term) approach would include use of a screening technique (such as a soil gas survey or cone penetrometer technology [CPT] sensor method for UMS 1 and FLUTe for UMS 2 and 3) prior to selection of well installation locations.

Geophysics

Three-dimensional seismic surveying technology was evaluated to delineate DNAPL source zones at three specific military sites over the last four years (Sinclair and

Kram 1998). The main differences between the sites were lithologic characteristics and contaminant areal extent. Total costs included expenses for conducting the field measurements, generating vertical seismic profiles, data processing and interpretation, attribute analyses, confirmation drilling and sampling, laboratory analyses, and generation of plans and reports. Two of the sites consisted of alluvial deposits (similar to UMS 1 and UMS 2) while the other was comprised of dense fractured limestone and dolomite (similar to UMS 3). The average total costs incurred for the study were approximately $230,000 per site for each of the three sites investigated (Trotsky 1999). Costs and assumptions presented in Appendix I are normalized to account for the smaller study footprint for each UMS.

For subsurface geophysical approaches, we assume that a well will be necessary to lower the transmitting device and generate a more accurate subsurface lithologic characterization. Costs for an additional well (fully screened from 15 to 100 ft [4.6 to 30.5 m], omitting sampling and analyses) were added to each of the corresponding costs for the surface geophysical approach previously presented. It was assumed that one additional day of drilling and well installation was required for UMS 1, two days for UMS 2, and three days for UMS 3, plus two days for mobilization and demobilization. Additional assumptions and cost estimates are presented in Appendix I.

Cone Penetrometer Testing (CPT) Approaches: General

Because penetration using CPT through gravels and consolidated units is not feasible with current platforms, it is assumed that only UMS 1 can be characterized using the CPT approaches. Innovative developments such as sonic head CPT and laser drilling may soon allow for CPT applications in more consolidated materials. For this cost analysis, we consider both the conventional CPT push rigs, which consist of reaction forces of 13620 kg (15 English tons) or greater, and the lighter truck- and van-mounted push rigs. Although some smaller push rigs are capable of advancing sensor probes with a hydraulic ram system, most of these lighter weight systems operate via a hammer technique and, therefore, cannot advance many of the sensor systems available. The smaller rigs can be less expensive to operate than the larger CPT systems and services are generally charged on a per-foot or per-push rate. The larger CPT rig services are typically charged at a per-day rate, which sometimes includes reporting. For our study, we assume that the soil gas survey and the Waterloo (Ingleton) Profiler survey are conducted with a smaller rig, while all the other CPT approaches are conducted with the larger rig. Assumption details and cost summaries are provided in Appendix I and II, respectively.

CPT Approaches: Membrane Interface Probe

We assume that five membrane interface probe (MIP) pushes to 100 ft (30.5 m) are required to screen the site, plus two additional pushes for confirmation sampling. Grouting requires additional pushes (seven total) with a grout probe. Because soil lithologic data are collected along with the chemical screening information, this level of effort may be enough to identify potential remediation options. At a minimum, determination of required data gaps is feasible with this level of effort, because data profiles are relatively continuous with a resolution of a few centimeters. Use of a smaller truck- or van-mounted GeoProbe-type CPT system could save approximately $7500.

CPT Approaches: Hydrosparge

Hydrosparge field sampling and analytical operations require that probe advancement be stopped every 5 ft (1.5 m), resulting in 20 events for each push. We assume that approximately 15 Hydrosparge sampling events can be accomplished per day. As with the MIP approach, grouting requires additional pushes (seven total) with a grout probe. Therefore, it requires approximately seven field days to complete the 100 Hydrosparge sampling events. Soil lithologic data are collected using soil sensors, along with the chemical screening information; therefore, this level of effort may be enough to identify potential remediation options. Chemical data profiles are spaced at 5 ft (1.5 m) intervals, while soil type profiles are relatively continuous with resolution of a few centimeters. In practice, lithologic observations can be used to optimize the chemical data collection depths.

CPT Approaches: Fluorescence Techniques

This method assumes that the DNAPL contains fluorescing co-constituents, which is often but not always the case. Grouting for the fluorescence pushes does not require additional pushes, because the probe is equipped with grouting capabilities through the tip as the device is retracted; however, additional pushes are required to grout the two sampling holes.

This level of effort may be enough to identify potential remediation options, because soil lithologic data are collected along with the chemical screening information. At a minimum, identification of data gaps is feasible with this level of effort, because data profiles are relatively continuous with resolution of a few centimeters.

CPT Approaches: GeoVis

GeoVis operations require that probe advancement be run relatively slower than conventional CPT operations to be able to observe images in real time. We assume that approximately one run of the GeoVis to 100 ft/day can be accomplished. As with the LIF approach, two additional pushes are required to collect confirmation samples (three per push) to depths of approximately 75 ft (22.9 m). Also, grouting requires additional pushes (seven total) with a grout probe; therefore, it requires approximately eight field days to complete the five pushes, confirmation sampling, and grouting operations. Reporting costs are less than for the baseline approach, because the level of effort is relatively less.

This level of effort may be enough to identify potential remediation options. Soil images are continuous with resolution greater than a fraction of a centimeter, while soil type profiles are relatively continuous with resolution greater than one-third of a centimeter.

CPT Approaches: LIF/GeoVis

The considerations are the same as for the individual laser-induced fluorescence (LIF) or GeoVis CPT approaches. Grouting requires additional pushes (seven total) with a grout probe, because the current configuration does not allow for grouting through the tip. In addition, LIF/GeoVis operations require that probe advancement be run relatively slower than conventional CPT operations to be able to observe images in real time. We assume that approximately one run of the LIF/GeoVis to 100 ft/day can be accomplished. Therefore, it requires approximately eight field days to complete the five pushes, confirmation sampling, and grouting operations.

Soil images and fluorescence data are continuous with resolution greater than a centimeter for the video and the fluorescence data, while soil type profiles are relatively continuous with resolution about one-third of a centimeter. Costs are comparable to the GeoVis approach, but the data set is more complete (requiring additional reporting time) and the potential for false negatives is reduced.

CPT Approaches: Raman Spectroscopy

We assume that probe advancement is stopped every 5 ft (1.5 m), resulting in 20 events for each push. In practice, operators often couple Raman data with real-time lithologic sensor data and stop only for Raman data collection activities when a potential vertical barrier is encountered. Raman pushes are grouted through the probe tip upon retraction. Sampling efforts require additional pushes (two total) with a grout probe. We assume that approximately seven field days are required to complete the Raman pushes and confirmation sampling.

Because soil lithologic data are collected along with the chemical screening information, this level of effort may be enough to identify potential remediation options. Chemical data profiles are spaced at 5 ft (1.5 m) intervals, while soil type profiles are relatively continuous with resolution greater than one-third of a meter. For very detailed investigations, Raman spectra is sometimes acquired every 0.5 to 3 ft (0.2 to 0.9 m) as the penetrometer is advanced (Rossabi et al. 2000). For sediments likely to contain DNAPL based on knowledge of disposal, previous work, or lithologic characteristics indicative of potential contaminant migration pathways, the 0.5 ft (0.2 m) frequency is used; therefore, the time requirements outlined in this hypothetical case must be adapted to site-specific observations while in the field.

CPT Approaches: LIF/Raman

As with the Raman approach, we assume that the LIF/Raman probe advancement is stopped every 5 ft (1.5 m), resulting in 20 events for each push, and that grouting can be completed through the probe tip. Sampling efforts require additional pushes (two total) with a grout probe. We assume that approximately seven field days are required to complete the LIF/Raman pushes and confirmation sampling.

Raman data profiles are spaced at 5 ft (1.5 m) intervals, and LIF and soil type data profiles are generated with relatively continuous resolution greater than one-third of a meter. Costs are comparable to the Raman approach, since the Raman measurement is the rate-limiting step. The data set generated by coupled LIF and Raman is more complete (potentially requiring additional reporting time) and the potential for false positives and false negatives is reduced. As was mentioned, Raman spectra is sometimes acquired every 0.5 to 3 ft (0.2 to 0.9 m) as the penetrometer is advanced (Rossabi et al. 2000). For sediments likely to contain DNAPL based on knowledge of disposal, previous work, or lithologic or LIF characteristics indicative of potential contaminant migration pathways, the 0.5 ft (0.2 m) frequency is often used. Therefore, as with several other approaches described, the time requirements outlined in this hypothetical case must be adapted to site-specific observations while in the field.

CPT Approaches: Electrochemical Sensor

It is assumed that a 5-by-5 grid of pushes 20 ft (6.1 m) apart in north and south directions to depths of 15 ft (4.6 m) is required to characterize the potential DNAPL source zone based on vadose zone soil pore vapor chlorine concentrations. Soil gas samples are to be collected with a 15-ton or greater CPT rig every meter (approximately 3 ft). Therefore, for the 25 pushes required, 125 soil gas samples will be analyzed over four field days. Two additional confirmation sampling pushes, collecting three samples each to 20 ft (6.1 m), are included in the investigation. As with the soil gas survey example, we assume that a "hot spot" is identified in the vadose zone. An additional sampling effort consisting of two soil collection borings is conducted to depths of 100 ft (30.5 m) below grade, collecting samples at 5 ft (1.5 m) intervals with a drill rig over the course of three days; therefore, 21 samples per hole, for a total of 42 samples, are collected and analyzed. Samples exhibiting high concentrations are further analyzed for grain-size distribution and permeability.

Using the CPT for sampling may reduce costs, because an additional mobilization-demobilization charge will not be incurred, and less solid waste will be generated. In addition, some smaller direct-push rigs may be used (at a reduced cost) for both the vadose zone screening and sampling activities beneath the water table.

CPT Approaches: Waterloo (Ingleton) Profiler

To be consistent with the other approaches evaluated, we assume that five pushes to advance the Waterloo Profiler will be used to screen the site. In addition, we assume that field sampling and analytical operations are conducted at a 5 ft (1.5 m) frequency in the saturated zone, resulting in 18 samples (or sampling events) for each push. Two additional pushes are required to collect confirmation soil samples (three per push) to depths of approximately 75 ft (22.9 m). Waterloo Profiler pushes will be grouted through the probe tip upon retraction. Sampling efforts require additional pushes (two total) with a grout probe. Hydraulic conductivity via constant head analysis requires only a few minutes for each test. Ground water sampling requires variable amounts of time, depending on the formation. We assume that approximately one run of the Waterloo Profiler to 100 ft/day can be accomplished.

Because soil hydrogeologic data is collected along with the chemical information, this level of effort may be enough to identify potential remediation options. Concentration versus hydraulic conductivity, concentration versus depth, and piezometric surface can be useful for this purpose. Chemical and hydrogeologic data profiles are spaced at 5 ft (1.5 m) intervals for this scenario; however, the probe is capable of resolution down to a fraction of a meter. For very detailed investigations, profiler data are acquired every 5 to 7.5 cm (2 to 3 inches) as the probe is advanced (Pitkin 1998). This requires more time, and therefore more costs, than the scenario previously described. For sediments likely to contain DNAPL based on knowledge of disposal details, previous work, or hydrogeologic characteristics indicative of potential contaminant migration pathways, the 5 to 7.5 cm (2 to 3 inch) frequency may be used. Therefore, the time requirements outlined in this hypothetical case will need to be adapted to site specific observations while in the field.

CPT Approaches: Precision Injection Extraction

We assume that precision injection extraction (PIX) probe analytical operations will require that probe advancement be stopped every 5 saturated ft (1.5 m), resulting in 18 events for each push. We assume that approximately six PIX events can be accomplished per day, due to the solvent-solute equilibrium requirements. Grouting will require additional pushes (seven total) with a grout probe. Therefore, it will require approximately 15 field days to complete the 90 sampling events and two additional days for confirmation sampling.

In practice, use of the PIX approach for UMS 1 may require a less-extensive effort than that previously described, because operators generally try to identify potential barriers to vertical NAPL migration prior to running the PIX, thereby focusing on candidate source zones. If vertical barriers are readily apparent using soil classification sensors, costs for the PIX method could be significantly less expensive (by as much as 50%) than the estimate provided. Because soil lithologic data are collected along with the chemical screening information, this level of effort may be enough to identify potential remediation options. Chemical data profiles are spaced at 5 ft (1.5 m) intervals (for this scenario), while soil type profiles are relatively continuous with greater than one-third of a meter resolution.

Ribbon NAPL Sampler FLUTe

The Ribbon NAPL Sampler FLUTe method can be implemented using either a direct-push rig or a conventional drilling rig. For this assessment, we assume that a direct-push rig (13,620 kg [15 ton] or greater capacity) is used for UMS 1 and a conventional drilling rig is used for UMS 2 and UMS 3. Two additional pushes or borings are required to collect confirmation samples (three per push or installation) to depths of approximately 75 ft (22.9 m). In addition, grouting requirements are carried out by advancing the CPT grout probe (UMS 1) or auger flights (UMS 2 and 3) to total depths attained for the seven holes. Reporting requirements are relatively minimal compared to approaches requiring more intensive data processing and presentation.

For UMS 1, we assume that the project requires three days to complete plus one day each to mobilize and demobilize. We can also assume that there will be one hour/day of standby, one hour/day to decontaminate the equipment used, and each workday consists of 10 hours. For UMS 2, we assume that the FLUTe is advanced using a conventional drilling rig and that the project requires four days to complete plus one day each to mobilize and demobilize. For UMS 3, we use the same assumptions as for UMS 2, with the exception that we assume that the costs for drilling will be $20/ft and that the project requires five days to complete plus one day each to mobilize and demobilize.

Discussion and Conclusions

Appendix II presents the cost and savings estimates for each approach included in the analysis. Figures 1 through 3 display the cost values for each UMS graphically. The savings were derived by subtracting the cost estimate for each approach from the cost estimate for the corresponding baseline approach. A negative savings value indicates that the approach incorporating the particular DNAPL characterization method is more costly than the baseline approach. Approaches that cannot be implemented in gravelly or consolidated geologic materials, such as CPT approaches, are not included in the UMS 2 and UMS 3 comparisons.

The least-expensive approaches for UMS 1 include several CPT sensor approaches, such as Fluorescence and MIP, and the FLUTe approach. Note that the FLUTe approach was installed with a CPT device for UMS 1. The fluorescence and MIP approaches must always include confirmation efforts, either by use of conventional analyses or by coupling to additional sensors such as the GeoVis. However, MSE Technology Applications (2000) stated in a report that the FLUTe approach may not require chemical confirmation once a larger database has been generated. If supported by regulators, this substantially reduces the costs (by close to $6000) associated with the FLUTe approach. However, we believe that regulators will require confirmation efforts for at least the next few years. The FLUTe approach may be more definitive with respect to identifying DNAPL source zones. While the Fluorescence and MIP approaches generate soil-classification data, the FLUTe approach will require either that lithology sensors are operated during the preliminary pushes or that additional laboratory tests be conducted on soil samples to determine soil type and hydraulic properties. Several additional approaches, including soil gas, Hydrosparge, GeoVis, Fluorescence-GeoVis, Raman, Fluorescence-Raman, and the Waterloo Profiler are very competitive (ranging from $20,000 to $40,000) for UMS 1. The baseline approach was estimated to be approximately $46,000 for UMS 1.

The most expensive approach for UMS 1 is the PITT survey. While this approach yields detailed hydrologic information and DNAPL volume estimates, water treatment costs associated with hydraulic control, and costs associated with preliminary site characterization and setup (e.g., aquifer testing, well installation, etc.) can be very high. Once a site has been adequately characterized and wells are properly installed and screened in optimal locations, the PITT approach can be a useful endeavor. PITT approaches for evaluation of remediation effectiveness have been successfully demonstrated with remarkably accurate mass removal estimates (Meinardus et al. 1998). During one particular test conducted at Hill Air Force Base, Utah, a PITT was used to estimate that approximately 346 gal (1310 L) of residual DNAPL remained in a test area prior to removal with use of a surfactant. A post-remediation PITT indicated that 341 gal (1291 L) had been recovered, with approximately 5 gal (19 L) remaining in the swept volume. The effluent treatment system recorded 363 gal (1374 L) recovered.

The PIX approach was very expensive under the assumptions used for UMS 1. In practice, the PIX method would not generally be used to screen at frequent depth intervals. Provided that potential traps or vertical migration barriers can be adequately recognized, injection-extraction tests can be performed at fewer depth locations, thereby leading to costs lower than those presented. Although not considered in the cost analyses, a back-tracking approach could be coupled with radon analyses, potentially resulting in better indirect DNAPL source area resolution and estimates of NAPL saturation. The PIX and back-tracking approaches each include confirmation steps, unless NAPL is recovered in the wells or during extraction.

The geophysical approaches cost more than the baseline approach for UMS 1, because they require confirmation steps roughly equal in cost to baseline efforts. Although not generally capable of identifying DNAPL source areas, geophysical approaches have been used to assist with locating appropriate sample collection zones based on interpretation of lithology to predict potential flow pathways. This optimization approach is often unsuccessful under conditions presented in UMS 1, which consists of unconsolidated soils. This is because DNAPL commonly occurs as discrete blobs that are generally smaller that the spatial resolution of the geophysical technique.

The FLUTe approach (with confirmation efforts) is the least expensive of the approaches evaluated for UMS 2. Only the FLUTe approach resulted in costs lower than the baseline approach for this scenario. The Radon flux rate, back-tracking, and geophysical approaches range in costs from approximately $50,000 to approximately $70,000. The FLUTe approach generally provides more NAPL location detail and depth resolution than the other approaches under conditions presented in UMS 2. The most expensive approach for UMS 2 is the PITT survey. As mentioned, the PITT approach yields detailed hydrologic information and volume estimates; however, water treatment costs associated with hydraulic control and costs associated with preliminary site characterization and setup (e.g., aquifer testing and, well installation) can be prohibitive. If a site has been adequately characterized and wells are properly installed and screened in optimal locations, the PITT approach can be used to determine target removal volumes. Although current enhancement efforts are under way, CPT approaches cannot currently penetrate soils characteristic of UMS 2.

For UMS 3, the FLUTe approach (with confirmation efforts) is the least expensive of the candidate approaches and is the only approach costing less than the baseline for this scenario. As with UMS 1 and UMS 2, the most expensive approach for UMS 3 is the PITT survey.

This paper compares many of the methods and approaches currently used to detect and delineate DNAPL contaminant source zones. In Part I of this study, general performance comparisons were generated to identify potential site management considerations required to reach a level of site understanding adequate to initiate remediation design efforts. Specific advantages and disadvantages for several methods were presented. For this effort, characterization approach cost comparisons for conceptual sites exhibiting particular sets of physical characteristics were generated. Perhaps the most important issue raised deals with the recognition that each candidate method must be placed in its proper context within the characterization process. The process itself is therefore considered an approach comprising several methods, each applied in a logical sequence to obtain data sufficient for remediation design.

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Editor's Note: The use of brand names in peer-reviewed papers is for identification purposes only and does not constitute endorsement by the authors, their employers, or the National Ground Water Association.

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Appendix I
Approach and Cost Assumptions

Approaches	Approach Assumptions	Cost Assumptions
1. Baseline approaches	• Collection and analysis of 21 soil samples per hole, for 5 holes • Field observations based on shake-tests, UV lamp, addition of Sudan IV, drill cutting fluids soils and vapors, and other screening activities conducted simultaneously with sample collection activities • Chemical and physical laboratory analyses • Mob-demob • Reporting	• \$1500/day for the drilling equipment • \$10/ft (0.3 m) for drilling (UMS 1) • \$20/sample for collection • \$3/ft (0.3 m) for grouting • \$1000/day for mobilization and demobilization • \$300/day for per diem for a three-person crew • \$170/hour for standby labor • \$100/hour for decontamination • \$40/ft^3 (0.03 m^3) for drilling waste disposal (approximately 35 ft^3 [1 m^3] per 8-inch [20.3 cm] diameter hole) • \$150/sample for laboratory chemical analyses • \$200/sample (15 total) for laboratory physical analyses • \$3000 for reporting the results (including boring logs and chemical data)
2. Soil gas surveys	• 25 pushes to 15 ft in 5-by-5 grid • Pore vapor samples collected every meter (approximately 3 ft; 5 samples per push) • Confirmation sampling and analyses from 2 pushes (3 soil samples each) to 20 ft (6.1 m) • Mob-demob for push rig • Two additional sample borings (using a drill rig) collecting samples at 5 ft (1.5 m) intervals from 20 to 100 ft (6.1 to 30.5 m) • Chemical and physical laboratory analyses • Mob-demob of drill rig • Reporting	• \$150/push • \$20/soil gas sample analyzed • \$1/ft for grouting (1500 ft total) • \$200/day for mobilization and demobilization of the push rig • \$200/day for per diem for a 2-person push rig crew (6 days) • \$170/confirmation sample (6 total) for collection and analyses • \$1500/day for the drilling equipment • \$10/ft (0.3 m) for drilling • \$20/sample for collection • \$3/ft (0.3 m) for grouting; \$1000/day for mobilization and demobilization • \$300/day for per diem for a 3-person crew • \$170/hour for standby labor (3 hours) • \$100/hour for decontamination (10 hours) • \$40/0.03 m^3 (1 ft^3) for drilling waste disposal (approximately 35 ft^3 [1 m^3] per 8-inch [20.3 cm] diameter hole; two drilled holes) • \$150/soil sample (48 total) for laboratory chemical analyses • \$20/sample (6 total) for laboratory physical analyses • \$3000 for reporting results (chemical data and a map depicting VOC plumes indicative of potential DNAPL vadose zone sources)
3. Partitioning interwell tracer tests	• Initial field screening (via FLUTe) and confirmation efforts • 8 wells (4 injection, 3 extraction, 1 monitoring) to 75 ft (22.9 m) • Laboratory efforts to determine tracer attributes • Aquifer tests • Conservative tracer tests • Hydraulic control • Modeling • PITT • Mob-demob • Reporting	• \$28,800 to deploy the FLUTe (UMS 1) and collect and analyze 6 soil samples (chemical and physical analyses) • \$4000 (80 hours at \$50/hour) for laboratory tests to assess initial residual saturation, select candidate tracers and determine corresponding partition coefficients • \$1500/day for 4 days for the 8 wells drill rig expenses for well installation efforts • \$100/hour (2 hours for each well) for well development • \$300/day for field work (6 days) and assessment (3 days) for a conservative tracer test • \$19,520 for well development disposal costs and \$1600 for aquifer testing waste disposal • \$2000 for GAC treatment equipment • \$3500 for mobilization, demobilization, treatment system breakthrough analyses (18 water samples total [2/day]), operational supplies, and discharge permits • \$10,000 for tracer breakthrough analytical expenses • \$4000 for modeling expenses for PITT design and flow regime assessment • PITT labor expenses of \$400/day (plus \$200/day for per diem) over the period of 9 days for hydraulic control, injection of tracers for 0.5 days, injection of potable water for 6 days to flood and recover tracers, sampling, and on-site chemical analyses • Reporting (summary of the preliminary characterization efforts, well logs, aquifer test results, analytical results, interpretation, and modeling results) costs of \$5000

Appendix I (continued)

Approaches	Approach Assumptions	Cost Assumptions
4. Radon flux rates	• Initial field screening (via FLUTe) and confirmation efforts • Installation of 5 monitoring wells to 75 ft (22.9 m) • An aquifer pump test • Sampling for radon • Mob-demob • Modeling • Reporting	• $28,800 to conduct a FLUTe survey (UMS 1) and collect and analyze confirmation soil samples • $1500/day for drill rig expenses for well installation plus $10/ft (0.3 m) for the 5 wells described • Approximately $1000/day for two days for mobilization and demobilization • $100/hour for two hours each well (10 hours total) for well development • $2800 for disposal of wastes for well installation, and $1400 for aquifer testing waste disposal • Approximately $200 each for Rn analytical costs for 5 samples (total cost $1000 per round) • Approximately $3000 (60 hours at $50/hour) for modeling expenses (displaying Rn data distribution superimposed on aquifer test data) • $300/day (for 3 days) for the Rn survey labor • $4000 for reporting (to include an overall data summary package, estimate of residual NAPL saturation distribution, presentation of modeling results, and well design descriptions [construction and development details])
5. Back-tracking using dissolved concentrations in wells	• Collection and analysis of 21 soil samples per hole, for 5 holes • Installation of 5 monitoring wells to 100 ft (30.5 m) • One round of ground water sampling at 10 depths per well • Mob-demob • Reporting	• $1500/day for the drilling equipment • $10/ft (0.3 m) for drilling (UMS 1) • $20/sample for collection • $3/ft (0.3 m) for grouting • $1000/day for mobilization and demobilization • $300/day for per diem for a 3-person crew • 75 ft (22.9 m) of blank PVC riser at a rate of $3/ft (0.3 m); 425 ft (129.5 m) of PVC screen at a rate of $4/ft (0.3 m) • 50 sacks of graded filter pack material at $6 per sack • 5 traffic boxes at $75 each • 10 sacks of bentonite at $6 per sack • 5 sacks of concrete at $3 per sack • Solid waste disposal (175 ft^3 [5 m^3] at $40/ft^3 [0.03 m^3] for drilling waste disposal (approximately 35 ft^3 [1 m^3] per 8-inch [20.3 cm] diameter hole), well development costs (including generation of 262.5 ft^3 [7.4 m^3] of aqueous wastes per hole [3 well volumes] at $10/ft^3 [0.03 m^3], and sampling costs for 10 isolated depths per well (for a total of 50 additional samples) for the first round of water sampling • 5 of the soil samples from each boring evaluated for grain size distribution ($60/sample) to determine filter pack grain size and corresponding screen slot sizes • $170/hour for standby labor • $100/hour for decontamination • $150/sample for laboratory chemical analyses, $200/sample (15 total) for laboratory physical analyses • $4000 for reporting (to include sampling logs, boring logs, well construction and development logs, sampling results (soil and water), grain size distribution data, and results from modeling scenarios which depict particle-tracking flow paths in reverse direction (in time increments) based on assumed aquifer properties corresponding to soil types identified in the soil sampling efforts)
6 Surface geophysics	• Extensive predeployment site planning • Field measurements • Vertical seismic profiles (requiring boreholes) • Data processing and interpretation • Attribute analysis • Confirmation sampling from 5 borings (8 samples each) to 100 ft (30.5 m) • Mob-demob • Reporting	• $2000 for the field survey • $9545 for data processing and interpretation • 5 additional sampling borings consisting of 8 samples each, ranging from 30 to 100 ft (9.1 to 30.5 m) below grade • $6000 (40 samples at $150 each) for chemical analytical costs • $1000 (5 samples at $200 each) for physical analytical efforts • $4000 for reporting (processed geophysical information, confirmation results, and specific predictions for NAPL location)

Appendix I (continued)

Approaches	Approach Assumptions	Cost Assumptions
7. Subsurface geophysics	• Extensive predeployment planning • Field measurements • Vertical seismic profiles • Data processing and interpretation • Attribute analysis • Confirmation sampling from 5 borings (10 soil samples each) to 100 ft (30.5 m) • Installation of a well to 100 ft (30.5 m) • Sampling from the well (10 water samples total) • Mob-demob • Reporting	• In addition to costs articulated for the surface geophysical approach above, costs for an additional well (fully screened from 15 to 100 ft [4.6 to 30.5 m], omitting sampling and analyses) at a rate of $7690 (UMS 1), $9610 (UMS 2), and $11,530 (UMS 3) • One additional day of drilling and well installation was required for UMS 1, two days for UMS 2, and three days for UMS 3 • Two additional days for mobilization and demobilization
8. **CPT approaches**:		
8a. Permeable membrane sensor; membrane interface probe (MIP)	• Field measurements for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• $3500/day for a 3-man crew, pushing, near-real-time analyses with an ion trap mass spectrometer, ground water sampling (90 samples total), grouting, standby, and decontamination • Approximately $150 each for soil confirmation analyses (6 total) • $1000/day for 2 days for mobilization and demobilization • Approximately $300/day for 7 days total for per diem • Approximately $3000 for reporting (field and confirmation data and limited interpretation)
8b. Hydrosparge	• Field measurements on a 5 ft interval for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• $3500/day for a 3-man crew, pushing, near-real-time analyses with an ion trap mass spectrometer or gas chromatograph, confirmation sampling, grouting, standby, and decontamination • Approximately $150 each for soil confirmation analyses (6 total) • $1000/day for 2 days for mobilization and demobilization • Approximately $300/day for 9 days total for per diem • Approximately $3000 for reporting (field and confirmation data and limited interpretation)
8c. Florescence (e.g., laser-induced fluorescence [LIF]) techniques	• Field measurements for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• $3500/day for a 3-man crew, pushing, real-time analyses with a laser induced fluorescence system, confirmation sampling, grouting, standby, and decontamination • Approximately $150 each for soil confirmation analyses (6 total) • $1000/day for 2 days for mobilization and demobilization • Approximately $300/day for 6 days total for per diem • Approximately $3000 for reporting (field and confirmation data and limited interpretation)
8d. GeoVis	• Field measurements for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• $3500/day for a 3-man crew, pushing, real-time analyses with a laser induced fluorescence system, confirmation sampling, grouting, standby, and decontamination • Approximately $150 each for soil confirmation analyses (6 total) • $1000/day for 2 days for mobilization and demobilization • Approximately $300/day for 10 days total for per diem • Approximately $2000 for reporting (field and confirmation data and limited interpretation)
8e. LIF/GeoVis	• Field measurements for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• $3500/day for a 3-man crew, pushing, real-time analyses with a laser induced fluorescence system, confirmation sampling, grouting, standby, and decontamination • Approximately $150 each for soil confirmation analyses (6 total) • $1000/day for 2 days for mobilization and demobilization • Approximately $300/day for 10 days total for per diem • Approximately $3000 for reporting (field and confirmation data and limited interpretation)

Appendix I (continued)

Approaches	Approach Assumptions	Cost Assumptions
8f. Raman spectroscopy	• Field measurements on a 5 ft interval for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• \$3500/day for a 3-man crew, pushing, real-time analyses with a Raman system, confirmation sampling, grouting, standby, and decontamination • approximately \$150 each for soil confirmation analyses (6 total) • \$1000/day for 2 days for mobilization and demobilization • Approximately \$300/day for 9 days total for per diem • Approximately \$3000 for reporting (field and confirmation data and limited interpretation)
8g. LIF/Raman	• Field measurements for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• \$3500/day for a 3-man crew, pushing, real-time analyses with Raman and LIF systems, confirmation sampling, grouting, standby, and decontamination • Approximately \$150 each for soil confirmation analyses (6 total) • \$1000/day for 2 days for mobilization and demobilization • Approximately \$300/day for 9 days total for per diem • Approximately \$3000 for reporting (field and confirmation data and limited interpretation)
8h. Electrochemical sensor probe	• 25 pushes to 15 ft in 5-by-5 grid • Pore vapor samples collected every meter (approximately 3 ft; 5 samples per push) • Confirmation sampling and analyses from 2 pushes (3 soil samples each) to 20 ft (6.1 m) • Mob-demob for push rig • Two additional sample borings (using a drill rig) collecting samples at 5 ft (1.5 m) intervals from 20 to 100 ft (6.1 to 30.5 m) • Chemical and physical laboratory analyses • Mob-demob of drill rig • Reporting	• \$3500/day for a 2-man CPT crew, pushing, real-time analyses with a field gas chlorine sensor, confirmation sampling, grouting (through probe tip), standby, and decontamination • Approximately \$150 each for soil confirmation analyses (6 total) • \$1000/day for 2 days for push rig mobilization and demobilization • Approximately \$200/day for 6 days total for per diem (2-person crew) • \$1500/day for the drilling equipment; \$10/ft (0.3 m) for drilling • \$20/sample for collection; \$3/ft (0.3 m) for grouting • \$1000/day for drill rig mobilization and demobilization • \$300/day for per diem for a 3-person crew • \$170/hour for standby labor (3 hours) • \$100/hour for decontamination (10 hours) • \$40/0.03 m^3 (1 ft^3) for drilling waste disposal (approximately 1 m^3 [35 ft^3] per 20.3 cm [8-inch] diameter hole; two drilled holes) • \$150/soil sample (48 total) for laboratory chemical analyses • \$200/sample (6 total) for laboratory physical analyses • \$3000 for reporting results (chemical data and a map depicting VOC plumes indicative of potential DNAPL vadose zone and ground water sources)
8i. Waterloo (Ingleton Profiler)	• Field measurements on a 5 ft (1.5 m) saturated interval for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• Approximately \$2000/day (assuming that a GeoProbe-type rig is used for this deployment) for a 2-man crew, pushing, real-time aquifer analyses with the profiler components, sample collection, confirmation soil sampling, grouting, standby, and decontamination • Approximately 6 field days to complete the 5 pushes, confirmation sampling, and grouting operations • Approximately \$150 each (96 total) for laboratory analyses • Approximately \$200/day for 2 days for mobilization and demobilization • Approximately \$200/day for 8 days total for per diem • Approximately \$3000 for reporting (field and confirmation data and limited interpretation)
8j. Cosolvent injection/extraction; precision injection/extraction (PIX) probe	• Field measurements on a 5 ft (1.5 m) saturated interval for 5 pushes to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses from 2 pushes (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting	• Approximately \$3500/day for a 3-man crew, pushing, near-real-time analyses with a field gas chromatograph, confirmation sampling, grouting, standby, and decontamination • Approximately \$150 each for soil confirmation analyses (6 total) • \$1000/day for 2 days for mobilization and demobilization • Approximately \$300/day for 19 days total for per diem • Approximately \$3000 for reporting (field and confirmation data and limited interpretation)

Appendix I (continued)

Approaches	Approach Assumptions	Cost Assumptions
9. Flexible Liner Underground Technologies Everting (FLUTe) membrane	• Deployment of 5 FLUTe liners to 100 ft (30.5 m) • Data processing and interpretation • Confirmation sampling analyses (chemical and physical laboratory analyses) from 2 locations (3 soil samples each) to 75 ft (22.9 m) • Mob-demob • Reporting UMS 1 implemented using CPT while UMS 2 and UMS 3 implemented using conventional drilling equipment.	UMS 1: • \$3500/day for a 2-man crew, pushing, retraction and analyses using the FLUTe system, confirmation sampling, grouting, standby, and decontamination • Approximately \$150 each for soil confirmation analyses (6 total) • \$200/soil sample physical analyses (grain-size distribution and permeability) • \$1000/day for 2 days for mobilization and demobilization • Approximately \$200/day for 5 days total for per diem • Approximately \$3000 for reporting (field and confirmation data and limited interpretation) UMS 2 and UMS 3: • \$1500/day for the drilling equipment • \$10/ft (0.3 m) for drilling (\$20/ft [0.3 m] for UMS 3) • \$20/sample for collection • \$3/ft (0.3 m) for grouting • \$1000/day for mobilization and demobilization • \$200/day for per diem for a 2-person crew (6 days for UMS 2; 7 days for UMS 3) • \$170/hour for standby labor • \$100/hour for decontamination • \$40/ft^3 (0.03 m^3) for solid drilling waste disposal (approximately 35 ft^3 [1 m^3] per 8-inch [20.3 cm] diameter hole to 100 ft [30.5 m]; 26.25 cubic ft [0.74 m^3] per 8-inch [20.3 cm] diameter hole to 75 ft) • \$150/sample (6 total) for laboratory chemical analyses • \$200/sample (6 total) for laboratory physical analyses • \$2000 for reporting

Appendix II
Cost Comparisons for Each Approach

Approaches	UMS 1 $ (Savings)	UMS 2 $ (Savings)	UMS 3 $ (Savings)
1. Baseline approaches	$46,160 *(0)*	$50,300 *(0)*	$59,440 *(0)*
2. Soil gas surveys	38,360 *(7800)*	N/A *(N/A)*	N/A *(N/A)*
3. Partitioning interwell tracer tests	113,580 *(–67,420)*	126,130 *(–75,830)*	144,740 *(–85,300)*
4. Radon flux rates	70,870 *(–24,710)*	89,745 *(–39,445)*	104,425 *(–44,985)*
5. Back-tracking using dissolved concentrations in wells	62,290 *(–16,130)*	66,430 *(–16,130)*	75,570 *(–16,130)*
6. Surface goephysics	54,773 *(–8613)*	59,163 *(–8863)*	70,444 *(–11,004)*
7. Subsurface geophysics	62,613 *(–16,453)*	68,973 *(–18,673)*	82,224 *(–22,784)*
8. CPT approaches: Permeable membrane sensor; membrane interface probe (MIP)	25,500 *(20,660)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: Hydrosparge	33,100 *(13,060)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: Fluorescence (e.g., laser-induced fluorescence [LIF]) techniques	21,700 *(24,460)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: GeoVis	35,900 *(10,260)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: LIF/GeoVis	36,900 *(9260)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: Raman spectroscopy	33,100 *(13,060)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: LIF/Raman	33,100 *(13,060)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: Electrochemical sensor probe	47,070 *(–910)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: Waterloo (Ingleton) Profiler	31,400 *(14,760)*	N/A *(N/A)*	N/A *(N/A)*
CPT approaches: Solvent injection/ extraction; precision injection/ *extraction (PIX) probe*	76,100 *(–29,940)*	N/A *(N/A)*	N/A *(N/A)*
9. Flexible Liner Underground Technologies Everting (FLUTe) membrane	28,600 *(17,560)*	39,550 *(10,750)*	48,290 *(11,150)*

N/A = Not applicable.