Subsurface Oil Detection and Delineation in Shoreline Sediments

Phase 1—Final Report

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Executive Summary

This report summarizes the findings of Phase 1 of an American Petroleum Institute (API) Oil Spill Research and Development (R&D) Project to evaluate Current Practice and Prospective Developing Technologies for the Detection and Delineation of Subsurface Oil in Sediment Shorelines. This Phase 1 component of the project defines current practices and identifies selected developing technologies which promise to improve on the existing survey methods.

Current practice consists primarily of field surveys based on visual observations in excavated pits and trenches, in some cases supplemented by core samples and materials produced by water jet probes. These procedures can be labor intensive and time consuming, particularly when large areas are involved or repetitive surveys are necessary. In addition, typically, current practices rely on small horizontal samples, which may not be adequate to detect or define subsurface oil if the distribution is discontinuous. Developing technologies have a real potential to provide procedures that can either accelerate the collection of subsurface data or allow for continuous horizontal detection and delineation.

Attributes of the basic current and developing technology strategies, in terms of horizontal delineation, vertical delineation, survey speed, description of oil characteristics, and relative costs are summarized in Table E-1. Analysis of these attributes strongly suggests that no single technique is likely to be applicable to all situations that may be encountered and a combination of current practice and developing technology (green boxes) may be effective in providing better subsurface resolution at a quicker rate and with a more efficient commitment of resources.

This review promotes the opinion that efforts should continue to improve the efficiency of existing tactics and development of new technologies. The combined application of these tactics can significantly reduce the reliance on time-consuming practices, improve overall data quality and accelerate the collection of data. Some of the developing technologies identified herein (especially use of service dogs, electromagnetic, and surface vapor measurements) show significant potential for achieving operational status with minimal additional testing and trials and so represent a realistic potential for short-term (months to years), high value gains. The development of new technologies can proceed either through additional research or by trial applications on real-world events.

The results of this Phase 1 study form the basis for Phase 2 studies which include a "*Field Guide for Subsurface Oil Detection and Delineation in Shoreline Sediments*" (API Technical Report 1149-2, 2013) and a report which will provide recommendations for R&D studies to improve and demonstrate developing technologies.

Table E-1 Attributes of Subsurface Oil Survey Strategies

ATTRIBUTES	Existing Procedures			Developing Technology (Potential)			
	Excavation	Cores	Jetting	Push Probes	Service Dogs	Geophysical	Surface Gas
Delineation (Horizontal)	🟨	🟥	🟥	🟥	🟩	🟩	🟩
Delineation (Vertical)	🟩	🟩	🟨	🟩	🟥	🟨	🟥
Survey Speed	🟥	🟥	🟨	🟨	🟩	🟩	🟩
Oil Character	🟩	🟩	🟨	🟩	🟥	🟥	🟥
Relative Cost	🟨	🟥	🟨	🟨	🟨	🟩	🟩

- **Green** indicates a favorable application;
- **Yellow** indicates that the strategy may be effective, depending on circumstances, and
- **Red** indicates important limitations or “not applicable”.

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1.0 Introduction

Oil deposited on shorelines during oil spill events can penetrate into sediments, be mixed with underlying sediments, and/or be buried by natural shoreline processes. The resulting subsurface accumulations can consist of a continuous layer or layers of solid or emulsified oil, oil-saturated sediments, or scattered discontinuous deposits. Subsurface oil is also subject to reworking and re-deposition, depending on the character of the substrate and local wave and tidal energy conditions.

Field surveys to detect, delineate and understand the characteristics of subsurface oiling are essential in the development of shoreline treatment end points and cleanup plans. Survey techniques that have been, and are currently utilized for this purpose, focus primarily on excavations. Excavations provide trained observers with the opportunity to visually assess and document both vertical and horizontal characteristics of subsurface oil. Other data collection tactics have been tested over the years, and some continue to be used, although most do not allow for the diversity of observations that can be obtained from excavations.

Time is of the essence in a spill response in order to remove oil from shorelines before it can be remobilized or buried. The quicker field survey data can be collected and assessed, the faster cleanup plans can be developed and implemented. Faster methods of subsurface data collection are desirable. In addition, current strategies only provide a relatively small sample of the distribution and character of subsurface oil deposits. Better resolution of subsurface oiling is desirable.

Based on technological advances and response experience over the last decade, a variety of options have emerged that demonstrate significant potential for improving the state-of-the-art in shoreline protection and cleanup. Recognizing this factor, the API initiated an Oil Spill R&D Program to improve the overall capabilities for the Protection and Cleanup of Shorelines. One component of this effort addresses the improvement of shoreline surveys techniques for the detection and delineation of subsurface oil on sediment shorelines. The effort is divided into three phases:

- Phase 1: Description of current practice and identification of promising detection techniques (this report);
- Phase 2: Development of a "*Field Guide to the Detection and Delineation of Subsurface Oil in Shoreline Segments*", based on current technology and practices, and assessment of prospective new technologies, including recommendations for R&D studies appropriate to advance the application of these options; and
- Phase 3: Consideration of laboratory and field tests/trials to develop and verify the applicability of high potential subsurface oil detection techniques ("Proof of Concept").

There have been significant advances in technology over the past decade and undoubtedly there exist tools or techniques that may have an application to detect or delineate subsurface oil that are not covered in this review. Many ideas were evaluated during the Deepwater Horizon response as part of the Alternative Response Technologies ("ART") program, some of which involved oil detection on shorelines and some of which were field tested, such as a laser fluorometer to detect sunken oil in shallow water

(Cortez, 2011). Technology will continue to improve and there is a reasonable expectation that new strategies and tactics will evolve in the coming years. This study is one step in that evolutionary process. This review focuses on those classes of developing technology which promise short-term operational application to emergency response detection of spilled oil incorporated in shoreline sediments, with the ultimate goals of significantly reducing the reliance on existing time-consuming practices, improving overall data quality and accelerating the collection of data.

2.0 Phase 1 Objectives

- Identify and document current best practices for the detection and delineation of subsurface oil in sediment shorelines.

- Identify developing technologies that have demonstrated the potential to more effectively, in time and space, detect and delineate subsurface oil in shoreline sediments (in the context of information and presentations necessary to support emergency response efforts).

- Establish a framework within which research can be implemented to progress the highest potential alternative technologies.

3.0 Background Information on Subsurface Oil

3.1 Data Requirements

The objective of this study is to identify tactics and technologies that can support emergency response operations. Spill Management Teams (SMTs) require an appropriate level of knowledge regarding the location, extent and character of surface and subsurface oil on shorelines to design, manage, and control cleanup operations. As conditions can be expected to change with time, repeated situational surveys and updates are typically necessary. To be useful, information must be available on a near real-time basis. Historical (and current) practice for subsurface oil detection and delineation, and for the monitoring of cleanup, has relied heavily on visual observations. Although subsurface visual assessments typically provide adequate levels of information to support operations, this strategy is usually slow and labor intensive, particularly with chronic reoiling and dynamic shorelines. Other subsurface observation or detection and delineation strategies have been applied to expedite subsurface observations with varying degrees of success. Technological developments in the last decade have provided the opportunity to improve current survey tactics as well as a variety of new and promising instruments and techniques.

Current shoreline subsurface detection and delineation practice in the US has generally adopted a survey methodology formalized during the 1989 T/V *Exxon Valdez* oil spill response. This methodology, the Shoreline Cleanup Assessment Technique (SCAT) procedure, allows for the standardized and systematic description of shoreline oiling conditions, both on the surface and in subsurface sediments (NOAA, 2000; Owens and Sergy, 1994, 2000). The SCAT observations are intended to be used to develop shoreline treatment recommendations for consideration by the SMT and are used for:

- Development of treatment or cleanup end points;

- Monitoring and adjustment of cleanup tactics;

- Net environmental benefit analyses (NEBA);

- Monitoring of cleanup effectiveness;

- Inspections to verify that end points have been achieved; and
- Long-term recovery monitoring.

A basic assumption of this study is that the SCAT procedure, or its equivalent, will continue to be used to support shoreline cleanup decisions and operations. To function effectively within the framework of an emergency response operation, and the continually changing environmental and oiling conditions, situational data must be easily and quickly obtained and updated. In accomplishing this strategy, SCAT relies on the examination of visual information and documentation using trained observers. The subsurface component of this process, in particular, typically is labor intensive and time consuming.

In an evaluation of modifications to existing tactics, or an evaluation of new strategies, tactics and/or technologies, the following attributes should be considered:

❖ **Scope:** Individual tactics may not collect all of the required data. Combinations of existing and developing tactics are acceptable as long as they contribute to improve of the speed, quality and economics of data collection;

❖ **Availability:** Any necessary equipment, trained operators and/or other support services should be readily available;

❖ **Calibration:** Calibration requirements should be minimal and, preferably, field rather than laboratory protocols;

❖ **Data Turn-around Time:** Observations are extremely time sensitive and should be available to the SMT on a near real-time basis (i.e. a time scale of days). Immediate data processing and presentation of summary information is crucial to the decision process;

❖ **Delineation of Extent:** Sufficient detail should be provided to delineate the extent and the distribution of subsurface oil deposits both horizontally and vertically. This information may include: depth and thickness of oil or oiled sediment layer(s), characteristics and distribution of oil within those layer(s), and properties of shoreline sediments (grain size, mineralogy, water content/depth to beach groundwater, presence of burrows, sediment bearing capacity, etc.);

❖ **Detection Levels:** Detection levels must be consistent with the requirements of each situation. At a minimum, observations should be consistent with SCAT definitions (typically visual). Some promising technologies can offer much higher detection levels. In these cases, speed, reliability and cost factors should be considered;

❖ **Location Control (vertical and horizontal):** Precise positioning is essential in all surveys. Current practice increasingly relies upon GPS positioning/tracking equipment and GIS data management. High precision GPS and real-time data reduction are desirable (see Section 4.2).

3.2 Subsurface Oil on Sediment Shorelines

Spilled oiled can be incorporated in shoreline sediments by a variety of mechanisms that include:

- Fluid oil deposited on the shoreline surface may soak directly into underlying sediments. This typically occurs with oils that have a low viscosity, such as distillate fuels and some fresh, light crude oils. Penetration into the sediments is dependent on: oil viscosity, sediment grain size (porosity), water content, degree of sediment compaction, and factors such as presence of biogenic pathways (animal burrows). Normally, vertical penetration of oil stops at the beach groundwater surface. If there is sufficient available oil, the entire overlying zone may be saturated with oil and there may be a floating layer on the beach surface. A similar effect may occur when solid or viscous oil deposited on the surface is heated by the sun and decreases in viscosity sufficiently to migrate vertically. The latter effect is common when oil is deposited or stockpiled in the supratidal zone;

- Floating oil frequently is deposited on shorelines in discontinuous, irregular patterns in the swash zone or as scattered tar balls or residue accumulations;
- Oil deposited on the surface can be covered (buried) by wind-blown clean sediment or clean sand that is deposited by natural onshore or along-shore processes (accretion). Multiple layering with depth is possible;
- Surface deposits of oil can be covered by sand when dunes collapse during storms;
- Oil deposited on shoreline surfaces can be mixed with clean underlying or adjacent sediments by wave action and alongshore transport and can be re-deposited at depth and/or in adjacent locations. Downward mixing of oil may be deeper than the groundwater water level. The development of multiple oil layers is possible;
- Surface and subsurface oiling can coexist;
- Oil may flow or fall into animal burrows.

3.3 Oil Distribution

Oil on the surface or within sediments is unlikely to have a regular distribution. In most cases, oil is deposited on the mid- and upper-intertidal zones in irregular patterns by wave action, storm surges, and other processes which result in varying concentrations of surface oil. Burial processes add a vertical dimension to this irregular distribution. Understanding this typical irregular distribution pattern is critical to the design and assessment of detection equipment and evaluation techniques.

The SCAT manual (Owens and Sergy, 2000) defines the subsurface oiled zone as "*the vertical width or thickness of the oiled sediment layer when viewed in profile by digging a pit or trench.*" Standard SCAT terminology for describing subsurface oil distribution includes:

Saturated	(**Continuous**: 91–100 %)
Layers	(**Broken**: 51–90 %)
Patchy	(11–50 %)
Sporadic	(<10 %)

- Multiple layers
- Depth of over burden
- Water level

SCAT also defines specific characteristics of subsurface oil. These characteristics include:

- **Subsurface Asphalt Pavement (SAP):** cohesive mixture of weathered oil and sediment situated completely below a surface sediment layer;
- **Oil-filled Pores (OP):** pore spaces in the sediment matrix that are completely filled with oil; often characterized by oil flowing out of the pores when disturbed;
- **Partially Filled Pores (PP):** pore spaces filled with oil, but generally does not flow out when exposed or disturbed;
- **Oil Residue** as a **Cover (>0.1–1.0 cm thick)** or **Coat (0.01–0.1 cm) (OR)** of oil on sediments and/or some pore spaces partially filled with oil. Cover/Coat can be scratched off easily with fingernail;
- **Oil Film or Stain (<0.01 cm thick) (OF)** of oil residue on the sediment surfaces. Non-cohesive. Cannot be scratched off easily on coarse sediments;
- **Trace (TR):** discontinuous film or spots of oil on sediments, or an odor or tackiness with no visible evidence of oil; and
- **No Oil (NO):** no visible or apparent evidence of oil.

It is anticipated that equipment and techniques described or resulting from this study would be used in support of SCAT surveys.

3.4 Oil Characteristics

Crude oil and petroleum products exhibit a wide variety of properties which influence their persistence, movement through the environment, and their detection, monitoring, and cleanup requirements. Once exposed to the environment, these properties can be expected to: (a) differ from MSDS product specifications, unless the oil is very fresh; and (b) continually change (often significantly) over time as weathering and other processes proceed.

Oil properties relevant to the detection, delineation and characterization of subsurface oil, and the development of response strategies, include:

- **Density:** The density of crude oil and products is dependent on their composition and temperature. Oil will sink when the density is greater than water and float if it is less. Oil density will increase as evaporation and other weathering processes occur, and some oils that initially float may ultimately sink;
- **Pour Point:** Pour point is the temperature below which oil will not flow. Many crude oils have pour points that are near or at ambient temperature, with the effect that they can change from liquid to solid and back depending on the ambient temperature range. Pour point can be expected to change as the oil weathers;
- **Viscosity:** Viscosity is a measure of the resistance of a fluid that is being deformed by either shear or tensile stress, and may be thought of as a measure of fluid friction. Simply stated, the less viscous the fluid is, the greater its ease of movement (fluidity). Oils having a high viscosity are less likely to penetrate into sediments and may require special handling procedures during cleanup;

- **Emulsification:** Crude oil tends to form emulsions which, in most cases, consist of small drops of water incorporated in the oil as a result of mixing energy, such as wave action or turbulence associated with a well blowout or pipeline release. Formation of emulsions (mousse) typically increases the volume and persistence of the spilled oil and can impact behavior and cleanup requirements. Emulsions typically do not flow, although they may exhibit measurable viscosity. As a result, they tend not to penetrate into sediments when grounded on shorelines, although some emulsions have limited stability and may collapse into oil and water phases over time or when heated (as by the sun). Relatively stable emulsions were generated following the Deepwater Horizon response and these emulsions retained sand when they were deposited on beaches. Although originally friable in composition, these sand-oil emulsions typically did not collapse and became more cohesive over time, allowing their effective recovery by screening. Emulsion formation may reduce the rate of evaporative loss of the lower molecular weight hydrocarbons;

- **Asphalt/Paraffin Content:** Crude oils and residual fuels associated with refining, contain varying percentages of asphaltic and paraffinic (waxy) components, which can impact their behavior and persistence. Crude oils that contain significant amounts of asphaltic compounds tend to be viscous, sticky, and persistent. Conversely, paraffinic oils tend to be less viscous, slippery and less persistent;

- **Hydrogen Sulfide:** Hydrogen sulfide gas is present in some crude (sour) oils and residual fuels. It has the odor of rotten eggs and is detectable by humans to levels of approximately 1 ppm. This gas quickly deadens the sense of smell and may not be detectable (to humans) following short exposure. Hydrogen sulfide can be dangerous or fatal following short exposures at relatively low concentrations. In air, it is slightly denser (heavier) than air and may persists and be detectible in subsurface sediments for extended periods;

- **Weathering:** The term weathering is used to describe a variety of phenomena which degrade spilled oil. These processes include evaporation, photo-oxidation, biodegradation, and other degradation processes. Typically, these processes remove volatile low molecular weight hydrocarbons rapidly, although burial, formation of emulsions, and the development of weathered crusts on oil accumulations may slow weathering, allowing, for example, off-gassing of detectible volatiles over extended periods;

- **Color:** Crude oils, emulsions and refined products exhibit a wide variety of colors ranging from black, brown, tan, green, red, orange, and so on. Color is often an important criterion in the description and delineation of subsurface oil. Color can also be misleading as spilled and weathered oil frequently resembles natural shoreline materials (diatom and dinoflagellate blooms, seaweed, peat, heavy mineral deposits, decomposing organic material, etc.). Light products are often difficult to detect visually in sediments, particularly in lower concentrations; and

- **Friability:** Friability refers to the cohesiveness of accumulations of oil and sediment. This characteristic describes the ease with which residues or accumulations crumble. Cohesive accumulations can be recovered using techniques such as screening, whereas more friable material breaks into smaller particles which may require other tactics.

3.5 Beach and Sediment Character

Shoreline character can impact the implementation of subsurface oil detection and delineation techniques. The characteristics can include:

- ❖ **Access and Trafficability** (the ability to support foot and equipment operation) are critical for some field operations and cleanup techniques, particularly those involving machinery;
- ❖ **Surface Topography** can impact the performance of some detection tactics. Flat surfaces may be necessary for the deployment and operation of some technologies, in particular geophysical measurements;
- ❖ **Sediment Stability** affects excavation on a beach. The angle of repose of some beach materials is so low that excavations cannot be kept open long enough to complete observations. This commonly occurs with dry, coarse sands. Slumping of material into pits and trenches dug below the water table is typical. Slumping can also occur during coring operations; and
- ❖ **Environmental, Cultural and Political Sensitivity** of the area to be surveyed can impact the selection of techniques, with intrusive and high activity techniques often being problematic.

4.0 Historical and Current Practice

4.1 General

Historical and current practices for the detection of subsurface oil on sediment shorelines were examined by reviewing case histories and other literature on oil spills that impacted sediment shorelines. Document sources examined included the following:

- Proceedings of the International Oil Spill Conference (1969 to 2011);
- NOAA Summaries of Significant US and International Spill – Oil Spill Case Histories 1967–1991;
- Proceedings of the Arctic Marine Oil Spill Program (AMOP) Technical Seminars;
- CEDRE – Major Oil Spill Summaries;
- International Tanker Owners Pollution Federation, Limited – Oil Spill Case Histories; and
- A range of Internet locations.

The first section (4.2) deals with the basic positioning current Geographic Positioning System, (GPS) technology, which is an important and applicable component for all strategies and tactics to provide location data.

In general, subsurface oil surveys and detection procedures are poorly documented in the literature. However, based on available information and experience of the reviewers, current detection and delineation tactics can be grouped into the following general strategies:

- Pits and Trenches (Section 4.3);
- Core Sampling (Section 4.4);

- Water Jet Probing (Section 4.5); and
- UV Fluorescence (Hand Held) (Section 4.6).

The following discussion of these strategies is based on available literature and augmented by the professional experience of the authors and reviewers of this document. Approximate costs for different techniques are based on 2011–2012 US dollar estimates.

4.2 Geographical Positioning Systems (GPS)

4.2.1 General

Shorelines often exhibit dynamic sedimentary changes, particularly in response to storm wave action. Changes can include rapid erosion, accretion, and the redistribution of sediments and subsurface oil. Understanding these processes and the accurate location of subsurface features is essential. Historically, the location of observations has been plotted manually on maps or air photos, with depths of subsurface features measured with tapes. Beach profiles have been developed with the use of hand levels and chains or tapes and in some cases by instrumental surveying. Current GPS technology allows the collection of accurate both horizontal and vertical locations and recording of survey track lines and way points. Survey grade GPS equipment can also provide computerized profiling and 3-dimensional mapping capabilities.

4.2.2 Hand Held GPS

Hand held GPS units typically contain track logging capability which records movements of the unit over time. Units can be time synchronized to SCAT observations and photography. Data can be downloaded to a GIS system for data management and map production on a daily basis.

4.2.3 Beach Profiles

Subsurface observations are evaluated in the context of shoreline elevations, or profiles, perpendicular to the shoreline. Historically, profiles were surveyed using tapes stakes and hand levels, and in some cases using surveying equipment, such as levels. Current technology permits rapid and highly accurate profiling and development of 3-dimensional maps using Real Time Kinematic (RTK) satellite surveying technology. This technology can provide centimeter-level accuracy. Ideally, a control point (benchmark) with a fixed geodetic location (latitude, longitude and state plane coordinates) is established and a known elevation or datum (e.g. NAVD 88) is established for each survey location. A portable transceiver is set at each sample point, with data transmitted back to the base unit (Figure 4.1). The ability to quickly resurvey and compare profiles can be extremely valuable. Representative data presentations are shown in Figure 4.2.

Advantages:

- An existing technology that provides accurate horizontal and vertical positioning;
- Hand held units are relatively easy to learn to use; and
- Some equipment collects continuous position data and can be time synchronized to automatically track surveys and downloaded to a GIS for data management.

Figure 4.1 GPS Satellite Survey Equipment

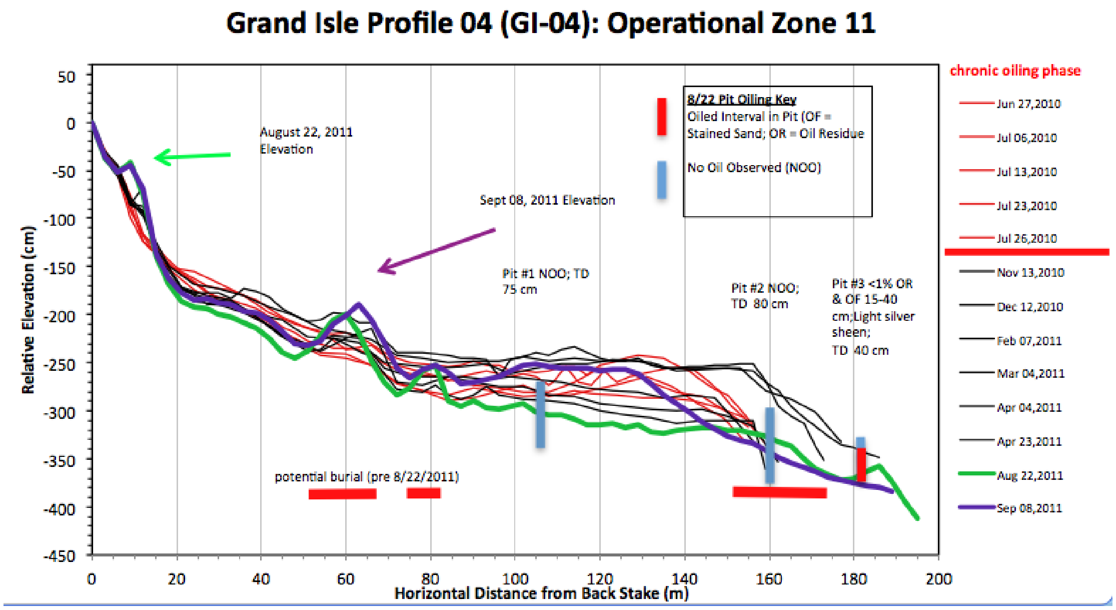


Figure 4.2 Combination of Time-series Beach Profile Data and Pit Information

Disadvantages:

- Survey grade equipment requires trained operators; and
- Requires establishment (or location) of control points (bench marks) and may also require office data reduction**.**

Availability:

- Hand-held instrumentation is readily available; and
- Survey grade equipment and operators are available through land survey companies.

Cost (*based on authors' estimates*):

- Prices for hand-held GPS units range from several hundred to several thousand dollars.
- There are no additional costs if used by SCAT personnel.
- Survey grade equipment requires a trained operator, and requires establishment of survey monuments. Also requires offsite data reduction.
- Survey costs are expected to be moderate.

4.3 Pits and Trenches

Excavated shallow pits and trenches have been used historically for subsurface observations and sample collection. This strategy continues to be the most commonly used method for subsurface data collection and is a standard element of Shoreline Cleanup Assessment Techniques (SCAT) surveys. Pits and trenches are recommended tactics in most of the primary shoreline procedure manuals, such as:

- Kerambrun, 2006
- Moore, 2007
- NOAA job aides
- Owens and Sergy, 1994, 2000, 2004
- Owens et al., 1995

The size and depth of observation pits varies according to shoreline and oiling characteristics, but pits typically are up to 1.0 m (3 feet) in diameter and extend to the beach water table. They permit point observations of the subsurface and many may be required to define the depth, length, width and characteristics of an oiled area. Trenches are essentially extended pits and are preferred over pits in most cases as they can provide a larger and more representative view of the subsurface. In theory, fewer trenches are necessary to characterize a section of beach, but their excavation is more labor intensive and in some cases a complete cross section of the beach may not be practical.

A common problem with pits and trenches is that they may not remain open long enough to complete the observations. Excavations in finer-grained and/or damp sediments tend to remain open fairly well, whereas coarser-grained, dry material (typically more common in the upper intertidal and supra tidal zones) tend to slump into the hole. Pits generally exhibit greater resistance to slumping than trenches.

4.3.1 Pits

Historically, observation pits have generally been excavated manually using shovels. Pit dimensions have been variable, but a diameter of approximately 0.5 to 0.75 m (1.5 to 2.5 feet) has generally provided a reasonable compromise between ease of excavation and sufficient room to adequately observe and photograph the pit walls. Pits are typically extended through the sediments to the beach ground water level, below which further excavation is generally impossible due to slumping. Scraping the pit walls flush with a trowel or other flat instrument improves the ability to discern oil layering and sedimentary structures (Figure 4.3).

Figure 4.3 Observation Pit Showing Scraped Side Wall

In cases where sediments are thin or the subsurface oil is not deep, manual excavation of pits can be rapid and may be the fastest method for comprehensive subsurface data collection. However, at excavation depths greater than 0.6 to 1.0 m (2 or 3 feet), and/or for large shoreline areas and recurrent recoiling, manual excavation can be time consuming and physically strenuous. In such cases, crews with mechanized equipment have been used to speed up pit excavations, thus accelerating the data collection process. Equipment employed for this purpose typically has consisted of power-take off augers on small vehicles or small backhoes. Hand-held augers that have large enough bits to allow adequate observations are considered potentially hazardous to operators for long term use and are not recommended.

The number and distribution of observation pits will vary according to the specifics of each situation. It is important that sufficient observations are collected to define subsurface conditions with confidence. It is also important that time is not wasted in the excavation of excessive pits. Two examples of observations plans are presented below.

During the Deepwater Horizon response, in excess of 80,000 pits were excavated over a two-year period during SCAT surveys. This number does not include pits excavated during non-SCAT surveys, for example, during routine inspection missions or by the Natural Resource Damage Assessment (NRDA) teams, nor does it include augering projects undertaken by the Operations teams. Powered augers, typically 60-cm (24-inch) augers mounted on skid steer loaders, were used extensively during this response and significantly increased the rate at which SCAT data could be collected (Figure 4.4).

Source: G. Shigenaka

Figure 4.4 Pit Excavation Using Power Auger

In terms of the survey density for detection and delineation, a typical design for a pitting survey could be based on the parameters presented in Table 4-1. This design clearly shows the shortcomings of excavations, and of all point sampling strategies.

Table 4-1 Example of a Design for a Point Sample (Pit, Auger, or Coring) Survey

Across-shore Spacing	• 3 hand-dug pits with a 25 cm (10 inch) radius spaced 5 m apart on a 10-m long transect perpendicular to the water line
Along-shore Spacing	• Pit transect every 100 m
Coverage	• In a shoreline survey of 1000 m, the survey area is 1000 by 10 m = 10,000 square m • 11 transects with 3 pits per transect = 33 pits • Pit area for 33 pits = [3.14 x (0.25 x 0.25)] = 0.2 m^2 x 33 = approximately a total area of 6.5 m^2 • Actual "sample" coverage of pits = 6.5 / 10,000 = 0.00065 %
Daily Productivity	• Assuming one team could excavate up to 200 pits day, 67 transects (less 1 at end) would cover a 6,600 m length of beach and an area of 66,000 m^2
Augering or Coring	• Typically a 60 cm (24-inch) pit or core, so total "sample" coverage in the same survey area is 0.001 % • "Sample" coverage may be better but offset by lower productivity of about 100 pits/day

Subsurface oil surveys were conducted during the 1993 Tampa Bay SCAT survey (Owens et al., 1995). Hand-dug pits were excavated on 92 transects normal to the shoreline during the lower half of the tidal cycle every one-tenth of a mile, with observations made every meter landward of the waterline and extending 5 m (15 feet) on each side of the transect line (846 pits). Zones of subsurface oil were marked with red flagging to guide cleanup operations. Because of concerns regarding beach stability and erosion issues, shoreline observations included a program of beach profile surveys followed up by additional profile surveys following the treatment operations to monitor for observable changes. As a note: these follow-up surveys showed no significant lowering of the beach by the sediment removal activities.

In all cases, pits must be backfilled immediately following excavation for safety reasons, and any significant amounts of excavated contaminants removed.

Advantages:

- Pit excavations are simple and require minimal equipment and training;
- Pits can be excavated manually in areas of limited access, and in most other situations using small machines (small tracked equipment may be required where shoreline trafficability is reduced); and
- Environmental impact is minimal.

Disadvantages:

- Pit observations provide only spot data;
- In cases where subsurface oiling is irregular, many pits may be required to adequately define the extent and nature of subsurface oil deposits;
- For extensive shoreline oiling, the time required for data collection may be longer than desirable;
- Pit observations are limited (in most cases) to sediments above the beach water table;
- Excavation is not possible during high tide; and
- Effort required can range from very low to extremely labor intense and strenuous depending on the situation.

Availability: Equipment and manual labor is readily available.

Cost (*based on authors' estimates*):

- A typical manual excavation team typically would consist of 3 persons and be capable of digging a maximum of 200 pits per day.

- Manpower costs are estimated at $1,500 to $2,500 per day. This estimate does not include the trained SCAT or other observers on the survey.

- If the excavations are dug by the trained SCAT observers the costs would increase to approximately $2,500 to $4,000 per day.

- The cost of an auger survey program using a skid-steer loader and operator would be on the order of $500 to $750 per day. This estimate does not include the trained SCAT or other observers on the survey.

4.3.2 Trenches

Trenches may be thought of as a series of connected pits and similarly permit direct observation of subsurface conditions. Technically, trenches are preferred over pits because they allow observations of larger cross sections of the beach. They are particularly useful when conducted across the shoreline. Many of the same conditions described for pits apply to trenches; however, trenches have longer unsupported side walls and are slightly more susceptible to caving in. Their use is generally limited to damp sediments (wetted portions of the intertidal zone). Trench observations were not used extensively during the Deepwater Horizon response for this reason. A typical trench is shown in Figure 4.5. Trenches are labor intensive and time consuming when excavated manually.

Figure 4.5 Typical Observation Trench

Mechanical equipment may be used to excavate trenches rapidly where access is adequate (Figure 4.6). Typical mechanical equipment can include backhoes and commercial trenching equipment. Trenching equipment may have limitations as trench widths are commonly narrow and may not allow for adequate observations. Trenches over may be up to a meter in depth and this may present safety issues due to the potential for caving and trenches greater than 0.5 m (~2 feet) should never be entered by observers. Trenches should be back-filled as soon as the observations have been completed and preferably tamped or compacted to match the surrounding beach character.

Mechanical trenching may be used as a rapid reconnaissance tactic whereby the equipment is used as a detection tool. If and when oil is observed in the trench spoil then a pit or trench could be excavated to delineate and characterize the subsurface oiling condition.

Advantages:

- Trenches provide more comprehensive observation platforms than point source pits;
- If machinery can access and operate on the shoreline, trenches can be excavated rapidly; and
- A trenching machine can be used for rapid detection ("reconnaissance") prior to delineation and characterization of any subsurface oiling that is encountered. This would be followed by more traditional excavation tactics.

Disadvantages:

- Extensive use of manually-excavated trenches is likely not feasible due to time and manpower requirements;
- Trenching is generally limited to damp or fine-grained sediments;
- Construction of trenches may be limited to manual excavation where access for machinery is not available;
- Subsurface representation, although typically better than provided by pit observations, is still limited by the number of observations collected; and
- Trenching is not possible during high tides.

Availability:

- Equipment for manual or power assisted trenching tools are readily available.

Cost (*based on authors' estimates*):

- Costs associated with trenching are dependent on the length of the trench (width of the beach).
- A skid-steer loader with a backhoe attachment and operator cost would be on the order of rents for approximately $750 per day, plus mobilization.
- Trenching rates vary with conditions, but a daily expectation of between 4 manual and 15–20 mechanical trenches, each 50 m long and 60 cm deep should be achievable.
- "Reconnaissance" trenching can achieve rates of meters/minute (possibly up to 100 m/hour).

Source: E. Owens (M/V Cosco Busan, Rodeo Beach, CA)

Source: G. McDonald (M/V Cosco Busan, Rodeo Beach, CA)

Figure 4.6 Mechanically-excavated Pit, and Across-beach Trenches Using Track Hoe

4.3.3 Shallow-water Snorkel Observations

A procedure (Snorkel SCAT) was developed during the Deepwater Horizon response for the detection and delineation of subsurface oil mats and other accumulations in the lower intertidal and adjacent shallow subtidal zone during periods when this zone was underwater. The procedure involved use of SCAT-trained observers with snorkeling equipment and shovels to evaluate shallow subsurface conditions (Figure 4.7). Over 80,000 underwater pits were dug in this manner over the two-year period July 2010 to May 2012. Semi-disturbed observations, adequate for detection of subsurface oil, could be conducted as deep as 18 inches below the sediment surface. Although effective during light surf conditions, the procedure is relatively slow and physically exhausting. Similar shallow water swimmer observations have been conducted on other spills, but have not included observations and documentation at shallow depth.

Source: USCG

Figure 4.7 Snorkel SCAT – Sampler and Data Logger

Advantages:

- Allows limited SCAT-type observations in water depths averaging 1.0 m or less.

Disadvantages:

- Observations are spot samples and may be semi-disturbed;
- Data collection is relatively slow and physically exhausting;
- Requires a calm wave environment; and
- Requires several support and safety personnel for each observer.

Availability:

- Equipment readily available; and
- Personnel may require specific safety training.

Cost:

- Uses SCAT team – no additional cost.

4.4 Core Sampling

Collection of undisturbed vertical sediment samples (core samples) have been used on many spills to (1) develop an understanding of the vertical distribution of subsurface oil, and (2) allow collection of samples for various types of physical and chemical analyses. Core samples provide small point observations and are generally superseded by pits and trenches for delineation of spill size.

A variety of core sampling techniques and equipment for the collection of cores on sediment shorelines have been used with varying degrees of success. These include:

4.4.1 Hand Coring

Hand coring is simple and allows examination of the subsurface to several feet in depth in most cases. Subsurface observations using hand cores have been attempted during many spills, but their use has generally been deferred to pits and trenches due to the small sample size they provide.

Commercial hand soil/sediment samplers are available and include:

- Simple tubes which are pushed into the sediment, removed and the retained column of sediment examined visually and/or sub-sampled;
- Push tube-type samplers (clam guns) which are equipped with a piston device or closable vent that creates suction at the top of the tube and improves sample retention significantly (Figure 4.8);
- Push-and-hammer driven tubes with or without plastic liners;
- Some tubes have core catchers or flap valves to minimize sample loss. These types can be equipped with extension handles to permit their use in submerged portions of the intertidal zone; and
- Hand soil samplers equipped with small bucket augers. These devices are screwed into the sediment and samples removed for examination in increments (Figure 4.9).

Advantages:

- Rapid sample collection; and
- Can be used by SCAT/operational personnel with minimal training.

Disadvantages:

- Core samplers provide spot samples; and
- Core samples are generally limited to several feet in depth, and/or above the water table.

Source: *www.jackscountrystore*

Figure 4.8 Manual Tube Sampler (Clam Gun)

Source: www.dormersoilsamplers

Figure 4.9 Hand Operated Bucket or Sand Auger

Availability:

- Generally available from geotechnical or agricultural supply houses.

Cost:

- Can be operated by SCAT personnel, minimal equipment cost.

4.4.2 Auger and Direct Push Coring

Truck- or ATV-mounted augers or direct push sampling rigs may be used to collect deeper undisturbed samples. Thin-wall tube samplers and core barrels with spoon samplers can be pressed or driven within the advancing hollow-stem auger to obtain undisturbed samples that can be examined in the field or shipped to a laboratory for analysis (Figure 4.10). This type of sampling is time consuming and generally used for post-emergency monitoring and analysis, rather than emergency phase delineation. For example, sampling of this type using larger equipment was conducted during the T/V *Prestige* response (Lorenzo et al., 2004).

Source: www.deeprock.com

Figure 4.10 Tractor Mounted Small Hollow-stem Auger

Advantages:

- Collects undisturbed samples useful for detailed vertical profiles;
- Can sample below the beach water table; and
- Equipment is typically used for geotechnical investigations and equipment/operators are generally available.

Disadvantages:

- Samples are spot samples;
- Sample collection is time consuming and not generally practical for large scale emergency response support;

- Larger equipment may have difficulty accessing and operating on some shorelines; and
- Trained equipment operators required.

Availability:

- Limited availability

Cost (*based on authors' estimates*):

- Equipment and crew costs dependent on type of machine.
- Typical crews consist of driller and driller's assistant.
- Costs for drill rig and crew may range from $1500/day upward, depending on equipment (Mob/Demob not included).

4.4.3 Vibratory Coring

Vibratory corers ("vibra cores") contain a cement vibrator or other mechanism which causes the sample tube to vibrate. This action allows unconsolidated sediments to move and the device to penetrate downward under gravity. Vibracorers are equipped with a core liner and core catcher to keep the sediment in the liner and a tower to extract the drill. Small units are capable of collecting 5 to 10 cm (1.75 to 5 inch) samples to a depth of 3 m (10 feet). They can be operated by two people and are man-portable or can be transported in a UTV (Figure 4.11). Setup and sampling is relatively quick (estimated 30 to 60 minutes per sample). Larger vibra-coring equipment is available, but is less suited to sediment beaches and is likely to experience operational problems.

Vibration causes some compaction of soils within the devices, thereby causing some shortening of the sample and loss of depth control precision.

Source: www.Vibracorer.com

Figure 4.11 Portable Vibracore Device with Extraction Equipment

Advantages:

- Capable of collection continuous shallow stratigraphic samples in loose sediments; and
- Provides vertical sample for visual inspection of subsurface oil.

Disadvantages:

- Vibratory samplers provide spot samples;
- Setup and coring process is time consuming making these systems impractical for emergency response applications other than collection of samples for analytical purposes;
- Shortening of the cores is common, limiting accuracy of depth measurements;
- Larger equipment may have difficulty accessing and operating on some shorelines; and
- Trained equipment operators required.

Availability:

- Land vibra coring equipment suppliers are limited.

Cost (*based on authors' estimates):*

- 2 person crews are required for smaller equipment.
- Estimated sampling rate is 8 to 12 cores per day.
- Estimated equipment day rate cost: $5,000 per unit.

4.5 Water Jet Probes

Water jet probes are commonly used to measure sediment thicknesses on coarse-grained beaches. Although not in common use for location and delineation of subsurface oil on sediment shorelines, water jets were successfully used to delineate subsurface shoreline oil following the 1969 Santa Barbara blowout response and locally during the Swanson Creek spill response (R.E. Castle, pers. comm., 2012). The required equipment consists of a length of galvanized pipe connected to a portable centrifugal water pump using standard garden hose. The pipe is inserted into the sediment vertically and the water jet blasts the sand below it upwards along the length of the pipe. Because of the cutting action of the jet, the pipe typically sinks by gravity. Cuttings reaching the surface are examined for the presence of oil, with depth approximated by the length of pipe inserted. In some cases, harder oil deposits can be detected by resistance and their depth measured more accurately.

Advantages:

- Individual observations and profiles can be taken rapidly;
- Can be used to visually detect oil presence, depth of layers, and depth of sediment; and
- Can be used during high tides.

Source: R. Castle

Figure 4.12 Water Jet Probe

Disadvantages:

- Technique collects spot samples only and may not be suitable to detect light or irregular oiling; and
- Probes require a source of water, pumps and hoses.

Availability:

- Equipment can be constructed from hardware store parts.

Cost (*based on authors' estimates*):

- <$1000 per setup.
- 2 laborers ($75/ hr x 2).

4.6 Ultra Violet (UV) Fluorescence (Hand Held)

UV light consists of electromagnetic radiation which has wavelengths shorter than visible light and longer than x-rays. Petroleum hydrocarbons exposed to UV wavelengths will typically fluoresce in the visible light range. This property has been used successfully during oil spills for the night-time field detection of petroleum on surfaces and side walls of pits and trenches using hand held, battery powered, UV lamps. UV radiation is commonly classified as:

• UVA (long wave)	400 nm to 315 nm
• UVB (medium wave)	315 nm to 280 nm
• UVC (Short wave)	280 nm to 100 nm

Oil deposited on the shorelines during the Deepwater Horizon event tended to present a yellow-orange signature under near-UV and long-wave UV radiation. An example of this is shown in Figure 4.12. Colors produced by oils may differ, ranging from whitish to red. Light oils and refined products are typically lighter, whereas the emission spectra from heavier oils tend to shift to the red. UVA lights are typically used for field oil detection. Shorter wavelengths can be hazardous, and protective glasses are recommended for all categories.

A variety of battery-powered lights are available for field application. These range from inexpensive bulb and Light-Emitting Diode (LED) UVA designs to larger hand-held units that can be attached to vehicles and ATVs.

Advantages:

- Portable;
- Oil is distinctive, although some natural materials, such as carbonate materials, may fluoresce; and
- May be useful for night-time reconnaissance to detect oiling with follow-up day-time SCAT surveys.

Disadvantages:

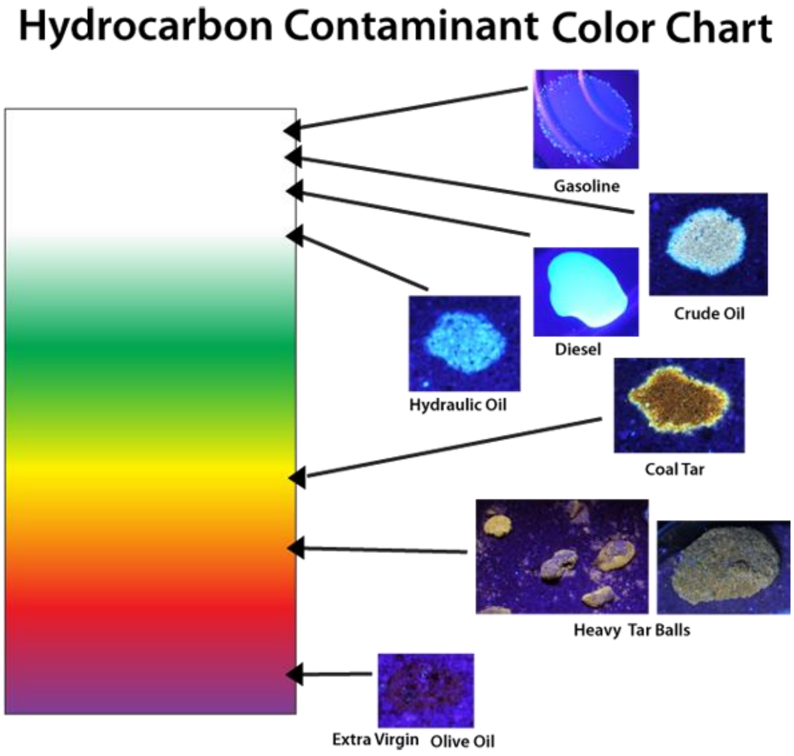
- Night observations required; and
- Shorter wavelengths require special safety glasses to protect user’s vision.

Availability:

- Good;
- Portable UV equipment dealers are available on line; and
- Equipment also available from pest exterminators.

Cost (*based on authors’ estimates*):

- Prices for suitable units range from ~$30.00 for small flashlights to $3,500.00 for larger high powered units.



Source: www.UVoil.com

Figure 4.13 UV Detection of Oil

5.0 Developing Technologies

5.1 General

A number of related operational technologies that may have application to subsurface oil spill detection and delineation on sediment shorelines have been identified. Some may be applicable "off the shelf" (with verification by demonstration and/or trials), whereas others may require technical modification. The term developing is used to indicate that, although the technology may have been shown to detect subsurface oil it has yet to be applied to a sufficient range of conditions to be considered "field ready". This section reviews selected developing technologies that have already shown significant progress within the context of four strategies:

- Service Dogs (Section 5.2);
- Push Probes (Section 5.3);
- Gas Detectors (Section 5.4); and
- Geophysical Methods (Section 5.5).

5.2 Service Dogs

Service dogs are routinely used to detect a wide range of materials including drugs, explosives and contraband food shipments. Dog's olfactory sensitivity is extremely acute and has been documented at detection levels ranging from tens of parts per billion (ppb) to 500 parts per trillion (ppt) for certain materials (Johnston, 1999). Initial trials have suggested that low threshold levels can be achieved for petroleum hydrocarbons (Bullas, 2010; Bradvik and Buvik, 2009). In addition, tests have indicated that dogs are extremely good at discriminating a target vapor from non-target vapors, even at relatively high concentrations (Johnson, 1999). Experiments initiated in 2006 by SINTEF and the Trondheim Hundeskole (Trondheim Dog Training Academy) have verified that dogs can be trained to detect and trace vapor emissions emanating from oil residues hidden in beach sediments or hidden in snow/ice to their source under spill response operational situations (Buvik and Brandvik, 2007; Brandvik and Buvik, 2009.

Rigorous field tests funded in part by MMS-BLM were conducted in Svalbard (Dickins et al., 2010). These tests indicate that the ability of dogs to locate hydrocarbon point sources is excellent; however, larger and potentially irregular subsurface oil deposits present challenges that need to be evaluated further. Larger deposits and their associated vapor plumes may emanate from many local concentrations and not present a clear point source target. Vapor plumes may also travel significant distances beyond actual subsurface source oil, and it is not clear based on field trials to date how oil edges can be discerned by the dogs. In addition, some subsurface oils can be very weathered (i.e. tar balls) and are likely to have very low detectible emissions, perhaps below sensory thresholds. Discussions with dog trainers have indicated that dogs may not perform as well with high vapor concentrations: these are as noxious to dogs as they are to humans. The same would be expected to apply equally to “sour” (hydrogen sulfide) crude oils. Additional investigation is recommended to evaluate these advantages and limitations of service dogs.

The key advantages for this tactic are the ability to cover large areas continuously and rapidly. Results from post-spill field trials at the site of the M/V *Server* (January 2007) spill in November 2008 by SINTEF demonstrate a survey speed of 2 to 3 km/hour (1 to 2 miles/hour), sometimes on challenging shorelines (bedrock and coarse sediments: Figure 5.1) (Buvik and Brandvik, 2009).

Advantages:

- Continuous survey coverage;
- One team can cover 10 or more km (15 miles) of shoreline each day, depending on the shore type;
- Very rapid (thousands of square meters/yards per day);
- Dogs can be equipped with GPS collars to allow location and track line logging;
- Capable of providing fast, non-contact and highly sensitive point source location of subsurface oil targets;
- Can distinguish between different oil types;
- Can distinguish high and low oil concentrations; and
- Can survey at night on amenity beaches.

Source: SINTEF

Figure 5.1 Service Dog and Handler on Field Trials in Norway

Disadvantages/Issues:

- Not depth discriminating, may not be able to detect subsurface oil underlying surface oiling;
- Ability to discriminate boundaries of subsurface oil needs further development;
- High vapor concentrations may reduce detection sensitivity and performance; and
- Calibration and confirmation observations (probably pits) would be required.

Availability:

- Limited adaptability of current domestic service dog services; and
- Needs additional research.

Cost (*based on authors' estimates*):

- Currently in the range of $5,000+ per day. Would be expected to drop considerably for US-trained and -based service dogs.

5.3 Push Probe Observations and Sampling

In Push Probe technology, small diameter rods and tools are pushed or driven into the unconsolidated subsurface sediments. Probes may be used to collect continuous soil, soil gas, groundwater samples and to conduct geophysical, geochemical, cone penetrometer, and digital photographic data. A comprehensive description of the technology is available from the Ohio EPA, Technical Guidance for Ground Water Investigations (Ohio EPA, 2005). This technology allows for single or simultaneous multiple parameter sensing and has the potential to significantly advance the current state-of-the-art in subsurface oil detection and delineation for shoreline subsurface oil assessment. This technology is currently in practice for onshore hazardous waste and geotechnical investigations.

Only shallow observations are anticipated for the delineation of shoreline subsurface oil. Shallow push probe technology is easily capable of sampling to 5 m (15 feet) utilizing lightweight equipment that can be mounted on 4x4 or 6x6 UTVs or light tracked vehicles, making it attractive for most beach operations. Representative equipment is shown in Figure 5.2 (AMS UTV/tracked probe equipment). Small equipment may be limited to pushing sampling devices only. Although the technology usually includes accessories for light hollow stem augering, larger vehicles are necessary for the preferred application.

A study combining push probe technology with a variety of analytical capabilities is currently being conducted by Vertek and the New England Divisions of Applied Research Associates, Inc. (ARA) to provide more efficient delineation of crude oil in the shallow (<2 m: <6 feet) beach and shoreline subsurface and to assist responders employing the SCAT approach in conducting subsurface oil spill detection and delineation. The proposed system would be driven by a truck-mounted cone penetrometer, which can provide trafficability data, and contain probes for the in-situ sensing of oil fluorescence (oil characterization), video (color and nature of oil accumulations), and Soil Moisture Resistivity (grain size and perhaps oil presence). Initial laboratory characterization studies have been conducted and bench-scale tests are planned for summer 2012. The progress of the Vertek/ARA study is being monitored as part of the API Shoreline Program.

Source: www.AMS-samplers.com

**Figure 5.2 Representative Push Probe Sampling Equipment.
Small Push Probe Unit (left) and Probe/Instrumentation (right)**

Advantages:

- Can be mounted on small all-terrain vehicles capable of operation on most beaches;
- Rapid multi-parameter data collection;
- Real time data processing available; and
- Sub-water table analysis possible for some parameters.

Disadvantages/Issues:

- Probes are narrow diameter and collect spot samples (more samples may be required for adequate representation);
- Trained equipment and operators required;
- Equipment may be subject to site access and operability issues; and
- Calibration and confirmation sampling (pits) required.

Availability:

- Push probe sampling technology is readily available; and
- Application instrumentation packages are under development.

Cost:

- Unknown.

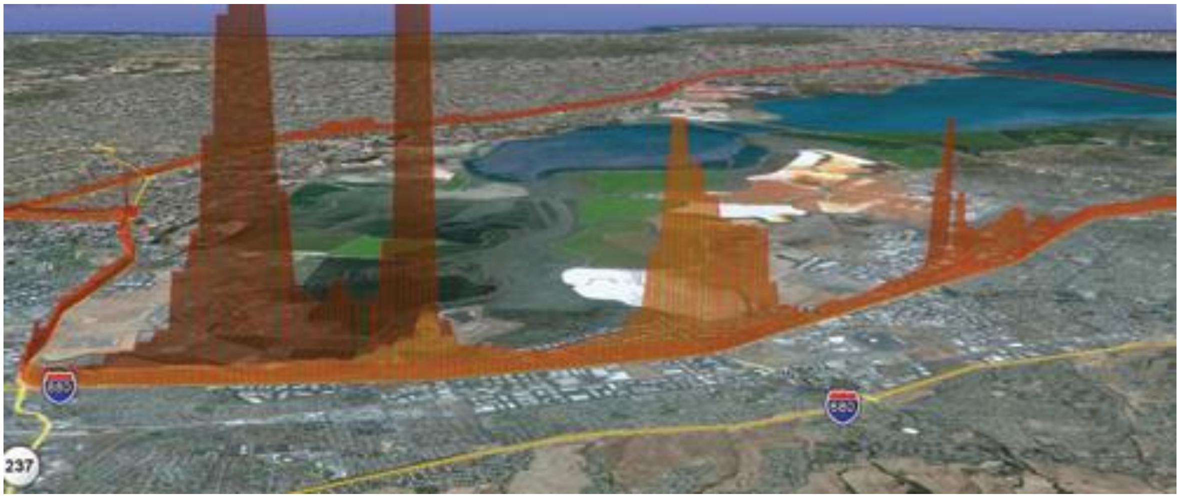
5.4 Hydrocarbon Gas Detectors (Ground Level Remote Sensing)

It is well known that crude oil and petroleum products contain volatile components that evaporate when spilled, often rapidly. Measurement of these gases has long been examined as a mechanism for location of petroleum sources and for leak detection (Horvitz, 1972, 1986; Hunt, 1981; Jones *e*t al., 1999; Jones and Drozd, 1983). Historically, special sample collection techniques and laboratory analyses were required to obtain sufficiently low detection levels, limiting their use as emergency response tools. Recent technological developments have resulted in field instrumentation that is capable of real-time measurements at extremely low detection levels of hydrocarbon concentrations.

Once spilled into the environment, oil is subject to a number of weathering and degradation processes which emit various hydrocarbon vapors. These emissions can include methane, ethane, CO_2 H_2S, and other gases. The low molecular weight hydrocarbon gases released by evaporation were measured in the field as part of an oil-in-ice detection experiment (Dickins, 2005; SIINTEF, 2009). These tests were conducted as part of the Joint Industry Oil in Ice Project and measured methane emissions from lightly weathered spilled crude oil at the Svea Test Site in Norway at concentrations suggesting that measurement from aircraft could be at least theoretically possible (Hirst and O’Conner, 2007).

The Joint Industry Oil in Ice Project study evaluated ethane measurement using a technology developed by Shell Oil (Dickins, 2005) which also demonstrated the potential for detection of measurable levels of ethane at significant distances from the source. Measurement of trace gases for detection of the presence of hydrocarbon deposits is not a new concept and has been evaluated for a considerable period of time with varying results. These early systems lacked portable, direct-reading instrumentation, limiting their suitability for emergency response applications on shorelines.

New technology has increased the detection sensitivity and spectrum of gases that can be monitored to parts per trillion levels and allowed the development of operational non-intrusive systems. Technologies and sensors are currently available which can measure and produce real-time plots of a variety of gases including methane, ethane, CO_2 and H_2S from mobile platforms and aircraft (Figure 5.3) These systems are being used for detection of gas pipeline leaks and have a potential application to subsurface oil detection and delineation.



Source: www.picarro.com

Figure 5.3 Remote Gas Sensing Technology. Real Time Plot of Vehicle Mounted Gas Detector – Brown Spikes Indicate High Gas Levels. Equipment Can Monitor Multiple Gases.

Aerial observations are not anticipated to provide sufficient resolution for the delineation of subsurface oil. Ground units, however, may provide for very rapid delineation and mapping, although differentiation from natural or elevated spill-related background may require investigation.

Advantages:

- Continuous real-time detection coverage;
- Non-contact instrumentation;
- Can be operated from electric ATV (to avoid combustion gases);
- Can discriminate source or zones;
- Highest potential for off-the-shelf equipment is for fresh oils or sour oils; and
- Onboard real-time mapping packages available.

Disadvantages/Issues:

- Requires specialized instrumentation and trained operator(s);
- Does not determine depth;
- Calibration/confirmation/layer detail observation (pits) will be needed; and
- Further research needed for weathered oil.

Availability:

- Operational non-intrusive systems are currently available which can measure and produce real-time plots of a variety of gases including methane CO_2 and H_2S from mobile platforms and aircraft.

Cost:

- Unknown.

5.5 Geophysical Methods

5.5.1 Ground Penetrating Radar (GPR)

GPR is a geophysical method that transmits electromagnetic energy (high frequency radio waves) into the ground. If these waves encounter subsurface objects or layers of contracting material, a reflected signal is recorded by a receiver in the instrument. These signals are used to create images of subsurface objects or sedimentary structure. GPR has been used for over a decade for location of metallic and other objects, voids and cracks, and differences in layers of relatively shallow soil. The procedure consists of pushing a transmitter/receiver unit mounted on a cart equipped with a GPS over the beach or along a predetermined grid. Ground contact is required. The surface should be as flat as possible to avoid signal disruption. A typical unit configured for beach operations is shown in Figure 5.4.

Source : http://www.frf.usace.army.mil/sandyduck/Exp-SandyDuck.stm#haines

Figure 5.4 Ground Penetrating Radar, Configured for Beach Operations

Typical survey depths can be as high as 15 m (~50 feet), but are limited by the electrical conductivity of the soil, and the frequency and strength of the transmitted waves. Penetration is higher in dry sandy soils or in massive materials, including ice (Dickins, 2005). The presence of clay and water (particularly salt water) may interfere with or limit depth of penetration. The depth of penetration also decreases as higher frequency signals are used, although these higher frequencies tend to provide better structural resolution. Higher frequencies do not penetrate as deeply as lower frequencies, but give better resolution.

GPR was used with varying results during follow-up monitoring of the 2002 T/V *Prestige* response (Lorenzo et al., 2004, 2009). Large volumes of heavy fuel oil grounded during this event and were subsequently buried on the shoreline. As a result of the presence of saltwater, use of GPR in the middle/lower intertidal zone was not successful: however, GPR was used successfully in upper intertidal and supratidal zones that were not regularly or were only infrequently exposed to salt water. In these latter zones, GPR was able to detect even small discontinuous layers (1 cm or less at depths of <2 m) in some areas.

GPR has been included in this study as a potential technique because of the high resolution potential and the potential ability to operate in the upper backshore where other tactics may experience difficulty.

Advantages:

- Continuous coverage over survey area;
- Non-intrusive; and
- Capable of providing detailed subsurface information in some cases.

Disadvantages:

- May not be applicable in saline or with rough surface terrain environments;
- Requires trained operator; and
- Offsite data reduction (which slows data turn-around time).

Availability

- Generally available from geotechnical companies**.**

Cost (*based on authors' estimates*):

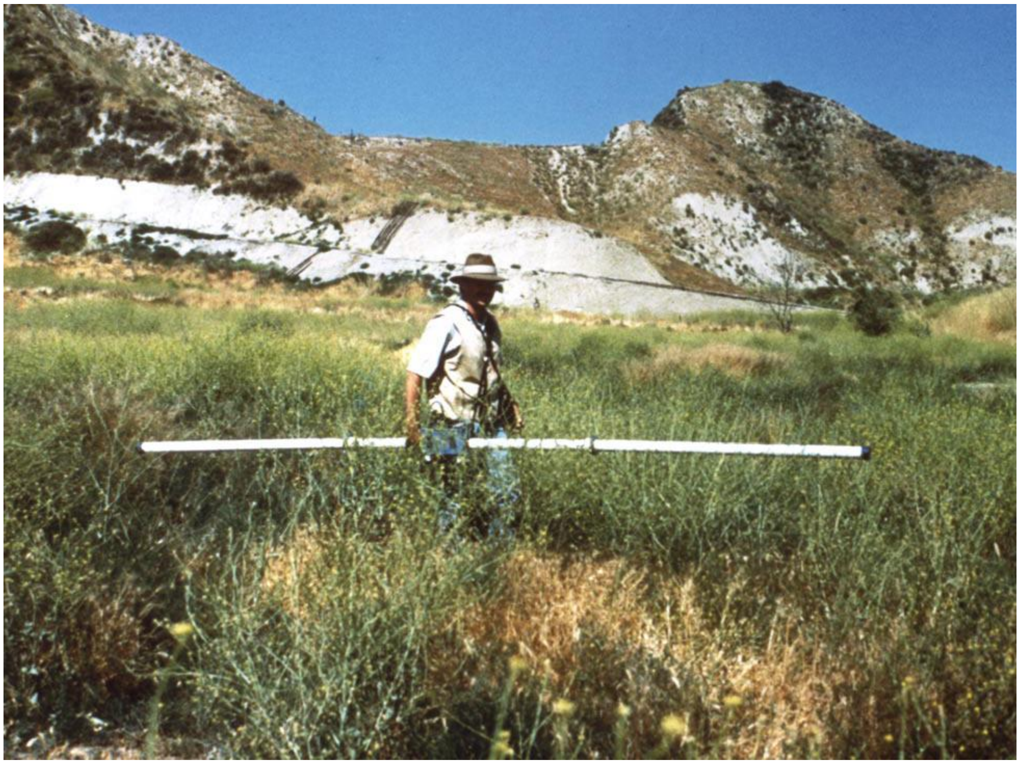
- Depending on site conditions, 5 to 10 km (3 to 6 miles) of survey lines can be surveyed per day by a 2 person crew.
- Cost approx. $2500 per day [inc. data processing (excluding mob/demob)].

5.5.2 Electromagnetic (EM) Profiling

Electromagnetic profiling, also known as terrain conductivity measurement, allows mapping of variations in the electrical conductivity of shallow sediments. The equipment uses the principle of induction to measure the electrical conductivity of subsurface materials. Oil is electrically resistive in comparison to sediments, which exhibit varying degrees of conductivity related to grain size, moisture, salt content, and other factors. Layers of non-conductive oil or oily sediment should therefore be detectable if in sufficient quantity (thickness) to provide a resistive signal in comparison to soils. If the differences are sufficient, this is a proven technique for delineation of subsurface contamination plumes (including petroleum hydrocarbons) (Saunders et al., 1983, 1987), although there is not extensive experience with subsurface oil detection on sand or other beaches.

A typical EM instrument is shown in Figure 5.5. The process is an inductive method and can be conducted over any surface including highly resistive materials such as sand without the use of electrodes or ground contact. The instrument is normally carried by the operator and can be equipped with onboard data loggers and GPS trackers. If successful, it may be possible to attach the instrument to an ATV and to expedite field surveys over large areas. Data can be integrated with detailed transects or used independently of surface elevation data.

This instrumentation is non-contacting (carried over the ground surface) allowing rapid coverage of large areas. EM profiling can survey to depths of at least 2 to 3 m (6 to 10 feet) in most cases, and can discriminate between layers of different conductivity. In a recent application an EM# instrument was used to survey a 4-hectare (10-acre) area and detected two pits in less than 3 hours. A third pit was not detected and this was eventually found after 3 days using a different instrument (Geoprobe) (R.F. Bernier, per. comm., 2012). Additional field trials are recommended to verify the ability of this equipment to detect subsurface oil layers in the beach environment and to establish limits of detection for various oil types and concentrations (i.e. weathered oil, scattered tar balls, etc.). Unknowns include the ability of the instrumentation to differentiate oil beach environments and the level of resolution that can be achieved.



Source: www.GeoVision.com

Figure 5.5 EM (Terrain Conductivity) Measurement

Advantages:

- Non-contact method;
- Rapid data collection; and
- Continuous coverage.

.**Disadvantages/Issues:**

- Limited depth discrimination;
- Requires trained operator/analyst;
- Requires calibration and confirmation (pit) observations; and
- Small feature discrimination may be limited.

Availability:

- Moderate; and
- Generally available as rental units or with operator (recommended).

Cost (*based on authors' estimates*):

- Two person crew; and instrument/data processing: $2500/day (excluding. mob/demob).

5.5.3 Electrical Resistivity (ER) Profiling/Imaging

Electrical Resistivity profiling or imaging is a method for measuring the capacity of subsurface materials to pass electrical current. This technique is used to locate boundaries between materials that have contrasting resistivity. Clays and water-saturated materials are generally electrically conductive and contrast with more electrically resistive materials such as coarse-grained sediments and petroleum hydrocarbons. Traditionally, resistivity is measured by driving metal stakes (electrodes) into the ground and connecting them to a cable that supplies current, inducing an artificial electric field and measuring voltage across electrodes, allowing development of a profile or image of irregularities in subsurface materials. A variety of arrays currently exist, including some that do not require fixed electrodes and can be dragged or towed by an ATV over the area of investigation (Figure 5.6).

The non-intrusive electrode technique is problematic at very shallow depths such as may be encountered in beach environments due to lack of resolution. Conventional systems can be configured for shallow investigations, but may be too slow for rapid surveys of large areas. A two-person crew can survey 3 to 8 km (2 to 5 miles) of line per day. No documentation of ER profiling was encountered during the preparation of this study and application of ER for shoreline oil detection and delineation will require field testing.

Advantages:

- Potential rapid survey method; and
- Continuous coverage.

Source: Advanced Geological Services

Figure 5.6 Electrical Resistivity Instrumentation

Disadvantages/Issues:

- May not be able to resolve very shallow layers (<0.3 to 0.5 m: <1 to 2 foot).

Availability:

- Labor and equipment costs are similar to those for EM surveys.

Cost (*based on authors' estimates*):

- Two person crew and instrument and data processing: $2500/day (excluding mob/demob).

6.0 Summary of Current and Developing Practice

6.1 Current Practice

Generally accepted technology for emergency response level detection and delineation of subsurface oil on shorelines has advanced only slowly in the last 40 years. Current practices typically consist of visual observations using excavations, various coring techniques, water jetting, and use of UV lights. Other tactics have been tested, but most did not increase the speed or quality of data collection. The expected performance of current practices by general groups is summarized in Table 6-1 in the context of the field conditions under which subsurface oil can be detected, delineated, characterized, and/or observed.

Field variables in Table 6-1 that are considered for evaluation and comparative purposes are:

- ❖ <u>Depth:</u> a range of depths is provided, based on the operational characteristics of various tactics.
- ❖ <u>Oil Characteristics:</u> based on visual criteria
  - — Fresh: fluid and mobile;

  - Emulsion: may flow sluggishly of behave as solid/semisolid;
  - Weathered: may be viscous or solid;
  - Tar Balls and tar-like solid or very viscous residue;
  - Pavement: very weathered, solid or semisolid.

- Distribution: Oil distribution is considered in terms of the tactic to describe both vertical and horizontal characteristics.
- Moisture: refers to water content of the sediment: Dry (prone to slumping), Damp, or Saturated. A category for presence of salt (saline) is included as the presence of salt may interfere with some tactics.
- Grain Size: can impact some tactics, and may influence cleanup. Clay/silt, sand to granules, and larger than granules.
- Sensitivity: the ability of a tactic to detect simple presence/absence, determine depth below surface, discriminate layer(s) or oil zones, distinguish individual tar balls or discrete residue accumulations, be effective below the water table, and detect trace levels of oiling (sub-visible).

A basic conclusion that is evident from Table E-1 (in the Executive Summary) and Table 6-1 is that there is no single current strategy that is applicable to all situations: however, as indicated by Table 6-1, most conditions can be assessed using excavation of pits and trenches. Pits and trenches, although primitive in nature, provide simple access to the subsurface for a variety of visual observations and sample collection. Trenches are favored over pits because they permit continuous observations across profiles or sections of shoreline. The primary limitation of all excavation tactics is that they provide only spot observations and may or may not detect subsurface oil or provide accurate delineation of the lateral extent of oiling. Excavation techniques are subject to caving in for some sediments and are limited to the unsaturated zone above the beach water table. For cases of oil or oiled sediments that are below depths greater than approximately 0.3 m (1 foot), excavation typically is labor intensive and slow. Due the potential for cave-in, no excavations (of any depth) should be entered and all excavations should be backfilled immediately on completion of observations or sampling.

Other tactics described in this review are also capable of providing useable subsurface information of various types. In general, however, most of these tactics ultimately require more time to complete and in many cases require confirmation from pits/trenches on specific subsurface oil conditions. As a result, these tactics often take second place to simple excavations. Nonetheless, all of the tactics described herein may have applications in certain circumstances and should remain in the responder’s tool kit.

Current practice for detection and delineation of subsurface oil on sediment shorelines is summarized in Table 6-2. In terms of potential impacts, relative cost, and pros/cons. This table provides a simplified guide to the important attributes of currently used tactics.

Table 6-1 Subsurface Detection Techniques Matrix: Current Practices

	Pits / Trenches			Cores			Water Jets	UV Handheld
	Manual	Mechanical	Snorkel	Manual	Auger / Probe	Vibrate		
Depth (m)								
< 0.5	√	√	?	√	–	–	√	√
< 1.0	√	√	–	√	√	√	√	√
< 2.0	–	?	–	?	√	√	√	√
> 2.0	–	–	–	?	√	√	√	√
Oil Character								
Fresh	√	√	√	√	√	√	√	√
Emulsion	√	√	√	√	√	√	√	√
Weathered	√	√	√	√	√	√	√	?
Tar balls	√	√	√	√	√	√	√	?
Pavement	√	√	?	√	√	√	√	?
Subsurface Distribution								
Vertical	√	√	?	√	√	√	√	√
Horizontal	–	–	–	–	–	–	–	?
Moisture								
Dry	?	?	–	√	√	√	√	√
Damp	√	√	–	√	√	√	√	√
Saline	√	√	–	√	√	√	√	√
Saturated (wet)	–	–	√	–	√	√	√	√
Grain size								
Clay/Silt	√	√	?	?	√	?	?	√
Sand/granules	√	√	√	√	√	√	√	√
>Granules	?	√	?	–	?	?	?	√
Sensitivity								
Presence (ONLY)	√	√	√	√	√	√	√	√
Depth Discrimination	√	√	?	√	√	√	?	√
Layer Discrimination	√	√	?	√	√	√	?	√
Tar / SRBs	√	√	?	√	√	√	?	√
Sub - Water table	√	√	–	√	√	√	?	?
Trace Level - Subvisible	–	–	–	–	–	–	–	–

√ = tactic operational under most conditions
? = tactic operational in most cases, subject to incident condtions,
– = tactic of limited applicability or not generally applicable

Table 6-2 Current Practices: Potential Environmental Impacts, Costs, Pros and Cons

Tactic	Status	Potential Environmental Impacts	Relative Cost	Pro	Con
Pits and Trenches					
Pits Manual	○ Accepted by industry and government	○ Minimally intrusive ○ Possible oil residue on surface	+++	○ Visual observation ○ Allows analytical sampling	○ Can be labor intensive ○ Not effective below water table ○ Depth Limitation (safety) ○ Spot samples – not continuous coverage across-shore nor alongshore
Pits Mechanical	○ Accepted by industry and government	○ Minimally intrusive ○ Mechanical equipment on shoreline ○ Possible oil residue	++	○ Relatively rapid excavation ○ Visual observation ○ Allows analytical sampling	○ Spot samples – not continuous coverage across-shore nor alongshore ○ Not effective below water table
Trenches Manual	○ Accepted by industry and government	○ Minimally Intrusive ○ Possible oil residue on surface	++++	○ Provides profile across shoreline ○ Visual observation ○ Allows analytical sampling	○ Excavation may collapse ○ Depth limitation (Safety) ○ Not effective below water table ○ Not continuous coverage alongshore
Trenches Mechanical	○ Accepted by industry and government	○ Minimally Intrusive ○ Mechanical equipment on shoreline ○ Possible oil residue on surface	++	○ Relatively rapid ○ Provides profile across shoreline ○ Visual observation ○ Allows analytical sampling ○ Can be a reconnaissance tool	○ Equipment operability ○ Excavation may collapse ○ Not effective below water table ○ Not continuous coverage alongshore
Snorkel	○ Accepted by industry and government ○ Developing	○ Insignificant	++++	○ Observations not dependent on low tide ○ Allows analytical sampling	○ Labor Intensive ○ Excavation less than 0.5 m ○ Spot sample ○ Only applicable for lower intertidal zone when underwater or shallow nearshore subtidal zone

Tactic	Status	Potential Environmental Impacts	Relative Cost	Pro	Con
Cores					
Hand Pushed	○ Accepted by industry and government	○ Minimally Intrusive ○ Possible oil residue on surface	+	○ Relatively rapid	○ Spot samples ○ Core shortening
Auger – Pushed	○ Accepted by industry and government	○ Minimally Intrusive ○ Mechanical equipment on shoreline	++++	○ Allows analytical sampling	○ Spot samples ○ Core shortening ○ Access and trafficability issues
Vibracore	○ Accepted by industry and government	○ Minimally Intrusive ○ equipment operation on shoreline	+++	○ Allows analytical sampling	○ Spot Samples ○ Core shortening ○ Slow
Water Jets	○ Existing technique	○ Minimally Intrusive ○ Equipment operation on shoreline ○ Possible oil residue on surface	++	○ Can be assembled from hardware store parts ○ Does not require skilled operator	○ Requires nearby water supply ○ Layer depth approximate ○ Spot samples
UV Hand Held	○ Existing technique	○ Minimally intrusive	+	○ Visual observation of presence/absence	○ Requires excavation ○ Night operation ○ May not detect very weathered oil ○ Not effective below water table ○ Safety – Potential eye damage

6.2 Developing Technologies

Current tactics for the subsurface detection and assessment of oil spills on shorelines when conducted as part of a systematic assessment program (such as SCAT) provide adequate information for the support of emergency shoreline response operations for most spills, with the exception of delineation of horizontal extent of subsurface oiling. Time is also of the essence in spill response, and In the case of larger spills or those where there is ongoing reoiling, in particular, current data collection procedures can require excessive effort and time. A number of developing tactics and technologies have been identified which promise to significantly improve current data collection capabilities, particularly in regard to the horizontal characterization of subsurface oil. These techniques also promise to accelerate speed up the SCAT process by reducing the number of subsurface observations required. These tactics include:

- Use of service dogs for detection, delineation and real time mapping of the extent of subsurface oiling;
- Application of multiple sensor push probe testing which may reduce the amount of excavations necessary for subsurface characterization;
- Non-invasive geophysical techniques which can delineate the horizontal extent of subsurface oiling; and
- Near-surface vapor detection tactics which can provide real time mapping of subsurface oiling;

Selected developing technologies as described in Section 5 are summarized in Table 6-3 using the same set of field observable criteria presented in Table 6-1.

As indicated in Table 6-3, with the exception of push probe technology, the developing technologies listed focus primarily on detection and horizontal delineation of subsurface oiling – one of the primary short-comings of the current capability.

Developing technology identified in this study is summarized in Table 6-4. In terms of potential impacts, relative cost, and pros/cons. This table provides a preliminary assessment of the important attributes of potential or promising survey tactics. In this tablet, the term “Developing” indicates that although the technology may have been proven to detect subsurface oil it has yet to be applied to a sufficient range of conditions to be considered “field ready”.

Table 6-3 Subsurface Oil Detection Techniques Matrix

		In situ	Geophysics		
	Service Dogs	Sensor Probe	GPR	EM / ER	Gas Detectors
Depth (m)					
< 0.5	√	?	?	?	√
< 1.0	√	?	?	√	√
< 2.0	√	√	√	√	√
> 2.0	√	√	√	√	√
Oil Character					
Fresh	√	√	√	√	√
Emulsion	√	√	√	√	?
Weathered	√	√	√	√	?
Tar balls	√	√	?	√	?
Pavement	√	√	√	√	?
Subsurface Distribution					
Vertical	-	√	?	√	-
Horizontal	-	-	√	√	√
Moisture					
Dry	√	√	√	?	√
Damp	√	√	?	√	√
Saline	√	√	-	√	√
Saturated (wet)	-	?	-	-	?
Grain size					
Clay/Silt	?	√	√	√	?
Sand/granules	√	√	√	√	√
>Granules	√	√	√	√	√
Sensitivity					
Presence (ONLY)	√	√	-	?	√
Depth Discrimination	-	√	√	?	-
Layer Discrimination	-	√	√	?	-
Tar / SRBs	√	?	?	?	?
Sub - Water table	-	√	-	-	-
Trace Level - Subvisible	?	?	-	-	?

√ = tactic operational under most conditions
? = tactic operational in most cases, subject to incident condtions,
– = tactic of limited applicability or not generally applicable

Table 6-4 Developing Technologies: Environmental Impacts, Costs, Pros and Cons

Tactic	Status	Potential Environmental Impacts	Relative Cost	Pro	Con
Service Dogs	○ Proven ○ Developing	○ No impact ○ Possible wildlife disturbance	++	○ Rapid assessment ○ Continuous horizontal coverage ○ Can operate in shallow water (<0.3 m: <1 foot) ○ Can survey at night	○ Availability of trained dogs/handlers ○ May require several weeks of training for handler/dog team ○ Requires physical verification (excavation/cores) ○ No vertical discrimination ○ May not detect subsurface oil if surface oiling is present
Sensor Probes	○ Developing	○ Minimally intrusive ○ Equipment operation on shoreline	+++	○ Multi-component measurements possible ○ Vertical observations	○ Spot samples ○ Requires physical verification (excavation/cores)
Gas Detection	○ Proven ○ Developing	○ Non-intrusive	+++	○ Relatively rapid ○ Continuous horizontal coverage	○ May not detect heavily weathered oils or tar balls ○ No vertical discrimination ○ Requires physical verification (excavation/cores)
Ground Penetrating Radar	○ Developing	○ Non-intrusive ○ Equipment operation on shoreline	+++	○ Fine layer discrimination possible ○ Continuous horizontal coverage	○ May not work in presence of salt water ○ Requires physical verification (excavation/cores) ○ May not work well on irregular surfaces
Electro-magnetic/ Electro-resistivity Profiling	○ Developing	○ Non-intrusive ○ Equipment operation on shoreline	++	○ Relatively rapid ○ Partial Layer discrimination ○ Continuous horizontal coverage	○ May not detect discontinuous deposits or thin layers ○ Requires physical verification (excavation/cores) ○ May not penetrate water-saturated sediments

Applications and limitations of these technologies remain to be evaluated, either through experimentation of trials or on actual spill events. As such, no attempt has been made to rank or prioritize the methodologies listed, other than some preference is given to those remote sensing techniques that allow comprehensive real-time horizontal extent of subsurface contamination surveys. Such surveys, if successful, could significantly reduce detection and delineation efforts in comparison to current practices.

7.0 Conclusions and Recommendations

7.1 Conclusions

This evaluation of current practices for subsurface oil detection and delineation on sediment shorelines suggests that the current practices are usually adequate for vertical delineation, but do not always provide a desirable level of horizontal detection or characterization. In addition, current practices can be labor-intensive and slow. Large and on-going (chronic) events can exert demands on turn-around time and manpower which can be difficult to meet using current technology. A reduction in turn-around time and overall costs are desirable targets for improvements to subsurface detection and delineation practices.

The ideal subsurface survey tactic, would:

- Be rapid, cost effective, and environmentally acceptable;
- Provide continuous horizontal coverage over a wide swath;
- Provide real-time data, including data reduction and plotting;
- Be able to discriminate the depth of oil deposits;
- Be able to determine the thickness of oil deposits; and
- Be able to characterize oil in terms of cleanup requirements.

No current technology meets all of the above criteria. A number of promising technologies have been identified in this study. These technologies promise to significantly advance current practice in some areas, including potential reduction in the intensity of current practices, but as with current practice, none are stand-alone. It is apparent that a combination of existing and developing technologies has the potential to significantly improve the ability to improve the speed and accuracy in which data can be acquired and assessed. Several of the developing tactics are in the process of demonstration testing and minor modification, and others show a high potential for becoming operational tools with minimal additional testing and/or demonstration.

7.2 Recommendations

Recommendations from this Phase 1 study include the following:

7.2.1 Improvements to Existing Practices

Subsurface detection and delineation tactics often are dependent on site–specific conditions. In addition, response efforts during the DWH response have resulted in a number of procedural improvements. The current state-of-the-practice should be updated and organized into a readily useable format. Phase 2 of this project includes development of a “*Field Guide to Detection and Delineation of Subsurface Oil in Sediment Shorelines*”. This Phase 2 document is intended to upgrade the subsurface assessment process and to include provisions to demonstrate, in some instances, the applicability and limitations of developing technologies and in others to test new, as yet unproven, technologies and techniques.

7.2.2 Recommendations for Further R&D

Products of Phase 2 of this study also may include recommendations for further research and development of tactics that could be made available to industry, the response community and related equipment and service industries.

7.2.3 Field Trials and Demonstrations

There is a large step between traditional R&D efforts and field applications where real world conditions and challenges are encountered. Some of the “developing” technologies identified in this investigation represent existing and functional techniques that can be evaluated and/or demonstrated through controlled experimental spills in real-world situations (spills of opportunity). Regardless of whether the evaluations are controlled tests or spills of opportunity, maximum benefit can be obtained if they are conducted side-by-side.

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