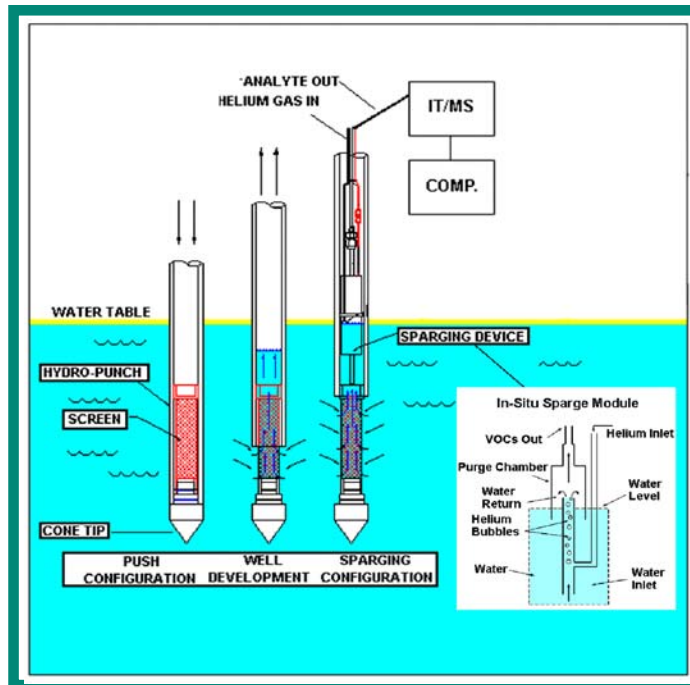


# ESTCP

## Cost and Performance Report

(CU-9603)



### Tri-Service Site Characterization and Analysis Penetrometer System (SCAPS) Hydrosparge Volatile Organic Compound Sensor

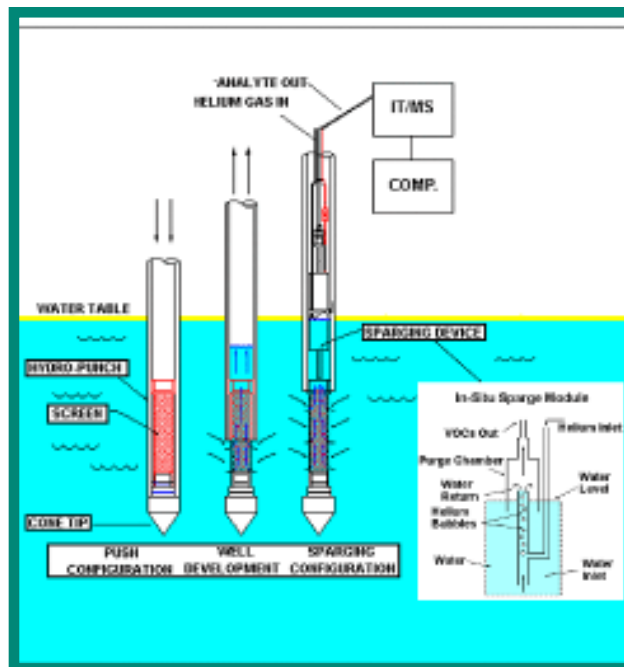
September 2001



ENVIRONMENTAL SECURITY  
TECHNOLOGY CERTIFICATION PROGRAM

U.S. Department of Defense

# ESTCP Cost and Performance Report



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U.S. Department of Defense

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## LIST OF ACRONYMS

---

|              |   |
|--------------|---|
| µg/L         | Microgram per Liter   |
| AEC          | U.S. Army Environmental Center  |
| ASTM         | American Society for Testing and Materials  |
| BETX         | Benzene, ethylbenzene, toluene, xylene  |
| BGS          | Below ground surface  |
| Cal EPA-DTSC | California Environmental Protection Agency, Department of Toxic Substance Control |
| CE           | U.S. Army Corps of Engineers  |
| CI           | Chemical impact ionization  |
| cm           | Centimeter  |
| CPT          | Cone penetrometer test  |
| DCE          | Dichloroethene  |
| DNAPL        | Dense non-aqueous phase liquid  |
| DOE          | Department of Energy  |
| EI           | Electron impact ionization  |
| EPA          | U.S. Environmental Protection Agency  |
| ERDC         | Engineer Research and Development Center  |
| ft           | Feet  |
| GC/MS        | Gas chromatograph/mass spectrometer   |
| ha           | Hectare   |
| HS/GC        | Head space/gas chromatograph  |
| IDW          | Investigation derived waste   |
| ITMS         | Ion trap mass spectrometer  |
| L            | Liter   |
| LNAPL        | Light non-aqueous phase liquid  |
| LOD          | Limit of detection  |
| m            | Slope of a regression line  |
| m/min        | Meters per minute   |
| mg/L         | Milligrams per liter  |
| mL           | Milliliter  |
| mL/min       | Milliliters per minute  |
| mm           | Millimeter  |

## LIST OF ACRONYMS (continued)

---

|                  |  |
|------------------|--|
| MSL              | Mean sea level   |
| MT               | Metric ton   |
| m/z              | Mass to charge ratio of an ion                         |
| NAS North Island | Naval Air Station North Island                         |
| ng/g             | Nanogram per gram                                      |
| ng/mL            | Nanogram per milliliter                                |
| ORNL             | Oak Ridge National Laboratory                          |
| PCE              | Tetrachloroethene                                      |
| PECS             | Performance evaluation check samples                   |
| ppb              | Parts per billion; equivalent to ng/g, g/kg and µg/L   |
| ppm              | Parts per million; equivalent to g/g, mg/kg and mg/L   |
| SCAPS            | Site Characterization and Analysis Penetrometer System |
| TCE              | Trichloroethene  |
| TPH              | Total petroleum hydrocarbon                            |
| U.S.             | United States  |
| USACE            | United States Army Corps of Engineers                  |
| UST              | Underground storage tank                               |
| VOC              | Volatile organic compound                              |
| WES              | Waterways Experiment Station                           |

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## 1.0 INTRODUCTION

A July 1998 demonstration of the Hydrosparge volatile organic compound (VOC) sensor was conducted at the Naval Air Station (NAS) North Island, Coronado, CA. The purpose was to demonstrate the ability of the Hydrosparge VOC sensor to characterize the extent of groundwater contamination in a single field deployment and to evaluate the sensor with regard to the accuracy of analytical results, time required to characterize the extent of contamination, and the sensor's reliability and ruggedness.

The Hydrosparge VOC sensor utilizes a commercially available direct push groundwater sampling tool to access groundwater. The in situ sparge module is then lowered directly into the groundwater and purges VOC analytes in situ from the groundwater with helium gas bubbles. The volatiles sparged from the water are carried via transfer tubing to a surface-deployed ion trap mass spectrometer (ITMS) where the contaminants are analyzed in real-time. The analysis is performed in accordance with U.S. EPA draft Method 8265 (U.S. EPA 1994) to a detection limit ranging from 1 to 5 ppb ( $\mu\text{g/L}$ ).

A total of 115 groundwater samples collected from 50 locations were necessary to characterize the extent of contamination at the NAS North Island, Building 379 site. Eight conventional groundwater monitoring wells were installed after the Hydrosparge demonstration and the analysis of water samples collected from these wells verified the extent of contamination.

The Hydrosparge VOC sensor demonstration cost \$158,173 for the collection and analysis of VOC samples and the completion of 16 cone penetrometer soundings that provide continuous soil lithology classification. A cost comparison between the actual costs of this demonstration and the estimated costs of completing a similar effort with monitoring wells showed that using the Hydrosparge VOC sensor potentially saved \$75,000. This equates to approximately a 32 percent cost savings. However, the Hydrosparge VOC sensor system provided onsite contaminant speciation and quantification in near real-time. At the end of the demonstration, the site managers were at a site restoration decision point that they may not have reached for several months if conventional well installation, sampling, and offsite analysis techniques were used.

The time savings was made possible by completing the characterization during a single field investigation/demonstration. An experienced field crew that was allowed to make deployment decisions during the demonstration was responsible for this efficiency. The willingness of the site managers to accommodate changes in the demonstration plan as sample analysis results became available and more optimum locations for interrogation were identified also made this efficiency possible.

The Hydrosparge VOC sensor is a quick and efficient tool used to screen a site for contamination and to gain insight into the nature and extent of groundwater contamination. Groundwater monitoring wells are essential for site verification and long-term monitoring. Both methods of groundwater interrogation are integral to cost-effective site remediation.

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## 2.0 TECHNOLOGY DESCRIPTION

This section describes the Hydrosparge VOC sensor technology, a sensor which collects and analyzes groundwater samples in the subsurface saturated zone. The sensor is deployed by a Tri-Service Site Characterization and Analysis Penetrometer System (SCAPS) (Figure 1).



**Figure 1. SCAPS Penetrometer Truck.**

### 2.1 TECHNOLOGY BACKGROUND

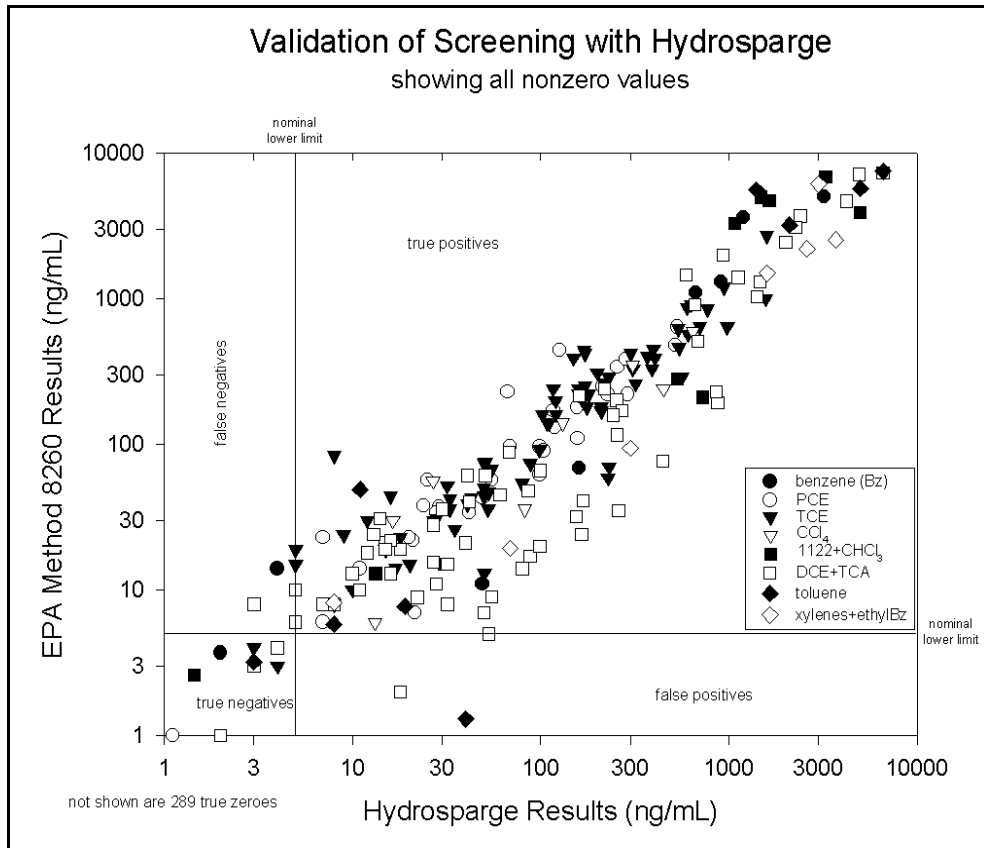
This technology was developed to address the need to rapidly characterize chlorinated solvent contamination in groundwater at Department of Defense (DoD) sites in a cost-effective manner. The Hydrosparge VOC sensor performs rapid field screening to determine either the presence or absence of volatile organic compound contaminants in subsurface media. In addition, the Hydrosparge VOC sensor provides identification of specific analytes based on their mass spectra and provides estimates of contaminant concentrations.

The Hydrosparge VOC sensor utilizes a commercially available Hydropunch® or Powerpunch™ direct push groundwater sampling tool to access the groundwater via temporary microwells. The Hydropunch is pushed to the desired depth and the push pipes are retracted, exposing the screened interval to the groundwater. The groundwater enters the microwell and is allowed to come to equilibrium, which generally takes less than 15 to 20 min.

The in situ sparge module, developed by the Department of Energy (DOE) Oak Ridge National Laboratory (ORNL), is then lowered into the microwell screen. The sparge module purges the VOC analytes in situ from the groundwater using helium gas. The volatiles sparged from the water are carried to an ITMS, where the contaminants are analyzed in near real-time. The analysis is performed in accordance with EPA draft Method 8265, to a detection limit of the 1 to 5 ppb ( $\mu\text{g/L}$ ) range.

The reliability of the Hydrosparge VOC sensor has been successfully demonstrated at seven geographic locations to date. The analyses of Hydrosparge (Figure 2) field data compared with onsite laboratory analyses of samples from the same wells (EPA Method 8260A) yield a coefficient of correlation of 0.84 with a slope of 1.2 over a contaminant concentration range from 1 ppb to 10 ppm (Davis et al. 1998a).

The Hydrosparge VOC sensor collects a sample from a discrete depth depending on the length of the screened interval used. Analysis requires 3 min to complete and is available before the next sample depth is reached. The following sections describe each of the Hydrosparge VOC sensor components in detail.



**Figure 2. Hydrosparge VOC Sensor Validation.**

### 2.1.1 SCAPS

The SCAPS is the result of a Tri-Service effort to utilize the capabilities of cone penetrometer technology for characterizing subsurface contamination at military installations. Cone penetrometry has long been used to characterize soil for geotechnical parameters such as soil strength and liquefaction potential. This is accomplished by advancing (pushing) a standard cone penetrometer probe into the ground by hydraulic ram force.

The SCAPS truck is a standard 18.2 MT (20-ton) mobile cone penetrometer testing (CPT) platform used to advance contaminant and geotechnical sensing probes. The forward portion of the SCAPS truck houses the hydraulic rams (Figure 3) used to translate the weight of the truck (reaction mass) into pushing force. The combination of reaction mass and hydraulics can advance a 1-m-long by 3.57-cm-diameter steel rod into the ground at a rate of 1 m/min in accordance with American Society of Testing and Materials (ASTM) Method D3441 (ASTM 1991), the standard for geophysical sensing CPT. The rods, various sensing probes, or sampling tools can be advanced to depths in excess of 50 m (164 ft) in nominally compacted soils. Some SCAPS sensor probes are configured with retraction grouting capability. As the rods are withdrawn, a sacrificial cone tip is ejected and grout is transferred from a surface mounted grout pumping station through 6.35-mm-(0.25-in.-) diameter tubing within the SCAPS probe umbilical cables, and is injected hydraulically to seal the penetrometer hole. Also, while the rods are withdrawn, they are cleaned within a hot



**Figure 3. SCAPS Truck Hydraulic Rams.**

water-manifold housed outside and beneath the truck. The rinse water is contained for proper handling and disposal. The rear portion of the SCAPS truck houses the data collection components of SCAPS sensor technologies and onboard data acquisition/processing computers.

### 2.1.2 Geophysical Cone Sensor

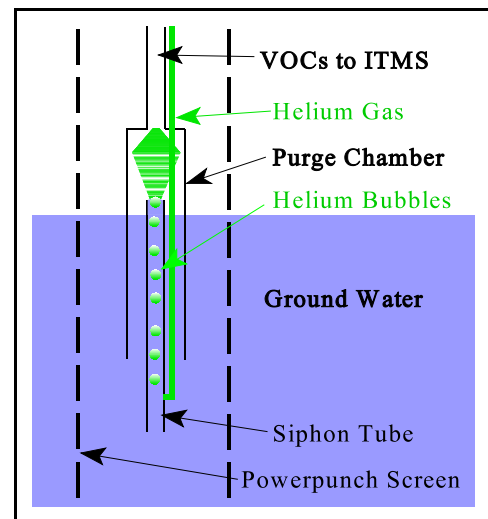
The SCAPS standard cone penetrometer probes are instrumented with a soil classification module consisting of strain gauges that measure cone pressure and sleeve friction in accordance with ASTM Standard D3441. The soil type is then determined from a ratio of cone pressure and sleeve friction using an empirically derived classification scheme (Lee et al. 1994).

The soil class information is crucial for the Hydrosparge application in selecting the soil region(s) that are likely to yield groundwater.

### 2.1.3 In Situ Sparge Module

The in situ sparge module (Figure 4) consists of a siphon tube that extends 0.5 m (18 in.) below the purge chamber where VOC's are collected. Helium is delivered at a low flow rate (100 to 160 mL/min) to the siphon tube; as the helium rises through the groundwater it causes water to flow up and into the siphon tube and strips the VOC from the groundwater. The helium gas and VOC's are then pulled into the return transfer line which is under a slight vacuum. The return line is connected to the direct sampling ITMS which is mounted within the SCAPS truck.

The differential in the density of the water column that is being purged within the siphon tube and the surrounding water creates a pumping action that continually draws fresh sample into the sparge device. The module can be deployed at any depth below the water surface (Wise et al. 1997).



**Figure 4. Hydrosparge VOC Sensor In Situ Sparge Module.**

### 2.1.4 Direct Sampling Ion Trap Mass Spectrometer

The direct sampling ITMS comprises of a quadrupole ion trap mass spectrometer, a capillary restrictor interface and a variety of sample inlets for use with gas (air and soil gas), soil and water (Wise and Guerin 1997). The system employed can use one of three ITMS models: (a) a Teledyne 3DQ ITMS, (b) a Finnigan ITMS 40, or a (c) Varian Saturn. Each ITMS is fitted with a 20-cm-long, 100  $\mu\text{m}$  internal diameter capillary (J&W part #160-2635) restrictor heated interface (Scientific Information Service, Inc. part #912000) operated at 105 EC. The capillary interface limits flow into the ITMS to 0.1 to 1.0 mL/min, and is compatible with both electron impact (EI) and

chemical ionization (CI) sources. Chlorinated solvents are analyzed using EI and benzene, ethyl benzene, toluene, and xylenes (BETX) are analyzed using water CI with the ITMS operated in the full scan mode (40 to 250 Daltons)

The ITMS is operated in a full scan mode during calibration and Hydrosparge VOC sensor data collection. Since no separation technique is used before vapor samples are introduced into the ITMS, the resulting mass spectral data consist of a series of scans containing ions that indicate the presence of VOC analytes (Wise and Guerin 1997). Individual compounds are identified and quantified based on ions of selected masses (Figure 5) indicative of the individual compound (i.e. 130/132 m/z for trichloroethene by EI and 79 m/z for benzene by water CI). Data acquired during calibration are reduced by integrating a fixed number of mass spectra scans (typically 80 to 100 scans) of the specific ions for a given analyte (U.S. draft EPA Method 8265). Typical linear calibration curves for said contaminant analytes extend over three to four orders of magnitude and are quite linear (Davis, Furey, and Porter 1998b). During data collection from groundwater, the ITMS is operated in the full scan mode and performs an analysis of the sample returned by the in situ sparge module every second over a period of 3 min. Data acquired during the Hydrosparge VOC sensor experiment are reduced in an analogous manner to the calibration standards and are quantified based on the calibration curves previously discussed. Daily calibration check standards and performance evaluation check standards (PECS) are analyzed to ensure data quality.

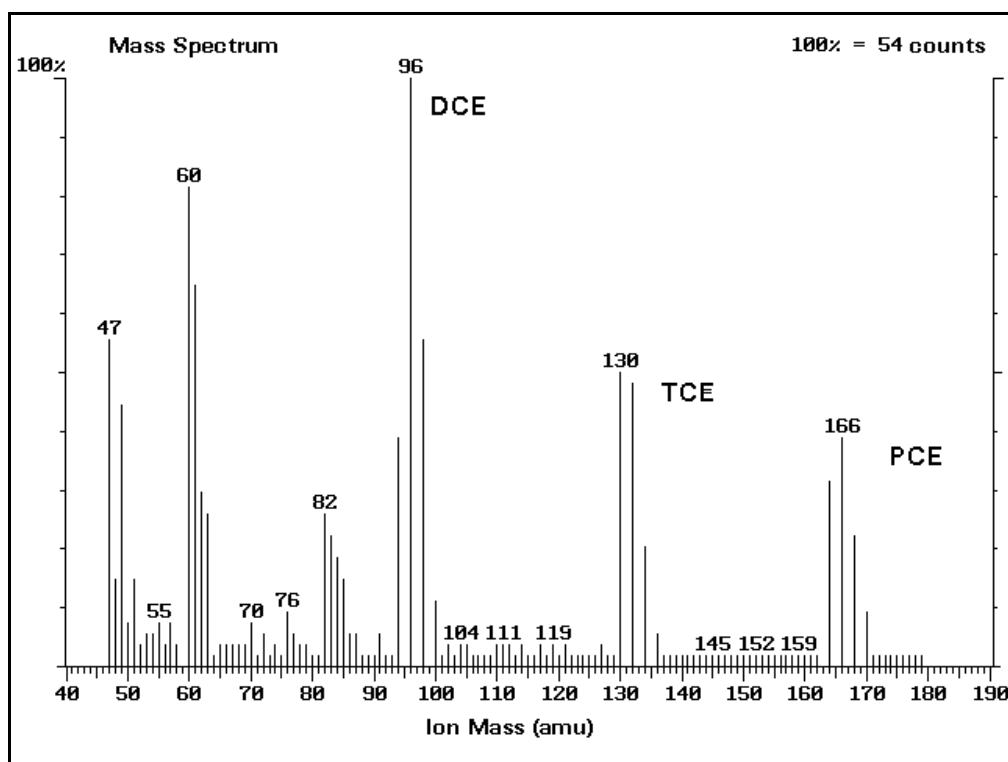


Figure 5. Example of ITMS Ion Scan.

**Dynamic range.** The linear dynamic range of the SCAPS Hydrosparge VOC sensor depends on the dynamic range of the ITMS. Previous investigations using the ITMS have found that the linear portion of the response curves extends well beyond three orders of magnitude from low micrograms per liter (parts per billion) to milligrams per liter (parts per million) (Davis, Furey, and Porter 1998b). Nonlinearity tends to occur at concentrations greater than tens of milligrams per liter in water. The linear dynamic range of the ITMS also depends on operator-controlled instrumental parameters. The linear dynamic range may be extended to higher concentrations by adjusting the ionization time of the ITMS detector, but this results in decreased sensitivity at lower concentrations.

**System limit of detection.** Three quantities are needed to determine the Hydrosparge systems detection limits: electronic noise, background, and sensitivity. As with the linear dynamic range, these three parameters are related to the ITMS. These quantities are determined using the calibration samples prepared immediately prior to the site visit and standard analytical techniques (U.S. EPA 1993; Davis, Furey, and Porter 1998b).

Limits of detection (LOD) were calculated according to the method outlined in SW 846 (USEPA 1993). This method involves  $n$  replicate measurements of a low but detectable analyte concentration, estimation of analytical system noise as the variance of the  $n$  replicate measurements, and calculating the LOD using the following equation:

$$\text{LOD} = t_{n-1, \alpha/s} S$$

where  $t_{n-1, \alpha/s}$  is the student  $t$  value for  $n$  replicates at the 95 percent confidence level and  $S$  estimate of the standard deviation. For  $n$  values between 5 and 9, the  $t_{n-1, \alpha/s}$  ranges between 2.78 and 2.23. Measurements for LOD calculations are made using the entire Hydrosparge VOC sensing system; therefore, measuring the expected overall system performance during the in situ application. Typical LOD values calculated for data obtained in actual field operations are consistently single  $\mu\text{g/L}$ . The SCAPS Hydrosparge VOC sensor detection limits will vary somewhat from site to site, but is in the range of 2 to 5  $\mu\text{g/L}$  for the 34 VOC analytes listed on the EPA Target Compound List.

### 2.1.5 Quantitative Calibration of Hydrosparge Sensor

The ITMS, like any other analytical instrument, provides an intensity response relative to the amount of contaminant present in the sample analyzed. The ITMS does not directly provide the concentration of the contaminant in the sample. To estimate the concentration present in the field sample, a series of analytical standards spiked with known quantities of contaminant are analyzed by the instrument and a calibration curve is generated. The actual concentration value can never be known and is always an estimate.

The in situ sparge module and ITMS are calibrated by spiking a 250 mL volumetric flask containing distilled water and a known concentration of analytes. The sparge module is inserted into the flask, the helium flow rate is adjusted at the beginning of the calibration (generally between 100 and 160 mL/min) and remains constant during calibration and Hydrosparge in situ sample collection and analysis. The calibration procedure is conducted under the same operating conditions used during the Hydrosparge field operation.

## **2.2 PERSONNEL TRAINING REQUIREMENTS**

Personnel operating the SCAPS CPT platform should be trained in the installation of groundwater monitoring wells and other traditional drilling methods. Operators of the ITMS vary in skill and training but should be experienced in the operation of standard laboratory equipment. All personnel operating the Hydrosparge direct sampling ITMS should be familiar with the operation of computer software and should be familiar with safety requirements for working around heavy equipment. Other than yearly Hazardous Waste Worker Update Training requirements, there is no mandated training required to operate the CPT or the ITMS during field investigations.

## **2.3 ADVANTAGES**

The SCAPS Hydrosparge VOC sensor is an in situ field screening device for characterizing the subsurface distribution of volatile organic compound contamination without the installation of conventional groundwater monitoring wells. The method is not intended to be a complete replacement for traditional monitoring wells, but is a means to optimize the placement of monitoring wells and usually results in the placement of a reduced number of monitoring wells to achieve site characterization and/or long-term monitoring.

The Hydrosparge VOC sensor uses a CPT platform to provide near real-time field screening of the distribution of VOC contamination at hazardous waste sites. The current configuration is designed to quickly and cost-effectively distinguish VOC contaminated areas from uncontaminated areas and to provide semiquantitative estimates of groundwater VOC contaminant concentrations. This capability allows further investigation and remediation decisions to be made more efficiently and reduces the number of samples that must be submitted to laboratories for costly and time-consuming analysis. In addition, the SCAPS CPT platform allows for the characterization of contaminated sites with minimal exposure of site personnel and the community to toxic contaminants, and minimizes the volume of investigation derived waste (IDW) generated during conventional drill/sample site characterization activities.

## **2.4 LIMITS OF THE TECHNOLOGY**

This section discusses the limits of the SCAPS Hydrosparge VOC sensor as they are currently understood.

### **2.4.1 Truck-Mounted Cone Penetrometer Access Limits**

The SCAPS CPT vehicle is an 18.2 MT (20-ton) push platform built on a commercially available diesel-powered truck chassis. The dimensions of the truck require a minimum access width of 3 m (10 ft) and a height clearance of 4.6 m (15 ft). It is conceivable that some sites, or certain areas of sites, might not be accessible to a vehicle the size of the SCAPS CPT truck. The access limits for the SCAPS CPT vehicle are similar to those for conventional drill rigs and heavy excavation equipment. However, the Hydrosparge VOC sensor can be run out of the back of a van with groundwater accessed by smaller direct push rigs.



## **2.4.2 Cone Penetrometer Advancement Limits**

The CPT sensors and sampling tools may be difficult to advance in subsurface lithologies containing cemented sands and clays, buried debris, gravel units, cobbles, boulders, and shallow bedrock. As with all intrusive site characterization methods, it is extremely important that all underground utilities and structures be located using reliable geophysical equipment operated by trained professionals before penetrometer activities are initiated. This should be done even if subsurface utility plans for the site are available for reference.

## **2.4.3 Extremely High Level Contamination Carry-Over**

The effective dynamic range for the Hydrosprage VOC sensor is determined by two factors: the dynamic range of the ITMS (discussed previously) and the potential for carry-over or cross contamination of the in situ sparge module and analyte transfer line. All analytical systems have upper limits of detection as well as lower limits of detection. The upper limit of detection for the ITMS is determined by the number of molecules that it can analyze before the detector is "saturated" with ions (Wise and Guerin 1997). However, it is the internal contamination of the transfer lines that often determine the lower limit of detection.

Extremely high levels of subsurface VOC contamination will cause carry-over of analytes between successive runs. That is, after sampling a high contaminant concentration, residual VOC analytes may remain in the sampler transfer lines. This is considered sample carry-over between runs. This problem cannot be completely eliminated, but the effects of residual sample carry-over can be controlled. After an extremely high level sample has been analyzed, a system blank is analyzed. Residual sample carry-over is observed when VOC analytes are detected in blank samples above the system background response. When residual sample carry-over is detected, the sample transfer lines are replaced and the contaminated lines are left to purge with helium gas for approximately 30 min. Thus, by using two interchangeable in situ sparge modules and transfer lines, there is no lost production time.

## **2.4.4 ITMS Limitations**

The ITMS is operated as the detector for the Hydrosprage VOC sensor as detailed in EPA draft Method 8265 and as described in Davis, Furey, and Porter (1998b). This method is intended for field screening applications via direct sampling ITMS. One of the limitations of the ITMS is the inability of the ITMS to distinguish between analyte pairs that yield identical mass fragments. For example, 1,1,2,2 tetrachloroethane and chloroform (trichloromethane) yield ions primarily at masses 83 and 85. Using the current ITMS technology it is not possible to differentiate these two analytes; therefore they are reported as a sum of the two analytes. It should be noted that the current EPA laboratory method (EPA Method 8260) using gas chromatography/mass spectrometry is also not able to differentiate some analyte pairs such as meta and para-xylene. Nevertheless, even when samples are contaminated with complex mixtures of analytes, the ITMS can usually provide a useful level of qualitative and quantitative contaminant screening information.

#### **2.4.5 Direct Push Well Limitations**

Direct push microwells have many of the same limitations that conventional monitoring wells have: difficulty obtaining water samples from low conductivity soils, difficulty with installation in flowing sands, and the potential for spreading contamination during installation.

Currently, during the water access phase of the Hydrosparge operation, the direct push well is installed without casing to minimize expense of operation. Without casing to prevent movement of contaminants in the annulus, there is an increased potential for cross layer contamination. Aquitards and isolating lithologies that separate contaminated regions should not be breached.

The NAS North Island site has a suspected low permeability layer at 13.7 m (45 ft) below ground surface (BGS) which was never breached during the investigation.

### **3.0 DEMONSTRATION DESIGN**

This section discusses the technology claims, demonstration objectives, sampling design, and data analysis protocols that will be used to evaluate the results of the demonstration.

#### **3.1 PREVIOUS DEMONSTRATIONS**

The HS VOC sensor technology was previously demonstrated under this program at three sites:

- a. Bush River Study Area, U.S. Army Aberdeen Proving Ground, Edgewood, MD; June and August 1996.
- b. Davis Global Communication Site, McClellan Air Force Base, Sacramento, CA; November 1996 and February 1997.
- c. U.S. Army Fort Dix, NJ; June and July 1997.

While the data were not used in this demonstration report, each site and its results are discussed briefly in the following paragraphs.

##### **3.1.1 Data Validation for Bush River Study Area, Aberdeen Proving Ground**

The validation sample results from the HS VOC sensor demonstration performed at Bush River Study Area (BRSA) during June 1996 indicated that the HS VOC Sensor was underestimating the VOC concentrations when compared with the verification samples measured by EPA Method 8260. The data collected during the June demonstration were collected using a Teledyne DSITMS. In mid-August, the ERDC-WES SCAPS team performed additional HS VOC Sensor penetrations at the BRSA to identify the source of the low bias provided by the Teledyne DSITMS. This work was conducted using a Finnigan ITMS 40 and the results were compared with data collected using the Teledyne DSITMS. This comparison indicated that the Teledyne did yield a low bias for high VOC concentrations. It should be noted that the bias was only observed at concentrations  $> 1,000 \mu\text{g/L}$ . The instrumental bias was not detected during previous field operations since that the highest concentration PE check standard analyzed was  $50 \mu\text{g/L}$ . All subsequent HS VOC sensor demonstrations incorporated higher concentration PE check standards.

The source of the bias in the Teledyne data appeared to be due to a thermal cold spot in the DSITMS heated inlet where the helium purge gas from the in situ purge module entered the DSITMS. The cold spot was brought to the attention of the Teledyne manufacturer and the problem was corrected.

Based on problems encountered with the Teledyne DSITMS, only the data collected using the Finnigan DSITMS were used for data comparisons between the HS VOC sensor and the validation samples analyzed using EPA Method 8260. Linear regression statistics of the BRSA data show a correlation of 0.63 and a slope of 1.2.

##### **3.1.2 Well Comparison Study at Davis Global Communication Site**

At the Davis Global Communication Site (DGCS), HS VOC sensor data were compared to conventional, established monitoring wells and to groundwater from the direct push wells. Results from the demonstration indicate, regardless of the source of water (direct push miniwell, or

conventional monitoring well), that the in situ sparge/DSITMS measurement of the groundwater VOC concentrations are comparable to measurements made by offsite sample analyses using EPA Method 8260. Correlations between the Hydrosparge data and conventional EPA Method 8260 data from existing monitoring wells, however, showed a definite low bias. Experiments involving clustering direct push wells at different depths around existing monitoring wells were conducted to determine the cause of this bias. Using the HS VOC sensor along with the Thermal Desorption VOC Sampler, it was demonstrated that the wells at DGCS had been improperly designed allowing uncontaminated groundwater to leach contaminants from the contaminated clay-confining layer into the groundwater.

Since the low bias for the data was explained, the comparison of the HS VOC data to existing monitoring well data was omitted from the DGCS data comparison. Linear regression statistics for the direct push groundwater comparison of the Hydrosparge /DSITMS data to conventional EPA method 8260 data show a correlation of 0.88 with a slope on 1.1.

### **3.1.3 Hydrosparge Data Collected at Fort Dix**

All Hydrosparge in situ and verification data collection activities at the Fort Dix demonstration were conducted as planned. No problems were encountered with either the HS VOC sensor or the Hydrosparge/conventional well comparison study. Linear regression statistics show a correlation of 0.85 and a slope of 1.2.

## **3.2 PERFORMANCE OBJECTIVES**

This technology was developed to address the need to rapidly characterize chlorinated solvent contamination in groundwater to a degree of precision that is economically feasible. Therefore the Hydrosparge VOC sensor should not only approach the accuracy of traditional sample collection and analysis techniques, but also should be able to complete contaminant characterization in less time at a significantly lower cost. With this claim in mind the SCAPS Hydrosparge VOC sensor performance will be compared to conventional sampling and analytical methods for:

- a. Accuracy of analytical result.
- b. Time required to characterize extent of contamination.
- c. Reliability and ruggedness.

### **3.2.1 Accuracy**

As part of the objectives outlined above, the SCAPS Hydrosparge VOC sensor was evaluated to determine agreement between data produced in situ and the results of laboratory verification sample analyses by EPA Method 8260A. The Hydrosparge VOC sensor detection limit was determined according to EPA draft Method 8265 procedures. When the ITMS response exceeded the detection limit, the data were considered to be a “detect.” The detection limit for the verification samples was determined by an offsite independent laboratory using EPA Method 8260A.

The Hydrosparge VOC sensor produced data that were reduced to concentration units of  $\mu\text{g/L}$ . These are the same data type and concentration units used for reporting data from the verification method (EPA Method 8260A). Hence, direct comparison of the SCAPS Hydrosparge VOC sensor analysis results with those from the verification sample analyses was simple and straightforward.

The strength of comparisons between the Hydrosparge VOC sensor data and the conventional methods of analysis for verification samples was evaluated using least squares linear regression over the entire concentration range of data collected. The Hydrosparge VOC sensor analysis results and conventional analysis results were considered to strongly agree if the correlation coefficient of the linear regression was  $1.0 \pm 0.2$  and the slope of the regression line was  $1.0 \pm 0.2$ . Previous field demonstrations of the Hydrosparge VOC sensor indicate strong correlations between in situ analysis results and EPA Method 8260A analysis of verification samples (Davis et al. 1998a).

### **3.2.2 Time Required to Characterize Extent of Contamination**

Field implementation of conventional characterization technology is typically a rigid process. Once the sample collection locations are chosen they are not changed while the sampling crew is in the field. The lapse of time between collecting samples and receiving a report detailing the sample analysis results is nominally 6 months to a year. Once the analysis results are available they usually reveal that more samples are required before remediation decisions can be made. Another lapse in time occurs in completing contractual details to prepare sample collection plans. Yet another lapse in time occurs in completing contractual details to implement the sampling plans. These time lapses can easily exceed a year. An objective of this demonstration was to characterize the extent of chlorinated solvent contamination in a single field deployment.

### **3.2.3 Reliability and Ruggedness**

The reliability of the Hydrosparge VOC sensor is a measure of how many consistent days sample collection and analysis occurs. Ruggedness refers to physical, thermal, and chemical shocks endured by the sensor that do not interfere with repeatability of measurements.

## **3.3 PHYSICAL SETUP AND OPERATION**

The demonstration was conducted July 1998. The goal to characterize the extent of contamination in one field deployment required the close cooperation of a variety of people. Table 1 provides the partnered organizations and their respective responsibilities.

## **3.4 MONITORING PROCEDURES**

Monitoring the Hydrosparge VOC sensor performance consisted of quality assurance checks and independent analysis of verification sample analysis. Method Blanks (consisting of reagent water) were analyzed at the beginning of each work day to document system background and to insure that residual VOC contaminants were purged from the Hydrosparge VOC sensor system. Triplicate calibration samples of a single known concentration were analyzed at the beginning of each working day (daily calibration check standards). In addition, a single calibration check sample of known concentration was analyzed immediately prior to in situ Hydrosparge VOC sensor data collection. Once daily, an externally prepared calibration check standard was analyzed to evaluate the accuracy of the working calibration stock solution and continuing calibration.

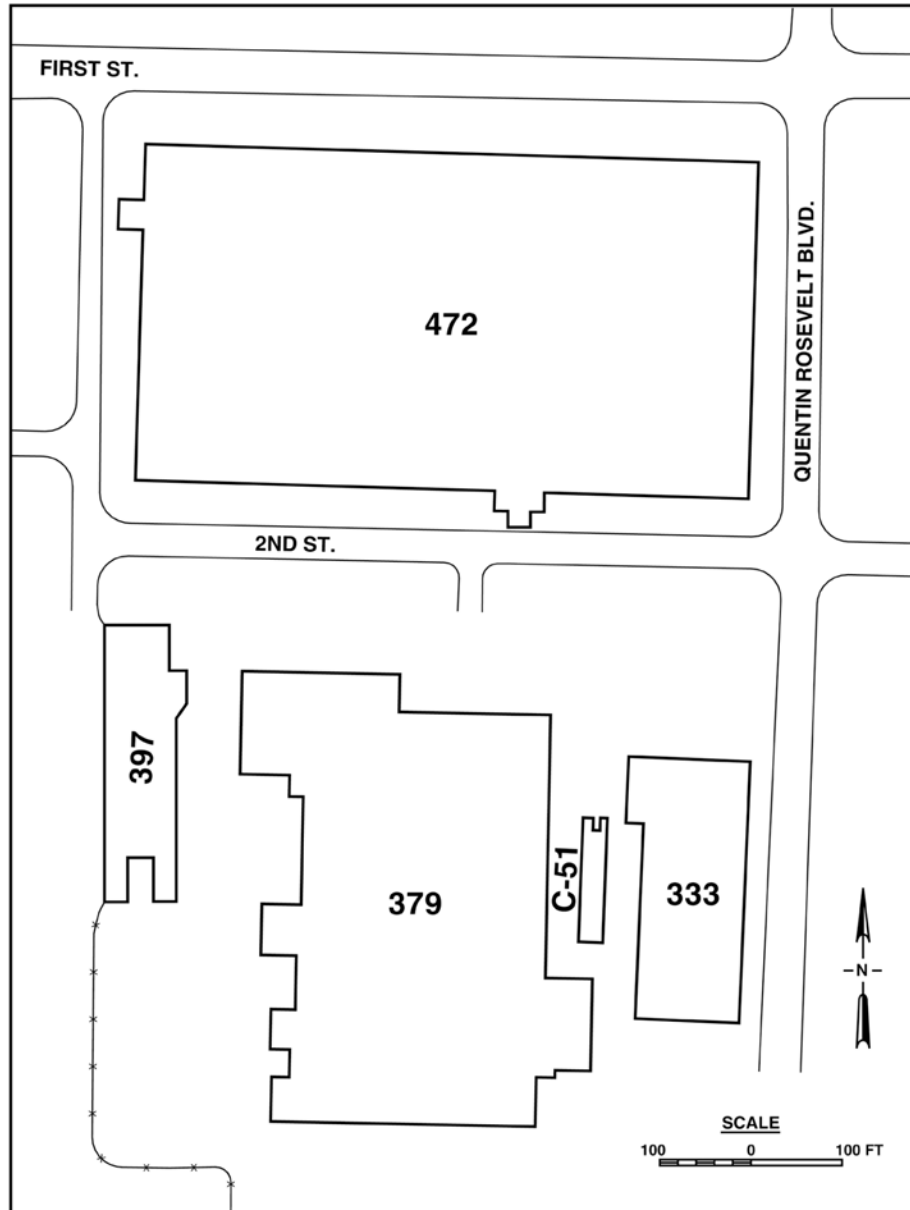
**Table 1. Demonstration Participants.**

| Organization  | Responsibility  |
|---|---|
| <i>ESTCP Funded Activities</i>                                |   |
| U.S. Engineer Research and Development Center (ERDC)          | Communicate sample analysis results with OHM Remediation Services<br>Ensure verification samples are collected and sent to fixed laboratory<br>Maintain Hydrosparge VOC sensor<br>Generate demonstration plans and final report for ESTCP     |
| <i>NAVFAC Funded Activities</i>                               |   |
| U.S. Naval Facilities Engineering Command, Southwest Division | Remedial project manager duties<br>Overall project direction  |
| OHM Remediation Services Corp.                                | Design and implementation of remediation system<br>Permitting and utility clearance<br>Managing investigative derived waste<br>Understand and communicate previous days sample analysis results<br>Recommend next sample collection locations |
| NAS North Island Public Works Office                          | Coordinate NAS North Island operations and movement of SCAPS truck  |
| U.S. Army Engineer District, Tulsa                            | Operate SCAPS truck<br>Responsible for logistics of each push hole<br>Operate Hydrosparge VOC sensor<br>Final report for Naval Facilities Engineering Command, SWDIV  |
| CalEPA DTSC   | Review demonstration findings for accuracy and completeness   |
| U.S. Naval Facilities Engineering Service Center              | Build conceptual model from previous existing data<br>Provide instruction on the visualization model to Tulsa personnel on procedure to update model with each sample analysis result   |

Groundwater samples were collected from within the direct push microwells and from conventional monitoring wells. These verification samples were analyzed by an offsite, independent laboratory by EPA Method 8260A.

### **3.5 DEMONSTRATION SITE/FACILITY BACKGROUND**

NAS North Island is part of the largest aerospace-industrial complex in the Navy. It includes Naval Amphibious Base Coronado, Outlying Field Imperial Beach and Naval Air Landing Facility, San Clemente Island. The complex's 2,024 ha (5,000 acres) in San Diego and 130 commands bracket the city of Coronado from the entrance to San Diego Bay to the Mexican border. NAS North Island is host to 23 squadrons and 75 additional tenant commands and activities, one of which, the Naval Aviation Depot, is the largest aerospace employer in the vicinity of San Diego, CA. The NAS North Island was commissioned a naval air station in 1917. The air station resembles a small city in its operations. The NAS North Island provides police and fire departments, operates large factories such as the Naval Aviation Depot that employs 3,800 civilians, and provides parks, beaches, housing, and recreation areas for military personnel.



**Figure 6. Hydrosparge VOC Sensor Demonstration Site, U.S. Naval Air Station North Island, Coronado, CA.**

The site selected for the Hydrosparge VOC sensor demonstration is near Buildings 379 and 397 at the Naval Aviation Depot (Figure 6). The site is located in the northeast quadrant of NAS North Island and is surrounded by three buildings: Building 379 to the east, Building 397 to the west and Building 391 to the south. Jet engine tests and maintenance are conducted in Building 379. Numerous former and existing underground storage tanks (UST's) are located within, between, and around Buildings 379 and 397. Buildings 379 and 397 overlie a previously delineated light nonaqueous phase liquid (LNAPL) plume. Building 391 is down gradient from this plume (OHM Remediation Services Corp. 1997).

### 3.6 DEMONSTRATION SITE/FACILITY CHARACTERISTICS

Petroleum hydrocarbon characterization efforts prior to this demonstration are summarized in Table 2. Initial site assessment of potential leaks for USTs was conducted by Jacobs Engineering Group Inc. in 1991. Seven soil borings and three monitoring wells indicated contamination in the area around and below the buildings. Contamination was identified by measuring total petroleum hydrocarbons (TPH) in soil and benzene in groundwater. Free product LNAPL was detected in one of the initial three monitoring wells. Based on the initial results, Geosciences conducted further site assessment during 1993. Ten soil borings and nine monitoring wells were installed and sampled. The TPH laboratory tests identified contamination in many of the soil boring samples and LNAPL was detected in two of the monitoring wells (OHM Remediation Services Corp. 1997).

**Table 2. Initial Petroleum Hydrocarbon Characterization.**

| Year      | Monitoring Wells | Recovery Wells |
|-----------|------------------|----------------|
| 1991      | 3                | --             |
| 1993      | 9                | --             |
| 1996-1997 | --               | 67             |

Based on these results, an LNAPL removal system was designed. During initial construction of the LNAPL removal system in 1996, the areal extent of LNAPL contamination was found to be four times greater than originally estimated. Construction was halted and the extent of LNAPL contamination was further investigated and delineated in the summer of 1997. Some of the groundwater samples collected were submitted for chlorinated VOC analysis in addition to BETX and TPH analysis. The presence of trichloroethylene (TCE) in a number of existing monitoring wells resulted in a re-evaluation of the proposed site remediation plan. Additional site characterization was recommended (OHM Remediation Services Corp. 1997).

#### 3.6.1 Hydrogeology

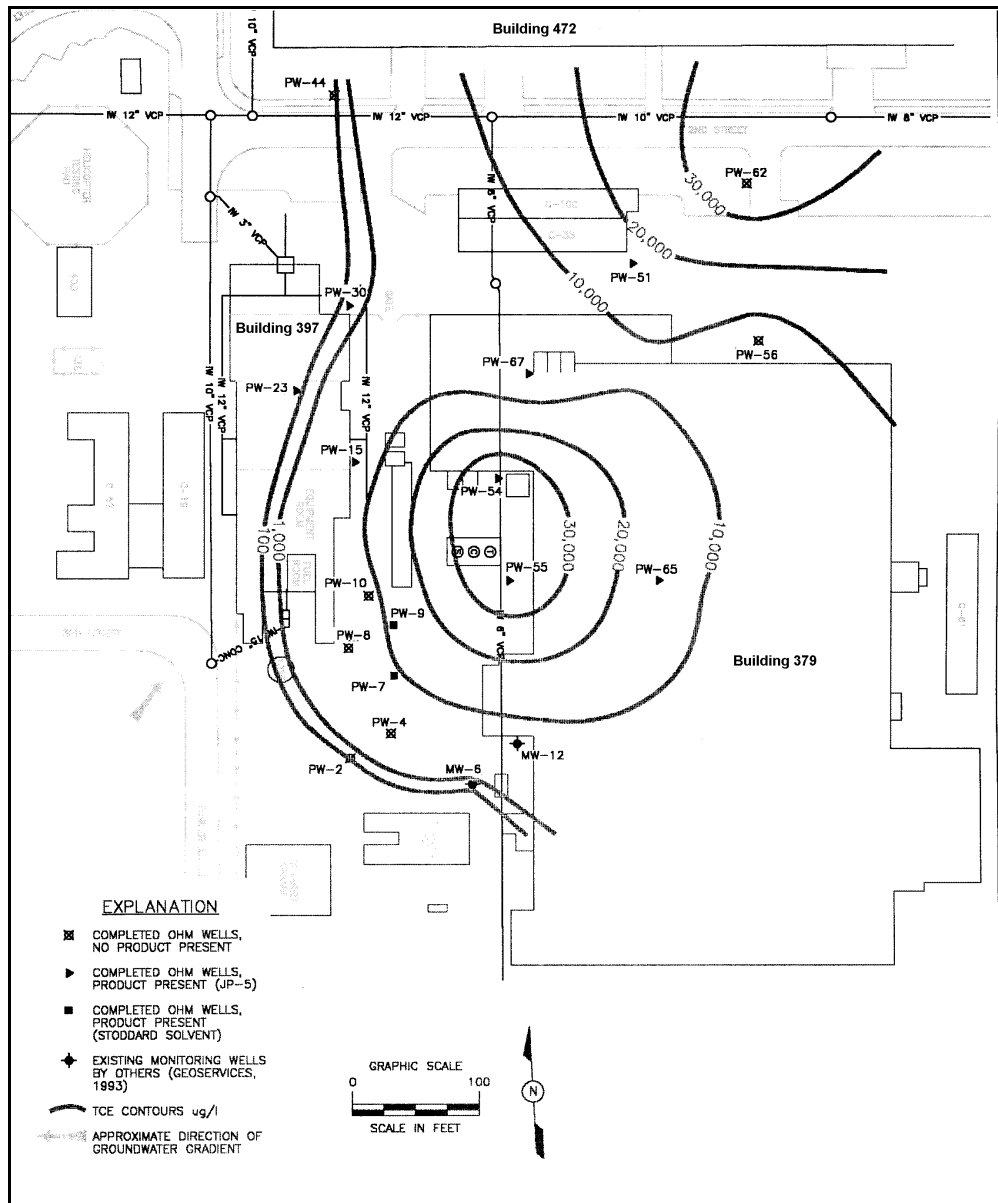
Previous investigations at the site have identified two primary geologic units at NAS North Island: an upper well-graded sand to silty sand underlaid by a poorly graded sand to silty sand. The upper unit of well-graded fine to medium sand and silty sand contains some coarse grains and is up to 20 percent silt. The upper unit extends from the surface to approximately 4.6 to 6 m (15 to 20 ft) BGS. The lower unit is a poorly-graded very fine to fine-grained sand and silty sand with less than 10 percent medium grains and up to 10 percent silt. The top of this unit is generally encountered 4.6 to 6 m (15 to 20 ft) BGS. The upper unit is constructed land that was hydraulically placed for the development of NAS North Island. The lower unit is native land formed by deposition in a near shore environment (Geosciences 1993).

Groundwater at the site appears to flow towards the north-northwest. The average hydraulic gradient across the site has been reported to be 0.0016 m/m (0.0017 ft/ft) and slug tests have measured the hydraulic conductivity to be 0.04 m/day (0.12 ft/day) in the lower geologic unit. These data have been used to conclude that the surficial aquifer is unconfined (Geosciences 1993).



### 3.6.2 Extent of Contamination

The extent of petroleum contamination was defined in OHM Remediation Services Corp. (1997). Additional investigation of soil and groundwater at depths between 6 and 12 m (20 and 40 ft) BGS in February 1998 indicated that there may be free product TCE or dense nonaqueous phase liquid (DNAPL) present at the site in the vicinity of monitoring well PW-62 (Figure 7). A contour map of the groundwater contamination at the Buildings 379 and 397 site was developed, based on data from the February 1998 investigations. The wide range of contaminant concentrations present at this site made it an ideal site to demonstrate the rapid site characterization capabilities of the SCAPS Hydrosparge VOC sensor.



**Figure 7. Known Extent of Groundwater Contamination at the NAS North Island Prior to the Hydrosparge VOC Sensor Field Demonstration.**

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## 4.0 PERFORMANCE ASSESSMENT

Determination of the SCAPS Hydrosparge VOC sensor performance was in comparison to conventional sampling and analytical methods. Three specific criteria for comparison were:

- a. Accuracy of analytical results.
- b. Time required to characterize the extent of contamination.
- c. Reliability and ruggedness of the system.

The Hydrosparge VOC sensor system technology verification demonstration was conducted in 22 working days. During the demonstration, the Hydrosparge was used at 50 direct push locations and 115 VOC samples were analyzed.

### 4.1 ACCURACY

Several methods of determining accuracy were used during the demonstration. The primary validation method employed during previous Hydrosparge demonstrations consisted of collecting water samples from the same direct push well used for the in situ analysis. These samples were sent to an offsite laboratory and analyzed by EPA Method 8260A. This type of validation was limited at NAS North Island because of the extensive previous validation efforts as shown in Figure 2. The four verification samples collected from direct push microwells and analyzed by an independent laboratory for this demonstration are shown in Table 3.

A second validation/verification method involved installing monitoring wells near Hydrosparge locations. Water samples from the monitoring wells were collected and submitted for offsite laboratory analysis by EPA Method 8260A. This effort validated not only the analytical portion of Hydrosparge but also the direct push microwells. Table 4, which summarizes the co-located monitoring well validation effort, reveals a striking difference in the analytical techniques. Large contaminant concentrations can significantly increase the quantitation limit for the fixed-laboratory procedure while not affecting the ITMS. This is particularly obvious in the analysis results for HS38-36 and MW-70B (quantitation limits of 0.2 and 12000 µg/L respectively). While the elevated quantitation limit did not mask the presence of contaminant according to Hydrosparge results, it does point out the utility of combining the two analytical techniques.

**Table 3. Validation Comparison Based on Split Sample Analysis.**

| Contaminant                  | Analytical Method | HS06-32 | HS06-39.5 | HS37-26 | HS37-36 |
|------------------------------|-------------------|---------|-----------|---------|---------|
| Vinyl Chloride<br>µg/L       | Hydrosparge       | nd      | nd        | 8000    | 2000    |
|                              | Fixed-Laboratory  | nd      | nd        | 4400    | 3050    |
| Total Dichloroethene<br>µg/L | Hydrosparge       | 2373    | 2767      | 467     | 2230    |
|                              | Fixed-Laboratory  | 4000    | 4100      | 900     | 2986    |

Note: Hydrosparge analysis is by EPA draft Method 8265 and Fixed-Laboratory by EPA Method 8260A; nd is non-detect.

**Table 4. Validation Comparison Based on Co-Located Monitoring Wells.**

| Sample Location | TCE (µg/L) | DCE (µg/L) | PCE (µg/L) | VC (µg/L)  | BTEX (µg/L) | Sample Depth m (ft) | Distance m (ft) | Soil Type       |
|-----------------|------------|------------|------------|------------|-------------|---------------------|-----------------|-----------------|
| HS16-26         | 3706       | 2031       | nd (0.2)   | nd (0.2)   | nd (0.2)    | 7.9 (26)            | 4.8 (15.9)      | sand            |
| MW-68A          | 750        | 344        | 6.3 J      | nd (50)    | nd (50)     | 8.1 (26.7)          |                 | sand mix        |
| HS16-40         | 47236      | nd (0.2)   | nd (0.2)   | nd (0.2)   | nd (0.2)    | 12.2 (40)           |                 | gravel and sand |
| MW-68B          | 120000     | 6900       | nd (6200)  | nd (6200)  | nd (6200)   | 12.5 (41)           |                 | sand            |
| HS37-26         | 31         | 467        | nd (0.2)   | 8000       | 94          | 7.9 (26)            | 8.6 (28.1)      | sand mix        |
| MW-69A          | 17 J       | 1207.5     | nd (120)   | 370        | 5.9 J       | 8.3 (27.2)          |                 | sand            |
| HS38-26         | 98         | 3          | nd (0.2)   | nd (0.2)   | nd (0.2)    | 7.9(26)             | 7.1 (23.2)      | sand mix        |
| MW-70A          | 2000       | 54         | 7.7 J      | nd (120)   | nd (120)    | 8.4 (27.4)          |                 | sand            |
| HS38-36         | 58000      | nd (0.2)   | nd (0.2)   | nd (0.2)   | nd (0.2)    | 11 (36)             |                 | sand mix        |
| MW-70B          | 150000     | nd (12000) | nd (12000) | nd (12000) | nd (12000)  | 11.6 (38)           |                 | silt mix        |
| HS06-24         | 38         | 78         | nd (0.2)   | nd (0.2)   | nd (0.2)    | 7.3 (24)            | 0.9 (3.1)       | sand            |
| MW-71A          | 25         | 35.58      | nd (5)     | nd (5)     | nd (5)      | 7.6 (25)            |                 | sand            |
| HS06-39.5       | 1499       | 2767       | nd (0.2)   | nd (0.2)   | nd (0.2)    | 12 (39.5)           |                 | sand            |
| MW-71B          | 650        | 3000       | nd (250)   | nd (250)   | nd (250)    | 12.2 (40)           |                 | sand            |
| HS51-45         | 2          | 1          | nd (0.2)   | nd (0.2)   | nd (0.2)    | 13.7 (45)           | 21.5 (70.6)     | sand            |
| MW-72B          | nd (5)     | 1.3 J      | nd (5)     | nd (5)     | 3.4 J       | 14 (46)             |                 | sand mix        |
| HS35-24         | 5          | nd (0.2)   | nd (0.2)   | nd (0.2)   | nd (0.2)    | 7.3(24)             | 1.8 (5.8)       | silt mix        |
| MW-73A          | 3.4 J      | 0.34 J     | 0.28 J     | nd (5)     | 0.76 J      | 7 (23.1)            |                 | silt mix        |
| HS32-26         | 2          | nd (0.2)   | nd (0.2)   | nd (0.2)   | nd (0.2)    | 7.9 (26)            | 9.5 (31.2)      | sand            |
| MW-74A          | 2 J        | nd (5)     | 0.24 J     | nd (5)     | 0.41 J      | 8.8 (29)            |                 | sand            |

Note: Quantitation limit shown in parenthesis adjacent to nd, i.e. (0.2 µg/L)

TCE - trichloroethylene

PCE - tetrachloroethylene

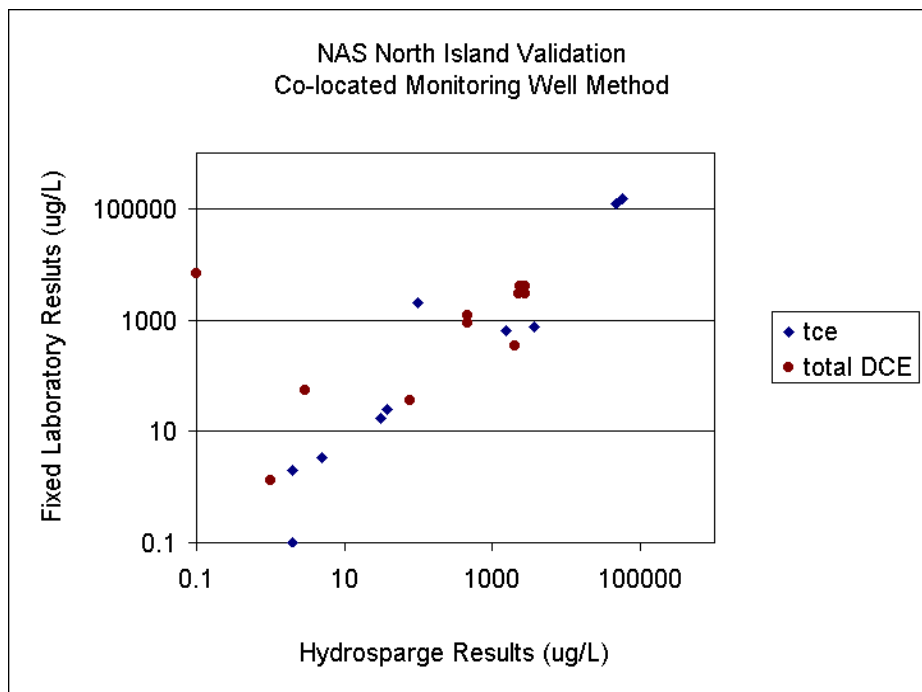
DCE - dichloroethylene

VC - vinyl chloride

BTEX - benzene, toluene, ethylbenzene, xylenes

Table 4 also shows the remarkable variability in the distribution of contamination. This is pointed out in the difference between the vinyl chloride concentrations in HS37-26 and MW-70A at 12.2 m (40 ft) BGS. The VC concentration of 8000 µg/L reported by Hydrosparge compares well with the split sample analysis result at 4400 µg/L (Table 3) while just 8.6 horizontal meters (28.1 ft) and 0.4 vertical meters (1.2 ft) away the concentration within the monitoring well was 370 µg/L. This dramatic difference may reveal a bias in sampling procedures or it might be caused by the slight lithology change separating the two measurements.

Figure 8 shows that the agreement between Hydrosparge results and the fixed-laboratory analysis of water samples from co-located wells is good, but not strong. However, when the differences in sample collection procedure are considered, the results obtained from the different methods are remarkably good despite a few individual variations.



**Figure 8. Comparison of Hydrosparge and Fixed Laboratory Analysis.**

The purpose of the demonstration was to verify that the Hydrosparge can expedite site characterization/screening. The results shown in Table 5 indicate that the Hydrosparge VOC sensor system performed on an overall basis approximately as well as monitoring wells and fixed-laboratory analysis for site screening purposes.

What Table 5 does not show is that of all locations chosen for validation, both Hydrosparge and Method 8260A indicated the presence of contamination.

The following quote summarizes Hydrosparge performance at NAS North Island, "...downgradient confirmation wells confirmed that the horizontal extent of the TCE plume above 40 ft BGS had been fully characterized" (OHM Remediation Services Corp. 1999).

#### **4.2 TIME TO CHARACTERIZE EXTENT OF GROUNDWATER CONTAMINATION**

It had taken the Navy nearly 8 years (from 1991 to 1997) to characterize the hydrocarbon plume using conventional groundwater monitoring wells. This is in contrast to the 22 days the Hydrosparge VOC sensor required to determine the extent of the shallow chlorinated hydrocarbon plume.

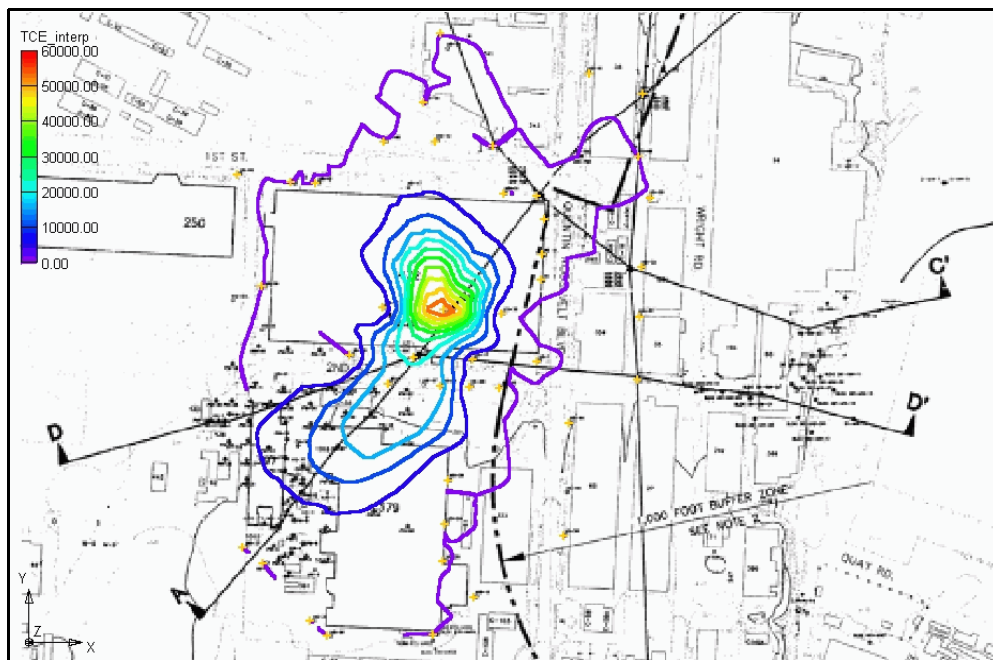
The major advantages of the Hydrosparge VOC sensor are the use of temporary well points and analyzing samples as they are collected. However, these advantages are of little use without having personnel committed to using the information in real-time as it is produced.

**Table 5. Hydrosparge vs. Fixed Laboratory Analysis Response.**

| Contaminants | Negative | Positive | False Positive | False Negative | False Negative <sup>1</sup> |
|--------------|----------|----------|----------------|----------------|-----------------------------|
| TCE          | 0        | 9        | 1              | 0              | 0                           |
| Total DCE    | 2        | 6        | 0              | 1              | 1                           |
| PCE          | 6        | 0        | 0              | 0              | 4                           |
| VC           | 9        | 1        | 0              | 0              | 0                           |
| BTEX         | 6        | 1        | 0              | 0              | 3                           |
| Totals       | 23       | 17       | 1              | 1              | 8                           |

<sup>1</sup> 8260A estimate value well below stated quantitation limit.

Having an analysis result before advancing to the next sample collection location allowed the field crew to make decisions regarding the importance and position of the next location. This allowed the investigation to be completed in an efficient manner so that the extent of contamination could be known before the crew left the site. An interpolation of all the TCE contamination at approximately -5 m (-17 ft) msl (Figure 9), was made available before the crew left the site. In fact, the daily analytical results were incorporated into this graphic presentation each day and the graphic was used to help decide on the location of the next sample collection point. The use of the dynamic work plan approach significantly reduced the time required to complete the project. The original work plan called for 80 push locations with three discrete chemical measurements at different depths. The time estimate required for the 240 penetrations was four weeks. The use of dynamic work plan reduced the number of locations to 50 and the number of discrete chemical measurements to 130. The Hydrosparge site characterization was completed in 22 days.



**Figure 9. TCE Contamination at -5 m (-17 ft) msl.**

### **4.3 RELIABILITY AND RUGGEDNESS**

There were no production delays caused by the ITMS or transfer lines. The only delays were caused by logistical constraints - clearance for the next sample location, striking an unmarked waterline, etc. One of the major requirements for the Hydrosparge VOC sensor to work properly was to have facility personnel ready to accommodate changes as the work proceeded. Since Hydrosparge ITMS results were available as samples were collected, onsite real-time decisions to modify the test plan were made to increase the efficiency and cost-effectiveness of the site characterization plan.

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## 5.0 COST ASSESSMENT

Costs associated with conventional monitoring well installation, groundwater sampling from monitoring wells, and offsite laboratory analysis are well known. The costs for conventional technologies were obtained from managers at each demonstration site. These costs were not always broken out in ways that could be related directly comparable to the HS VOC sensor technology. For comparison purposes, costs associated with 3 technologies (HS VOC sensor onsite analysis, conventional monitoring well installation and sampling with offsite analysis, and direct push monitoring well installation with offsite analysis) were itemized for a similar site characterization project consisting of ten 30-ft pushes and the analysis of 10 samples for VOCs. A comparison of each technology is summarized in Table 6.

When compared on a unit cost basis, the SCAPS HS VOC sensor with DSITMS shows a considerable cost saving to conventional groundwater monitoring methods. In addition, the HS VOC sensor has the advantage of real-time turn around. During several demonstrations, immediate sample turn around enabled the SCAPS crew to take additional samples to fill in gaps in the data set. Using conventional technology, the drill rig and sampling crew would have had to be resmobilized. This alone is a great cost savings that cannot be factored into costs on a per unit basis.

**Table 6. Comparison of Unit Costs for the HS VOC Sensor and Conventional Technologies.**

| SCAPS HS VOC Sensor in Situ Measurement       |                     | Conventional Monitoring Well Installation with Offsite Analysis |                               | Direct Push and Offsite Analysis                           |                     |
|---|---------------------|---|-------------------------------|--|---------------------|
| 10 pushes to 30 ft                            | Cost                | 10 wells to 30 ft (10 water samples for VOC analysis)           | Cost                          | 10 wells to 30 ft (10 water samples for VOC analysis)      | Cost                |
| 1 field day @ \$4,500/day                     | 4,500               | Well installation (300 ft @ \$30/ft) and sample collection      | \$13,000                      | Well installation (300 ft @ \$10/ft) and sample collection | \$8,000             |
| Analysis for 10 samples                       | Included in cost    | VOC Analysis for 10 samples @ \$200/sample                      | \$2,000                       | VOC analysis for 10 samples @ \$200/ sample                | \$2,000             |
| Geotechnical data for 1 sample/inch           | Included in cost    | Geotechnical analysis for 10 samples @ \$100/ sample            | \$1,000                       | Geotechnical analysis for 10 samples @ \$100/sample        | \$1,000             |
| 1 waste drum @ \$40/drum                      | \$40                | 28 waste drums @ \$40/ drum                                     | \$1,120                       | 1 waste drum @ \$40/ drum                                  | \$40                |
| Decon water testing                           | \$1,000             | Decon water testing   | \$1,000                       | Decon water testing  | \$1,000             |
| Waste soil testing                            | \$0                 | Waste soil testing  | \$3,000                       | Waste soil testing   | \$0                 |
| Waste soil disposal                           | \$0 (none produced) | Waste soil disposal for 20 drums @ \$100/drum                   | \$2,000                       | Waste soil disposal  | \$0 (none produced) |
| Decon water disposal for 1 drum @ \$100/ drum | \$100               | Decon water disposal for 8 drums @ \$100/drum                   | \$800                         | Decon water disposal for 1 drum @ \$100/ drum              | \$100               |
| 4 man crew                                    | Included in cost    | Geologist for 40 hr @ \$60/hr                                   | Geologist for 40 hr @ \$60/hr | Geologist for 24 hr @ \$60/hr                              | \$1,440             |
|   |                     | Technician for 40 hr @ \$40/hr                                  | \$1,600                       |  |                     |
| <b>TOTAL</b>                                  | <b>\$5,640</b>      | <b>TOTAL</b>  | <b>\$27,920</b>               | <b>TOTAL</b>   | <b>\$13,580</b>     |
| Unit cost per sample                          | \$564               | Unit cost per sample  | \$2,792                       | Unit cost per sample                                       | \$1,358             |

Note: To obtain meters, multiply feet by 0.3048.

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## APPENDIX A

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