ESTCP
Cost and Performance Report

(ER-200921)

Demonstration of the Gore Module for Passive Ground Water Sampling

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COST & PERFORMANCE REPORT
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ACRONYMS AND ABBREVIATIONS

%RSD	percent relative standard deviation
12DCA	1,2-dichloroethane
112TCA	1,1,2-trichloroethane
1122TetCA	1,1,2,2-tetrachloroethane
124TMB	1,2,4-trimethylbenzene
135TMB	1,3,5-trimethylbenzene
AFB	Air Force Base
AGI	Amplified Geochemical Imaging LLC
APG	Aberdeen Proving Ground
ASTM	ASTM International
bgs	below ground surface
BNZ	benzene
BP	bladder pump
BTEX	benzene, toluene, ethylbenzene, and xylene
CCl_4	carbon tetrachloride
cDCE	cis-1,2-dichloroethylene
CLB	chlorobenzene
CLF	chloroform
CRREL	Cold Regions Research and Engineering Laboratory
DoD	Department of Defense
DOE	Department of Energy
DP	direct push
DQO	data quality objective
EBNZ	ethylbenzene
ELAP	Environmental Laboratory Accreditation Program
ePTFE	expanded polytetrafluoroethylene
ERDC	U.S. Army Engineer Research and Development Center
ESTCP	Environmental Security Technology Certification Program
FAA	Federal Aviation Administration
FLRS	flight-line refueling system
GC/MS	gas chromatography/mass spectrometry
GCB	Geochemical Sciences Branch
GT	glacial till
HSE	Health and Safety Executive
IEC	International Electrotechnical Commission
IRP	Installation Restoration Program

ISO	International Organization for Standardization
ITRC	Interstate Technology and Regulatory Council
K_{OW}	octanol-water partition coefficient
LF	low flow
LNAPL	light non-aqueous phase liquid
LS	lower sand
LTM	long-term monitoring
µg/L	micrograms per liter
MCL	maximum contaminant level
MCS	marine clay and silt
MDL	method detection level
MS	matrix spike
MSD	matrix-spike duplicate
MTBE	methyl tert-butyl ether
NAPH	naphthalene
NELAC	National Environmental Laboratory Accreditation Conference
NH AGQS	New Hampshire Ambient Groundwater Quality Standards
O&M	Operations and Maintenance
OMB	White House's Office of Management and Budget
PCE	tetrachloroethylene
PDA	Pease Development Authority
PDB	passive diffusion bag
PE	polyethylene
PH2	Pump House 2
PI	Principal Investigator
PP	peristaltic pump
PTFE	polytetrafluoroethylene
PVC	polyvinyl chloride
QA	quality assurance
QC	quality control
RM-ANOVA	Repeated-Measure Analysis of Variance
ROD	Record of Decision
RSD	relative standard deviation
SBR	Southern Bush River
SVOC	semi-volatile organic compound

TCE	trichloroethylene
tDCE	trans-1,2-dichroloroethylene
TetCA	tetrachloroethane
TNT	trinitrotoluene
TOL	toluene
UNH	University of New Hampshire
US	upper sand
USEPA	U.S. Environmental Protection Agency
UST	underground storage tank
VC	vinyl chloride
VOC	volatile organic compounds
W.L. Gore	W.L. Gore & Associates, Inc.
XYL	total xylene

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

The objectives of this project were to determine if the GORE® Module, passive groundwater samplers, can provide: 1) technically defensible analytical data for volatile and semi-volatile organic compounds (VOC and SVOC) and 2) substantial cost savings when compared with conventional low-flow purging and sampling methodology. To achieve these objectives, the Gore Technology was compared with conventional low-flow purging and sampling at two test sites: the Southern Bush River section of Aberdeen Proving Ground (APG), MD, and the former Pease Air Force Base (AFB) in Portsmouth, NH.

TECHNOLOGY DESCRIPTION

At both sites, GORE Modules were placed at the same depth in the well as the pump or tubing used to collect the low-flow samples. Additional Modules were placed in most wells to allow the project team to profile analyte concentrations in the wells with depth. The wells were initially sampled with the GORE Modules (i.e., the pre-purge samples), low-flow samples were collected, and finally a second set of Modules were collected (i.e., the post-purge samples). Analytes at the APG site included several chlorinated VOCs: tetrachloroethylene (PCE), *cis*-1,2-dichloroethylene (cDCE), trichloroethylene (TCE), 1,1,2,2-tetrachloroethane (1122TetCA), and chloroform. VOCs and SVOCs at the former Pease site included: benzene, toluene, ethylbenzene, and xylene (BTEX), 1,2,4-trimethylbenzene (124TMB), 1,3,5-trimethylbenzene (135TMB), naphthalene, isopropylbenzene, and 2-methylnaphathalene.

DEMONSTRATION RESULTS

The analyses of field duplicate Modules revealed that this method provided good reproducibility in most instances. For three of the analytes (TCE, tetrachloroethene [TetCA], and benzene) at APG, 90% of the replicate samples had a relative standard deviation (RSD) that was 20% or less. For the remaining analytes (PCE, cDCE, and chloroform), at least 70% of the duplicate pairs had a similar RSD. In instances when there was poor reproducibility, the project team observed that this primarily occurred in a few wells after purging and where the upper portion of the screen was near the water table.

At the Pease site, reproducibility was very good for almost all of the analytes, and 80% of the duplicate pairs had a RSD that was 20% or less. For three other analytes (benzene, ethylbenzene, and the xylenes), at least 60% of the sample pairs had a similar RSD. The poorest reproducibility was with toluene. In instances where the reproducibility was poor, it was observed that this could be attributed to sampling three wells where the samplers had been left in the well for more than 2 hours and the depth below the water table for the samplers was at least 40 feet. It may be that leaving the samplers for more than 2 hours is too long a contact time especially given the sampling depth.

At APG, 10 percent of the samplers were also analyzed by an independent contract laboratory using the same analytical method used by the Gore Laboratory. There was excellent agreement

between the analyte concentrations of the replicate samples analyzed by the two different laboratories for all the analytes that were compared.

With respect to the sensitivity of the sampling method, the GORE Modules at the Aberdeen site provided data that was below the action level, i.e., the U.S. Environmental Protection Agency's (USEPA) maximum contaminant level (MCL) for drinking water (USEPA, 2011). However, the detection capability of the low-flow method was one twentieth of that for the GORE Modules. Because some agencies require or recommend lower quantitation limits, we recommended to the manufacturer that they continue work to develop a lower detection capability (i.e., prior to our next field trial).

Subsequently, at the Pease site, the detection capability for the Gore method was comparable to that for the low-flow samples for most of the analytes (e.g., BTEX, 124TMB, 135TMB, and naphthalene). For the remaining analytes (*n*-butylbenzene, *n*-propylbenzene, isopropyltoluene, isopropylbenzene, TCE, and 1,2-dibromoethane), the MDLs were higher for the GORE Modules than they were for the low-flow samples. However, in all cases, the MDLs were below *one tenth* of the USEPA's MCLs.

Also at the Pease site, the project team found that in many instances low concentrations of contaminants were detected when using the GORE Modules but not when low-flow sampling was used, even though these concentrations were well above the detection capability of the analytical method used for the low-flow samples. It is believed these data reflect enhanced sensitivity of the GORE method and recommend that this difference should be examined further.

The data for the mid-level samplers and the data for the mean concentrations for the three samplers (at three depths) were compared with the data for the low-flow samples for each of the analytes. At both sites and in all cases but one, there was a statistically significant linear relationship between the Gore data and the low-flow data. This relationship was typically one to one (i.e., the slope of the line was not significantly different from 1.0). The exceptions to a one-to-one relationship were TetCA and chloroform (mid-level data only) at APG and benzene and toluene at the Pease site.

Although there was generally good agreement between the Gore data and the low-flow data, plots of the GORE Modules with depth showed that there was substantial stratification of some contaminants with depth in some of the wells at both sites. This was especially true for the wells near a contaminant source. At APG, pronounced stratification of VOC was observed in a shallow well with a short (5-feet) screen; analyte concentrations were up to 50 times higher in the upper Module than in the lowest.

IMPLEMENTATION ISSUES

With respect to where to place passive samplers within the well screen, there was good agreement between the mid-level sampler and the low-flow concentrations for some wells and thus placement of the sampler at the mid-point of the well screen would be advisable. However, in other instances, purging brought water into the well from a more permeable upper or lower zone and thus low-flow analyte concentrations agreed best with the upper or bottom sampler. While the mid-level sampler did not always best represent analyte concentrations obtained by

low-flow sampling, the opposite is also true where low-flow sampling did not always collect the highest concentrations of contaminants in the wells and this is important to regulators.

The field crew found that the Modules were easy to use and did not require any special training. The project team also found that this sampling method was not time consuming; required very little auxiliary equipment or clean up; and there were less concerns with sample handling and safety. The project team does not foresee any scale-up constraints that would prevent wide-scale use of this technology. These samplers can be used in any well or piezometer that is larger than 0.25 inches in diameter.

The long-term monitoring costs were determined for each sampling method for 10 years using the initial startup costs, annual field sampling costs, annual sample processing and analyses costs, and the estimated operations and maintenance costs over the 10-year period. Based upon those numbers, the estimated cost savings were determined for the Gore sampling method. For the GORE Modules, it was determined that 99.75% of the total 10-year long-term monitoring (LTM) cost is associated with sample collection, and 85% of that cost is the price of the samplers (labor is the other 15%). For low-flow sampling, sample collection accounts for 45% of the total LTM costs, and of that amount 93% is labor. Laboratory analyses account for another ~ 25% of the total LTM costs, and the start-up costs (including dedicated pumps and the equipment for measuring purge parameters) account for less than 10% of the total LTM costs. Although it was determined that the estimated cost was lower with the GORE Modules, the degree of the cost savings depends heavily on the price of the samplers. As an example, cost savings of ~ 30 to 45% can be achieved if the price of the Modules is ~ $190 per sampler.

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1.0 INTRODUCTION

1.1 BACKGROUND

Passive sampling methods are based on the concept that water within the open interval of a well is continuously refreshed by the continuous natural flow of groundwater through the well screen (Robin and Gillham, 1987; Powell and Puls, 1993). Several studies (Vroblesky and Peters, 2000; Vroblesky and Petkewich, 2000; Vroblesky, 2001; Parker and Clark, 2004) have shown that the polyethylene diffusion bag (PDB) samplers can provide quality data and equivalent analyte concentrations of most volatile organic compounds (VOC) when compared with the conventional low-flow purging and sampling method. Findings from other studies conducted using the Snap Sampler (Parker and Mulherin, 2007; Parker et al., 2009, 2011a, and 2011b) and the regenerated-cellulose membrane (or dialysis membrane) sampler (Imbrigiotta et al., 2007; Imbrigiotta and Trotsky, 2011a, and 2011b) also yielded quality data and comparable analyte concentrations with low-flow sampling method for a variety of inorganic and organic analytes in most instances. Where the use of passive sampling is appropriate, data-quality improvements can also include better delineation of contamination with depth within the screened zone such as shown by Vroblesky and Peters (2000), Vroblesky and Petkewich (2000), and Vroblesky et al. (2003).

Although the improvements and potential cost savings associated with passive sampling are significant, many passive sampling devices currently being used have limitations. For example, the PDB sampler can be used only for (selected) VOCs, and other devices such as the Snap Sampler cannot be used in smaller diameter wells such as many of the smaller direct-push (DP) wells. Like the PDB Sampler, the GORE® Module is easy to use and requires minimal labor to obtain a sample. However, this sampler can be used for a broader range of organic compounds than the PDB sampler and can be used in smaller diameter wells and piezometers.

Unfortunately, the applicability of the GORE Module technology has not been demonstrated for sampling groundwater following recent changes in the design and use of this technology. An independent third party evaluation, would promote greater acceptance of this technology. Anticipated benefits for the Department of Defense (DoD) and the Department of Energy (DOE) associated with using this sampler could include substantially reduced costs for long-term monitoring (LTM) and better plume delineation, which can result in more effective and less costly remediation.

1.2 OBJECTIVES OF THE DEMONSTRATION

The objectives of this demonstration were to determine the utility, sensitivity, comparability, and potential cost savings of passive groundwater sampling of VOCs and semi-volatile organic compounds (SVOC) using the GORE Modules when compared with conventional low-flow purging and sampling methods. Data-quality objectives included equivalent or better plume delineation with the Gore Modules and reproducible data. Qualitative objectives included that the sampler was easy to use, was technically robust, and that there were not any scale-up constraints.

To meet these objectives, sampling was conducted at two sites: the Southern Bush River (SBR) Area of the Edgewood Area of Aberdeen Proving Ground (APG), Maryland and at the former Pease Air Force Base (AFB), Portsmouth, New Hampshire. Samples were collected from the same wells using GORE Modules and the U.S. Environmental Protection Agency's (USEPA) low-flow purging and sampling protocol (USEPA Region 1, 1996). Analytes at the SBR site included five chlorinated VOCs. The primary contaminants at the former Pease AFB were hydrocarbons including VOCs and some SVOCs (including naphthalene and methylnaphthalene).

The Gore Modules were deployed at the same depth as the inlet of the pump or tubing used to collect low-flow samples and when possible (i.e., in wells with longer screens), they were also deployed half way between the top of the screen and the midpoint and half way between the bottom of the screen and the mid-point. This allowed us to observe the contaminant stratification in the well under ambient flow conditions.

1.3 REGULATORY DRIVERS

The most commonly accepted and practiced method for sampling a groundwater monitoring well is to use a low-flow purging and sampling method that was first outlined by Puls and Barcelona (1996) and subsequently formalized by USEPA Region 1 (1996), Nielsen and Nielsen (2002), ASTM International (ASTM) (2003a), and several others. However, low-flow sampling requires substantial investment in equipment (preferably dedicated pumps or tubing, field parameter monitoring equipment, etc.), is relatively time consuming, and costly. Therefore, finding a sampling method that is less labor-intensive and costly but able to yield quality (or perhaps better quality) data is clearly desirable.

Also, alternatives to low-flow sampling are desirable from a data-quality perspective. Typically, low-flow sampling collects a sample that is mixed as a result of flow-weighted averaging of inflow along part or all of the length of the well screen. However, this approach tends to pull samples from the more transmissive parts of the formation, which may not be where the highest concentrations of the analytes are contained. In contrast, passive sampling collects samples under ambient flow conditions and can provide vertical profiles of contamination in some wells and presumably the formation.

The primary driver for conducting this demonstration has been the lack of third-party verification of the GORE Module technology.

2.0 TECHNOLOGY

2.1 TECHNOLOGY DESCRIPTION

The GORE® Module is a passive sampler that W. L. Gore & Associates, Inc. (W.L. Gore) (Elkton, Maryland) developed to sample air and water for a variety of VOCs and SVOCs. Recently, this technology was acquired by Amplified Geochemical Imaging LLC (AGI) (Elkton, Maryland), and the sampler is now known as the AGI Universal Passive Sampler. However, because this transition occurred after this work was completed, the text will continue to refer to these samplers as GORE Modules or simply as Modules.

The Module consists of a GORE-TEX® membrane tube approximately 1 foot in length and ¼ inch in diameter (Figure 1). This membrane is expanded polytetrafluoroethylene (ePTFE) and is chemically-inert, vapor-permeable, and waterproof. Housed inside the membrane tubing are several packets of hydrophobic sorbents that have an affinity for a broad range of VOCs and SVOCs. Each sampler has its own unique serial number provided by the manufacturer and comes in a vial with the same serial number.

Figure 1. Photos of the GORE Module.
(Courtesy of W. L. Gore)

To collect a sample, the analyte must first partition to the vapor phase. Once in the vapor phase, the molecule can then diffuse through the membrane while liquid water is prevented from passing through the (waterproof) membrane (as shown in Figure 2). Once the analyte passes through the membrane, it is then sorbed by the adsorbent contained in the sampler. The sampler can be deployed in unsaturated and saturated soils, sediments, air, and water.

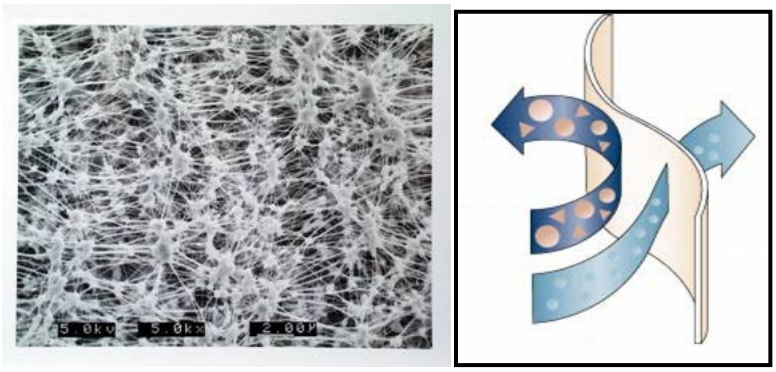

Figure 2. Enlargement of the pores in the GORE-TEX membrane (left) and a schematic representation of vapors diffusing through the membrane (right).
(Courtesy of W. L. Gore)

In groundwater monitoring wells, the sampler is deployed by tying it to a line of the desired length (for the sampling depth), placing weights on the end of the string, and lowering it into the well. Typical deployment times range from 15 minutes to 2 hours. Depending upon the flow dynamics in the well, high-resolution vertical profiling can be achieved in some cases by simply placing the Modules at multiple sampling depths.

After recovering the Modules from the well, they are returned to their respective coded sample vials and shipped to the Gore laboratory. Analyses are by thermal desorption gas chromatography/mass spectrometry (GC/MS) using either USEPA SW-846 Method 8260C for VOCs or 8270 for SVOCs that has been modified for thermal desorption. The mass of each analyte desorbed can also be converted to concentration values for those customers that need this information.

2.1.1 Technology Development

The GORE Modules have been commercially available for more than 15 years. While the original (and continued) application of this sampler was for soil gas and air sampling for site assessment programs, these samplers have also been used in vapor intrusion investigations, sediment porewater sampling, remediation monitoring, pipeline integrity testing, and surface-water and groundwater sampling.

The USEPA (Einfeld and Koglin, 2000) conducted a verification study on the performance of the GORE Module for sampling groundwater. The Modules were first tested in a 5-feet diameter, 100-feet tall standpipe containing a test solution of six VOCs. In the first trial, concentrations were relatively low (~ 20 micrograms per liter [µg/L]). In the second trial, the samplers were tested in a test solution with higher concentrations (~ 200 µg/L) that varied with depth. The samplers were left in place for 48 hours. Control samples were collected from the sampling ports on the side of the standpipe. At the 14-feet depth, the percent relative standard deviation (%RSD) for the target VOCs were comparable to that seen for the control samples (~ 2 to 17 %RSD). However, at the 28-feet depth, the precision was considerably poorer; the %RSD ranged from ~ 12 to 28%.

In the same study, these samplers were also deployed in five monitoring wells containing TCE contamination. Reference samples were collected at 12-hour intervals throughout the 48-hour exposure period using a co-located (dedicated) submersible pump. (Samples were collected in 12-hour intervals so that a time-weighted average concentration could be determined for the pumped samples.) Plotted results indicated good linearity across nearly three orders of magnitude for the Module data when compared with the pumped data for both Module types. However, the precision for the Modules was poor, with RSDs ranging from ~10 to 65%. The researchers had previously noted that water had penetrated the membrane on two occasions yielding spurious data. They concluded that the sampler had limited versatility in terms of deployment depths.

Prior to our conducting this study, the manufacturer substantially shortened the deployment time from what had been used in the previous study. The new deployment times were between 15 minutes and 4 hours. According to the Gore chemists, this substantially shorter deployment time reduces issues with water intrusion at deeper sampling depths.

While the company claims that they have successfully used these samplers at depths that are 1000-1200 feet below ground surface (bgs) and where the water levels were ~ 550-750 feet bgs, the Gore chemists noted that in instances where the deployment depth below the water table exceeds 32 feet, concentrations for analytes with higher aqueous solubility and lower Henry's law are biased low (Anderson, 2013; W.L. Gore, personal communication). In this instance, methyl tert-butyl ether (MTBE) is lost entirely and 1,2-dichloroethane (12DCA), 1,1,2-trichloroethane (112TCA), and 1,1,2,2-tetrachloroethane (1122TetCA) are biased low by about 40% (Anderson, 2013; W.L. Gore, personal communication). Where possible, these losses have been addressed by modifying the physically-based model that was developed by the Gore Chemists to calculate groundwater concentrations. This algorithm incorporates the uptake rate of the analytes from aqueous solution by the Module (determined in the laboratory), water temperature, and water pressure. The foundation for this model mirrors accepted ASTM methodology used to report concentration data in air from passive, sorbent-based samplers (ASTM, 2003b, 2008; Health and Safety Executive [HSE], 1995). This model is discussed in more detail in Parker et al. (2014).

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY

Reported advantages associated with using the GORE Module include: ability to sample for a broad range of VOCs and SVOCs; minimal training is needed to use the sampler; and installation is quick and easy. The ease of use minimizes the costs associated with collecting a sample. In addition, there is no power required to use this sampler and there is no purge water generated; this also reduces the logistical burdens and cost of this sampling method. Another advantage is that there is no minimum volume constraint associated with the Module other than the sampler must remain fully submerged during deployment; this is especially an advantage when having to sample wells with low recharge rates. Multiple Modules can be used to sample multiple depths within the well, and this can provide additional information on contaminant concentrations in the formation with depth. These samplers can be deployed in any well or piezometer with a diameter greater than ¼ inch. Also, the samplers do not require low-temperature storage before or after sample collection including during shipping or when stored in the laboratory. This reduces the logistics and costs associated with shipping coolers full of ice or blue ice to the laboratory.

One limitation associated with using the GORE Module is that, like all no-purge sampling methods, it relies on the assumption that there is continuous natural flow through the well screen that is representative of the aquifer. However, the primary limitation with these samplers, especially for some regulators, is that the concentration of contaminants in the groundwater is not measured directly but must be calculated from the mass sorbed by the sampler using an experimentally derived algorithm. The concern is that analyte concentrations may not be comparable to those obtained by the low-flow purging and sampling method. The plan is that this demonstration will address these concerns.

2.2.1 Other Commonly Used Passive Groundwater Sampling Technologies

Depending upon the analytes of interest, there are a number of other passive groundwater sampling methods that can be used to collect groundwater samples. These methods vary in the degree of development; many have been used in research studies, others are better known, and many are commercially available and are discussed below.

If only VOCs are the target analytes, then the Passive Diffusion Bag Sampler can be used for most analytes; exceptions include ketones and MTBE. This sampler provides a time-integrated concentration over the time the sampler is in the well (which is most heavily weighted on the last few days the sampler is in the well). The Regenerated Cellulose (or Dialysis) Membrane Diffusion Sampler can collect samples for a broader range of dissolved organics including several SVOCs (i.e., energetics such as trinitrotoluene [TNT]) and for dissolved inorganics (including metals). This sampler also provides time-weighted average concentrations. However, the cellulose membrane in this sampler can undergo biodegradation and this limits the length of time this sampler can be deployed in a well. Thus, two trips to the field are needed; one to deploy the sampler, and one to recover it. (As compared to other passive samplers that can be deployed at the conclusion of a sampling event and left in the well until the next sampling event.) In addition, this sampler is not commercially available and therefore must be fabricated in a lab or clean environment. The Snap Sampler can be used to collect a broad range of organic and inorganic analytes but will not fit in smaller diameter wells. The HydraSleeve sampler can be used to collect a broad range of organic and inorganic analytes and is considered by some groups to be a passive sampler (Interstate Technology and Regulatory Council [ITRC], 2006, 2007). However, it is not clear to us whether this sampler recovers a discrete sample from a given depth within the well screen, or whether in some instances the sample is collected from the casing above the well screen.

While these are some of the better known passive samplers, individuals interested in additional information on these and other passive sampling methods are recommended to consult documents by the ITRC Diffusion/Passive Sampling Team (Vroblesky, 2001; ITRC, 2004, 2006, and 2007) Additional information on passive sampling methods other than those mentioned in the ITRC documents can be found in review papers by Kot et al. (2000), Mayer et al. (2003), Petty et al. (2004), Namieśnik et al. (2005), Vrana et al. (2005), Stuer-Lauridsen (2005), Seethapathy et al. (2008), Söderström et al. (2008), and Verreydt et al. (2010).

3.0 PERFORMANCE OBJECTIVES

The performance criteria used to evaluate the GORE Modules focused on the data quality (including the sensitivity and reproducibility of the method) and the comparability of the method when compared with low-flow purging and sampling. Also, the utility and the potential cost savings of the method were determined. Cost savings were based upon the cost of this method compared with the cost of low-flow purging and sampling. Table 1 summarizes the performance objectives used, as well as the data requirements, the success criteria, and findings.

Table 1. Performance objectives.

Performance Objective	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
Equivalent or better plume delineation with GORE Modules vs. low-flow sampling	Concentration data for both sampling methods, with depth for GORE Modules	Equivalent or lower analyte sensitivity	APG site: • The MDL for GORE method was below the MCL. However, it was ~20 times greater than the low-flow MCL. Pease site: • For most analytes, equivalent MDLs with low-flow sampling. • GORE MDLs were 1/10 of the USEPA's MCLs. • In many instances, low concentrations were detected with the Modules (with good reproducibly) but not with low-flow sampling.
		One-to-one linear relationship between the Gore and low-flow data	At both sites: • Statistically significant linear relationship between the GORE and low-flow data, typically with a slope of 1.0. • Instances where the slope was not 1.0 were TetCA and CLF at the APG site and TOL at the Pease site. Revision of the algorithm for these analytes may be able to correct this.
		Statistical tests of data reveal no significant difference between sampling methods	APG site: • Significant differences for several analytes. However, results generally agree with tests that determined whether the slope of the line was equivalent to one. Pease site: • Generally no significant differences; poorest agreement was with BNZ and XYL.
		Vertical profile of wells with GORE Modules	• Vertical profiles found at both sites. • Pronounced concentration gradients in wells near plume epicenters, even in a well with a 5 foot screen. • Mid-level Modules did not always yield best agreement with low-flow data. • Highest concentrations of contaminants not always found in mid-level sample.

Table 1. Performance objectives (continued).

Performance Objective	Data Requirements	Success Criteria	Results
Reproducible data	Replicate samples	A relative standard deviation (RSD) of 20% (or less)	APG site: • Generally good (70% to 90%) agreement for most analytes (i.e., RSD <20%); agreement poorest in three shallow wells. Pease site: • Generally good agreement; agreement poorest for three wells where Module depth was more than 40 feet or more below water table and contact time was 2 hours or more.
	Analyses by independent laboratory	No significant difference between concentrations found using two sampling methods	APG site: • Excellent agreement between labs for all analytes, except possibly pentadecane. • No data collected at the Pease site.
Reduced sampling cost	Records of sampling time, equipment costs, waste disposal, and other costs associated with both sampling methods	A minimum of a 20% cost savings	APG site: • Cost savings of 18% to 35%, depending upon the size of field crew. Pease site: • Cost savings of 10% to 25%, depending on size of field crew. For both sites: • Cost savings heavily dependent upon cost of Modules. • Cost savings of 30% to 40% using newer price quote for Modules.
Qualitative Performance Objectives			
Ease of use	Feedback from field crew on usability of technology, time required to train an individual in its use.	• Samples are easy to collect • Samplers work as described • One person can conduct the sampling • Minimal training required	• Samples were easy to collect. • Samplers worked as described. • Only one person was needed to collect these samples. • No special training was needed.
Technology Robustness	Written records during sampling	No issues with the strength, sampling depth (below water table), or durability of samplers	• No issues with strength or durability of samplers. • There may be an issue with water intrusion for samplers left in well more than 2 hours when samplers are >30 feet below the water table.
Scale -up constraints	Observation of issues that would limit or require modification for large scale use	Lack of significant issues preventing large scale use of GORE Module	• There were not any significant issues that would prevent large-scale use of the GORE Modules.

3.1 COMPARABILITY OF THE GORE MODULES AND LOW-FLOW SAMPLING

To determine the comparability of the data, analyte concentrations in samples collected using low-flow sampling and those derived from using the GORE Modules were compared. Linear regression using a least-squares method was used to determine if there was a statistically significant relationship between the Gore data and the low-flow data, and if the relationship was one to one. One of the requirements for success included a one to one relationship between the analyte concentrations in samples collected with the GORE Modules and the low-flow samples, and that the sensitivity of the Gore method was similar to or better than low-flow sampling. Statistical analyses that compared the results from the passive samplers with those from low-flow sampling using a Repeated Measure Analysis of Variance (RM-ANOVA) test (or when needed, a non-parametric equivalent test) were also conducted. Those findings generally support the findings from examining the linearity of the data (i.e., whether the slope of the line was equivalent to 1.0) are not discussed here but can be found in Parker et al. (2014).

When comparing a passive sampling method with an active sampling method, such as low-flow sampling, it is important to understand the conceptual differences of each technology because the mechanism used to collect the sample is different and the data may not always agree. Low-flow purging and sampling yields water that is mixed over the length of the well screen. The degree of mixing is a function of the hydrogeology of the formation (especially for the portion of the formation adjacent to the well screen), the permeability of the filter pack materials, the mesh size and length of the well screen, and the pumping rate. Purging the well until the purge parameters stabilize is designed to pull water from the aquifer into the well and thus allow collection of a fresh sample, as opposed to collecting water from the stagnant casing.

In contrast, passive samplers, such as the GORE Modules, sample the water in the well screen and rely on water flowing through the screen to provide fresh water. Flow through the well screen may be horizontal and laminar or there may be mixing in the well bore and screen. Under ambient conditions, the degree of mixing in the well and well bore is a function of the hydrogeology of the formation where the well screen is located (especially the permeability of any and all zones), well construction (including the size and length of the well screen and filter pack materials), contaminant concentration differences (in water coming from different strata or within the well), and temperature differences (in water coming from different strata or within the well). Therefore, the GORE Module data can reflect stratification of contaminants with depth within the well screen; whereas the low-flow samples reflect a concentration value that results from the mixing that has occurred with purging. Although, in some cases, the pumping rate may be such that most of the water collected is from the most permeable zone.

Therefore, where possible, additional Modules were deployed at three depths within the wells and this concentration data was compared with the low-flow data. This allowed us to examine the differences between the passive and sampling methods with depth in the well and to visualize contaminant stratification in the wells.

3.2 REPRODUCIBILITY OF THE GORE METHOD

Another primary objective for this demonstration was that the GORE Module technology provides data with good precision. For each analyte with detectable concentrations, the following

measure of success was used. For concentrations that were three times the detection limit or more, the RSD for the Gore data should be 20 % or less. For each analyte, the percentage of wells that met this goal was then determined.

Also, replicate samples were collected for 10% of the GORE Modules that were collected at the first test site; these samples were sent to an independent contract laboratory for analyses. Statistical analyses were used to determine if there was a significant difference between the values determined by the Gore and MRI laboratories, whether a linear relationship existed and if the relationship between the two methods was one to one.

3.3 COST SAVINGS

Another important criterion was that this sampling method be less costly than low-flow sampling. This was achieved by determining the costs associated with each of these methods. The cost comparison was based upon the field crew's time, which included sample site cleanup and waste disposal, the cost of the equipment, and the cost of analyses. The cost of the analyses was included in these analyses because it wasn't the same for the two sampling methods; the price of the analyses of the GORE Modules is included in the purchase price. A minimum cost savings of 20% was set as the goal.

3.4 OTHER SUBJECTIVE MEASURES

Other subjective criteria for measuring the success of this sampling method included ease of use, durability, and minimal training. To determine success, any problems associated with using these samplers were documented, user acceptance was noted, and the time needed for training was recorded. Also, the sampler should work as designed, even at depths more than 30 feet below the water table where problems have been encountered in the past. Finally, there should not be any significant scale-up constraints that would prevent wide-scale use of this technology.

4.0 SITE DESCRIPTIONS

4.1 FIRST TEST SITE LOCATION: ABERDEEN PROVING GROUND, MD

Our first test site was the SBR area of the Edgewood section of APG, MD (Figure 3).

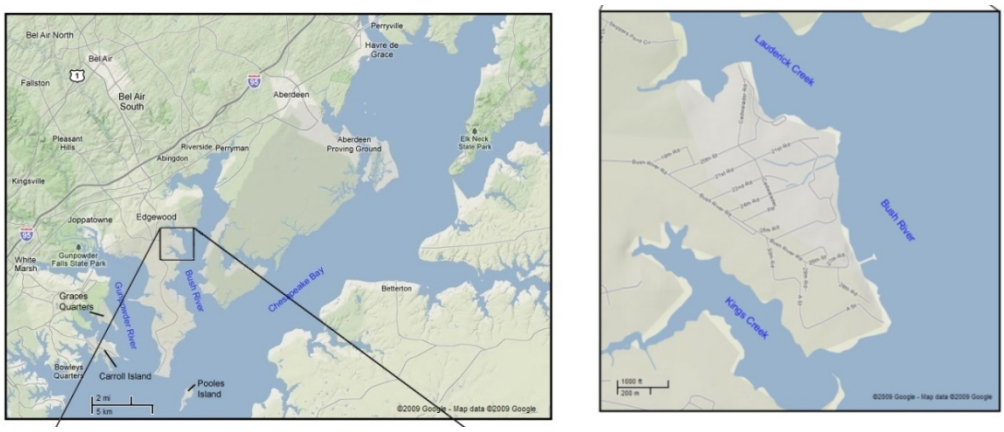

Figure 3. Location of the SBR site on APG, Maryland.

APG is located in the headwaters of the Chesapeake Bay and lies on two peninsulas separated by the Bush River. The northeastern section of APG is known as the Aberdeen Area and the southwestern section is referred to as the Edgewood Area and was formerly known as the Edgewood Arsenal.

The Edgewood Arsenal was used for the development and testing of chemical agent munitions. From 1917 to the present, this area has been used to conduct chemical research programs that have included the manufacture, storage, testing, and disposal of chemical agents and other toxic materials. The SBR Area is located on a peninsula that is bounded by the Bush River to the east and south, and Kings Creek to the southwest (Figure 3). The area has been designated for industrial land use and is listed as a Superfund site.

4.1.1 Site Geology/Hydrogeology

The SBR area is characterized by thick, wedge-shaped deposits of unconsolidated Coastal Plain sediments that dip southeastward while resting over an unconformity of older crystalline rocks of the Piedmont Physiographic Province (Owens, 1969; Lorah and Clark, 1996). The hydrogeology of the area consists of the surficial aquifer, the upper confining unit, the Canal Creek Aquifer, the lower confining unit, and the lower confined aquifer (Figure 4).

The surficial aquifer consists primarily of sediments of the Talbot Formation. The lithology of this unit consists of both sands and gravels as well as areas of silts and clays and is highly variable due to disturbances from excavation and land-fill activities (Lorah and Clark, 1996). Paleochannels of various sizes and orientations have been mapped throughout the SBR Peninsula (Davies et al., 1995).

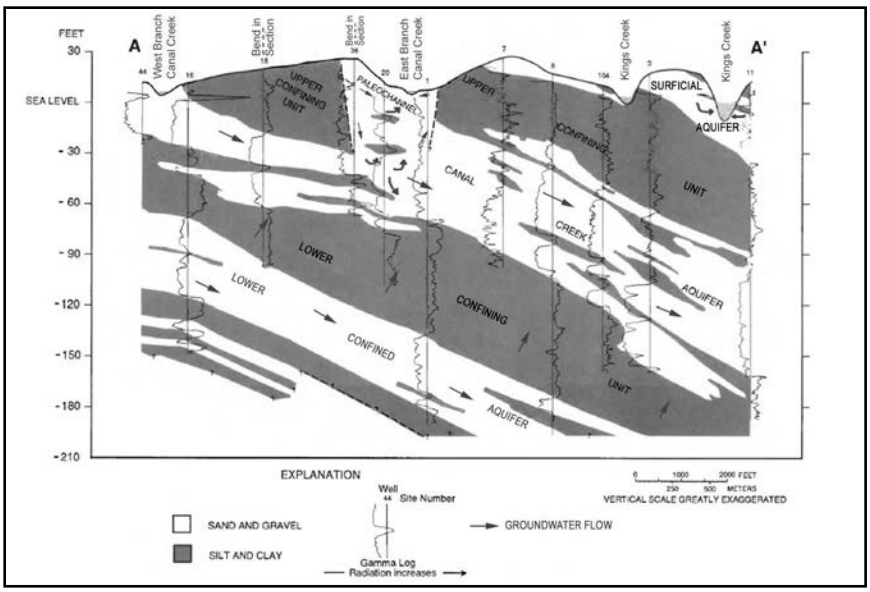

Figure 4. Cross-section of the SBR Area.
(Taken from Oliveros and Vroblesky [1989] as modified by Lorah and Clark [1996]).

The underlying upper confining unit, Canal Creek Aquifer, lower confining unit and the lower confined aquifer are all composed of Cretaceous Potomac Group sediments (Oliveros and Vroblesky, 1989; Lorah and Clark, 1996) (Figure 4). Both the aquifers and confining units contain laterally non-continuous beds as well as variations in thickness common for fluvial deposits. The upper confining unit outcrops in the western portion of the study area. The Canal Creek aquifer ranges from 30 to 70 feet thick in the Canal Creek area (Lorah and Clark, 1996). The lower confined aquifer underlies the approximately 60-feet thick lower confining unit.

The surficial aquifer is recharged from infiltration of both precipitation and surface water as well as from upward flow from the underlying Canal Creek aquifer. The surficial aquifer discharges to surface water, leaky sewers and storm drains as well as the underlying Canal Creek aquifer (Lorah and Clark, 1996). Groundwater flow in the Canal Creek aquifer is generally from the northwest-to-southeast. Overall, groundwater flow directions in the three aquifers do not differ significantly in the study area as a result of seasonal fluctuations (Lorah and Clark, 1996).

4.1.2 Contaminant Distribution

Chlorinated VOCs are considered the primary groundwater contaminants in the SBR and Canal Creek areas although, some inorganic and other types of organic compounds are also present in the area (Lorah and Clark, 1996). Contamination in the Canal Creek area to the west of the SBR area is present in both upper surficial and underlying Canal Creek aquifer where they are not hydraulically separated by the upper confining unit. Studies have shown that the major contaminant has been 1122TetCA. Other VOCs included carbon tetrachloride (CCl_4), tetrachloroethylene (PCE), CLF, trichloroethylene (TCE), trans-1,2-dichroloroethylene (tDCE), 112TCA, 12DCA, vinyl chloride (VC), BNZ, chlorobenzene (CLB), and XYLs (Lorah and Vroblesky, 1989; Lorah and Clark, 1996). Figure 5 shows the location of two 1122TetCA plumes in the upper surficial aquifer in 2009.

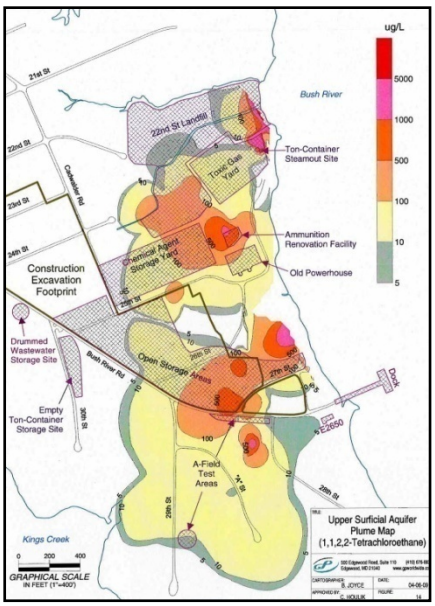

Figure 5. Map showing location of 1122TetCA plumes in the Upper Surficial Aquifer.
(General Physics, 2009)

4.2 SECOND SITE LOCATION: FORMER PEASE AFB, NH

4.2.1 Site Location and History

The former Pease AFB is located on a peninsula in southeastern New Hampshire in the town of Newington and the City of Portsmouth. The former AFB occupies approximately 4,365 acres and is bounded on the west and southwest by Great Bay, on the northwest by Little Bay, and on the north and northeast by the Piscataqua River (Figure 6).

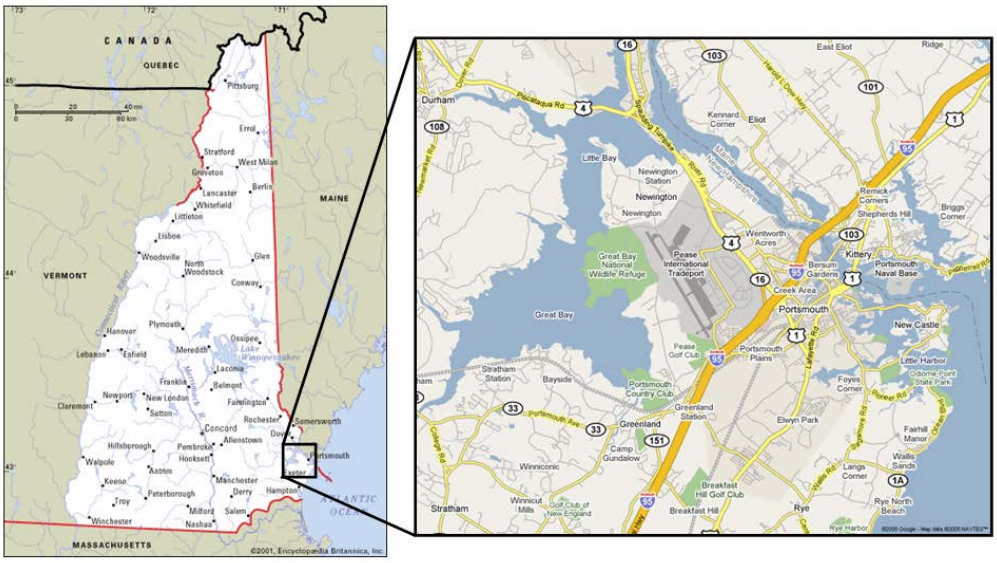

Figure 6. Location of the former Pease AFB.

At the beginning of World War II, the airport was used by the U.S. Navy, and in 1951 the U.S. Air Force assumed control of the site. Over time various quantities of fuels, oils, lubricants,

solvents, and protective coatings were used, and as a result of these activities, contaminants from these substances were released into the environment.

The base remained active until it was closed in 1991, and the Air Force transferred most of the property to the Pease Development Authority (PDA). The airfield is now a commercial airport and other portions of the PDA property are being used for light commercial and industrial facilities and as a national wildlife refuge. The Air Force retained 229 acres for use by the New Hampshire Air National Guard.

The Department of Defense's Installation Restoration Program (IRP) established eight IRP zones in 1991. Eleven Record of Decisions (ROD) (representing all the major Superfund cleanup decisions) were completed between 1993 and 1997, and initial remedial design and construction activities for the base were completed (MWH Americas, Inc., 2004). Operation and maintenance (O&M) and LTM activities with modifications to the remedial activities have been on-going.

The monitoring wells selected for this demonstration are located in the flight-line area of Zone 3. The flight-line area includes the runway, aircraft parking apron, and the grassy infield between the parking apron and the runway. The flight-line area is a major feature of the base and comprises nearly ⅓ of this 440-acre zone.

The U.S. Air Force is currently conducting remedial action activities associated with the Underground Storage Tank (UST) Program on the flight-line. A total of 72 petroleum hydrocarbon plumes have been identified in association with the flight-line refueling system (FLRS). The FLRS was designed to deliver aircraft fuel from large above-ground tanks at the bulk fuel storage area to the pump house USTs along the flight line. The system also included hydrant laterals and pump houses used to collect fuel from aircraft defueling operations.

For this demonstration, we sampled the Pump-House 2 (PH2) site, which consists of plumes 6, 7, 8, and 9 and their periphery (Figure 7). This site consists of a pump house, USTs, a collection storage tank, and hydrant laterals.

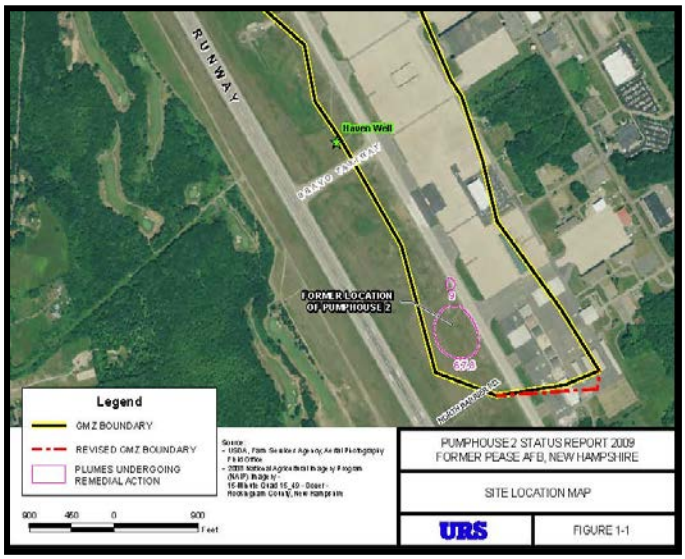

Figure 7. Flight-line area of Zone 3 showing plumes 6, 7, 8, and 9.

4.2.2 Site Geology/Hydrogeology

The shallow subsurface beneath Zone 3 consists of four unconsolidated lithologic units: upper sand (US), Marine Clay and Silt (MCS), lower sand (LS), and glacial till (GT). The bedrock underlying these lithologic units is either the Kittery or Eliot formation, depending on the specific location within the zone. The thickness of the overlaying unconsolidated lithologic units varies across the site. The elevation of the bedrock interface is also highly variable, presumably because of the Zone's glacial history. A cross section of the geology of Zone 3 can be seen in Figure 8. Groundwater flow in the US, LS, and bedrock units of the PH2 site is generally from northeast to southeast (URS Group Inc., 2010).

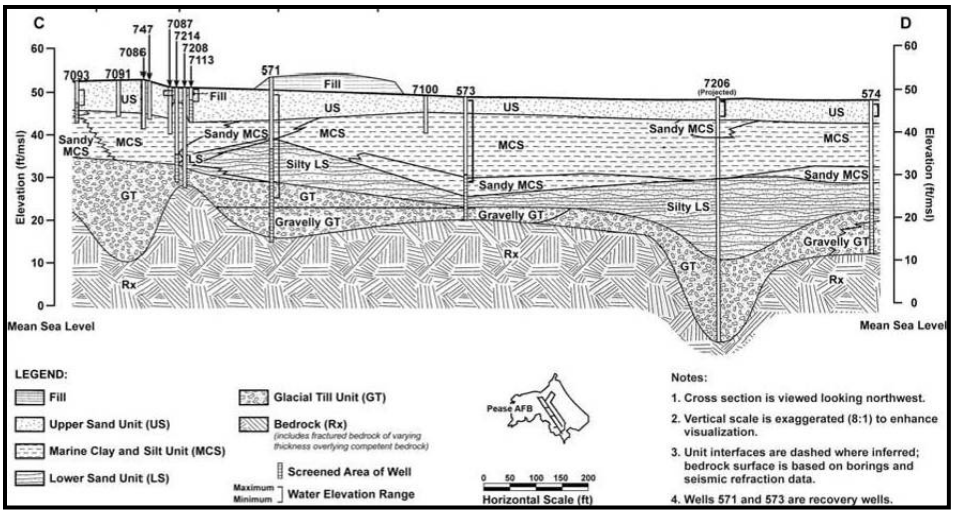

Figure 8. North-south cross section of the hydrogeology of Zone 3.
(Roy F. Weston, Inc. 1992).

4.2.3 Contaminant Distribution

Meter Pit 5

Meter Pit 5 is the most contaminated portion of the PH2 site and is the source of the large, downward-plunging plume of groundwater contamination to the south and west of the meter pit (URS Group, Inc., 2010). The primary source area is approximately 250 feet long, extending west-southwestward from Meter Pit 5. In 2009, the five LS monitoring wells in the source area exhibited concentrations of BNZ, TOL, ethylbenzene (EBNZ), XYLs, naphthalene (NAPH), 1,2,4-trimethylbenzene (124TMB), and 1,2-dibromoethane that were above the New Hampshire Ambient Groundwater Quality Standards (NH AGQS) (URS Group, Inc., 2010). In 2009, residual light non-aqueous phase liquid (LNAPL) was still detected in three of the wells at this location. However, there does not appear to be any expansion or migration of the plume (URS Group, Inc., 2010).

Meter Pit 6

In 2009, BNZ, NAPH, and 124TMB were detected at concentrations that exceeded NH AGQS in the one of the US wells in the Meter Pit 6 source area. Naphthalene also exceeded NH AGQS in one of the LS wells within the source area. Since 1999, there has been no indication of

contaminant migration from the Meter Pit 6 source area toward the Meter Pit 5 plume (URS Group, Inc., 2010).

5.0 TEST DESIGN

At both test sites, samples were collected from the same wells using GORE Modules and the USEPA's low-flow purging and sampling method, and the data were then compared. The general experimental design was as follows. First, the GORE Module(s) were deployed in each well and left for the recommended deployment time. These samples are referred to as the "pre-purge samples" because they were collected prior to low-flow purging and sampling. The analyte concentrations found with these samplers are what would be normally obtained when passive sampler technology is used. After these samples were collected, the wells were purged and sampled as described in the USEPA's low-flow sampling protocol (USEPA Region 1, 1996). After the low-flow samples were collected, a second set of GORE Modules were deployed in each of the wells and recovered. These samples were referred to as the "post-purge" samples.

In all the wells, either a bladder pump or the inlet of the sample tubing (used with a peristaltic pump) was located at the midpoint of the well screen. In all the wells, GORE Modules were also deployed at the midpoint of the well screen. In the wells with longer screens, two additional Modules were deployed within the well screen. One Module was placed half way between the top and mid-point of the well screen, and the other was placed halfway between the bottom and mid-point of the well screen. All three Modules were deployed on a single line, in series. Stainless steel weights were tied at the bottom of each sampling line to prevent the samplers from floating in the well. Using three Modules in a well allowed us to examine the distribution of contaminants with depth. Figure 9 shows the location of the sampling equipment in the wells at the APG site.

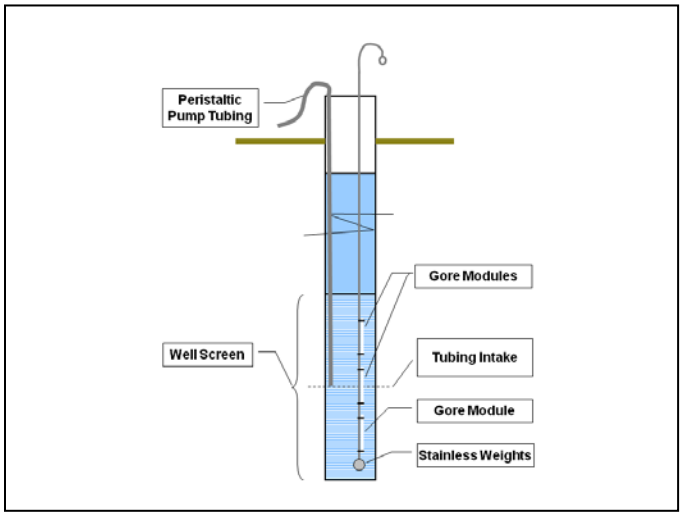

Figure 9. Diagram showing the location of the sampling equipment in each well.

The Gore chemists were provided historical information on analyte concentrations in all the wells so that they could determine the proper deployment times for the Modules in each of the wells. However, we did not provide them with the identity of any of the wells.

5.1 APG TEST SITE

5.1.1 Conceptual Experimental Design

The demonstration at this site focused on the use of the GORE Module to sample for VOCs. Contaminants included BNZ, CLF, cis-1,2-dichloroetheylene (cDCE), TCE, PCE, and TetCA.

5.1.2 Baseline Characterization

Louise Parker, Tommie Hall, Ron Bailey, and Kelsey Gagnon (a summer student from the University of New Hampshire), all with U.S. Army Engineer Research and Development Center-Cold Regions Research and Engineering Laboratory (ERDC-CRREL), conducted the field work at this site.

Our initial list of prospective wells included 2-inch and 4-inch diameter conventional monitoring wells and some smaller diameter piezometers and DP wells. The piezometers and DP wells had been used previously by General Physics (2009) to characterize the site. Our initial task was to locate the wells and piezometers, and then to note their condition and measure the depth. None of the DP wells or piezometers had been sampled in several years, and we found that they were all either damaged or could not be located (and presumably were destroyed). The measured depths of the wells were compared with construction details to determine the extent of silting in the wells. The list of wells to be sampled was then revised based on this information.

Because many of the conventional monitoring wells used in this study had not been sampled for almost a decade, it also was necessary to cut vegetation around the wells so we could access them. Tubing for the peristaltic pumps was then placed in each of the wells, and each well was purged at a low flow rate. The flow rate was slowly increased to determine the maximum pumping rate for the well (with minimum drawdown), and the water quality of the water in the well was noted to determine if the well needed to be redeveloped. However, all of the preselected wells were found to be suitable for sampling purposes. The tubing was then left in the wells for approximately 1 month prior to starting the demonstration. This provided time for the tubing in the well water to equilibrate with the analytes in well water.

5.2 FIELD TESTING

In all, 48 wells were sampled at this site. All the wells had polyvinyl chloride (PVC) casings and screens. While most wells were 4 inches in diameter, several were 2 inches and one was 6 inches in diameter. Most of the wells had 10-foot screens although there were some wells with 3-foot, 5-foot, 7-foot, and 9-foot screens. There also were two wells with 12-foot screens and one well had a 20-foot screen. None of the wells used in this study contained free product.

Low-flow samples were collected using a peristaltic pump with polyethylene (PE)-lined polytetrafluoroethylene (PTFE) tubing that was dedicated to each of the wells.

Additional GORE Modules were deployed in all wells that had a screen of 7 feet in length (or longer). Three samplers were also placed in two of the wells with 5-foot screens. Uncolored

plastic zip-ties were secured to the ends of the Modules so that they remained in the same position throughout the deployment period.

Standard quality assurance (QA)/quality control (QC) samples were collected for both sampling methods. For low-flow sampling this included: 20% low-flow field duplicates, 10% matrix-spike (MS) samples, 10% matrix-spike duplicate (MSD) samples, and trip blanks (one per cooler).

QA/QC samples for the GORE Modules included 10% duplicate samplers (that were analyzed by the Gore laboratory) and trip blanks (one per box of samplers). Because of the nature of the mechanism by which the GORE Module collects a sample, it is not possible to have spiked (MS and MSD) samples. Therefore, a second set of duplicate samples were collected and sent to an independent laboratory that was knowledgeable with the Gore analytical method. The duplicate samples were not marked as duplicates or identified by well number so the laboratory analyses were completely blind for both laboratories. We also requested that the Gore laboratory analyze both sorbent packets in some of the samplers; these are duplicate "analytical" samples.

During sampling, the following information was recorded in the field notebook for each of the wells: the well number and sample date; arrival time at the well; and departure time from the well. During low-flow sampling the following information was recorded: water-level and time initially and during purging, purge rate, purge parameter readings and time for each reading, and the start and finish time for sample collection. For sampling with the GORE Modules, the following was also recorded: the deployment times for the samplers; the serial numbers on the Modules; the depth to groundwater (determined by using a water depth probe, which was determined after collecting the pre-purge samples but before purging the well); sampling depths of the Modules; the groundwater temperature (determined by using a temperature probe); and the retrieval times. The information on the time involved in various aspects of sampling was used in the cost analyses.

5.2.1 Chemical Analyses

The low-flow samples were analyzed using USEPA Method 8260B GC/MS (USEPA, 1996) by White Water Associates, Inc. (Amasa, Michigan). They are a National Environmental Laboratory Accreditation Conference (NELAC) and DoD- Environmental Laboratory Accreditation Program (ELAP) certified laboratory. Additional information on calibration and other QA/QC requirements for the contract laboratory can be found in the Final Report (Parker et al., 2014).

Most of the GORE Modules were analyzed for VOCs at the Gore laboratory using EPA Method 8260C GC/MS that has been modified for thermal desorption. Ten percent of the GORE Modules collected at this site were replicate samples that were sent to an independent laboratory for analyses, MRI Global (Kansas City, MO). This laboratory was familiar with the analyses of the GORE Modules, and is a NELAC and ELAP certified laboratory.

5.2.2 Data Analyses

All the statistical analyses of the test data were conducted on an analyte-by-analyte basis. The precision of the GORE method and the low-flow sampling method was determined by

calculating the RSD among the respective replicate samples. The percent of the wells that met this criterion out of the total number of wells was then calculated for each of the analytes.

For the remaining comparisons, standard statistical analyses were utilized to determine if there were significant differences between either the analyses of replicate samples by the two laboratories (using a paired t-test) or between the three sample types (i.e., the low-flow-samples, GORE Module pre-purge samples, and the Gore post-purge samples) using a RM-ANOVA test. Both the mid-point data sets were compared with the low-flow data and the mean Gore data (i.e., mean for the three sampling depths) were compared with the low-flow data. Whenever possible, conventional parametric analyses of the raw (or if need be log-transformed) data were used because these tests typically are more rigorous than non-parametric tests. In instances where conventional parametric tests could not be used on either the raw data or the log-transformed data, non-parametric tests were used.

Linear regression analyses using the least-squares method was also used to determine if there was a statistically significant linear relationship between the raw data for the two laboratories and if that relationship was one-to-one (i.e., if the slope was significantly different from 1.0). These analyses were also used to compare the low-flow and Module data.

GeoSoft Oasis Montage software was used to construct maps of the contaminant plumes at this site by using the low-flow and Gore data.

5.2.3 Additional Information

Additional information on the methods used in this study can be found in Parker et al. (2014).

5.3 SAMPLING METHODS FOR THE FORMER PEASE AFB

Because the experimental design, sampling methods, and data analysis were essentially the same at this site as they were at the previous site, the project team only noted instances where there were differences in the procedures.

5.3.1 Conceptual Experimental Design

Focus at this site was on hydrocarbon contamination, including SVOCs and VOCs. Contaminants included: BNZ, TOL, EBNZ, XYLs, NAPH, 124TMB, 1,3,5-trimethylbenzene (135TMB), n-butylbenzene; n-propylbenzene; sec-butylbenzene; tert-butylbenzene; isopropylbenzene; p-isopropyltoluene, and 1,2-dibromoethane.

5.3.2 Baseline Characterization

The wells at this site had been sampled on a quarterly basis so it was not necessary to prepare the field site for sampling or evaluate the condition of the wells. However, because the test site was located in the flight-line area of the Pease International Airport, it was necessary to obtain from the Federal Aviation Administration (FAA) security clearances and training on proper procedures for operating in the flight-line area.

5.3.3 Field Testing

A total of 26 monitoring wells were selected in the PH2 area to sample. Most of the wells at this site (16 in all) had shorter screens, either 3 or 5 feet in length. The remaining wells had 10-foot screens. While some of the wells were at the epicenter of the plume, none of them contained free product.

Some of the wells that were selected to be sampled were completed by URS employees, as part of their quarterly sampling round. For those wells, the URS personnel used a Grundfos pump with dedicated Teflon tubing to collect the low-flow samples. The Grundfos pumps were only used in wells with similar analyte concentrations and were decontaminated prior to placing them in each of the wells. The remaining wells were sampled by the CRREL personnel that included Louise Parker, Ron Bailey, and Gordon Gooch. For these wells, all but two were sampled using a dedicated bladder pump with dedicated PE-lined PTFE tubing; the two shallowest wells were sampled using a peristaltic pump and dedicated PE-lined PTFE tubing.

Prior to starting any field work, the bladder pumps that were to be used at this site were returned to the manufacturer where they were cleaned, refurbished with new materials including new bladders, cleaned again, and rinsed with deionized water. The clean bladder pumps were installed 2 weeks before the field tests were conducted. At that time, they were pumped to make certain the pump worked and to allow time for the materials in the pump and tubing to equilibrate with the analytes in the well water. At the same time, dedicated tubing was also placed in the two wells that we sampled using peristaltic pumps.

Both the CRREL and URS sampling crews used the protocol given by USEPA Region 1 (1996) for low-flow sampling. All sampling with the GORE Modules was conducted by the CRREL field crew. The deployment of the Modules differed from the APG site in that the Modules were only attached at the top of sampler. This allowed the bottom of the sampler to float upwards rather than being tethered at both ends to the sampling line. For the 16 wells with the shorter length screens (3-feet, 5-feet, and 8-feet), only a single mid-depth Module was deployed.

QA/QC samples were collected as described previously, with two exceptions. All the replicate Module samples were blind, in that the laboratory did not know the identity of any of the samples, and there was no analysis of replicate samples by a second independent laboratory.

5.3.4 Chemical Analyses

All of the low-flow samples were analyzed using USEPA Method 8260B GC/MS (USEPA, 1996) by Katahdin Analytical Services, Scarborough, Maine, a NELAC and DoD-ELAP certified laboratory. The GORE Modules were analyzed at the Gore laboratory using EPA Method 8260C GC/MS that has been modified for thermal desorption.

5.3.5 Data Analyses and Additional Information

Data handling and analyses were the same as described previously in section 5.1.5. Additional information on all the methods used in this study can be found in Parker et al. (2014).

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6.0 SAMPLING RESULTS FOR APG

A more in-depth discussion of these results can be found in Parker et al. (2014), including the raw data from all the chemical analyses and the results from all the statistical analyses.

6.1 REPRODUCIBLILITY OF SAMPLING METHODS (REPLICATE SAMPLES)

6.1.1 Reproducibility of the GORE Modules

The results from co-located field duplicate samples were compared to determine whether the Gore technology is able to yield good analytical precision. Most of the replicate samples were "blind samples" in that the laboratory did not know that the two samples were replicates. However, there were also some samples where the Gore Laboratory analyzed two different sorbent packets from the same Module. In those cases, the laboratory was aware that the samples were replicates.

Relatively stringent guidelines were set for precision by requiring the RSD be 20% or less for those analytes where the concentrations were at least three times the detection level. (This is equivalent to a Relative Percent Difference of 28%.) By way of example, two values that differ by a factor of two (e.g., 50 and 100) yield a 47% RSD and those that differ by an order of magnitude (e.g., 25 and 250) yield a 116% RSD.

Generally, there was an excellent agreement between the replicate GORE Modules. For TCE, TetCA, CLF, and BNZ, all or almost all (>90%) of the blind replicate pairs met the 20% RSD guideline. For PCE and pentadecane ~60% and 67% met the guideline, respectively. For cDCE, none of the three replicate samples met the 20% guideline but the RSD was only slightly greater (between 25% and 30%).

It is interesting that much of the poor reproducibility occurred in three samples. Because the screened interval of two of these wells was just below the water table and the samples were collected after the well was purged, it was suspected that purging may have been the cause for the poor agreement in those cases.

As one might expect, the RSD was considerably better (less than 10% in all cases) for the duplicate samples where two different sorbent packets from within the same sampler were analyzed.

6.1.2 Agreement between Analyses by the Gore Laboratory and the Independent Laboratory

For 10% of the Gore samples, a replicate sample was collected and sent to an independent laboratory familiar with the analyses of the GORE Modules. These replicate samples were blind in that neither laboratory knew the identity of any of the samples. There was excellent agreement

between the two laboratories for TCE, TetCA, PCE, and cDCE.[1] The results for TCE and PCE are shown in Figures 10 and 11.

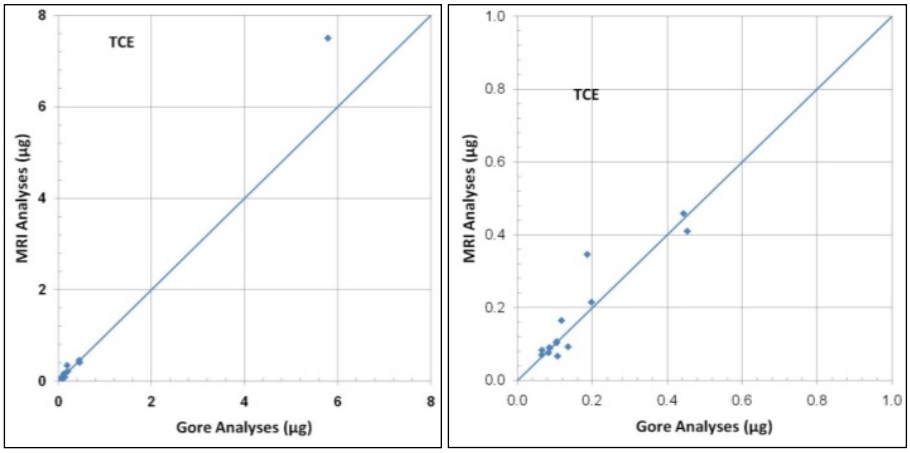

Figure 10. Comparison of the analyses of GORE Modules by the two laboratories for TCE for all analytes (left) and an enlargement for low recoveries of the analyte (right).

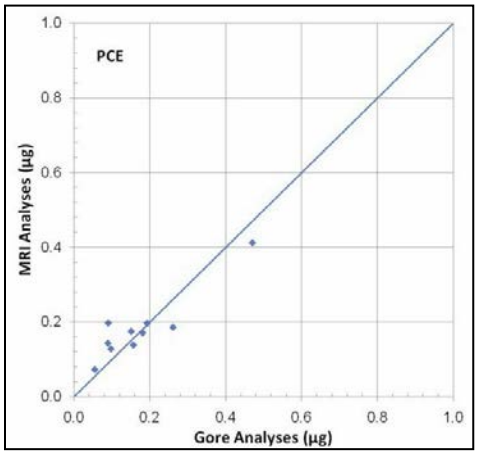

Figure 11. Comparison of the analyses of GORE Modules by the two laboratories for PCE.

6.1.3 Reproducibility of the Low-Flow Samples

The data for the replicate samples for low-flow sampling met our guideline (i.e., 100%) for all the analytes. These results are not surprising given that these replicate samples were taken consecutively without stopping the pump. Therefore, these samples were not true co-located field duplicate samples, and have defined by the USEPA (2005) as subsample field duplicates.

[1] The significance of the F value for the linear model was significant for cDCE [i.e., less than 0.04] and highly significant for the other analytes [i.e., less than 0.01]. The correlation coefficient, r, ranged from 0.8 [for cDCE] to 0.999.

6.2 AGREEMENT BETWEEN GORE MODULES AND LOW-FLOW DATA

Analytes that were detected in enough wells to allow statistical analyses of the data included PCE, CLF, TetCA, TCE, cDCE, BNZ, and CLB.

6.2.1 Sensitivity of the Two Analytical Methods

The MDL for the analytical method used for the low-flow samples was approximately one twentieth of that for the Gore method. For the low-flow samples, the detection limit generally was 0.2 µg/L and for the GORE Modules it was 4.4 µg/L. However, even the higher detection level for the GORE Modules was still below the action level for these contaminants; i.e., the USEPA's MCL. This would allow the Remedial Program Manager, or other interested parties, to make decisions based on the action levels.

A lower detection level is often desired and in some cases required by regulatory agencies, such as in the USEPA's Quality Performance Project Plan Manual (USEPA, 2005). Figures 12a and 12b show the TCE plumes as determined by the pre-purge and post-purge GORE Modules, respectively. Figure 12c shows the TCE contaminant plumes as determined by low-flow sampling, and Figure 12d shows an overlay between the pre-purge Gore data and the low-flow data. It is clear that while there is excellent agreement between the two sampling methods, the lower detection capability of the low-flow analyses provides more detail. Because of this difference, we recommended to the manufacturer that the laboratory continue to work on lowering the detection capability of the method.

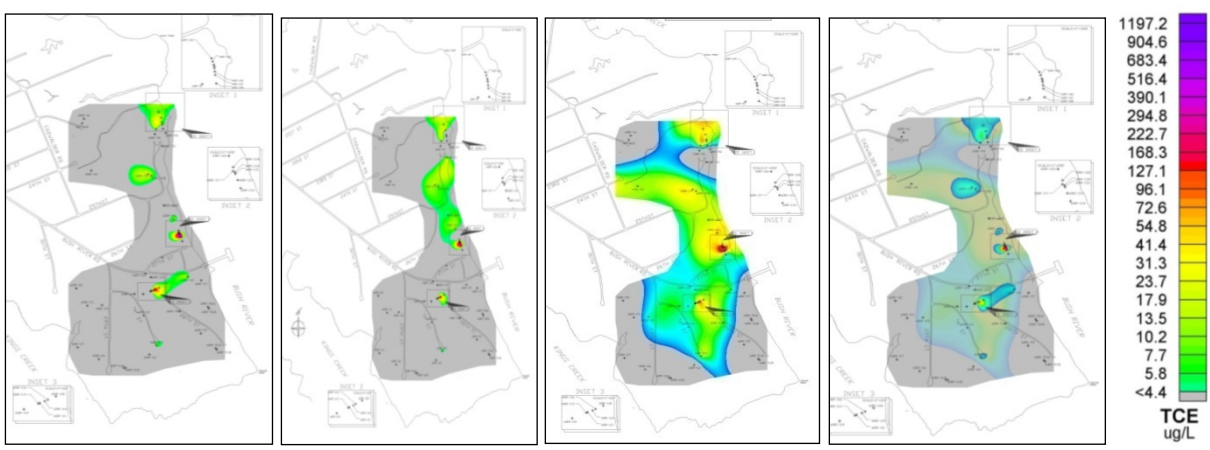

Figure 12. (a) Map of TCE contaminant plumes as delineated by pre-purge GORE Module data; (b) Map of TCE contaminant plumes as delineated by post-purge GORE Module data; (c) Map of TCE contaminant plumes as delineated by low-flow data; and (d) Overlay of pre-purge GORE data on low-flow data for TCE.

6.2.2 Comparison of the Mid-Level GORE Module with the Low-Flow Data

We first compared the data for the pre-purge mid-level Module with the low-flow data, and the post-purge Module with the low-flow data. Because the mid-level sampler was at the same depth as the pump intake, we thought that the concentrations would be similar. For PCE, TetCA, TCE,

cDCE, and CLF, there was a highly significant linear relationship.[2] For PCE, TCE and cDCE the slope of the line was not significantly different from 1.0 (as seen in Figure 13 for PCE). However, the slope of the line was less than 1.0 for TetCA (Figure 14) and CLF; the slopes were approximately 0.6 and 0.7, respectively.

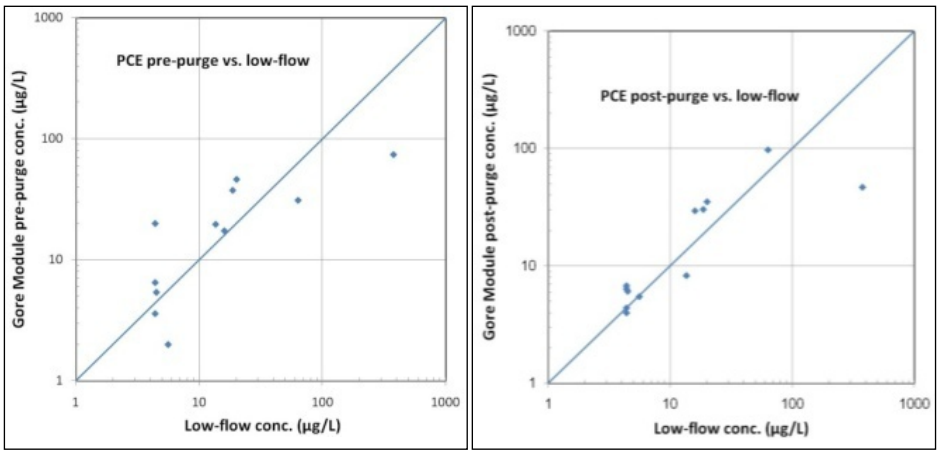

Figure 13. Comparison of the pre-purge and post purge (right) GORE data for the mid-level samples versus low-flow data for PCE.

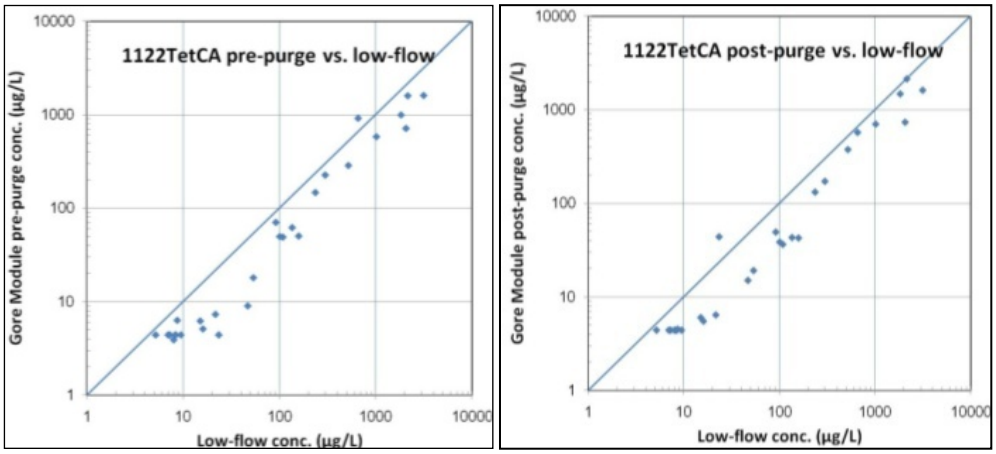

Figure 14. Comparison of the pre-purge (left) and post-purge (right) GORE data for the mid-level samples versus low-flow data for TetCA.

The project team might expect that the post-purge Module data would agree more closely with the low-flow data than the pre-purge data. While it was found that this was true for PCE, TCE, and CLF, we found the opposite was true for cDCE and TetCA. There were no statistically significant differences between the pre-purge and post-purge Gore data found for any of these analytes.

[2] The significance of the F value for the linear model was less than 0.002 in all cases; the correlation coefficients ranged from 0.78 to 0.99.

6.2.3 Comparison of the Mean Data (for the Three Modules) with the Low-Flow Data

The mean concentration value for the Modules for the three sampling depths for both the pre-purge and the post-purge Gore data for each analyte and well were determined and then were compared with the low-flow sampling results. Because low-flow sampling is reported to provide a flow-weighted average sample of the groundwater pumped from the well, it also thought that the mean values might agree better with the low-flow samples.

Once again, the statistical analyses revealed that there was a strong, statistically significant linear relationship between the Gore and low-flow data for all the analytes.[3] The slopes of these lines were not significantly different from 1.0 for PCE, cDCE, or for the pre-purge data for TCE (Figure 15). However, the slope of the line for the post-purge/low-flow data for TCE was significantly less than 1.0 (0.73) (Figure 15). The same was true for TetCA for both the raw pre-purge data and the raw post-purge data; the slopes of these lines were approximately 0.6. We did not use a linear regression model on the CLF data because there were only a few wells with concentrations that were well above the detection level.

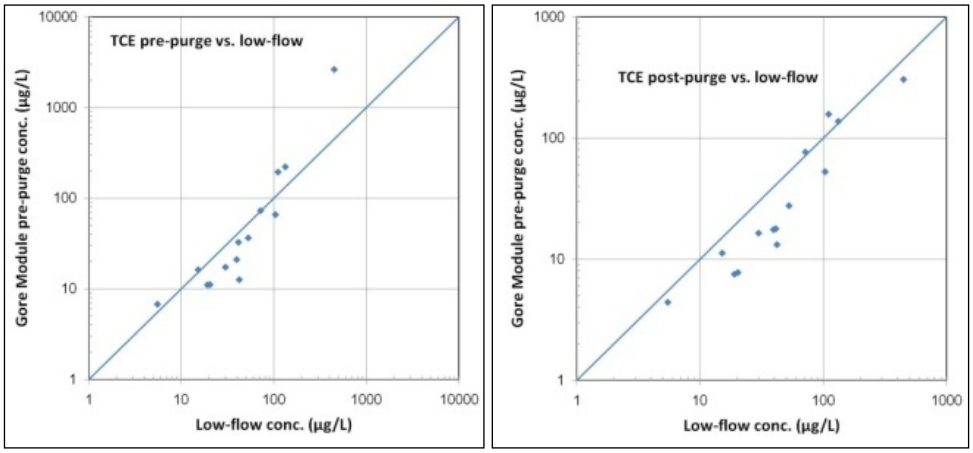

Figure 15. Comparison of the pre-purge (left) and post-purge (right) mean concentrations for the modules versus low-flow concentrations for TCE.

Once again, there was no consistent trend with respect to whether the post-purge data agreed better with the low-flow data or whether the pre-purge data did, and there was no statistically significant difference between the pre-purge and post-purge Gore data for any of the analytes.

6.2.4 Profiling Concentrations with Depth in the Wells

There were approximately 14 wells where analyte concentrations with depth were determined and concentrations were above the detection level. Generally, the data from the Modules revealed that there was not much difference in concentration with depth in most of these wells. This was true for both the pre-purge and post-purge data. However, there were five wells where

[3] This relationship was highly significant for all the comparisons except for the pre-purge data for PCE, where the significance level was 0.039. The correlation coefficients ranged from 0.93 to 0.97 for all the analytes except PCE, where they were 0.54 and 0.83 for the pre-purge and post-purge data, respectively.

substantial differences were observed in some of the analyte concentrations with depth. Each of these wells was located at the epicenter of their respective contaminant plume. By way of illustration, the results from four of these wells will be presented.

6.2.4.1 Analyte Concentrations with Depth in Well 111

In Well 111, the Modules were located ~ 30 to 40 feet below the water table. Analytes found in this well included TCE, TetCA, and cDCE. For both the pre-purge and post-purge samples, concentrations were typically highest in the bottom portion of the well and lowest at the mid sampling depth (Figure 16) even though the screen was 20 feet in length and one might expect that the samples would be more mixed because of the length of the screen. There were two sets of (blind) duplicate Modules in this well, and there was good agreement between them for these analytes.

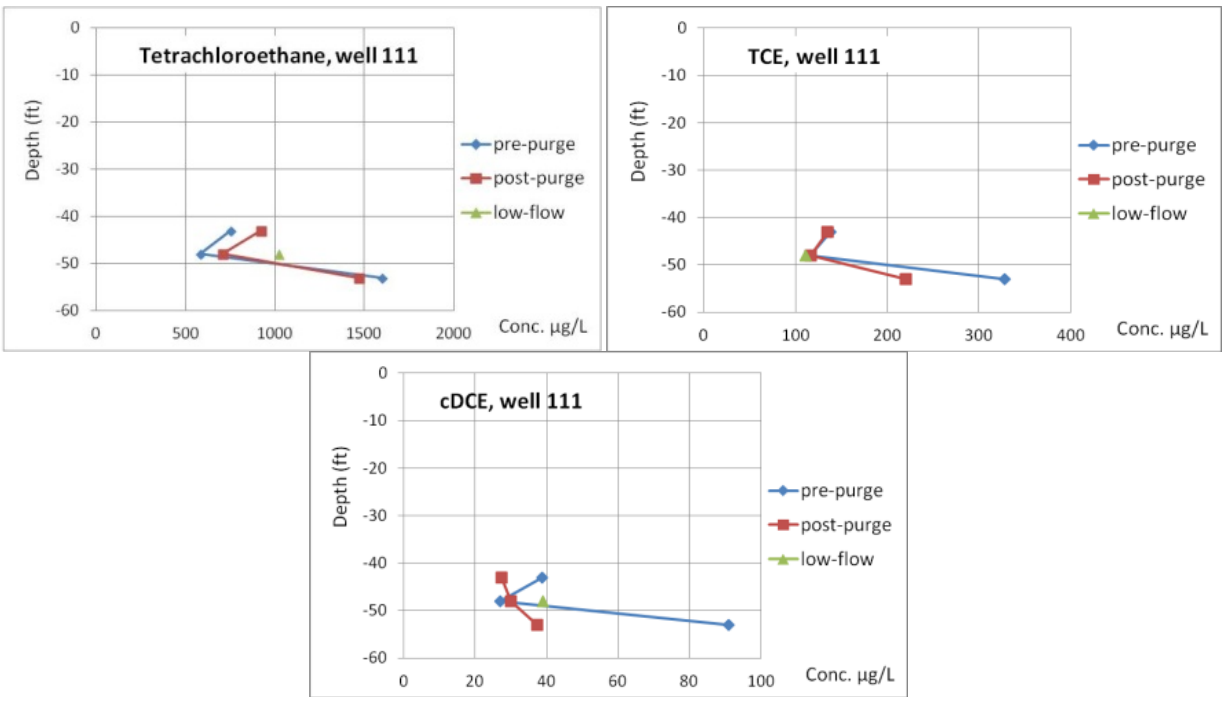

Figure 16. Concentrations of PCE, TCE, and cDCE with depth in Well 111.

6.2.4.2 Analyte Concentrations with Depth in Well 114

The depths of the Modules were well below the water table (~10 feet for the shallowest sampler). This well also showed some stratification of TCE and TetCA with depth but only after purging (Figure 17). In most instances the post, purge data appears to agree best with the low-flow data. These results indicate that low-flow sampling drew water from a zone (or zones) that is more contaminated with TetCA but was less contaminated with CLF.

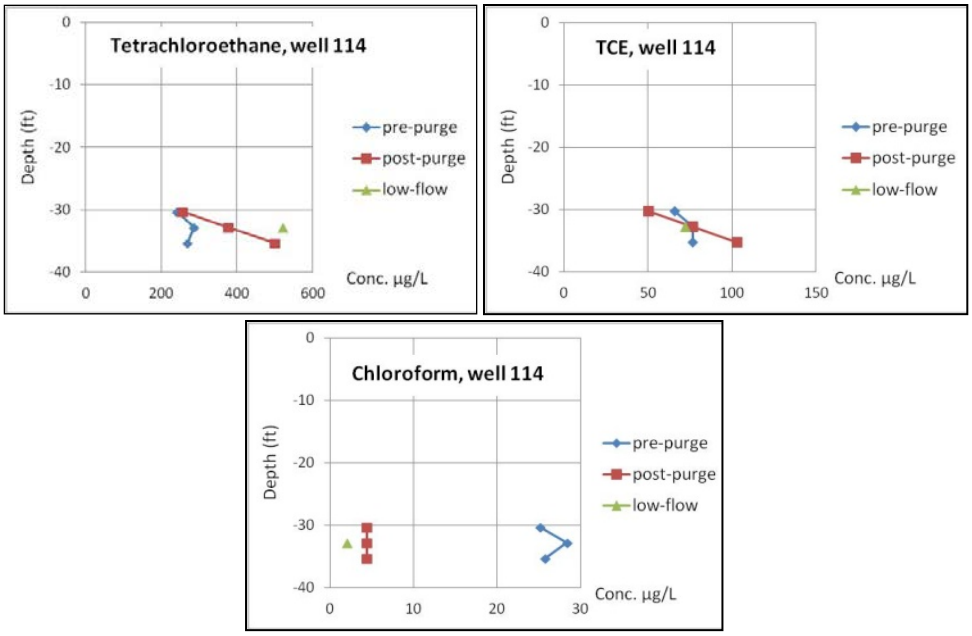

Figure 17. Concentrations of TetCA, TCE, cDCE, and CLF with depth in Well 114.

6.2.4.3 Analyte Concentrations with Depth in Well 116

Only three analytes were found in this well, TetCA, TCE and cDCE. There were very pronounced concentration gradients for the pre-purge samplers for all three of these analytes (Figure 18) with concentrations much higher in the bottom of the screen than at the top. In contrast, the post-purge samples showed little variation in analyte concentrations with depth and agreed best with the low-flow concentrations indicating that pumping the well resulted in mixing any stratification that was initially present in the well.

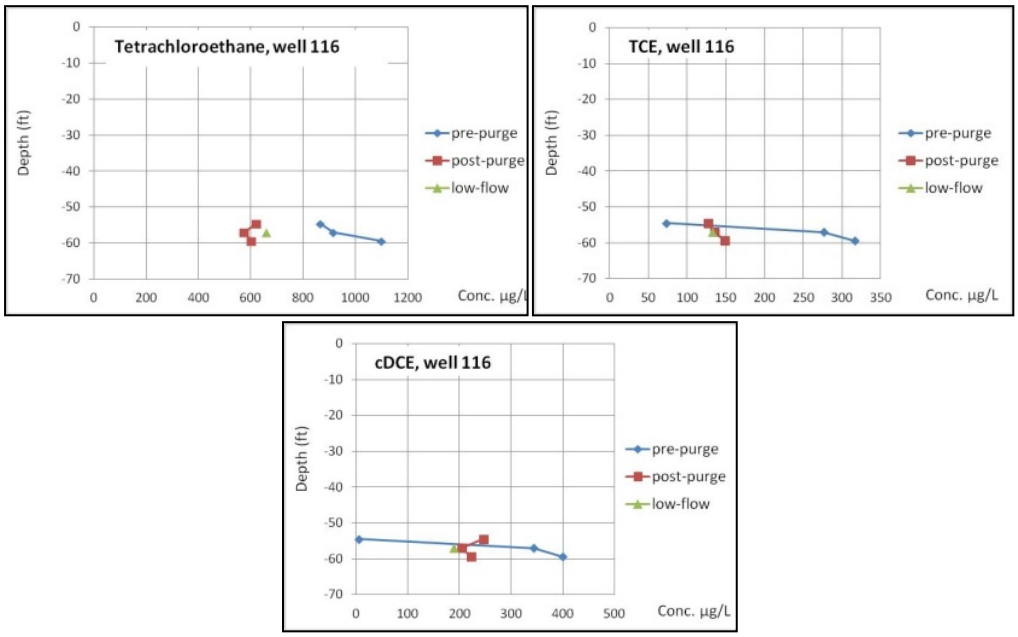

Figure 18. Concentrations of TetCA, TCE, and cDCE with depth in Well 116.

6.2.4.4 Analyte Concentrations with Depth in Well 131

Well 131 was a relatively shallow well that had a 5-foot screen. Prior to purging this well, there were very steep gradients in analyte concentrations for all five analytes (TCE, TetCA, CLF, cDCE, and PCE) found in this well, with concentrations much higher in the upper portion of the well screen (Figure 19). The low-flow concentrations of TCE, CLF, and PCE agreed most closely with the mid-level GORE Module data. In contrast, the low-flow concentration of TetCA agreed most closely with the upper-level (pre-purge) Module, and the low-flow concentration of cDCE agreed most closely with the mean of the concentrations reported for the mid-level and top-level (pre-purge) samplers. Overall, the low-flow concentrations of these analytes agreed better with the pre-purge samples than the post-purge samples. This may have been caused by partially dewatering the well, which is why there wasn't a post-purge sample from the upper portion of the well screen. Once again there was excellent agreement between the two replicate (mid-level) samples that were collected in this well. It is also interesting that there was such a pronounced concentration gradient in this well given that the screen was only 5 feet in length and that concentrations were much higher in the upper portion of the well screen, especially given that this well is relatively shallow and that the top of the screen was near the water table.

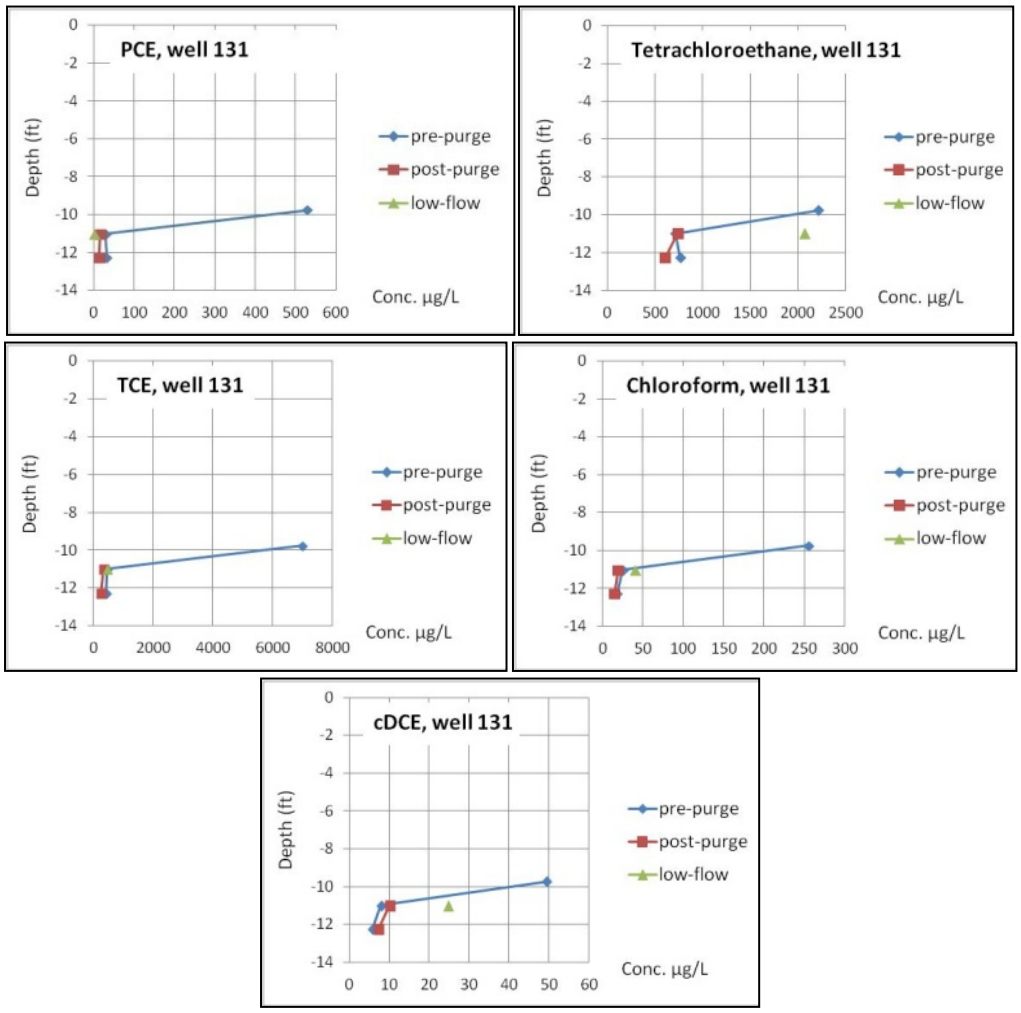

Figure 19. Concentrations of PCE, TetCA, TCE, CLF, and cDCE with depth in Well 131.

6.2.5 Discussion

In some instances when the data from the GORE Modules were plotted against the low-flow data for each of the wells, there were samples that appeared to be outliers. For some wells, the apparent outliers appear to be due to stratification in the well. An example can be seen in Figure 15 where the mean pre-purge Gore data are compared with the low-flow data for TCE. The apparent outlier in that series was Well 131 where the pre-purge concentration of TCE in the upper portion of the well screen was more than order of magnitude higher than the mid section. Taking the mean for these three values would yield a considerably higher value than that for the low-flow sample and explains why the mean value appears to be outlier in Figure 15 (left). In contrast, the TCE concentrations for the pre-purge samplers at the bottom and mid-point of the screened interval agreed well with the low-flow value.

Another example of the impact that concentration gradients in the well can have on the agreement between the two sampling methods can be seen by examining the TetCA concentrations in Well 131 (Figure 19). The concentration of this analyte in the upper section of the screen agreed well with the low-flow concentration, while the mid-level Gore data or the mean of all three pre-purge values would have yielded much poorer agreement.

Low-flow sampling collects a sample that is a flow-weighted average for the well. Low-flow sampling collects a sample that is a flow-weighted average for the well. The degree of flow weighting depends upon the permeability of the formation, well construction (filter pack, screen size, screen length, etc.), and the presence of concentration or temperature gradients in the water (from different zones) entering the well.

Instances where the low-flow concentrations agreed best with samples collected from only one portion of the well screen (by the GORE Modules) are seen. Presumably, in these instances low-flow sampling drew its sample from the same zone in the formation that was interrogated by the Module. In other instances, it was seen that low-flow sampling did not collect a sample from what flows into the well under ambient conditions. These differences point to the question of where to place a passive sampler in the well. Depending upon the data quality objectives (DQO), it may desirable to place the sampler where the analyte concentrations agree best with the low-flow sample while in other instances, it may be best to place the sample where one will obtain the highest concentrations and thus obtain a higher estimate of the level of contamination.

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7.0 SAMPLING RESULTS FOR THE FORMER PEASE AFB

Contaminants that were detected in at least some of the wells at this site using both sampling methods and thus allowed us to compare these technologies included: BNZ; TOL; EBNZ; XYLs; NAPH; 124TMB; 135TMB; isopropylbenzene; and p-isopropyltoluene. All the data, the results from the statistical analyses, and more in-depth discussion of the findings can be found in Parker et al. (2014).

7.1 REPRODUCIBLILITY OF SAMPLING METHODS (REPLICATE SAMPLES)

7.1.1 Reproducibility of the GORE Modules

For this demonstration, all of the replicate samples were "blind" in that the laboratory did not know that the two samples were replicates. For most of the analytes, there was excellent agreement between the results for the duplicate Modules. That is for a given analyte, more than 80% of the duplicate pairs met the project team's guideline (i.e., the RSD was 20% or less). This was true for 135TMB, NAPH, 2-methylnaphthalene, octane, undecane, n-propylbenzene, isopropylbenzene, n-butylbenzene, and isopropyltoluene. The exceptions were BNZ, EBNZ, and XYLs, where 60% or more of the replicates met the 20% RSD guideline; 124TMB, where 73% of the replicates met the guideline; and TOL, with the poorest agreement with only 35% of the replicates meeting the guideline.

Once again, it was seen that the poor replication occurred primarily in a few wells. The duplicate samples were taken before purging the well in two of the wells and after purging in the other two wells. The generally low analyte concentrations in the two pre-purge wells could explain the higher variability in those wells. For the other two wells, reproducibility was poorest for BNZ and TOL. The Modules in these four wells were placed at least 40 ft or more below the water table. As noted previously in Section 2.1.1, some analytes are lost from the Modules when the depth below the water table is greater than 32 feet. (This is because the water entry pressure of the membrane is such that water will pass through the membrane and come in contact with the solid sorbent. Sorption then also becomes a function of the partitioning coefficient of the analyte by the sorbent.) Among the analytes found at this site, Gore has found that EBNZ, XYLs, and 124TMB are more readily lost than BNZ and TOL; this also agrees with what one would expect based upon the octanol-water partition coefficient (K_{OW}) values of these analytes. Given that the analytes reported to be most prone to penetrate the membrane were not the analytes that were found to have the poorest reproducibility, it is suspected that depth below the water column was not the primary cause of the poor reproducibility in these wells.

However, it was also observed that the samplers with the poorest reproducibility had been left in the wells for longer than 2 hours. It may be that this contact time was too long and that uptake was no longer in the linear portion of the curve. Or, it may be that the flow within the well was such that one sampler was in a preferential location with respect to the flow of contaminants into the well. (Two of the wells may have been crowded as there were replicate samplers at all three depths.) Based upon these findings and until this is better understood, it is recommended that the samplers should not be left in the well for longer than 90 minutes, especially if they are deployed more than 32 feet below the water table.

7.1.2 Reproducibility of the Low-Flow Samples

For most of the analytes found in these wells, the replicate samples met the 20% RSD guideline. The exceptions were 135TMB and NAPH where the RSD was 45% and 28%, respectively. Again, when comparing the low-flow results with those for the Modules, it is important to remember that the duplicate low-flow samples are taken sequentially without stopping the pump. Duplicate samples where the pump is stopped and started would probably yield substantially higher RSDs. In contrast, the Modules were true field duplicate samples.

7.2 AGREEMENT BETWEEN GORE MODULES AND LOW-FLOW DATA

7.2.1 Sensitivity of the Two Analytical Methods

Previously at the APG site, the analytical method used for low-flow purging and sampling was able to provide greater sensitivity than the method for the GORE Modules. Since that time, the Gore laboratory has worked on lowering their detection capability and they have been able to obtain an equivalent detection capability for most of the analytes at this site (e.g., BNZ, TOL, EBNZ, XYLs, 124TMB, 135TMB, and NAPH) by modifying the currently accredited method. For the remaining analytes (n-butylbenzene, n-propylbenzene, isopropyltoluene, isopropylbenzene, and 1,2-dibromoethane), the MDLs remain higher with the Modules than with the low-flow samples. However, in all cases the detection capability was below 1/10th of the USEPA's MCLs (USEPA, 2011).

7.2.2 Comparison of the Mid-Level GORE Module Data with the Low-Flow Data

When the mid-level GORE data were compared with low-flow sampling, generally there was very good agreement between the two sampling methods for all the analytes, with the exception of instances where concentrations were near the detection level. This was true for TOL, EBNZ, 124TMB, 135TMB, NAPH, isopropylbenzene, and n-propylbenzene. Figures 20 and 21 show these comparisons for TOL and EBNZ, respectively. Also, the relatively good agreement between the two sampling methods once values at or near the detection level are removed is illustrated for TOL in Figure 20b. BNZ and the XYLs appeared to have the most scatter of all the analytes (not shown).

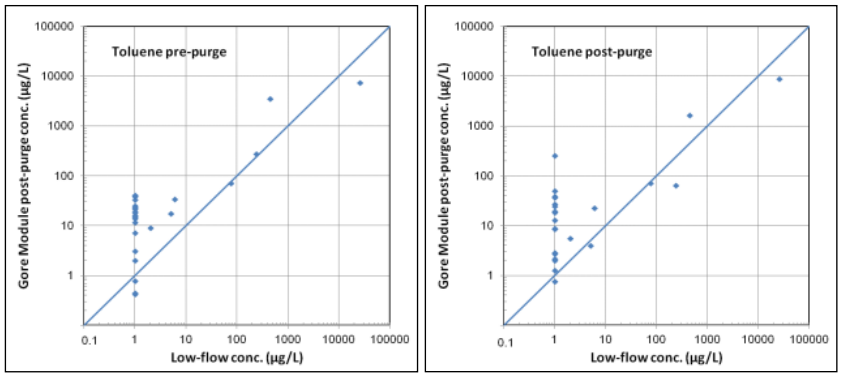

Figure 20a. Comparison of the pre-purge (left) and post-purge mid-level GORE data with the low-flow data for toluene.

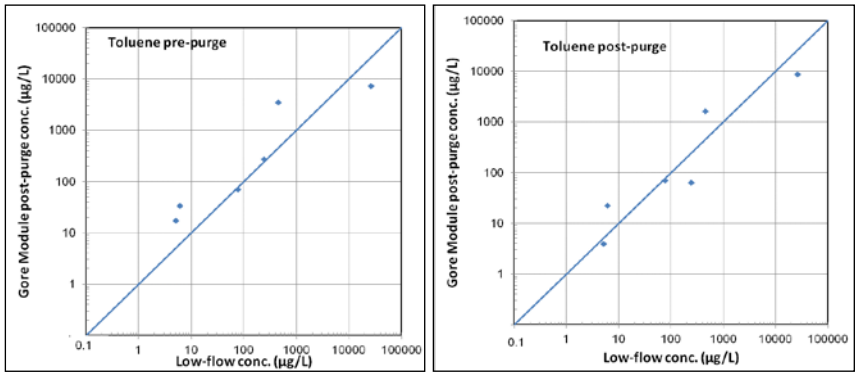

Figure 20b. Same comparisons with the values at or near the detection limit removed.

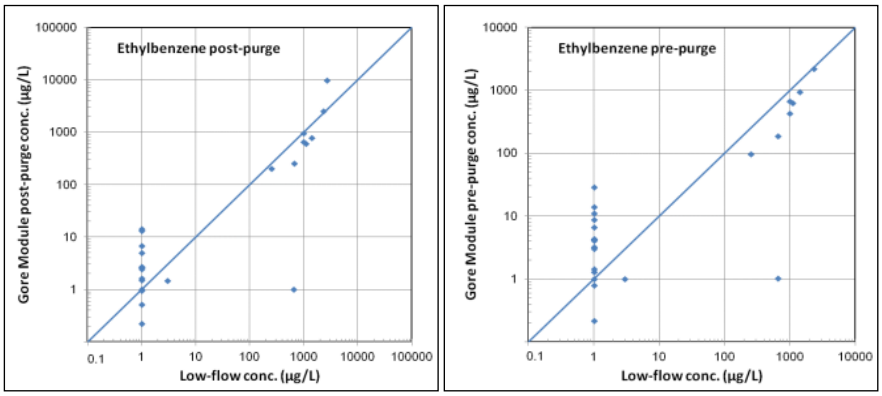

Figure 21. Comparison of the pre-purge (left) and post-purge (right) mid-level GORE data with the low-flow data for ethylbenzene.

The analyses of the raw data using a linear least-fit model confirmed that there was a statistically significant linear relationship between the pre-purge Gore data and the low-flow data for all the analytes[4] and that the slope of the line was not significantly different from 1.0, with the exception of BNZ (> 1.0) and TOL (< 1.0). The same was true when the post-purge and low-flow raw data were compared except that the linear model did not fit the data for BNZ.[5] The Gore chemists have also reported that they have noticed that the concentrations of BNZ derived with the Modules are higher than other environmental samples although they do not know the cause for this (Anderson, 2013).

Generally, it might be expected that there would be slightly better agreement between the post-purge and low-flow data than between the pre-purge and low-flow data. However, there was no statistically significant difference between the pre-purge and post-purge Gore data for any of the analytes.

[4] The significance of the F value for the linear model ranged from 0.020 to 3.4 E-05, and the correlation coefficients ranged from 0.73 to 0.99.

[5] For BNZ, the F value was *not* significant (0.934) (r equal to 0.032). The significance of the F value for the other analytes was highly significant, i.e., less than 0.003 (and the correlation coefficients ranged from 0.82 to 0.986).

7.2.3 Comparison of the Mean Gore Data with the Low-Flow Data

When the mean pre-purge values (for the three sampling depths) and the mean post-purge values were compared with the low-flow data for each of the analytes, there was good agreement in both cases. Again, the exceptions were instances where the concentrations were at or near the detection limits. This has been illustrated in Figures 22 and 23 for 135TMB, and isopropylbenzene, respectively. Once again, the analyte with the poorest agreement (i.e., with the most scatter in these plots) was BNZ (Figure 24a and b).

Analyses using a linear least-fit model (on the raw data) confirmed that there was a highly significant linear relationship between the pre-purge and low-flow data and between the post-purge Gore and low-flow data for all the analytes. The slope of this line was not significantly different from 1.0 for EBNZ, the XYLS, 124TMB, 135TMB, NAPH, isopropylbenzene, and n-propylbenzene. As with the mid-level data, the exceptions were the post-purge BNZ data (slope > 1.0) and the pre-purge and post-purge data for TOL (slope < 1.0).

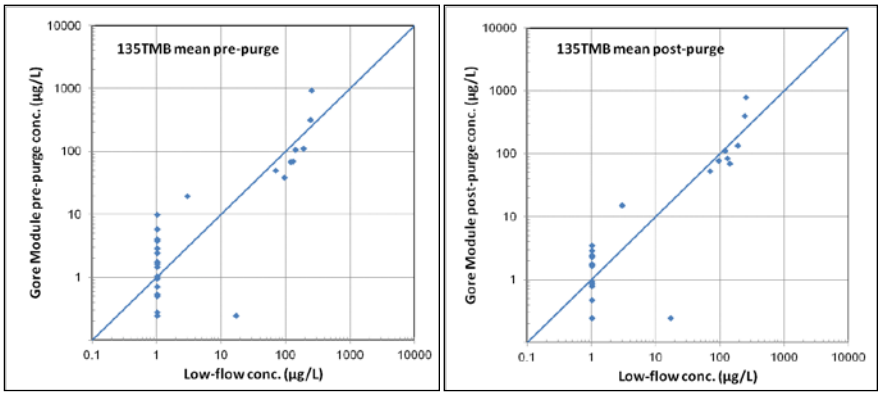

Figure 22. Comparison of the mean pre-purge (left) and post-purge (right) GORE data with the low-flow data for 135TMB.

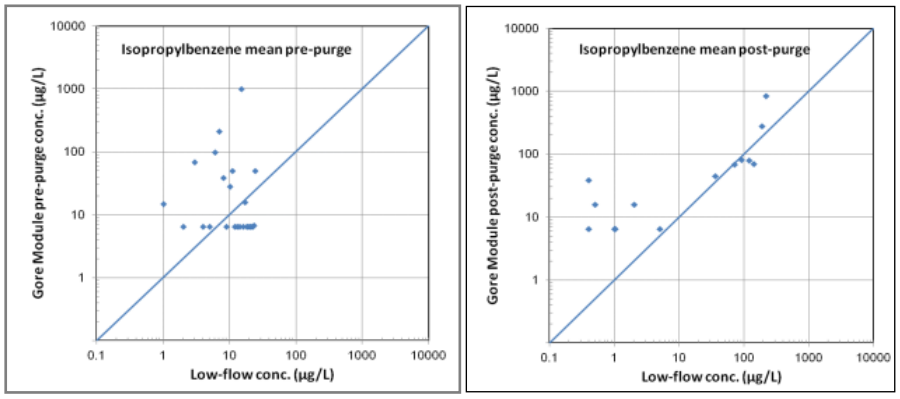

Figure 23. Comparison of the mean pre-purge (left) and post-purge (right) GORE data with the low-flow data for isopropylbenzene.

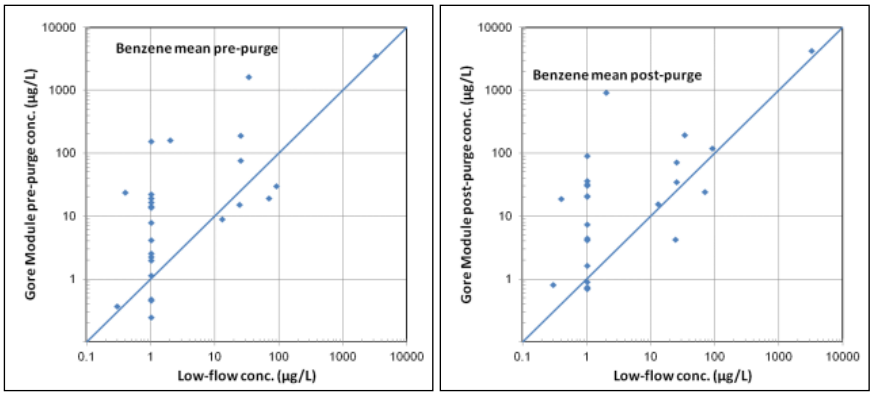

Figure 24a. Comparison of the mean pre-purge (left) and post-purge (right) GORE data with the low-flow data for BNZ.

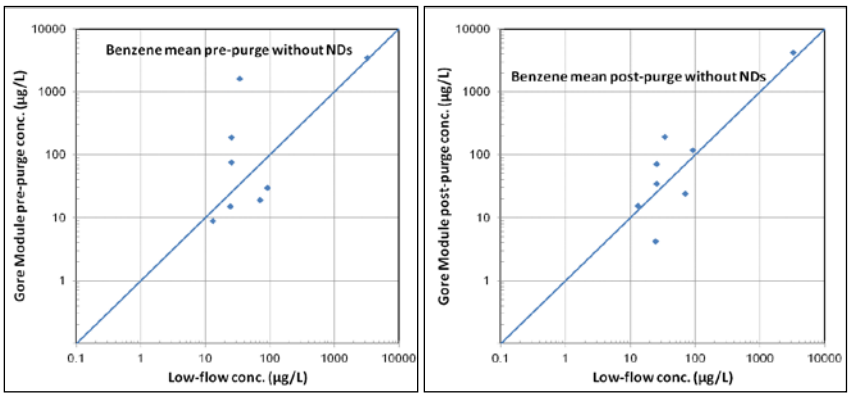

Figure 24b. Similar comparisons for BNZ with the values near the detection removed.

Again, although there was slightly better agreement between the post-purge and low-flow data than between the pre-purge and low-flow data, there were no statistically significant differences between the pre-purge and post-purge Gore data for any of the analytes.

7.2.4 Profiling Contaminant Concentrations with Depth

Because most of the wells at this site had relatively short well screens, only eight wells were profiled. With the exception of the Modules in well HY2-4460, which was a shallow well, all the Modules were at least 30 feet below the water table.

7.2.4.1 <u>Well Number PH2-5369</u>

This well is located at the source in deep overburden. For both the pre-purge and post-purge GORE Modules, there was a very pronounced concentration gradient with increasing depth for most analytes. This trend was most pronounced for the post-purge samples (Figure 25). This finding is not surprising given that pronounced stratification was previously found in the wells at the epicenter of the plumes at the APG site.

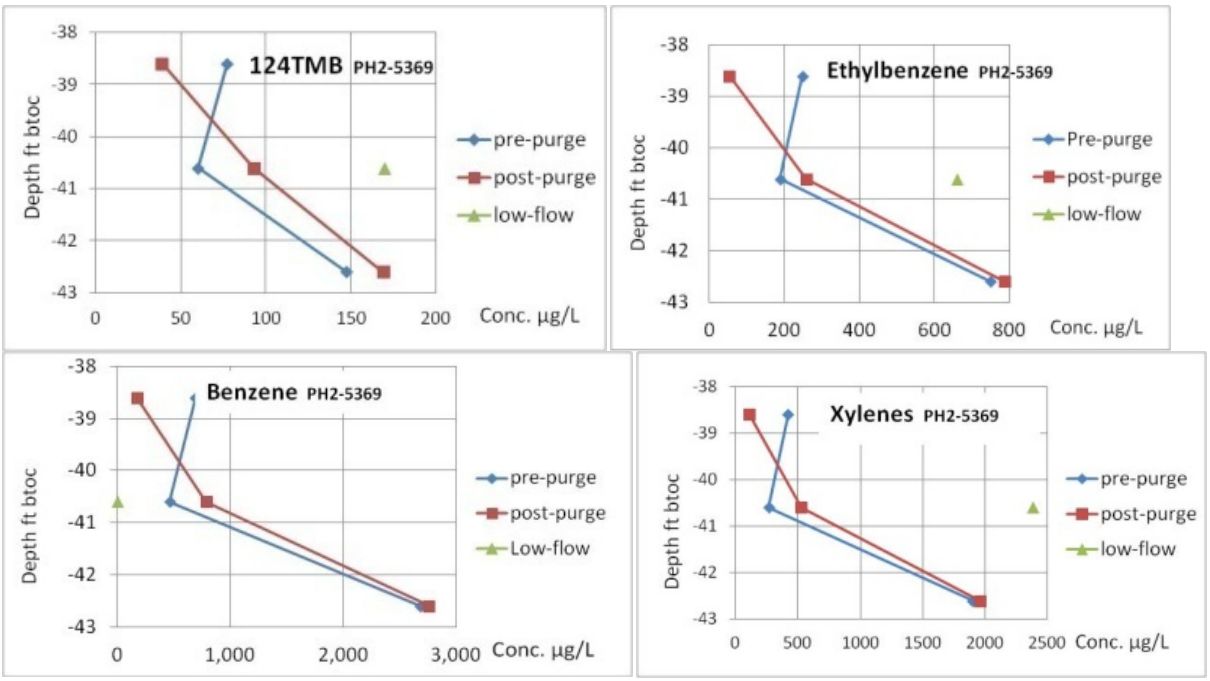

Figure 25. Contaminant profiles for well PH2-5369 for 124-TMB, EBNZ, BNZ, and XYLs.

When low-flow sampling was used, concentrations of most analytes agreed most closely with the concentrations found in the Modules collected from the deepest part of the screened interval. This was generally true for both the pre-purge and post-purge samples. The poorest agreement was for BNZ, where the reported low-flow concentration was near the detection level and was two to three orders of magnitude less than the concentrations found with the Modules. It is not clear to us why the BNZ concentration was so low in the low-flow sample compared with high levels found with the Modules. However, the high concentrations of BNZ found with the GORE Modules agree well with what one might expect given the concentrations of the other BTEX compounds in this sample.

Clearly placing the GORE Modules at the mid-level of the screen does not yield the highest concentrations of most of these analytes or the best agreement with low-flow sampling.

7.2.4.2 Well Number PH2-6660

This well is located in bedrock, downgradient of the source in the dissolved plume. There also was a pronounced concentration gradient in this well for several analytes. Unlike the previous well where concentrations were highest in the deepest portion of the screened interval, concentrations tended to be highest in the mid-section of the screen, especially for the pre-purge samples.

When the low-flow sample is compared with the Modules, it was seen that concentrations of several analytes agreed best with the samplers collected from the shallowest portion of the well screen (Figure 26). The poorest agreement between the two sampling methods was for EBNZ, which was not detected in the low-flow sample but was with the GORE Modules. These data

indicate that low-flow sampling collected cleaner water that apparently came from the upper portion of the well screen.

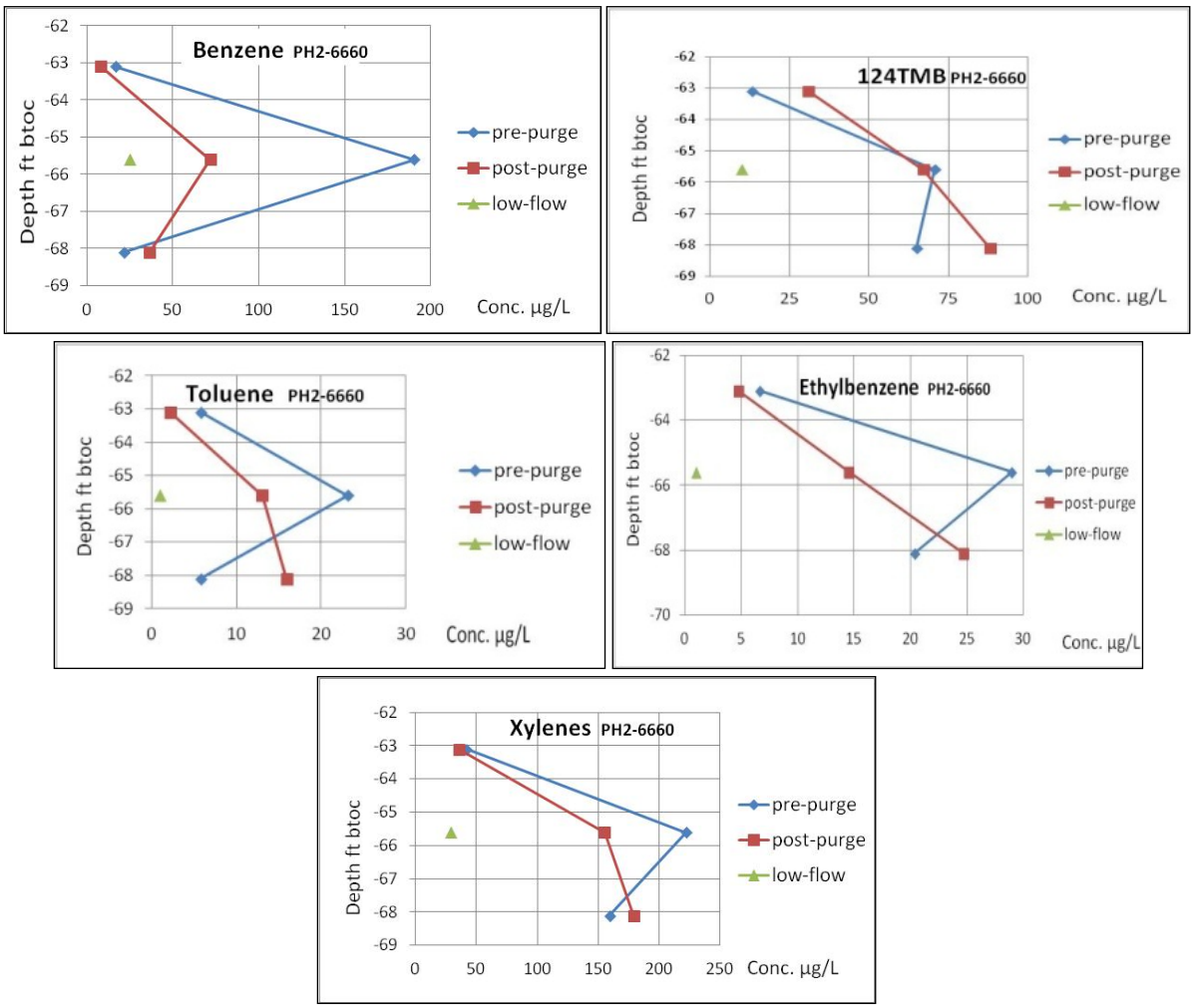

Figure 26. Profile of contaminant concentrations in well PH2-6660 for BNZ, 124-TMB, TOL, EBNZ, and XYLs.

Because this was a downgradient well and low concentrations of analytes were expected, the Modules were left in the well for a longer contact time (3 hours). It is interesting that apparently by leaving the Modules in the wells for a longer period that the project team was able to detect low concentrations of some analytes (EBNZ and TOL) that were not detected using the current analytical method used for the low-flow samples. A good agreement was found between replicate samples for EBNZ, 124TMB, and the XYLs, but not for BNZ and TOL (these were post-purge samples).

Once again, placing the GORE Modules at the mid-level of the screen did not yield the best agreement with low-flow sampling.

7.2.4.3 Well Number PH2-6627

Well PH2-6627 is located downgradient in the shallow overburden and is considered a sentry well so once again the Modules were left in the well for the longer 2-hour period. When low-flow sampling was used, concentrations of TOL, EBNZ, the XYLs, 124TMB, and 135TMB were below the detection limit, and the concentration of NAPH was at the detection level. In contrast, concentrations well above the detection level were found for these analytes using the GORE Modules. Unlike the previous wells, there was no indication of any substantial contaminant stratification for any of these analytes either before or after purging (Figure 27). Again by using a longer deployment time for the Modules, one is able to detect concentrations of several analytes that were not detected by using low-flow sampling. For most of the analytes, there was excellent agreement between the two replicate samplers.

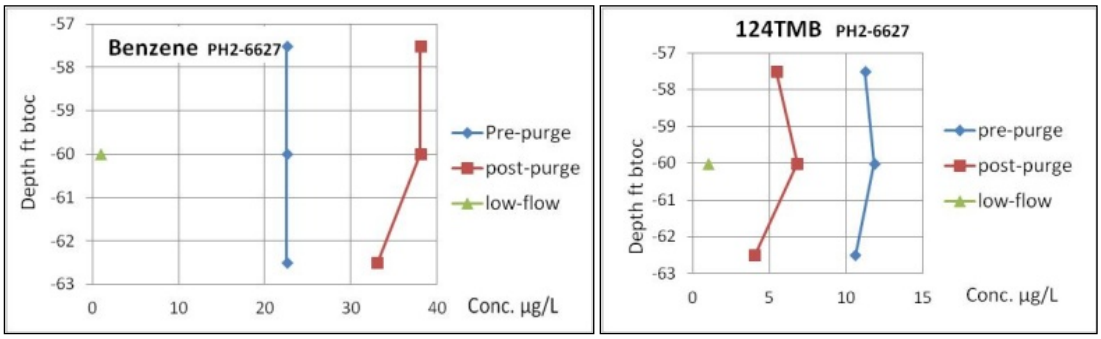

Figure 27. Contaminant profiles in well PH2-6627 for benzene (left) and 124TMB (right).

7.2.4.4 Well Number HY2-4460

HY2-4460 is a source well that is located in the shallow overburden. As it has been seen in other wells near a source, there was a pronounced concentration gradient with depth in this well.

Concentrations were considerably lower for the shallowest sampler than for the two deeper samplers (Figure 28). For some analytes the deepest sampler had the highest concentration, while for other analytes the highest concentration was associated with the mid-level Module. This tended to vary depending upon whether the sample was collected prior to purging or after.

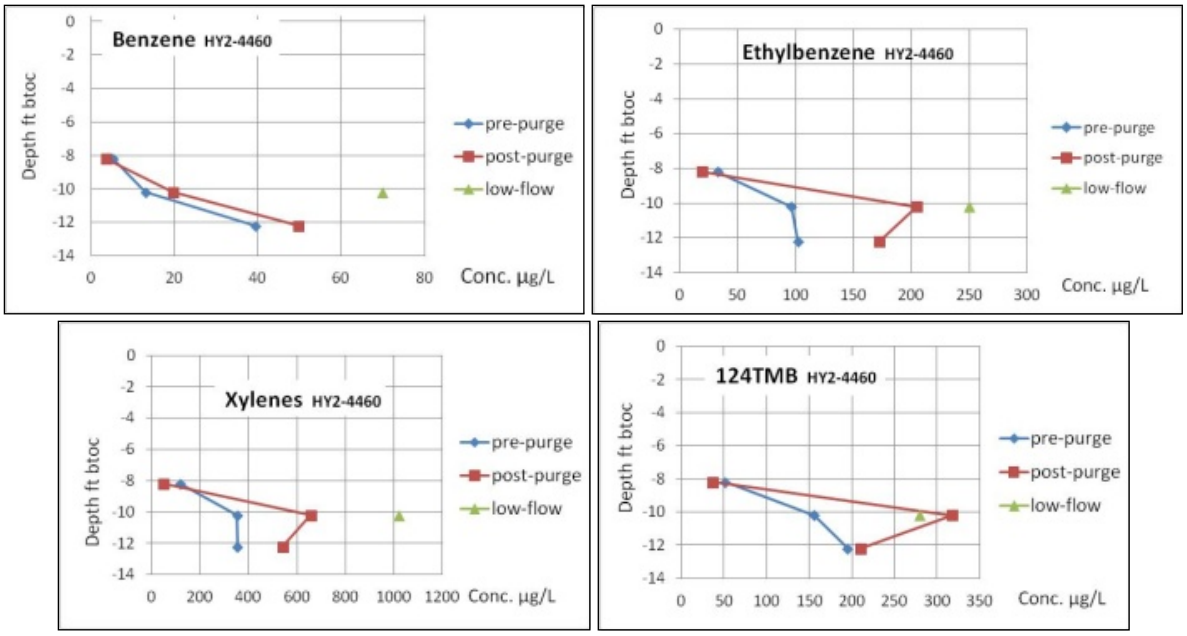

Figure 28. Contaminant concentrations with depth in well HY2-4460 for BNZ, EBNZ, XYLs, and 124TMB.

Generally, the post-purge Gore data agreed better with the low-flow data than did the pre-purge data. For most of the analytes, concentrations were highest in mid-level, post-purge sampler and agreed best with low-flow concentrations. These data indicate that purging the well brought in water with generally higher concentrations, most likely from the same source that is interrogated by the mid-level Module.

7.2.5 Discussion

Although good agreement has been seen between the two sampling methods for both the mid-level Gore data and the mean Gore data, we see that there was substantial scatter along the y-axis at the detection level for the low-flow samples for most of the analytes (e.g., as shown for TOL in Figure 20 and for EBNZ in Figure 21). This is primarily due to differences in the way the low-level data was reported. For the low-flow samples, the laboratory used the reporting limit while for the Modules the data was reported at the MDL level. Thus, the Gore data tends to scatter above and below the reporting limit for the low-flow samples. This was true for most analytes. However, for other analytes, the MDLs for the GORE Modules were higher than the reporting limits for the low-flow samples and thus the scatter is about the x axis (e.g. as shown for isopropylbenzene in Figure 23 left).

With respect to the placement of the passive samplers within the well screen, for some wells there was good agreement between the mid-level sampler and the low-flow concentrations and thus placement of the sampler at the mid-point of the well screen might be advisable. However, in other instances, purging brought water into the well from a zone that was not interrogated by the mid-level sampler and thus low-flow analyte concentrations agreed best with the upper or bottom sampler. This is not surprising given the differences in how passive and active sampling

methods obtain a sample. The project team also found that the mid-level sampler did not provide the highest concentrations of contaminants in the wells, which is important to regulators.

The differences in contaminant concentrations with depth explain some of the scatter in the data when the Gore data were plotted against the low-flow data. These differences also explain why for some wells the mid-level sampler agreed better with the low-flow data, while in other cases the mean concentration of the samplers yielded better agreement with the low-flow data.

The team also learned that in many instances analytes were detected using the Modules at levels substantially above the reporting limit for the low-flow samples (i.e., ten times greater or more), while the values reported for the low-flow samples were below the detection level. This was especially true in the wells where analyte concentrations would be low and had left the samplers for an extended deployment time. These differences contributed to additional scatter in the plots at the detection level for these two methods. However, the good agreement between replicate Modules in these wells suggests that these analytes were actually present at a measurable level and that additional evaluation or calibration of the Modules for the longer deployment times may be needed.

8.0 PERFORMANCE ASSESSMENT

The primary success criteria for this demonstration were that the GORE Module could provide equivalent (or better) plume delineation and analyte sensitivity when compared with low-flow purging and sampling, that the method has good reproducibility, and that using this method would result in a substantial cost avoidance or cost savings (preferably at least 20%). Secondary criteria included the ease of use of the technology, whether the technology is robust, and that there would not be any significant scale-up constraints.

8.1 EQUIVALENT OR BETTER PLUME DELINEATION

8.1.1 Sensitivity of Method

For the analyses at the APG site, the MDL for the analytical method used for the low-flow samples was approximately 1/20 of that of the method used for the GORE Modules. While the detection levels for the Modules were below the action levels (i.e., the USEPA's MCLs) for these contaminants, some agencies require or recommend quantitation limits that are 1/3 to 1/10 of the action levels. For this reason, the project team recommended to the Gore Laboratory that they should continue work to lower detection capability for this technology.

Subsequently, at the Pease site, the detection capability of the GORE method was found to be comparable to the analytical method used for the low-flow samples for most of the analytes (i.e., the MDLs were equivalent). For the remaining analytes, the MDLs were still higher for the GORE Modules than the analytical method used for the low-flow samples. However, even for these analytes the GORE Modules provided data that was below one-tenth of the USEPA's MCLs for drinking water. This demonstrates the improved sensitivity of the analyses of the Modules because of the work conducted at the APG test site.

At the Pease site, low concentrations of contaminants were detected by using the Gore Modules that were not found using low-flow sampling, even though the concentrations were well above the detection levels of the low-flow sampling method. In several instances, these findings were confirmed by replicate data for the Modules. Overall, these differences and differences in the MDLs for the two methods resulted in considerable scatter at the detection levels when the two methods were plotted.

8.1.2 Agreement between Analyte Concentrations for the GORE and Low-Flow Data

At both sites, we compared the data for the mid-level samplers and the data for the mean values for the Modules (at the three depths) with the data for the low-flow samples. In most instances, we found that there was good to excellent agreement between the two sampling methods.

Specifically, at the APG site there was a strong, statistically significant linear relationship between the raw GORE data and the raw low-flow data for all five analytes. For three analytes, this relationship was typically one to one (i.e., the slope of the line for the plotted data was not significantly different from 1.0). For two other analytes, it was found that the slope of the line for the raw data was significantly less than 1.0. It was thought that perhaps the post-purge data

would agree better with the low-flow data than the pre-purge data, but this was found not to be the case.

For the Pease site, when the data for the mid-level samplers and the data for the mean concentrations were compared to the data for the low-flow samples, in all cases (but one) there were statistically significant linear relationships between the GORE data and the low-flow data; and the slopes of these line were not significantly different from 1.0. These relationships were slightly better for the mean data than the mid-level data. The poorest agreement was for the mid-level BNZ data, and the slope of the line for the raw TOL data was significantly less than 1.0. As with the previous site, there was no better agreement between the post-purge and low-flow data than there was between the pre-purge and low-flow data.

8.1.3 Vertical Profiles of Wells with GORE Modules

While the lack of statistically significant differences and the presence of statistically significant linear agreements between the low-flow sampling data and the GORE data were criteria that we used to evaluate the GORE sampling method, it is important to remember the conceptual differences of each sampling technology (as mentioned in section 3.2) when interpreting the data from this demonstration or at any site where a similar comparison is made.

Although there was generally good agreement between the GORE data and the low-flow data at both sites, there was pronounced stratification found in analyte concentrations with depth in some wells. This stratification was greatest at the epicenters of the plumes and even occurred in a well with a short (5-foot) screen and another with a long (20-foot) screen.

There were instances where the low-flow concentrations agreed best with the mid-level GORE Modules. However, there were other instances where purging brought water into the well from a zone that was not interrogated by the mid-level sampler; and thus, low-flow analyte concentrations agreed best with the upper or bottom sampler. In some cases, either the upper or lower Module had much higher concentrations than the mid-level sampler. Also, the post-purge samples agreed best with the low-flow concentrations in some wells while in other wells, the opposite was true. These findings have implications when selecting a sampling method (i.e., when considering whether to use a passive method or a pumped method and also when trying to decide where to place a passive sampler in the well screen).

8.2 REPRODUCIBLE DATA

8.2.1 Reproducibility of the GORE Modules among Replicate Field Samples

Another important objective for this demonstration was that the GORE-Module method could yield good precision. We set as a guideline that the RSD should be 20% or less.

At the APG site, reproducibility was generally good. For three analytes, at least 90% of the replicate samples met the guideline and at least 70% of the replicates for the three other analytes also met the guideline. It was noted that at this site, most of the poor reproducibility occurred in three of the shallowest wells that had screens near the top of the water table. Because these samples were collected after purging the well, we believe that purging may have lowered the

water table sufficiently to affect reproducibility. This would not be a concern when using the GORE Modules because the wells would not be purged with this sampling method.

At the Pease site, the reproducibility was good for most (nine) of the analytes where at least 80% of the samples met the guideline. The reproducibility of three other analytes was not quite as good but at least 60% of these samples met the guideline. The reproducibility was poorest for TOL where only 35% of the replicate samples met the guideline. However we noted that, like the Aberdeen site, the poor reproducibility was primarily associated with samples collected from a few of the wells. Specifically, the samplers were left for more than 2 hours in three deep wells where the water table was 40 feet, or more, above the shallowest Module. While it is known that water can penetrate the membrane at these depths, this is accounted for in the model used to calculate analyte concentrations. However, it may be that when samplers are left in the well for longer periods at these depths that the uptake of some analytes is no longer linear, and/or it may be that the algorithm needs some minor modification.

Because each GORE Module contains a duplicate packet of sorbents, samples with questionable results can be rerun without having to go back to the field to collect additional samples. Given that the samples can be rerun months later if need be (since the shelf life for the Modules is three months rather than the 14-day holding time for water samples), this could produce additional cost savings that were not included in the cost analyses.

8.2.2 Agreement in the Analyses of the GORE Modules among Different Laboratories

At the APG site, the analyses of the Modules by the Gore Laboratory were compared with the independent analyses of the Modules by a contract laboratory. In all cases, there was excellent agreement between the results by the two laboratories.

8.3 REDUCED SAMPLING COST

Another primary objective was that this sampling device provides a minimum cost savings of 20% when compared with conventional low-flow purging and sampling. This will be discussed in more detail in the next section. However, using the initial quoted price, cost savings ranged from 18% to 35% at the APG site and from 10% to 25% at the Pease site, depending upon whether the field crew consisted of one or two individuals. Using a more recent price quote from Gore, cost savings would be greatly improved and would range from 30% to 45% at APG and from 30% to 40% at the Pease site.

8.4 EASE OF USE

The field crew found that these samplers were easy to use. The project's principal investigator (PI) was amazed to see how many wells could be sampled in a day when the pumping associated with low-flow sampling was eliminated. The only complaint was that the Gore crew instructed our project team that when blotting the samples, to be sure to carefully remove any residual water. It was hard to remove the residual water from under the tag with the serial number on it.

8.5 ROBUSTNESS OF THE TECHNOLOGY

The samplers worked as designed although there were some concerns with samplers left for more than 2 hours if they were placed more than 30 feet below the water table. Because there is very little ancillary equipment associated with this technology, there are fewer handling and safety concerns, such as possibly spilling gasoline, keeping the power cord from the generator dry in the rain, keeping the samples cold in the field (especially on hot, sunny days), and during shipping, and packing the coolers to prevent leaking during shipping. Also, there are no moving parts in the Modules that can break, and this also could result in additional cost savings that were not accounted for in the cost analyses.

8.6 SCALE-UP CONTRAINTS

The project team do not foresee that there would be any scale-up constraints that would prevent wide-scale use of this technology except in small diameter piezometers. While these samplers cannot be used in the smallest of piezometers, they can be used in wells and piezometers that are larger than 0.25 inches in diameter.

9.0 COST ASSESSMENT

9.1 COST MODEL

One of the objectives of this demonstration was to determine the potential cost avoidance or cost savings associated with using the GORE Modules vs. using conventional low-flow purging and sampling methods. The cost models used in these analyses include the initial site work, initial capital costs, sample-collection costs, costs associated with sample processing and analyses, and expected long-term O&M costs. We based the cost estimates for each site on specifics for the site (e.g., the depth of the wells) and information gathered during work at the site (e.g., the average purge time for a well, average set-up time, clean-up time, etc.). For these determinations, we made the following assumptions:

- Each site has 50 monitoring wells.
- The wells are to be sampled quarterly over a period of 10 years.
- Low-flow sampling is conducted either with dedicated bladder pumps or with peristaltic pumps with dedicated tubing.
- The average sampling depth for the wells determines the length of the tubing or sampling line needed to sample the site.
- The labor rate for members of the field crew is $50 per hour.
- A work day is limited to 8 hours (to avoid overtime charges).
- Sampling is conducted by a crew that is on site, thus, travel expenses are not included in the cost analyses.
- Low-flow sampling uses a crew of two quarterly sampling costs include the cost of the Modules; the labor for one person to take the water level and temperature measurements, to deploy the samplers in the well, and to decontaminate the water-level meter; and the labor for another person who follows later and retrieves the samplers and cleans up the site.

The primary sample processing and analyses costs include a small amount of labor to fill out the chain-of-custody forms and to box up the samplers, and the cost of shipping the samples via regular mail. No ice is needed to ship the samples; and no special handling is needed for shipping, such as over-night delivery, because the samplers are stable for approximately three months. Also, there is no separate cost associated with the laboratory analyses; this cost is included in the purchase price of the Modules.

Table 2 gives the cost model for the GORE Module technology. Initial site work is relatively minimal and includes labor for purchasing equipment and supplies and for preparing the sampling lines for deployment in the wells. The major initial capital cost is the purchase of a water-level and temperature probe. Other less costly expenses are the sample lines, reusable weights, plastic sheeting (for laying out the sampling line to measure it), sprayers for decontaminating and rinsing the water-level probe, and a small drum for holding the wastewater generated from cleaning the water-level probe.

Table 2. Cost model for the GORE Modules.

Cost Element	Data Tracked During the Demonstration	Costs	
(1) Initial startup	• Labor: initial planning fieldwork, purchasing equipment and supplies • Labor measuring lines for deployment	Field personnel	$50/ hour
	• Equipment and supplies: one-time purchases (50 wells)	Water-level and temperature meter	$1364/each
		Sampling line, 225 feet	$3/role
		Stainless weights	$24/50
		Decon buckets	$5/each
		Sprayer for decon	$9/each
		Plastic tarp	$13/each
		Drum for waste water	$40/each
(2) Quarterly sampling costs	• Samplers	GORE Modules	$190/each
	• Labor: sampler installation and retrieval, water level and temperature readings, site cleanup	Field personnel	$50/hour/person
(3) Sample processing and analyses	• Shipping	Samplers to lab	$15/ box
	• Analytical costs	Included in purchase price	$0
(4) O&M	• Replace equipment and supplies	Sampling line, 225 feet	$3/role
		Water level and temperature meter	$1364/each
		Sprayer for decon	$9/each
		Tarp	$13/each
		Drum for waste water	$40/each
(5) LTM costs	• Total Costs, no inflation	(a) Annual sampling cost	Sum
		(b) Total costs after 1 year	Sum of start-up costs and annual sampling cost
		(c) After 10 years	= #5b + (9 × #5a)
	• Cumulative Costs, using OMB's* 2.25% annual inflation	After 1 year	= #5b
		After 2 years	= #5b + (1.0225 × #5a)
		After 10 years	Cumulative sum based upon compounded interest

*OMB is the White House's Office of Management and Budget
Website: www.whitehouse.gov/omb

Quarterly sampling costs include the cost of the Modules; the labor for one person to take the water level and temperature measurements, to deploy the samplers in the well, and to decontaminate the water-level meter; and the labor for another person who follows later and retrieves the samplers and cleans up the site.

The primary sample processing and analyses costs include a small amount of labor to fill out the chain-of-custody forms and to box up the samplers, and the cost of shipping the samples via regular mail. No ice is needed to ship the samples; and no special handling is needed for shipping, such as over-night delivery, because the samplers are stable for approximately 3

months. Also, there is no separate cost associated with the laboratory analyses; this cost is included in the purchase price of the Modules.

The primary sample processing and analyses costs include a small amount of labor to fill out the chain-of-custody forms and to box up the samplers, and the cost of shipping the samples via regular mail. No ice is needed or special handling (such as overnight delivery) is needed for shipping because the samplers are stable at room temperature for approximately three months. Also, there is no separate cost associated with the laboratory analyses; this cost is included in the purchase price of the Modules.

O&M costs would primarily be the purchase price to replace those items listed in the start-up costs.

9.1.1 Cost model for low-flow sampling

Table 3 gives the cost model for low-flow sampling. The labor costs for initial site work include purchasing equipment, setting up a contract for laboratory analyses, and deploying the pumps in the wells and purging them. (Initial purging of the well is recommended so that the field crew can confirm that the pumps are working, and it allows time for the materials in the pumps to equilibrate with analytes in the well water; thereby reducing potential losses of analytes due to sorption.)

Table 3. Cost model for low-flow sampling.

Cost Element	Data Tracked During the Demonstration	Costs	
(1) Initial startup	Labor: initial planning fieldwork, purchasing equipment and supplies Labor: installation of equipment in wells	Field personnel	$50/hour/person
	Major equipment and supplies: one-time purchases (50 wells)	Bladder pump	$684/pump
		Tubing (49 foot roll)	$116/roll
		Generator	$1100/each
		Air compressor	$180/each
		Pump controller	$2260/each
		Water quality meter	$3650
		Turbidity meter	$1100
		Flow-thru cell	$300/each
		Water-level meter	$575/each
		Coolers	$100/each
	Assorted other smaller equipment and supplies	Purge buckets, decon equipment, gas cans, moisture traps, GFI power strips, rain canopy, table, chairs, waste drum, etc.	Actual costs
(2) Quarterly sampling costs	Materials and supplies		Actual costs
	Labor: sampling 50 wells and waste disposal	Field personnel	$50/hour/person

Table 3. Cost model for low-flow sampling (continued).

Cost Element	Data Tracked During the Demonstration	Costs	
(3) Sample processing and analyses	Labor: sample preparation	Field personnel	$50/hour/person
	Express shipping	Per cooler	Actual costs
	Miscellaneous supplies	Ice, plastic bags	Actual costs
(4) O&M	Labor: purchase, repair, and replace equipment; purge wells with new equipment	Field personnel	$50/hour/person
	Repair/replace equipment	Meter for purge parameters	$3650/each
		Turbidity meter	$1100/each
		Water-level meter	$575/each
		Generator	$1100/each
		Compressor	$180/each
		Bladder pumps	$684/each
		Pump controller	$2650/each
		Coolers	$100/each
		Waste storage drums	$60/each
		Tubing	$116/roll
(5) LTM costs	Total costs, no inflation	(a) Annual sampling cost	= #2 + #3 + (#4/10)
		(b) Total costs after 1 year	= #5a (above) + #1
		(c) Total after 10 years	= #5b + [9 × (#5a)]
	Cumulative costs, using OMB's 2.25% annual inflation	Year 2 year	= #5b + (1.0225 × #5a)
		After 10 years	Cumulative sum based on compounded interest

With respect to the initial capital costs, there is a considerable amount of equipment that must be purchased. This includes dedicated bladder pumps and tubing, generators, controllers, extension cords, air compressors, air hose, purge-parameter equipment and initial supplies, decontamination equipment, waste buckets, storage drums for purge water, chairs and tables, and canopy for use in bad weather. The number of items that are needed depends upon the number of sampling crews that are deployed at the same time.

Sampling costs include labor and some supplies. Labor costs include packing up equipment and materials needed for sampling; filling coolers with ice; setting up the needed equipment on site, including calibration of the equipment; purging the well until the purge parameters stabilize; collecting and labeling the samples; decontaminating the water-level meter and purge-parameter equipment; disposing of decontamination and purge water; and site cleanup. Supplies include gasoline, deionized water and detergent for decontamination, purge-parameter supplies (standards), ice, desiccant, etc.

Analytical costs are the primary cost associated with sample processing and analyses. Other costs include the labor needed to pack the coolers and complete the chain-of-custody forms. The other major cost would be for shipping the coolers. However, we have found that it is becoming increasing more difficult to use express carriers to ship coolers that contain water samples and loose ice. Typically, these carriers now will only accept the coolers if the water samples and ice is double packed in zip-locked plastic bags. Even with double bagging the samples and ice, one of the carriers told us that in the future they will require customers to sign a document accepting financial responsibility for any damage caused by coolers that leak. While shipping costs can be eliminated by using a local laboratory, the cost of a courier to transport the samples from the

field to the laboratory would have to be borne by the sampling crew or added to the laboratory's cost.

O&M costs include replacing tubing, which would tend to crack with use, especially at the top of the wells; replacing and repairing the pumps, purge-parameter equipment, and water-level meter; and replacing coolers.

9.2 COST DRIVERS

The cost analyses revealed that the major cost drivers are the following:

- The sampling time for low-flow sampling and for the GORE Modules, especially the number and size of the field crews;
- Equipment costs for low-flow sampling;
- Cost of GORE Modules; and
- Analytical costs for low-flow sampling.

9.3 COST ANALSYSIS

9.3.1 Cost Analysis for Sampling at APG

Tables 4 and 5 summarize the estimated costs for sampling using the GORE Modules and low-flow sampling, respectively, at a site similar to the SBR site at APG. More detailed information on the cost analyses (for both sites) can be found in Parker et al. (2014).

Table 4. LTM costs associated with using the GORE Modules at the APG site.

Cost Element	Data Tracked During the Demonstration	Details	Cost ($)
(1) Initial startup	Labor		$550
	Equipment and supplies	Equipment subtotal	$1556
	Total costs for startup	**Initial startup costs**	**$2106**
(2) Quarterly sampling	Labor		$1832
	Samplers and supplies		$10,462
	Total costs for sampling	Quarterly sampling costs	$12,294
		Annual sampling cost	**$49,176**
(3) Sample processing and analyses	Labor		$16
	Shipping		$15
	Analyses by laboratory		$0
	Total costs for sample processing and analyses	Quarterly processing & analyses costs	$31
		Annual processing & analyses costs	**$125**
(4) O&M	Equipment replacement over 10 years		$1453
		Annual O&M subtotal	**$145**
(5) LTM	Total costs, no inflation	Annual sampling cost	$49,301
		Cost after Year 1	$51,406
		Cost after Year 10	$496,564
	Cumulative costs, assuming OMB's 2.25% annual inflation average	After Year 1	$51,406
		After Year 10	**$538,911**

Table 5. LTM costs associated with using low-flow sampling at the APG site.*

Cost element	Data Tracked During the Demonstration	Details	Cost ($)
(1) Initial startup	Labor	One crew of 2 individuals	$8840
	Equipment		$61,183
	Total costs for startup	**Initial startup subtotal**	**$70,023**
(2) Quarterly sample collection	Labor	One crew of 2 individuals	$10,295
	Supplies	.	$730
	Total costs for sampling	Quarterly sampling subtotal	$11,025
		Annual sampling subtotal	**$44,100**
(3) Sample processing and analyses	Labor: processing samples		$900
	Supplies and shipping		$1983
	Laboratory analyses		$6050
	Total costs for sample processing and analyses	Quarterly sample processing & analyses subtotal	$8933
		Annual cost	**$35,732**
(4) O&M	Equipment replacement		$28,007
	Labor		$2075
	Total costs	O&M subtotal for 10 years	$28,007
		Annual O&M subtotal	**$2801**
(5) LTM	Total costs, no inflation	Annual sampling cost	$79,833
		Cost after Year 1	$141,016
		Cost after Year 10	$892,185
	Cumulative costs, assuming OMB's 2.25% annual inflation average	After Year 1	$141,016
		After Year 2	$22,645
		After Year 10	**$978,102**

*Based upon a field crew of two individuals.

For the Modules, the LTM costs were initially determined using the most recent price quoted to the project team. Additional cost were analyzed using the original price estimate received from W. L. Gore. The LTM costs were calculated based on some or all of the wells needing to be redeveloped or rehabilitated; and the costs were determined if the price of the Modules were to be further reduced (from the most recent price quote) as a result of large-scale production of the Modules.

For these samplers, it was determined that 99.75% of the total 10-year LTM cost for the Modules is associated with the sample collection phase (Table 4); and of that cost, the price of the samplers is approximately 85%, and labor (sampler deployment, retrieval, etc.) is the other 15%. In contrast, the initial start-up costs, sample processing and analyses costs, and costs for O&M are essentially negligible with this method (i.e., the costs for each of these were less than 0.4%).

Although, the initial cost analysis for low-flow sampling was based upon the assumption that dedicated bladder pumps would be used in each well, the wells sampled were relatively shallow and were sampled using a peristaltic pump (with dedicated tubing). Therefore, a cost analysis was completed assuming equipment was used to collect the samples. The number of peristaltic pumps needed would vary depending on the number and size of the field crews.

There are areas at this site where there are a lot of wells that are close together, and that would reduce the sampling time, especially for low-flow sampling. However, there are other wells that are remote. For those wells, access is more difficult; and thus more time is needed to sample these wells. Typically, the most common practice in the industry for low-flow sampling is to use a team of two individuals at each well. This assumption was used initially in determining the cost of low-flow sampling, provided in Table 5. While using two people to sample a site is the safest procedure (in case of injury) and there are time savings associated with set up and tear down of a site, the time spent purging the well is typically more than a half hour and does not require two individuals. Therefore, the cost analyses was performed based upon a field crew that consisted of two individuals and also based also upon two field crews (of one individual each).

Because many laboratories will negotiate on the price of analyses and offer their services at a reduced cost, a cost analyses was conducted for low-flow sampling assuming that the analytical costs were lowered by 10% for the APG site and by 15% for the Pease site. The project team also calculated what the LTM costs would be if some of the wells had to be redeveloped or rehabilitated.

In contrast to the findings for the GORE Modules, the start-up costs for low-flow sampling (Table 5) account for about 7% of the total LTM costs for 10 years; and the sampling equipment (dedicated pumps, purge equipment, etc.) accounts for 87% of that amount. Sample collection accounts for 45% of the total LTM costs; and of that amount, 93% is labor. Laboratory analyses account for another 25% of the total LTM costs, and the O&M costs are only about 3% of the total LTM costs. The team believes that these figures agree with what most practitioners believe; i.e., that low-flow purging and sampling is a labor-intensive and costly sampling method and that although dedicated sampling equipment is expensive, it is only a small amount of the total LTM costs. It was calculated that the equipment accounts for only 9% of the total LTM costs, which was determined by combining equipment costs for initial start up and for O&M.

Table 6 shows the cost avoidance or cost savings that can be achieved with the various scenarios mentioned previously. By using the original (higher) price quote for the Modules and using one sampling team of two individuals to sample the wells using low-flow sampling, the cost savings is about 35%. This is well above the desired goal of a 20% cost savings. However, if two teams (of one individual each) were used to sample the site using low-flow sampling, the cost savings for the Modules would only be about 18%, which is just slightly below the desired 20%. This indicates that the price of the Module is a critical element for cost savings to occur. Clearly, if it was necessary to recondition either all or some of the wells for the Modules (but not low-flow sampling) would reduce the cost savings below the desired goal.

Table 6. Cost savings for LTM using GORE samplers at the APG site based upon different assumptions about work at the site.

Comparison	% of LTM Cost	% Cost Savings
Original Gore price estimate/2 teams using BPs	82.2	17.8
Original Gore estimate/1 team of 2 (using BPs)	64.5	35.5
Original Gore estimate/LF, 1 team using PPs	67.1	32.9
Original Gore estimate/LF, 2 teams using PPs	85.5	14.5
New Gore estimate/LF, 2 teams (using BPs)	70.2	29.8
New Gore estimate/LF, 1 team (using BPs)	55.1	44.9
New Gore estimate/LF, 2 teams (using PPs)	73.1	26.9
New Gore estimate/LF, 1 team (using PPs)	57.3	42.7
New Gore estimate, recondition *all* wells/LF, 2 teams (using BPs)	70.6	29.4
New Gore estimate, recondition *some* wells/LF, 2 teams (using BPs)	70.4	29.6
New Gore estimate, recondition *all* wells/LF 1 team (using BPs)	55.4	44.6
New Gore estimate, recondition *all* wells/LF, 2 teams (using BPs), recondition some wells	70.5	29.5
20% lower Gore/LF, 2 teams (using BPs)	58.4	41.6
New Gore estimate/LF, 2 teams (using PPs), with 10% lower analytical cost	77.3	22.7
LF, 2 teams (BPs)/LF, 1 team of 2 (using BPs)	78.5	21.5
LF, 2 teams: PPs versus BPs	96.1	3.9
LF, 1 team: PPs versus BPs	96.1	3.9

If peristaltic pumps were used (instead of bladder pumps) for low-flow sampling of the wells, the cost savings for the Modules are now only 21% and 14% based upon using two and one low-flow team, respectively.

When we use the more recent price quote for the Modules, the cost savings are substantially greater, approximately 30% and 45% compared with using two low-flow teams and one low-flow team, respectively. Using peristaltic pumps for low-flow sampling only decreases these cost savings by a few percent. Reconditioning either some or all of the wells where the Modules are used still provides nearly 30% cost savings, even when compared with the more cost-effective option of using two teams to collect the low-flow samples. However, it is more likely that at least some of the wells where low-flow sampling is used would also require reconditioning. In this case, the cost savings for the Modules would be about 30% (again assuming that two low-flow teams were used). If the laboratory reduced the price of the analyses for the low-flow samples by 10%, the cost savings for the GORE Modules would still be over 20%.

In conclusion, as long as the more recent price provided by W. L. Gore is used in these analyses, this technology can provide a cost savings of 25% to 45% at this site when compared with low-flow sampling.

9.3.2 Cost Analysis for Sampling at the Former Pease AFB

Tables 7 and 8 show the estimated costs for sampling with the Modules and low-flow sampling (using a team of two), respectively, a site with similar conditions to those found at the former Pease AFB. Most of the assumptions made for the cost analyses at the APG site hold for this site as well. One of the differences with this site is that most of the wells were too deep to use a

peristaltic pump, so a cost analysis was not conducted that considered using peristaltic pumps. For this analysis, we assumed two field crews (each consisting of one person).

Table 7. Cost estimate for LTM using the GORE Modules at the former Pease AFB site.

Cost Element	Data Tracked During the Demonstration	Details	Cost ($)
(1) Initial startup	Labor		$550
	Equipment		$1574
	Total costs for startup	**Initial startup costs**	**$2124**
(2) Quarterly sample collection	Labor		$1732
	Samplers and supplies		$10,4774
	Total costs for sampling	Quarterly sampling subtotal	$12,206
		Annual sampling subtotal	**$48,824**
(3) Sample processing and analyses	Labor		$16
	Shipping	Regular mail	$15
	Analyses		$0
	Total costs for sample processing and analyses	Quarterly sample processing & analyses	$31
		Annual cost	**$125**
(4) O&M	Equipment replacement	Water-level and temperature meter	$1471
	Total costs	O&M subtotal for 10 years	$1471
		Annual O&M subtotal	**$147**
(5) LTM	Total costs, no inflation	a) Annual sampling cost	$48,949
		b) Cost after Year 1	$51,072
		c) Cost after Year 10	$493,080
	Cumulative costs, assuming OMB's 2.25% annual inflation average	After Year 1	$51,072
		After Year 10	**$545,935**

Table 8. Cost estimate for LTM using low-flow sampling at the former Pease AFB site.

Cost Element	Data Tracked During the Demonstration	Details	Cost ($)
(1) Initial startup	Labor	One crew of 2 individuals	$10,590
	Equipment		$54,913
	Total costs for startup	**Initial startup costs**	**$65,503**
(2) Quarterly sample collection	Labor	One crew of 2 individuals	$10,370
	Supplies		$730
	Total costs for sampling	Quarterly sampling subtotal	$11,100
		Annual sampling subtotal	**$44,401**
(3) Sample processing and analyses	Labor		$840
	Supplies & shipping		$1354
	Laboratory Analyses		$6050
	Total costs for sample processing & analyses	Quarterly costs	$8244
		Annual cost	**$32,975**
(4) O&M	Equipment replacement	(Over 10 years)	$26,645
	Labor		$2075
	Total costs	O&M subtotal for 10 years	$28,720
		Annual O&M	**$2872**
(5) LTM	Total costs, no inflation	Annual sampling cost	$77,376
		Cost after Year 1	$142,879
		Cost after Year 10	$867,980
	Cumulative costs, assuming OMB's 2.25% annual inflation average	After Year 1	$142,879
		After Year 10	**$956,042**

Table 9 presents the cost savings that could be achieved at this site by using the Modules based upon the various scenarios discussed previously. Based upon the original estimate for the Modules, the cost savings would be slightly more than 20% versus using a single team of (two individuals) for low-flow sampling. However, if two field crews (of one individual each) are used for low-flow sampling, the cost savings for the Modules is only 10%.

Table 9. Cost savings for LTM using GORE samplers at the Pease site based upon different assumptions about work at the site.

Comparison	% Cost	Cost Savings %
Original estimate Gore/LF, 2 teams	89.8	10.2
Original estimate Gore/LF, 1 team	77.0	23.0
New estimate for Gore/LF, 2 teams	70.9	29.1
New estimate for Gore/LF, 1 team	60.8	39.2
New Gore estimate, recondition *all* wells/LF, 2 teams	72.7	27.3
New Gore estimate, recondition *all* wells/LF, 1 team	62.4	37.6
New Gore estimate, recondition *all* wells/LF, 2 teams recondition *some* wells	71.0	29.0
Lower price (by 20%) for Modules/LF, 2 teams	59.6	40.4
New Gore estimate/LF, 1 team −15% analytical	63.5	36.5
New Gore estimate /LF, 2 teams −15% analytical	73.9	26.1

When the more recent (newer) price estimate is used for the Modules, the cost savings become 30% and 40% when compared with either two or one low-flow sampling team, respectively. Even if all the wells with the samplers had to be reconditioned, the cost savings would only be a few percent lower and would be well above the desired 20%. The same is true if the field crew could obtain a 15% cost savings on the analytical costs for low-flow sampling. In contrast, if the manufacturer were able to reduce the cost of the Modules by for example another 20% (as a result of mass production of the Modules), the cost savings would increase from 30% to 40% (based on the assumption that two low-flow teams conducted the sampling at this site).

9.3.3 Summary of Cost Analyses for Both Sites

These cost analyses show that for the use of the GORE Modules to be desirable from a cost perspective (i.e., cost savings greater than 20%), the price of the Modules needs to be about $190 per sampler (i.e., the newer price estimate). Using that price, the field crew can achieve a cost savings of 30% to 45%, depending on the size of the crew used for low-flow sampling. Unlike low-flow sampling where the majority of the cost is associated with labor, the majority of the cost for the GORE technology is associated with the purchase price of this sampler, which also includes the analytical costs.

10.0 IMPLEMENTATION ISSUES

Although this demonstration has shown that analyte concentrations of GORE Modules samples generally agree well with low-flow sampling and that this technology can provide substantial cost savings, there are several other issues that need to be addressed in order to promote greater acceptance of this technology.

10.1 REGULATORY ISSUES

10.1.1 Regulatory Issues with Passive Sampling in General

A survey sent to the ITRC's state points of contact in 2007 found that at that time, there were some regulatory barriers (i.e., statutes, regulations, or guidance) that either prohibited or impeded the use of passive sampler technologies (ITRC, 2007). Of the 16 states responding to the survey, 25% believed their state prohibited the use of passive sampling technologies because they required either three-well-volume purging or low-flow purging and sampling. Other states required that the wells be purged although they do not necessarily specify how or to what extent they must be purged. This also would preclude using passive sampler technologies. However, all the states appeared receptive to passive sampling although they tended to lean towards requiring an on-site demonstration to verify their reliability. New Jersey was the only responding state that has published guidance on using a specific passive sampling technology for groundwater.

To broaden knowledge of passive sampling and to address regulatory concerns, the ITRC Passive/Diffusion Sampling Team has published several guidance documents on various passive sampling technologies including: two documents on the use of PDB samplers for sampling VOCs (Vroblesky, 2001; ITRC, 2004); an overview document on 14 passive sampling technologies, which includes the GORE Modules (ITRC, 2006); and a protocol document on the use of five passive samplers, which also includes the GORE Modules (ITRC, 2007). All of these documents are available for free on the ITRC website (http://www.itrcweb.org/). ITRC also provides on their website an archived copy of the free internet training class offered previously on using the five passive sampling devices, which included the GORE Modules.

More recently, the ASTM D.18.21.04 team (that focuses on sample collection for groundwater monitoring) has developed a standard guide on the selection of passive sampling techniques; this standard has been recently revised and balloted at the main committee level and presumably should be available before the fall of 2014.

10.1.2 Regulatory Concerns with the GORE Modules

Two of the primary concerns with this technology has been regulatory acceptance of the analytical method and the conversion of the mass data to concentration values. In September 2010, the Gore Laboratory became accredited to International Organization for Standardization (ISO)/International Electrotechnical Commission (IEC) 17025, DoD ELAP, and NELAC quality standards for USEPA Method 8260C (Parker et al., 2014). Recently, they were able to add their concentration capabilities to that accreditation. The Gore chemists are also working with ASTM to develop a standard method of generating concentration data from passive sampling methods.

10.2 END-USER CONCERNS

For the most part, the GORE Module sampling method appears to be a reliable, easier, less expensive sampling method than low-flow sampling of VOCs and SVOCs. However, the use of these samplers is limited to those analyte types. Therefore, if a user has a site with other analyte types, they may want to continue using low-flow sampling, which has broader analyte capability. Or, they may want to consider using another passive sampler such as a passive-equilibrated grab sampler (Snap Sampler) or an equilibrium sampler with a Regenerated Cellulose (Dialysis) Membrane.

In addition, the Modules cannot be used for all VOCs. According to data presented by W. L. Gore (Parker et al., 2014), analytes that are highly soluble, such as MTBE, tend to be desorbed too rapidly to be accurately quantified. Also, the project team recommends working closely with the Gore chemists if using these samplers to detect low concentrations of analytes where the sampler will be more than 32 feet below the water table and left in the well for more than 90 minutes. It is assumed that the algorithm will undergo some modification(s) and improvement(s) with time as more analytes are studied and there is more data to compare. The project team recommends that users be careful that they measure the water temperature at the sampling depth in wells rather than near the surface since temperature affects concentrations values. This would be especially important in wells where the sampling depth is 30 feet or more below the water surface.

One of the concerns with the use of this technology has been whether an independent laboratory can be used for the analyses of the samples. While the analytical method used by the Gore laboratories is USEPA 8260C, the method used for desorption is currently proprietary. Therefore, at this time, any lab wishing to conduct these analyses would have to develop this portion of the method. It is not clear whether this portion of the method will become available as an USEPA method in the future. However, if a user wants to have another laboratory conduct the analyses, the manufacturer would have to modify the purchase price of the Modules because the current price includes the analyses; and it would not be economically feasible to pay for another laboratory to analyze the samples when the analyses have already been paid for.

The cost savings associated with this technology depend primarily upon the pricing used for the GORE Modules. Currently, to obtain cost savings of 30% to 45%, the price of the Modules would have to be $190 or less. (This price would be expected to increase with inflation.) Because this method does not use much equipment, the long-term O&M costs are low.

A final concern is whether wells that are sampled with passive samplers will need to be reconditioned more often than wells that undergo active sampling, such as low-flow purging and sampling. While this may be a concern, others in the industry would argue that wells where low-flow sampling is used may actually require more frequent redevelopment because of the fines brought into the well with each sampling event. In either case, our cost analyses show that even if the wells did need to be redeveloped more often with the GORE Modules, it could still be cost effective to use this technology.

11.0 REFERENCES

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APPENDIX A

POINTS OF CONTACT

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