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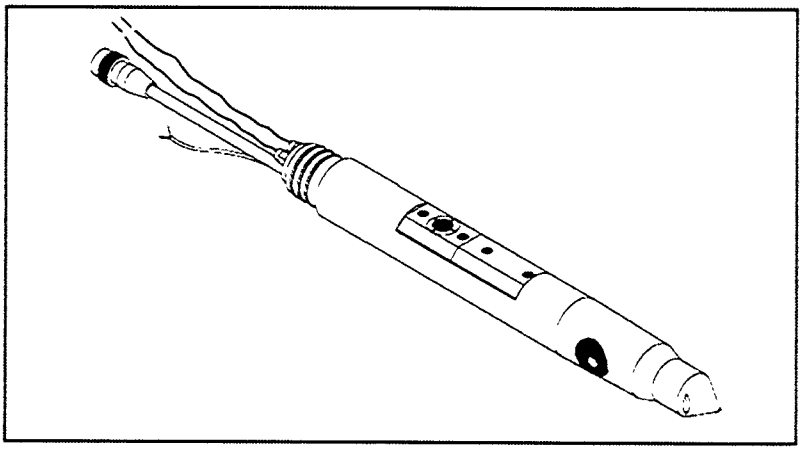
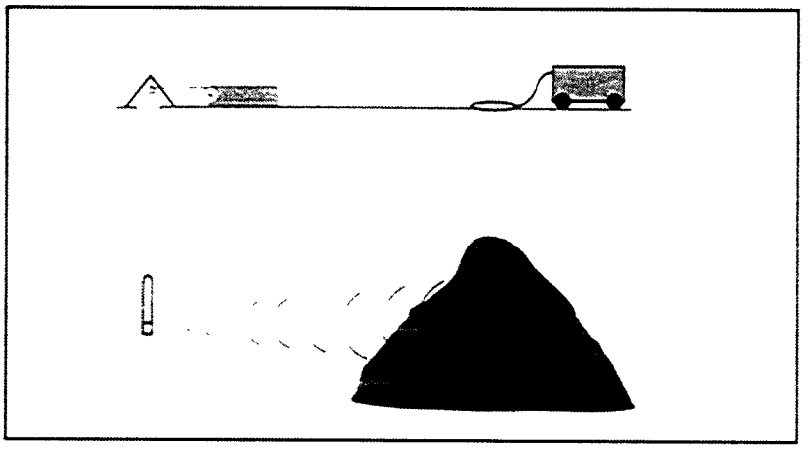
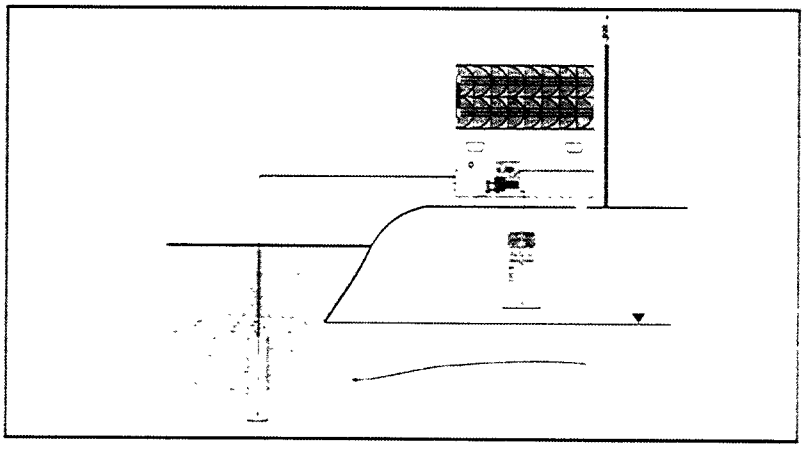
Sensor Technologies Used During Site Remediation Activities - Selected Experiences







Solid Waste
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Sensor Technologies Used During Site Remediation Activities – Selected Experiences

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ACRONYMS AND ABBREVIATIONS

1, 2-DCE	1, 2-dichloroethene
2D-Recon	Two-dimensional gradiometer
ASTM	American Society of Testing and Materials
BAAP	Badger Army Ammunition Plant
Bgs	Below ground surface
BRL	Basic relay logic
BTEX	Benzene, toluene, ethyl benzene, and total xylenes
COC	Contaminant of concern
CPU	Central Processing Unit
CPU	Central Processing Unit
Cr-VI	Hexavalent chromium
DA	Data acquisition
DBG	Deterrent Burning Ground
DELCD	Dry electrolytic conductivity detectors
EC	Electrical conductivity
ECD	Electron capture detector
EOL	Electromagnetic offset log
EPA	U.S. Environmental Protection Agency
FID	Flame ionization detector
ft/day	Feet per day
GC	Gas chromatograph
HMI	Human machine interface
HOA	Hand-off-auto
Hz	Hertz
IrriMAX	Vendor-supplied standard calibration model
LED	Light emitting diode
LPZ	Low permeability zones
MFA	Moffett Federal Airfield
MIP	Membrane interface probe
mL/min	Milliliters per minute
mV	Millvolts
NELP	Navy Environmental Leadership Program
NIBW	North Indian Bend Wash
NPDES	National Pollutant Discharge Elimination System
NTS	Nevada Test Site
°C	Degrees Centigrade
Ogden	Ogden Environmental and Energy Services Co., Inc.
OSHA	Occupational safety and health administration
PC	Anywhere (communications software)
PC	Personal computer
PID	Photoionization detector
PLC	Programmable logic controller
PLC	Programmable logic controllers
ppb	Parts per billion
R&D	Research and development

RI	Remedial investigation
SCADA	Supervisory control and data acquisition
SDI	Serial data interface
Sol Lynn	Sol Lynn/Industrial Transformer Superfund
Sprague Road	Sprague Road Ground Water Plume Superfund
SRI	Supplemental remedial investigation
TCE	Trichloroethene
THM	Trihalomethanes
USDA	U.S. Department of Agriculture
UST	Underground storage tank
UV	Ultraviolet light
VC	Vinyl chloride
VECTOR	Variably Emitting Controlled Thermal Output Recorder
VOC	Volatile organic compounds.
WBZ	Water bearing zones
WBZ	Water bearing zones

NOTICE AND DISCLAIMER

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1.0 INTRODUCTION

1.1 WHAT ARE SENSORS?

A sensor is a device that produces a discernable response to external stimulus. Some examples of sensors are thermometers, photoelectric cells, pressure transducers, and smoke detectors. Electronic sensors respond to stimulus by producing standardized electrical signals. This enables them to interface with devices that display a readable output or larger systems providing sensory input to a decision-making device. For example, sensors may be used inside a storage tank to supply information on fluid levels to a system controller who would in turn use this information to make decisions on starting or shutting down pumps that fill or drain the tank. Sensors can be used in environmental remediation for the following activities:

- Characterization
- Monitoring
- Automation

When properly applied, sensors can provide long-term benefits for remediation projects by reducing manpower requirements, reducing analytical costs, and generating information that facilitates process optimization.

1.2 PURPOSE OF REPORT

Environmental remediation includes many activities that require measurement and monitoring of parameters such as contaminant concentrations, media characteristics, and systemic parameters. In recent years, there has been an increase in the number and types of sensor technologies used during site remediation. These include technologies that are used for performing real-time and continuous measurements, remote monitoring, remote operation, and system automation.

The U.S. Environmental Protection Agency (EPA) prepared this report to provide an overview of several types of sensor technologies and a summary of selected experiences with using the technologies during site remediation activities. The report highlights the applications, implementation, strengths and limitations, and lessons learned from actual projects that have used one or more sensor technologies as part of an overall site remediation strategy. Appendices one through seven provide case studies for specific sites that have used sensor technologies during site remediation activities.

This report does not provide guidance on the selection of a specific type or vendor of sensor technology; these technologies are most cost-effective under specific environmental, chemical, and physical conditions. Numerous site-specific considerations, such as site geology, soil, and aquifer characteristics, chemical, physical, and biological parameters of affected media, and chemicals of concern, among many others, can impact the overall cost-effectiveness of a system.

1.3 METHODOLOGY

In preparing this report, EPA collected available information on sensor technologies for remedial projects performed at Superfund sites, federal/military sites, and other sites. EPA attempted to compile information that was readily available and current for each project as of Summer/Fall 2004, however, in some cases, EPA was not able to confirm the available information. Some case studies include information provided primarily by the technology vendor, with limited input from a regulatory authority. In addition, for many of the projects, there were gaps in the types of information available (e.g., for some sites, performance data were not available, or there was a limited amount of data that independently evaluated sensor performance). This report is not a comprehensive review of all available sensor technologies or vendors.

2.0 OVERVIEW OF SENSORY SYSTEMS

Sensory systems used for automation, characterization, and monitoring can consist of a number of different components, including mechanical sensors, electronics, analytical (chemical) sensors, control systems, telemetry systems, and software. These components may be used alone or together to form relatively simple or highly complex systems.

Mechanical sensors by definition contain moving parts. For instance, turbine flow meters contain turbines that rotate as water flows through a pipe. Flow rate is measured by counting the number of revolutions per minute. When coupled with electronic transmitters, flow meters can form sensory systems that are able to measure and communicate flow data to a control unit or display. Other examples of mechanical sensors include floats (used in tank float switches) and pressure gauges.

Electronic sensors are electrically powered and can measure a variety of parameters such as pressure, specific gravity, the presence of liquid (water level meters and interface probes), pH, temperature, and conductivity.

Analytical sensors are typically used to measure chemical parameters such as contaminant concentrations. Some examples of analytical sensors include pH probes, and optical sensors used for colorimetric measurement

Control systems that work in conjunction with sensors include programmable logic controllers (PLC) and other electronic microprocessor devices. Control systems are able to receive sensory inputs, process information, and trigger specific actions.

Telemetry systems facilitate system control or data acquisition from remote locations. They can be radio or telephone based. Radio-based systems use radiofrequency communication devices to send and receive information. Telephone-based systems use modems to send and receive information through telephone lines.

2.1 CHARACTERIZATION OR MONITORING

Sensors used in characterization are typically used to measure environmental parameters. For example, a membrane interface probe may be used to detect and locate subsurface contamination; an electrochemical probe may be used to measure ground water parameters such as pH; and a thermometer may be used to measure sample temperature. Sensors in monitoring are typically used to measure both environmental and systemic parameters. For example, an anemometer may be used to measure wind velocity at a site; a water-level sensor may be used to measure long term fluctuations in ground water elevation; and a flow meter may be used to monitor flow through a pipe.

2.2 AUTOMATION

Automation systems use sensory devices to measure parameters necessary for proper system operation. Some examples of these parameters are water levels in wells and tanks, temperature, pressure drop, flow rate, and effluent concentration. These parameters are then used by microprocessor devices such as PLCs to make operational decisions including starting up or shutting down components of the remediation system.

Additional Sources of Information about Sensor Technologies

Field Analytic Technologies Encyclopedia (FATE) – an online encyclopedia intended to provide information about technologies that can be used in the field to characterize contaminated media, monitor the progress of remedial efforts, and in some cases, perform confirmation sampling and analysis for site close out. FATE includes information on several types of fiber optic chemical sensors. *http://fate.clu-in.org/index.htm*

Measurement and Monitoring Technologies for the 21st Century (21 M2) – through this initiative, EPA's Office of Solid Waste and Emergency Response (OSWER) will identify and deploy promising measurement and monitoring technologies in response to waste management and site cleanup program needs by matching existing and emerging technologies with OSWER program and client needs. Current projects include open path monitoring and sampling for contaminated sediments, as well as a summary of available literature on measurement and monitoring technologies. *http://www.cluin.org/programs/21m2/*

Remediation and Characterization Technology Database (EPA REACHIT) – an online database with powerful search options for information on treatment and characterization technologies, plus updated information from remediation projects undertaken by EPA. The database includes the following information for characterization technologies (as of March 2004): 158 technology vendors, 241 technologies, and 186 vendor source sites. *http://www.epareachit.org*

EPA's "A Review of Emerging Sensor Technologies for Facilitating Long-Term Ground Water Monitoring of Volatile Organic Compounds" – This report summarizes the status of emerging sensor technologies for facilitating long-term ground water monitoring for volatile organic compounds (VOCs). It also describes a number of factors, including regulatory acceptance and cost-effectiveness, that influence the applicability of these technologies. *http://www.clu-in.org/s.focus/c/pub/i/1040/*

Superfund Innovative Technology Evaluation (SITE) Program – established by EPA to aid engineers, scientists and other remediation professionals in the efficient monitoring, characterization and remediation of hazardous wastes. In this program, technologies are field-tested to assess performance. Cost and performance data are then presented in technology evaluation reports. *http://www.epa.gov/ORD/SITE/*

3.0 EXAMPLES OF REMEDIATION SITES THAT HAVE USED SENSOR TECHNOLOGIES

Table 1 identifies seven case studies on sensor technologies that illustrate their use in site characterization, monitoring, and process automation. The sites discussed in these case studies used the following types of technologies:

3.1 SITE CHARACTERIZATION

- Membrane Interface Probe – for contaminant concentrations
- Geophysical surveys – for evaluation of hydrocarbon contamination

3.2 MONITORING

- Capacitance probe – for soil moisture content
- VECTOR technology – for ground water flow velocity
- Burge System – for sampling and analysis

3.3 AUTOMATION

- Ozone analyzers and SCADA with PLC – for ground water pump and treat operation
- SCADA with PLC – for ground water pump and treat operation

Five of the seven case studies present characterization and monitoring sensor technologies; the other two (Moffett Federal Airfield, and Sprague Road Superfund Site) discuss sensor-dependent automation technologies. The technologies discussed in this report are commercially available, and have had at least one full-scale implementation. Projects for which case studies were completed were selected based on information in available databases and Internet resources, such as EPA's Clu-In Web site (*www.cluin.org*), and discussions with remediation project managers (RPMs), staff of both EPA Headquarters and Regional Offices, project managers from other Federal, state, and local government agencies, consultants, and vendors.

Each case study includes site background information, an overview of the sensor technology used and the goal for using the technology, a brief summary of remedial efforts at the site, information about the implementation of the sensor technology, and lessons learned. In addition, each case study presents cost data for the specific sensor technology. Where actual cost data are not available, estimated information is provided. Conclusions in the case studies are not limited to site-specific details. In most cases, conclusions include site-specific information and general information about the technology that might benefit potential users. References used in preparation of each case study are provided at the end of the case study.

TABLE 1. SELECTED CASE STUDIES ON SENSOR TECHNOLOGIES						
Site Name	**Technology Employed**	**Time Period of Use**	**Media of Concern**	**Contaminants**	**Goal for Use of Technology**	**Comments**
Sol Lynn/ Industrial Transformer Superfund Site, Houston, Texas	Membrane Interface Probe	January – June 2001	Ground water	TCE and its degradation products	Delineate ground water contamination and screen locations requiring further characterization.	MIP technology was used to identify highly contaminated regions in soil and ground water, as well as delineate the extent of the contaminant plumes in the various water-bearing zones.
Hotel Pier Site, Pearl Harbor, Hawaii	Geophysical survey techniques – 2D-Recon and 3D EOL	Not provided	Soil and ground water	Hydrocarbon contamination	Characterize areas of hydrocarbon contamination and assist in evaluation of remedial alternatives.	Electromagnetic surveys characterized hydrocarbon contamination based on the concept that soils contaminated with hydrocarbons feature higher resistivity than clean soils.
Badger Army Ammunition Plant, WI (Sub-Site BAAP-06-Deterrent Burning Ground)	Capacitance probe (for soil moisture content)	2004 – ongoing	Soil	Munitions based compounds	Measure soil moisture levels beneath a cap, to assess potential for leaching contaminants to GW at 100-110 ft bgs.	A nutrient infiltration gallery encouraged biological degradation of residual contamination beneath the cap. The capacitance probes served as sentinels against inadvertent flooding of the remediation zone that could potentially contaminate the ground water almost 100 feet bgs.

TABLE 1. SELECTED CASE STUDIES ON SENSOR TECHNOLOGIES						
Site Name	**Technology Employed**	**Time Period of Use**	**Media of Concern**	**Contaminants**	**Goal for Use of Technology**	**Comments**
China Lake Naval Weapons Station, CA velocity)	VECTOR technology (for ground water flow	1999 – ongoing (data through September 2004)	Ground water	Not provided	Monitor GW flow along southern property boundary, with potential for transport to nearby municipal well fields.	Each velocity sensor interfaces with an above-ground datalogger that records sensory data at a predetermined interval. Downloaded data is fed into an accompanying computer program which translates measured data to ground water flow speed and direction.
Moffett Federal Airfield, CA (West-side Aquifers)	Ozone analyzers and Programmable Logic Controllers (PLCs) in a ground water pump and treat system	2001 – ongoing (data through September 2004)	Ground water	TCE	Automate pump and treat system and monitor ozone in aqueous and gaseous media.	The ozone monitors work in conjunction with the PLC to ensure that (1) the correct dosage of ozone is applied to the influent water, (2) the off gas treatment system is meeting the air emission standards, and (3) the ambient air meets occupational safety and health administration (OSHA) standards.
North Indian Bend Wash, AZ, and Nevada Test Sites, NV	Burge System – (optical sensor)	North Indian Bend Wash: Jan 2002 – July 2003	Ground water	TCE	Analyze TCE in influent and effluent of ground water treatment plant on a daily basis.	The TCE monitoring system was used to provide automated monitoring of influent and effluent from a ground water treatment system.
		Nevada Test Site: December 2003 and March 2004	Ground water	Cr-VI	Analyze Cr-VI in ground water (pilot test).	The Cr-VI monitoring system was used for sample acquisition and analysis of Cr-VI contaminated water in a pilot test. This system is currently in use at the Hanford site near Richland, Washington.

TABLE 1. SELECTED CASE STUDIES ON SENSOR TECHNOLOGIES						
Site Name	**Technology Employed**	**Time Period of Use**	**Media of Concern**	**Contaminants**	**Goal for Use of Technology**	**Comments**
Sprague Road Superfund Site, TX	PLC and SCADA	2003 – ongoing	Ground water	Cr-VI	Automation of pump and treat system.	PLCs used to control valves and pumps. They interface with field sensors and interpret real-time sensory data to make system-control decisions (e.g., turn pump on or shut valve). The PLCs communicate through a wireless network and interface with desktop computers that serve as data loggers, continuously recording system operation data such as flow rates and totalized flow.

4.0 REFERENCES

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Federal Remediation Technology Roundtable. 2004. Field and Innovative Sampling and Analysis Technology Matrix, version 1.0. *www.frtr.gov*.

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Vendor Web Sites

- Advantech at *www.advantech.com*
- Ametech, Inc. at *http://www.drexelbrook.com/*
- Analytical Measurements, Inc. at *http://www.anyliticalmeasurements.com*
- Bowles Corporation, Inc. at *http://www.bowles-corp.com/cet.htm*
- Burge Environmental at *http://www.burgenv.com/index.html*
- Campbell Scientific at *www.campbellsci.com/sensors.html*
- Clean Earth Technology at *http://www.bowles-corp.com/cet.htm*
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- Containment Solutions at *http://www.containmentsolutions.com/*
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- Controlotron at *http://www.controlotron.com/*
- Diversified Remediation Controls, Inc. at *http://www.drc1.com/prod01.htm*
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- Geophysical Survey Systems, Inc. at *http://www.geophysical.com/SIR20.htm*
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- Turner Designs, Inc. at *http://www.turnerdesigns.com/*
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- Wonderware at *www.wonderware.com*
- YSI at *http://www.ysi.com*
- ZISTOC Corporation at *http://www.zistos.com/*

Appendix 1

Sensor Technology Case Study
Use of Membrane Interface Probe Technology for Detection of VOCs at the Sol Lynn/Industrial Transformer Superfund Site

Sensor Technology Case Study

Use of Membrane Interface Probe Technology for Detection of VOCs at the Sol Lynn/Industrial Transformer Superfund Site

Summary Information [1, 5, 6]

The membrane interface probe (MIP) is a semi-quantitative field-screening tool for the detection of volatile and semi-volatile organic compounds. It facilitates quantitative measurement, but the results produced at any given location are relative and not absolute. It is often used as a precursor to future more accurate analysis. For instance, site characterization with MIP could paint a qualitative picture of subsurface contamination that distinguishes between areas of low, medium or high contamination. This could then be used to develop a plan for media sampling and laboratory analysis to assess the amount of contamination.

MIP technology works by advancing the MIP through the strata to be explored. The MIP heats the matrix in contact with it and volatilizes contaminants. Volatilized contaminants enter the probe through a membrane covered window and are transported to the surface by a continuous draft of inert carrier gas. The contaminated gas stream is conveyed to a measurement device which then produces a quantitative result. The result is fed to a computer which displays it on the screen as a real-time graph of detected contamination versus depth of probe penetration. The computer also logs this data for future use.

The Sol Lynn/Industrial Transformer Superfund (Sol Lynn) site is located about 6 miles southeast of downtown Houston, Texas. Historical operations at the site resulted in contamination of several water bearing zones with trichloroethene (TCE). The 1988 record of decision selected a pump and treat remedy for this site which operated for several years before ongoing groundwater monitoring revealed that it was ineffective. A supplemental remedial investigation (SRI) was initiated in 2001 to better understand the nature and extent of contamination. During this SRI, MIP technology was used to detect subsurface volatile organic compounds (VOC).

MIP exploration was conducted at 99 locations between January 17, 2001, and June 5, 2001. A truck mounted Geoprobe® rig was used for probe advancement. Equipment used in combination with the probe included an MIP controller, a field computer (to display and log real-time measurements), and a gas chromatograph (GC) for gas-phase detection.

Real time results made it possible to employ a dynamic method of site investigation that steered locations of subsequent investigations. MIP showed limited use as a quantitative tool.

Technology Description [1, 5, 6, 8]

MIP is a semi-quantitative screening tool for detection of volatile and semi-volatile organic compounds. Strictly speaking, the probe in itself has no sensory capability; it merely transfers vaporized samples of subsurface contaminants to gas-phase detectors at the surface. However, MIPs are used in tandem with electrical conductivity (EC) sensors. The two have been integrated into a single probe that is still called an MIP. Present day MIPs both serve as collection devices for subsurface contaminants, as well as measure soil EC. The primary use of the EC sensor in this probe is to map stratigraphy.

The MIP is manufactured by Geoprobe® Systems. It is a pen shaped device with stainless steel construction consisting of an EC sensor, a heater block, and a semi-permeable

membrane. Figure 1 displays an MIP. The membrane is a replaceable steel-impregnated thin-film polymer approximately 6.35 mm in diameter, and sits on the probe's heater block. The block is raised at the leading edge to protect the membrane. Teflon tubing conveys carrier gas to and from the probe. Power wires supply electrical energy to the heater block, and control wires facilitate sensory feedback from the EC unit to the field computer. A model MP3500 surface unit - called the MIP controller - monitors and controls carrier gas supply. The MIP controller feeds clean nitrogen gas to the probe, and conveys contaminant laden gas to the gas detector. A model FC4000 field computer interfaces with the EC sensor and the gas detector to acquire and log all sensory data. Figure 2 displays the field computer, the MIP controller, and the gas detector. The field computer has a screen which provides a graphical display of real-time measurements as the probe advances through the soil. This tells the operator the location of the contaminant, the relative concentration, and the type of soil in which the contaminant is located.

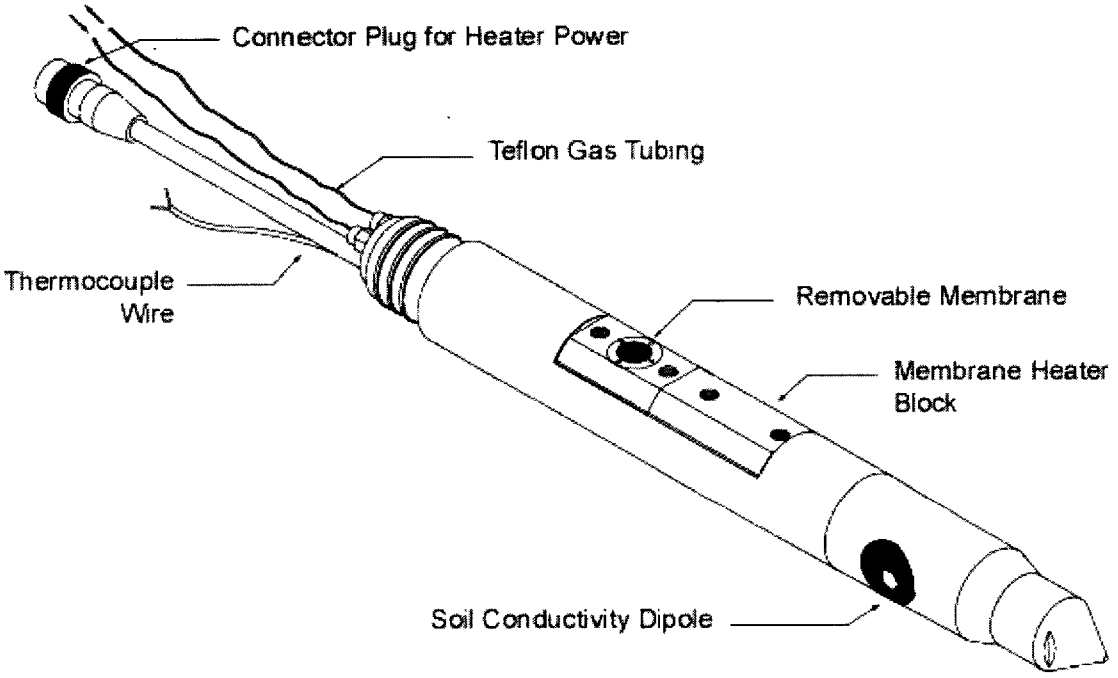
This technology exploits the phenomenon of gas transfer across membranes to detect subsurface contamination. The membrane used in an MIP is semi-permeable, which means that the passage of substances through it is selective. The membrane retains liquids, but allows compounds in their gaseous state to pass through. Cross-membrane transfer of gaseous-phase contaminants occurs through the process of diffusion motivated by a concentration gradient across the membrane. The heater block speeds this transfer by elevating the temperature of the surrounding matrix. The block is heated to approximately 120 degrees Centigrade (^{o}C). Heat from the block vaporizes contaminants in the surrounding matrix causing higher vapor pressures, and consequently higher concentration gradients. Once past the membrane, contaminants are transported to a detection unit by a continuously flowing stream of carrier gas. Carrier gas sweeps behind the membrane at a constant flow rate of 35-45 milliliters per minute (mL/min). Travel time from the membrane to the detector is approximately 30-60 sec (depending on the length of trunk line and flow rate).

The ability to detect a contaminant depends on the type of gas detectors being used. Any laboratory grade gaseous phase detector with an analog output of 1-5 Volts may be used. Most commonly used detectors include the photoionization detector (PID), electron capture detector (ECD), and the flame ionization detector (FID). Each of these detectors is best suited to a group or type of contaminant. The ECD is usually used for the detection of chlorinated contaminant (such as TCE, PCE, etc.); the PID is best suited for the detection of aromatic hydrocarbons (BTEX compounds); and the FID is best used for straight chained hydrocarbons (such as methane, butane, etc.). These detectors may be used in series with the least destructive detector being first and the most destructive detector coming last. The MIP field computer (FC4000) system can process up to four detector signals simultaneously. Figure 2 shows a GC -housing a PID and an FID- being used as a gas-phase detector.

The essential components of an MIP characterization effort are: (1) a direct push mechanism (such as Geoprobe® or Cone Penetrometer [CPT]); (2) an MIP; (3) an MIP controller; (4) gaseous phase detectors; and (5) a data display and logging system.

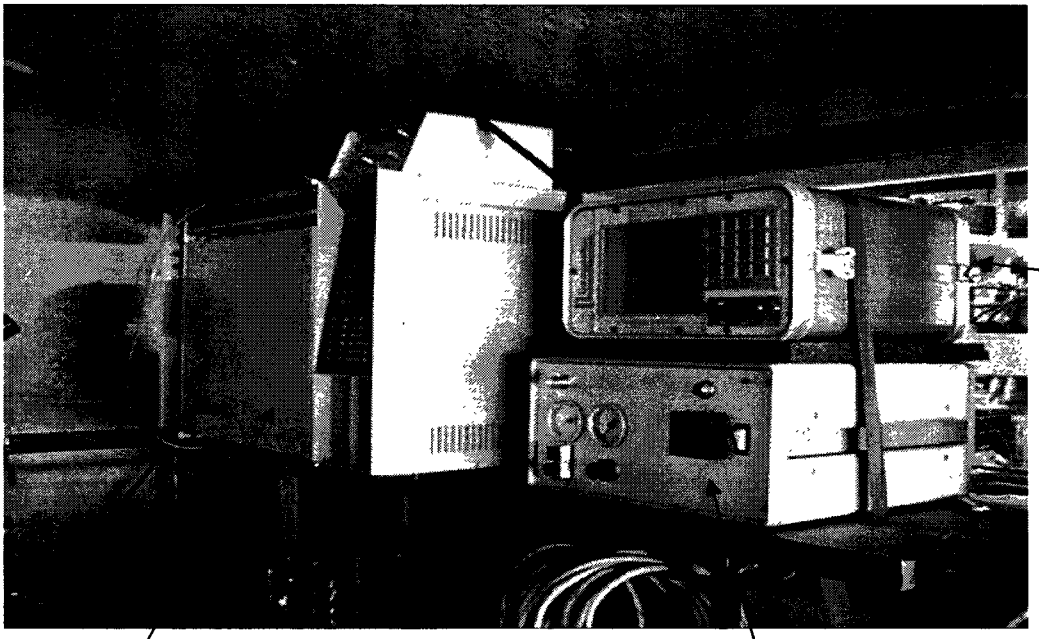
MIP exploration typically requires a three-man crew including a geologist. Though not an unchangeable standard, MIP advancement is usually accomplished one foot at a time. The waiting periods between subsequent advancements typically last a minute. This is necessary for sample collection and transfer to the surface detector.

Figure 1
Membrane Interface Probe



Source: Geoprobe® Systems

Figure 2
MIP Detection Equipment



FC4000 Field Computer

Gas Chromatograph

MP3500 MIP Controller

Source: Geoprobe® Systems

Site Information [1, 4, 6]

The Sol Lynn site is located about 6 miles southeast of downtown Houston, Texas. Historical activities at the site lead to contamination of the groundwater with TCE. Following a remedial investigation (RI) and feasibility study, a pump-and-treat system was designed to address the groundwater problem at the site. The system was installed in 1990. After several years of monitoring the contaminant plume, it became evident that the pump-and-treat system had failed to mitigate the problem or achieve plume containment. As a result, the pump-and-treat system was shut down in 1999.

An SRI was initiated in late 1999 to gain a better understanding of the hydrogeology and contaminant distribution at the Sol Lynn site.

The site hydrogeology at Sol Lynn was found to be extremely complex. While the first RI had concluded that there were only 3 water bearing zones (WBZ) at the site, the SRI found that there were in fact 9 WBZs in the first 200 feet below ground surface (bgs). Shallow groundwater at the site occurred within the more permeable units of the Beaumont formation. The surficial hydrogeologic units were a part of the upper Chicot aquifer. Each of the WBZs was separated by low permeability zones (LPZ) which acted like aquitards between the individual WBZs.

TCE was the primary contaminant of concern (COC) in groundwater. TCE by-products, primarily 1, 2-dichloroethene (1, 2-DCE) and vinyl chloride (VC), were also present in groundwater.

MIP was used to delineate groundwater contamination at the site and serve as a field screening tool to identify locations requiring additional characterization.

Ninety-nine MIP advancements were made at the site between January 17, 2001, and June 5, 2001. Figure 3 displays MIP advancement in progress at Sol Lynn.

A truck mounted Geoprobe® 5410 unit was used for probe advancement. A Model 14A Shimadzu GC was used for gas-phase detection. The GC housed an ECD and PID detector. The ECD was particularly sensitive to chlorinated compounds. The FC4000 Geoprobe® field computer was used for data display and logging. The system displayed membrane temperature, probe advancement rate, and plotted EC and contaminant response versus depth. The system produced data that was readily transferable to spreadsheet programs such as Microsoft Excel.

The steps in a typical advancement included setup over the desired location, anchoring equipment in place, performing pre-advancement response tests on the MIP, MIP advancement, and response monitoring. The locations for MIP exploration were not entirely predetermined. In many instances the location of the next MIP advancement was based on the results of the previous.

Since one objective of the investigative effort was to delineate the extent of the contaminant plume, the general methodology used in determining exploratory locations was to move outwards in the direction of decreasing contamination. The original plan anticipated a total of 82 MIP advancements, but the dynamic nature of the exploration effort lead to a total of 99 advancements.

The advancement rate at Sol Lynn was approximately one foot per minute. This coupled with the waiting period between advancements resulted in an approximate 2.5 to 3-hour duration for complete penetration at any given location. As a result, 3 to 4 locations could be explored per day. The depth of MIP penetration was limited by its physical durability. Soil resistance made direct push advancement infeasible beyond a certain depth. At some locations, direct push was not possible beyond 20 ft bgs. The actuating force for advancement beyond this depth involved impact loading using a hydraulic hammer. The MIP had a limited tolerance for this type of loading, and that is why its durability restricted the depth of exploration. The average depth of MIP/EC exploration at Sol Lynn was 42.86 ft bgs, and the maximum depth was 64.10 ft bgs.

Gaseous phase detectors quantified MIP carrier gas contaminant concentrations in millvolts (mV). The measurements represented a family of contaminants rather than one specific contaminant. Analytical results from groundwater samples collected in the vicinity of specific MIP advancements later revealed that the minimum detection limit of MIP exploration at that site was greater than 100 parts per billion (ppb) of total volatiles.

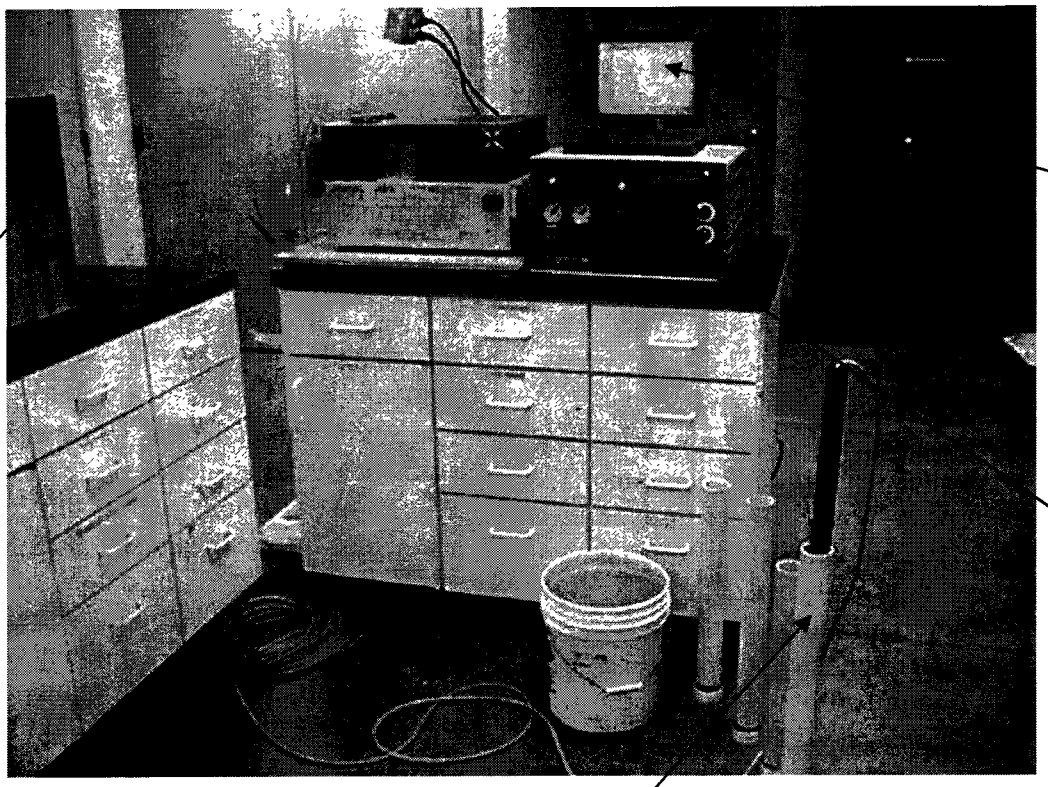
A response test was performed at every new location prior to MIP advancement. This was done to evaluate the condition of the membrane. The test involved immersing the probe in a standard solution and observing the response on the detectors. The response was compared to that of previous tests. A decline in response indicated the need for membrane replacement. Figure 4 presents an example of the same test being performed at a Geoprobe® facility.

Figure 3
MIP Probe Advancement Using a Geoprobe® Direct Push Rig

Source: Tetra Tech EM Inc.

Source: Tetra Tech EM Inc.

Figure 4
MIP Response Test



Source: Geoprobe® Systems

Cost [2, 4]

The total cost of the investigative field effort at Sol Lynn was approximately $150,000. However, part of this cost did not pertain to MIP exploration. Costs quoted by contractors offering MIP field services varied from roughly $3,000 to $3,700 per day. On an average, 250 to 300 feet of strata could be explored in one day. Costs could be influenced by factors such as the depth of penetration, and the media to be penetrated. There could be a surcharge for requiring penetration beyond a certain depth. Similarly there could be a surcharge to compensate for equipment wear if impact loading were used for MIP advancement. A typical probe withstands approximately 1,000 ft of cumulative advancement through clays and sands. However, probe advancement through gravel would likely result in shorter life spans and consequently, additional charge for exploration. Difficulty in accessing locations for MIP exploration could be another factor increasing cost. Equipment mobilization and demobilization charges varied from $2 to $15 per mile.

Conclusions [1, 2, 3, 4]

In general MIP technology worked well as a screening tool at Sol Lynn. Although repeatability of measurement was observed in a few cases, MIP was not found to be significantly useful as a quantitative tool. There were a few instances when highly contaminated media were encountered. In such cases contaminant concentrations were found to lie outside the detectors' range of measurement. The results of MIP exploration at Sol Lynn played a large role in developing the monitoring well plan for the site.

The remainder of this section discusses important issues about MIP. These are not necessarily site-specific issues, and include general opinions gleaned from contractors that offer MIP field services. Two such contractors are Plains Environmental and Applied Research. Plains Environmental was the contractor at Sol Lynn, and Applied Research was contacted to serve as an alternate source for this case study.

Although theoretically suitable for any VOC, there seemed to be agreement that MIP worked especially well for chlorinated VOCs. Chlorinated VOC in-situ detection limits were stated to range from 200 to 500 ppb. The use of MIP as a field screening tool would not be advisable at in-situ concentrations below the aforementioned. Variation in detection limits were attributed to probe peculiarities, contaminant chemistries, and specifics of the strata being penetrated. At the other end of the spectrum, extremely high in-situ concentrations could also be troublesome with MIP exploration. Penetrating a zone of free-phase contamination could lead to saturation of the MIP carrier gas trunk line. Once saturated, further exploration would not be possible until the line were completely purged. Purging could take from a few to several minutes. Purging is not a special procedure; it is implemented by simply letting the system operate without advancing the probe. While the probe remains in place, cross-membrane contaminant transfer continues until the contaminants' gaseous phase in the vicinity of the membrane is depleted. Once the ingress of contaminants has stopped, the continuing flow of nitrogen carrier gas renders the trunk line purged in the duration it takes to flush an entire tube volume. An MIP carrier gas trunk line would be considered purged when the detectors read zero. In extreme cases, purging could be impracticable. In such cases, the trunk line would have to be replaced to facilitate further exploration.

There seemed to be some difference of opinion in the preferred method of MIP advancement. One contractor stated that they preferred to use CPT instead of Geoprobe® rigs for MIP

exploration. This was because CPT rigs were said to provide considerably greater pushing force, which consequently afforded penetration to greater depths. CPT rigs also made it possible to use a wider variety of probes in combination with MIP/EC probes to collect additional geological data. Another contractor stated that they preferred to use Geoprobe® rigs for MIP advancement because those rigs facilitated impact loading which permitted deeper penetration than possible with direct push.

As implied by the sensitivity of various detectors to different contaminant groups, knowledge of existing contaminant types in the media to be explored was considered advantegeous. Prior knowledge of contamination not only facilitates selection of the most suitable detectors, but also lets one evaluate the applicability of MIP as an exploration tool. In general, dry electrolytic conductivity detectors (DELCD) and ECDs are considered best suited for detection of halogenated VOCs. PIDs though able to detect low molecular weight VOCs including halogenated VOCs, cannot distinguish between halogenated and non-halogenated VOCs. FIDs are characterized by low sensitivity, but are useful for detecting straight chained hydrocarbons. The likelihood of detection decreased with increasing molecular weight. Another detector that has been used with MIP is the mass spectrometer. This showed promise when it was first used in the mid nineties, but - according to a contractor- has been sparingly used since.

According to the lead agency's contractor there seems to be a deficiency of quantitative guidance to predict the effectiveness of MIP in detecting any given compound in a given strata. Since the working principle is based on vaporization of contaminants, it is likely that the contaminant's boiling point, and Henry's Law constant could help predict its response to MIP. Consequently, it might be safe to doubt the effectiveness of MIP for contaminants with boiling points above the temperature (120 °C) attained by its heating block. One contractor stated that MIP could be expected to lose effectiveness with compounds at least as heavy as xylenes (which have a boiling point of 140 °C). The same contractor also verified that MIP was unable to detect dichlorobenzene which has a lower molecular weight than xylenes, but a higher boiling point (172 to 174 °C). However, this does not imply that MIP will work for any compound with a boiling point less than 120 °C. Heavier compounds that volatilize and pass through the membrane could still condense in the trunk line and drop out of the carrier gas before they reach the detector. Given the current incomprehensive knowledge on the potential for this technology, one might best be served by discussing their investigative needs with the MIP vendor before assuming the applicability of MIP to their site.

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Appendix 2

Sensor Technology Case Study
2D-Recon and EOL Geophysical Survey Techniques
for Characterizing Hydrocarbon-Contaminated Soils at the Hotel Pier Site

Sensor Technology Case Study
2D-Recon and EOL Geophysical Survey Techniques for Characterizing Hydrocarbon-Contaminated Soils at the Hotel Pier Site

Summary Information

Surface and subsurface geophysical surveys were completed at the Hotel Pier site on Pearl Harbor Naval Base in Hawaii to characterize hydrocarbon contamination and help evaluate remedial alternatives. Geophysical resistivity surveys were useful for characterizing hydrocarbon contamination sites because soil with hydrocarbons within the soil pores (contaminated areas) have a relatively higher resistivity to electromagnetic current than similar soil without hydrocarbons within the soil pores (uncontaminated areas). A surface two-dimensional gradiometer (2D-Recon) survey was used initially to measure relative resistivity and determine the probable plume boundaries across a 7-acre site. The subsurface 3D electromagnetic offset log (EOL) survey was then completed to define and map resistivity using a 10-foot grid spacing over 1.4 acres of the Hotel Pier site.

Surface and subsurface geophysical surveys took place in January 1999. The 2D-Recon survey was completed in 2 days while the EOL survey required an additional 7 days for data acquisition. Final data processing and reporting required approximately two months to complete. The geophysical surveys at the Hotel Pier site provided additional surface and subsurface information on the extent of hydrocarbon contamination in a rapid manner. Geophysical surveys provide the greatest characterization value for sites with large and complex hydrocarbon contamination.

Technology Description [10, 11]

While 2D-Recon is used to determine the horizontal extent of subsurface contamination, 3D EOL is used to determine vertical variations in contaminant distribution. 2D EM surveys and EOL surveys have been used for over 15 years to identify and model hydrocarbon contamination associated with leaking underground storage tank (UST) sites.

2D-Recon

The 2D-Recon survey (a surface electromagnetic [EM] gradiometer technique) evolved from geophysical techniques developed for petroleum and mining exploration. Such techniques were used to detect subsurface zones with unusually high contrasts in electrical resistivity.

2D-Recon measurements are made by moving a surface EM gradiometer along closely spaced transects around and over suspected areas of contamination. The data acquired is processed to filter noise and produce a horizontal outline of subsurface contaminant plumes.

The surface EM gradiometer data acquisition system uses pairs of EM sensor coils normally aligned vertically; one sensor near the ground surface and the other sensor five feet above it. Figure 1 shows sensor coils mounted on a golf cart for faster data collection. Each pair of coils measures the difference in signal voltage (or the voltage gradient) between the coils. Anomalies in soil resistivity are indicated by large changes in the voltage gradient, and imply the presence of subsurface contamination.

Figure 1
2D-Recon Survey Data Acquisition

Source: Pritchard Geophysics

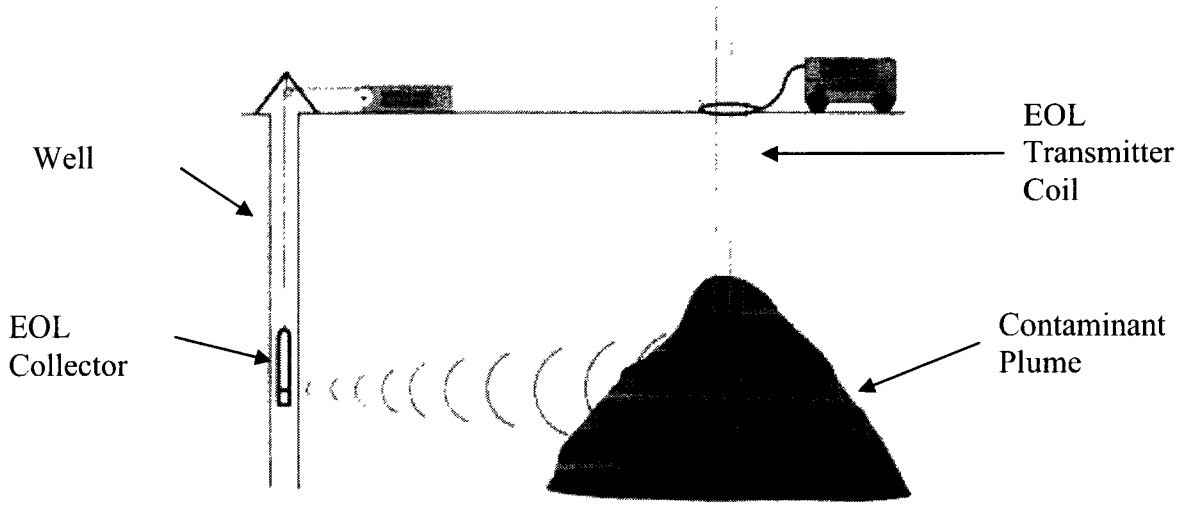
EOL

The EOL survey is an established electromagnetic induction technique which measures resistivity variations in the subsurface. For example, all free hydrocarbons are highly resistive while subsurface waters are much lower in resistivity. By measuring resistivity variations of the subsurface, one can predict the presence of hydrocarbon plumes. The resistivities are plotted to provide a three dimensional information on subsurface contamination.

The EOL survey utilizes a very large surface transmitter coil at low frequency to induce a magnetic field in the subsurface. A receiver coil is placed in a nearby well and measures the signal. The strength of the measured signal is proportional to the resistivity of the soil it passed through. This measurement is transmitted to a data collection unit on the surface. The measurements are taken and recorded at 0.1 foot intervals. Figure 2 shows a typical layout for an EOL system. Once measurements are made at a location, the transmitter coil is moved to a new data point on the surface for another set of measurements.

Once all the necessary data has been collected, it is edited to eliminate extraneous noise. The data is then normalized to eliminate differences caused by data acquired from separate receiver wells.

Figure 2
3D EOL Typical Setup



Source: Gehm Environmental

Once this is done, apparent resistivity and second order resistivity logs are generated versus depth. These logs are then interpreted to identify contaminated zones.

Site Information [1, 2, 3, 4, 5, 6]

The Hotel Pier site is located at Fleet Industrial Supply Center, Pearl Harbor Naval Base, Oahu, Hawaii. A non-time-critical removal action was proposed for the Hotel Pier site and EOL was completed as part of the remedial site evaluation for the site. Previous investigations at the site included an underground storage tank (UST) investigation, soil gas survey, a site reconnaissance, and a remedial investigation (RI). The RI for the site concluded that a plume of free product existed and that local groundwater was impacted with petroleum constituents. Preliminary fate and transport calculations conducted under the RI suggested that free product might be releasing to the surface waters of Pearl Harbor.

In addition, several fuel spills have occurred at the Hotel Pier site. The most recent fuel spill occurred in July 1997 when an estimated 1,500 to 3,500 gallons of diesel fuel leaked from a damaged fuel line. As a result of historic fuel leaks, elevated levels of benzene, toluene, ethyl benzene, and total xylenes (BTEX) were detected in soils and groundwater samples collected from soil borings located across the site. Based on the RI and other site investigations, the subsurface free product contamination at the Hotel Pier site may be associated with the historic spills, leaking subsurface product lines, or the preferential pathways for plume migration along subsurface electrical and sewer utility lines.

Hotel Pier site has a gentle relief with elevations from 2 to 10 feet above mean sea level. Pearl Harbor is essentially a series of drowned river valleys that formed between the Waianae and Koolau Volcanoes through a complicated history of rising and falling sea levels, subsequent erosion and deposition of alluvial

material, and additional deposition of pyroclastic ash from eruptions at Salt Lake and Makalapa. Pearl Harbor is underlain primarily by soils of the lualualei-fill land-ewa associations which are well-drained and fine- to moderately-fine textured soils. The primary surface soil across Hotel Pier site is composed of fill material with brown silt with angular tuff and coral fragments, and occasional basalt fragments.

2D-Recon at the Hotel Pier Site

The 2D-Recon survey used present EM noise fields generated by existing overhead power lines as the source field. The EM fields may penetrate into the ground to depths of 300 feet. In cases and sites where electrical noise is low or weak, a temporary EM power source can be supplied for the survey by hanging a temporary line between buildings or other aboveground objects. The 2D-Recon technology components included two sensor coils (upper and lower), a laptop computer with data acquisition software, and a measuring wheel to record distance and location. The lower sensor measures the resistive change in the earth and the upper sensor is used to account for and correct errors in the power readings of the lower sensor. The 2D-Recon survey coils and components were mounted on a rented electric golf cart for fast and effective data collection (Figure 1). The 2D-Recon survey measured resistivity changes in the soil and geology below it as the sensors were moved over the surface. The data was processed to develop a 2-D aerial picture of the subsurface hydrocarbon contamination.

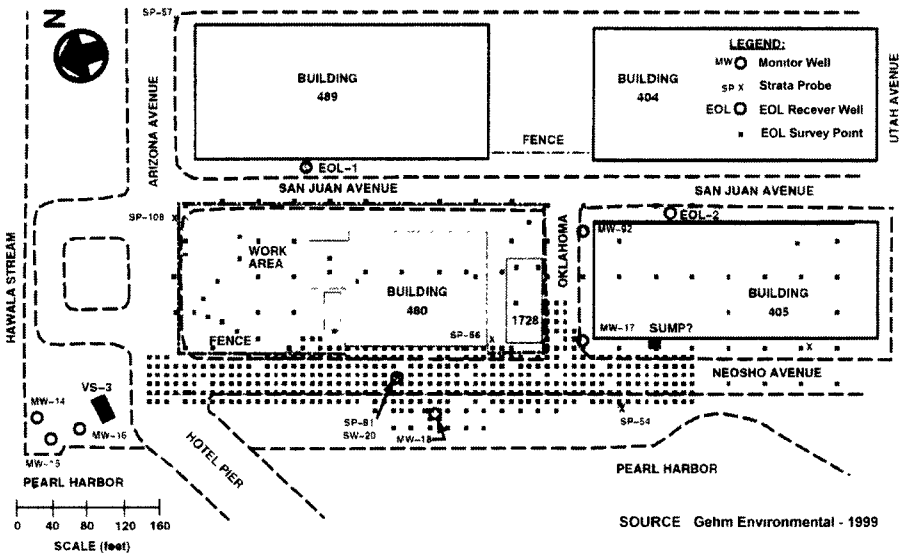
3D EOL at the Hotel Pier Site

The 3D EOL geophysical survey used a surface source coil (transmitter) with an area of approximately four square meters. The surface source coil was constructed with more than 30 loops of low resistance wire and connected to a transmitter power unit consisting of a 1,600 watt 60 hertz gas-powered generator and a power amplifier capable of up to 12 ampere output. The amplifier was set at a 5.00 amperes signal and the transmitter coil and receiver were tuned to around 270 Hertz (Hz) with a narrow bandwidth. This tuning procedure, along with choosing EM receiver wells in low noise level areas, can filter out most of the excess and unwanted electrical noise and allows the EOL technology to be used in and around most manmade structures and other sources of subsurface electrical noise. A grid pattern with approximately 10-foot spacing was used to survey a central 100 feet by 600 feet area of the Hotel Pier site (1.4 acres). Figure 3 shows the EOL transmitter and receiver locations for the Hotel Pier site. The transmitter coil was a portable, self-contained unit that was placed at each grid point one at a time, and the electrical signal transmitted.

The EM receiver was mounted on a 2-inch diameter, 4-foot long probe and connected to a wire-line winch and EOL data acquisition system. To receive the induced signal from the transmitter, the receiver was mechanically pulled up through the receiver well hole measuring the primary and secondary EM fields produced at the transmitter coil location. A large, long wavelength response was created representing the primary EM field. Superimposed on this response were responses related to the secondary EM fields caused by eddy currents moving around the boundaries of resistivity contrasts in the earth.

The EM receiver was mounted on a 2-inch diameter, 4-foot long probe and connected to a wire-line winch and EOL data acquisition system. To receive the induced signal from the transmitter, the receiver was mechanically pulled up through the receiver well hole measuring the primary and secondary EM fields produced at the transmitter coil location. A large, long wavelength response was created representing the primary EM field.

Figure 3
EOL Survey Transmitter and Receiver Locations



Source: Gehm Environmental

Superimposed on this response were responses related to the secondary EM fields caused by eddy currents moving around the boundaries of resistivity contrasts in the earth.

The raw data were computer processed to remove the primary field and calculate and verify the secondary fields. The secondary fields were converted to apparent resistivity measured in ohm-meters to compare directly to the physical properties in the earth. The computer processed data were presented in both three dimensional figures and as depth-specific slices and cross sectional views across the Hotel Pier site.

System Operation

Calibration and maintenance checks on the EOL transmitter and receiver tools were typically performed at the beginning of each day of survey and at changes between receiver well locations. The portable generator required typical oil and fuel checks. Both 2D-Recon and EOL data acquisitions were collected in real time, therefore it was obvious when the equipment was not properly functioning. Each completed resistivity logging data set was uniquely named and saved to a laptop computer. The primary operation and maintenance tasks involved making routine checks of the wiring and wiring connects and the transmitter's output and signal level.

EOL measurements were not affected by asphalt, reinforced concrete features, or buried steel utility lines and pipelines. However, the Hotel Pier site had several underground product fuel lines and sewer lines with cathodic protection that could have potentially interfered with the EOL survey. To avoid interference, the cathodic protection was turned off at the beginning of each day and turned back on at the end of each day, allowing an 8 to 10 hour time interval for the EOL survey to be conducted without interference.

Cost [7, 9]

A complete 2D-Recon survey costs about $2,500 per day with coverage of between two to five acres per day, depending on data point density. Mobilization and demobilization are additional costs. The 2D-Recon produces qualitative data and the data are available within two days of the final data collection.

A complete EOL geophysical survey costs about $10,000 per day including all materials, supplies, equipment rentals, data acquisition, two field staff, one geophysicist, data processing, and report preparation. The daily rate of data acquisition is dependent on the contamination depth, groundwater depth, and overall logging time at each EOL location. Based on observations at three sites (North Island, San Diego; Makalapa Field, Hawaii; and Hotel Pier site, Hawaii), between 50 to 100 individual EOL survey locations (0.1 to 0.25 acres per day) can be completed during an eight hour day. Mobilization and demobilization and completion of any additional monitoring wells are added costs. Final data processing and reporting, performed using Silicon Graphics' ShowCase and word processing software, required approximately two months to complete.

At Hotel Pier, 2D-Recon and EOL surveys cost approximately $10,000 and $90,000 respectively.

Conclusions [8]

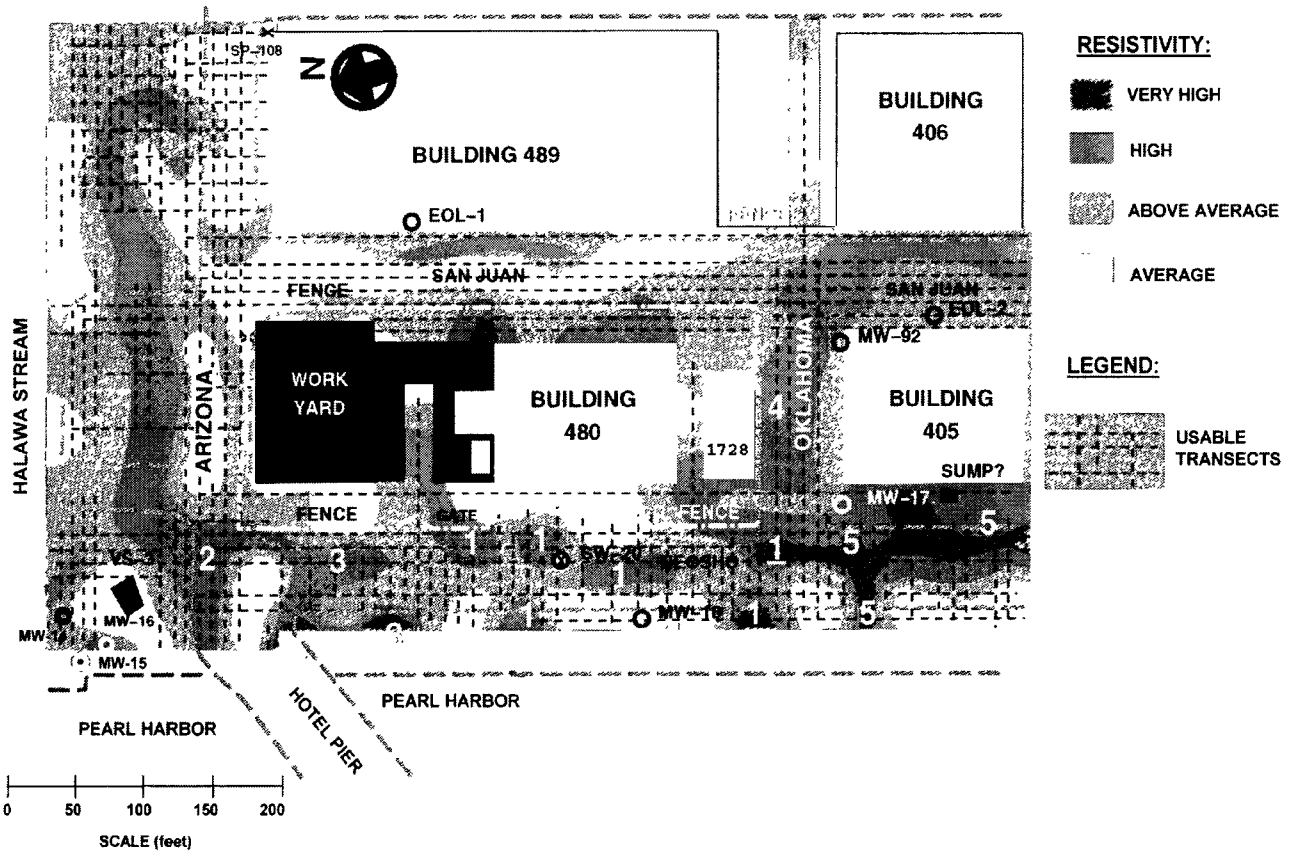
Data from the 2D-Recon and EOL survey were used to characterize the lateral extent of the hydrocarbon plume and define the general boundaries of larger subsurface anomalies. Qualitative results were presented in graphical format using five-color resistivity maps correlating to low, average, above average, high, and very-high resistivity values (Figure 4). The project geophysicist stated that the high and very high resistivity features identified in plan view depth intervals and in cross-section may be associated with the soils with hydrocarbon filled pores. Many of the high resistivity anomalies were found to be positioned around and along utility and pipeline corridors which are known to be preferential conduits for hydrocarbon movement.

Post EOL survey soil sampling was completed but locations were limited to areas outside of the buildings and depths only reached fifteen feet below ground surface. Laboratory analytical data identified hydrocarbon contaminated soil which agreed with the resistivity model. Multiple anomalies were identified from the 2D-Recon and EOL surveys that likely would not have been identified through traditional subsurface soil sampling. The remedial alternative selection criteria and feasibility and effectiveness of a subsurface barrier to control hydrocarbon seepage into the harbor were supported through this survey.

Technology Performance and Factors

Factors that affected the performance of this technology at the Hotel Pier site were (1) the experience of the data acquisition team (two or three field staff), (2) experience and interpretive skills of the senior geophysicist, (3) availability of the Senior Geophysicist to be on site during the field data acquisition and to provide quality control, (4) access to all areas of the site (inside and outside of buildings), (5) timing and logistics to complete additional monitoring wells at specific locations within a few days, and (6) other site-specific factors such as depth to groundwater, inherent resistivity of the contaminated and uncontaminated areas, nature and amount of overhead and buried utilities, and general size of the contaminated area. The overall qualifications and capability of the geophysicist to generate good data and process the data into a usable and accurate model were paramount.

Figure 4
Apparent Resistivity Map from 2D-Recon Survey



Source: Gehm Environmental (Best available copy)

A weakness of EOL surveys is the need for site characterization data to distinguish and calibrate the soil resistivity measurements. A significant contrast between the resistivity of contaminated and the non-contaminated material is needed in order to have a high degree of confidence in the data.

Some subsurface site characterization data is necessary to discern the initial resistivity measurements. For example, subsurface geology information from monitoring well boring logs, previous subsurface sampling, and groundwater monitoring are all potentially valuable characterization data helpful for an EOL survey.

Suitable existing EM receiver wells for the EOL receiver will not be available at all hydrocarbon contaminated sites; therefore time and costs may be needed to properly install new EM receiver wells. The most suitable EOL receiver wells are clean monitoring wells located just outside the central edge of the plume. The radial coverage from a receiver well is dependent on site geology and subsurface features but is approximately 200 to 300 feet.

One improvement that has occurred during the last 15 years is the phased approach in which the geophysical survey begins with a more cost effective 2-D surface gradiometer survey. Then, if contamination and site logistics concur, the

survey proceeds to the more labor-intensive and costly 3D EOL survey. Smaller, more portable laptop computers and the use of commonly available database software packages have helped with the data acquisition and storage of large data sets.

Lessons Learned

A site should have a potentially large and complex area of hydrocarbon contamination to afford the use of surface and subsurface geophysics. The 2D-Recon and EOL geophysical surveys can quickly provide additional subsurface information on the extent of hydrocarbon contamination. Data are collected in real time allowing for on-site qualitative assessments of the plume boundaries, appropriate locations for new monitoring wells, and subsurface sampling efforts which may all help to expedite the entire remediation effort.

Though the geophysical survey techniques provided information on hydrocarbon entrained in the soil, additional analysis was needed to determine the fraction of it that was mobile and recoverable.

The EOL technology performance was evaluated at North Island Navy Base under the Navy Environmental Leadership Program (NELP) in 1997.

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Appendix 3

Sensor Technology Case Study
Use of Capacitance Probes to Measure Soil Moisture at the Badger Army Ammunitions Plant

Sensor Technology Case Study
Use of Capacitance Probes to Measure Soil Moisture at the Badger Army Ammunitions Plant

Summary Information [1, 2, 3, 4, 5, 6, 10, 12]

There are several devices that can be used to measure soil moisture content in the vadose zone. Some of these devices include dielectric permittivity probes, radio-frequency probes, lysimeters, tensiometers, and capacitance probes. This case study focuses on capacitance probes.

Capacitance probes have long been used to measure soil moisture in the agricultural industry for irrigation scheduling. They have also been used in environmental applications as part of containment type remedies. They measure soil moisture content by measuring the capacitance (a measure of charge storing capacity) of the soil around them.

Capacitance probes are being used to monitor the moisture content in soil at the Badger Army Ammunition Plant (BAAP). The BAAP is a 7,354 acre site located in Sauk County, approximately 7 miles south of Baraboo, Wisconsin. Intermittent war-time plant operations over a 33 year period resulted in contamination of the site with munitions based compounds. The remedial approach at Badger was to address sub-sites individually. This case study presents use of soil moisture sensors used at sub-site BAAP-06 also called the Deterrent Burning Ground (DBG).

The DBG is located in the northeastern portion of BAAP. The DBG was a former two-acre borrow pit that was used as a landfill for demolition debris, and for the open burning of deterrents, structural timbers, asphalt shingles, cardboard, papers, and office waste. The primary contaminants are volatile organic compounds and munitions based compounds. The most contaminated soil in the top 15 feet of the waste pit was removed. The remedy for the site included the construction of a 7-acre low-permeability cap above the contaminated zone. This was to prevent leaching of contaminants into the groundwater during large rainfall events. Another component of the remedy involved in-situ bioremediation of residual contamination in the vadose zone.

The bioremediation system was installed in the summer of 2003. The system supplies water and nutrients to native microbes in the vadose zone through an infiltration gallery. Capacitance probes were used to measure soil moisture in the vadose zone to evaluate overall system performance. In addition, capacitance probes provided the sensory means to observe the potential for excessive infiltration, and thus prevent inadvertent contamination of the underlying groundwater.

Four capacitance probes were installed at BAAP. The probes continuously measure soil moisture content, and four separate dataloggers periodically retrieve measured data from their respective probes. The data is downloaded from the datalogger and examined to understand soil moisture response during infiltration. Inferences from soil moisture data are used to determine the need for modification in infiltration gallery operation.

To date, the system has not been able to detect infiltration beyond the first two feet beneath the infiltration gallery. This is possibly due to the lack of a detectable moisture front during infiltration.

Technology Description [1, 2, 3, 4, 7, 8]

Capacitance probes use the principal of electrical capacitance to measure soil moisture.

Capacitance is a measure of a device's ability to store electrical charge. A device that can store charge is called a capacitor and consists of two metal plates separated by a dielectric substance (or insulator). The device's capacitance depends on the dielectric substance used. When an alternating current is applied to a capacitor, it charges and discharges sequentially causing an apparent change in the frequency of applied current. This change in frequency is a function of the device's capacitance, and by measuring the altered frequency, one can determine the device's capacitance.

The soil-sensor system is in essence a capacitor. The sensor's electrodes serve as the plates, and the soil around the sensors serves as the dielectric substance. The capacitance of the sensor-soil system is a function of the moisture in the soil. By measuring the capacitance of the system, the probe in essence measures the amount of moisture in the soil.

Capacitance probes have been used to measure soil moisture in the agricultural industry for several years. The technology has been commercial for at least 15 years.

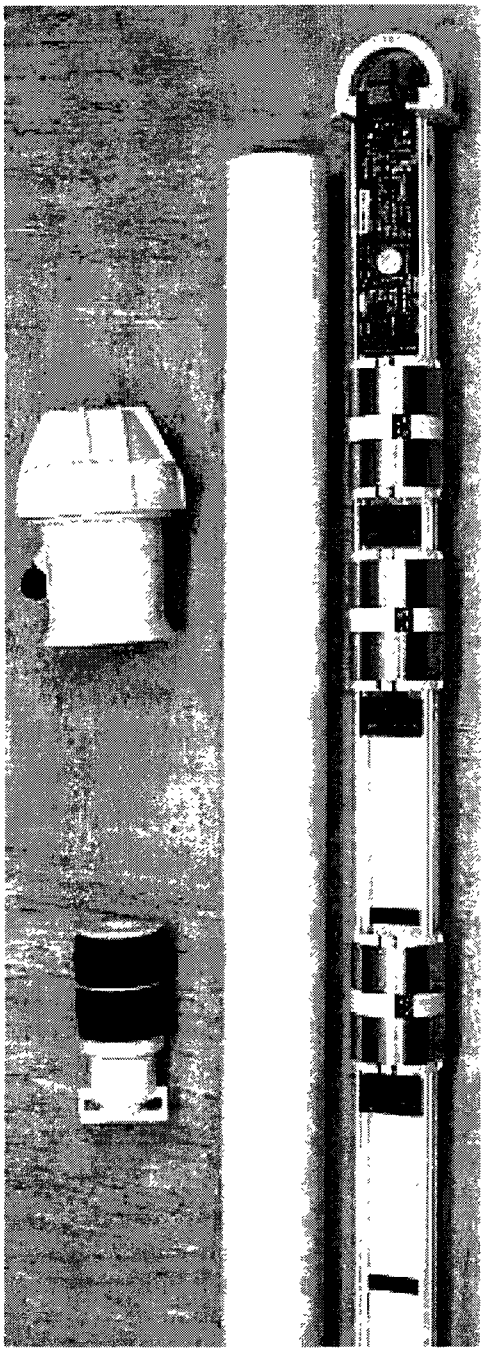
The probe consists of vertically spaced sensor assemblies enclosed in a snug-fitting PVC access tube (Figure 1). The number of sensors used in a probe, and the sensor spacing along the access tube can be varied as desired. Different manufacturers have different constraints on the maximum number of sensors allowed in a probe. Probes in the agricultural industry are typically 3 feet long and rarely exceed 6 feet in length. The access tubes are installed in direct contact with the lithology using a suitable augur method.

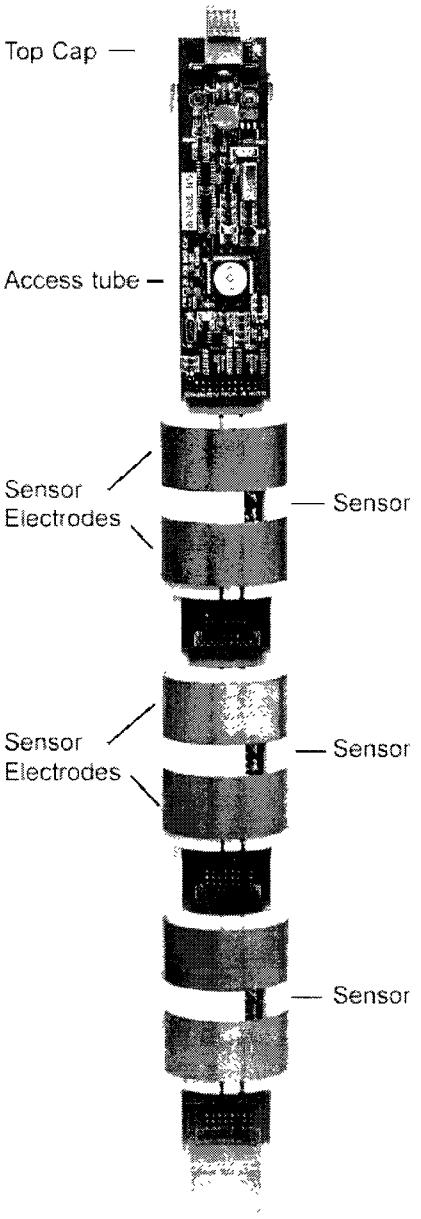
Once the access tube is in place, the sensor assembly can be inserted into it. However, the sensors typically need to be normalized before this. Alternately, one can purchase normalized sensors for an additional charge. Normalization is a process through which sensor outputs are standardized to lie on a common scale. Normalization is necessary because there is a slight variation in outputs produced from sensor to sensor. EnviroSMART™ probes are normalized using vendor-supplied software to set the sensor's maximum output to 1, and its minimum output to zero. The maximum corresponds to complete saturation, and the minimum corresponds to zero moisture content. Therefore normalized probes produce outputs on a unitless zero to 1 scale.

Probe installation involves drilling a hole to the required depth. After the probe casing is lowered into the hole, a bung is inserted to seal off the bottom. The sensors and controlling electronics are then inserted into the casing. Finally the cap is installed to seal-in the sensors and associated electronic devices. The cap is weather proof, but cannot withstand continuous submergence. The cap contains a desiccant to prevent moisture from entering the casing. The probe head is typically not flush mounted with the ground. It usually sits about 5 inches above ground level.

After the probe has been installed in place and all the necessary electrical connections have been made, the sensors may be field-calibrated. Field calibration in essence involves correlating the sensor's normalized output to actual soil moisture. However, according to the vendor, field calibration is a rare practice. Most of the time customers use the vendor-supplied standard calibration model (IrriMAX) which converts retrieved output data to approximated volumetric soil moisture contents. Sometimes normalized results produced by the sensors meet the customer's requirements, in which case not even the standard calibration model is used. However, field-calibration is recommended for applications that need accurate measurement of volumetric soil moisture content. Field calibration takes into account all the peculiarities of the soil surrounding a given

Figure 1
Soil Moisture Probe





Source: Campbell Scientific Inc.

sensor thereby minimizing measurement error. It involves developing a mathematical relationship between the sensor's normalized output and actual soil moisture content. Data required for this correlation is obtained by sensory measurement followed immediately by collection of a soil sample for laboratory analysis. The EnviroSMART™ probe's user manual provides instructions on deriving this mathematic relationship. Once derived, a spreadsheet program such as Microsoft Excel can be used to convert sensor outputs to volumetric soil moisture content.

The table below provides specifications of the probes used at the Badger site. These probes were manufactured in Australia by Sentec Inc. and marketed in the United States by Campbell Scientific Inc.

EnviroSMART™ Probe Specification	
Parameter	**Value**
Maximum Cable Length	200 ft
Maximum Sensors per Probe	16
Accuracy (field calibration)	R^2=0.99
Precision	(+/-) 0.03% by volume
Measurement Range	Oven-dry to saturation
Temperature Effects	(+/-) 3% (at temperatures between 41° and 95°F)
Operating Temperature Range	32° to 158°F
Time to Read One Sensor	1.1 seconds
Sphere of Influence	99% of measurement within 3.94 inch radius from the outside of the access tube
Sensor Diameter	2 inches
Access Tube Diameter	2.22 inches

Site Information [2, 5, 10, 12]

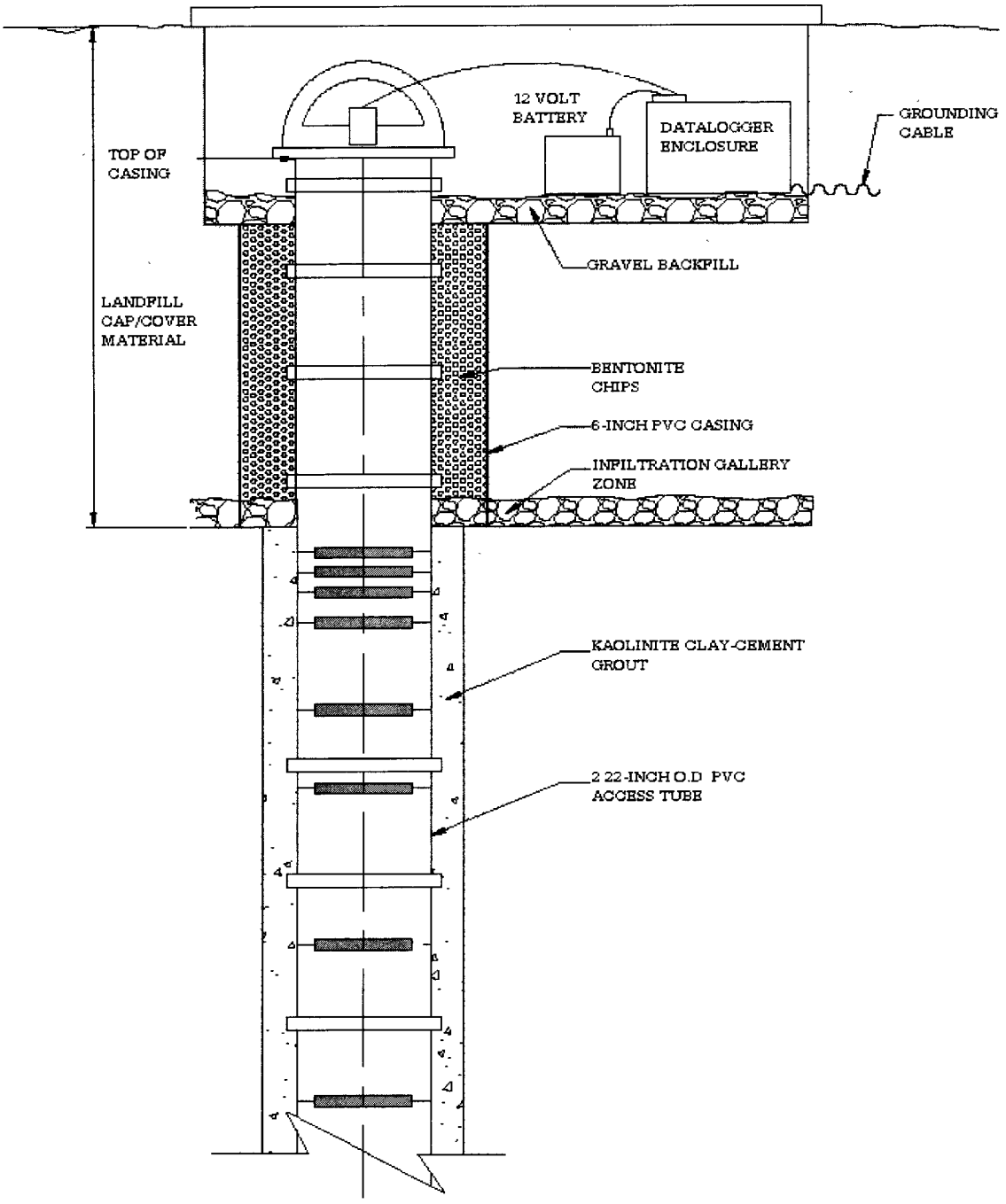
BAAP is a 7,354 acre site located in Sauk County, approximately 7 miles south of Baraboo, Wisconsin. The BAAP site contains several sub-sites. The DBG, where the probes were installed, is one of the sub-sites at BAAP.

The lithology at the site comprises layers of sand and gravel with interspersed layers of silt. The first water bearing zone is encountered approximately 100 to 110 feet below ground surface (bgs).

A low permeability cover was part of the remedy for the DBG. The low permeability cover reduced surface water infiltration through the contaminated vadose zone, thereby preventing the leaching of contaminants into the groundwater. The other component of the remedy involved bioremediation of contaminants in the vadose zone. Bioremediation of the vadose zone involved the supply of water and nutrients to sustain contaminant-degrading microbial communities. Water and nutrients were supplied through infiltration galleries constructed approximately four feet beneath the surface of the low permeability cap.

Capacitance probes were installed in June 2003 (as part of the bioremediation system) to monitor infiltration. In addition to serving as indicators for conditions favoring bioremediation, the capacitance probes were expected to provide the sensory means to recognize excessive infiltration into the vadose zone. The probes spanned the entire depth of the vadose zone, extending from the ground surface to a few feet above the water table. Figure 2 presents a section of the installed probes at Badger. Each installed probe was approximately 100 feet deep, but the deepest sensor in each probe laid only 50 feet bgs.

Figure 2
Soil Moisture Probe Assembly



Note: Modified from as-built drawing (Shaw Environmental, Inc. 2004)

Two infiltration galleries were constructed in the remediation area. One measured 100 feet by 80 feet, and the other located southeast of the first measured 320 feet by 100 feet. Of the four Sentek EnviroSMART™ probes used at the site, one was installed beneath the smaller gallery, two were installed beneath the larger gallery, and one was installed in an area adjacent to both galleries to serve as a control.

Sonic drilling was used to drill 4-inch-diameter holes for each of the probes. Segments of the access tube were then spliced together and lowered into the borehole. Each segment was approximately 6.8 feet long and had a 2.22-inch outside diameter. The deepest segment had a PVC cap at the bottom to provide a moisture-tight seal. The segments were spliced together using glued PVC slip joints. PVC centralizers were installed at each slip joint and at the bottom of the assembled access tube. After the access tube was in place, a kaolinite clay-cement grout was used to fill the annular space between the borehole and the access tube. The grout was placed along the entire length of borehole from the bottom of the borehole to the ground surface. After the grout had set, the sensors and related electronics were lowered into each tube. Each probe contained 14 sensors. Sensor spacing varied along the length of the probe. In general, the spacing increased with increasing depth.

The data retrieval system included a serial data interface (SDI) operating at a baud rate of 1,200 to receive and record data from each soil moisture sensor. A Campbell Scientific Model CR510-2M datalogger was used to query each probe's SDI and store soil moisture data for future retrieval. The datalogger could be programmed to record soil moisture measurements in intervals that ranged from as small as five minutes to greater than one week.

The Intelligent Probe Utility Software provided by Campbell Scientific, Inc. was used to normalize each sensor through the probe's SDI. The probes were not field-calibrated.

System Operation [1, 2, 11]

The infiltration gallery operated only one day per quarter to simulate percolation caused by precipitation. The moisture probes, however, operated continuously to measure soil moisture response during, and after infiltration gallery operation. The only human effort in operation of the moisture probes involved data retrieval from the dataloggers. Soil moisture measurements were automatically collected from the probes by the dataloggers at 30-minute intervals for a period of up to 4 weeks.

Soil moisture data downloaded from the dataloggers was closely examined to gain an understanding of the changes in soil moisture content during infiltration gallery operation. To date, the only observed spikes in soil moisture content were observed in the upper two feet of soil beneath the infiltration gallery.

Over the months, there was a decreasing trend in soil moisture measured by some of the deeper sensors. This supported the claim that the low permeability cap was reducing the amount of infiltration through the contaminated zone.

System maintenance included periodic checks for probe cap seal, and changing the desiccant in the cap as necessary. The probe head enclosures were replaced with watertight enclosures to prevent recurrence of sensor malfunction previously caused by the entrance of moisture into the probes.

Cost [4, 6, 9]

Costs for installation of the probes at the Badger site were not available. However, a cost estimate for a similar system is presented in Table 1.

TABLE 1
ESTIMATE FOR A TYPICAL SYSTEM USING ONE SOIL MOISTURE PROBE

EnviroSMART™				
Item	**Qty**	**Unit**	**Unit Price ($)**	**Subtotal ($)**
EnviroSmart Probe [1] (50 feet long)	1	ea	2,837	2,837
Sensors [2]	16	ea	200.00	3,200
SDI-12 Interface	1	ea	375.00	375
Interface Cable [3] ($20 + $0.23/ft)	50	ft	0.23	12
Yellow Cutting Edge	1	ea	10.25	10
Expandable Bung	1	ea	19.00	19
Gel Bags	1	set	34.00	34
Ferrite Beads	1	pack	12.60	13
Normalization Container	1	ea	157.00	157
Programming Cable	1	ea	120.00	120
Probe Utility Software	1	ea	63.00	63
Datalogger (Campbell Scientific CR510-2M)	1	ea	895.00	895
TOTAL [4]				**6,840**

Note:
1 Cost varies with length
2 Number of sensors in a probe can vary from 1 to a maximum of 16
3 Cable runs from the datalogger to the SDI-12 interface
4 Cost does not include installation

Source: Campbell Scientific Inc. 2004 Price List

There are several variables that affect the cost for installing such a system. However, the two major variables are depth of installation and number of sensors used. The depth of installation (or the length of probe) directly impacts total cost of the system. Shorter probes are less expensive than longer ones. The depth of installation also influences the cost of drilling. For shallow probes not exceeding 7 feet in length, the hole may be drilled using the installation kit purchased (or rented) from the supplier. On the other hand, deep installations such as the one at Badger require drilling rigs, and more involved probe installation methods. The cost of the system also depends on the number of sensors used per probe. The number of sensors can vary from 1 to a maximum of 16. As in other systems, the number of probes purchased influences the selling price per probe. Optimizing datalogger use by using the maximum number of probes per datalogger can reduce unit cost per probe.

The estimate presented in Table 1 assumes that the probe contains 16 sensors that interface with a Campbell Scientific Model CR510-2M datalogger, the deepest sensor being 50 feet deep. In practice the datalogger to be used depends on requirements of the application, and not the probe. The simplest datalogger that can be used with this probe is Campbell Scientific's Model CR200. The estimate does not include drilling or probe installation.

Conclusions [1, 2, 4, 10]

According to the owner's contractor, Sentek's capacitance probes were used at Badger because they were the only probes amenable to deep installation.

The cap on the probe's access tube is weatherproof but does not provide a watertight seal when submerged. This should be taken into account while designing systems that use this probe. Moisture entry into a probe caused it to malfunction at Badger. This resulted in replacement of the then-existing probe-head enclosures with watertight enclosures. The vendor recommends replacement of the desiccant inside the access tube's cap as needed to prevent moisture build-up.

Sensors can be removed and re-used as desired. The access tube might have to be abandoned in place (depending on the depth of installation), the sensors, according to the Vendor, can always be removed and used at another location. Modification of installed probes by adding or removing sensors is also possible. Addition of sensors to an existing probe would be constrained by the space available inside the access tube, and the maximum number of sensors (16) that can be used per probe.

According to the Vendor, most customers are satisfied with normalized outputs or the vendor-supplied standard calibration model. Nevertheless, in applications where accurate soil moisture measurement is required, field-calibration is essential. Field-calibration is a tedious and time consuming process, and should not be neglected in budgetary estimates. It is important to note that deep installations (such as those at Badger) can make field-calibration impractical. This is because collecting a deep soil sample within the sensor's zone of measurement, immediately following sensory measurement, can be difficult if not impossible. For this reason, one must discuss the requirements of the application with the vendor before incorporating the probe into the design for a remediation system.

The access tubes supplied by the vendor required splicing using glue and slip joints. According to the owner's contractor, this method of splicing presented problems during installation. Since glue was used, care had to be taken not to strain the joint until the glue had dried. This increased the time and effort required to install the access tubes. In this regard, the owner's contractor was of the opinion that threaded PVC pipe would have made for a better access tube. At one location, an obstruction was encountered at a slip joint in the access tube during sensor installation. The inner walls of the access tube had to be reamed to smooth the slip seams before the sensors could be re-inserted. In another instance, grout entered the access tube presumably through a separated slip joint. The access tube was abandoned in place, and a new access tube had to be installed a few feet away from the first one.

To date there have been no observed spikes in measured soil moisture beyond the first two feet beneath the infiltration gallery. Although this seems to imply that there is no infiltration beyond this point, this is not necessarily the case. Soil vapor vents used to monitor biological activity have detected gases in concentrations indicative of enhanced biological activity. This suggests successful nutrient delivery, and consequently infiltration of water to the remediation zone. It can be theorized that infiltration may not have been detected due to the lack of a saturated front, and the resulting irregular migration of moisture through the soil pores. Whatever the migratory path, it appears that the moisture did not pass sufficiently close (3.94 inches from the outside of the access tube) to the probes to be detected.

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Appendix 4

Sensor Technology Case Study
Use of In-Situ Sensors to Monitor Groundwater Velocity at the China Lake Naval Air Weapons System Site

Sensor Technology Case Study
Use of In-Situ Sensors to Monitor Groundwater Velocity at the China Lake Naval Air Weapons System Site

Summary Information [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]

Variably Emitting Controlled Thermal Output Recorder (VECTOR) technology is used to measure groundwater flow speed and direction in three dimensions. It works on the principle of heat perturbation, whereby measured displacements in the heat-flow field around the probe are used to calculate groundwater velocity. The measurement range for velocity magnitude is 0.01feet per day (ft/day) to 2.00 ft/day. Three-dimensional directional measurement has an accuracy of (+/-) 5 degrees. These probes are installed in situ, much like a monitoring well, using a suitable method such as hollow stem auger drilling. Following installation, the system is connected to 120 volt power supply. Once all of the necessary electrical connections have been made, the probe is turned on, calibrated and allowed to collect flow data.

VECTOR technology is being used at the China Lake Naval Weapons Station to monitor groundwater flow in various water bearing zones (WBZ) along the southern boundary of the property.

VECTOR probes were installed in 1999. Data from the probes were used to monitor local groundwater flow as well as seasonal and background impacts to local flow fields (such as agricultural or municipal pumping) located several thousands of feet away from the probes.

Quarterly site visits to download stored data from automatic data collection devices constituted the only human effort in system operation. Although the option for remote access via telephone or cellular phone was available, this was not used at China Lake. Once downloaded, the data was analyzed using HTFlow, the analysis software provided with the VECTOR system.

Although a few probes have stopped operating since their installation in 1999, they have generally lasted longer than their predicted one-year lifespan. Operation to date has resulted only in minor data corruption, attributed to system wear and electrical anomalies.

The probe requires a minimum five-foot saturated thickness above it to function properly. This has been a limitation at China Lake, where saturated thicknesses are usually less than 10 feet.

Technology Description [1, 4, 5, 6, 7, 8, 9]

VECTOR technology is used to measure groundwater flow velocity (Darcy velocity). It is a full-scale technology and VECTOR systems are available for purchase from Hydrotechnics Inc. Probes are generally made to order with lead times on delivery ranging from one to five weeks.

Since velocity is a vector characterized by magnitude and direction (three dimensional in this case), this document uses the term "velocity" to imply both magnitude and direction.

Following in-situ installation, the probe is field-calibrated. Field-calibration is usually performed just once in the lifetime of a probe provided there is no drastic change in the probe's environment. For instance, a 50 degree change in groundwater temperature caused by a local thermal influence, or a significant change in saturated zone composition through intrusion of another liquid may warrant re-calibration.

Calibration includes heating the probe to a steady temperature approximately 25 degrees Centigrade (°C) above the ambient groundwater temperature. As groundwater flows past the heated probe an equilibrium temperature distribution forms on the probe's surface. The analysis software supplied with the VECTOR system then correlates measured temperature distribution to groundwater velocity. Just as the coldest side of a wet finger held up in the air indicates which way the wind is blowing, the coldest side of the submerged probe indicates the direction from which the groundwater is flowing.

The VECTOR system is made up of several different components: a probe, a power source, wiring to transmit data, a data collector often called a datalogger, and data analysis software (HTFlow). Some of these components come with differing capabilities depending on the requirements of the application. The datalogger can be connected to a maximum of 12 probes and the power supply can be tailored to accommodate any number of probes. Figure 1 depicts a typical VECTOR system.

The VECTOR probe is a cylinder measuring 2.375 inches in diameter and 36 inches in length connected to industry-standard flush-mounted Schedule 40 PVC well pipe. Alternating current (110 Volt) runs a power supply which is used to constantly heat the probe with about 60 watts, maintaining it at a temperature between 20 and 30 °C above ambient groundwater temperature. An integrated array of 30 carefully calibrated temperature sensors or thermistors forms the outermost layer of the probe. This layer measures temperature variations along the surface of the probe caused by groundwater flow. These thermistors are extremely sensitive and can accurately measure differential temperature to within (+/-) 0.01 °C.

The VECTOR probe has the following measurement capabilities:

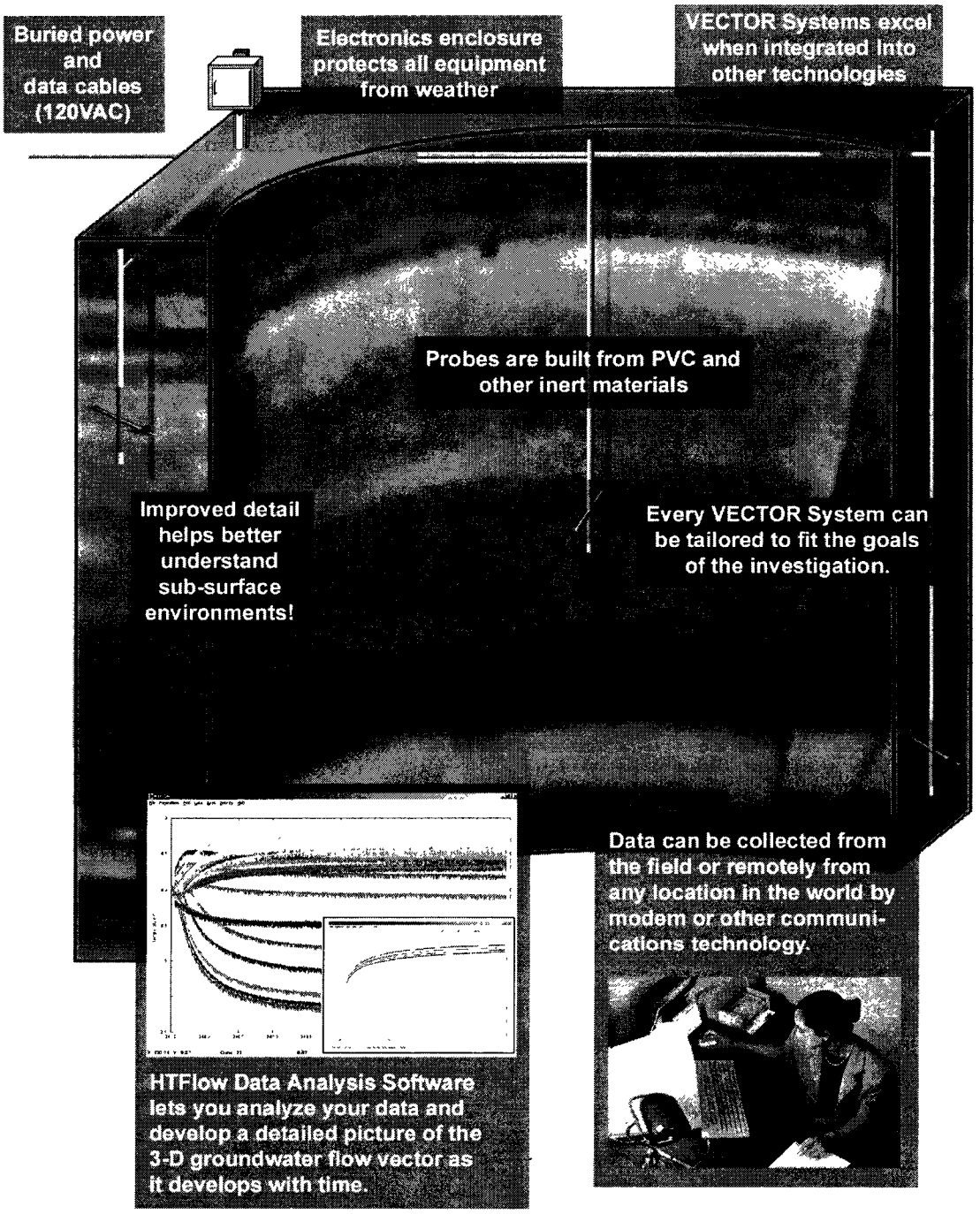
Minimum Darcy Velocity = 0.01 feet per day (ft/day)
Maximum Darcy Velocity = 1.00 ft/day
Resolution = 0.001 ft/day
Minimum Flow Rate Measured = 0.01 ft/day
Max. Flow Rate Measured = approximately 2 ft/day
Thermistor Accuracy = (+/-) 0.01 °C
Directional Accuracy = (+/-) 5 degrees

The probes are installed in direct contact with saturated soil using a method of drilling that allows uniform collapse of the lithology around the probe. According to the manufacturer, hollow-stem auger drilling has so far yielded the most consistent results. Although this method of drilling disturbs the lithology, there is the certainty that a saturated sand lithology will uniformly collapse around the VECTOR probe when the auger flights are removed. Other drilling techniques have successfully been used for installation in deeper and more difficult formations. Good results have also been obtained using mud-rotary drilling. According to the manufacturer, resonant sonic drilling has the potential to replace hollow-stem auger drilling as the method of choice.

Groundwater flow direction measurements made by the probe are relative to the probe's reference direction which is carefully recorded during installation of the probe. Conversion of the probe's directional measurements to azimuths is performed by HTFlow.

The datalogger currently supplied with the VECTOR probe is a CR10X datalogger manufactured by Campbell Scientific. Although there are other similar dataloggers, the manufacturer recommends use of the CR10X because of the variety of remote downloading capabilities it offers. The CR10X datalogger

Figure 1
Vector System Layout



Source: Hydrotechnics Inc.

requires a simple wall-mounted 12 Volt direct current power source for operation. To make communication possible, an interface box (Campbell Scientific Model SC32B) must be used. The data logger comes with industry-standard software allowing a user to program data collection schedules as well as simultaneously manage data collection from several probes. The datalogger can be fitted with a modem that communicates through landlines or cellular phones to facilitate remote data acquisition.

Site Information [3, 8, 9]

The VECTOR system was used at the Naval Air Weapons Station in China Lake, California.

The concern at China Lake was the proximity of the site to the municipal well fields in the City of Ridgecrest. The closest well field was located less than a mile south of Inyokern Road which marks the boundary between China Lake and the City of Ridgecrest. Although no contamination was found along the boundary, the VECTOR probes were installed to monitor the potential for off-site migration of contaminants to safeguard against the possibility of their detection at a later date.

The Navy's monitoring well network included 64 wells (5 equipped with pressure transducers) screened in the shallow WBZ, 36 wells (3 equipped with pressure transducers) screened in the intermediate WBZ, 23 wells screened in the deep WBZ, and 9 VECTOR probes installed at four strategic locations along the facility's property boundary in the shallow and intermediate WBZs.

The probes were installed in 1999 using hollow stem auger drilling. They were installed 50 feet and 180 feet bgs in the permeable (sand and gravel) portions of the shallow and intermediate WBZs respectively. Data collected from the nine VECTOR probes and pressure transducers, coupled with the water level measurements collected quarterly from the fence line monitoring well network facilitated the following:

(1) Determination of the direction and rate of groundwater movement from the China Lake Complex to the City of Ridgecrest

(2) Monitoring changes in horizontal and vertical groundwater gradients and velocities

(3) Evaluating the interconnectivity between the three WBZs (shallow, intermediate, and deep)

According to the Owner's contractor, VECTOR technology in concert with other monitoring programs in place at China Lake, provided a cost-effective approach to monitoring horizontal and vertical groundwater movement (within the different WBZs) from the China Lake Complex to the municipal well field.

The VECTOR probes, coupled with the pressure transducers in adjacent monitoring wells, collected hourly measurements of groundwater velocity and groundwater level data to provide temporal continuity to the network of 123 wells that were being used to monitor groundwater flow within an 84-square mile area.

The entire field effort for installation of the VECTOR systems, including well drilling, probe installation, and electrical connections took place over a two-week period. The VECTOR manufacturer provided installation services during this period. No problems were encountered during probe installation.

The electronics were housed in weatherproof NEMA4 enclosures next to electrical utility poles that served as power sources. The locked enclosure allowed limited access for downloading data and adjusting probe power levels. All power and control wiring to the probes were run below ground to allow for unimpeded site access.

System Operation [3, 8]

Following initial calibration, probe operation required no human supervision. The datalogger continuously logged probe data and recorded hourly averages. Stored data was manually downloaded for analysis every three months. Data retrieval involved connecting the datalogger to a laptop computer through an interface box. The supplied software was then used to download the data onto the laptop computer's hard drive. Downloaded data was analyzed in the office using HTFlow.

According to the Owner's contractor, the probes operated as expected. Minor flaws in recorded data were distinguishable and could be excluded from analysis. The HTFlow software was able to calculate a "fit error," for calculated velocities. This error was presented as an upper and lower confidence interval bounding the velocity curve. It was a useful feature for determining the quality of retrieved velocity data. In addition, error analysis allowed users to separate the few data flaws caused by electrical anomalies from real measurements.

Being a relatively new and untested technology (first installed in 1996), the expected lifespan for a constantly operating submerged probe was not known. Although the probes were said to have life expectancies ranging from one to two years, nearly all probes installed at this site operated without malfunction for at least five years. Recently, however, several of the probes ceased to function. The Owner's contractor attributed their failure to possible electrical problems resulting from earth moving operations on site rather than probe malfunction. Over the operating life of the probes, there were only minor problems involving the data logging and retrieval system, including some data loss caused by power surges.

Cost [5, 7]

Incurred costs for installation of the nine-probe VECTOR system at China Lake were not available. However, the estimated cost (excluding well drilling) in 2004 dollars is approximately $50,000. Table 1 presents a cost estimate for a similar three-probe VECTOR system. Unit prices are in 2004 dollars. This estimate is based on the assumption that the purchaser would have total ownership of the equipment and all data processing. This type of procurement is beneficial when equipment rental costs for long-term groundwater monitoring exceed that of outright ownership.

Based on Table 1, the unit price for installation was $8,145 per probe. This included material and installation costs for the VECTOR probes and datalogger; assuming that the well had already been drilled. Consequently, drilling costs were not part of this estimate.

Material costs account for the bulk (82 percent) of the total capital cost of the technology. In comparison, installation costs are small at only 18 percent of the total capital cost. Although costs for operation were not available, the main cost components are expected to include energy and quarterly site mobilization for data download.

Some factors that influence capital costs are:

(1) Number of probes. The unit cost of implementing this technology is inversely proportional to the number of probes purchased.

(2) Production volume and demand for the VECTOR system. High production and low demand would decrease costs, while low production and high demand would increase costs.

TABLE 1
COST ESTIMATE

Typical System Using Three Vector Probes				
Description	**Qty**	**Unit**	**Cost ($)**	**Total ($)**
VECTOR In Situ Permeable Flow Sensor includes down-hole multiplexer, lab-calibration with associated files, and introductory technical support.	3	Each	3,080	9,240
Campbell Scientific CR10X Data Logger (with 2 (two) meg memory option, RS232 optically isolated interface, manual, 12V power supply and all com port connection cables)	1	Each	2,650	2,650
60V/1.5A Protek DC adjustable digital readout power supply for single-probe operation	3	Each	400	1,200
Probe/cable packaging and handling, basic insured ground-shipping w/2-3 week advance notice	3	Each	65	195
VECTOR System assembly, down-hole installation with driller assistance, establish reference direction, assistance with cable burial and well head completion, all cable/power connections, enclosure installation, and initial probe powering for field calibration	5	Days	900	4,500
NEMA-4 weather-proof hinged enclosure for power supply and/or datalogger. Construction with cooling fans and back-plate mounted instruments	1	Each	350	350
HTFLOW software license (Free to US Government)	1	Each	300	300
TOTAL				**24,435**
UNIT COST (per Probe)				**8,145**

Source: Hydrotechnics Inc. Estimate # 1802 from Richard Fagioli

(3) Peripheral costs. Some components of the VECTOR system (such as the data logger) are manufactured by a different entity. Capital costs of the VECTOR system would therefore be influenced by price changes in peripherals.

According to the manufacturer, apparent, large up-front capital costs are an obstacle to probe use. Though the technology might have an initially high capital cost, the minimal operation and maintenance costs imply increasing cost-benefit over time. For example, if a one-time-only snapshot measurement of groundwater flow were required at a site, VECTOR technology might prove more expensive than a three-point piezometric analysis. On the other hand, if continuous measurements were required over a period of time and over differing flow scenarios, cost analysis would reveal the benefits of using VECTOR technology over conventional methods.

In general, the level of effort and associated costs for implementing VECTOR technology are less than those for setting up and performing a week-long constant rate discharge test representing a location of equal size.

Conclusions [3, 5, 8, 10]

Information presented in this section was derived from conversations with the Navy's contractor at China Lake, and the technology vendor.

This section summarizes technology strengths, weaknesses, and useful facts learned through implementation at China Lake. This section also includes useful knowledge gained from implementation at other sites, as provided by the vendor.

The accuracy in measurement of groundwater flow direction is a function of the magnitude of velocity and the geometry of flow past the probe. HTFlow can graphically illustrate the potential margin of error in measured flow direction at a given point in time. Another factor influencing directional accuracy is the diligence exercised by the field-installer in recording the compass orientation of the probe's reference meridian. This is thought to be the greatest contributor to error in directional measurement. Discounting human error, these probes usually have (+/-) 5 degree azimuthal accuracy at low groundwater flow velocities. This is considered more than sufficient for typical hydrogeologic applications. Another important factor in directional measurement is magnetic declination. After the orientation of the probe's meridian has been determined using a compass, a correction must be applied. This is because compass measurements are in reference to the earth's magnetic poles, while true azimuths are in reference to its geographic poles.

Continued accuracy of groundwater flow measurement is contingent on the assumption that groundwater temperature will remain relatively constant. Strictly speaking, measurement is only valid at the temperature at which the probe was calibrated. As a result, one must be cognizant of heat sources in the vicinity that could alter groundwater temperature after calibration. Early tests on shallow probes installed in very thin aquifers revealed detrimental effects related to diurnal heating and cooling of overlying soils. To mitigate these effects, the probes must be installed in a lithology that provides at least 4 feet of saturated overburden.

The probes have never been installed in aquifers deep enough to experience more than about 30 pounds per square inch (or 70 feet of water column) of pressure. Therefore, it is not known whether depth is a limiting factor in probe function. Though there are no theoretical limits, the depth of installation is currently restricted by the length of cable connecting the probe to the datalogger. The present configuration allows for a maximum cable length of about 500 feet.

Improper installation of the probe can produce errors in measurement. Improper installation could include a situation where the probe is in contact with a different lithology than presumed. This can be avoided by maintaining accurate lithologic logs while drilling the well. Improper installation may also constitute a probe encompassed by disturbed soil with hydraulic properties differing from the surrounding lithology. Minimizing surface disturbances during probe installation, and careful removal of the drilling augur can prevent this from happening.

Factors affecting the life span of the probe are not known. However, the manufacturer believes that the longevity of the thermistors used in the probe possibly has the greatest influence on the probe's life span. The manufacturer estimates a one to two year lifespan. However, the probes at China Lake lasted at least five years.

VECTOR systems function best in a wide variety of sands. This includes any material with grain sizes from 0.050 mm to 1.5 mm or U.S. Standard Sieve Series No. 270 to No. 12.

However, usable results have also been obtained in other lithologies.

In general, the VECTOR system has widespread potential application. Its potential uses include monitoring ambient groundwater flow, monitoring the capture zone of a groundwater extraction system, and monitoring bulk hydraulic conductivities of aquifer media during remedial processes that require such measurement.

The cost-benefit of VECTOR technology is a function of the user's needs. According to the manufacturer, the technology is generally underutilized in that customers typically use it to measure fewer parameters than it is capable of. For example, the probe in combination with pressure transducers in nearby wells can be used to measure and monitor changes in bulk hydraulic conductivity. However, if a user does not need to measure this parameter, the probes ability to measure it will not be considered a benefit.

Limitations

VECTOR technology allows users to manually regulate the power supplied to the probe; users are expected to record any change made, in HTFlow. Erroneous results could be produced if a user did not record the new power level.

Any lithology that does not produce a laminar groundwater flow past the probe's surface is inappropriate for the VECTOR. Fractured or solid bedrock, unsaturated sediments, excessively high groundwater flow velocities or grossly heterogeneous lithologies primarily consisting of cobbles and coarse glacial deposits will yield poor results. Conversely, super fine sediments such as silts and clays will also yield poor results because local convection will play a greater role in heat transfer than groundwater advection. However, thin lenses of these kinds of sediments within a suitable lithology can be accounted for when performing data analysis by simply isolating those thermistors in direct contact with the lenses.

This technology cannot be used in environments such as open boreholes, open streams, rivers, and open channels.

This technology is not suitable in any thermally heterogeneous environment such as within a narrow permeable reactive barrier, or near a formation with thermal properties differing from the surrounding lithology.

Improvements

Although the VECTOR was originally designed for emplacement in direct contact with a saturated granular lithology, efforts are underway to produce a tool that will measure three dimensional flow within any packed and backfilled open-borehole configuration.

The VECTOR manufacturer is also beta-testing their own down-hole datalogger (VeComm) system for use with the probes.

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Appendix 5

Automation Technology Case Study
Programmable Logic Controllers and Ozone Analyzers
at the Moffett Federal Airfield Site

Automation Technology Case Study
Programmable Logic Controllers and Ozone Analyzers at the Moffett Federal Airfield Site

Summary Information [3]

Ozone analyzers and a programmable logic controller (PLC) are used in an ozone/hydrogen peroxide groundwater treatment system to monitor system performance. This case study presents the use of real-time ozone analyzers in conjunction with a PLC in a pump and treat system. The ozone analyzers work in conjunction with the PLC to ensure that (1) the correct dosage of ozone is applied to the influent water, (2) the offgas treatment system is meeting the air emission standards, and (3) that the ambient air meets occupational safety and health administration (OSHA) standards.

In addition to the ozone analyzers, this case study presents the use of a PLC as well as a supervisory control and date acquisition interface. The supervisory control portion of the system consists of a PLC, which receives inputs from various sensors and instruments and operates the treatment system based on a set of programmed instructions. The data acquisition portion of the system consists of remote computers, the human machine interface (HMI), which stores all system operational data to assist the system operators during system troubleshooting, data logging for National Pollutant Discharge Elimination System (NPDES) and other reports, and system optimization.

This case study is based on the treatment system as initially designed and operated. Subsequent process modifications occurred, however they are not relevant to the PLC or ozone analyzers discussed in the case study.

Air strippers have commonly been used to treat TCE contaminated groundwater in pump and treat remedies. Air strippers remove contamination from the liquid phase and transfer it to the gas phase. Regulations do not always require treatment of this gas phase prior to discharge. Concerns about TCE emissions from phase-transfer processes have made destructive treatment options more prevalent. The ex situ ozone advanced oxidation process discussed here is one such treatment option to reduce atmospheric TCE emissions.

Additionally, ozone has been increasingly applied via sparging to oxidize groundwater and soil contaminants in situ. Monitoring of ozone emissions from these systems is important both for system optimization and worker safety.

Based on information received from the vendor, the ozone analyzer costs range from $2,500 to $15,000 and are generally reliable and require little maintenance. Typical problems result from nuisance shutdowns due to high levels of ambient ground level ozone.

Technology Description [4]

PLCs enable facility automation. However, they depend on field devices for sensory input. The ozone analyzer is one such device used at the Moffett Federal Airfield (MFA).

PLC

A PLC is a computer system that monitors inputs, makes decisions based on its program, and controls outputs to automate a process or machine. PLCs consist of input modules or points, a Central Processing Unit (CPU), and output modules or points. Input modules accept a variety of digital or analog signals from various field devices (such as level sensors or ozone analyzers) and converts them into a logic signal that can be used by the CPU. The CPU makes decisions and executes control instructions based on program instructions in

memory. Output modules convert control instructions from the CPU into a digital or analog signal that can be used to control various field devices (such as valves or switches). PLCs can be networked with other computer systems for data acquisition or display.

Ozone Analyzer

Ozone analyzers are devices that can be used to measure ozone concentration in gaseous media. The media sampling system consists of inlet needle valves for sample and zero gas collection, a flow meter, a solenoid valve, and a sample chamber. The zero gas is collected from atmospheric air that passes through a scrubber containing an ozone destruction catalyst to remove any background ozone concentration. The unit measures ozone concentration by comparing the absorption of the sample with the zero gas. Depending on the position of the solenoid valve, zero or sample gas is forced through the solenoid valve, the sample chamber, and flow meter. The intensity of the ultraviolet light (UV) traversing the sample chamber is attenuated as prescribed using the Beer-Lambert Law, that is, the presence of ozone reduces the intensity of the UV light, the amount of UV light reduction corresponds to the ozone concentration. The ratio of the intensities is determined and the results are processed by the microcomputer to determine the ozone concentration. Since the concentration determined by the photometer is based solely on the ratio of light intensities, the actual intensity of the light is not important. Slow changes in light intensity due to lamp aging or dirt buildup in the optics will not affect the concentration reading.

Site Information [1, 2, 3, 5, 6]

MFA is located in Santa Clara County, California, at the southern end of San Francisco Bay. From the 1930s until its closure in 1994, the base was operated by the Navy as Naval Air Station Moffett Field. In 1994, the base was transferred to the National Aeronautics and Space Administration (NASA) and continues to operate as a federal airfield. MFA was placed on the national priorities list (NPL) in 1987.

In 1991, the EPA and other agencies divided MFA into six operable units (OUs). OU4 consisted of the west-side aquifers. These aquifers were contaminated with a mixture of gasoline and diesel from several leaking USTs, as well as tetrachloroethylene (PCE) and its breakdown products from an on-site dry cleaner. However, in 1992, the EPA determined that the west-side aquifers were affected by a regional plume (primarily TCE and its daughter products) that emanated from the adjacent Middlefield Ellis Whisman (MEW) NPL site. As a result, EPA determined that the west-side aquifers were subject to the 1989 record of decision (ROD) already written for the MEW site, directing remediation of the west-side aquifers. Consequently, OU4 was deleted and has since been referred to as the west-side aquifers.

The west-side aquifers consisted of two highly heterogeneous interconnected aquifer zones of alluvial channel deposits composed of sand and gravel incised in and interbedded with clayey floodplain deposits. The aquifers extended from 5 to 65 feet below ground surface.

The MEW site ROD designated pump-and-treat with air stripping as the remedy. A subsequent explanation of significant differences in 1996 allowed the use of liquid-phase granular activated carbon (GAC). Design of the west-side aquifers treatment system (WATS) was completed in 1997 and construction was completed in 1998. Table 1 lists the contaminants, concentrations, and treatment requirements for extracted water at the WATS.

Table 1
Influent Contaminant Concentrations
West-Side Aquifers Treatment System

Contaminant	Average Influent Concentration (µg/L)[1]	Federal MCL (µg/L)	California MCL (µg/L)	NPDES Treatment Requirement (µg/L)
Trichloroethene (TCE)	1,850	5	5	5
Tetrachloroethene (PCE)	24	5	5	5
Vinyl Chloride	31	2	0.5	0.5
1,1-Dichloroethene (1,1-DCE)	26	7	6	5
Cis-1,2-Dichloroethene (1,2-DCE)	270	70	6	5
Trans-1,2-Dichloroethene (1,2-DCE)	10	100	10	5
1,1-Dichloroethane (1,1-DCA)	6	N/A	5	5
1,1,1-Trichloroethane (1,1,1-TCA)	1	200	200	5
Freon 113	21	N/A	1,200	5
TPH-purgeable	180	N/A	N/A	50
TPH-extractable	11	N/A	N/A	50

Notes:

[1] Based on operational sampling data from December 1998 through March 2000
µg/L Micrograms per liter
MCL Maximum contaminant level
N/A Not applicable—no MCL for this parameter
NPDES National Pollutant Discharge Elimination System
TPH Total petroleum hydrocarbons

Source: Tetra Tech EM Inc.

Remediation System

The WATS consists of eight extraction wells piped to a treatment system located north of Building 45. All system equipment is controlled by a PLC. The extraction wells maintained a constant groundwater drawdown to maximize extraction rates from each well. Contaminated water collected in two on-site sumps near Hangar 1 was also treated in the WATS. Contaminated water was pumped from the extraction wells and treated to remove groundwater contaminants to levels specified in the MFA NPDES permit before being discharged to the MFA storm sewer.

Extracted groundwater was first passed through bag filters, which remove sediment from the influent. Then, ozone and hydrogen peroxide were mixed with the water in three 1,400-gallon reaction tanks (ozone and hydrogen peroxide combine to form hydroxyl radicals that are stronger oxidants than ozone and hydrogen peroxide alone. The hydroxyl radicals destroy about 99 percent of the influent contaminants). The remaining contaminants were removed by the air stripper and GAC units and the treated water was discharged to the MFA storm sewer under an NPDES permit. Offgas from the oxidation tank, consisting of a mixture of unreacted ozone and oxygen, was heated and treated with a proprietary ozone destruction catalyst. Figure 1 presents a simplified process flow diagram of the WATS.

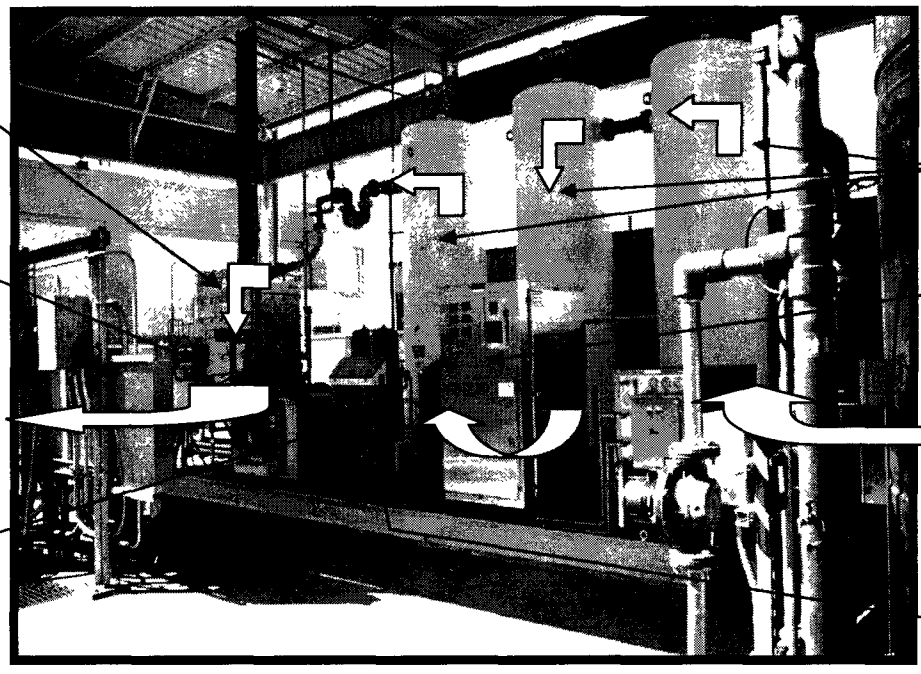
Control System

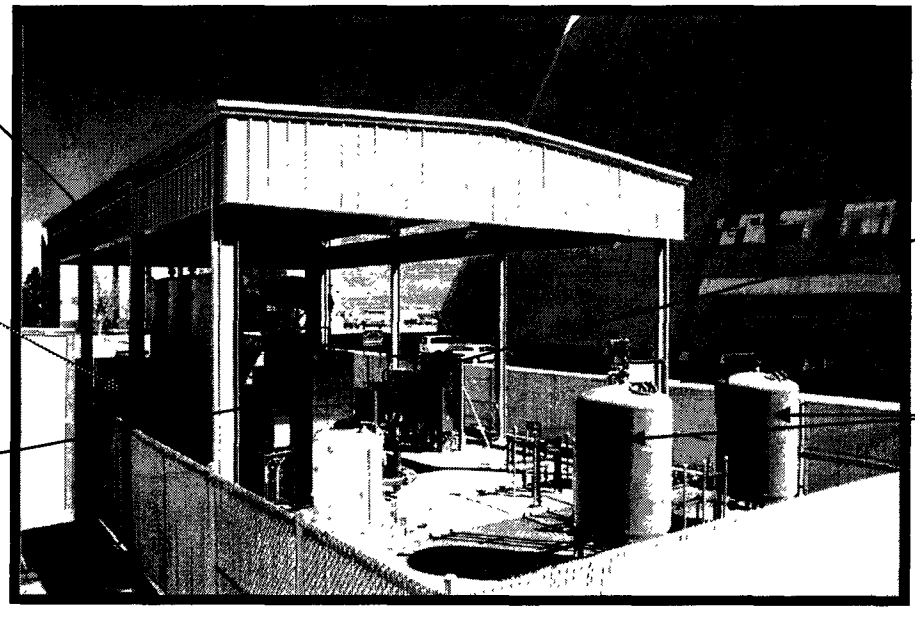
PLC control and sensors served five main functions on the system, (1) they allowed the system to operate automatically, (2) they shut down the system if water or offgas treatment was not functioning correctly, (3) they shut down the system before an unsafe worker safety condition, such as an ozone leak, existed, (4) they allowed remote monitoring of system status, allowing the operator to schedule site visits, and (5) they logged operational data, which could then be mined and trended to troubleshoot problems or optimize system performance. A pump-and-treat system of the complexity at the WATS would be extremely difficult to operate manually or even with a solid-state control system.

In order to maintain a constant groundwater drawdown, a capacitance-type level probe was used in each extraction well to continuously monitor the water level and relay this data to the PLC. The PLC then sent a signal to a flow control valve. If the water level was rising, the flow control valve opened slightly to increase the pumping rate, and thus the drawdown. Conversely, if the water level was decreasing, the flow control valve closed slightly to decrease the pumping rate. This automatic adjustment of well flow rate adjusted for changes in well yield due water table fluctuations caused by precipitation events.

The PLC was also used to regulate ozone and hydrogen peroxide dosage which was critical to obtaining maximum destruction efficiencies. This was accomplished using an influent flowmeter which measured the flowrate into the treatment system. The PLC processed this information and calculated the corresponding hydrogen peroxide injection rate and sent a signal to the hydrogen peroxide pump to inject the correct dosage. The gas flow rate into the oxidation tanks was constant, but ozone percentage of gas varied to achieve the proper ozone/hydrogen peroxide ratio for optimal treatment. Thus, the PLC also processed the water flow rate, calculated the correct ozone concentration, and sent a signal to the ozone generator which converted oxygen into the proper percentage of ozone sparged into the tanks to maintain the correct dosage.

Figure 1
West-Side Aquifers Treatment System





The universal shutdown interlock programmed into the PLC shut down the entire WATS, including the eight extraction pump motors, based on activation of any of the following system alarms:

- High-high bag filter differential pressure (indicates that the bag filters are clogged)
- Low hydrogen peroxide flow (indicates that the hydrogen peroxide pump has failed)
- Low hydrogen peroxide tank level (indicates that the hydrogen peroxide tank is nearly empty)
- Air compressor general fault
- Air receiver low pressure
- Low ozone generator voltage
- Ozone generator fault
- Oxygen low flow
- Low oxidation tank inlet ozone concentration (ensures that correct dosage of ozone is injected into the oxidation tanks)
- High-high ozone generator discharge temperature (prevents the ozone generator from overheating)
- Low catalytic oxidizer temperature (indicates that the ozone destruction system is not functioning)
- Low-concentration ozone analyzer general failure (indicates that the analyzer has malfunctioned)
- High catalytic oxidizer exhaust ozone concentration (indicates that the ozone destruction system is not working properly)
- High air stripper sump level (indicates that the air stripper drain is clogged)
- Low air stripper blower pressure (indicates that the air stripper is not functioning)
- High-high secondary containment sump level (indicates that a spill has occurred within the treatment pad)

These alarms were selected to activate the universal shutdown interlock because they indicate that a spill could occur, that the system may not be treating the water effectively, or that the offgas treatment system may not be working correctly. Immediately shutting down the system in response to any of these alarms would avoid spills, the discharge of untreated water, or the discharge of untreated offgas.

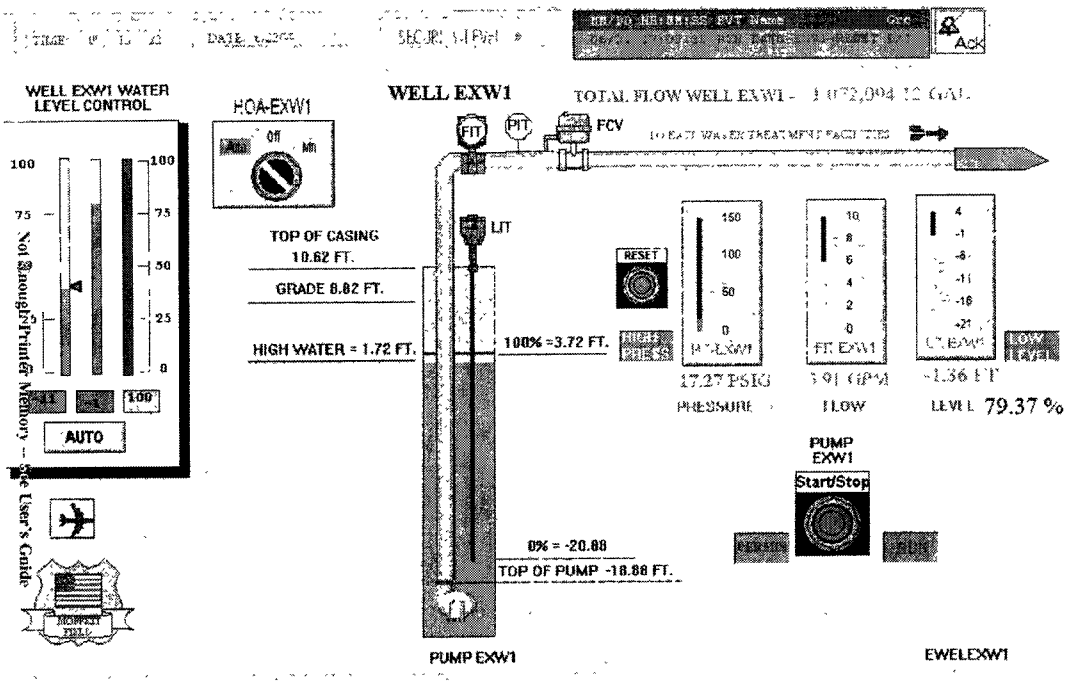
An ozone analyzer continuously monitored the ozone concentration in the ambient air. If an ozone leak occurred, it could immediately endanger the health of any on-site worker. Thus, when the ozone analyzer detected an ambient air ozone concentration of 0.1 ppm, the entire system (including the ozone generator, presumably the source of the ozone) would shut down, well before the OSHA permissible exposure limit of 0.1 ppm could be exceeded for an 8-hour time-weighted average (TWA).

Data Acquisition

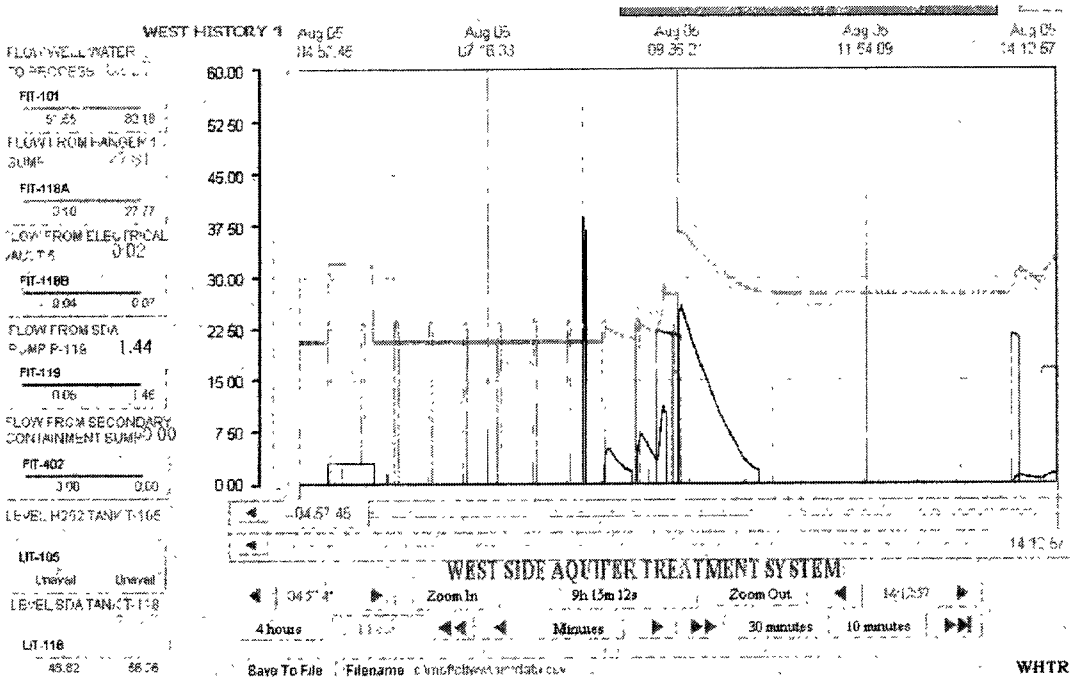
The WATS PLC was connected via modem to remote PC-based human-machine interfaces (HMI) at offsite locations. This allowed the system operator to view system status. Thus, some troubleshooting could be conducted from offsite. Additionally, the operator could remotely view the status of various parameters, such as bag filter pressure drop, and hydrogen peroxide volume to remotely schedule bag filter changeouts and chemical deliveries respectively. Finally, the operator could remotely turn extraction wells on or off as needed. Figure 2 presents the HMI for a typical extraction well that shows the current pump status (auto), pump discharge pressure (17.27 psi), flow rate (5.91 gpm), and water level -1.36 feet mean sea level).

The HMI logged all system parameters, such as flowrates, extraction well water levels, and pressures, on a remote computer. This information was useful in the preparation of the

Figure 2
Human Machine Interface



Extraction Well Status Screen



Process Variable Trending Screen

NPDES reports and quarterly progress reports, where individual well flow rates could be plotted for each reporting period. The extraction well water level data could be trended over any user-defined period. Figure 2 displays a typical process variable trending screen on the HMI.

The datalogging also maintained a record of all alarms and the causes of all system shutdowns, which significantly simplified system troubleshooting. Otherwise, with such a complex system, it could often be difficult to determine what equipment failure or process variable initiated the system shutdown sequence. Reviewing the data logs allowed the operator to quickly identify the initial cause or causes of the problem.

Design of the WATS began in 1996, before use of the internet was widespread. Thus, the HMI was originally connected to the PLC via modem. In 2001, the HMI was upgraded to an internet-based version which allowed easier access to the system operating conditions. The internet-based version had a firewall and was password-protected to prevent unauthorized system modifications.

Ozone Analyzers

The most complex of these sensors were the two ozone analyzers. There were two ozone analyzers (Figure 3), a high concentration ozone analyzer and a low concentration ozone analyzer. Both worked in the same manner.

The ozone analyzers (PCI Model LC-400 and HC-400) provided a digital readout of ozone concentrations. The high concentration ozone analyzer measured percent ozone (0 percent to 15 percent) in oxygen from the ozone generator. The low concentration ozone analyzer measured ozone in ppm from 0.001 ppm to 10 ppm. The high concentration ozone analyzer measured the actual ozone concentration of the gas that was sparged into the oxidation tanks. The PLC compared this value to the target ozone concentration based on the influent water flow rate. If the concentration was not within 10 percent of the target ozone concentration, the system shut would down before partially-treated water was released.

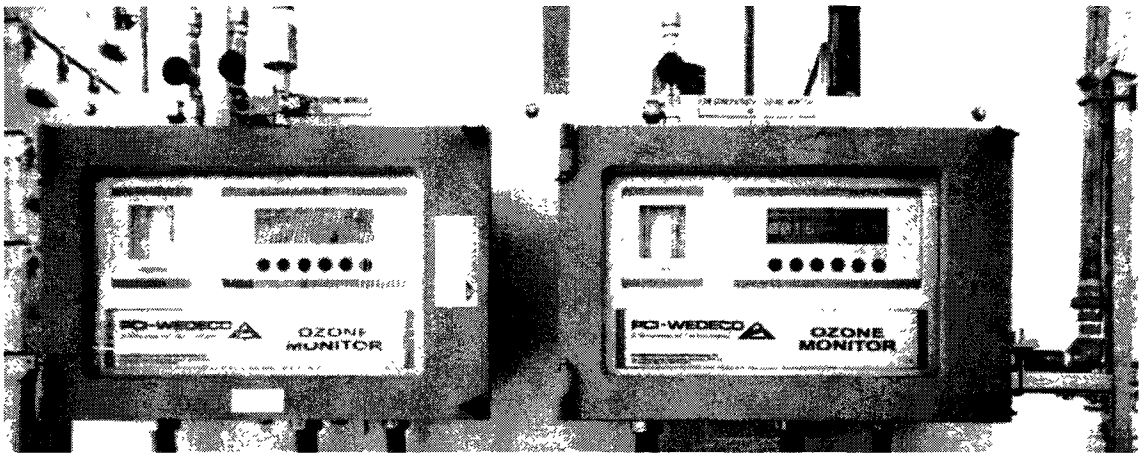
The offgas ozone analyzer measured the ozone concentration in the system offgas. The Bay Area Air Quality Management District (BAAQMD) limit for nonpermitted ozone emissions was 1 pound per day. The offgas ozone analyzer monitored the ozone concentration in the system offgas. When the offgas ozone concentration exceeded 9 ppmv (based on the maximum concentration the unit can detect without damage), the PLC would shut down the entire system. At 9 ppm, the WATS ozone emissions would be about 0.026 pound per day.

System Operation [7]

The pump and treat system has been in operation since 1998 and has treated approximately 190,000,000 gallons of contaminated water. The PLC control system has not experienced significant problems and has not required maintenance.

The ozone analyzers required little maintenance. The units were factory-calibrated. For reasons stated previously (that is, always comparing the UV absorption by sample to absorption by a zero gas), the units did not require field calibration. However, there were some minor maintenance items. First, the zero gas and the sample gas particulate filters required replacement every 6 months (this depended on the site gas quality). Second, the UV bulbs required annual replacement. An internal check warned the operator when UV bulbs were nearing the end of their operational life.

Figure 3
Ozone Monitors



The gas scrubber that produced zero gas for the ozone analyzers did not required maintenance. However, future maintenance could be required depending on exposure of the zero gas scrubber to ozone and potential catalyst poisons.

Both ozone analyzers were replaced with newer models in fall 2004 as replacement parts became hard to find. The high concentration ozone analyzer was replaced with a Mini-HiCon manufactured by IN USA, Inc. The low concentration analyzer was replaced with a Series 930 ozone analyzer manufactured by Aeroqual Ltd.

Cost [3, 6, 7]

According to the construction contractor, the instrumentation and controls system installation cost was $95,454 (Tetra Tech 2001). However, this number may not reflect the total control system installation cost, some of which is likely lumped in with the $319,060 system startup cost. Tetra Tech estimates that the actual installation and startup cost for the instrumentation and control system was approximately $200,000. The ozone analyzers cost approximately $15,000 at the time of installation. However, costs have decreased considerably since then and now range from $2,500 to $15,000 depending on sensitivity of the instrument, the input/output options, and the type of enclosure (NEMA 3, NEMA 4X, etc.)

Operation and maintenance cost for the PLC and HMI system are minimal. Once the software license is purchased and the system is programmed, installed, and debugged, O&M costs are similar to the costs of operating several PCs with internet access.

System changes or upgrades can be more costly, especially when a programming subcontractor is unfamiliar with the system and must learn the system operations as well as familiarize himself/herself with the program.

Ozone analyzer O&M costs are approximately $500 per year in parts and approximately 16 hours in labor.

Lessons Learned [1, 2, 3, 5, 6]

The primary troubleshooting problem with the offgas ozone analyzer occurred during system startup and shakedown when the unit began displaying extremely variable ozone concentrations (from 0.00 ppmv to exceeding

100 ppmv, beyond the range of the instrument). It was determined that the zero gas ozone destruction catalyst had become poisoned (due to hydrochloric acid in the oxidation tank offgas). Thus, the zero gas actually contained ozone. Replacement of the catalyst remedied the problem.

Another problem with the ozone analyzer resulted from high ground-level ozone concentrations due to normal sources, such as automobile exhaust. The ambient air ozone analyzer is designed to detect leaks in the ozone injection system and shut the system when worker safety is at risk. However, using the OSHA 8-hour TWA as the system shutdown criteria would potentially delay system shutdown during a catastrophic leak. To prevent such a delay in system shutdown, the more conservative National Institute for Occupational Safety and Health (NIOSH) instantaneous recommended exposure limit of 0.1 ppm was chosen as the system shutdown criteria. Using this instantaneous criterion, the system would respond immediately to a leak in the ozone piping or failure of the ozone offgas destruction.

However, during the first few years of system operation, numerous system shutdowns occurred because of high ambient ozone concentrations. The offgas ozone destruction system was found to be functioning correctly and leak testing of all ozone piping (via pressure testing and soap) did not identify any leaks. After further investigation, it was determined that the cause of the shutdowns was elevated background ozone concentrations, which are common urban areas. In fact, in 1998, the maximum instantaneous ozone concentration in Santa Clara County was 0.15 ppm, and the highest 8-hour TWA was 0.11 ppm.

To balance the need for minimizing nuisance system shutdowns with worker safety, the ambient ozone system shutdown setpoint was adjusted from a 0.1 ppm for one instantaneous reading, to 0.1 for a 1-minute rolling average (approximately 2 readings). This change eliminated nuisance shutdowns while maintaining worker safety.

Conclusions [5, 6, 7]

PLC system control and instrumentation at the WATS has been a success to date in that there have been no exceedences of the BAAQMD ozone discharge requirements or exceedences of the NPDES permit due to incomplete oxidation of the chlorinated solvents, and there have been no spill events. Additionally, system troubleshooting has been greatly simplified by studying the datalogs of system shutdown.

However, programming the HMI requires advanced programming knowledge of the system software (Wonder Ware). Making minor changes to the HMI often required a significant effort and could be expensive as it required specialized contractors. Newer versions of HMI software have incorporated more user-friendly programming tools that should allow minor changes to the HMI to be made more easily.

During system startup, Tetra Tech conducted proof of performance testing of the ozone offgas analyzer using a handheld ozone analyzer (Bionics TG-800). The handheld monitor uses an entirely different method for ozone detection (gas membrane galvanic cell) and its range of detection was substantially different (0 to 2 ppmv, in 0.05 ppmv increments) than the low concentration ozone analyzer. Based on a comparison of results, Tetra Tech was able to determine that the analyzers were accurate to within 0.05 ppmv.

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Appendix 6

Sensor Technology Case Study
Automated Sampling and Analysis of Trichloroethene and Hexavalent Chromium Using the Burge System at the North Indian Bend Wash and Nevada Test Sites

Sensor Technology Case Study

Automated Sampling and Analysis of Trichloroethene and Hexavalent Chromium Using the Burge System at the North Indian Bend Wash and Nevada Test Sites

Summary Information [1, 2, 3, 4, 5, 6, 7, 8, 9, 10]

The research and development (R&D) of automated sampling and analysis systems described in this report began in 1988 and initially focused on a device called an optrode developed by Lawrence Livermore National Laboratory, for the analysis of volatile chlorinated hydrocarbons.

As the etymology of "optrode" suggests; it is an instrument that provides a pathway for light. Although sometimes incorrectly used in a broader sense, the term optrode was originally meant to refer to a colorimetric instrument that measured a rate of change in light intensity as the compound of interest (analyte) diffused into the optical pathway through the instrument's semi-permeable membrane. Following beta testing, Burge Environmental made the optrode-based analytical system available to the environmental industry in March 1998. The system was only able to detect trichloroethene (TCE). Since then the vendor has developed the skeletal technology to permit the use of other sensors to measure various analytes.

There are several sensors today that use analytical methods suited to specific, or sometimes an entire range of analytes. However, they sometimes never make it past the R&D stage due to the lack of a suitable platform for field deployment. This report discusses a modifiable automated sampling and analysis platform developed by Burge Environmental. The report focuses on two systems in particular. One is an optrode based system developed for the analysis of TCE, and the other is a non-optrode based colorimetric system developed for the analysis of hexavalent chromium (Cr-VI).

Case studies on these systems cover implementation of this technology at two different sites: (1) The North Indian Bend Wash (NIBW) Superfund site; and (2) The Nevada Test Site (NTS). The implementation at the NIBW site involved sampling the influent and effluent of a groundwater treatment plant and analyzing the samples for TCE on a daily basis. The field effort at the NTS was a pilot test preceding deployment of the Cr-VI sampling and analysis system for groundwater monitoring at the Hanford site along the Columbia River near Richland, Washington.

Implementation of this technology at both sites proved to be satisfactory. Lessons were learned along the way and improvements have been made.

This technology is potentially useful in situations requiring frequent sampling and generation of large amounts of data. Since this technology has not yet been approved by the U.S. Environmental Protection Agency (EPA) for regulatory monitoring, it has limited application in compliance monitoring. However, it has been used in the past to augment regulatory monitoring for groundwater and treatment processes.

Technology Description [1, 3, 5, 6]

The Burge system facilitates automated sampling and on-site analysis for monitoring of groundwater or treatment processes. The system was specifically designed for deployment of sensors in the field.

The system essentially consists of two separable modules; a sampling module and an analytical module. As their names suggest, the sampling module is responsible for sample acquisition,

and the analytical module quantifies the amount of analyte present in the acquired sample. The system also has a waste module that manages wastes produced during analysis and system purging. The entire system is powered by a 12 Volt energy source.

Sampling Module

The sampling module is built to suit the sampling effort. For instance, the module used to sample the effluent of a wastewater treatment system might consist of a peristaltic pump with associated tubing for sample conveyance. A groundwater sampling module on the other hand may be significantly more complex especially if it involved sampling at multiple depths. The sampling module would be built to fit into or just above the well casing and would include valves, pneumatic tubing, conveyance tubing, and electrical wiring.

In general most sampling modules are pneumatically actuated. Compressed air serves as the driving force to convey liquids from one point to another. High pressure air (15 pounds per square inch [psi]) drives sample collection.

Analytical Module

Figure 1 presents an illustration of a well-sampling and analysis module. The illustration shows the sampling module inside the well and the analytical module to its right in a subsurface enclosure. The enclosure also contains the battery power source shown connected to the solar cell on the surface. The waste module and compressed air tank are seen to the left of the well.

The analytical module is in essence a miniature laboratory small enough to fit in a two-foot cube. The module can be configured for use with multiple sensors. In practice, the module may be located within the monitoring well, adjacent to the monitoring well, or both. The analytical module houses interconnected vials used to hold samples, store reagents, and facilitate proper chemical reaction. Low pressure compressed air (1.5 psi) drives fluids in the analytical system from one stage to the next.

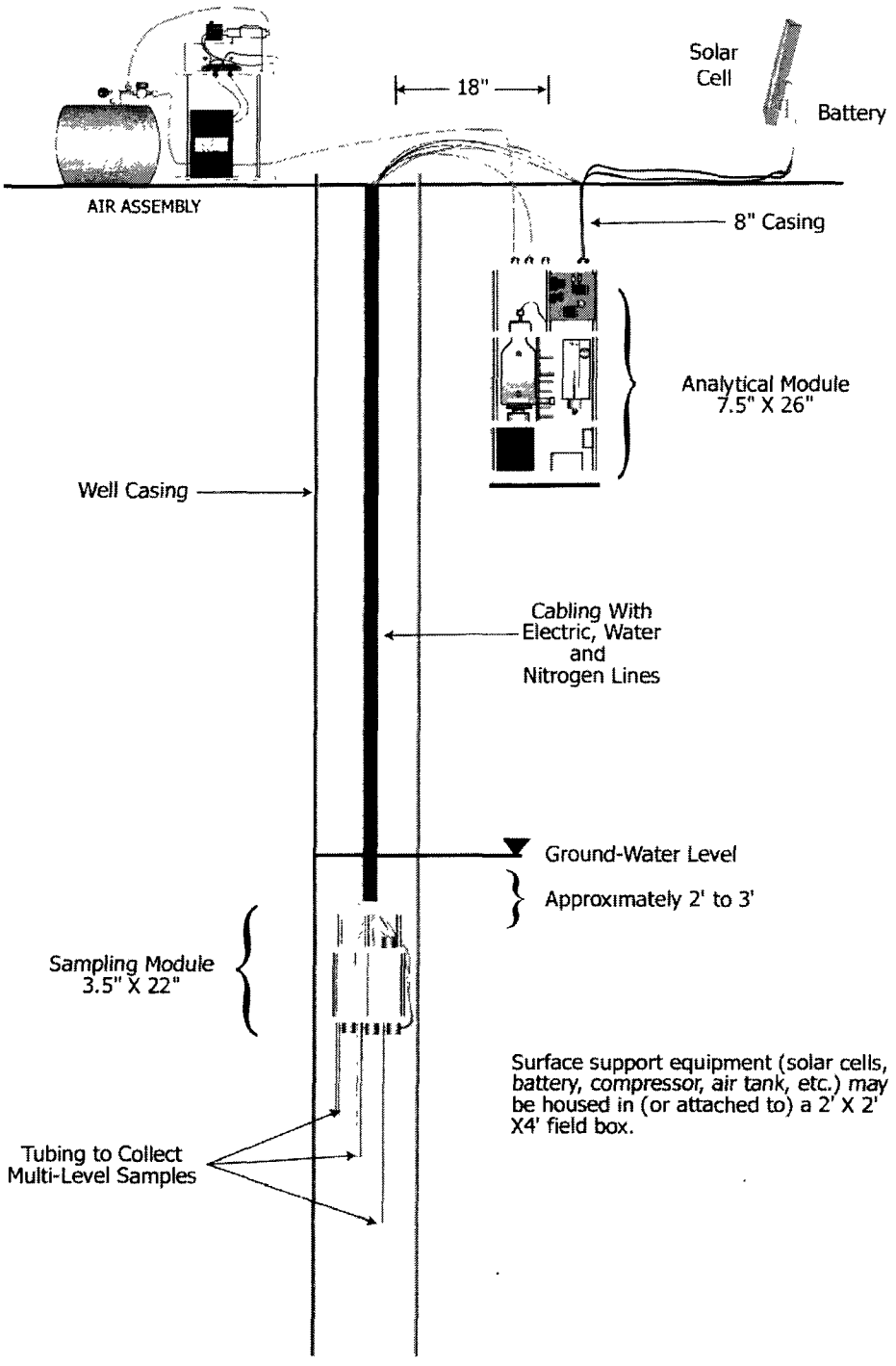
Although the specifics of the analytical system vary with the analyte, the module in general facilitates reagent component storage, reagent blend preparation, sample preparation, sample dilution, reactant mixing, system flushing, and measurement using a sensor. Reagent storage containers typically vary in size from 250 to 500 milliliters. However the amount of reagent stored can be increased to reduce the frequency of reagent replacement. Assuming one sample per day, reagent storage is usually designed to last at least 6 weeks.

According to Burge Environmental, the analytical platform is flexible enough to even allow the integration of sensors manufactured by other entities. Some of the analytical methods available for use are: (1) molecular spectroscopy; (2) electrochemical measurement; (3) colorimetric measurement, and (4) photo-ionization.

The analytical process consists of three important stages: (1) instrument calibration; (2) sample analysis; and (3) post-test calibration check.

Instrument calibration is generally performed before the first analysis, after which calibration is performed manually (from the remote computer) only as required. For instance, re-calibration may be necessitated by a change in the ambient temperature recorded by the instrument's thermometer. Calibration involves analysis of samples bearing known concentrations of the analyte. Analytical results are compared with the known concentrations and the instrument is adjusted to minimize the difference between the two. Samples used for calibration represent a minimum (zero), a

Figure 1
Burge Groundwater Sampling and Analysis System



Source: Burge Environmental

maximum (varies), and a mid analytical range. The analytical range is designed such that the required detection range for the analyte falls between the minimum and the maximum, and is bisected by the mid. The analytical module produces the minimum-, maximum-, and mid-calibration samples from varying blends of stored standard solution and prepared blanks. Blanks are analyte-free samples that are made in the analytical module by passing contaminated water through the appropriate treatment medium. The treatment medium in the TCE analytical module is activated carbon, and in the Cr-VI analytical module is granular ferric hydroxide. All process wastes are pumped to a waste storage tank.

Sample analysis is a two or three stage process involving the transfer of a metered volume of prepared sample to the analytical cell followed by measurement using a sensor.

To verify the validity of the result of analysis, the module performs a post-test mid-calibration check. This involves analysis of a prepared mid-calibration sample soon after analysis of the acquired media sample. If the result of post-test mid-calibration shows more than 20 percent deviation from the true value, the module marks the previous result for review.

TCE Analysis

Analysis for TCE involves a colorimetric measurement technique that uses a device called an optrode. The optrode consists of a U-tube, a light source and a collector. The U-tube is constructed of a semi-permeable material with a reflective inner surface. Being in essence an optic fiber, the u-tube allows the passage of light from one end to the other with undiminished intensity. A green light emitting diode (LED) at one end of the u-tube serves as the light source and a collector at the other end measures the intensity of exiting light. The optrode is located in the head space (volume above liquid level) of the sample vial.

Prior to every analysis, the optrode is filled with a freshly prepared solution of a TCE-specific reagent. When an aqueous sample is introduced into the vial containing the optrode, an equilibrium results between the liquid and vapor phases of volatile contaminants in that sample. Vapor in the headspace permeates the wall of the optrode and enters the reagent. The reagent reacts with TCE forming a red colored product. This product absorbs light produced by the green LED as it passes through the u-tube. Consequently, the intensity of light exiting the u-tube decreases. As the reaction proceeds and more product is formed, the collector records continuously diminishing light intensity. At the end of the three-minute reaction period, the instrument uses the measured rate of decrease in light intensity to estimate the concentration of TCE in the aqueous sample.

The detection limit of the TCE analytical module is 1 ppb. However, since chloroform interferes with TCE analysis, the TCE detection limit is a function of the amount of chloroform present in the sample.

Cr-VI Analysis

The analysis package used for Cr-VI also uses a colorimetric technique. However, the technique does not involve the measurement of a reaction rate and thus does not use an optrode.

The analytical cell is a cylindrical tube with a green LED at one end and a collector at the other. Metered portions of the sample and reagent (1,2-diphenylcarbazide) are mixed in a reaction cell. Cr-VI in the sample reacts with the reagent to form a red colored product. The intensity of the coloration is directly proportional to the amount of Cr-VI present in the sample. After a predetermined waiting period, the red liquid is transferred to the

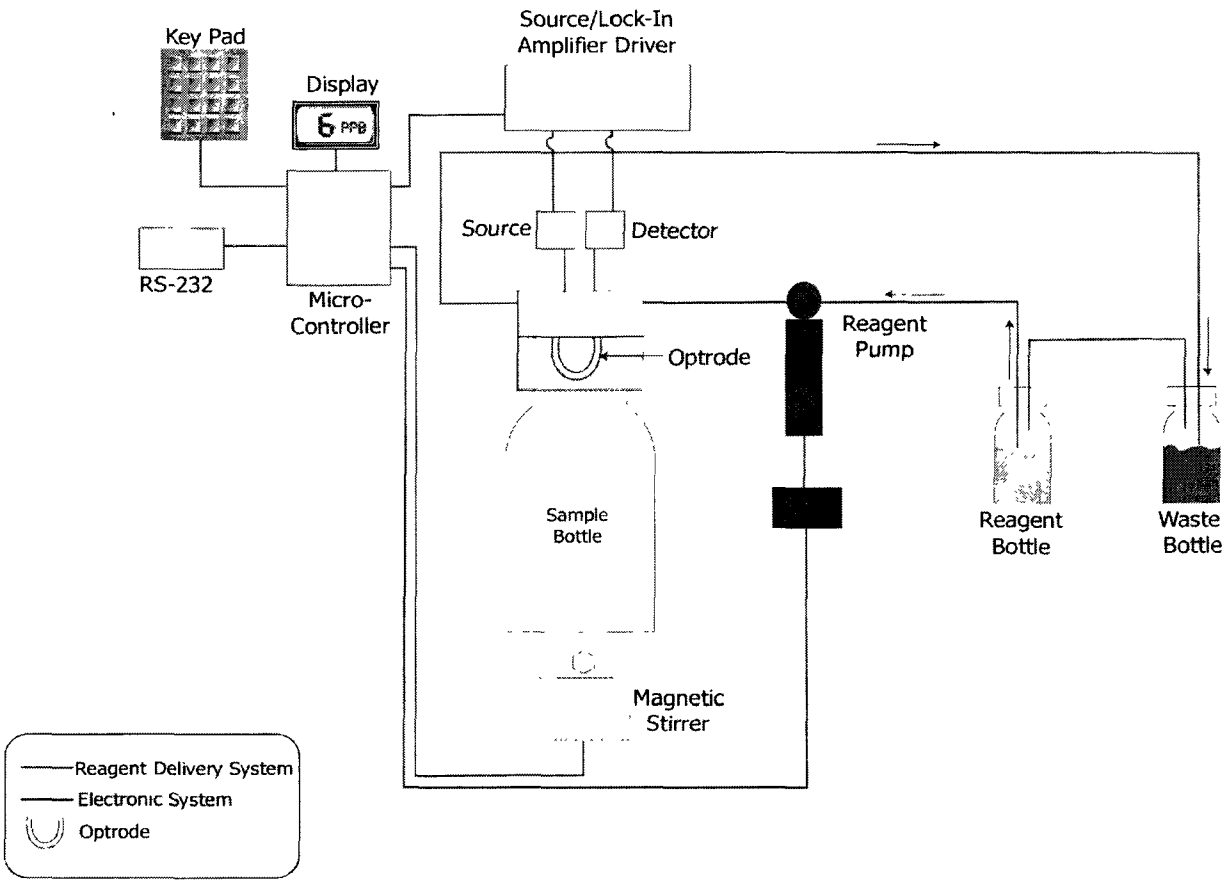
analytical cell. The red liquid absorbs green light produced by the LED causing a decrease in intensity of green light measured by the collector. This decrease in intensity is used to estimate the concentration of Cr-VI in the sample.

The detection limit of the Cr-VI analytical module was found to be 1 ppb during precision tests. However, detection limit can be reduced by increasing the length of the optical path through the sample.

Control System

The control system for the sampling and analysis modules comprises level sensors, electrically actuated valves, and an on-board logic controller. The logic controller interfaces with a personal computer (PC) through an RS-232 interface to receive instructions and transfer data. Figure 2 presents a schematic of an optrode-based analytical system.

Figure 2
Schematic of the Analytical System



Source: Burge Environmental

The system has fail-safe provisions. A watchdog program continuously monitors system components and shuts down the system if a malfunction is detected. An error code on the PC screen identifies the component of the system that caused shutdown.

Remote operation of the system is facilitated by PCAnywhere (communications software). This commercially available software developed by Symantec makes it possible for the user's PC to communicate with the system's PC over a phone line. The graphical user interface used to operate the system was developed by Burge Environmental. The program allows the user to monitor system operation, perform analytical system calibration, actuate sampling and analysis, view results, and store data in a Microsoft Excel spreadsheet.

Construction

Components of the sampling and analysis system including all containers and electrical components are typically housed in an insulated weather-proof box unless they are being used indoors. Figure 3 provides an illustration of both an indoor and an outdoor system.

Other than the above common features, each system usually has to be custom-designed to suit a given site. This is due to variations in client requirements, site infrastructure, and the nature of the system being tied-in to. For example, at a site where electricity is easily available, there would be no need for an autonomous solar-cell and battery power supply. Similarly, where a phone connection is easily available for an indoor system, the data transfer system would not need radio telemetry. In extremely cold climates, below ground construction and allowance for a space heating system would influence system enclosure design. Reasons such as these are what force the vendor to be flexible; and the very same reasons preclude the manufacture of a standardized off-the-shelf system.

Site Information [1, 2, 6, 9]

This report presents two different sites to illustrate implementation of both the TCE and Cr-VI systems.

The TCE system had been previously used to monitor both groundwater and treatment processes. This report presents a site that used sampling and analysis modules to test the influent and effluent of a groundwater treatment system.

The Cr-VI analytical system became available for use more recently. A groundwater sampling and Cr-VI analytical system was designed for use at the Hanford site near Richland, Washington and was deployed in mid July, 2004. However, before this, as a precursor to full-scale implementation, a pilot-scale test of the system was performed at the Nevada Test Site near Las Vegas, Nevada. This report presents details of this pilot test.

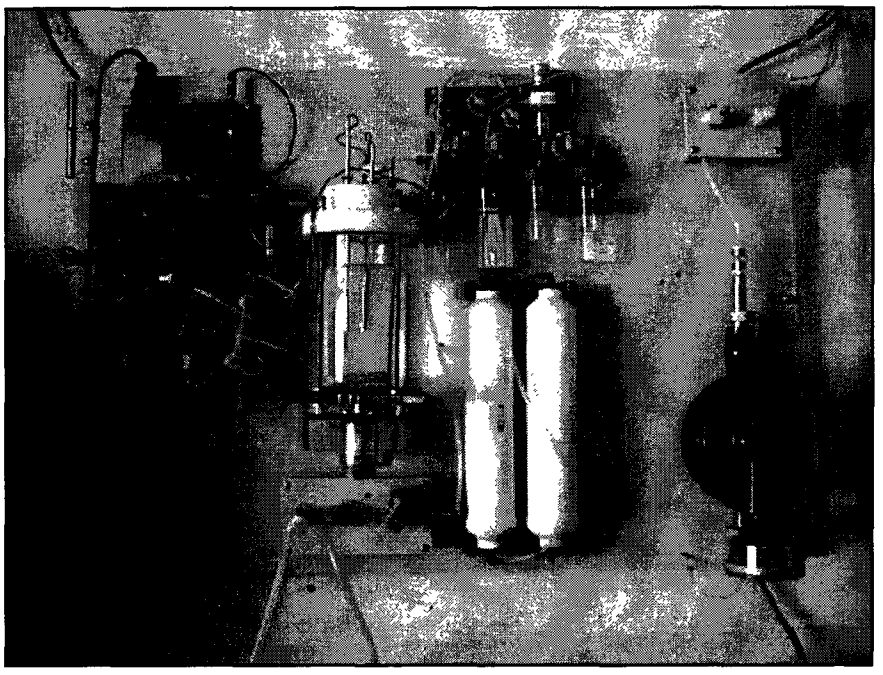
From this point forward in this report, the sampling and analysis system will be called the Burge system.

North Indian Bend Wash Site

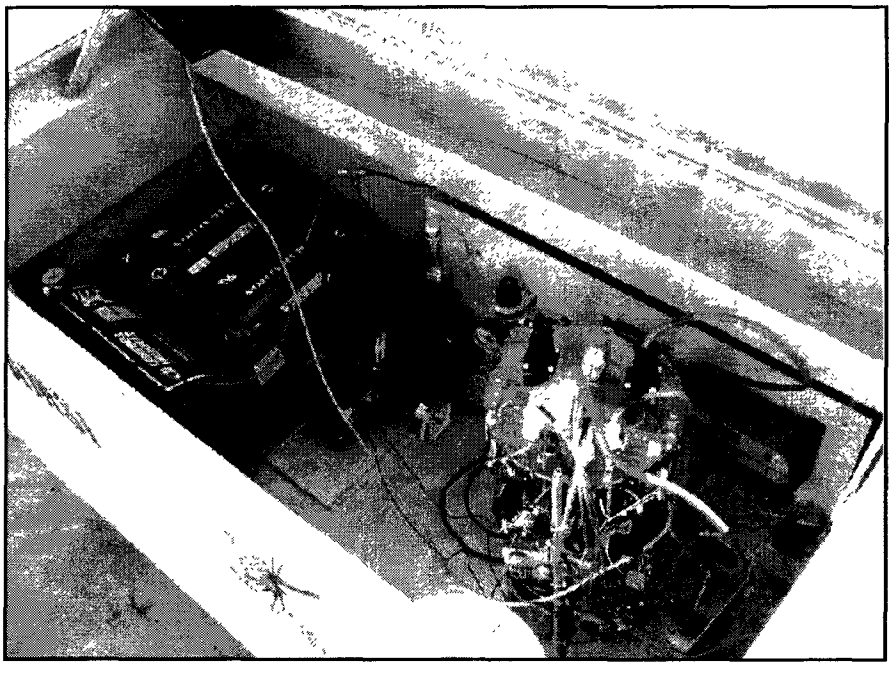
Groundwater at the North Indian Bend Wash (NIBW) Superfund site in Arizona was contaminated with several volatile organic compounds (VOC). A groundwater pump and treat system was being used to extract and treat contaminated groundwater. TCE was the primary contaminant of concern.

The groundwater treatment system used air-stripping and carbon adsorption to remove VOCs from the groundwater. The treatment plant was operated by the City of Scottsdale and

Figure 3
Sampling and Analysis System Photos



Indoor Wall-Mounted Sampling and Analysis System for Process Monitoring. Source: Burge Environmental



Outdoor Sampling and Analysis System for Groundwater Monitoring – Used at the Nevada Test Site. Source: Burge Environmental

processed 10.7 million gallons of water per day. The Burge system was installed as part of an agreement with the EPA to allow reduced regulatory monitoring at the facility.

The Burge system was installed at the plant in January 2002 to monitor pre- and post-treatment concentrations of TCE in extracted groundwater. Influent and effluent monitoring served as a measure for treatment plant performance. Effluent monitoring also served to warn against accidental discharge above the regulatory threshold of 5 ppb. The influent water had a TCE concentration averaging 100 to 120 parts per billion (ppb) and the effluent had a concentration below the laboratory's detection limit (0.5 ppb). The Burge system tapped directly into the influent line for influent sample acquisition. Since the treatment plant effluent outlet was much farther away, the facility provided a continuously flowing open loop system to make fresh effluent water continuously available to the Burge system. The Burge system tapped into this open loop for sample acquisition.

The Burge system performed daily analysis of influent and effluent waters, and performed a post-test mid-calibration check after each analysis as a quality control measure. The calibration process used a blank, 6 and 12 ppb standards and a 6 ppb post-test check standard. The calibration curve range was selected to bracket the regulatory threshold concentration of 5 ppb. Consequently influent water underwent dilution prior to analysis.

Burge Environmental remotely operated the system from their office in Tempe, Arizona. Operation included setting times to initiate sampling and analysis, as well as retrieving and reviewing testing data. All other functions including sampling, calibration and analysis were automated.

Nevada Test Site

As a precursor to full scale implementation at the Hanford site, the Cr-VI Burge system was pilot-tested at the Nevada Test Site near Las Vegas, Nevada. These tests were conducted in December 2003 and March 2004.

The sampling module used a peristaltic pump to collect water samples from storage containers. The module facilitated sampling from four different sources.

Communication between the Burge system and the remote PC was made possible through a wireless modem link. This was functionally equivalent to using a serial cable. One modem was connected to the on-board logic controller in the field deployment box, and the other was connected to a PC at a remote facility. The modems required line of sight, and had a 12-mile communication range. The radio modem in the field deployment box was powered by the system's 12-Volt power supply. The PC in the remote facility hosted a data acquisition and control software developed by Burge Environmental.

The test system included a waste module that was used to remove and store all analytical process wastes. There were two waste streams created by the monitoring system. One was water from the monitoring wells used to rinse the sampling lines. The other waste stream contained leftover reagents, standards, and sample after an analytical run.

The test system was not an exact replica of the system to be used at Hanford because it had the benefit of operator supervision. The communication system used at Hanford was more involved because system monitoring, control, and data acquisition was to be based in Arizona while the field unit was located in Washington. A combination of a wireless modem link and a phone line was required to

link the field unit to the monitoring station. The wireless modems linked the Burge system to the on-site PC. Telephone modems linked the on-site PC to the remote PC. Figure 4 provides an illustration of the Burge system used at Hanford.

System Operation [1, 2]

This section discusses operation of the Burge systems installed at the two sites.

North Indian Bend Wash Site

System operation was automated and did not demand supervision. However, Burge Environmental remotely monitored the system as part of the service offered with the contract. Daily monitoring was performed in ten minutes and was meant to observe system function and view test results. Results of the post-test mid-calibration determined the validity of the test. If the result was within 20 percent of the true concentration of the standard, the test was considered valid. On the other hand, deviation beyond the stipulated 20 percent limit resulted in either repeating a test, or re-calibrating the instrument. Table 1 presents monthly average TCE concentration for treatment plant influent, treatment plant effluent, and the mid-calibration standard (6 ppb).

The system experienced only two mechanical problems from January 2001 to July 2003. Both problems were attributed to malfunctioning valves.

Maintenance involved a site visit once every three weeks to visually inspect the system and discuss system performance with the treatment plant operator. Other maintenance activities included refilling reagents and standards. Maintenance frequency was therefore a function of storage capacity and sampling frequency.

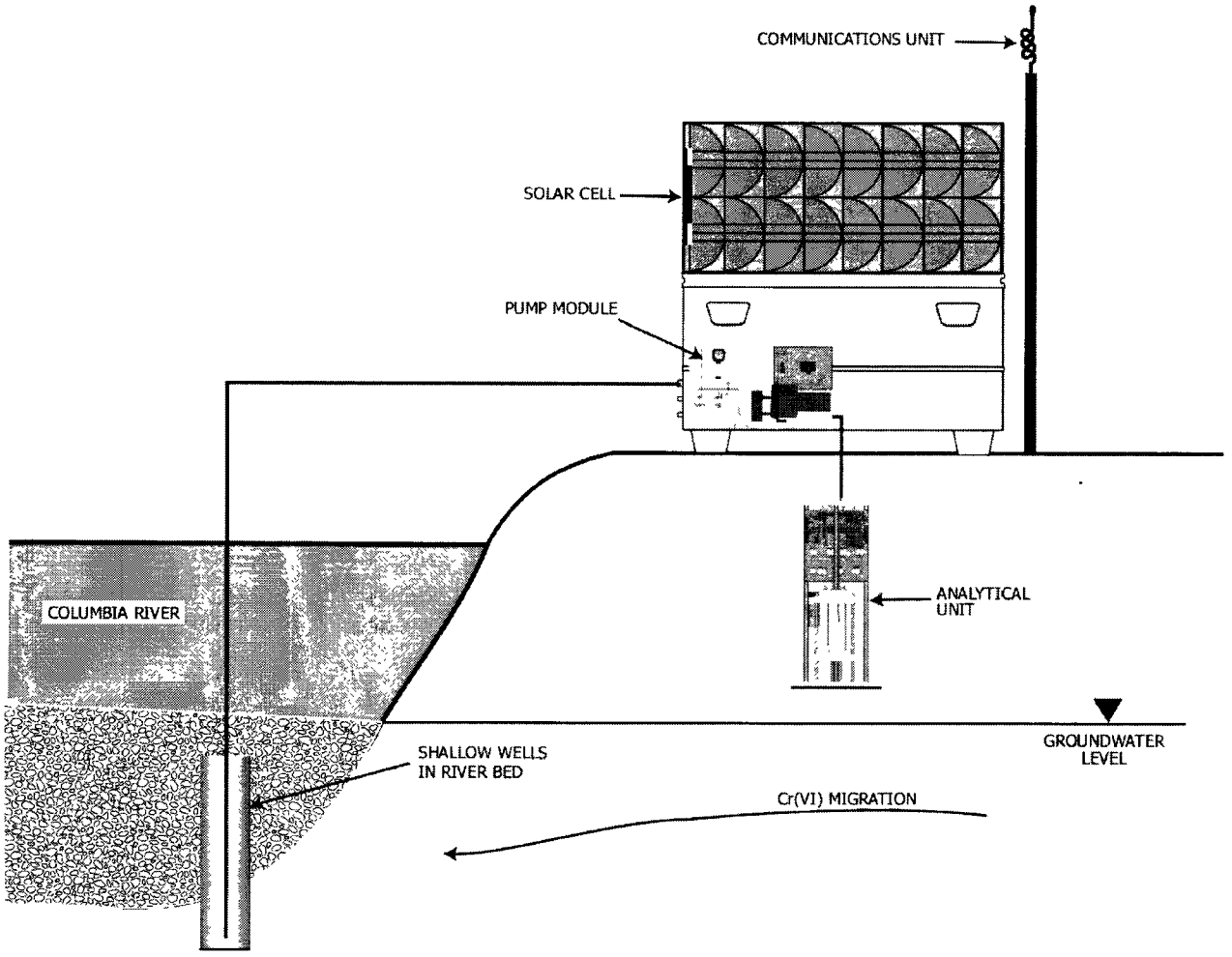
Temperature was the main factor that affected performance. Varying temperatures sometimes made sample analysis invalid because the test temperature was different than the calibration temperature. As a result the instrument had to be re-calibrated several times. Other instances of failed tests were triggered by factors such as insufficient reagent, insufficient standard, and power surges. Tests were repeated in each case.

Nevada Test Site

The system was tested at the Nevada Test Site on two different occasions. The first testing event spanned December 1, 2 and 3, 2003, and the second spanned March 16, 17, 18 and 19, 2004. During these events the system underwent extensive laboratory and field testing. Since the implementation at the NTS was a supervised limited-duration operation, there was no need for system maintenance.

The well-sampling module was not tested at the NTS. Samples to be analyzed were prepared and stored in a container. A peristaltic pump delivered the sample from the storage container to the analytical module. In order to simulate site-specific sample chemistry, some of the samples were prepared using groundwater from the Hanford site. All samples tested by the analytical module were also tested by an analytical laboratory. The average concentration of Cr-VI measured by the Burge system in 11 separate tests was 1,161 ppb. The standard deviation of the results was 2.1 percent. The result of laboratory analysis for the same sample was 1,200 ppb. The sampling module operated autonomously using its own power supply unit. Power supply constituted a solar cell and a battery. The battery was sized to facilitate four days of continuous operation without solar recharging and was found to have more than sufficient capacity for uninterrupted operation.

Figure 4
Hanford Field Implementation Conceptual Model



Source: Burge Environmental

Table 1
North Indian Bend Wash Analytical Results

TCE Concentration Monthly Averages (October 2002-April 2003)					
	Treatment Plant Effluent		Treatment Plant Influent		Mid-Calibration [3]
	Burge System	Laboratory [4]	Burge System [1]	Laboratory [2, 4]	
Month	Average Concentration (ppb)				
October	<1	<0.5	109	112	6.6
November	<1	<0.5	98	118	6.3
December	<1	<0.5	106	113	5.9
January	<1	<0.5	105	106	5.2
February	<1	<0.5	111	132	5.5
March	<1	<0.5	110	138	6.2
April	<1	<0.5	106	122	6.2

Note:

TCE Trichloroethene
ppb Parts per billion
[1] Based on an average of at least 28 samples per month
[2] Based on an average of 4 to 5 samples per month
[3] Mid-calibration standard sample had 6 ppb TCE concentration
[4] Laboratory analysis used EPA Method 8260B

Source: Burge Environmental

The system performed well at the NTS. The analytical module –as seen above- demonstrated precision and good agreement with the results of laboratory analysis.

Cost [1, 4]

Actual costs for implementation at the NIBW site and the NTS were not available. Approximate present day costs for various components of a Burge system are presented in the following table:

Burge System Cost Estimate	
Item	**Cost Range**
Sample acquisition system [1]	$500-$3,000
Base system (includes analytical system) [2]	$10,000 – $12,000
Solar cells & batteries (sold without markup) [3]	$1,500
Wireless modems [4]	$3,200
TOTAL	**$10,000 – $19,700**

Note:

[1] Depends on whether sample acquisition is from a treatment process or a well
[2] Depends on the type and number of sensors
[3] Only for remote system where no power is available
[4] Only for remote units where no phone line is available

Source: David Hoffman, Burge Environmental, Inc.

The bare cost for purchase of a Burge system could therefore range from $10,000 to $19,700. Installation costs are sensitive to several factors and could vary. The main operation and maintenance cost items would include: (1) monthly fee for monitoring and data acquisition services provided by Burge Environmental; (2) monthly fee for a telephone line; (3) reagent and standard solution replacement; and (4) treatment media (activated carbon or granular ferric hydroxide) replacement.

If the unit is leased instead of purchased, Burge Environmental estimates total cost for lease, operation, and services at $1,000 per month.

Conclusions [1, 2]

This section discusses the advantages and disadvantages of this technology, and its potential uses based on information provided by the vendor and one of its users.

Although the Burge system uses the same method for colorimetric analysis of Cr-VI as the EPA-approved method, it is not yet recognized by the EPA as suitable for regulatory monitoring. Consequently, neither the TCE nor the Cr-VI analytical system can currently replace laboratory analysis. However at the NIBW site, the combined effect of the facility's track record and the use of the Burge system resulted in reduced regulatory monitoring.

The Burge system is currently more of an optimization and management tool than a regulatory tool. Its potential applications include treatment process monitoring, long term groundwater monitoring, and breakthrough monitoring in permeable reactive barriers. Though never used in this capacity, the Burge system, according to Burge Environmental, is amenable to integration into larger systems controlling facility operation. In such a role, the Burge system might be used to trigger independent alarms, or provide input to a supervisory control system.

Customers have never sought autonomous control of the Burge system and have always required that it be operated and maintained by Burge Environmental. As a result, Burge Environmental provides remote oversight of system operation, and keeps system automation at a minimum. However, further automation can be incorporated upon request. For example, though the system does not currently flag results that do not meet testing standards it can be programmed to check for compliance of results with testing standards. Similarly, the system can be programmed to trigger an alarm or call an operator if an analytical result exceeds a compliance limit.

According to Burge Environmental, system operation is easy to learn, and new users can be walked through and taught to operate the control program in about 15 minutes. System troubleshooting however is more complex and requires substantial knowledge of the Burge system.

To reduce the amount of waste produced, the Burge system does not purge well volumes while sampling monitoring wells. Analysis usually requires 500 ml of sample for TCE and 20 ml of sample for Cr-VI. According to Burge Environmental the sample is acquired at a rate that is not significant enough to produce drawdown in the well, or alter chemical equilibrium in a way that invalidates the sample as being representative of the groundwater in the formation.

Mechanical problems experienced by the Burge system during previous field deployments have included air compressor malfunction, valve malfunction, and analytical system clogging due to excessive solids. The solids problem was solved by using an in-line filter.

The Burge system had minor problems with hardness-related scale formation at the NIBW site. Although the analytical system itself is protected by inline solids removal, the sample acquisition line needs to be monitored for scale when sampling water with high hardness. Monitoring durations for sample collection has been an effective method of checking for scale. According to Burge Environmental, none of their submerged sample acquisition systems have had problems with scale or biofouling. So far the longest duration of submergence for any of their system components has been 6 months.

Temperature is the most important environmental variable influencing TCE analysis. The Cr-VI analytical system on the other hand is not as sensitive to temperature. Although possible, the Burge system does not adjust analytical results for temperature. To mitigate temperature effects, the Burge system incorporates sufficient engineering controls and testing strategies. Engineering controls include thermal insulation of outdoor units, space heating, construction below the frost line in extremely cold environments, and a thermometer to record temperatures during testing. The validity of a test rests on the proximity of temperature during testing to the temperature during calibration. Temperature variations can be minimized by constraining testing to a certain part of the day.

Although the use of an optrode for headspace analysis of TCE negates turbidity-related problems, it inherits problems associated with vapor-phase analysis. Headspace analysis operates on the assumption that TCE vapor in the headspace is at equilibrium with its dissolved phase during sample analysis. This complicates analysis, as changes in sample chemistry can affect equilibration times. TCE analysis therefore requires greater diligence to detect potentially flawed results. The validity of questionable results has in the past been confirmed by test repetition. Consistency in results during repetitions is considered a strong indicator of equilibrium. According to the NIBW facility's representative, the TCE analytical system seemed to perform better at high, than with low concentrations.

Carbon dioxide was identified as a hurdle in TCE analysis. Groundwater samples bearing high carbonate concentrations when brought to the surface tend to re-equilibrate under the reduced hydrostatic pressure. This re-equilibration sometimes results in the release of carbon dioxide into the head space. According to Burge Environmental, carbon dioxide was found to inhibit the migration of TCE across the optrode's semi-permeable membrane.

The shelf life of reagents used in the Burge system was cause for concern during early stages of development. However, the TCE system now stores components with indefinite shelf lives separately and uses them to prepare fresh reagent prior to sample analysis. The reagent used in the Cr-VI system on the other hand has a finite shelf life.

According to Burge Environmental, none of the analytical modules have experienced problems with method contamination. Method contamination can theoretically result from leakage of standard solution into the sample, or residual contamination from a previous analysis. According to Burge Environmental, the Burge system has sufficient controls in place – including long flushing cycles- to prevent this from occurring.

Although not an issue at the sites in this case study, it is important to note that the presence of cosolvents or surfactants in an aqueous sample can affect the measurement of TCE. Since both co-solvents and surfactants affect the partitioning of TCE into the vapor phase, it is possible that the Burge system would underestimate TCE concentration when such compounds are present in the water sample.

The Burge system has not yet been able to resolve the problem posed by trihalomethanes (THM) in the analysis of the TCE. The TCE optrode is unable to distinguish between THMs and TCE. However, since THMs in the environment have usually been related to chlorination activities (such as disinfection), this has not been much cause for concern. At the NIBW site, chlorination of some of the wells to discourage biological growth resulted in elevated concentrations of THMs in the treatment plant influent. The Burge system detected this as elevated concentrations (1 to 2 ppb) of TCE.

At the end of their current field deployments the system will undergo testing for compliance with American Society of Testing and Materials (ASTM) requirements for analytical systems. The standards to be met will be the similar to those required of EPA Method 8021. This will be the first in a series of steps towards recognition by the EPA as a technology capable of regulatory monitoring.

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Appendix 7

Automation Technology Case Study
Supervisory Control and Data Acquisition Using Programmable Logic Controllers at the Sprague Road Superfund Site

Automation Technology Case Study
Supervisory Control and Data Acquisition Using Programmable Logic Controllers at the Sprague Road Superfund Site

Summary Information [1, 2, 3, 4, 5, 6, 8, 9]

Programmable logic controllers (PLC) are used to automate processes. Before the commercialization of PLC technology, process automation was achieved by hard-wired relays and timers, also called basic relay logic (BRL). Any change in process operation required rewiring of the control circuits. PLC technology changed the emphasis in automation from hardware to software. Though skilled electricians were still required to integrate the PLC into the control system, the logic that drove process automation was embedded in computer programs as opposed to hard-wired circuits.

PLC technology is being used at the Sprague Road Ground Water Plume Superfund (Sprague Road) site to operate the remediation system. The site is located in Ector County outside the northwest city limits of Odessa, Texas, and consists of three inactive or abandoned metal plating facilities located within 1 mile of each other: Machine & Casting, Inc. (M&C), Leigh Metals (LM), and National Chromium Corporation (NC).

Historical operations at those facilities resulted in contamination of the groundwater with hexavalent chromium. The contaminant plumes beneath each facility are physically distinct, but due to their proximity the remedial approach was to address the three facilities as one single site. The selected remedy for the Sprague Road site was groundwater extraction, treatment (ion exchange) and re-injection.

The system was designed for continuous operation with minimal human intervention, and continuous centralized monitoring over the anticipated ten-year remediation period. This is facilitated by a supervisory control and data acquisition (SCADA) system.

PLC technology is used at this site to facilitate supervisory control over the extraction, treatment and re-injection system. However, the control system encompasses much more than just the PLC. Sensory equipment, actuators, and the PLC form the bone structure of the control system. Sensors are the "eyes," of the control system, and provide the PLC with information on the status of the system. The PLC is the decision-making unit of the control system and uses its programmed instructions to processes sensory information ultimately leading to a response. The response may be: to do nothing; to command an actuator to start an associated device; or to command an actuator to stop an associated device.

Sensors at this site include liquid level and pressure sensing devices. Actuators include switchgears and hand-off-auto (HOA) switches that start and shut down pumps, or open and close solenoid valves. All pumps at this site have manual overrides, that is, the "hand," mode. An actuator will respond to PLC commands only when the HOA switch is placed in the "auto," mode.

The data acquisition (DA) system is comprised of a network of three personal computers (PC) that interface with the PLC at each of the three sites. A program called Lookout installed on each of the PCs accomplishes the "data acquisition," from the PLCs and depicts the information on user interface screens. Lookout is essentially a window into the sensory information available to the PLC.

The remediation and automation system has been in operation since September 2003, and

there have been no PLC breakdowns as of this case study (Fall 2004). The DA system malfunctioned in April 2004. The cause was software-related, but the exact nature of it was never determined. The SCADA system was operational within two weeks of the observed malfunction. The time taken to implement the solution was small compared to that consumed by administrative tasks and logistical hurdles. The remediation system itself functioned normally during this time.

Technology Description [2, 3, 6]

PLCs, also referred to as programmable controllers, are in the computer family. They are most commonly used in commercial and industrial applications. Figure 1 shows the PLC used at the Sprague Road site.

A PLC monitors inputs, makes decisions based on its program, and controls outputs to automate a process or machine. PLCs consist of input modules or points, a Central Processing Unit (CPU), and output modules or points. An input accepts a variety of digital or analog signals from various field devices (sensors) and converts them into a logic signal that can be used by the CPU. The CPU makes decisions and executes control instructions based on program instructions in memory. Output modules convert control instructions from the CPU into a digital or analog signal that can be used to control various field devices (actuators). A programming device is used to input the desired instructions. These instructions determine what the PLC will do for a specific input. An operator interface device allows new control parameters to be entered.

DA systems go hand-in-hand with PLC technology. A DA system refers to DA software and the computer system hosting the software. DA software can be loaded on any personal computer (PC) that meets the software's minimum requirements. Some examples of DA system software are:

(1) Lookout developed by National Instruments;
(2) InTouch developed by Wonderwear;
(3) Intellutions developed by GE Fanuc;
(4) Cimplicity developed by GE Fanuc; and
(5) Iconics developed by Iconics Inc.

The DA system interfaces with the PLC and continuously gathers real-time process information. The DA system uses this information to update graphical or numerical depictions of system status on the user interface screen. DA systems can be programmed to maintain electronic records of desired process data at any desired interval, and generate reports. The total amount of data that can be recorded would be limited only by the host computer's hard disk storage space. The DA system does not control any components of the remediation system.

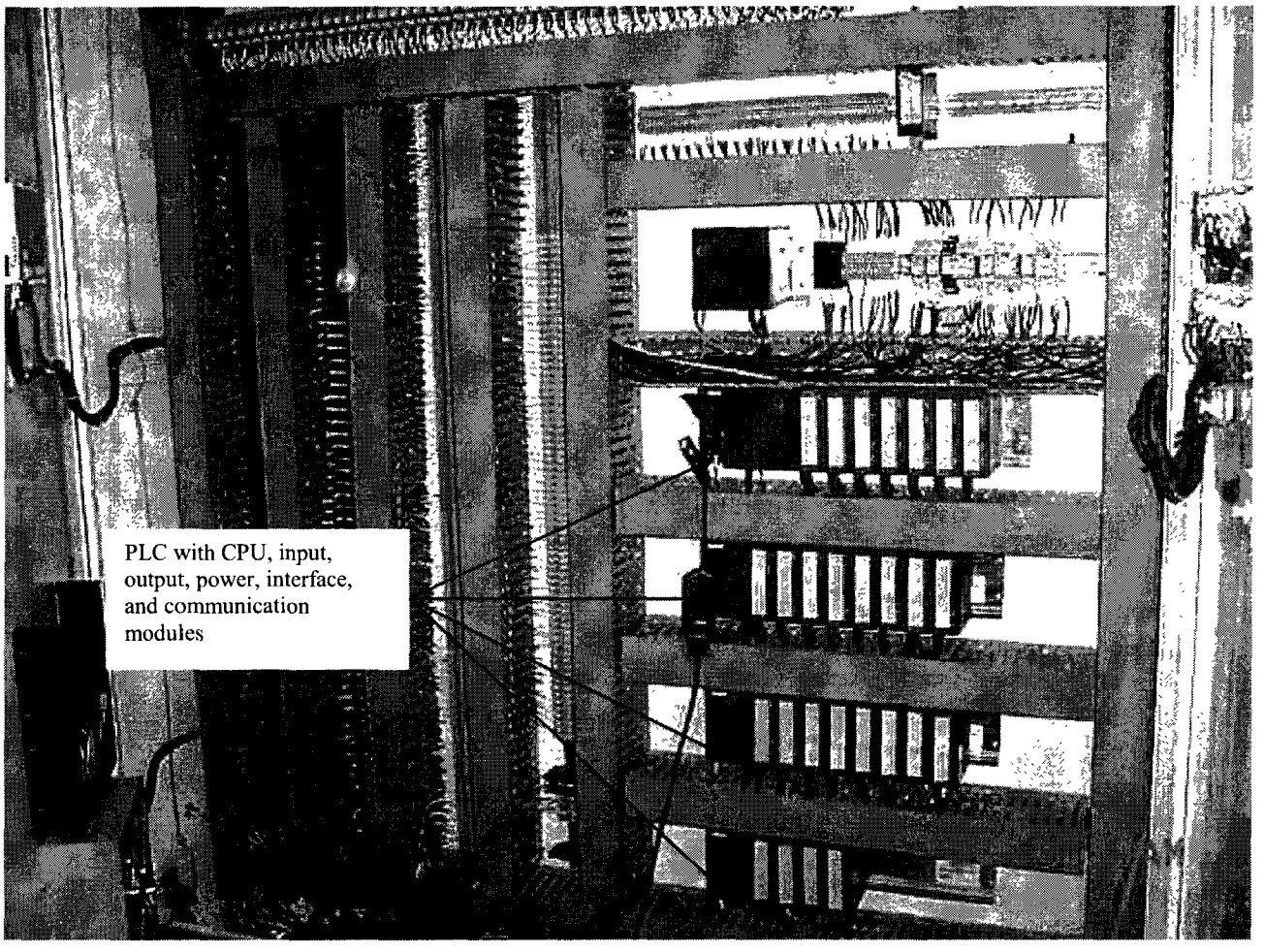
Site Information [1, 3, 4, 5, 8, 9]

The site is located in Ector County outside the northwest city limits of Odessa, Texas, and consists of three inactive or abandoned metal plating facilities (M&C, LM and NC) located within 1 mile of each other.

Past waste management practices at those facilities led to contamination of the groundwater with hexavalent chromium. The plumes associated with each facility were physically distinct, but the three facilities were collectively termed the Sprague Road Ground Water Plume Superfund (Sprague Road) site.

The selected remedy was a comprehensive approach for all three facilities. It entailed extraction of contaminated groundwater through three localized networks, treatment by an ion exchange process at LM, followed by distribution of treated water for re-injection at the three facilities.

Figure 1
Control Cabinet Housing PLC



Remediation System

A network of recovery wells (7 at M&C, 27 at LM, and 23 at NC) formed the ground water recovery system. Recovery systems at M&C and NC each pumped contaminated ground water into local collection tanks. Pumps transferred water from these collection tanks to the treatment system. The recovery wells at LM pumped water directly to the treatment system.

The treatment system was located at LM and included a surge tank, a pump tank, pumps, bag filters, and an ion exchange system. The ion exchange system consisted of two banks, each consisting of five resin tanks. Resin tanks within a bank were connected in parallel, and the two banks were connected in series. At any given time one bank acted as the worker (or primary) resin, and the other acted as the polisher (or secondary)

The injection system consisted of three separate networks of injection wells (8 at M&C, 8 at LM, and 27 at NC), and a vadose zone flushing system at NC. Injection pumps in the treatment building at LM delivered treated water to each of these networks.

System monitoring data along with groundwater monitoring, and hydrogeological modeling was used to periodically modify operation of the remediation system to address the current state of the plume in the most efficient manner.

The process flow diagram of the remediation system is shown in Figure 2.

Control System

System control was shared by three local control centers, one each at M&C, LM, and NC. The three control centers communicated through telemetry making real time data globally available. However, field devices associated with a given facility could only be actuated by a local control center. The M&C and NC control centers had supervisory control over extraction pumps, injection well shutoff valves, and transfer pumps at their respective facilities. The LM control center performed similar functions at the LM facility, except that it also controlled operation of the treatment system, and injection pumps. The control centers were prefabricated air-conditioned metal buildings that contained a motor control center, panelboards, a control cabinet housing the PLC, and a desktop computer that displayed real time system information and recorded operating data.

The PLC at each facility was a SIMATIC S7-300 manufactured by Siemens. The PLC's central processing unit was a CPU-315-2-DP-new. The PLC had digital input modules – each capable of receiving 16 inputs- as well as analog input modules – each capable of receiving 8 inputs. The number of modules used at a given control center depended on the number of local field sensors providing input. The PLC also had digital output modules, each permitting output to 16 different devices. The number of output modules depended on the number of field device actuators to be controlled by the PLC. The PLC had an interface module that permitted interface with other devices to receive programming or transfer system status information.

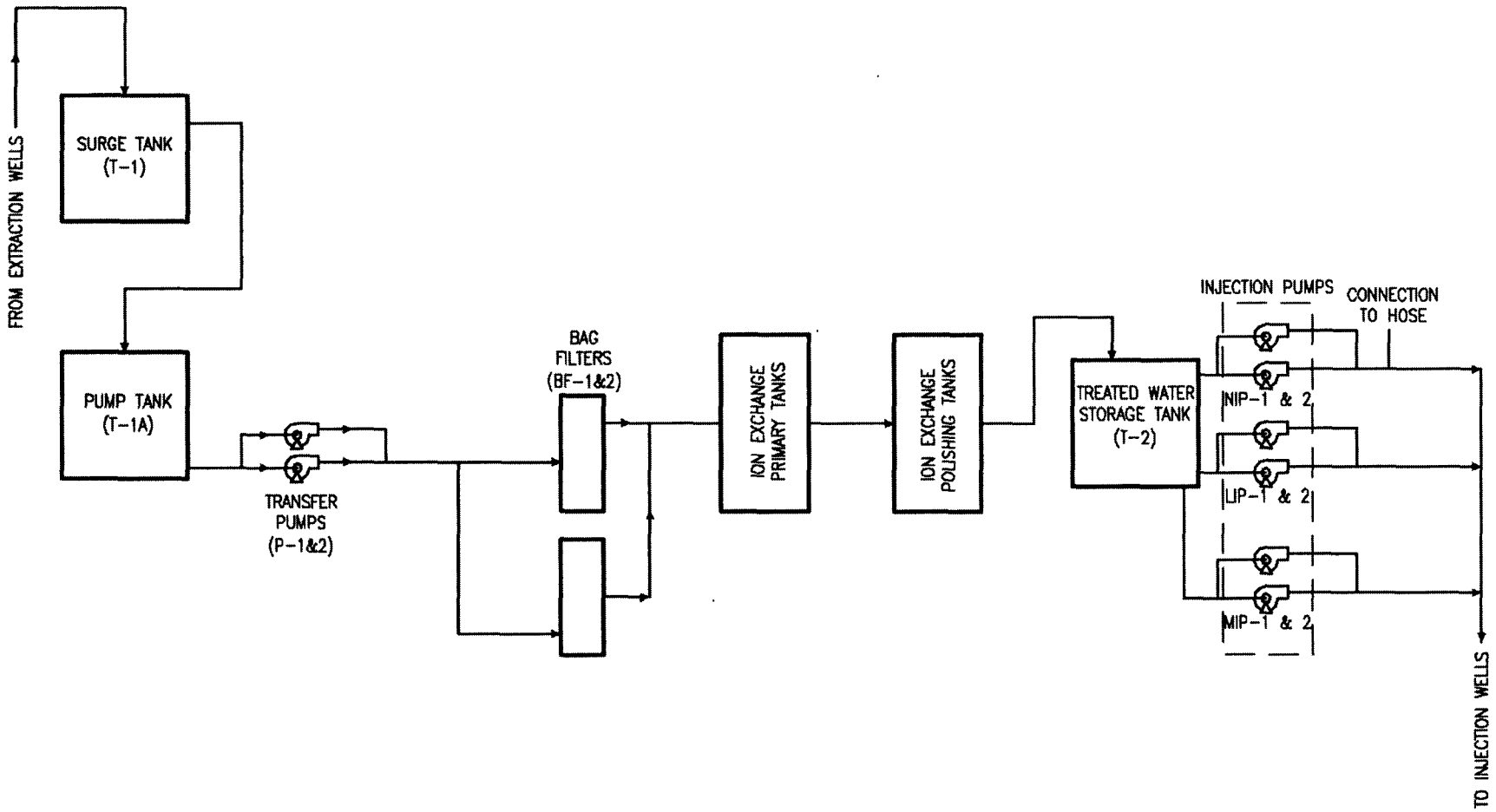
Each PLC had a communication module. The communication module had its own processor dedicated to information exchange. This module facilitated communication between PLCs, and with the internet through various available protocols. At this site the three PLCs used their communication modules to communicate with each other through a wireless industrial Ethernet link. A PLC at M&C was therefore able to recognize a high level in a tank at LM and respond by shutting down the appropriate transfer pump at M&C.

Each PLC contained custom- programmed instructions on the appropriate response to be taken based on the input received from sensory devices. For example if the PLC at M&C received a low level signal from the level sensor in an extraction well, it would respond with an output signal to the corresponding pump actuator telling it to shut down that pump.

Some of the functions performed by the PLC included:

(1) Start and shut down of groundwater extraction pumps based on the water levels in the extraction wells.
(2) Start and shut down of transfer pumps based on the water levels in receiving and supplying tanks.
(3) Opening and closing of injection well valves based on the water levels in the injection wells.
(4) Start and shut down of transfer pumps based on the presence or absence of radio communication between facilities.
(5) Shut down of ion exchange system feed pumps based on the differential pressure across the bag filters.
(6) Complete system shutdown during alarm conditions such as high-high (above high), or low-low (below low) levels in tanks.

Figure 2
Process Flow Diagram



Data Acquisition System

The DA system at Sprague Road consisted of three desktop computers – one at each facility – running the Enterprise version of a DA software (Lookout) developed by National Instruments. This version of Lookout was necessary for the development of applications facilitating process monitoring through the internet. Lookout was used to develop the facility-specific applications that performed the required DA functions at those facilities. The computers hosting the DA software were all Dell PCs with 2.0 gigahertz Pentium 4 processors. Each PC was connected to its local PLC through a communication port. The DA software retrieved real-time system status information from the PLC and graphically depicted this information on the various user-interface screens.

Some of the functions performed by the DA system included:

(1) Displaying operating status (on or off) of extraction, transfer, and injection system pumps.
(2) Displaying water levels in tanks as a percentage of total volume.
(3) Displaying water level status (high or low) in injection and recovery wells.
(4) Displaying injection well valve status (open or closed).
(5) Computing and displaying flow rates (gallons per minute) through each extraction well, injection well, and transfer pump.
(6) Displaying fluid pressure at various nodes.
(7) Displaying presence or absence of radio communication between facilities.
(8) Recording minimum, average, and maximum flow rates.
(9) Recording totalized flow.
(10) Summarizing data and automatically printing daily, weekly, and monthly reports.

The DA system is in the process of being improved to provide internet access to real-time system-status information. When this update has been made, authorized users will be able to access the system's website from anywhere in the world to view the various user interface screens showing real-time process information.

System Operation

The system has been in operation since September 2003. As of May 16, 2004, 97,160,690 gallons of water were recovered, treated and re-injected.

The only maintenance associated with the supervisory control system was the replacement of PLC input/output fuses. There had been no PLC malfunctions since system startup. The DA system malfunctioned in April 2004. The cause of the malfunction was never determined, but it apparently resulted in corruption of the DA application. The problem was fixed by updating the Windows operating system, installing the latest Windows service packs, then re-installing the DA application. Since the DA system played no role in supervisory control, the remediation system functioned normally even when the DA system was inoperable.

The flexibility offered by PLC technology was evidenced during the initial stages of system operation. The radio antennae used for remote communication between the three PLCs occasionally lost contact with each other. When this occurred there was the potential for transfer pumps at M&C and NC to flood tanks at LM. To facilitate safe system operation, the automation logic had to be modified. PLC programmers were able to easily change the program to cause transfer pumps at M&C and NC to shut down when communication was lost with LM.

Cost [6, 7, 8]

The total cost for purchase and installation of the control system at Sprague Road was $415,000. This included labor and materials costs for the motor control centers, panelboards, control cabinets, sensors, DA system, PLCs and peripherals. The actual portion of this cost that was spent on PLC and DA system purchase and installation was not available. However, the table below provides the estimated cost of PLC hardware at one of the facilities (LM) at Sprague Road. The unit price for each component is the manufacturer's listed price.

PLC (SIMATIC S7-300) COST ESTIMATE			
Item	**Qty**	**Unit Price ($)**	**Subtotal ($)**
CPU	1	1,760	1,760
Digital input module	5	198	990
Digital output modules	3	275	825
Analog input module	1	765	765
Interface module	1	230	230
Communications processor	1	1,780	1,780
Power supply module	1	365	365
TOTAL [1]			**6,715**

Note:

[1] Cost does not include installation

Unit Price Source: Siemens Energy and Automation

Lessons Learned [3, 8]

According to the lead agency's contractor, the following were lessons learned with respect to construction of the SCADA system at the Sprague Road site.

The bid should require that all project submittals be approved by the prime contractor prior to mobilization by the subcontractors. The subcontractors must bear the burden of meeting every requirement of the submittal process, including accuracy, relevance, detail, completeness and timely submission. The sheer volume of submittals associated with such projects requires the above measures to ensure strict compliance with design specifications, and timely approval by the engineer.

Subcontracts for this type of work should be "performance-based." This implies payment for services based on the achievement of project milestones as opposed to payment for time and effort. Subcontractors would therefore be compelled to complete all tasks on schedule in order to maintain their profit margins.

The inclusion of a professional Electrical Engineer in the design, procurement and oversight team proved to be absolutely critical to the successful installation of the SCADA system.

After about a year of operation, it was suggested that the project could have benefited from certain SCADA system functions that were not believed to be essential during system design. One such function was for the system to contact the plant operator via telephone or pager if a problem occurred. Another was remote access to the SCADA system via direct dial that would allow programmers to fix DA software glitches, or modify the SCADA program from remote locations. This was thought to be potentially more cost effective than having programmers travel to the site to fix problems.

In general, it is important to remember that the overall functionality of the SCADA system is only as good as the information being provided to it. The selection, installation, and maintenance of the sensors that communicate with the PLC are therefore just as important as the PLC itself.

Conclusions [3, 6]

Information in this section was derived from conversations with the project Electrical Engineer.

The complexity and scale of the pump and treat system at Sprague Road makes manual operation impractical. This section uses BRL technology as a benchmark to discuss system automation using PLC technology.

The main advantage of PLC technology is its flexibility. System automation is based in software as opposed to hard wiring in the older basic relay logic (BRL) technology. PLC technology makes it possible to change the operating logic of the system merely by modifying the programmed instructions. On the other hand changing the operating logic of a system using BRL would require re-wiring and the addition of relays and interlocks. This is a tedious and complex task.

PLC technology requires a lot less space than BRL technology. For example, if BRL were used at Sprague Road, the control cabinet could be at least twice its current size.

PLC technology is relatively inexpensive compared to BRL. For example a $1,500 investment in a PLC would purchase a lot more process control power than BRL technology of equal cost.

A drawback to using PLC technology is the high level of skill and sophistication required of those who implement this technology. PLCs are programmed by educated and skilled computer programmers. In addition, various PLC manufacturers market their own PLC programming software. Even though programming in different software environments may lack conceptual differences, there often are differences in method. Therefore an expert programmer in one software environment may not be as skilled in another. This somewhat restricts the options available when looking for programmers after a specific PLC has been selected. On the other hand, BRL does not require the same level of skill. Any skilled electrician experienced with control panel wiring would be able to interpret design drawings to efficiently implement BRL technology irrespective of who the components are manufactured by.

Another drawback to PLC technology is centralized control. If the PLC breaks down, the entire process shuts down. A damaged relay in BRL on the other hand only leads to shut down of the component controlled by it. For example if a groundwater extraction pump were controlled by BRL, break down of a relay would only affect the one pump, and the rest of the system would function normally.

PLC technology is weaker than BRL in its weatherability. PLCs require greater environmental controls than BRL to function normally.

Generally system reliability can be increased by blending PLC and BRL technology. However, this type of blend may not be required for a system such as that used as Sprague Road. This is because there is no noticeable consequence to system shut down for a few days or even a week at a time. Critical systems on the other hand would benefit from backup automation circuitry in the event of PLC failure. One method uses parallel processing to add reliability to the control system. This essentially means two PLCs are simultaneously used to control the

same process. One is the primary and the other serves as a backup. The backup PLC takes over when the primary fails. The two techniques used for this type of redundancy are called "hot backup," and "fault tolerant backup." Other than the few inherent software-depended operational differences, these terms for redundancy techniques can be used interchangeably. The system at Sprague Road is not critical enough to require such measures.

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