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- Soil chemistry
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Into Africa

Al Conklin, our regular Academix columnist, has a new prospective on the industry. A perspective from halfway round the world. He has taken a temporary hiatus from his position as professor in the agriculture department at Ohio's Wilmington College. Today, Al is a senior Fulbright professor and researcher at the University of Zimbabwe. Currently, he is involved in research on soybean production and on nitrate pollution of groundwater. We, his readers, will look forward to this new international viewpoint in future Academix columns.

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June July 1999

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10 Advanced techniques for enhanced recovery of NAPL
By Gaylen Brubaker

12 1999 BUYERS GUIDE

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Wood treating activities began in 1923 at the Bell Lumber and Pole Company (Bell Pole) site in New Brighton, Minn. Treatment activities have included creosote and pentachlorophenol (PCP) in a fuel oil carrier. Creosote was used as a wood preservative from 1923 to 1958. A 5% to 6% mixture of PCP in fuel oil has been used as a preservative from 1952 to the present. Provalene 4-A, a non-slagging fuel oil type carrier for PCP, was used from 1952 until it was no longer available in 1968. From 1968 to the present, a fuel oil type carrier P-9 has been used.

Site characterization
The contaminated soil at the Bell Pole site is contained in the New Brighton Formation. It has been described as a relatively uniform silty fine-medium grain sand, seven to 14 meters thick beneath the site. The contaminated soil is underlain by the Twin Cities Formation which is a silty to sandy clay till. The New Brighton Formation is highly permeable. Conversely, the underlying Twin Cities Formation has a low permeability which has provided an effective lower boundary to fluid migration and has limited the downward migration of the organic material. A continuous aquifer lies at a depth of three to six meters below ground surface. Groundwater flows radially from a pond, located to the northeast, and flows across the Bell Pole site toward the southwest where the water discharges into a drainage ditch.

In early 1990, 22 boreholes were drilled to define the extent of the contamination. Based on boring data, it was determined that the contaminated interval has an elongated teardrop shape which dips toward the northeast. (Figure 1) The maximum contaminated thickness in the center of the area is approximately eight meters, while the edge of the contaminated area is less than a meter thick. The horizontal extent of the contaminated area is approximately 8,094 m².

Core material was also taken and analyzed from seven wells drilled in the contaminated pattern area. From this material, organic saturations were calculated on a pore volume basis. Organic saturations were then determined by contouring the measured data. From this method, the contaminated pattern organic-in-place was estimated to be 1,848 m³.

In situ remediation project
Prior to initiating the in situ remediation project, a pilot test was conducted to assist in designing the full scale process. The pilot test consisted of injecting hot, potable water into the NAPL saturated area.

Continues on page 8 →

L.J. Fahy is principal engineer and L.A. Johnson Jr. is program manager with Western Research Institute, Laramie, Wyo. D.A. Thingvold is environmental manager with Bell Lumber and Pole Co., New Brighton, Minn.

Figure 1. Bell pole contamination and phase one well pattern.
of the aquifer at injection well IW1, producing groundwater and NAPL from an existing extraction well, PW1, and treating the produced water for sanitary sewer discharge. (Figure 1)

Based on the results from the pilot test, the following conclusions were made:

- The pilot test provided sufficient hydraulic information to design the full-scale remediation system. The pumping test portion of the pilot test indicated uniform aquifer properties. The entire thickness of the aquifer reached the target temperature range, and containment of the injected hot water was achieved.
- Pre-test injection and extraction rate predictions were achieved.
- The post-test soil boring data indicated hot water injection displaced more than 80% of the NAPL near the injection well. The data indicates that a NAPL residual saturation of approximately 19% (pore volume basis) and a 500 fold decrease in PCP concentration can be achieved with 20 pore volumes of flushing.
- The produced water treatment system used during the pilot test was effective in reducing PCP and polynuclear aromatic hydrocarbon (PAH) compounds to concentrations acceptable for sanitary sewer discharge.
- The microbial assay of the post-test samples found an encouraging increase in microbial population compared to data collected before the pilot test.

Based on the results from the pilot test, conditions and procedures were developed for implementing full scale in situ remediation of the remaining contaminated soil at the Bell Pole site. After considering several options, a multi-phase approach was implemented to remediate the contaminated area. Phase One was designed to remediate the upgradient, one-third of the contaminated area which was estimated to contain approximately 757 m³ of organic matter.

During 1993, additional injection wells were drilled and by using the existing extraction well, PW1, an inverted five spot pattern was installed. (Figure 1) Injection to extraction well spacings vary between 27 and 44 meters, compared to only 15 meters during the pilot test.

Because of the high volume of traffic in the contaminated pattern area, all wells have been completed with at-grade installations. Surface piping was buried below frost level which also reduces heat loss. All surface tanks, equipment and instrumentation are contained in a building. The project was designed for long term operation, consequently, many potential problems due to weather have been eliminated.

During the pilot test and the Phase One field operation, the extraction well, PW1, has been overpumped compared to the amount of water reinjected. By extracting more water than is injected, a cone of depression is created around the extraction well and water is drawn into the pattern area. This procedure has resulted in containment of the injected water.

Based on results from the pilot test, a produced fluid treatment system was designed and installed. Water and oil is produced at an average rate of 1×10³ m³/s from well PW1 and is pumped to a 150 m³ process tank after sulfuric acid has been added to lower the pH to approximately 3.5. The produced oil is slightly heavier than water and is primarily pumped from the bottom of the tank and then routed to an oil holding tank. This is a batch operation that is done daily.

Water is continuously pumped from the process tank to an air flotation unit where the oily water is aerated and the majority of the remaining organic material is removed and returned to the process tank.

The treated water leaving the air flotation unit is treated with sodium hydroxide to raise the pH and then pumped to the 40 m³
equalization tank. From this tank, part of the water, 1.9x10^4 m³/s, is pumped to an ozonation unit which removes the PCP. The water is then treated with hydrogen peroxide to breakdown the remaining PAH compounds and then disposed to the sewer. The remaining water that is not pumped to the ozonation unit is recycled through a boiler/heat exchanger system where it is heated to about 55°C and then reinjected at an average rate of 8.2x10^4 m³/s into the four injection wells. The water treatment system is shown in Figure 2.

After addressing initial system startup problems, continuous groundwater extraction was established in February 1996 and continuous hot water injection began a week after extraction. Continuous hot water injection was terminated in July 1996 due to a heat exchanger failure. At that time, aquifer temperatures were approaching 49°C and 21°C water was being produced at the extraction well. Cold water injection and extraction continued while efforts were made to replace the heat exchanger. Hot water injection began again in April 1997 and continued until late September 1997 when after 194 days of continuous operation, the system was shut down for maintenance, but was restarted again in December 1997.

Oil production has been estimated from the daily transfer of oil from the 150 m³ tank to the oil storage tank. At the end of September 1997, 159 m³ of oil had been transferred to the oil storage tank with 60 m³ of this produced oil used in Bell Pole's treating operation.

Aquifer temperature measurements are routinely taken and give an indication of how the hot water flood is progressing. The hot water injection appears to be establishing an interconnected front in the upgradient direction. The hottest temperature in the pattern is in the area of monitoring well BP27, as the downgradient part of the pattern is not responding as fast as in the upgradient direction. The extraction well has not yet seen a high temperature response.

**Conclusions**

The Bell Pole Phase One Remediation Project has not achieved the design flow rates and temperature, however, oil production has exceeded expectations. The injection to extraction well

spacings for the Bell Pole aquifer are approaching the maximum limits for the achievable flow rates and temperatures.

Recycled water injection has been contained by over pumping the extraction well.

The produced oil is a usable product in the Bell Pole operation which is partially offsetting the cost of remediation.

---

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**Soil & Groundwater Cleanup June/July 1999**
Considering advanced techniques for enhanced recovery of NAPL

By Gaylen Brubaker

Over the past ten years, our perceptions of the degree to which soil and groundwater remediation is possible have evolved extensively. Since 1995, thousands of pump and treat systems have been deactivated. This has occurred as a result of our understanding that nature can remediate many of these sites nearly as quickly and at a fraction of the cost. No matter what remediation system is used, we are often frustrated by the realization that groundwater may be impacted for decades because of the seemingly endless supply of contaminants that reside within the soil matrix. This is particularly true at sites impacted by non-aqueous phase liquids (NAPL).

Most regulations require that NAPL be removed to the "maximum extent practicable". Although this term is loosely defined within regulations and guidance documents, this requirement is generally satisfied by: 1) eliminating the risk that NAPL will migrate into previously unimpacted areas, 2) reducing the thickness of NAPL that accumulates in recovery wells, and/or 3) removing NAPL using a traditional product recovery methods until the rate of recovery decreases exponentially.

Although these actions would address regulatory issues, they may have no beneficial impact on human health and the environment. This is because at most sites, 90 to 99% of the residual NAPL must be removed to achieve a sufficient reduction in dissolved groundwater concentrations to alter the long-term risk profile of the site. Most groundwater professionals agree that removing sufficient residual NAPL is technically infeasible using traditional product recovery methods, such as dual phase extraction.

Considering advanced techniques

Creative scientists and engineers have been developing new in situ remediation technologies (enhanced NAPL recovery techniques) which, in some instances, will accelerate groundwater remediation by reducing the mass of residual NAPL below that which could be removed with traditional technologies. Even so, advanced techniques may be technical and financially infeasible at many sites because a risk reduction benefit may not be gained by removing incremental quantities of residual NAPL.

Some of the reasons for this limitation are:

- The mass of residual hydrocarbon is a relatively small factor in determining the size of the stable groundwater plume that exists downgradient of a hydrocarbon impacted area. The primary influences on the size of a groundwater plume are the groundwater flow rate and the rate of intrinsic biodegradation at the site.
- Groundwater that enters a hydrocarbon impacted area becomes saturated with benzene after traveling a few feet in the presence of residual NAPL. As a result, groundwater leaving an impacted area that contains 100 gallons of residual NAPL will not be very different from groundwater leaving a source zone containing 10,000 gallons of residual NAPL.
- Since benzene is one of the most soluble constituents in hydrocarbon mixtures, it is more easily extracted from the NAPL than other hydrocarbons. As a result, the effective solubility of benzene decreases in water as the remediation progresses, because the fraction of benzene in the residual NAPL decreases over time. It is always much easier, therefore, to reduce benzene concentrations from 500 ug/L to 50 ug/L than from 50 ug/L to 5ug/L.

Using enhanced advanced NAPL recovery techniques is most likely to be effective and cost effective when:

- The source and extent of NAPL contamination are known.
- The geology of the impacted area is relatively homogeneous, well understood and the hydraulic conductivity is 10^4 cm/sec or greater.
- The NAPL impacted area is relatively shallow (less than 25 feet) and relatively small.
- The degree of short term enhancement desired is relatively small.
- A large reduction in risk or a substantial increase in property value will result from the anticipated improvement in groundwater quality.
- A lower confining unit, such as a clay zone under the impacted groundwater zone, to control NAPL migration.

Removing residual diesel fuel

Consider, for example, a site containing a six foot smear zone of hydrocarbon that covers 1/2 acre. If the hydrocarbon is diesel and the soils are medium sand,
the highly impacted soils would typically contain about 4,000 
mg/Kg of diesel, which equates to 242,000 pounds (33,600 
gallon) of residual hydrocarbon. If this hydrocarbon contains 3% 
benzene by weight (and 0.015 mole fraction) a typical benzene 
concentration in groundwater would be about 2.6 mg/L 
(25% of the theoretical concentration estimated by 
multiplying the mole fraction 
times the solubility of pure benzene in water). Typical 
remediation goals for dissolved benzene are 0.005 to 0.05 
mg/L. The total mass of benzene in solution near these 
highly impacted soils is about two pounds, less than 
0.03% of the total mass of benzene present (7,260 lbs). 

Figure 1 illustrates the change in benzene concentration 
that would be expected during groundwater 
remediation at this site. This particular calculation 
represents a site where the pore water within the NAPL 
impacted zone is replaced by clean water an average of 
2.5 times each year and where most of the dissolved 
oxygen at the site is consumed degrading other 
constituents that comprise the majority of the 
hydrocarbon mass. (The linear flow velocity is assumed 
to be 500 feet per year through an impacted area that is 
200 feet long and 115 feet wide.) 

This figure also shows 
predicted concentrations of 
dissolved benzene after 
removing 90% or 95% of the 
initial hydrocarbon. Although 
these actions clearly accelerate 
the rate of benzene removal, the 
resulting benzene 
concentrations are still 10 times 
higher than typical benzene 
surface water standards and 100 
times higher than benzene 

drinking water standard after 100 years.

Conclusion

In summary, the more stringent the groundwater 
standard, the less likely that initial source removal or 
aggressive in situ remediation options will achieve those 
standards, and the more likely it is that a long term, low 
cost groundwater containment system will be the most 
cost effective groundwater management option. 

However, in those instances where site conditions and 
enhanced NAPL techniques combine to remove greater 
than 95% of the initial material and where the resulting 
decline in dissolved phase concentrations will eliminate 
or dramatically shorten the remediation time, advanced 
NAPL removal options should be evaluated.

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Camp Dresser & McKee Detroit
Canyon Springs, LLC
Cardinal Engineering
Cascade Earth Sciences
CC EnvironKleen
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Civrotech Engineering, Inc.
Clark Environmental Services, PC
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Continental Planner, Inc.
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Corp. for Environmental Mgmt
CSA Group, Inc.
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Dames & Moore
De Minimis, Inc.
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Doty & Associates
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Downey & Gutenlag, LLC
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Dragun Corp.
DSM Environmental Services, Inc.
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EarthTech of Minnesota, Inc.
Emcon Alaska
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ENSRI
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Environmental Compliance Mgmt
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Environmental Consultant & Investig.
Environmental Corp of America
Environmental Fuel Systems, Inc.
Environmental Management, Inc.
Environmental Mgmt & Eng.
Environmental Mgmt Services, Inc.
Environmental Mgmt Solutions
Environmental Mgmt Associates
Environmental Mgmt Consultants
Environmental Mgmt Resources
Environmental-Materials Consult.
Environmental Mitigation Group
Environmental Resources Mgmt
Environmental Risk Management
Environmental Risk Managers
Environmental Sciences & Eng.
Environmental Solutions Group
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Enviroproc Inc.
EnviroTrac Ltd.
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Evergreen Environmental Group
Fero Environmental Engineering
First Environment Inc.
Foremost Solutions
Foster Wheeler Environmental
Free Flow Technologies, Ltd.
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Gabbard Environmental Services
Garrett Fleming
Gartner Lee Limited
Gaudet Associates, Inc.
GCI
Gehrin Environmental
Gem Star Associates, Inc.
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Hoffman Consulting, Inc.
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Holzinger, Inc., McLenon & Murrell
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HRP Associates, Inc
HSI GeoTrans
Huggins, Faulkner & Flynn
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Keister Engineering
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Larsen Engineers
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McLaren/Hart
McNamee, Porter & Seeley
Mercotec Argentina
Meredit/Boli & Assoc.
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Omega Envr. Services.
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Ontario Centre for Env. Tech.
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TEG North Atlantic
Teledyne Brown Eng.
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Terrasat, Inc.
Tetra Tech EM
Tierra Dynamic
Tighe & Bond
RJ Toll & Assoc.
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Triad Envr. Consultants
TNC
Tymco Bros. Envir. Serv.
Universal Tech. Res. Serv.
UPAH Tech.
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Vanasse Hangen Brustlin
Vista Information Solutions
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Wagner Envr. Consultants
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Wesco Environmental Consulting
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Environmental Mgmt Solutions
Geller-Ryan, Inc.
Holzmacher, McLendon & Murrell
Integra Plastics, Inc.
KayMo, LLC
Larsen Engineers
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Services, from page 15

Montgomery Watson
Nassef Eng. & Equip.
O'Brien & Gere
Ogdens Envir. & Energy Serv.
Omi Associates
RSA
SFN OES
Superior Environmental
Tierra Dynamic
Universal Tech. Res. Serv.
Wasatch Environmental
Zimmerman Tech. Serv.

DECONTAMINATION
ARD Environmental, Inc.
Global Solutions, Inc.

DEMOLITION
Global Solutions, Inc.

DESIGN
ARM Group, Inc.
Benchmark Env, Eng, & Science

DEWATERING
Corporate Environmental Advisors
Green Mountain Technologies, Inc.
Severson Envr. Serv.
Thompson Pump & Mfg

DIRECT PUSH TECHNOLOGY
Directec

DREDGING
Severson Envr. Serv.

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Accel Environmental Services, Inc.
Aces Environmental Corp.
A.L.I., L.C. Eng. & Consulting
E. Roberts Alley & Assoc., Inc.
Alliance Environmental, Inc.
Aquatech
Artesian Environmental
Associated Soils Analysis, Inc.
Astbury Environmental Engineering
ATC Associates, Inc. - Cincinnati
ATC Associates, Inc. - Nashville
ATLATL, Inc
Atlantic Screen & Manufacturing
ATW, Inc.
Barron & Associates, P.C.
BBC International, Inc.
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Bison Engineering, Inc.
BlueRidge Environmental, Inc
BMS Consultants, Inc
BMS, Inc.
Boart Longyear
BSK & Associates
Camp Dresser McKee Cambridge
Camp Dresser & McKee Detroit
CDG Engineers & Associates, Inc.
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Clark Environmental Services, PC
Clayton Group Services, Inc.
Close Environmental Consultants
Coastal Environmental Services
Compass Environmental, Inc.
Compliance Engineering, Inc.
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CW Environmental Services, Inc.
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Dames & Moore
Directec
Directional Technologies, Inc.
Drilling Equipment Supply, Inc.
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EnecoTech
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Mountain Research
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Page & Kraemer Envr. Serv.
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Pennco Corporation
Pennsylvania Drilling
Petro-Probe Investigations
Prism Science & Tech.
PSI
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Remedial Solutions
Remedex Remediation Serv.
REP Associates
RSA
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S&ME, Inc.
SFN OES
Shannon & Wilson
SITE Envir. Serv.
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Stantee Consulting
Sunpro
Superior Environmental
Tall Environmental Mgmt
TEG North Atlantic
Terra-Mar, Inc.
Tierra Dynamic
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TRAK Environmental
Truespin
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Evergreen Environmental Group
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Dames & Moore
Dotty & Associates
Dougherty Sprague Environmental
DPRA Environmental
Dragun Corp.
DSC Environmental Services, Inc.
Duke Engineering & Services
EarthFax Engineering, Inc.
EFX Systems Inc.
ENGEO Incorporated
Engineering & Environment, Inc.
Ensaf Services
ENSR
Enviro-Logical Solutions, Inc.
Enviro-Sciences, Inc.
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Environmental Corp of America
Environmental Fuel Systems, Inc.
Environmental Management, Inc.
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Environmental-Materials Consult.
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Environmental Solutions Group
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Enviropro Inc.
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Evergreen Environmental Group
Fero Environmental Engineering
First Environment Inc.
Foremost Solutions
Foster Wheeler Environmental
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GCI
Gehm Environmental
General Eng. & Envir. Consultants
Genesis Environmental Consulting
GenTec Environmental
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GeoSyntec Consultants
Geotechnical Services, Inc.
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Groundwater Mgmt Associates
Groundwater Services Inc.
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GZA GeoEnvironmental
Handex
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Hocage Consulting, Inc.
Hoffman Consulting, Inc.
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Anchor E. Holm, P.E.
Holzmacher, McLeod & Murrell
Horizon Environmental, Inc.
HRP Associates, Inc.
HSI GeoTrans
Hydro Geo Chem, Inc.
Hydro-Environmental Tech.
IMS Envir. Serv.
Inland Environmental
Integrated Solutions
Intl. Research & Evaluation
J&W Engineering
K.C. Johnson & Malhotra
K Chem Lab, Inc.
K&S Engineers
KayMo, LLC
KCI Technologies
Keistler Engineering
Keramida Environmental
Killam Associates
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LAN Associates
Landchek, Inc.
Langan Eng. & Envir. Serv.
Larsen Engineers
LBFH
Lee & Ro, Inc.
LFR Levine Frickel
Lincoln Environmental
LMH Environmental
Longworth Environmental
Los Alamitos Tech. Assoc.
Lourie Consultants
LRC Technologies
Maddock & Assoc.
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Mantech Envir. Corp.
Marathon Eng. & Env. Serv.
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McLaren-Hart
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Mid-Kansas Eng. Consult.
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PBS&J
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R3 Technologies
Rapp Eng. & Applied Science
Reid Engineering
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Resource Controls
RESPAC
Rindt-McDuff Assoc.
Roux Associates
RSA
RT Environmental
S&ME, Inc.
Sanborn, Head & Assoc.
S/D Engineers
SEA Consultants
Secor International
SEY Engineers
SFN OES
Shannon & Wilson
Shifrin & Assoc.
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SPEC Consulting Serv.
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Custom Environmental Services
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Doty & Associates
 Duffy Sprague Environmental
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EnecoTech
ENGEO Incorporated
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Environ-Sciences, Inc.
Envi-Zyme International, Inc.
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Environmental Consultants & Serv.
Environmental Consult & Investig.
Environmental Corp of America
Environmental Fuel Systems, Inc.
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Environmental Mgmt & Env.
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Environmental Mgmt Consultants
Environmental Mgmt Resources
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Environmental Mgmt Solutions
Environmental-Materials Consult.
Environmental Sciences & Eng.
Environmental Solutions Group
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Enviropac Inc.
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ESDM, Inc.
ETUS Inc.
Evergreen Environmental Group
Evergreen Environmental Group
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Foremost Solutions
Foster Wheeler Environmental
Free Flow Technologies, Ltd.
Garrett Fleming
Gartner Lee Limited
Gaudet Associates, Inc.
GCI

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Gem Star Associates, Inc.
Genesis Environmental Consulting
Geo-Cleanse International, Inc.
Geocore, Inc.
Geonics
GeoEngineers, Inc.
Geologic Services Corp.
GeopheX, Ltd.
GeoSyntec Consultants
Geotechnical Services, Inc.
Gettler-Ryan, Inc.
Global BioSciences, Inc.
Global Remediation Technologies
Global Solutions, Inc.
GME Consultants, Inc.
Golder Associates
Howard R. Green Company
Griggs & Maloney, Inc.
P.W. Grosser Consulting
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Groundwater Mgmt Associates
Groundwater Recovery Systems
Groundwater Services Inc.
C.H. Guernsey
Marcus F. Guidy and Associates
GWM Consulting, LLC
GW/S Environmental Consulting
GZA GeoEnvironmental
H2 Oil Recovery Equip., Inc.
Hall Geological Services, Inc.
Handex
Hayward Baker, Inc.
HDC Engineering, Inc.
Hocage Consulting, Inc.
Hoffman Consulting, Inc.
Holquin, Fahan & Associates, Inc.
Holzmerch, M. Gordon & Murrell
Horizon Environmental, Inc.
HRP Associates, Inc
HSI GeoTrans
Hydro GeoChem, Inc.
Hydro GeoChem, Inc.
Hydro-Environmental Tech.
IMS Envir. Serv.
Inland Environmental
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LRC Technologies (D)
McPhee Envr. Supply (D)
Nassal Eng. & Equip. (D)
OP-TECH Envr. Serv. (D)
Page & Kraemer Envr. Serv. (D)
Spill Prev. Containment (D)
Surface Technology (M)
Sybron Chemicals (M)
West. States Bio Solve (M)

CHEMICALS, WATER TREATMENT
ALI, L.C. Eng. & Consulting (D)
Atlantic Screen & Mfg (D)
Carbonair Environmental Sys. (D)
Carus Chemical Company (D)
Coles-Parmer Instrument Co. (D)
John P. Cummings & Associates
Drilling Equipment Supply, Inc. (D)
Envr. Mgmt Consultants.
Enzyme Technologies, Inc.
ETUS Inc.
Geotechnical Services, Inc. (D)
In-Situ Oxidative Tech. (D, M)
KayMo, LLC (D)
Landchek, Inc. (D)
LRC Technologies (D)
Mantech Envr. Corp. (M)
MV Technologies (D)
Nassal Eng. & Equip. (D)
Page & Kraemer Envr. Serv. (D)
Spill Prev. Containment (D)

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EXCAVATORS
A.L.I., L.C. Eng. & Consulting (D)
Environmental Management, (D)
Excel Machinery Ltd. (D)
Hertz Equipment Rental (D)
Tyree Bros. Evir. Serv. (D)

FABRIC STRUCTURES
Universal Fabric Structures (M)

FEED SYSTEMS
A.L.I., L.C. Eng. & Consulting (D)
Andersen 2000, Inc. (M)
BioVac Environmental Serv. (M)
Carbonair Environmental Sys. (D)
Carus Chemical Company (M)
Excel Machinery Ltd. (M)
Rock Systems (M)
Texas Incinerator (M)
UPAH Tech. (M)

FIELD SAMPLING CONTAINERS
Eagle-Picher/ESAT (M)

FILL MATERIAL
A.L.I., L.C. Eng. & Consulting (D)
Drilling Equipment Supply, Inc. (D)
Mt. Hope Rock Products (D, M)
Page & Kraemer Envr. Serv. (D)
TRAK Environmental (D)
Tyree Bros. Evir. Serv. (D)

FILTER PRESSES, BELT
Carbonair Environmental Sys. (D)
Groundwater Recovery Sys. (D)

FILTERS, FILTER BAGS
AbTech Industries (D, M)
Bioram Technologies Inc. (M)
Carbonair Environmental Sys. (D)
CC EnviroKlean (D)
Cole-Parmer Instrument Co. (D)
John P. Cummings & Associates
EPG Companies, Inc. (D)
Geotechnical Services, Inc. (D)
Groundwater Recovery Sys. (D)
H2 Oil Recovery Eqip., Inc. (D)
Handex (D)
Lewis Envr. Group (D)
McPhee Envir. Supply (D)
Napco (D)
Page & Kraemer Envr. Serv. (D)
QED Environmental (M)
RAM Environmental (D)
SBT Group (D)

FLOATING COVER
Permalon (M)

FLOCULATION EQUIPMENT
Carbonair Environmental Sys. (D)
ETUS Inc.
Green Mountain Technologies, (M)
Handex (D)
LRC Technologies (M)
Nassco Env. & Equip. (M)
Page & Kraemer Envr. Serv. (D)
RAM Environmental (D)
SBT Group (D)
Unique Environmental (M)

FLOWMETERS
A.L.I., L.C. Eng. & Consulting (D)
Brewer Environmental Serv (D)
Carbonair Environmental Sys. (M)
Clean Environment Equipment (D)
Cole-Parmer Instrument Co. (D)
John P. Cummings & Associates
EHS Marketplace.com (D)
EPG Companies, Inc. (M)
Forestry Suppliers (M)
Geotechnical Services, Inc. (D)
Global Water
Groundwater Recovery Sys. (D)
H2 Oil Recovery Eqip., Inc. (D)
Handex (D)
Hydrotechnics, Inc. (M)
Indust. Envr. Monitoring Inst. (D)
ISTEC Corp. (M)
KVA Analytical (M)
Nepco
North American Mfg (M)
SBT Group (D)
Soil-Vac (D)
Tyree Bros. Evir. Serv. (D)
Unidata Americana (D)
Zellweger Analytics (M)

GAS CHROMATOGRAPHS
A.L.I., L.C. Eng. & Consulting (D)
Baseline Industries, Inc. (M)
Buck Scientific Inc.
Cole-Parmer Instrument Co. (D)
Geotechnical Services, Inc. (D)
Indust. Envr. Monitoring Inst. (D)
INFICON (M)
Intek Corp/Rent-Alyzer (D)
Sentex Systems (M)
West-Tech Supply (D)

GEOTEXTILE DRAINAGE SYSTEMS
Aeron Environmental (D)
A.L.I., L.C. Eng. & Consulting (D)
CC EnviroKlean (D)
C.H. Hanson Company (D)
IMS Envr. Serv. (D)
Integra Plastics, Inc. (D)

GLOBAL POSITIONING SYSTEMS
Aeron Environmental (D)
A.L.I., L.C. Eng. & Consulting (D)
Artesian Environmental (D)
Cole-Parmer Instrument Co. (D)
Baker Instruments Co. (D)
Forestry Suppliers (M)

GROUND PENETRATING RADAR
Sensors & Software (M)

GROUNDWATER CIRCULATION WELLS
Dames & Moore (D, M)

GROUNDWATER CLEANUP EQUIPMENT
Aardvark Corporation (M)
Aeron Environmental (D)
AbTech Industries (D, M)
A.L.I., L.C. Eng. & Consulting (D)
Alternative Envr. Solutions (D, M)
Albetta Corporation
Applied Earth Sciences, Inc. (M)
Atlantic Screen & Mfg (M)
Barnes & Butler Corp. (M)
Barron & Associates, P.C. (M)
Bask, Inc. (M)
BBC International, Inc. (D)
Bioremediological (D)
Bioscience Inc. (M)
BioVac Environmental Serv. (M)
Brewer Environmental Serv (D)
Carbonair Environmental Sys. (M)
CH2M Hill (D)
Clark Environmental Services, (M)
Clean Environmental Equipment (M)
John P. Cummings & Associates
EPX Systems Inc. (M)
Enviro-Logical Solutions, Inc. (D)
Envir. Consultants & Serv. (D)
Envir. Mgmt Consultants,(D)
Environmental Management, (C)
EnviroTrac Ltd.
Envirotol Inc. (M)
Enzyme Technologies, Inc.
EPG Companies, Inc. (M)
ETUS Inc.
Geoprobe Systems (D, M)
Global BioSciences, Inc. (M)
Global Remediation Tech. (M)
Groundwater Recovery Sys. (M)
GWG Consulting, LLC (D)
H2 Oil Recovery Equip., Inc. (M)
Handex (D)
Hydro-Environmental Tech. (D)
Indust. Envr. Monitoring Inst. (D)
In-Situ Oxidative Tech. (D, M)
K Chem Lab, Inc. (D)
KVA Analytical (M)
Landtech, Inc. (D)
Lewis Envir. Group (D)
Milan Tech Envir. Corp. (M)
Mobile Process Tech. (D)
Monolab (M)
Nassco Eng. & Equip. (M)
NEEP Systems (M)
Nepco
Page & Kraemer Envr. Serv. (D)
Penney Engineering (M)
Purafil Envr. Tech. (M)
QED Environmental (M)
Rain for Rent (D)
Remedial Solutions (M)
Remedex Remediation (M)
SBT Group (D)
Soil-Therm Equipment (M)
Soil-Vac (D)
Stainless Envr. Services (M)
Sybron Chemicals (M)
Testwell Industries (M)
Timco Manufacturing (M)
TPH Technology (D)
TRAK Environmental (D)
Tyree Bros. Evir. Serv. (D)
USFilter (M)
West-Tech Supply (D)

GROUNDBOARD PACKERS
Aardvark Corporation (M)

HAZARDOUS WASTE STORAGE
A.L.I., L.C. Eng. & Consulting (D)
A.L.I., L.C. Eng. & Consulting (D)
Baker Tanks (D)
John P. Cummings & Associates
Environmental Management, (D)
GWG Consulting, LLC (D)
Lewis Envr. Group (D)
Losberger U.S. LLC (M)
McPhee Envir. Supply (D)
Permalon (M)
TRAK Environmental (D)
U.S. Microbiotics (M)

RECALCIFICATION EQUIPMENT
Airlite Technologies, Inc. (M)

RECLAIM EQUIPMENT
A.L.I., L.C. Eng. & Consulting (D)
Andersen 2000, Inc. (M)
King, Buck Tech. (M)
McPhee Envr. Supply (D)
North American Mfg (M)
O'Brien & Gere (M)
Remedex Remediation (M)
SoilPure, Inc. (D)
Texas Incinerator (M)

INFLUENT/EFFLUENT EQUIPMENT, REPAIR
A.L.I., L.C. Eng. & Consulting (D)
EnviroTrac Ltd.
Page & Kraemer Envr. Serv. (D)
Sentex Systems (M)
Stealth Industries (M)
TPH Technology (M)
Tyree Bros. Evir. Serv. (D)

INSURANCE
Aaron Environmental (D)
Accent Environmental Services, Inc.

LAB EQUIPMENT, SUPPLIES
ABB (M)
A.L.I., L.C. Eng. & Consulting (D)
Biesz, John L. (D)
Bioscience Inc. (M)
Buck Scientific Inc.
Canberra (M)
Cole-Parmer Instrument Co. (D)
Eagle-Picher/ESAT (M)
Enviro Logix, Inc. (D)
Forestry Suppliers (M)
Geotechnical Services, Inc. (D)
K Chem Lab, Inc. (D)
Tyree Bros. Evir. Serv. (D)
Zellweger Analytics (M)

LANDFILL COVER MATERIALS
A.L.I., L.C. Eng. & Consulting (D)
Environmental Serv. & Products
Integra Plastics, Inc. (M)
King, Buck Tech. (M)
Losberger U.S. LLC (M)
McPhee Envr. Supply (D)
Permalon (M)
TRAK Environmental (D)
U.S. Microbiotics (M)

LANDFILL GAS RECOVERY SYSTEMS
Aardvark Corporation (M)
A.L.I., L.C. Eng. & Consulting (D)
Applied Earth Sciences, Inc. (M)
Atlantic Screen & Mfg (D)
CH2M Hill (D)
Clean Environmental Equipment (M)
Drilling Equipment Supply, Inc. (D)
EnviroTrac Ltd.
Fero Environmental Eng. (D)
H2 Oil Recovery Equip., Inc. (M)
Handex (D)
Integra Plastics, Inc. (M)
Lewis Envr. Group (D)
QED Environmental (M)
Stealth Industries (M)
TPH Technology (M)

LINERS, LANDFILL
A.L.I., L.C. Eng. & Consulting (D)
H&E Ecosystems (D)
Handex (D)
C.H. Hanson Company (D)
Page & Kraemer Envr. Serv. (D)

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Permalon (M)
UPAH Tech. (D)

LINERS, TANKS
A.I.I., L.C. Eng. & Consulting (D)
CC EnviroKleen (D)
Chicago Env. Eng. Corp. (D)
Page & Kraemer Envir. Serv. (D)
Permalon (M)
Tyree Bros. Envir. Serv. (D)
UPAH Tech. (D)

LITTER CONTROL FENCE
SYSTEMS
Environmental Serv. & Products

LONG-TERM INDUSTRIAL
MARKETING
Alternative Industrial Marketing

LOW NOX BURNERS
A.I.I., L.C. Eng. & Consulting (D)
Alzeta Corporation
EPG Companies, Inc. (M)
H2 Oil Recovery Equip., Inc. (D)
King, Buck Tech. (M)
North American Mfg (M)
Soil-Therm Equipment (M)
Texas Incinerator (D)

MAINTENANCE, SERVICE
ABB (M)

MEMBRANES
A.I.I., L.C. Eng. & Consulting (D)
C.H. Hanson Company (D)
Integra Plastics, Inc. (M)
Permalon (M)

METALS RECOVERY SYSTEMS
A.I.I., L.C. Eng. & Consulting (D)
Andersen 2000, Inc. (M)
ATA Technologies
CH2M Hill (D)
Handex (D)
K Chem Lab, Inc. (D)
Mobile Process Tech. (D)
Nassief Eng. & Equip. (M)
Terraform Corp. (M)
Unipure Environmental (M)
USFilter (D, M)

METHANE RECOVERY
SYSTEMS
Aardvark Corporation (M)
A.I.I., L.C. Eng. & Consulting (D)
Andersen 2000, Inc. (M)
Atlantic Screen & Mfg (M)
Fero Environmental Eng. (D)
Nassief Eng. & Equip. (M)
TPH Technology (M)

MOBILE TREATMENT SERVICE
Enviro-Logical Solutions, Inc. (D)

MONITORING PACKERS
Aardvark Corporation (M)
A.I.I., L.C. Eng. & Consulting (D)

MONITORING SYSTEMS
Aardvark Corporation (M)
Aaron Environmental (D)
Alternative Envir. Solutions (D, M)
Atlantic Screen & Mfg (M)
Baseline Industries, Inc. (M)
Baski, Inc. (M)
Bioscience Inc. (M)
Canberra (M)
Carbonair Environmental Sys. (M)

CH2M Hill (D)
CHEMetrics, Inc. (D, M)
Chicago Env. Eng. Corp. (D)
Cole-Palmer Instrument Co. (D)
Drilling Equipment Supply, Inc. (D)
Envr. Consultants & Serv. (D)
Envr. Mgmt Consultants.(D)
Environmental Serv. & Products
Gas Tech Inc. (M)
GeoMetrix (M)
GeoProbe Systems (D, M)
Geotechnical Services, Inc. (D)
Global Water
Groundwater Recovery Sys. (M)
H2 Oil Recovery Equip., Inc. (M)
Handex (D)
Hydrotechnics, Inc. (M)
Indust. Envir. Monitoring Inst. (D)
INFICON (M)
Monarch Instrument (M)
Pennsylvania Drilling (D,M)
QED Environmental (M)
Sentry Systems (M)
Salmoisture Equipment (M)
Testwell Instruments (M)
Timco Manufacturing (M)
TPH Technology (M)
TRAK Environmental (D, M)
Tyree Bros. Envir. Serv. (D)
Unidata America (D)
Veeder-Root (M)
Xerxes Corp. (M)

MULTI-LEVEL WELL
COMPLETION
Baski, Inc. (M)

ODOR CONTROL
Biorem Technologies Inc. (M)
Environmental Serv. & Products

OIL SKIMMERS
Abanaki Corp., Oil Skimmer Div. (M)
Altech Industries (D, M)
A.I.I., L.C. Eng. & Consulting (D)
Atlantic Screen & Mfg (M)
BBC International. Inc. (D)
CC EnviroKleen (D)
Clean Environment Equipment (M)
Envr. Mgmt Consultants.(D)
Environmental Management, (D)
EPG Companies, Inc. (D)
Geotechnical Services, Inc. (D)
Groundwater Recovery Sys. (M)
GWMC Consulting, LLC (D)
H2 Oil Recovery Equip., Inc. (M)
Handex (D)
HDC Engineering, Inc.
IMS Envir. Serv. (M)
Lewis Envr. Group (D)
LRC Technologies (D)
McPhee Envir. Supply (D)
McTighe Industries (M)
Nassief Eng. & Equip. (M)
NEEP Systems (M)
Nepco
Page & Kraemer Envir. Serv. (D)
Parker Systems (D)
Purificns Envir. Tech. (M)
QED Environmental (M)
Rain for Rent (D)
RAM Environmental (D)
Remedial Solutions (M)

Remedix Remediation (M)
SBT Group (D)
Soil-Therm Equipment (M)
Soil-Vac (D)
Spill Prev. Containment (D)
Stealth Industries (M)
Texas Incinerator (M)
TPH Technology (M)
Tyree Bros. Envir. Serv. (D)
Water Link Great Lakes (M)
Wilson Environmental (D)
Xerxes Corp. (D)

OXIDIZERS
Airex Corporation (M)
Airnet Technologies, Inc. (M)
A.I.I., L.C. Eng. & Consulting (D)
Alzeta Corporation
Andersen 2000, Inc. (M)
Artesian Environmental (D)
Biotreatment Inc. (D)
Carus Chemical Company (M)
Custom Environmental Serv. (M)
Environmental Management, (D)
EPG Companies, Inc. (M)
Falmouth Products (D, M)
Global Technologies (M)
Groundwater Recovery Sys. (D)
H2 Oil Recovery Equip., Inc. (M)
H&H Ecosystems (D)
Handex (D)
King, Buck Tech. (M)
Landchem, Inc. (D)
LRC Technologies (M)
NEEP Systems (M)
Page & Kraemer Envir. Serv. (D)

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SBT Group (D)
Soil-Therm Equipment (M)
Stealth Industries (M)
Terran Corp. (D)
Texas Incinerator (M)
TPH Technology (D)
West-Tech Supply (D)

PACKERS, DOWN HOLE
Baski, Inc. (M)

PH METERS AND ELECTRODES
A.L.I., L.C. Eng. & Consulting (D)
Biesz, John L. (D)
Carbonair Environmental Sys. (D)
CHEMetrics, Inc. (D, M)
EHS Marketplace.com (D)
Cole-Parmer Instrument Co. (M)
Drilling Equipment Supply, Inc. (D)
EPG Companies, Inc. (D)
Fero Environmental Eng. (D)
Forestry Suppliers (M)
Geotechnical Services, Inc. (D)
Handex (D)
Indust. Envir. Monitoring Inst. (D)
Intek Corp/Rent-Alyzer (D)
IQ Scientific Instruments (M)
Ben Meadows Co. (D)
Nassef Eng. & Equip. (D)
QED Environmental (M)
Tyree Bros. Ehrv. Serv. (D)
West-Tech Supply (D)

PHASE CONVERTERS
A.L.I., L.C. Eng. & Consulting (D)
Carbonair Environmental Sys. (D)
EPG Companies, Inc. (D)
Soil-Therm Equipment (D)

PIPING AND EQUIPMENT
Aardvark Corporation (D)
A.L.I., L.C. Eng. & Consulting (D)
Andersen 2000, Inc. (M)
Atlantic Screen & Mfg (M)
Baker Tanks (D)
Carbonair Environmental Sys. (D)
John P Cummings & Associates
Drilling Equipment Supply, Inc. (D)
Empaco Equipment Corp. (D)
Envir. Mgmt Consultants.(D)
Geotechnical Services, Inc. (D)
H2 Oil Recovery Equip., Inc. (D)
Handex (D)
Hydro-Environmental Tech. (D)
Monoflex (M)
Nepco
Page & Kraemer Envir. Serv. (D)
Rain for Rent (D)
Remedex Remediation (M)
SBT Group (D)
Smith Fiberglass Products (M)
Soil-Therm Equipment (M)
TPH Technology (D)
TRAK Environmental (D)
Tyree Bros. Evir. Serv. (D)
West-Tech Supply (D)

POLUTION CONTROL EQUIPMENT
A&P Inc. (D)
Aaron Environmental (D)
Abakan Corp., Oil Skimmer Div. (M)
AbTech Industries (D, M)
A.L.I., L.C. Eng. & Consulting (M)
Alternative Envir. Solutions (D, M)
Alzeta Corporation (D)
Andersen 2000, Inc. (M)
Biorem Technologies Inc. (M)
Bioremedial Technologies (M)
Bioscience Inc. (M)
Brewer Environmental Serv (D)
Carbon Resources, LLC (D)
Carbonair Environmental Sys. (M)
Chicago Envir. Corp. (D)
Clean Harbors Envir. Services (M)
John P Cummings & Associates
Current Environmental Solutions
Custom Environmental Ser. (M)
Envir. Mgmt Consultants.(D)
EPG Companies, Inc. (M)
GenTec Environmental (M)
Global Technologies (M)
Handex (D)
IMS Envir. Serv. (D)
Indust. Envir. Monitoring Inst. (D)
King, Buck Tech. (M)
LRC Technologies (D)
McPhee Envir. Supply (D)
Mobile Process Tech. (D)
Nassef Eng. & Equip. (M)
NEEPS Systems (M)
Nepco
North American Mfg (M)
Page & Kraemer Envir. Serv. (D)
Parker Systems (M)
Purtics Envir. Tech. (M)
QED Environmental (M)
Sentex Systems (M)
Soil-Therm Equipment (M)
Staht Industries (M)
THP Technology (D)
TRAK Environmental (D)
Tyree Bros. Evir. Serv. (D)
Unipure Environmental (M)
USFilter (D, M)
Water Link Great Lakes (M)

POWER SUPPLY
A.L.I., L.C. Eng. & Consulting (D)
Groundwater Recovery Sys. (M)
Handex (D)
Hydrotechnics, Inc. (D)
Manchev Envr. Corp. (M)
Tyree Bros. Evir. Serv. (D)

PUGMILLS
A.L.I., L.C. Eng. & Consulting (D)
Excel Machinery Ltd. (M)
GenTec Environmental (M)
Mason Industries
Page & Kraemer Envir. Serv. (D)
Pugmill Systems (M)
Rock Systems (M)

PUMPS
Aardvark Corporation (M)
A.L.I., L.C. Eng. & Consulting (D)
Alliance Environmental, Inc. (D)
Alternative Envir. Solutions (D, M)
AquaCare International, Inc. (D)
Atlantic Fluidics, Inc. (M)
Atlantic Screen & Mfg (D)
Baker Tanks (D)
Brewer Environmental Serv (D)
Carbonair Environmental Sys. (D)
Clean Environmental Equipment (M)
Cole-Parmer Instrument Co. (M)
John P Cummings & Associates
Envr. Mgmt Consultants.(D)
Environmental Management. (D)
EPG Companies, Inc. (M)
Fero Environmental Eng. (D)
Forestry Suppliers (M)
Gast Manufacturing, Inc. (M)
Geotechnical Services, Inc. (D)
Gorman-Rupp Co.
Groundwater Recovery Sys. (D)
H2 Oil Recovery Equip., Inc. (D)
Hanex (D)
Hertz Equipment Rental (D)
Hydro-Environmental Tech. (D)
IMS Envir. Serv. (D)
Indust. Envir. Monitoring Inst. (D)
King, Buck Tech. (D)
KVA Analytical (M)
Ben Meadows Co. (D)
Modoflex (M)
Nassef Eng. & Equip. (D)
Nepco
Page & Kraemer Envir. Serv. (D)
QED Environmental (M)
Rain for Rent (D, M)
Remedex Remediation (M)
SBT Group (D)
Soil-Therm Equipment (D)
Spectra Environmental (M)
Thompson Pump & Mfg (M)
Timco Manufacturing (M)
TPH Technology (D)
Tyree Bros. Evir. Serv. (D)
UPAH Tech. (D)

R&D TESTING
Applied Process Eng. Lab

RECYCLING EQUIPMENT
ABB (M)
A.L.I., L.C. Eng. & Cons. (M)
Andersen 2000, Inc. (M)
Excel Machinery Ltd. (M)
GenTec Environmental (M)
Mobile Process Tech. (D)
Nassef Eng. & Equip. (M)
Page & Kraemer Envir. Serv. (D)
Rock Systems (M)
USFilter (D, M)

REMEDATION SYSTEMS
Applied Earth Sciences (M)

ROLL OVER CONTAINERS
Baker Tanks (D)

SAFETY PRODUCTS, EQUIPMENT
A.L.I., L.C. Eng. & Cons. (M)
BioSolve-Westford Chemical (M)
Cole-Parmer Instrument Co. (D)
EHS Marketplace.com (D)
Environmental Management. (D)
Fero Environmental Eng. (D)
Forestry Suppliers (M)
Gas Tech Inc. (M)
Geotechnical Services, Inc. (D)
C.H. Hanson Company (M)
Hertz Equipment Rental (D)
Indust. Envir. Monitoring Inst. (D)
Intek Corp/Rent-Alyzer (D)
K Chem Lab, Inc. (D)
Ben Meadows Co. (D)
O'Brien & Gere (D)
Page & Kraemer Envir. Serv. (D)
Parker Systems (D)
Spill Prev. Containment (D)
Tyree Bros. Evir. Serv. (D)
U.S. Microbes (D)
Zellweger Analytics (M)

SAMPLE CONTAINERS
Quality Envir. Containers (M)

SAMPLERS
Aaron Environmental (D)

A.L.I., L.C. Eng. & Consulting (M)
Alternative Envir. Solutions (M)
Atlantic Screen & Mfg (M)
Brewer Environmental Serv (D)
Clean Environmental Equipment (M)
Clements Associates Inc.
Cole-Parmer Instrument Co. (D)
Custom Environmental Ser. (M)
Drilling Equipment Supply, Inc. (D)
EHS Marketplace.com (D)
Environmental Management. (D)
Fero Environmental Eng. (D)
Forestry Suppliers (M)
Geotechnical Services, Inc. (D)
Global Water
W.L. Gore & Associates, Inc. (M)
GWM Consulting, LLC (D)
IMS Envir. Serv. (D)
Indust. Envir. Monitoring Inst. (D)
Intek Corp/Rent-Alyzer (D)
K Chem Lab, Inc. (D)
KVA Analytical (M)
Ben Meadows Co. (D)
Modoflex (M)
Page & Kraemer Envir. Serv. (D)
Parker Systems (D)
Pennslyvania Drilling (D, M)
QED Environmental (M)
Strategic Diagnostics ( M)
TPH Technology (D)
TRAK Environmental (M)
Truespin (M)
Tyree Bros. Evir. Serv. (D)
Wilks Enterprise (M)

SCRUBBERS
A.L.I., L.C. Eng. & Consulting (D)
Alzeta Corporation
Andersen 2000, Inc. (M)
Biorem Technologies Inc. (M)
Carbonair Environmental Sys. (M)
Clean Harbors Envir. Services (M)
Containment Solutions, Inc. (M)
Custom Environmental Ser. (M)
GenTec Environmental (M)
Global Technologies (M)
SoilPure, Inc. (D)
Soil-Therm Equipment (M)
Stealth Industries (M)
Texas Incinerator (M)

SENSORS
A&P Inc. (D)
A.L.I., L.C. Eng. & Consulting (M)
Baseline Industries, Inc. (M)
Carbonair Environmental Sys. (D, M)
CH2M Hill (D)
Cole-Parmer Instrument Co. (D)
EPG Companies, Inc. (M)
Gas Tech Inc. (M)
Geometrics
Geopex, Ltd (D, M)
Global Water
Groundwater Recovery Sys. (M)
H2 Oil Recovery Equip., Inc. (M)
Hydrotechnics, Inc. (D)
Indust. Envir. Monitoring Inst. (D)
Indust. Scientific Corp. (M)
Ben Meadows Co. (D)
Monarch Instrument (M)
QED Environmental (M)
Testwell Instruments (M)
Transcoil (M)
Tyree Bros. Evir. Serv. (D)
Unidos America (D)

SEPARATORS
A.L.I., L.C. Eng. & Consulting (D)
Andersen 2000, Inc. (M)
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Crude oil is derived from the organic remains of ancient organisms which have been slowly heated within the Earth’s crust. The variety of ancient organisms, e.g., algae, land plants, and bacteria, that had accumulated at different places and times throughout Earth’s history, and the level to which these remains are heated, ultimately yield crude oils with unique chemical ‘signatures’. Comprising these unique signatures are ‘biological markers’ or ‘biomarkers’, def., organic compounds in petroleum whose chemical structure can be unequivocally linked to a naturally-occurring biochemical. The degree of this similarity is demonstrated in Fig. 1 which shows the chemical structures of a common biomarker, cholestanol, and its well-known precursor, cholesterol.

Petroleum chemists involved in the exploration and production of crude oil have long made use of biomarkers, e.g., to determine if two crude oil reservoirs contain the same crude oil and are likely to be ‘connected’.

The use of biomarkers in environmental forensic problems has been slow to follow. However, the knowledgeable investigator will quickly grasp the utility of biomarkers in certain environmental forensic problems. For example, if different crude oils contain unique biomarkers or biomarker patterns, then the petroleum products refined from these crude oils could be similarly unique. In this article various aspects of biomarkers are discussed along with a demonstration of their applicability in environmental forensic investigations.

**Analysis of biomarkers**

The analysis of biomarkers is most easily performed on free phase petroleum contamination. Very small quantities (< 5 ml) of free product, collected in a glass container, is all that is necessary. The analysis of biomarkers in petroleum-impacted soils is also possible following a thorough extraction of the soil. However, in some instances the occurrence of modern, living microbes in soil samples can complicate the interpretation of petroleum-derived biomarkers due to the presence of ‘modern’ biochemicals in the soil’s extract. This shortcoming is easily overcome by an analysis of uncontaminated background soil from the site. Soil extracts are generally ‘cleaned-up’ by alumina column chromatography in order to remove any non-hydrocarbons from the extract. Free phase products and cleaned-up extracts can be further processed (e.g., removal of n-alkanes) or directly analyzed for biomarkers in either a qualitative or quantitative fashion, depending on the application.

The analysis of all but the simplest biomarkers (e.g., pristane and phytane) requires use of a gas chromatograph-mass spectrometer (GC/MS). This analysis is generally performed in a selected ion monitoring (SIM) mode in order to increase sensitivity. The ‘output’ from this type of GC/MS-SIM analysis is a series of mass chromatograms, each one representing a different group of related biomarkers with similar chemical structures. Each mass chromatogram serves as a ‘fingerprint’ for that particular sample. A single GC/MS-SIM analysis can produce numerous diagnostic fingerprints which represent the biomarkers in a single sample. In an environmental forensic investigation the biomarker fingerprints between samples are compared as any other, more conventional types of fingerprints would be compared. Naturally, since the story often lies in the details, a familiarity with biomarkers is necessary to determine what differences are meaningful.

**Diversity of biomarkers**

There are three commonly used biomarker classes (Table 1). The simplest class are the acyclic isoprenoids. This class includes the ubiquitous C19 and C20 isoprenoids, pristane (Pr) and phytane (Ph), which are readily recognized in most gas chromatographic-flame ionization detector (GC/FID) fingerprints. These and other acyclic isoprenoids are thought to be derived from chlorophyll and therefore, occur in nearly every petroleum. The ratio of Pr/Ph is dependent upon the degree of oxidation in the petroleum source rock and therefore, this simple ratio can distinguish among some forms of petroleum contamination.

The biomarker classes most commonly used in forensic investigations are the terpanes and steranes. The terpane class includes numerous groups of biomarkers derived from a variety of land plant- and microbe-derived organic matter. The latter includes the pentacyclic triterpanes known as ‘hopanes’. A large number of C27-C35 hopanes are ubiquitous in crude oils and their specific distributions allows for their use in correlating some fugitive petroleum contamination with suspected crude oil or petroleum product source materials. Fig. 2 shows the distributions of hopanes (i.e., a m/z 191 mass chromatogram) obtained from fugitive oil slick and a suspected source Bunker C.
fuel. Distinct differences in the distribution of hopanes, differences which cannot be attributed to weathering (see below), argues that the oil slick was not derived from this particular Bunker C.

Steranes are biomarkers derived from sterols (Fig. 1). Sterols occur in nearly all living creatures but their distribution varies widely, and they are highly sensitive to thermal conditions in the subsurface. This results in different crude oils having distinct sterane distributions. The concentration of certain steranes can be used to compare petroleum contamination with suspected sources. Ternary plots of these data provide a powerful comparative tool (Fig. 3).

The high molecular weight of hopanes and steranes limits their applicability to fugitive materials containing high boiling fractions (e.g., crude oil, lubricating oils, or heavy fuel oils). Contamination stemming from middle distillate fuels are often devoid of these particular biomarkers and therefore, alternative biomarkers must be utilized in assessing sources of this type of contamination. Some candidate 'low boiling' biomarkers include the sesquiterpanes, diterpenoids, and extended tricyclic terpanes (Table 1). These low boiling biomarkers will be discussed in a future Environmental Forensics column.

**Resistance to weathering**

Any comparison between a fugitive contaminant and a suspected source must consider the question, 'how has weathering affected the biomarker patterns?'. The volatility and aqueous solubility of most biomarkers are extremely low. Thus, any changes in their concentrations and distributions in petroleum-derived contamination are primarily the result of biodegradation. Biodegradation of the hydrocarbons in crude oil and petroleum products following their release into the environment occurs in a well-known pseudo-stepwise sequence. (See Aug./Sept. 1998 Environmental Forensics column.) The generalized sequence of susceptibility is n-alkanes > acyclic isoprenoids > steranes > hopanes > aromatic steranes. Thus, the biomarkers are among the most degradation-resistant hydrocarbons which occur in crude oil and petroleum products. This makes them particularly useful in 'fingerprinting' severely weathered forms of contamination.

The rate at which biodegradation proceeds is highly site-specific. In the human time-scale (~decades) over which environmental forensics issues arise biodegradation is generally very slow. As a result the susceptibility sequence described above rarely includes biodegradation of the sterane or hopane biomarkers. However, caution is sometimes warranted in assessing levels of biodegradation since many crude oils are significantly biodegraded long before they ever reach the refinery or are accidentally released into the environment. If conditions permit, biodegradation of crude oils can occur in their subsurface or near-surface reservoir on

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### Table 1: Common biomarkers and the mass/charge ratio used to 'fingerprint' them.

<table>
<thead>
<tr>
<th>Class or Group</th>
<th>Mass/Charge</th>
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<td>triaromatic steranes</td>
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</tbody>
</table>

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**Figure 3:** Ternary plot showing sterane distributions in tar balls versus suspected source oils. [20S- and 20R- isomers of the 5α(H), 14β(H), 17β(H)-C_{27}, C_{28}, and C_{29} regular steranes obtained from a m/z 218 mass chromatogram]

**Summary**

The specificity, diversity, complexity, and resistance to weathering make biomarkers extremely useful in identifying the source(s) of fugitive crude oils and refined petroleum products released in the environment. Qualitative or quantitative analysis of biomarkers is readily achieved on both free phase contamination and impacted soils. Biomarkers should play an important role in determining liability and allocating costs for spill cleanup and damages.

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**Figure 2:** Hopane fingerprints (m/z 191) for a fugitive oil slick and its suspected source. Different T_{S}/T_{M} ratios and abundances of C_{35} hopanes indicates a *negative* correlation.

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Red soil is all I see. The soil on which the University of Zimbabwe is built is a typical tropical red soil. It is red because of iron left behind during the weathering process. Harare, where the University is located, receives 1000 to 1200 mm (39 to 47 inches) of rain a year. This year is unusual in that we have gotten that much and more rain since January. Because of the altitude the temperature never gets too hot, but then again it never gets below freezing for very long, and the soil never freezes. This type of climate leads to intense weathering of soil parent material.

The parent material from which the soil is forming is an interesting story in and of itself. One of the common images in Zimbabwe is that of the balancing rock. Common enough to be on the Zim 20 dollar bill. When one tours Zimbabwe one sees these incredible granite rocks sitting on the land as if they are dropped playthings of some giant. These rocks are resistant to degradation and are thus left on the soil surface as the soil forms around them. Decomposed granite is the major source of parent material from which the soils of Zimbabwe form.

In the soil profile of the red soil the A, or horizon surface has a clay content around 45% while the B horizons have clay contents around 65%. Looking at the textural triangle below both the surface and subsurface soil textures would be clay. They do not have enough sand or silt to make them a sandy or a silty clay. Our expectation would be that these soils would have very slow water infiltration and be hard to work. Neither is true.

The clay is kaolinite. It is the least active silicate clay and is left when the other, more active silicate clays, have been decomposed. It does not shrink nor swell. The iron which is present is even more resistant to decomposition than kaolinite. Iron and organic matter in the soil result in the formation of good soil structure which is water stable. Soil structure or peds result from the cementing together of sand silt and clay particles to form larger structures. Good structure results in the formation of large pores which allow rapid infiltration and percolation of water through soil.

Thus in spite of what we might expect, these red soils have high water infiltration and percolation rates. The rates are as high or higher than those of sandy soils. The lesson here is that it is not sufficient to know that the soil contains clay. The type of clay and other components, such as iron and organic matter, may dramatically alter the characteristics of the soil. Thus one must know the type of clay and the type and water stability of soil peds to understand water movement in a soil.

At the other extreme there are the black Vertisols which occur in some parts of Zimbabwe. These are soils that have a large amount of smectite clay in the profile. This clay has tremendous shrink swell characteristics. When dry, these soils have cracks 1 m deep and 30 cm wide at the surface. On wetting, the cracks swell shut and seal the surface. Wet Vertisols have percolation rates in the range of 1 cm per 24 hours. Thus it would take 30 days for water or a pollutant to move 30 cm deep in the profile. As a consequence, once a pollutant gets into this soil it is not feasible to remove it by leaching.

An additional interesting characteristic of Vertisols is their water holding capacity. They hold large quantities of water even when dry. When a Vertisol is as dry as it can get by air drying, it will still contain 15% water on a dry weight bases. Thus, a 100 g sample of air dry Vertisol would contain 85 g of solid matter, and 15 g of water. Vertisols are important agricultural soils particularly for growing sugarcane. Keeping them free of pollutants is important. The most common pollutant is not industrial but is residual salt left after irrigation. Irrigation must be practiced carefully to prevent salt build up. The only way to remove salt is by washing it off the soil surface. Very slow percolation rates make leaching and subsurface drainage impossible.

The third major soil type in Zimbabwe is the acidic sandy soil. These soils have low clay, iron, and organic matter contents, which means that not only does the soil not hold water or plant nutrients, it also will not hold pollutants. They are thus light in color and not productive of agricultural crops. These are the soils that are common in the communal areas. The areas to which most of the black population has been relegated.

The sandy soils are coarse with significant amounts of gravel. Gravel particles are greater than 2.0 mm in average diameter. Because of the coarse soil texture water infiltration and percolation is very rapid. It is thus easy to have contamination of water by agricultural chemicals including fertilizers. In addition any chemicals spilled on these soils are likely to leach into the underlying water table. Thus, these soils are suitable for neither agricultural nor industrial purposes. The management of the red soils is rather easy. The management of the Vertisols and the acid sandy soils is not.

A major source of industrial pollution in Zimbabwe takes the form of acids and other undesirable products.
released as a result of mining operations. Perhaps the most important is the acid produced in the mine spoils from coal mining. There has been some research to determine the best methods of reclaiming these spoils such that plants, particularly trees, will grow on them. Perhaps the best solution to date is to cover the spoils with top soil and plant trees. The topsoil provides a rooting medium for trees and other vegetation, protects the spoils from erosion and limits percolation of water through it into water supplies.

The soils of Zimbabwe make the case for the importance of knowing the soil. It is not sufficient to assume that by knowing a few general characteristics of a soil, such as clay content, that all the characteristics of the soil are known. Also it is not sufficient to know a few general characteristics of the geology or climate. One must know the specifics of clay type, other minerals and organic matter present if one is to predict how the soil will act when it is contaminated.
Deep well groundwater monitoring
Blackhawk Environmental Company, Glen Ellyn, Ill., announces the Anchor Piston Pump for monitoring groundwater in small diameter wells up to 700 feet deep. The positive displacement pump uses an active recovery process that draws liquid or product from a specified depth at a specified rate. The Anchor Piston Pump can operate using pneumatic or electric power, can be installed vertically or horizontally and operate when the well is wet or dry.

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Mobile oil removal
Biomin Inc., Ferndale, Mich., offers a mobile oil removal system. A canister is filled with the company's specially formulated organoclay EC-100 to remove oil and other low solubility organic hydrocarbons from water.

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TPH test kit

AZUR Environmental, Carlsbad, Calif., offer the Remediaid Test Kit as a fast and reliable TPH testing system. The kit is designed for on-site soil remediation surveys as well as testing for spillage and leakage anywhere petroleum hydrocarbon contamination is an issue.

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Hydrocarbon recovery pump controller

QED Environmental Systems, Ann Arbor, Mich., introduces the new C100 Digital Controller. The device improves recovery of floating hydrocarbons without pumping water. The C100 allows the user to match recovery system performance to specific hydrocarbon properties and site conditions.

Write in 819

Practice PE exams

Professional Publications Inc., Belmont, Calif., announces the publication of Environmental Engineering Practice PE Exams. Designed as a study guide for the environmental Professional Engineer licensing exam, the book offers three complete mock exams.

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Continues on page 64 ➔

Laboratory meters for pH

WTW Measurement Systems Inc., Ft. Myers, Fla., introduces the new inoLab series of laboratory meters for measuring pH/mV, ORP, ISE, temperature, dissolved oxygen conductivity or salinity. The instruments are offered in three configuration levels to meet various application requirements.

Write in 820

Remediation of pesticides

Harding Lawson Associates, Knoxville, Tenn., announces a new bioremediation technology called Xenorem to treat soils contaminated with pesticides. Test results show concentrations of a wide range of pesticides can be reduced to levels acceptable to regulators. Remediated pesticides include DDT, toxaphene, endrin, chlordane, BHCs and several others. Tests show as much as a 97% reduction is possible for this broad range of contaminants.

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Soil & Groundwater Cleanup June/July 1999 63
Soil gas and groundwater sampling
Timco Manufacturing Inc., Prairie du Sac, Wisc., introduces the StrataSampler, a device that will allow for the collection of soil gas and groundwater samples from multiple depths within a single borehole. The StrataSampler threads directly to the well casing, and consists of a slotted chamber used to collect samples that are brought to the surface via tubing.

Water analysis product line
CHEMetrics, Calverton, Va., announces the Molybdate Water Analysis test kit. The patented, self filling ampoule contains a unit dose of liquid reagent sealed under vacuum, which eliminates the need to measure and mix chemicals, simplifies testing and virtually eliminates reagent spoilage.

3-D imaging technology
Vermeer Manufacturing Company, Pella, Iowa, has enhanced a utility contractor's ability to identify and locate subsurface obstacles with new developments in three-dimensional imaging technology. The company introduced the Terravision™ Ground Penetrating Radar System, a high resolution system designed to transfer GPR signals into 3-D blocks of data.

Water level instrument
Unidata America, Lake Oswego, Ore., offers the Model 6541 Precision Water Level Instrument. The device has an accuracy and resolution of up to 0.2mm.

Soil probing unit
Geoprobe® Systems, Salina, Kan., offers the Model 54DT soil probing unit. This track-mounted system was designed for site investigation in tight, congested areas and rough terrain.

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Portable spectroradiometer
Analytical Spectral Devices Inc., Boulder, Colo., has introduced the FieldSpec® JR spectroradiometer. The device provides a broader base of user access to a portable and versatile spectroradiometer for remote sensing needs.

Unattended monitoring of water
In-Situ Inc., Laramie, Wyo., offers the Multi-Parameter TROLL 8000 for unattended monitoring of water quality. The MP TROLL can measure and record pH, conductivity, dissolved oxygen, pressure, temperature and ORP.
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Soil & Groundwater Cleanup June/July 1999 65
The International Journal of Phytoremediation — CRC’s international, peer-reviewed, multidisciplinary quarterly — keeps you abreast of all the latest innovations in this swiftly developing field. Turn to the International Journal of Phytoremediation to learn:

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