Investigation of subsurface sites before and after disposal of hazardous waste is a new and growing field for oilfield technology. Whether the problem is identifying and monitoring contaminated layers in the subsurface or characterizing a potential waste repository, techniques designed for hydrocarbon exploration and production are finding applications in a new environment.

Keeping the Earth’s ecosystem a safe and healthy place to live and work is a challenge today and will remain so into the 21st century. For thousands of years, humanity has sought protection from natural hazards and defense against predators and foes. Ironically, some activities designed to provide such protection—the energy, defense and medical industries—also threaten us with another danger: hazardous and radioactive waste. To safeguard against unnecessary exposure to these wastes, governments now regulate the treatment, disposal and storage of industrial leftovers. A whole new industry, for management of environmental protection, has sprung up to defy this new danger with technologies tailored to the specific substances and hydrogeological settings in question.

The goals of environmental management are many: to minimize generation of and exposure to hazardous waste; to dispose of waste in a manner that meets government regulations and community standards; and to assess, monitor and remediate damage caused by disposal gone awry. Several disciplines, including agriculture, soil and groundwater engineering, and hydrocarbon exploration and production (E&P), are contributing measurement methods, modeling, and treatment and containment technologies to achieve these goals. This article examines how oilfield technologies are helping to identify and characterize zones where waste or other substances have accumulated after leakage or disposal and to assess potential subsurface repositories for hazardous and radioactive waste. (For definitions of types of waste see “Hazardous Waste and Radiation Basics,” page 48.)

Successful application of oilfield technology for disposal site characterization and monitoring is based on understanding the differences and similarities between the E&P industry and the environmental management industry. The most significant difference is in the economic incentives in the two fields. In the oil industry, the driving force behind use of technology is increased oil recovery, leading to increased profits. In contrast, in environmental management the driver is cost-effective protection of people and the environment in compliance with government regulations. In the latter case, simple, inexpensive technologies are usually chosen over sophisticated, expensive ones. Soil and groundwater samples are more routine data sources than borehole logs; in some environmental management firms “logging” is a term generally associated with forestry, not with boreholes.

In spite of the emphasis on low-cost solutions, the environmental management industry worldwide has annual revenues estimated at $250 billion. Demonstrating the value of E&P technologies is a first step to ensuring that site evaluation and restoration efforts harness the most effective technologies available.

The main similarity between the oilfield and environmental management industries is the need to describe subsurface fluid behavior through cost-effective technologies (next page). This implies accurate
Characterization of soil, rock and fluids for managing environmental protection. As in the oil field, description of subsurface layers and prediction of fluid movement require cost-effective technologies.
measurement of fluid constituents and prediction of their movement with time. Other similarities—such as the actions taken to mobilize, extract or contain fluids—depend on the disposition of fluids and the desired results. In the oil field, the goal is to extract the maximum percentage of hydrocarbons while keeping injected or connate water away from producing wells. In the arena of waste disposal, characterization is required for design of repositories, so that hazardous materials are kept out of aquifers and reservoirs that may communicate with the surface ecosystem. Whenever water supplies are threatened to unacceptable levels, action is necessary to extract, treat or isolate the contaminants.

In both industries, characterization of the subsurface is essential. The following case studies show how technologies designed for understanding hydrocarbon reservoirs are being advanced to address this need.

**Hanford Site, Washington State, USA**

An example of successful application of E&P technology for environmental management is the delineation and monitoring of radioactive and hazardous wastes in the sedimentary layers below the Hanford Site in Washington, managed by the US Department of Energy (DOE) in the northwestern USA.

Built on the banks of the Columbia River in the 1940s, Hanford is the site of the world’s first full-scale nuclear reactor and spent-fuel reprocessing plant, designed to produce plutonium (\(^{239}\)Pu) for atomic weapons ([above right]). The location was chosen for its remoteness, ease of defense, mild climate, ample supply of electricity and availability of water for cooling the reaction process.

Plutonium was produced at Hanford from 1944 to 1987. At one time up to nine reactors and five reprocessing plants were active at the site. All are still present, though inactive and scheduled for decontamination and decommissioning. High-level radioactive waste from the plutonium extraction chemical separation process, or reprocessing, was placed in single- and double-shelled carbon-steel tanks ([below]). The tanks were encased in cement and buried in “tank farms” located on the Hanford site central plateau, approximately 10 miles [16 km] west of the Columbia River and about 200 ft
[60 m] above the water table. Tank waste includes about 250,000 metric tons of mostly sodium nitrite and nitrate plus 215 million Curies of mostly cesium (\(^{137}\text{Cs}\)) and strontium (\(^{90}\text{Sr}\)) and smaller quantities of various metal hydroxides. With time, however, 67 of the 149 single-shelled tanks (none of the 28 double-shelled tanks) have leaked or are suspected to have leaked. It is now the responsibility of the US DOE to clean up the site, and the DOE has awarded the environmental restoration contract to Bechtel Hanford Inc. This contract includes cleanup of groundwater and soil and decommissioning of surplus facilities.

If the exact locations of leaked contaminants are not known, they must be identified cost-effectively before restoration is undertaken. Though several large plumes of contaminated groundwater exist beneath Hanford, most of the waste intentionally or unintentionally released into the subsurface remains in the vadose zone—the partially saturated layers above the water table. Observation boreholes drilled in the tank farms and surrounding areas are air-filled and steel-cased with no cement and no rathole. They occasionally contain radioactive contamination. Ordinary cased-hole logging tools and interpretation techniques are ineffective in this environment. Under a cooperative research and development agreement (CRADA)—initiated and funded by the Department of Energy—with groups at the Hanford site, Schlumberger modified existing wireline logging tools and conducted extensive computer and laboratory modeling to calibrate tool responses to the unique operating conditions.\(^1\)

Data quality objectives (DQOs) were established for each of the measurements, based on requirements set by a CRADA committee consisting of data users, technology providers, state and federal regulatory agency representatives and service company representatives. For natural gamma measurements, the DQOs included operation in high-level radioactive fields and identification of man-made radioisotopes of cobalt (\(^{60}\text{Co}\)) and cesium (\(^{137}\text{Cs}\)) in addition to naturally occurring radioisotopes thorium (Th), uranium (U) and potassium (K) measured during oilwell logging. All concentrations were to be reported in picocuries per gram (pCi/g).

To achieve these objectives, the Hostile Natural Gamma Ray Sonde (HNGS), which measures the energy of incident gamma rays with two scintillation detectors, was adapted to allow interpretation of high levels of radioactivity and man-made isotopes.\(^2\) This required modifications to the tool gain regulation system and new methods for constructing elemental standards for calibration. No \(^{60}\text{Co}\)- or \(^{137}\text{Cs}\)-rich test formations or API test pits were available, as are used for Th, U and K. Calibration was achieved through measurements in scaled models of field conditions built in a laboratory and combined with Monte Carlo simulations for normalization. The sonde was also turned upside down so that the detectors—now 4 ft [1.3 m] from the bottom instead of 40 ft [13 m]—could log more of the borehole. Acceptable comparisons are found between HNGS-logged values and radioactivity of samples evaluated in the laboratory (top).

An additional objective of the CRADA was to measure formation moisture. Without human intervention or natural disturbance, such as earthquakes, waste is assumed to stay where it is placed, discharged or leaked as long as it is not dispersed by fluid flow. If

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liquid, or moisture, is not present, contaminants are immobile, and so less likely to move away from the site. The DQO set accuracy standards for measuring moisture in formations of up to 40% porosity with 12.5%, 30% and 50% of the porosity filled with water. Standards were also set for measurements in beds of different thicknesses and through different casing size. The Accelerator Porosity Sonde (APS), a neutron porosity tool that emits neutrons and detects them again after they have interacted with hydrogen in the formation, was chosen.3

No calibration standards existed for logging moisture content, so these had to be designed and built. By carefully mixing dry pure-quartz sand, SiO2, and aluminum trihydrate, Al(OH)3—a dry material containing a known amount of equivalent bound water—and presettling the mixes on vibrating tables, well understood moisture models were created.4 Precision and accuracy of the moisture measurements were demonstrated to meet or exceed required specifications in tests on the specially designed calibration standards.

The natural gamma and moisture measurements were successful, so the CRADA was extended to develop a through-casing density measurement for porosity determination. The Litho-Density Sonde, an openhole density tool, was altered for this purpose. This

### Hazardous Waste and Radiation Basics

Every country uses different terminology to categorize hazardous waste, but the two main types contrasted here are nonradioactive and radioactive. Nonradioactive hazardous waste means chemicals and materials that are toxic, corrosive, reactive or ignitable. These may include hydrocarbons, explosives, asbestos, metals, solvents, medical wastes, pesticides and polychlorinated biphenyls—PCBs. In the groundwater, many of these contaminants are considered hazardous at levels several parts per billion (ppb). In the US, for example, groundwater limits in ppb are 0.5 for PCBs, 5 for benzene, 5 for carbon tetrachloride and 15 for lead. Limits in soil may be different.

Within the radioactive waste category, there may be further distinctions depending on the concentration levels of radioactive material and the half-life of the radionuclides. Low-level radioactive waste, such as clothing, equipment and soil contaminated with minute concentrations of radioactivity, or medical and oilfield tracers that decay rapidly with time, constitute the largest volume of radioactive waste. These wastes are generally considered safe if stored in the shallow subsurface. High-level radioactive waste, such as spent fuel from nuclear reactors, must be isolated from the surface for thousands of years.

Standards of isolation differ from country to country. In the United States, the Environmental Protection Agency standards state that a high-level waste repository may pose no greater risk than unmined uranium ore from which the high-level waste was produced.1

#### Radiation Basics

The four principal types of nuclear radiation are alpha particles, beta particles, gamma rays and neutrons. Alpha and beta particles are both charged, so they are easily stopped by electrostatic forces in matter. An alpha particle is a helium atom nucleus, and can be stopped by paper, clothing or skin. Beta particles—high-energy electrons—can be stopped by a thin sheet of metal or wood, but will penetrate water or skin. Gamma rays and neutrons are highly penetrating and require dense shields, such as lead or thick concrete. Natural radiation from the sun and earth makes up about 82% of the average person’s exposure to radiation. The rest typically comes from medical sources, such as X-rays.2

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density logging sonde irradiates formations with medium-energy gamma rays that collide with electrons in the formation. With each collision, a gamma ray loses some of its energy and continues. The reduced-energy gamma rays that reach the detector are counted as an indication of the electron density of the formation.

The Litho-Density algorithm for measuring density was calibrated to compensate for casing and the air gap between casing and formation, since there is no annular fill material in the Hanford holes. Laboratory experiments were conducted at the Schlumberger Environmental Effects Calibration Facility in Houston, Texas, USA to verify that the new algorithm performed within the data quality objectives set by the CRADA committee.

The modified measurement techniques have been run commercially in 75 boreholes at Hanford, including an injection experiment designed to predict subsurface transport models (previous page).3 Radioactive tracers $^{134}$Cs and strontium ($^{85}$Sr) were injected in a central well in 1980. These are short-lived isotopes of the same elements whose long-lived isotopes, $^{137}$Cs and $^{90}$Sr, have contaminated portions of the Hanford subsurface.6 In 1995, the three modified nuclear probes were run in eight holes along a transect of the injection test volume (right). Density logs from the Litho-Density tool chart the natural sedimentary layering of the shallow unconsolidated formation. Gamma ray logs from the HNGS show the same layering, as well as the anomalously high levels of $^{134}$Cs radioactivity near the injection well. Moisture logs from the APS show no anomaly associated with tracer injection.

The logging was able to locate the 15-year-old cesium plume and verify that the only detectable $^{134}$Cs remaining from the injection was located near the injection point. No strontium was detected. During the 15 years since the injection, $^{85}$Sr had


6. The half-life of $^{134}$Cs is 2.06 years and that of $^{85}$Sr is 64.8 days—short compared to 30.2 years for $^{137}$Cs and 27.7 years for $^{90}$Sr.
decayed to less than 0.01% of the original amount, and 134Cs to less than 1%. The fact that after 15 years Cs was detected only near the injection point is an indication of the high sorption potential in the sediments.

In another part of the Hanford facility, at the N reactor site near the river, Bechtel Hanford has recently completed a limited field investigation of two radioactive liquid waste disposal facilities (LWDFs). An LWDF is an engineered soil-column waste disposal system designed for reactor effluent disposal. Starting in 1963, demineralized Columbia River cooling water was run through the N reactor. Sometimes the cooling water became contaminated with radioactive waste products. This water was discharged into LWDFs up to millions of gallons per day. From there it percolated through surface layers, and most of the contaminants were retained in the soil column. Tritium and strontium were among those contaminants that reached the groundwater and eventually contaminated some river bank seeps known as the N-springs. A second facility was constructed farther from the river in 1985, but contamination in the groundwater and N-springs remained. Currently a "pump and treat" process has been implemented to protect the Columbia River from contaminant migration. Contaminants are pumped, or extracted, for treatment at the surface. Bechtel and Battelle Pacific Northwest National Laboratory (PNNL) are investigating permeable barriers for long-term protection of the river (see "Containing Contaminants," next page).

To design a remediation program, Bechtel must locate and quantify the volume of contaminated soil and groundwater in a cost-effective way. Usually, subsurface samples are collected and analyzed to help characterize the contaminated volume. The use of well logs enhances the characterization by giving continuous readings with depth, reduces worker exposure to contaminants, and helps keep costs down. In one area, the cost of a multimillion-dollar characterization program was cut in half by optimizing the drilling and sampling plan and supplementing it with logs.

The logs revealed a highly contaminated zone less than a foot thick (above left). Natural gamma readings taken by the HNGS ran off scale at 200,000 API units at a depth of 10 ft (3m), but the Litho-Density tool delineated the thin contaminated layer.

**Safe Logging at Hanford**

Working near hazardous waste requires precautions and special training to assure worker health and safety. At contaminated sites, access to all areas is highly restricted and monitored (above).

Training required for workers at Hanford and other US environmental management sites includes a 40-hour Occupational Safety and Health Administration course, consisting of instruction on hazardous materials, cardiopulmonary resuscitation and emergency first aid, and training on use of respirators and special personal protective equipment (PPE).

There are four levels of PPE, from A for the most stringent requirements to D for the least. Level D, reminiscent of oilfield operations, requires steel-toed shoes, coveralls, eye protection, gloves and hard-hat. Level C requires chemical-resistant clothing and boots, inner and outer chemical-resistant gloves and a full-face air-purifying mask with specially designed filters to remove anticipated contaminants. For level B, the highest PPE level required at Hanford, impermeable suits and supplied-air respirators are required (next page, top left). The respirators—connected to portable air tanks or to stationary air tanks with umbilicals—are
Dressed for work. Personal protective equipment (PPE) level B is required for this worker lowering a video camera into a hole at Hanford. The worker must be qualified through special safety training to wear a respirator and to operate equipment near hazardous materials.

necessary for work at Hanford where the exact combination of contaminants to be encountered is unknown. Level A, an absolutely impermeable “moon-suit,” is required when there is risk of contaminants that can be absorbed through the skin.

On-site health and radiation protection technologists caution workers on all aspects of job safety. Typically the biggest health risk to Hanford workers is overheating brought on by the cumbersome protective equipment and the high summer temperatures—in excess of 100°F [38°C]. The technologists’ role ranges from reminders about bringing water to drink when it’s hot out and where workers can sit during lunch breaks, to monitoring tools for contamination as they come out of the hole. Any tool found with the smallest amount of contamination is wiped clean, and the contaminated cloth disposed of in an impermeable barrel stored on site.

Field crew at the Schlumberger Wireline & Testing division in Bakersfield, California, USA who work at the Hanford site, and those at the division in Charleston, West Virginia, USA—in preparation for work at the Savannah River site in South Carolina, USA—have completed training required for logging hazardous waste sites.7

(continued on page 54)

7. Savannah River, near Aiken, South Carolina, is a DOE-managed site where tritium was produced.

Current practice for addressing a subsurface volume of liquid hazardous waste, or plume, is to pump and treat the liquid. Once the contaminated liquid is located, it is pumped out and treated to remove or neutralize the contamination. In some cases the treated water is reinjected.

Pumping continues until the incoming liquid is contaminant free, at which point the site may be considered restored—but subject to further monitoring. This process may take years. When contaminants attain parts per billion concentrations, often the process of treatment reaches an asymptotic level.

This technique may have some merit in homogeneous formations, but inhomogeneities—the bane of the oil and gas reservoir—also plague environmental management sites. In an inhomogeneous formation, pumping draws liquid only from high-permeability zones. In cases of large permeability contrast, it can be easier to pump liquid from a high-permeability zone miles away than from a low-permeability zone only a few feet away. Pumping may continue until water comes out clean, but a few months later, monitoring may indicate that the water is contaminated again due to the desorption of contaminants from the soil.

Rather than pumping contaminated liquids to the surface, scientists at Battelle Pacific Northwest National Laboratory (PNNL) are capitalizing on the dispersive nature of the contaminants to do part of the work. Treatment is accomplished by creation of a permeable barrier—also called a permeable reactive wall—to treat the contaminated liquids as they pass through.

Permeable barriers can be constructed by at least two different methods. The first, and simplest, is a ditch filled with gravel or absorbent or chemically reducing material through which waste liquids are drained. Gravel ditches are known as trenches, and typically are used to treat solvent-contaminated shallow groundwater by aeration. Absorbent minerals such as zeolites, which act like “kitty litter,” can trap some specific contaminants. Reducing agents, such as finely ground particles of iron, are sometimes effective for treating some contaminants, especially chromate, uranium and chlorinated solvents. Chemically reducing treatments work by reducing the valence state of the contaminant. This reduction in valence destroys organic contaminants, such as chlorinated solvents, and causes certain metallic contaminants to precipitate, trapping them in the filter.

If the contaminants are already deep below the ground surface, conventional trenching methods will not be able to reach them. Researchers at PNNL are investigating a second category—the injectable permeable barrier—that acts as a subsurface filter to treat spreading contaminated liquids (above). Injectable permeable barriers have...
been tested in the laboratory and in pilot-scale field experiments at Hanford. In addition to absorbent filters and chemical-reducing materials, iron-reducing bacterial treatments—similar to those applied in the oil field to treat sour wells—have been tested.

Laboratory tests conducted on soils reduced by one chemical agent, sodium dithionite, indicate a strong ability to treat chromate-contaminated liquid. Soils treated with dithionite were able to filter up to 120 contaminated pore volumes. A field experiment monitored the same reaction, but at full scale. Dithionite was injected to reduce the iron in a volume of the subsurface, then chromate was injected. Chromate levels were sampled in monitor wells surrounding the injector out to a radius of 90 ft [27 m]. Over the course of more than ten months, in wells monitored within 30 ft [9 m] of the injector, no chromate was detected.

Similar tests are under way for examining the ability of the technique to handle greater time and length scales. A current experiment is using a line of injector wells to treat a 2000-ft [608-m] wide chromate plume, already identified on the Hanford site.

Modeling

Modeling the distribution of fluids and contaminants is a vital part of planning any containment or treatment effort. As in the case of oil and gas reservoirs, small-scale variations in formation properties can have large-scale effects on ultimate fluid distribution.

Scientists at PNNL are simulating fluid and contaminant flow through small but realistically complicated 3D volumes in hopes of understanding flow in larger volumes. A 3D cube representing part of a complexly layered river sand has been constructed based on field observations on a meandering river. Migration of a nonreactive tracer through the cube has been modeled at a series of five time steps. Tracer migration is constrained by low-permeability features in the model volume.

1. For a video rendition see the PNNL web site: http://etd.pnl.gov:2080/EESC_public/vis_examples/scaling/part.mpg
Three-dimensional representation of permeability distribution in a complexly layered river sand. Yellow-green represents high permeability and blue represents low permeability. The small-scale sedimentary features are based on field observations on a meandering river in Indiana, USA. Development of this model is described in Scheibe TD and Freyberg DL: "Use of Sedimentological Information for Geometric Simulation of Natural Porous Media Structure," Water Resources Research 31, no. 12 (1995): 3259-3270.

Simulated nonreactive tracer transport through the 3D model at five different time steps. Tracer particles were released as an instantaneous pulse in a plane at the rear of the cube (white line), and their movement is constrained by the low-permeability layers. Using massively parallel computers and particle-tracking methods, transport was simulated through the model composed of nearly 17 million grid cells. Further description of these studies—including an animation of the particle plume—is available on the world-wide web at: http://etd.pnl.gov:2080/EESC_public/vis_examples/scaling/scaling.html.
Characterization Before Storage

A primary lesson learned from the restoration of sites contaminated with hazardous materials is that future waste storage facilities must be engineered with care. Countries that rely on nuclear energy are taking a hard look at how to manage the inevitable waste products. Most countries plan deep underground repositories, and the search continues for the best locations.

The goal is to isolate hazardous material from the surface for tens of thousands of years—no small task. The subsurface volume selected should be an effective shield, remain tectonically stable, reduce contact of waste with groundwater and air, and contain no useful mineral resources that would tempt human intervention. The storage facility should allow for retrieval of the waste at such time that technologies become available for treatment. Some countries, including Belgium, Finland, France, Germany, Sweden, Switzerland, the UK and the USA have identified locations that appear to have many of the desired qualities.8

In the UK, United Kingdom Nirex Limited (Nirex) is responsible for providing and managing a national facility for underground storage of solid intermediate- and some low-level radioactive waste. Geologic and hydrologic investigations have been in progress around Sellafield in West Cumbria, England since 1989, to determine whether a site adjacent to the existing nuclear establishment is suitable for a deep repository (left).9

Groundwater is the most likely medium by which radioactive waste from a repository could return to the surface. Controls on groundwater flow include driving forces, such as gravity and salinity, and also the geometry of rock units and properties of the rock mass, such as permeability and fracture characteristics.10

The building blocks for the geological site characterization consist of 27 deep boreholes, some down to 1900 m [6200 ft] and the majority with continuous core; 2000 km [1250 miles] of 2D seismic data and 8000 km [5000 miles] of airborne geophysical data. Hydrogeological testing and groundwater sampling provide additional information on flow properties of the volcanic formation targeted for study.

A volume of the Borrowdale Volcanic Group at about 650 m [2133 ft] below sea level, is under consideration as an underground laboratory, or rock characterization facility (RCF). The RCF is being constructed to permit detailed examination and testing of rock at depth before selecting a final repository design and location. Investigations have shown that groundwater flow within the volcanic formations occurs through a limited number of fractures, and current work focuses on characterizing hydrogeologically significant fractures.

Many techniques developed to identify and characterize fractures in the oil field are playing the same role at Sellafield. Integration of several measurements at many scales is essential for determining which fractures are open and connected. At the finest scale, electrical conductivity logs of the borehole

Fracture orientation and aperture visualized with the UBI Ultrasonic Borehole Imager tool. Like thread winding around a spool, ultrasonic scans of the borehole track hole rugosity in detail. In this image, breakouts—stress-related damage in the plane of least horizontal stress—are seen on opposite sides of the borehole.

Borehole acoustic reflection surveys (BARS) for tracking fractures far from the borehole. In this case, sonic-frequency data from a research prototype tool were migrated to obtain reflections of primary (P) waves (left) and converted waves (right). The center of each image corresponds to the wellbore position (yellow). Fractures identified on borehole televiewer images are plotted in black along the borehole.

Fracture orientation and aperture may also be interpreted on borehole scans made by the UBI Ultrasonic Borehole Imager tool. The UBI tool takes 180 transit-time samples around the borehole circumference for every 0.2 in. [0.5 cm] the tool moves uphole. Transit times converted to distance yield an image that looks like a mold of the borehole. Where fractures intersect the borehole, extra rugosity may occur, and the 3D UBI image allows visualization of these geometries. Stress-related borehole damage may also occur in the direction of least horizontal stress and manifest itself as hole enlargement, or breakouts, on opposite sides of the borehole (right). The breakout direction is an important clue to the stress regime present in the Sellafield area.

Looking beyond the wellbore, borehole acoustic reflection surveying (BARS) offers a greater range of penetration for fracture tracking. Similar to surface seismic surveys but recorded in the borehole, this new technique can image fractures extending as far as 30 ft [9 m] away from the borehole (below). In other situations, BARS images

wall, such Formation MicroScanner and FMI Fullbore Formation MicroImager scans, show where fractures intersect boreholes. These borehole images help identify and orient fractures, but may also be combined with other data, such as sonic waveforms, to calculate fracture aperture.11
may be obtained of fractures and other features near but not necessarily intersecting the borehole. These seismic waveform data are acquired with multiple source and receiver arrays on a single tool. For Nirex, BARS data were recorded with a research prototype tool; commercial introduction of the service is scheduled for early 1997.

The signals of interest—those from reflections—arrive after the primary (P) and before the shear (S) waves that are typically analyzed for borehole sonic slowness values (left). Borehole acoustic reflection surveys are processed using seismic data-processing algorithms, and yield both P and S reflections. Shear waves help image features at high angles to the borehole, and are better than P waves at resolving some near-wellbore features.

At a larger length scale, seismic images have been obtained for several pairs of boreholes (below left). Seismic travel-time data are acquired with a downhole seismic source in one borehole and the Cross Well Seismic Imager—an array of 16 hydrophone receivers spaced at 4 m [13 ft]—in the second one. Travel times are processed to yield an image of velocities in the inter-borehole region. Abrupt changes in velocity, represented by changes in color, indicate discontinuities. Combined with other log data, borehole-to-borehole correlations become clear, reinforcing the integrated interpretation (next page). For example, fractures evident in one borehole can be tracked across seismic images, and linked with fracture indicators in neighboring boreholes.

Incorporating flow information is vital to an integrated interpretation. To identify significant fractures, flow tests have been carried out. Testing is conducted while the drilling rig is on location, and with a workover rig after drilling. Long-term monitoring and testing with permanent multpacker systems is continuing in several boreholes (below right). These systems allow liquid samples and pressures to be analyzed at multiple levels in any one borehole with only one tool position.

Hydraulic conductivity of the volcanic formation is typically low, even measured over fractured intervals. Most fractures intersecting boreholes have no detectable flow, but those that do are characterized and related to structural features such as faults. As more data are acquired and interpreted to help build and test conceptual models, scientists at Nirex will improve their understanding of the controls on groundwater flow through the subsurface volume.

Future Efforts
Many challenges await the environmental management industry. Parties responsible for hazardous waste sites and repositories need to be able to make informed decisions. Service providers help by acquiring data and turning them into usable information. The application of wireline logging to site characterization and monitoring pro-

vides a comprehensive body of information and early warning of possible problems. If migration of contaminants is discovered, then there is time for an informed decision on whether to remediate. If the choice is to do nothing—either because the problem isn't severe enough or more time is required to develop the proper technology—the site still must be monitored for regulatory purposes and for continued decision making.

If action is required, adequate characterization of the site is necessary to build conceptual models for simulating treatment and optimizing treatment strategies. During remediation, monitoring can provide valuable feedback that ensures success. And once remediation has been achieved, further monitoring is required. Geophysical logging provides a means for permanent and remote monitoring.

The environmental management industry is growing at different rates in different countries, and changing as it grows. Managing the vast amount of data requires special skills and tools. The rapid pace at which new technologies are introduced leads some environmental managers to predict that the industry is moving toward deferred remediation. Full site characterization—with sensitive detection of contaminant migration before it exceeds regulatory guidelines—allows time for solutions to tough problems to be developed. Regulations also change, usually becoming more stringent and all-embracing. Information from geophysical logging allows the design of environmental management schemes flexible enough to accommodate changes.

Also predicted is a move toward performance-based compliance, in which governments regulate what the end results of compliance and remediation should be, but not how to achieve them. As the industry evolves, environmental management firms will continue to require technologies that solve problems in a cost-effective manner so that decisions can be made in a framework of knowledge. —LS

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Complete set of image data for one pair of boreholes—B2 (left) and B4 (right). Dipmeter stick plots (track 1) indicate apparent dip of identifiable fractures (red sticks). A Formation MicroScanner image (track 2) shows disruptions at depths corresponding to the stick plot. Sonic waveform displays (track 3) plot fracture indicators as breaks in the continuity of vertical color stripes. The event at 650 m in B2 can be tracked across the crosshole seismic image (center) to a similar signal in the sonic display of B4 at 840 m. High-velocity (orange) and low-velocity (blue) zones indicate different lithologies. Linear discontinuities in color may be interpreted as fractures. Intervals in which flow is detected in B2 (blue circles) and B4 (purple circles) are plotted on either side of the cross-well image. Logs for B4 are in the reverse order of those for B2, with the exception of an FMI image in B4 instead of a Formation MicroScanner image.