Battelle, one of the world's largest independent research and development organizations, operates the Pacific Northwest National Laboratory (PNNL) for the U.S. Department of Energy's Office of Science. Through a unique contracting mechanism between Battelle and DOE, companies can access 4,200 staff and more than two million square feet of facilities at the PNNL locations in Richland, Seattle and Sequim, Wash.; Portland, Ore. and Washington, D.C. Battelle has 14,000 staff in more than 100 locations worldwide.

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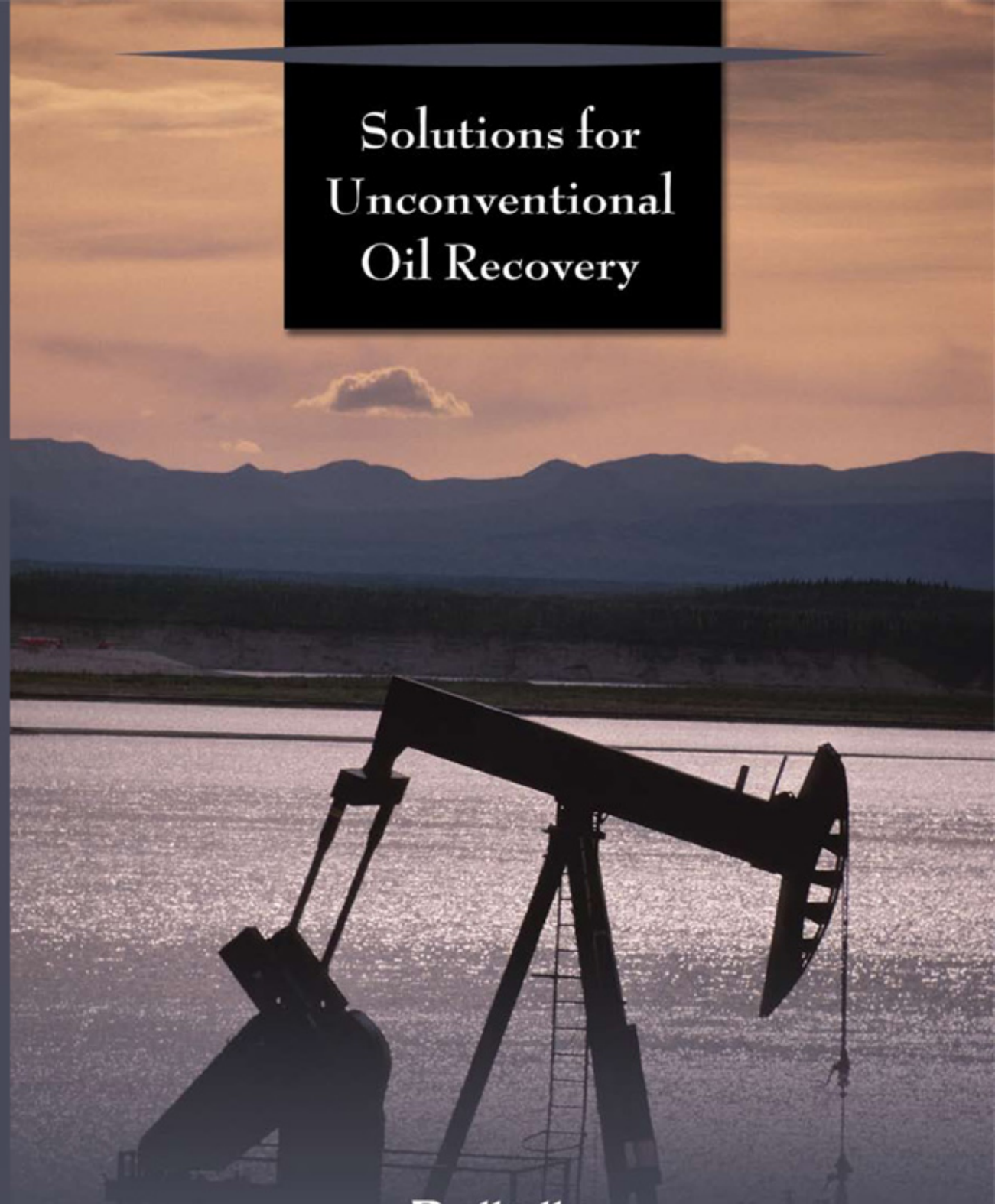
PNNL-SA-52109

Solutions for Unconventional Oil Recovery



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As the price of oil continues to increase and global oil production nears its peak, pursuing unconventional oil supplies, such as oil shale, heavy oil and oil sands becomes increasingly attractive. Of particular significance is that these unconventional resources exist in North America and provide the opportunity to develop cutting-edge technologies for characterization, production, processing and environmental management—allowing the United States to lead in global solutions. Battelle can deliver these breakthroughs.

Battelle offers cutting-edge technology that has the potential to accelerate the economic and environmentally acceptable exploitation of shale and heavy oil recovery making unconventional resources more cost competitive.

Battelle's clients have access to resources and expertise, including nearly 1,500 scientists and engineers at Pacific Northwest National Laboratory located in Richland, Washington. PNNL conducts approximately $100 million in energy-related research each year. Our researchers understand that oil shales are one of the largest untapped hydrocarbon resources in the continental United States and possess the expertise to realize oil recovery from those untapped resources – potentially trillions of barrels of oil.

As the operator of a multi-program national laboratory, Battelle draws upon a wide range of expertise and disciplines to meet advanced research and technology development needs for improving oil recovery from heavy oil, oil sands and shale reservoirs, including:

- Environmental solutions
- Petroleum separation processes
- Pipeline systems
- Fuels and emissions
- Heating and stabilization
- Carbon management
- Stakeholder interactions
- Security and pre-emptive planning
- Power management

Providing environmental solutions through world-class science and management

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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Environmental Solutions

Electrical resistance heating, an award-winning in-ground technology, in use at Fort Lewis.

Extracting petroleum and gas from conventional and unconventional reservoirs naturally creates environmental challenges. Battelle's Pacific Northwest Division (PNWD), which manages the Pacific Northwest National Laboratory in Richland, Washington for the U.S. Department of Energy, is uniquely qualified to mitigate and often preempt these challenges through technical innovation and proactive environmental management. By tapping into our broad spectrum of scientific disciplines and experience, customers can harness Battelle's life-cycle approach to environmental management at strategic and site-specific levels.

Innovative Science

Battelle scientists and engineers conduct cutting-edge research to develop and deploy solutions to address a range of environmental challenges. Our scientists excel in chemistry; geochemistry; hydrology; aquifer control; flow modeling; multi-phase flow in contaminant fate and transport; subsurface media reactive transport; bioremediation; ground water degradation mitigation and management; and ecosystem assessment.

With more than 120 subsurface scientists, PNWD is uniquely positioned to address the constant challenges in subsurface research. Capabilities range from advanced methods for geophysical and physiochemical leak detection to geochemistry, subsurface microbiology, and interfacial and surface chemistry.

Battelle's expertise in terrestrial and aquatic ecology has garnered the Laboratory support roles in environmental projects for large-scale oil and gas production. For example, we are involved in comprehensive environmental and socioeconomic assessments for offshore oil and gas exploration in the Sonda de Campeche region of México. The Laboratory also has performed biological risk and impact assessments of oil well blowouts in Novara, Italy. This was the largest terrestrial remediation effort in Europe.

These and other projects of similar scale utilize Battelle's expertise in fisheries risk-assessment; surface and groundwater quality; air quality/emissions; soil

Paraho oil shale beds.

contamination; effects from flares; biological uptake; benthic communities; application of fate-and-transport models to ecosystem dynamics; cultural/natural resources and environmental compliance.

In addition, Battelle researchers offer world-class numerical simulation capabilities to analyze subsurface flow and transport of contaminants. With leading edge computational resources, one of the world's most powerful supercomputers on Pacific Northwest National Laboratory's campus and undisputed leadership in academic and applied knowledge of hydrology, Battelle can deliver solid solutions for your challenges associated with the development of unconventional hydrocarbons.

Site Management

Battelle manages a number of significant regional projects involving geologic evaluation for natural gas storage, feasibility research for carbon dioxide sequestration in Columbia River basalts, and ongoing groundwater monitoring for the entire Hanford Site. This monitoring project is responsible for tracking ground-water behavior and contaminant plume migration over the entire 540 square mile complex. The analytical support function alone responds to more than 12,000 analytical requests per month. Other high-profile work includes the Waste Treatment Plant Project, one of the world's largest environmental management projects. Battelle's role includes science and engineering support for the high-level nuclear waste vitrification project, the world's largest high-level waste processing plant located at the Hanford Site in Eastern Washington. The project is conducted under the direction of the DOE.

Experience in Achieving Results

Battelle offers a range of capabilities that can be indispensable to the petroleum industry in overcoming regulatory obstacles while achieving business goals. We have a history of coordinating the complex interplay of federal regulations, including the Resource Conservation and Recovery Act (RCRA) and the Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA) as well as state and local statutes.

Our years of experience working with the DOE, the Department of Defense, the Environmental Protection Agency and the Nuclear Regulatory Commission, and our depth of staff and capabilities, give Battelle a unique perspective on managing the National Environmental Policy Act (NEPA) process to timely and successful outcomes. During the entire NEPA process, we worked interactively with the client and stakeholders to formulate optimal solutions. Battelle has the tools and techniques to perform rigorous analysis of the tradeoffs between cost, public risk and stakeholder value.

Maintaining and building our wealth of experience in these areas has allowed us to provide services to a long list of corporate and public stakeholders, including more than four decades of leading environmental management at the Hanford Site. Battelle's consistency in providing best-in-class scientists and engineers to its projects rank the company among the world's most renowned research and development organizations.

Selecting and delivering these technology solutions in an effective and efficient manner is no simple feat. Battelle's systems are mature, effective and demonstrate a reduction in cost through increased efficiency—not just in the near term but over the long term as well.

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PNNL-SA-52148 October 2006

Meeting petroleum separation challenges with leading capabilities

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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Petroleum Separation Processes

The oil and gas industry is currently developing subsurface techniques for extracting usable petroleum from accumulations of shale oil and viscous oil. These techniques generally rely on heat to release petroleum-rich fluids. This results in a complex, sub-surface mixture of water, dissolved salts, rock matter, petroliferous gasses, liquids, and solid/semi-solid material. To extract only the economically-valuable products from these accumulations of oil in an efficient and cost-effective manner is no simple feat. As a partner to ventures designed to exploit these types of augmentations, Battelle offers a significant collection of monitoring, extraction and site management capabilities to meet this challenge.

Paraho above-ground retort.

Above-ground Retorting Experience

Bench-scale retort studies on how process parameters affect oil separation from raw oil shale, spent shale, retort water or off-gas enhance the efficiency of an extraction project. For example, temperature can be monitored at various points with in-line thermocouples, and mass flow meters can be implemented to monitor the production gas flow. Indicators such as these allow the operator to consider process options that may affect the efficiency and safety of production during the different phases of retorting.

Battelle has superior experience and capabilities in developing bench-scale retorts. To gain the maximum business benefit from a separations process, we have developed project-specific systems to best understand the variations in temperature to mobilize and partition elements and matrix them into viable product streams.

Subsurface Retorting Phase Extraction

Battelle's experience working with in situ oil shale retorting processes dates back to the early 1980s during the federal government's prototype land leasing program for oil shale mining activities. At Colorado's Tract C-a Program, the Rio Blanco Oil Shale Company mined a portion of the oil shale (producing different void volumes) prior to blasting and carrying out in situ burns. Battelle then performed on-site real-time off-gas analyses from Rio Blanco's Retort 0 and Retort 1 to help monitor how changing retort conditions affected off-gas production, specifically sulfur- and nitrogen-containing species. These characterizations and comparisons of products, effluents, and wastes were conducted at the Logan Wash, CO and near Vernal, UT sites.

Hydro-Retorting

Hydro-retorting and extraction using supercritical and sub-critical water has important potential applications in the separation and solubility of hydrocarbon compounds from rock reservoirs.

Because of the difficulty of experimentally probing extreme solvent environments, there is a lack of fundamental information in this area. Our expertise and ongoing scientific studies can be leveraged to determine extraction efficiency and to characterize porous media under these extreme conditions. For example, by using XAFS (X-ray Absorption Fine Structure) we have demonstrated a powerful method of determining the local solvent environment around a particular ion and the solvent structure of hydrated species under typical supercritical and sub-critical hydrothermal conditions.

Near Well-head Separations and Management

Battelle's exceptional capabilities in modeling, predicting, and monitoring multi-phase flow through pipelines can be used to optimize project-specific current and changing conditions that occur in traditional separations systems—whether simply oil-water separator applications, or more sophisticated multiphase systems. Coupling these capabilities with our expertise in computational fluid dynamics and above-ground separation facility operators can verify or suggest modifications to improve operational efficiencies. In addition, our chemical engineers can assess downstream separation of extraction products or other upgrading options.

Effective Hydrocarbon Extraction

Using supercritical solvents such as CO_2, ethane or propane, our scientists can extract practically any hydrocarbon compound from porous media characterizing the extraction down to nano-scale pores through the use of our unique facilities for investigating micro-porosity in natural and artificial media at the bench scale. This capability can definitively ascertain the degree to which hydrocarbons have been extracted from source or reservoir rocks, and determine in which size range of pores hydrocarbon compounds remain, or are most resistant to extraction and test the efficacy of extraction methods. Again, applying our computational fluid dynamics capability can yield critical information to reliably design, construct, and operate pilot-scale or full-scale extraction systems.

Systems for infrared, Nuclear Magnetic Resonance (NMR), X-ray fluorescence spectroscopy and for small angle X-ray scattering are used to probe a variety of phenomena including phase behavior, molecular-scale structure, particle aggregation and reaction kinetics at micro and meso-scales. Fundamental studies of reaction chemistry in supercritical fluids, through leveraging our spectroscopy capabilities, can determine the performance and function of modifiers, the solubility of relevant hydrocarbons, the behavior of shale, coal or tar, and the extent of hydrocarbon production.

The knowledge base of membrane separations in liquids and gases is very extensive, but very little work has been done in the supercritical regime. We have designed selective polymer inclusion membrane separation systems for cation separation from complex aqueous media. Membrane-based separations can significantly improve the overall efficiency of existing supercritical processes by eliminating the depressurization step used to effect the separation of the solute from the fluid solvent. This significantly enhances energy efficiency and substantially lowers the costs associated with commercial separation processes.

Waste Water Management & Treatment

Battelle scientists have developed exceptional methods for extracting metals from aqueous or mixed streams capable of removing contaminants at parts per billion concentrations in oil and process water. Our SAMMS (self-assembled monolayers on mesoporous supports) technology extracts mercury and other heavy metals, and the resulting products are stable enough to permit disposal as a non-hazardous waste. SAMMS shows promise for becoming an effective sorbent to separate colloidal mercury from crude oil and to remove contaminants from stack gases.

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PNNL-SA-52150 October 2006

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Improving pipeline performance and integrity with predictive and diagnostic technology

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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Pipeline Systems

Battelle experimental flow loop.

Near-field and in-field product transportation, while very well understood in the traditional oil field, will likely incur more challenges in the unconventional petroleum business. Extraction wells will produce more varied mixtures over time. In addition, the pipeline infrastructure is aging and the integrity must be ensured. Fortunately, Battelle has developed sophisticated system modeling and engineering capabilities that can be used to address the pipeline integrity issues and the ever-changing transportation issues of these varied product mixtures.

Reducing Viscosity for Improved Flow

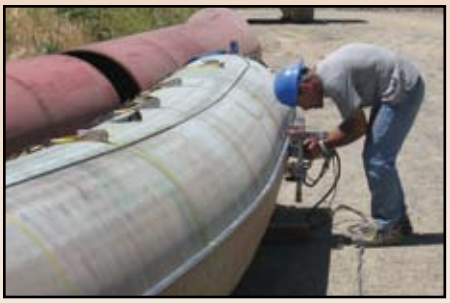
As higher-gravity crudes (lighter oil) become increasingly scarce, operators are looking more to low-gravity crudes (heavy oil) to prop up declining oil output. Recovery of such crudes requires enhanced oil recovery methods to reduce the viscosity of the oil to a point where it will flow from the formation. Beyond the formation, the viscosity of the crude oil needs to be maintained to ensure efficient recovery, especially in cold environments. Battelle is developing an ultrasonic crude oil processing technology that may be useful in maintaining the reduced viscosity states of heavy oils as they flow through transport pipelines.

This technology sonicates the crude oil externally from outside the pipe. Sonication results in the crude product itself being heated and mixed from the inside out. The heat generated by the ultrasonic technology simultaneously maintains the reduced viscosity state of the oil and prevents the deposition of paraffin waxes. The mixing helps keep oil in a semi-single-phase state to prevent the precipitation of other pipeline fouling heavy organic deposits such as asphaltenes.

Pipeline Integrity and Diagnostics

The nation's pipeline infrastructure for oil and gas delivery is aging. There are several types of mechanical damage that can impact pipeline integrity. Battelle has developed novel ultrasonic technologies that measure the strain in damaged pipelines. Our infrastructure monitoring techniques are truly groundbreaking in that we measure strain and residual stress in pipeline structures directly. Some of our applicable capabilities include monitoring for small leaks and direct stress and strain measurements in order to compute remaining life-span of bent, bulged, dented or corroded sections. The strain measurements are critical for meeting the strain-based codes for pipeline operation.

Battelle's sensor technologies have been successfully field tested on pipes with dents, bulges and field bends. The sensor scans the inside and the outside of the pipe and can easily be configured for PIG operations. It can both detect the damaged region and characterize the degree of deformation by providing a measure of



Ultrasonic sensors effectively detect damage to pipelines that can compromise performance and safety.

the effective plastic strain. Excellent for comparisons of pre- and post-deformation comparison and resulting changes in operating strength, the sensor technology is suitable for measuring integrity damage from subsidence, earth movement and wind induced vibration. Field test results indicate that we can measure strains as small as 1-2% with an uncertainty of approximately 1% strain.

Instrumentation used in research experiments has been integrated into online diagnostics for operating equipment. For example, a specialized package of diagnostic instruments has been developed to monitor oil properties in operating diesel locomotives to target maintenance and get early warning of problems. The package includes X-ray fluorescence, non-dispersive infrared and viscometric modules, as well as ferromagnetic and non-ferromagnetic particle detection. Strategies have also been developed to use existing instruments to monitor the onset of pipe plugging and to recover from an off-normal event by re-suspending settled solids.

Predicting Pipeline Performance

The oil industry is facing more complex pipeline hydraulic issues with the shift toward petroleum of lower quality, higher solids content and heavy crudes. Such issues may include the sedimentation of suspended sands, increased pressure losses from increased pump power requirements, fouling, erosion and corrosion. Battelle's research experience and capabilities can help operators evaluate and mitigate these problems—before they happen, using the latest in modeling technologies and predictive sciences.

Our scientists understand the phenomena associated with fluid flow through a long history of experimentation in both single-phase and complex fluid scenarios. For example, we have designed customized flow loops and applied diagnostics to accurately characterize fluid flow. Our work has ranged from fundamental studies of particle-wall interaction to aid in the development of multiphase turbulence models, to variably-inclined loops to understand particle sedimentation behavior.

Models are often used to translate experimental findings to predictions and operational guidance to actual pipeline design. Battelle scientists have implemented models used to maintain fluid velocity above a critical point to prevent sedimentation while minimizing pressure loss. Fundamental physics models are used to gain insight into specific flow problems and to investigate nucleation in waxy crude and buildup on pipeline walls. Reactive flow models are used for understanding hydro processing with catalyzed particulates.

Pipeline erosion and corrosion are addressed from similar experimental and modeling approaches. Coal slurry pipelines have been studied using a rotating pipe loop, and erosion/corrosion studies have been conducted for piping, pipe components, instrumentation, mixing blades, jet pumps and jet impingement.

Battelle can characterize pipeline flow and rheology using real-time process monitoring sensors and monitor the integrity of the infrastructure of the system itself to ensure optimal performance. By characterizing the flow, information can be provided about the nature of the mixtures and distribution of particulates or mixed phases in real time. As a major research and development organization, we have the staff, capabilities and experience necessary to solve the most complex problems facing the oil industry today.

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PNNL-SA-52108 October 2006

Meeting emissions standards by applying state-of-the art characterization and analysis tools

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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Fuels and Emissions

The 2010 heavy-duty diesel emissions standards mandate a 90% reduction in both particulate matter and oxides of nitrogen. To help meet these emissions standards, Battelle's Pacific Northwest Division (PNWD) is applying advanced capabilities in the areas of surface chemistry, catalyst mechanisms, material synthesis, aerosols and modeling—both multiphase flow and chemical processes.

Overhead view of the Exhaust Emissions Science Laboratory.

Fuels and Lubricants

PNWD, located on the campus of Pacific Northwest National Laboratory (PNNL) in Richland, Wash., maintains a state-of-the-art petroleum and fuels characterization laboratory with a full array of chemical analysis instrumentation and physical property measurement capabilities. PNNL offers unique fuel fingerprinting and statistical-based pattern matching technologies that are used to identify and compare fuels. Fuel forensics are applied to link fuel to source and to determine abnormalities associated with source or composition. Major chemical characterization capabilities include:

- High resolution gas chromatography with flame ionization, nitrogen-phosphorous, electron capture and mass spectrometry detection; liquid chromatography with refractive index, UV/Vis, and mass spectrometry (electrospray ionization, atmospheric pressure chemical ionization, atmospheric pressure photoionization) detection
- Fourier transform infrared spectroscopy with attenuated total reflectance, flow cell, and microscope sampling and Raman spectroscopy
- High-speed two-dimensional gas chromatography with time-of-flight mass spectrometry, and inductively-coupled plasma mass spectrometry
- Low level sulfur detection via both X-ray and UV fluorescence
- Automated solid-phase extraction
- UV/Vis spectrophotometry

Physical property characterization includes all American Society for Testing Materials methods needed to characterize diesel and biodiesel to meet ASTM specifications listed in D975 and D6751, respectively. Examples include: simulated distillation; determination of flash, cloud, pour, and freeze points; correlated cetane number and cetane index; correlated octane number; carbon residue and Ramsbottom carbon residue; free and total glycerine; acid number; copper strip corrosion; sulfated ash; and water and sediment.

Emissions—Exhaustive Capabilities

PNNL's Exhaust Emissions Science Laboratory (EESL) is a research center intended to support the DOE's FreedomCAR and Vehicle Technology Programs. The principal activities conducted in the EESL include: probing and understanding performance-limiting nanometer to micrometer scale phenomena in after-treatment devices; experimentation and modeling focused on mesoscale aspects of emissions reduction technology; the use of unique analytical observatories to characterize each emissions phenomenon; rapid materials innovation and evaluation of parameters specific to each after-treatment approach; and the use of an integrated approach covering mechanism investigation, modeling, and materials/system optimization, leading to validation in engine/dynamometer tests.

At EESL, Battelle researchers apply expert capabilities in the areas of surface chemistry, catalyst mechanisms, models, material synthesis, and aerosols to the problem of diesel engine exhaust emissions abatement. The facility is home to a variety of instruments, including: chassis dynamometer; engine dynamometer; Fourier transform infrared spectroscopy; gas chromatograph; scanning mobility particle sizer; electrical low pressure impactor; NOx analysis (Ecophysics); thermography; and various data acquisition systems.

Diesel Capabilities

Diesel Particulate Filter Characterization & Modeling—The EPA has mandated a 90% reduction of particulate matter by 2007 and of nitrogen oxides by 2010. To accomplish this, diesel engines will have to utilize exhaust after-treatment technologies which have a potentially negative impact on engine efficiency. Battelle researchers are helping the diesel industry overcome these challenges by helping develop high efficiency NOx reduction catalysts and soot filtration devices for diesel engines. Challenges include plugging, thermal failure, particulate trapping effectiveness and high cost. Battelle uses the Lattice-Boltzmann technique to develop a sub-grid model of a diesel particulate filter to determine how to best express soot burn rates and to identify the soot cake layer's intrinsic properties.

Diesel Soot Filter Regeneration Phenomena—Soot filter devices are prime candidates for future diesel particulate control. PNWD's are extremely effective. Our filter devices burn off captured material or subject it to catalytically enhanced regeneration to avoid high back pressure. And our NOx adsorber research holds promise for effective control of NOx emissions. Current work includes thermal imaging of regeneration and Lattice-Boltzmann simulation for modeling pressure drop in filters.

Cross-Cut Lean Exhaust Emissions Reduction Simulations—CLEERS is a R&D focus project of the Diesel Cross-Cut Team designed to develop improved simulation tools for realistic full-system performance of lean-burn engines and the associated emissions control systems. The Diesel Cross-Cut Team has three main objectives: 1) to promote the development of performance models for emissions control components such as exhaust manifolds, catalytic reactors, and sensors; 2) to provide a consistent framework for sharing information and making timely, informed choices among emissions control technologies; and 3) to identify R&D needs and priorities and provide endorsements for critical projects. CLEERS is coordinated by a subcommittee of industry, government and academic representatives.

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PNNL-SA-52183 October 2006

Realizing safe, effective petroleum extraction with emerging technology

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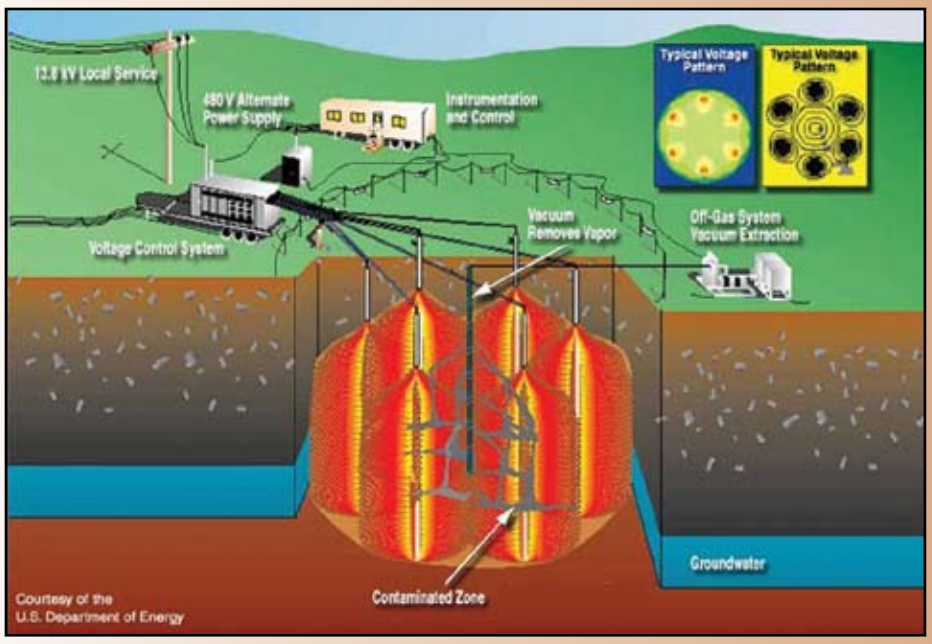
Heating and Stabilization



A model of an in-ground retort system.

Emerging techniques for the extraction of petroleum products from oil shale and tar sands underground rely on heat to release the petroleum-rich fluids to transport them to the surface for refining. Accomplishing this in a controlled, efficient and cost-effective manner is no simple feat. As a major research and development organization, Battelle offers unique capabilities to meet these challenges.

Underground Heating—Longer, Hotter

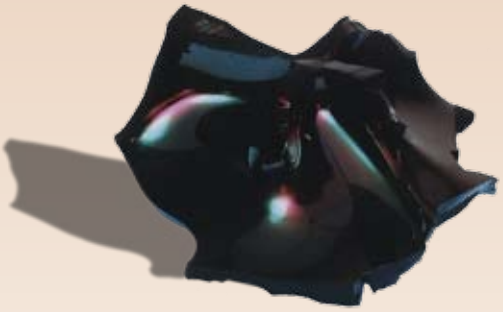
One method of extracting oil shale involves the use of underground electrical heaters. In this process, very long heater cables are deployed in oil shale deposits and heated to at least 500° C. One of the greatest technical challenges is the development of heater cables capable of long-term, high-temperature operation in downhole environments. These heater cables need to provide high power at high voltages. Another typical challenge is the short life of the underground heaters itself because of corrosion.

At Battelle's Pacific Northwest Division (PNWD), a materials development group specializes in developing and testing high-temperature materials. We have been evaluating and developing high temperature alloys for applications in power systems such as high-temperature fuel cells. Dozens of high-temperature corrosion alloys have been evaluated in real fuel cell operating conditions, and oxidation and corrosion have been studied in environments that resemble the downhole environments of oil shale. In addition, electrical insulating and conductive ceramic coatings have been developed dramatically, improving the lifetime and performance of the metallic interconnection—a common point of failure.

Tapping Our Vitrification Expertise

Battelle pioneered the application of electricity for subsurface heating with 6-Phase Soil Heating, a technology generally used for mid-range temperatures such as for viscous oil, or steam generation. A follow-on to that technology is underground or in situ vitrification (ISV). PNWD has more than 40 years of experience vitrifying a range of materials. ISV is used to turn contaminated soil into glass and also to make subsurface barriers. This process passes electric current between subsurface electrodes until the soil or rock is melted and then cools to form a glass monolith.

Battelle has applied this expertise to form glasses with targeted properties such as durability, melting point and viscosity. For subsurface systems, glass formulation begins with analysis of the soil or rock composition. Once processing requirements are calculated and verified, the subsurface vitrification is then modeled using computer simulations to design the optimum system.



A sample of vitrified soil.

Modeling 'Model-Behavior' in Extraction Processes

Subsurface retorting is a complex process but can be explained quite simply. Heat is applied to the oil shale to release the desired products to an extraction well. Then the fluids flow to equipment at the ground surface for refinement.

In reality, developing and managing an oil extraction system is much more complicated. Battelle scientists have created new computational fluid and thermal subsurface modeling capabilities. These discoveries allow for optimal design of the extraction system to make the extraction process not only more productive but easier and safer. Each project environment is complex and therefore can require modifications to the system to yield exceptional results. These modifications, however, can frequently result in further complications. Computational models allow changes to the system to be understood before they are made—potentially eliminating costly errors.

Typically, subsurface flow models are based on one-dimensional experiments that leave uncertainties between the real system and the ideal experiment. Unresolved details (such as those in multiphase permeability models based on air-water void fraction or water-oil volume fraction) can go unnoticed. To mediate this risk, most of our larger-scale models are based on actual representative experiments or generated from pore-scale behavior to simulate flow more effectively.

Since properties at the pore scale determine reservoir behavior, our researchers apply pore-scale simulations to develop models based on larger-scale properties. Pore-scale simulations are performed using a Battelle-developed lattice kinetics simulation method used for discreet modeling of phase change in unsaturated media. The surface tension is adjustable and may be correlated with local variables. This discreet two-phase capability has been used to model permeability in unsaturated soils and flow through a catalyzed hydrogen production reactor. This method includes reactive transport features, which can be applied to catalyzed reactions, hydrocarbon polymerization or the formation of tars. It can also be used to examine particle entrainment, stresses applied to the rock structure resulting in further fracturing, gas penetration and pore scale combustion.

Modeling is ideal for developing and managing the most efficient and cost-effective extraction process and system. Battelle's extensive research and development capabilities, facilities, and expertise in applied mathematics, physics, and computational sciences make Battelle an ideal partner for this task.

Stabilization Technologies

As a stabilizing technology, grouts are applied to protect boreholes and to form subsurface structures that protect the extraction areas from groundwater flow. Battelle is experienced in the rheological characterization, reactive chemistry, and long-term stability of grout slurry materials. While the use of grouts is relatively straightforward, the choice of grout formulations and injection conditions is not. Success is dependent upon knowledge of the formation porosity, modeling of the grout injection, and design of the proper grout. A good physical grout does not necessarily make it able to flow through a porous formation for a desired distance under an attainable pressure and then stay put while it sets up.

Groundwater flow is a major concern both when groundwater will make heating the shale difficult and when groundwater flow through the spent oil could cause groundwater contamination. Vitrified barrier walls can be used to stabilize the system by protecting the oil shale extraction area.

Selecting and delivering heating and stabilization technology solutions in an effective and efficient manner is no simple feat. Battelle's systems are mature, effective, and demonstrate a reduction in cost through increased efficiency—not just in the near term but over the long term as well.

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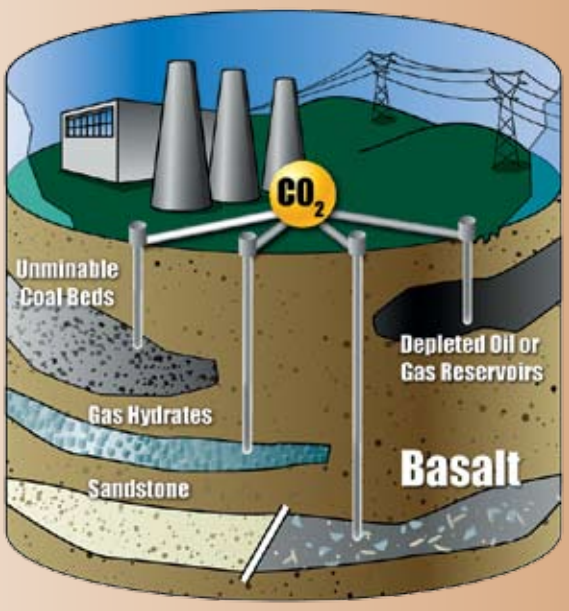
PNNL-SA-52149 October 2006

Carbon Management

Underground carbon sequestration is an attractive part of developing unconventional resources; however, it can be an expensive process. Lowering the cost of carbon management requires two things: 1) cost-effective management of CO_2 emissions, and 2) affordable sequestration.

Scientists at Battelle's Pacific Northwest Division (PNWD) are developing both new materials for separation and capture of CO_2 emissions and new approaches to carbon sequestration with a careful eye to atmospheric and environmental impacts.



Battelle researchers at Pacific Northwest National Laboratory are seeking the best geological formations for safely storing carbon dioxide. In this model, carbon dioxide is injected 3,000 feet down into basalt, demonstrating a possible solution for carbon dioxide storage.

Using affordable and efficient carbon management techniques for unconventional oil resource development

Global Climate Change

The increase of carbon dioxide in the atmosphere is believed to be a key contributor to global climate change. Society now faces the challenge of understanding the processes that can reduce or eliminate carbon emissions and the technologies that can help manage carbon on a global scale. Battelle is a leader in defining not only the magnitude of the challenges posed by global change, but also potential technological and management solutions. We have developed one of the world's leading integrated assessment modeling capabilities for linking climate and carbon cycle science to human activities and ecosystems. Our scientists are recognized internationally for their ability to understand the complex interactions and feedbacks that exist between the climate system and human activity.

CO_2 Emissions Management

Clathrates—Battelle has developed a series of new crystalline nano-porous organic clathrates that utilize molecular recognition to remove CO_2. These molecules show promise for commercial large-scale gas separations offering two to three times the CO_2 uptake of conventional amine solvents, very high selectivity for CO_2 over H_2, and gas separation and retrieval cycles with low heat requirements and without degradation.

Functionalized Nanoporous Materials—Battelle has developed CO_2 sorbent materials based on tethering high density amine functional groups to a nanoporous silica support. These have higher capacity, faster kinetics and better stability than liquid amine-impregnated sorbents. Also in development are high-T sorbents with integrated water-gas shift catalytic functions for enhanced hydrogen production from gasified coal.

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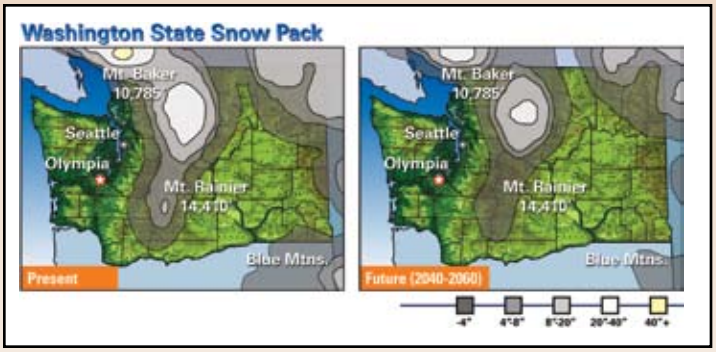

Battelle scientists have some of the best climate modeling capabilities in the business. This example highlights the high reduction of mountain snow pack in Washington's Cascade Mountains, an example of how currently increasing carbon dioxide emissions may negatively impact water supply for irrigation and hydropower generation.

Integrated Economic Analysis— Battelle's research has been integrated from the outset with process economic analyses for pre-combustion and post-combustion capture of CO_2. The economic analyses guide research and provide feedback during development to improve life-cycle economics.

CO_2 Sequestration

Battelle has developed four main areas of expertise in sequestering CO_2: the fundamental geochemistry of CO_2 and aquifer media under simulated subsurface conditions; numerical simulation of the injection of CO_2; phase and physical behavior and monitoring of the CO_2-aquifer system; and assessments of cost and storage capacity.

The fundamental geochemistry of CO_2—Battelle has developed unique equipment for measuring pH under down-hole conditions simulated in the laboratory. Researchers are making important discoveries, including correcting the value for pH in the saline aquifers and aqueous systems in the presence of supercritical CO_2, and conditions for carbonate precipitation. For example, in basalt aquifers, under down-hole conditions, we see $CaCO_3$ precipitating in a few days at pH 4.5 to 5; to date no one has identified a saline aquifer of a composition adequate to drive precipitation.

CO_2 injection simulation—The Battelle-developed STOMP-CO_2 simulator, an operational mode of the STOMP simulator, is being used to assess the potential for geologic sequestration of CO_2 in deep geologic reservoirs. The objective of this simulator is to predict CO_2 injection rates. Uncertainty is addressed by sensitivity tests using multiple geostatistical realizations of the geological parameters. The STOMP-CO_2 simulator has been developed with two implementations: 1) sequential for execution on single processor computers, and 2) scalable for execution on massively parallel computers. This simulator has reactive transport capability for investigating the mineralization of injected CO_2 into typical saline aquifers, deep basalts or other formations.

Behavior and monitoring of the CO_2-aquifer system—Battelle is investigating the fate and transport of injected CO_2 and its interaction with the cap rock seal that prevents the CO_2 from migrating out of the aquifer. Our scientists have developed an approach to monitoring the long-term storage of CO_2 using tracer-sensor networks, including simulating the 500-1000 year behavior of the super-critical CO_2 bubble.

Cost and Capacity Assessments— Battelle has conducted cost and capacity studies to provide policy and research decision support. Cost studies, not including capture or credits, across all types of storage media indicate costs of -$7.13 to $54.70, with isolated cases to $70 per ton of CO_2 sequestered. (Negative costs represent benefits from enhanced oil recovery.) Most deep aquifers range from $12 to $15 per ton of CO_2 sequestered. Capacity studies to determine how much CO_2 could be stored in various targets go hand-in-hand with the cost studies in determining the overall feasibility of sequestering CO_2. Capacity studies have been completed for aquifers (21 in the US and one in Canada), depleted gas basins (36) and already-produced oil reservoirs (to various degrees for 75 to 100 oil reservoirs in the US and Canada).

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PNNL-SA-52146 October 2006

Getting solid results through stronger relationships, effective communication and strategic processes

Battelle
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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Stakeholder Interactions

Face-to-face interactions provide useful forums for understanding the sometimes conflicting needs of stakeholders.

Exploiting unconventional energy resources can create conflict among the involved parties. Principals and stakeholders are set on a multifaceted path of developing, testing, deploying and monitoring new technologies and approaches. Successful energy development projects require effective collaboration with local communities and state agencies to prioritize needs and create strategies that enhance the project's benefits while reducing adverse consequences.

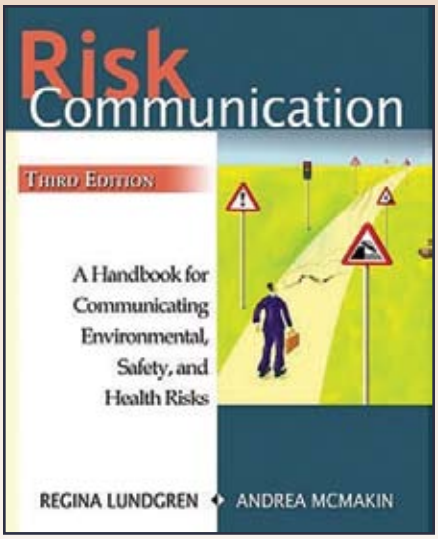
To develop sound solutions, project developers must link the social context of problems—the demands and expectations of their own organizations, regulatory requirements, and political and community considerations and pressures—with scientific information and technology applications. Success can often hinge on the effective communication of project risks and benefits to both workers and stakeholders so the best solutions can be fully understood and realized.

Blending Social Systems and Technology

Battelle has an integrated management and social systems capability that helps project initiators use the latest information and technology to create viable solutions for specific challenges while developing problem-solving organizations. We focus on helping clients:

- Understand how social systems affect the development and deployment of innovative solutions to complex natural resource and technology management problems
- Articulate the impact of proposed solutions on social systems, and design and assess the effectiveness of potential mitigation measures
- Develop community and stakeholder interactions and risk communication strategies and skills.

Battelle offers a wealth of experience assembling and managing the kind of multi-disciplinary teams needed to address the social, institutional and communication challenges of technology-based energy development projects. Our team includes social scientists—anthropologists, psychologists, sociologists and communications experts—management specialists, and lawyers, all who frequently



collaborate with natural and physical scientists and engineers to provide interdisciplinary research and technical assistance.

Experience That Matters

With a diverse base of experts, Battelle can create a balance of knowledge across disciplines and perspectives to assess impacts and risks, develop integrated solutions, and transfer technical knowledge and skills—from initial planning and scoping to implementation and close-out. Our experienced team takes on socioeconomic impact assessments, public involvement, risk communications and technical training because we understand the delicate balances between stakeholder concerns, technology limitations, appropriate workforce skills and facilities, the risks and consequences of the hazards, and the need for available and effective management, response and recovery resources. As a result, Battelle is uniquely qualified to advise program managers and technical experts on technology acceptability issues, interaction and socioeconomic mitigation strategies, and communication principles and skills.

Our team has extensive experience providing community and stakeholder support from a variety of industry programs. We have experience in resource extraction (including coal, oil and gas, uranium and oil shale, and hard rock mining); processing (including milling and sweetening); power generation (such as coal, oil, natural gas, nuclear and hydro); and transportation/transmission (for pipelines, transmission lines and roads). Our experience encompasses direct involvement in intermountain west development of coal, oil, gas and oil shale. Battelle scientists have completed technology assessments, and have developed and delivered technical training for energy, environmental remediation, and resource monitoring and management systems. Our efforts aim to help clients succeed at their projects safely and promptly.

Leveraging Established Relationships

As a result of our government ties—managing five of the U.S. Department of Energy's national laboratories—Battelle possesses expertise in assessing, communicating and mitigating impacts associated with hazardous materials and new technologies that may entail public health, environmental and safety risks. We understand a project's life-cycle—from initial planning and scoping through implementation and close-out. And further, we can cite extensive examples of projects working across communities and groups of diverse ethnic, cultural and language backgrounds, including Native American stakeholders. In addition to a variety of federal and local governmental agencies, Battelle has provided support to private companies across the United States.

Over the years, Battelle has honed its understanding and skills to help project teams deal with the organizational and interpersonal dynamics, constraints and interaction processes that accompany large-scale energy development programs and the introduction of new technologies. Work with Battelle to address these challenges.

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PNNL-SA-52147 October 2006

Using the best response tools to plan for worst-case scenarios while developing an unconventional energy resource

Battelle
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Operated by Battelle for the U.S. Department of Energy

Security and Pre-emptive Planning

Battelle tools cover pre-event planning and event management to minimize the damage in an emergency situation.

Preparing for the unexpected is paramount when balancing natural resources with community and environmental responsibility. The ability to obtain, track and analyze highly-dynamic information is a fundamental requirement for emergency decision support and crisis management. Maintaining timely status information is needed to effectively support both daily operations and response activities. Battelle offers three key tools for rapid information updates: **EMA***DVANTAGE*, for situational awareness; WebOSB, for sharing and tracking information across multiple jurisdictions and users; and FRAMES, an information technology platform that allows seamless linkage of disparate models, databases and frameworks with refined capabilities in Rapid Risk Assessment. These decision support systems are used at oil refineries such as PEMEX in Minatitlan, México, and for government programs such as NASA and the Chemical Stockpile Emergency Preparedness Program.

Real-time Communication, Timely Response

The continual management of timely status information is needed not only in emergencies but also for daily monitoring. Because natural and man-made disasters have the potential to impact far beyond the immediate workplace, the ability to acquire and share status information quickly between multiple entities is extremely important.

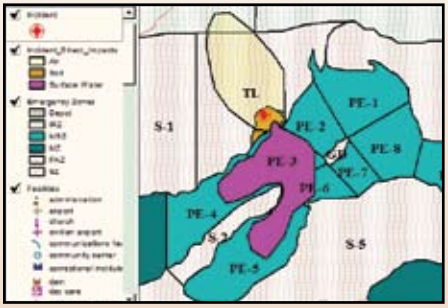
EMA*DVANTAGE* is an automated decision support system that supports emergency planning and response for events ranging from accidents to global disasters. It provides situation planning and response capabilities for a large multi-user environment. Teams can simultaneously access information within an emergency operation center or remotely via web browser or wireless hand-held device. Hospitals and other key resources can be notified in real time in emergency situations. Combined with WebOSB, a high-tech architecture that enables users to create status boards of real-time information on the fly, emergency management personnel will have complete control of virtually all emergency situation information to support decisions, share information and involve those who need to be involved.

Effective Pre-emptive Planning

Whether planning for or responding to a specific threat, one of the first steps is to understand the kinds of threats that exist in accurate context and identify

their impacts. With that information potential vulnerabilities can be identified, and emergency planning and training become more valuable. Additionally, insights gained in the planning process can aid in thinking through long-term impacts, clean-up alternatives and the ramifications of delaying clean-up.

Multi-thematic modeling technology is used to characterize and consolidate impacts from a single threat. Battelle developed FRAMES for this purpose. FRAMES integrates multiple models into a single multi-thematic modeling environment allowing users to quickly and easily comprehend the full impact of an incident. In the example image below, users simultaneously track a surface water plume (purple), contamination on land (brown), and through air (yellow) using disparate models designed for those different environments.



FRAMES integrated systems can manage and display data to support all aspects of planning and response.

FRAMES is more than just a software product. It is a framework for adding and applying new user-specified models that allows emergency personnel to assess simultaneously multiple incidents using models and approaches of varying degrees of sophistication. For example, the oil and gas industry has unique needs that require creative technologies that deal with non-atmospheric media and sustained response responsibilities. Multi-thematic software, databases, and visualization systems can do this; their strength being the ability to access quickly and utilize models and databases to manage data collection, data display and sustainable recovery. A 3D model can easily be constructed using innovative modeling programs such as WebEDMS (also known as EarthVision). These tools can be animated to track the success of a remediation plan.

Relevant Experience

Battelle scientists and engineers, located at Pacific Northwest National Laboratory in Richland, Washington, have been engaged in one of the world's largest environmental cleanup and monitoring projects for ten years at the U.S. Department of Energy's Hanford Site in southeastern Washington. The site's emergency operations center (EOC) is manned by more than 50 dedicated staff who are on call around-the-clock. The most recent event requiring the full activation of that emergency response team was the 2000 Hanford Site Wildfire, which burned more than 75,000 acres.

By leveraging the event communication and response technologies, the EOC was able to coordinate, share information and make critical real-time decisions based on the activities of multiple emergency response teams, exponentially reducing the potential devastation of this wildfire.

An emergency response center reviews information from multiple sources to make critical real-time decisions.

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PNNL-SA-52157 October 2006

Building new technologies and offering new tools for the next generation's power needs

Battelle
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Pacific Northwest National Laboratory
Operated by Battelle for the U.S. Department of Energy

Power Management

The Electricity Infrastructure Operations Center is a new user-facility dedicated to energy and hydro power research, operations training and back-up resources for energy utilities and industry groups.

Research conducted by Battelle suggests the demand for electricity in the United States will require $500 billion in new investments by 2020, with a parallel need to reduce greenhouse gases. Battelle is addressing these challenges with new technologies that address both the demand-side and the supply-side of the energy equation, such as clean conversion of fuels into electricity; new transportation fuels; fuel cells; building technologies and efficient lighting; and new tools to increase grid efficiency and reliability.

The Grid—Researchers at Battelle are developing a market-driven system that allows a real-time flow of information that facilitates customizing energy purchases based on economics, types of power and time of use. This dynamic, interactive system can maximize productivity and offset traditional infrastructure investments while increasing robustness, flexibility and security. In our GridWise™ Demonstration, researchers are studying about 200 homes in Washington and Oregon that are receiving real-time price signals and that are equipped with technologies that allow homeowners to customize and automate the way their appliances respond to those signals.

Other R&D is focused on how to improve the data and models that grid operators use so they can more quickly see a potential problem arise and take corrective actions. The Electricity Infrastructure Operations Center on the Richland campus is a unique platform to research, develop and test next-generation tools and concepts for operating the energy infrastructure. It offers a control center

environment with real-time data flows moving the operation of the grid from minutes to seconds.

Biomass—PNWD is developing new technologies that transform low-value bioproducts into higher-value plastics, adhesives, fibers, liquid fuels and power via "biorefineries," an important step for biofuels. In addition, PNWD is able to create new products and fuels from novel filamentous fungi, via advances in proteomics and bio-informatics. To further this work, Pacific Northwest National Laboratory and Washington State University broke ground in 2006 on the Bioproducts, Sciences, and Engineering Laboratory, which will be located in Richland, Wash.

Nuclear Energy—Nuclear energy generates 20 percent of the electricity in the United States, and because it emits no greenhouse gasses, will likely play a role in the future. Battelle is working with the Nuclear Regulatory Commission (NRC) in re-licensing activities helping to ensure that materials in active nuclear reactors are safe and reliable. For new reactors, Battelle anticipates playing a lead role in the NRC's combined construction and operation license process.

Building Technologies—Battelle's Buildings Program reduces the energy intensity of our nation's buildings, without sacrificing security, health or productivity. Battelle's core work areas include energy codes and standards, operations and maintenance, market transformation, and technology demonstration and deployment. Battelle is focusing its areas of research on advanced building diagnostics and controls (to enable real-time building and equipment condition monitoring and enable better management of peak demand), and solid-state lighting (particularly organic light emitting diodes).

Hydrogen—Hydrogen is a potentially limitless energy source that can play a major role in meeting our country's need for clean energy. One of the main barriers to a hydrogen economy is safe and economical hydrogen storage. Battelle is applying its expertise in chemistry, catalysis and materials to explore innovative chemical storage mechanisms for hydrogen; we are also developing codes and standards for the safe use of hydrogen in the field.

Fuel Cells—Battelle is a leader in developing solid oxide fuel cells (SOFCs), the fuel cell of choice for converting fuel into electricity. SOFCs operate on hydrogen or separate hydrogen from other fuels. As part of its fuel cell work, PNWD and the National Energy Technology Laboratory are co-leading the Solid State Energy Conversion Alliance, a Department of Energy program that also involves several industry teams; the alliance is devoted to promoting and accelerating the development and commercialization of low-cost, environmentally friendly SOFCs for a variety of applications.

Additional power management topics include:

- Carbon Capture and Sequestion—see *Carbon Management* within the portfolio
- Emissions—see *Fuels & Emissions* within the portfolio

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PNNL-SA-52127 October 2006