Partnership Progress

July 2000 No. 15

Natural Gas & Oil Technology Partnership

U.S. Department of Energy ■ National Laboratories ■ U.S. Petroleum Industry

Changes

Changes in leadership have occurred within the Partnership. Dexter Sutterfield was named the Associate Director for Technology Management at the National Petroleum Technology Office. In this position, he assumes primary responsibility for Partnership activities for the Department of Energy.

At the Idaho National Engineering and Environmental Laboratory, Dick Rice retired, leaving a legacy of strong support of the Partnership. Charles Thomas has assumed the vacancy left by Rice.

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Inside

The Partnership on the World Wide Web:
http://www.sandia.gov/ngotp/

Featured Partnership Project

Brine composition focus of research to improve recovery

Waterflooding is by far the most widely applied method for improved oil recovery and accounts for more than one-half of U.S. domestic oil production; similar proportions hold worldwide. The injected brine in a waterflood is normally obtained from the most convenient source and is usually of different composition than the connate water. Treatment of injected water and modification of its composition are dominated by considerations related to avoiding formation damage, and mitigation of souring and corrosion. It has generally been thought that composition of the injected brine is immaterial to the efficiency of oil displacement. However, laboratory studies over the past 10 years of crude-oil/brine/rock interactions have shown that brine composition can have a significant effect on recovery of crude oil by waterflooding. Laboratory corefloods have confirmed that changes in brine composition can increase waterflood recovery by up to 20%. Modifications to the brine chemistry have resulted in changes in the wetting state as well as increasing the oil recovery.

Laboratory corefloods have confirmed that changes in brine composition can increase waterflood recovery by up to 20%.

Through an NGOTP project, Improved Waterflooding Through Control of Brine and Other Factors, researchers at the Idaho National Engineering and Environmental Laboratory (INEEL) and their industry participants are working to obtain a more complete understanding of the effects of brine composition on oil recovery. Their objective is to create a framework, based on laboratory experiments and field evaluation, that operators can use to improve waterflood oil recovery from specific reservoirs.

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Increased Oil Recovery

Continued from Page 1

Many examples of increase in oil recovery with change in injection brine salinity have been reported (Yildiz et al., 1999; Tang and Morrow, 1997). The project team is focusing on the increased recovery observed with decrease in salinity. Results for oil recovery for oil from a field selected by INEEL's industry participant, BP Amoco, for potential application is shown in Figure 1. In these tests, the rock was Berea sandstone, which is outcrop sandstone in common use by the industry as model reservoir rock. The large increase in recovery of CS crude oil (a waxy crude oil from a North Sea oil field) with dilution was consistent with previous observations on oil from another field. In these tests, the water initially present in the core (which represents the reservoir connate water) was of the same composition as the injected water. In practice the connate and injected brine will be of different composition. Figure 2 shows the results of injecting dilute brine into a CS reservoir sandstone sample in which the connate water matched that of the reservoir. The increase in recovery of more than 20% is the largest observed to date.

For mature waterfloods—especially common in the United States—oil is produced at high water-to-oil ratios. The possibility of decreasing the water/oil ratio through injection of dilute brine has been investigated in the laboratory. Results have been obtained showing an increase in recovery of about 5% for CS crude oil after establishing a well-defined residual by extensive waterflooding. Furthermore, it has been shown that the increased recovery rate can be reversed by injection of brine in which calcium ion content was increased (Tang and Morrow, 1997). An advantage of field testing the impact of changing the injection-water composition in a mature waterflood situation is that a decrease in water/oil ratio would provide a definitive measure of reservoir response.

It is a common practice to reinject produced water commingled with the original source water following breakthrough to minimize the cost of water disposal. For example, in Wyoming Powder River Basin waterfloods, the source water is often fresh brine (~ 900 ppm solids). It is common practice to commingle produced brine of much higher salinity that originates from the formation with the dilute injection brine. A comparable situation occurs in Utah's Greater Monument Butte region where fresh water is the basic source water and produced water is reinjected in various proportions with the fresh source water. The consequences of this practice with respect to ultimate oil recovery and the economic trade off of alternative operational strategy have never been investigated. Operators in these areas have agreed to collaborate in investigating these opportunities for improved oil recovery.

See Recovery Mechanism, Page 3

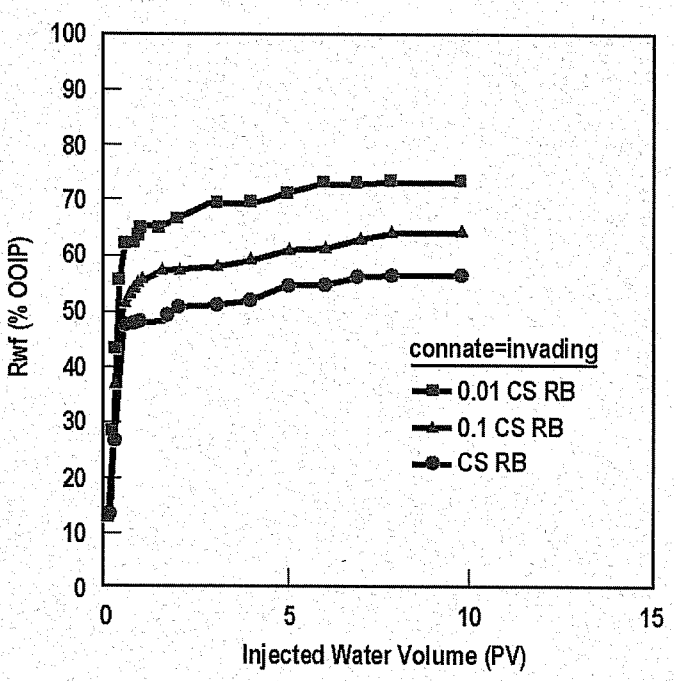

Figure 1. Recovery of CS crude oil from Berea sandstone; CS Reservoir Brine (RB), 0.1 CS RB, 0.01 CS RB.

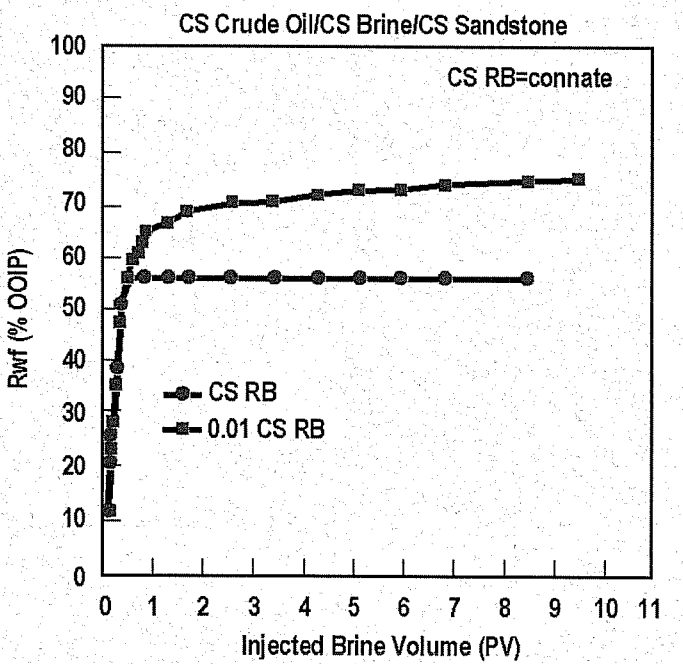

Figure 2. Effect of the concentration of injection brine on waterflood recovery for reservoir core.

Recovery Mechanism

Continued from Page 2

In addition to the observations of improved recovery described above, we have also found crude oil/brine/rock combinations where there was little or no response to injection brine composition. For example, only slight response was observed for chalk reservoir core samples. Therefore, laboratory evaluations are essential to identifying potential candidates for application.

To date, laboratory testing has identified three key conditions for the process to be effective:

- polar components in the crude oil that can adsorb on the rock surface,
- presence of clay in the rock, and
- the presence of connate water.

Current work at INEEL and the University of Wyoming is focused on the types of crude oil; rock properties including the types, amount, and distribution of clay; the composition and amount of connate water that are optimum for oil recovery; and an economic evaluation of the process for field applications. A primary goal of this project is to improve understanding of the mechanism of increased recovery and to develop screening criteria for reservoir selection for detailed evaluation.

Field Application

Economic analysis of potential applications by BP Amoco including the development of sources of low-salinity brine was encouraging. Tests on specific reservoirs with reservoir crude oil, rock, and brine at reservoir conditions are being performed by BP Amoco for several candidate reservoirs. Improved recovery has been observed for dilute injection brine and a single-well field test is being planned.

INEEL is currently working with a domestic operator to evaluate the potential impact of commingling produced water with the fresh injection water in an existing waterflood. INEEL is also seeking an opportunity to test the impact of converting from commingled brine to fresh brine to test the impact on the water/oil ratio in a mature flood as discussed above.

Publications

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Acknowledgment

This research was funded by the National Petroleum Technology Office of the U.S. Department of Energy through the NGOTP, the Enhanced Oil Recovery Institute of the University of Wyoming, BP Amoco, ARCO, Chevron, ELF/Total/Gas de France / Institut Français du Pétrole, Japan National Oil Company, Phillips, Shell, and Statoil.

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Partnership News

2001 Review Cycles Begin

The Partnership is organizing for the FY01 review cycles. Several calls for proposals are expected this summer with preproposals due in late summer and very early autumn.

Full-proposal reviews are planned for early October for the Downstream Environmental and Processing Technology area and the new Ultra-Clean Fuels Technology area. Reviews for Drilling, Completion, and Stimulation; Oil and Gas Recovery; and Diagnostic and Imaging technology areas are planned for mid-November. Details will be forthcoming for the Upstream Environmental Technology review.

The U.S. Department of Energy has directed that the Partnership increase emphasis on the Downstream Environmental Technology area through the Clean Fuels Initiative, a new research effort targeting development of new ways to produce ultra-clean fuels and better pollution control devices for automobiles. The initiative follows the Clinton Administration rule requiring the nation's gasoline suppliers to meet an average sulfer level of 30 ppm by 2005.

This shift comes at the expense of the Diagnostic and Imaging Technology area, specifically, and the upstream program, as a whole. Diagnostic and Imaging Technology is an area where the Partnership has had significant impact on domestic exploration and production. The Partnership's challenge is to maintain a strong program in such areas, which have a significant record of success.

Upstream Environmental Projects Awarded Funding

A recommendation for funding was made to the National Petroleum Technology Office (NPTO) based on the 13 proposals presented to the Upstream Environmental Technology Industry Panel. The Partnership thanks Dave Schmalzer, of ANL, and David Alleman, of NPTO, for their efforts in the successful completion of this cycle for the environmental technologies.

Dexter Sutterfield Named NPTO's Associate Director for Technology Management

Dexter Sutterfield was named the Associate Director, for Technology Management, at the National Petroleum Technology Office (NPTO). In this role, he takes on the tasks that Alex Crawley spearheaded since the inception of the Partnership until his retirement at the beginning of the year.

Sutterfield, a chemical engineer with a doctorate from the University of Tulsa, has been associated with NPTO and its predecessor organizations for 32 years. In 1969, after four years as a health and environment chemist for the federal government, he joined the U.S. Bureau of Mines at the Bartlesville Energy Research Center in Oklahoma, which later became the Department of Energy's National Institute for Petroleum and Energy Research (NIPER). From 1983 to 1997, he managed research programs at NIPER for IIT Research Institute and BDM-Oklahoma, Inc., directing contract research for public and private entities in exploration, drilling, production, processing and end use. Sutterfield rejoined the NPTO in 1997 as Technology Manager for Process Research.

The Partnership looks forward to working with Sutterfield, especially to his guidance and support as we expand with the Clean Fuels Initiative.

The Partnership also wishes to thank Mike Ray of the NPTO for his efforts as the interim DOE lead for the Partnership. Ray helped the Partnership through the five-month transition and insured its progress and funding.

INEEL Representative Retires; New Representative Named

Dick Rice, the INEEL representative for the Partnership, retired June 2. Charles Thomas assumed the responsibilities of the Partnership representative.

The Partnership thanks Rice for his great efforts in the Partnership, both as laboratory representative and lead of the drilling area. Over the past several years, he strengthened the Drilling, Completion, and Stimulation area through his outreach to industry and the Drilling Engineering Association.

At INEEL, Rice was the Fossil Energy Manager. His career at INEEL lasted more than 27 years, where he held six different managerial positions. His retirement plans include hunting and fishing.

Thomas will take over as INEEL's Partnership representative and as leader of the Drilling, Completion, and Stimulation Technology area. He is a Science and Engineering Fellow and a project manager for reservoir and environmental projects for the Fossil Energy Technologies Department at INEEL. He has more than 30 years of experience in petroleum industry, national laboratory, and university research and development, engineering, and operations. At INEEL, Thomas has led multidisciplinary research and development groups for EOR process development and applications, and managed project teams for resource evaluation, reservoir characterization, and environmental remediation process development.

Technology Transfer Process Under Review

The Partnership is tackling the issue of technology transfer. Consistently, technology area reviewers ask how a project insures the successful hand-off of technology to industry. Partnership projects perform such transfers with varying degrees of completeness. The Partnership is reviewing this process and looking for ways of improvement. As always, suggestions and comments are welcome.

Publications

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Jenneman, G., G. Bala, R. Clement, S. Fox, D. Gevertz, K. Sublette, and T. E. Ward. 1999. "Characterization of novel sulfide-oxidizing bacteria for use in desulfurization of produced water and gas." In *Proceedings of Sixth Annual International Petroleum Environmental Conference*, Houston, TX, November 1999.

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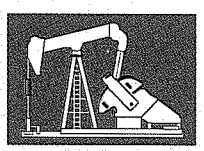

Oil & Gas Recovery Technology

Optimizing Reservoir Production

Research for this project, as funded under the NGOTP program, has concluded. Project researchers successfully developed a new scale-up technique that provides four orders-of-magnitude speed up in simulating two-phase flow for a wide variety of flow regimes in 2D and 3D.

A summary of project methods, "Effective medium boundary conditions in upscaling," will be presented at the Seventh European Conference on the Mathematics of Oil Recovery–ECMOR VII, in September, at Lake Maggiore, Italy. The paper compares analytic and computational results for scale up, in 2D and 3D, for one- and two-phase flow.

LANL presented another paper at the "Upscaling Downunder" conference that presents the theory of effective medium boundary condition pseudos, together with computational validation for 2D waterflood processes, for a variety of permeability fields.

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Improved Prediction of Multiphase Flow

PNNL completed a series of experiments to find and confirm the relationship between the reversal point on the main drainage branch and the residual oil saturation for two-phase systems. Earlier, a relationship confirming the theoretical relationship was found using a porous medium with a uniform grain-size distribution. The final set of experiments used a porous medium with a non-uniform grain-size distribution. PNNL is analyzing the data.

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Improved Waterflooding

This project's research is the focus of the feature article on the cover of this newsletter.

New-Generation Petroleum Reservoir Simulator

ANL developed the "dual approach" to solving multiblock or domain decomposition problems with non-matching grids. In the multiblock, mortar-space approach, the current guess of pressures close to the interface is used to determine fluxes that are matched in an average sense. In contrast, for the dual approach, the fluxes across the interface are used to determine pressures in the gridblocks adjacent to the interface. The dual approach uses an extension of a regular linear solver to resolve the overall system, instead of iteration on interface.

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The two approaches were tested against solutions obtained without domain decomposition, demonstrating that the dual approach gives results comparable to the mortar approach. Both offer agreement to single-block solutions sufficient for practical applications. The dual approach, however, appears to be of lower-order accuracy in the case of non-matching grids, offers more geometrical flexibility, and may be more efficient to use in some, especially coarse-grid, cases. Both approaches allow coupling of different physical models with the constraint that these models must be implicit.

The team identified some of the critical efficiency issues in using multiphysics models on multiprocessor platforms. Specifically, the team considered the cost ratio between the individual models and size of the model subdomains as the main factors in determining appropriate load balancing.

Multicommunicator capability for treating multiphysics problems was added to the IPARS (Integrated Parallel Accurate Reservoir Simulator) framework. A Web-based user interface was developed to assist in input of scalar data for five physical models.

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Fluid Identification Acoustic Logging Tool

LANL made successful measurements of single-phase and mixed flow with the swept-frequency acoustic interferometry sensor system in a flow-loop. LANL tested the sensor from static to the maximum flow condition. The data show that the sensor performed flawlessly up to the highest possible flow rate.

The sensor will be incorporated into a logging tool and tested in the flow loop with flowing liquid. The tool is used to lower the sensor inside a flow-loop pipe and clamp it in position.

LANL is also developing electronic circuitry to extract the physical-property information from the sensor.

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High-Resolution Reservoir Characterization

LBNL is generalizing its streamline-based inversion of water-cut data to include the effects of gravity. LBNL derived the relationship between the arrival time of the water front and reservoir parameters such as permeability, porosity, relative permeability, the pressure field, and fluid densities.

In anticipation of obtaining a North Sea dataset, LBNL is revising the inversion code to enable simultaneous treatment of tracer, transient pressure, and water-cut information. These field data contain injected saline fluid breakthroughs, downhole pressure data, and water-cut information. An initial simulation indicates that gravity plays a role in reservoir production.

LBNL is also relating seismic attributes to reservoir fluid flow properties. For example, researchers are developing computer routines to compute synthetic seismograms using an equivalent-medium theory. In this approach, the medium is parameterized in terms of porosity and saturation, rather than in terms of seismic velocity and attenuation.

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Measuring Sucker Rod Pump Parameters Downhole

Instrumentation of the clear plastic sucker rod was completed. Tests at the University of Texas-Austin demonstrated the value of higher sampling rates (over 100 samples per second) for monitoring transient behavior. Phenomena that must be observed with the clear instrumented pump include gas interference, slippage past plunger, delayed valve action caused by fluid "acceleration effects," mechanical friction, and velocity effects.

The value of high-speed compression-chamber pressure measurements in diagnosing sucker rod pump problems was confirmed when analysis techniques being developed for future field work were applied to laboratory data. Because analysis identified a friction problem in the laboratory pump, techniques for diagnosing friction problems are being investigated. Although this investigation was not an anticipated part of the project, it demonstrates the value of the joint laboratory/university approach. The field instrumentation design is being modified, and preliminary results indicate that the same quality data can be gathered in the field.

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Formation Logging Tools for Microboreholes

Project studies indicated that the radiation flux incident on a microtool sensor deployed in a microhole would always be greater than that for a conventional tool in a cased 8-1/4-in hole. As theory dealing with the gamma capture efficiency of sodium iodide (NaI) crystals has yet to deal effectively with cylinders of the high aspect ratios found in logging tools, the team designed and fabricated a prototype detector assembly to compare the efficiency of the microtool to a conventional tool. Making this comparison early in the design effort is important to determine the relative counting time for the two tools in a constant gamma flux. If the counting time for the microtool is excessively long compared to the commercial tool, the mass of the

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NaI crystal will have to be increased in the final microtool design.

A major logging service company provided a commercial logging tool for making this comparison. The tool has a 1-11/16-in diameter that houses a 1×6-in cylindrical NaI crystal. The performance of this tool in a simulated 8-1/4-in-diameter hole will be compared to the performance of a 7/8-in microtool housing a 1/2×4-in NaI crystal in a 1-3/8-in microhole.

A microhole test pit-consisting of a 55-gallon drum, Ottowa sand, potash, crushed granite, and a variety of casing sizes ranging (conventional to microhole) was assembled. The radioactivity in the rock materials is intended to cover the energy spectrum of typical logging tools and is not intended for calibration measurements.

Comparative measurements were made in air of the relative response of a conventional tool and the microhole tool to various point sources using ^{207}Bi (207 isotope of bismuth). Photopeak efficiencies for the microhole tool were 10–50% of that for the conventional tool over the energy range 0.5–1.5 Mev, which is comparable to that expected from theory without attenuation. The signal-to-noise and spectral resolution of bismuth peaks of the two tools appeared comparable.

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Semiautomatic System for Waterflood Surveillance

Aera Energy LLC, an industry participant, provided the first part of the South Beldridge field data (about 600 MB) for analysis. The data include tiltmeter readings and satellite digital images for the same field section. The xyz coordinates of each producing and injecting well, along with production/injection information, are yet to be obtained.

A special software module was developed to analyze and correlate the results of different independent measurements with well locations and injection/production data. It converts data from different sources in various formats into digital and text files. LBNL also achieved a substantial optimization of data storage that results in file compression without special data compression algorithms. Thus, further processing and visualization of the data can be performed at shorter time on a personal computer.

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Drilling, Completion, & Stimulation Technology

Directional Underbalanced Drilling and Microdrilling

In preparation for project close out, the work on underbalanced drilling conducted over the past five years is being summarized, An outline for a final report is being prepared.

A major deliverable for this project, the coiled-tubing microdrilling rig, will be subsumed and further developed by a new project: Coiled-Tubing Deployed Microdrilling with Real-Time, Downhole Monitoring. (see page 10).

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Real-Time Coiled Tubing Inspection System

To determine magnetic stripe spacing and polymer particle loading for a coiled tubing marking system, INEEL is first developing techniques and parameters for spraying polymer paint with finely dispersed magnetic particles and selecting magnetic material.

Three hard magnetic materials, NdFeB (neodymium iron boron), magnetite (Fe_3O_4), and $CoFe_2O_4$ (iron cobalt oxide) are being investigated for marking. The initial states of these powders are essentially non-magnetic, and they are subjected to a magnetic flux to permanently align their moments to become strong magnets after deposition onto the work surface.

In April, INEEL used the Hall probe to test six samples (without pre-magnetization):

- three NdFeB-based paint strips with 9.74% powder loading,
- two magnetite-based paint strips with 8.42% powder loading, and
- one NdFeB-based paint strip with 82% powder loading.

The samples were magnetized and tested. The 9.74% NdFeB and 8.42% magnetite powder-loading samples showed no magnetic field measurement. However, the NdFeB-based paint strip with 82% powder loading registered a low magnetic field.

Further tests showed that magnetite cannot retain a strong permanent

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magnetic field once demagnetized, although NdFeB is a hard (permanent) magnetic material, and will out perform magnetite by 80 times.

NdFeB powder was also applied to seven samples with powder loading from 185% to 556%. The Hall voltage was lower for the high-powder-loading case, which could be caused by two factors: (1) paint compositions degrade the magnetic property, or (2) powders in the paint do not form a continuous matrix. The hypotheses are being tested.

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Perforation Dynamics in Geological Media

LLNL developed a network model to calculate the permeability changes induced by fines migration that occur after the penetration process has ceased. During jet penetration, permeability decreases when fluid porosity is decreased and interstitial (fracture surface) area increases. The induced shock wave pulverizes the clay binder in the sandstone, and the resulting particles are swept up by the subsequent pore fluid flow.

The results of a hydrocode simulation of the jet perforation of Berea sandstone cores with a Jet Research Center 2-in super-deep penetrator served as initial conditions, and calculations were made for two levels of underbalance. Results were compared to x-ray computed tomography experiments conducted at Penn State University with generally good agreement. However, there were some discrepancies that were traced partly to anisotropy in the cores and partly to unrealistic assumptions about the initial fines concentration and plugging pore fraction. To account for these factors, the model is being improved.

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Drill Cuttings Injection Field Experiment

Field work on the Mounds experiment was completed. Work in progress includes final analysis of the diagnostic data, a stress analysis of the reservoir to understand fracture patterns, and laboratory testing of slurry injections in weak rocks.

These analyses revealed that the tiltmeter data have a large component attributable to poro-elastic effects, and this component has not been included in previous analysis of the data. This component also affects the microseismic data, but interpretation of that data does not change because pore-pressure changes are already considered in the analysis.

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Seismic Stimulation for Enhanced Production

Final preparations were completed to begin the two-phase oil/brine flow runs on a Berea sandstone core. Modifications to the measurement procedures were made based on discussions with an industry collaborator. Given inherent difficulties associated with making accurate relative permeability measurements, test plans were altered to allow simpler measurements of induced changes in resistance to flow.

A conceptual design for modifying the core-flow apparatus to allow coupling of the mechanical actuator directly to the pore fluid pressure in the core samples was devised. Detailed design and procurement of required hardware continues.

The University of California-Berkeley will use its newly developed theoretical models to simulate physical conditions that were in effect during successful laboratory and field tests.

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In-Well Imaging and Heating: Multiple-Use Well Design

LLNL is exploring the potential for gaining additional vertical resolution in imaging the casing-to-casing configuration. The lab obtained field measurements in different configurations between vertical steel casings and combinations of point electrodes simulating discontinuous pipe in the subsurface. Processing of the datasets shows some differences that may help determine the relative depth of changes occurring during stimulation.

The first hybrid ohmic/steam stimulations indicate promise for use in a hybrid application, with ohmic heating as a preheat to a reservoir, followed by steam. The ohmic preheat simulation temperature field resulting from horizontal electrodes was utilized as a starting condition for Chevron's steam stimulation. The temperature distribution achieved after steam injection was substantially more homogeneous using the hybrid stimulation model than with a steam stimulation alone.

Using the configuration that results in the most homogeneous temperature distribution, LLNL is developing numerical models to assess the ability to monitor a hybrid stimulation process. The goal is to monitor and heat using the same casings.

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3D Analysis for Induction Logging in Horizontal Wells

Electrical structures defined by simple transverse anisotropy and a fully generalized anisotropy tensor, can now be evaluated by the finite-difference modeling software. The latter capability allows simulation of induction-log responses in, for example, cross-bedded sandstone reservoirs where assumption of simple transverse

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anisotropy is no longer reasonable.

The borehole induction tool response was evaluated in Eolian-deposited sandstones. The simulation results will be disseminated during two presentations at August's Society of Exploration Geophysicists exposition and meeting in Calgary, Alberta, Canada.

Participants at the University of Wisconsin-Madison are studying the effects of anisotropy on typical logging tools when placed in a horizontal well by examining the electric fields and currents induced in the formation, as well as tool sensitivities. They found that even modest values for the coefficient of anisotropy significantly deflect current-flow in the horizontal (low resistivity) direction. As this coefficient is increased, the effect of the deflection increases rapidly, and the current flow about the dipole source is almost entirely horizontal. This leads to dramatic departures in the spatial sensitivity of the tool from the typical assumption for induction logs. The sensitivity becomes elongated along the direction of current flow above and below the borehole, and goes to zero in the same horizontal plane as the borehole. Thus, simple interpretation schemes that have assumed radial flow about the well will no longer work, and the response to features in the same horizontal plane as the borehole will be minimized.

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Pre-Drill Detection of Shallow Water Flow Zones

The final report detailing results of sandbox experiments was received, and the project has been closed.

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Chemically Bonded Ceramic Borehole Sealants

This new project will develop a versatile sealing material for use in the drilling and completion of multilateral, horizontal, and deviated wells. Current cement formulations do not bond well to the rock formations and cannot be applied precisely to desired depths. ANL will adapt its chemically bonded phosphate ceramic technology—developed for stabilization of radioactive waste—for applications as ceramic borehole sealants.

Applications include:

- borehole wall sealing and stabilization;
- fluid diversion;
- setting plugs in vertical, deviated, and horizontal wells;
- sealing multilateral well junctions;
- sealing lost circulation zones; and
- stabilization of ocean floor muds, silts, and sands.

ANL initiated work by incorporating fibers in chemically bonded ceramics (CBCs) to improve their tensile properties and toughness. Glass fibers were selected and incorporated in CBC pastes made of ash and phosphate binder. Twelve cylindrical samples were made by varying ash-to-binder ratios. After curing for three weeks, the samples will be subjected to mechanical and physical properties tests.

To test the use of CBC for offshore drilling, ANL made samples using simulated seawater. Preliminary tests showed compression strength of 9,392 psi after one week of curing. This is more than twice the strength of conventional drilling cements. Detailed tests will be done after three weeks of curing.

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Coiled-Tubing Deployed Microdrilling with Real-Time, Downhole Monitoring

The repair and replacement of marginal drilling unit subcomponents are almost finished. The new mud pump was fabricated and shipped. The upgrade of the hydraulic control system was completed and demonstrated. The wheels and axles on the coiled-tubing drilling unit were replaced and modified to increase the legal load-carrying capacity of the trailer to accommodate the new, heavier mud pump. The new hydraulics system is being interfaced with the PC (LabVIEW data acquisition and control software) control system, facilitating a gradual transition from manual to automatic control of various drilling functions and processes.

The initial evaluation of weight-on-bit and torque sensors failed to find microsensors well suited to acquisition of these measurements. The most likely sensor for obtaining weight-on-bit data was procured and tested in a bench-top test. Thermal stability and repeatability were considerably lower than claimed. A creative solution for the required sensor is being sought.

A calculation method to predict the circulating mud pump pressure during drilling is being developed to include realistic bentonite-base drilling fluids and the effect of drill cutting transport at high penetration rates. Initially, the calculation method will assume a yield power law (Herschel-Buckley) fluid. However, the method will allow substitution of other relations if yield power law does not produce representative microdrilling fluid adequately.

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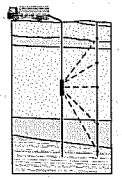

Diagnostic & Imaging Technology

Advanced Sensor Technology

The micromachine array-pod-printed circuit board was redesigned to include double-ended transmission of telemetry through a long cable. The circuit board is for transmission and conditioning microhole array signals to the surface. One of the boards was "stuffed" with components and successfully tested. Data taken from the prototyped circuit showed noise levels within anticipated and acceptable limits. Layout of the uphole circuit board has begun.

Comparative tests of the new electronics and associated micromachine sensor and a commercial geophone were conducted in the Quiet Room Facility at the Input/Output (I/O) plant in Stafford, TX. I/O designed the quiet room to provide as much isolation as possible from seismic, acoustic, and electrical noise. Additionally, the devices were placed on a vibration-isolation table. Data from these tests are being analyzed.

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Single-Well Seismic Imaging Technology

The INEEL Applied Engineering Development Laboratory design team completed a range of tests using simple clamp-on attenuators. The tests used smaller gas volumes and other features so that the damped signal remained intelligible above background noise. A database will help identify important parameters. Further analyses will extrapolate the effect for longer strings and deeper wells.

All tests have been hampered by poor reliability of the piezo pulser. The construction of a new pulser continues, including attempts to maintain a very similar pulse shape so as to maintain repeatability with good tests already performed.

The construction of the fully fieldable inflator continues.

LBNL continued to process the data acquired at Bayou Choctaw, LA, to assess the methodology. The lab is also planning a single-well survey at a Chevron site to monitor the effect of carbon dioxide (CO_2) injection into a hydrofracture. Cross-well and single-well baseline surveys will be conducted before CO_2 injection begins. Several months later, LBNL will perform a follow-up survey, repeating the measurements.

SNL is modeling elastic wave propagation around the salt dome as a function of geometry and geology.

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Large Downhole Seismic Sensor Array

When the pump and the bellows tool were tested in December 1999, the bellows tool powered by the downhole pump locked itself inside the well bore, and the bellows tool alone pressurized by air worked well.

The downhole pump was reassembled with a reversing controller and tested in March. In April, the downhole pump internal control wiring and electronics were reconfigured to eliminate the reversing relay. An optical switch was installed so that reversal of polarity activated the reversing circuit, and a full bridge rectifier maintained the polarity to the internal power supply. The design worked well. The only electronic consideration required for a fully fieldable unit is current-limiting corrections to the optical device to account for a wide range of voltage. With the new power supply, new batteries, and rubber centralizers, the performance of the integrated pump and bellows tool was excellent.

A proposed totally passive design is being developed. A testable prototype may be constructed.

Drawings are being generated that provide detailed documentation of the more capable of the INEEL-developed prototypes and tested module configurations.

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Improved Prestack Kirchhoff Migration

LANL implemented a robust method for calculating ray amplitudes into its wavefront construction ray-tracing code. The method is very fast and appears to be numerically stable. The amplitudes estimated with this new procedure were compared to amplitudes of first- and later-arriving phases calculated using finite-difference simulation of the acoustic wave equation. The comparison is favorable and gives encouragement that ray amplitudes can be reliably calculated, even in heterogeneous media. LANL is exploring the use of these ray-based amplitudes in a Kirchhoff migration procedure that uses multiple arrivals.

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3D Seismic Analysis Using SEG/EAGE Model Dataset

A new method for carrying out the downward-continuation portion of the common-azimuth migration technique was developed. It is based on the Fourier finite-difference methodology but is unconditionally stable, and is more accurate and more computationally efficient when multiple reference velocities are used.

The method was tested on a zero-offset cube from the SEG/EAGE salt dataset, and produced results superior to those from any previously published downward-continuation method.

The 3D seismic wave propagation code, E3D, was adapted to run efficiently on a Compaq/Digital massively parallel processor using the Alpha CPU. The cluster consists of 128 nodes, each of which has 4 CPUs. Test calculations were run of the SEG/EAGE salt structure with maximum frequencies of 10 Hz and 15 Hz. A total of 14 hours of computing time of a 240-CPU massively parallel processor was needed (i.e., 3,360 CPU-hours) for each shot. The acoustic-only simulations done to calculate the original dataset took about 13 CPU-hours for each shot. The comparison provides an estimate of the additional computing needed to carry out elastic simulations. E3D is being licensed for use by a service company.

Project work was documented in two journal articles (see Publications, p. 5). A paper will be presented at August's Society of Exploration Geophysicists exposition and meeting in Calgary, Alberta, Canada.

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Integrated Reservoir Vertical Seismic Profiling While Drilling

The project team received suggestions, regarding the use of a different suite of parameters during data processing, that are being implemented in the processing codes. Additional suggestions were (1) to process longer time intervals to test for improved signal-to-noise ratio in the autocorrelation estimation and (2) to process additional bit-depth data intervals to test for migration sensitivities.

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Monitoring Using Electromagnetics

Interpretation of the Texaco crosswell seismic and electromagnetic (EM) datasets from the Kern River Field in California are nearly completed. The seismic dataset first-break picking was completed making use of the 3-component geophones to pick on tool gathers. This allowed first-break picks to be made for near-horizontal source-receiver pairs where vertical geophones show little response. The crosswell EM dataset was inverted for electrical conductivity and correlated with water saturation to produce interwell water-saturation sections. LBNL and Texaco are wrapping up data interpretations.

LBNL also began testing the latest modifications to its 3D crosswell EM inversion code. The code was modified to use the 3D seismic surfaces to constrain inversion of conductivity within the reservoir units.

Testing is proceeding on the LBNL 3D numerical test case for the Snorre Reservoir that was the focus of previous 2D inversion work.

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Seismic Attributes of Fluids in Poorly Consolidated Sands

The first acoustic propagation and resonance tests on poorly consolidated sands were performed in the sand acoustics vessel. In the tests, the sand is housed in a thin-walled lexan tube. The sample length is 0.8 m, and the diameter is 4.1 cm. The first tests were performed on a coarse-grain sand under dry and partial water saturation conditions at a confining pressure of 7 MPa (1,000 psi). Nitrogen gas was used as the confining medium to minimize the acoustic coupling of the sample to the confining vessel. Acoustic measurements were made by exciting one end of the sample with an extensional mode PZT crystal and recording the resulting particle acceleration on the opposite end with a high three-component accelerometer.

The acoustic measurements on the (room) dry sand with 7 MPa hydrostatic confining pressure showed strong resonance peaks over the frequency range. Pulse propagation experiments showed a long time series of discrete reflections off the ends of the sample with observable phase shifts and small amplitude reductions.

Following the dry test, the sample was flushed with 4 L of carbon dioxide gas, and de-aired water was injected from one end. X-ray computed tomography scans over the length of the sample revealed only partial water saturation. The acoustic measurements showed smaller amplitudes in the pulse-transmission and resonance tests, particularly at the higher frequencies. Several modifications to the apparatus were made to ensure complete water saturation in the next test.

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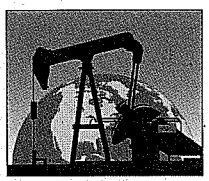

Upstream Environmental Technology

Monitoring of Particulate Matter and Particulate Matter Precursor Emissions

Measurements and samples were taken from the exhaust of a 1,100 bhp natural gas-fueled lean-burn spark ignition engine at Chevron's Warren Gas Plant in Lost Hills, CA. Components of filterable and condensable particulate matter were measured using laser-induced breakdown spectroscopy (LIBS) for metals, a photoelectric aerosol sensor for polycyclic aromatic hydrocarbons (PAH), U.S. EPA Method 201A for filterable particulate matter (total, PM_{10}, and $PM_{2.5}$), and U.S. EPA Method 202 for condensable particulate matter. The analysis and data reduction for the samples collected using the standard methods was completed. These results will be compared with the LIBS.

Advantages of the LIBS technique are high sensitivity for metalic elements, ability to follow transient behavior, and, when particle number densities are not too high and an estimate of the particle's apparent solid density can be made, ability to determine particle size. Calcium, which was the most abundant metalic element in the exhaust, arises from additives in the engine crankcase lubricant. Its mass emission rate, equal to the product of the calcium concentration in the oil and the rate of oil consumption, was extremely low.

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Development of an In-Well Oil/Water Separator

Bench-scale testing continues using CINC's model V-2 (2-in rotor) centrifugal separator and two crude oils provided by a Petroleum Environmental Research Forum industry participant. The first is a Gulf of Mexico (GOM) light crude. The second is a heavy North Sea crude.

The effect of temperature on the efficiency of the separator was determined using the North Sea crude and synthetic ocean water at a volume ratio of 10:1 water-to-oil in the feed. The concentration of water in the oil discharge stream averaged 0.8 vol% and did not change with temperature. The amount of oil in the water discharge stream decreased as the temperature increased. The viscosity of the oil decreases rapidly with temperature, which is the likely cause of the improved performance.

The effect of gas entrained in the oil stream was measured using the GOM light crude, a feed volume ratio of 1:1 water-to-oil. Air was added to the oil feed stream, just prior to its entering the separator. The presence of gas in the oil can completely disrupt the operation of hydrocyclones, which are also being tested for downhole oil-water separation. Air additions of 0 to 50% of the flow rate of the oil did not affect the operation of the separator.

Industry participants indicated that they were interested in the performance of the separator at high oil feed ratios. Tests were conducted using the GOM crude at feed volume ratios of 1:3 and 1:10 water-to-oil. The water concentration in the oil discharge was <0.2 vol% for all tests. For both ratios, the oil concentration in the water discharge increased as the total flow rate increased.

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Reducing Chemical Use and Toxicity in Produced Water Systems

A new, less-toxic inhibitor of corrosion was tested in ANL's test loop facility. Three recirculation systems that simulate pipelines with produced water were inoculated with sulfate-reducing bacteria (SRB) and acid-producing bacteria (APB). The phosphonium inhibitor prevented the growth of SRB but did not affect APB. One of the loops (B) was injected with the inhibitor at the beginning of the test. The other loop (C) was injected with the inhibitor in the middle of the test (after 1000 hours). After an additional 750 to 1000 hours, both loops were recolonized with SRB at levels comparable to the untreated control loop (A). Although the inhibitor can retard SRB activity, the effect of the treatments is temporary, and they must be repeated.

ANL found that over dosage of the inhibitor could also be responsible for higher general corrosion rates as well as sustained localized pitting (SLP). This was observed in loop B that was treated early in the experiment with 125 ppm of inhibitor and had approximately a sevenfold higher general corrosion rate than the control loop (A). It also developed severe SLP.

Project researchers developed a new-generation, user-friendly software for the ANL electrochemical noise analysis system. The new system will be able to continuously update the corrosion activity in the monitored environment and provide automatic data interpretation.

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Sulfide Removal in Produced Brines by Microbial Oxidation

The strain known as Coleville organisms (CVO) was identified as a species of Thiomicrospira and is now formally known as Thiomicrospira sp. strain CVO. The strain known as free water knock-out organism b (FWKO B) was identified as a species of Arcobacter and is formally known as Arcobacter sp. strain FWKO B.

Researchers completed long-term incubations of organisms capable of using thiosulfate as a sulfur source. It is now clear that microbial strains derived from cultures of CVO that were able to use both thiosulfate and tetrathionate as a sulfur-containing energy substrate were unable to appreciably oxidize sulfides following growth on thiosulfate (tetrathionate untested). The organisms did, however, grow robustly on thiosulfate, and control cultures of stock CVO oxidized sulfides rapidly.

Phillips, INEEL, and the University of Tulsa met to evaluate potential locations for field demonstration of technology. Their goal was to find properties that would allow a tangible evaluation of technical as well as economic impact of process success.

The best field test site identified thus far is a natural gas field with a well producing 1.4 million standard cubic feet (scf) per day containing about 3,000 ppm hydrogen sulfide. Current regional pricing for the "sour" gas is $0.90/1,000scf, and $2.40/1,000scf for "sweet" gas. The operator has determined that the gas is uneconomical to sweeten using conventional technology. Preliminary economic evaluation of this application shows that biotreatment of this gas will cost about $0.31/Mscf for consumables. Efforts to identify additional potential field sites for technology demonstration(s) continue.

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Characterization of Soluble Organics in Petroleum Waste Water

Laboratory methods are being adopted among Petroleum Environmental Research Forum members to ensure that results derived from North Sea and Gulf of Mexico (GOM) formation waters are directly comparable. To this end, ASTM D6081 (Proposed Standard Practice for Aquatic Testing of Lubricants: Sample Preparation and Results Interpretation) was selected by Statiol and ORNL to prepare formation water samples under conditions of ambient pressure and moderate temperature. A water accommodated fraction vessel was constructed for equilibrating crude oil/water phases prior to analysis.

Shell provided two barrels of crude oil to begin characterization of formation waters from a GOM drilling well. The crude oil will be contacted with a prepared water (defined by Phillips) simulating GOM brine at the drilling site. The contacts will be performed under various laboratory conditions (pH, temperature, water cut, alkalinity). Information concerning the type and quantity of organic constituents extracted into the brine simulant will be forwarded to Marathon to be incorporated into a predictive model for estimation of the extent of contamination of formation waters under drilling conditions. Remaining industry participants will supply crudes from other GOM sites, once the oil provided by Shell has been fully tested.

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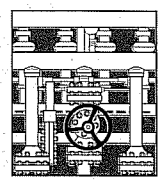

Downstream Environmental Technology

Bioprocessing of High-Sulfur Crudes

Base-case, liquid-phase horseradish peroxidase (HRP)-catalyzed reactions of dibenzothiophene (DBT) in acetate-phosphate buffer and in acetate-phosphate buffer/ethanol-propanol solvents were conducted. The liquid-phase experiments showed DBT conversion and the production of the DBT sulfoxide and/or sulfone, with propanol solvent increasing conversion and yield.

Critical-fluid HRP-catalyzed reactions in carbon dioxide were conducted (2,200 psi, 40°C) using HRP enzyme in which enzyme preparation and fluid composition were varied. Initial on-line sampling indicated that DBT was being consumed but did not detect any of the expected products. Follow-up control experiments were conducted to close the mass balance for DBT in the critical fluid experimental system. A mass balance for DBT was obtained without the HRP enzyme. In experiments repeated using HRP, no DBT oxidation products were observed. The on-line sampling procedure is still problematic, with efforts under way to improve it.

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Critical-fluid HRP-catalyzed reactions in 98/2 mol% ethane/methanol (2300 psi, 40°C, enzyme on reactor bottom) produced 0.3 to 3% sulfone product ($DBTO_2$). Aspen simulations demonstrate that two phases are present for 98/2 mol% ethane/methanol containing 0.45 mL water and that the liquid phase varies slightly in volume. It has been hypothesized that high concentrations of localized hydrogen peroxide are inactivating the enzyme.

When the HRP enzyme was placed in a sintered element in the gas phase, no oxidation product was observed for the ethane/methanol reaction or a 98/2 mol% ethane/ethanol reaction. However, reaction in the stainless steel autoclave reactor afforded 29.6% $DBTO_2$, which strongly supports the hypothesis that the reactions are taking place in the liquid phase.

Critical-fluid hemoglobin-catalyzed oxidation of DBT in alkane/alcohol solvents were also carried out. These experiments demonstrated oxidation of DBT to the DBT sulfone. However, conversion rates were lower in the critical fluid phase than at liquid-phase conditions. Conversion to the sulfone—dependent on solvent, temperature, and hydrogen peroxide concentration—ranged from 0.3 to 9%. The oxidation in pure methane did not proceed.

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Biological Upgrading of Heavy Oils

Industry participants identified two groups of alkanes of primary interest as targets for biocatalysis: C_8 to C_{10} alkanes and C_{12} to C_{16} alkanes. Three different biocatalysts were tested for their activity against target alkanes. Two of the biocatalysts were effective in the transformation of octane and pentane. One of the catalysts is commercially available in drum quantities.

Although there is a significant amount of work being conducted on the genetics of alkane biocatalysts, there is very little information available on the physiology and kinetics of alkane bioprocessing. Project research continues to focus on octane (C_8) as a model compound. Biocatalysts developed at LBNL have been partially characterized for octane transformation. Half-saturation constants are estimated to be in the order of 0.1 μg/L, suggesting a high enzyme efficiency.

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Kinetics of Biochemical Upgrading of Petroleum

BNL continues to adapt biocatalyst strains with a mixture of organosulfur compounds such as phenyl sulfide and dimethyl sulfide, in addition to dibezothiophene and its metabolic intermediates. Several strains were purified and selected for testing in biochemical-upgrading activities.

The adaptation process improves the bioavailability of sulfur compounds in the tested biocatalyst strains. One approach to increase the solubility of organosulfur compounds is to use polar sulfur compounds or a phase transfer agent incorporated into the culture media. The increased solubility has increased the lag period of growth of several strains tested. Adapted strains were purified and tested for desulfurization activity.

Accompanied by the adaptation process, ultraviolet radiation and nitrosogunadian were incorporated to initiate mutation. The goal was to adapt the produced mutant for use with sulfur compounds as a nutrient source. Preliminary results show a few strains recovered from the treatment and then grew well with heavy crude oil. Isolating the mutant strains is in progress.

In laboratory tests, it was difficult to isolate the treated oil from the reaction mixture with good sample recovery and without alteration of its volatile contents. Much effort has been spent on centrifugal and solvent extraction methods. Both methods require additional testing.

Results were presented at the First International Conference on Petroleum Biotechnology: State of the Arts and Perspectives, Mexican Institute of Petroleum (see Publications, p. 5, Premuzic).

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Enzymatic Upgrading of Heavy Crudes via Conversion of PAHs

Based on experimental results, three tasks were identified for further work: (1) enzyme-active site modification using molecular biology techniques, (2) chemical modification of active sites, and (3) thermodynamic analysis of substrate partitioning. The first two tasks are aimed at improving enzyme activity, while the third task would provide proof for the hypothesis explaining substrate polycyclic aromatic hydrocarbon (PAH) partitioning between solvents and the enzyme phase. Priority is being given to the first task, because genetic modification is expected to yield the most favorable results towards enzyme activity and stability improvements.

Task 1: Lignin peroxidase (LiP) was selected as the enzyme candidate for modification because of its high activity toward pyrene conversion. The enzyme is also known to depolymerize lignin, which is close to asphaltene breakdown. The University of California-Irvine provided the LiP gene to ORNL for experiments for expression

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of the enzyme into a recombinant-friendly host organism.

ORNL is attempting expression of LiP into a Pichia pastoris strain. Advantages of this host for expression of higher eukoryatic proteins include 10- to 100-fold higher expression levels, and suitable protein processing, folding, and post-translational modifications.

Task 2: ORNL attached alkyl groups at the active enzyme site via reductive alkylation. A two- to fivefold increase in activity was observed with pyrene and pinacyanol chloride as the substrates in 10% acetonitrile-water mixture. The researchers are producing larger quantities of the C1-modified enzyme to study the activity at higher solvent concentrations.

Task 3: Previous experiments for pyrene conversion in acetonitrile-buffer mixtures show negligible activity in higher than 40% acetonitrile concentrations. Additional experiments are being done to obtain a complete dataset. These results are expected to give thermodynamic reasons for the lack of pyrene conversion at higher organic phase concentrations using the unmodified enzymes.

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A Predictive Model of Indoor Concentrations of Outdoor $PM_{2.5}$ in Homes

Work began on an uncertainty analysis of size-conserved, chemically-inert $PM_{2.5}$ that includes the effects of air exchange rate, penetration factor, and deposition. Measured probability distributions of infiltration rates as a function of region of the United States and by season were obtained from published literature. Theoretically and empirically determined estimates for penetration factors and deposition rates were taken from published literature and current research. A model of size-conserved $PM_{2.5}$ was then coded in spreadsheet form, and a commercially available Monte-Carlo package (Crystal Ball) was identified to perform the numerical uncertainty analysis. A time-dependent model of ammonium nitrate formation and dissociation was then developed to express indoor nitrate particulate matter. Improvements were made to the integrated collection and vaporization technique for highly time-resolved measurements of fine-mode carbonaceous particles. With the technique, aerosol is deposited on a metal substrate that is subsequently heated by a flash vaporization process. The carbon in the deposited particles is assayed through measurement of the evolved carbon dioxide. Response of the system was increased from 25% to 85%.

Preliminary experiments investigating particle penetration and deposition were performed at the Richmond Field Station in California. The method reduced the particle concentration indoors and then measured the concentration rebound over time. During the entire experiment, tracer gas measurements were taken at three locations within the building. Particle concentrations were measured every three minutes with an aerodynamic particle sizer (APS), sizing 0.5 to 10 μm-diameter particles, and an optical particle counter (LAS-X), sizing 0.1 to 3 μm-diameter particles.

The building being used is fairly "leaky," and the day tested was windy, leading to high infiltration rates. Future tests will look at a variety of wind conditions, as well as controlled depressurization. Preliminary values from the first set of data yield good curve fits for all particle-size ranges.

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Industry Participants

The Partnership's World Wide Web site includes a complete list of industry participants and their project affiliations. See:

http://www.sandia.gov/ngotp

Real-Time Characterization of Metals in Gas and Aerosol Phases

The objectives of this project are to develop a high-precision field portable instrument for real-time measurement of elemental composition in gas and airborne particulate matter in source emissions. Researchers also plan to test this instrument in laboratory and field conditions to collect performance data for improving the ruggedness of the instrument. A program was developed based on the LabVIEW graphical language. Successful laboratory tests of the program will allow it to be incorporated into the field-portable laser-induced plasma spectrometer unit.

The spectrometer design utilizes a patent-pending aerosol beam-focusing technology that can concentrate airborne particles of diameters less than 2,500 nm to a focal point of spot size smaller than that of the laser plasma. ORNL demonstrated that this focusing improves the sensitivity of real-time spectroscopic measurement.

ORNL fabricated and tested the optical components of the aerosol-focusing module for repeated thermal stress in furnace and found that the module could withstand heat up to 18 hours.

Field experiments will be conducted at an oil-combustion facility in east Tennessee. The facility has several waste streams containing metals and metal compounds. The temperature in the test stream in which the instrument will be tested is approximately 200°C.

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