Partnership Progress

Natural Gas & Oil Technology Partnership

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A New Year

The new fiscal year brings opportunities for improvement. We must adjust to changes in the structure of the defense laboratories, current limitations on travel and foreign interaction, and decreased support for the application of defense computational science to oil and gas technology. However, we still seek growth, such as identifying ways for industry associations to communicate their needs to technology developers. Such guidance maintains program continuity and encourages development of new proposals. As both industry and the laboratories refocus their R&D efforts, we seek to maintain the connections that have made the Partnership successful.

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

Featured Partnership Project

Improved Prediction of Multiphase Flow

Most petroleum reservoirs appear to have wettability states other than strongly water-wet. However, most of the computer simulators used to predict fluid flow in these reservoirs are based on constitutive relationships among relative permeability, fluid saturation, and capillary pressures solely for water-wet porous media. In order to describe fluid flow accuately in mixed-wet reservoirs, simulators must account for the proper distribution of the different fluids in multiphase systems. This Partnership project focuses on the development of a model for multiphase flow in mixed-wet reservoirs. The model is based on fluid distribution for as many as three fluids (water, oil, and gas) in the reservoir pore spaces.

The Multiphase Flow Model

For the past three years, project researchers, including representatives from PNNL, the University of Texas-Austin (UT), Auburn University, Spirit Energy (Unocal), Mobil Oil, and Landmark Graphics, have worked to develop an advanced multiphase flow model. The new model will give oil producers a tool for predicting oil recoveries in mixed-wet reservoirs, which in this model describes a condition where the small pores in the rock are water-wet and the larger pores are intermediate or oil-wet. Important decisions concerning the commercial development of mixed-wet reservoirs already have been based on the project's modeling results. However, the industry needs models that can predict multiphase flow with greater accuracy.

Project participants have been developing and refining their multiphase flow model through a combination of theoretical, experimental, and numerical work. The results have been significant: Important aspects of the theory were tested against detailed laboratory experiments, the tested segments of a two-phase model were

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Multiphase Flow Model

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implemented in a UT numerical simulator, and a variety of numerical tests and laboratory waterflood experiments were completed to study the performance of the improved simulator.

Although the complicated issue of fluid flow in mixed-wet reservoirs is far from being resolved, the project has provided important new insights and datasets. The participants expect to conclude the project with full implementation of a three-phase model and transfer the acquired knowledge to the petroleum industry.

Modeling Mixed-Wet Systems

Wettability—the tendency of one fluid to adhere to a solid surface in the presence of other immiscible fluids—is important because it affects the distribution of fluids in the pore space and the rate of oil recovery by drive fluids, such as water. A successful reservoir model must be able to simulate mixed wettability, and that requires an accurate description of the relationships among relative permeabilities, fluid saturations, and capillary pressures (k-S-P relations) in mixed-wet systems.

Two approaches are used to describe the k-S-P relations in simulators. The most common interpolates among laboratory measurements. A drawback is that these data reflect only the saturation paths measured in the laboratory. Consequently, any simulations of saturation paths different from those measured will likely be in error, and investigations of alternative production scenarios will be very limited.

The other approach uses a parametric model that mimics fundamental fluid-flow processes to predict the linked behavior of capillary pressure and relative permeability. This method is preferable to extrapolating from measured data points because the models have greater utility and consistency. Parametric models can also be used to describe an infinite number of saturation path histories. However, these models are not without drawbacks: They often are complicated and require more calculations and computer storage. Also, in the petroleum industry, capillary pressure and relative permeability data are usually obtained using different samples in different experiments. This approach presents difficulties because the datasets may be inconsistent, which could lead to unrealistic predictions.

Testing the Model

A valuable resource for the industry would be a thoroughly tested capillary pressure/relative permeability model that does not have these limitations, that accounts for reservoir wettability conditions, and that yields accurate predictions of multiphase flow. The Partnership is testing such a model. The model can be used to simulate a variety of field operations. It also can be applied to environmental problems, such as product spills and remediation, and be used to evaluate new prospects where laboratory data are limited or not available.

Researchers have developed two- and three-phase (i.e., gas-oil-water) k-S-P models. The three-phase relationships are considerably more complex to model. The four combinations of drainage and imbibition saturation paths for a two-phase system multiply to eight in a three-phase system. In addition, experimental three-phase data for testing and developing models are scarce.

The Partnership has developed two- and three-phase hysteretic k-S-P models for mixed-wet reservoirs. The theoretical models have been tested against published S-P data, laboratory S-P data recently obtained at PNNL, and numerical simulation results obtained with a modified version of the UTCHEM (University of Texas CHEMical compositional simulator) code. Figure 1 shows the results of the published S-P data comparison. Agreement between the experimental data and the model predictions was good.

To test the model against recent laboratory S-P data from PNNL, two experiments were conducted using unconsolidated sand packs. In general, the model described the mixed-wet experimental data very well, indicating that the model is capable of describing S-P relations in mixed-wet, oil-water systems in porous media.

To test the model against numerical simulation results, simulations of waterflood oil recoveries in petroleum reservoirs were conducted using a modified version of UTCHEM—a multiphase, multicomponent, three-dimensional finite-difference simulator. The results yielded behavior like that observed in mixed-wet petroleum reservoirs, suggesting that the mixed-wet k-S-P model is capable of predicti-

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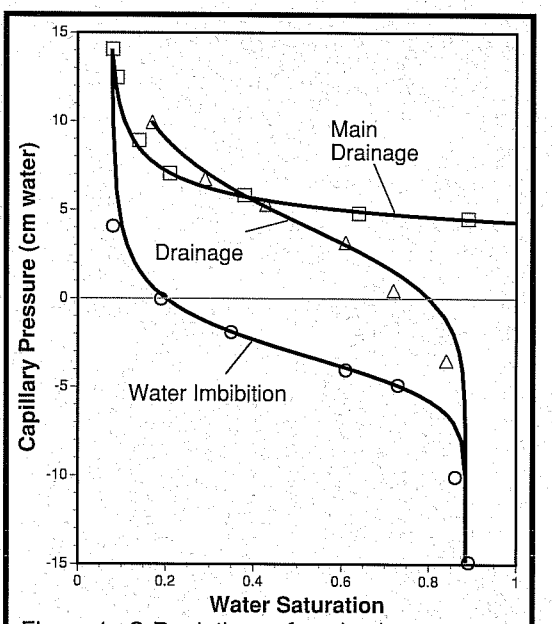

Figure 1. S-P relations of a mixed-wet core, showing experimental (symbols) and modeling (solid lines) results.

Model Testing

Continued from Page 2

ing fluid behavior in mixed-wet porous media. The best-fit modeling analysis suggests that the model is able to capture the salient characteristics of mixed-wet porous media, although further tests are needed.

The k-S-P model contains submodels for relative permeability and capillary pressure. Two experiments using two- and three-phase S-P measurements were conducted to test the submodels. Figures 2 and 3 show modeling results and experimental data for the first experiment. The model described the experimental mixed-wet capillary pressure data of the first saturation path scenario very well. There were only slight discrepancies in the water saturation paths.

The data from the two capillary pressure experiments did not include all possible saturation paths that the model is capable of describing. Therefore, these results are considered preliminary. A more rigorous test of the model will require measurement of different saturation paths.

For saturation paths in the first experiment, water and oil relative permeabilities were predicted using the relative permeability submodel. Predicted water relative permeabilities are shown in Figure 4, and predicted oil relative permeabilities are shown in Figure 5. The relative permeability submodel predicts a continuous change in water and oil relative permeabilities as the fluid system changes from a two-phase to three-phase system and back again to a two-phase oil-water system with entrapped gas.

Test results show that the capillary pressure submodel characterized the experimental capillary

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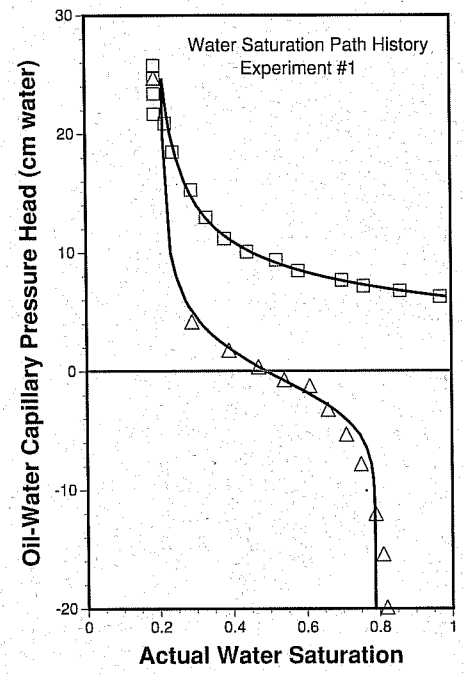

Figure 2. Two- and three-phase mixed-wet S-P data (symbols) and best-fit modeling results for water.

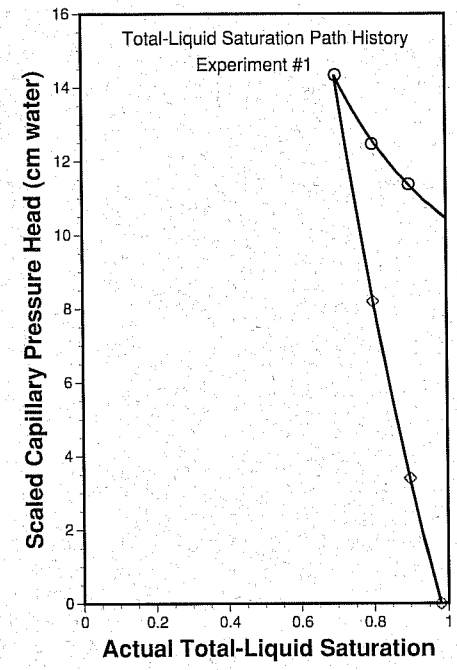

Figure 3. Two- and three-phase mixed-wet S-P data (symbols) and best-fit modeling results for total-liquid saturation.

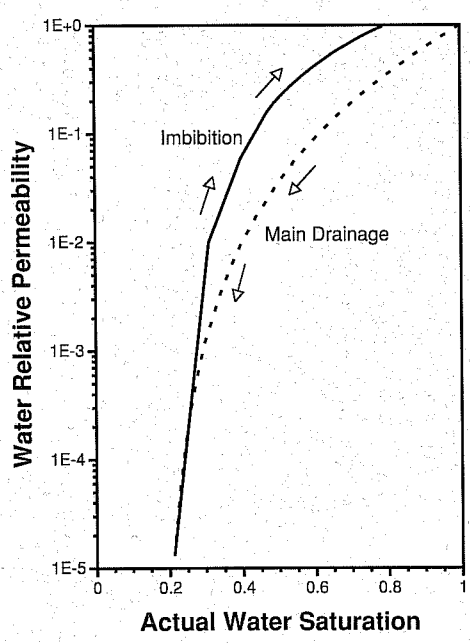

Figure 4. Predicted two- and three-phase water relative permeabilities for the saturation path history of the first experiment.

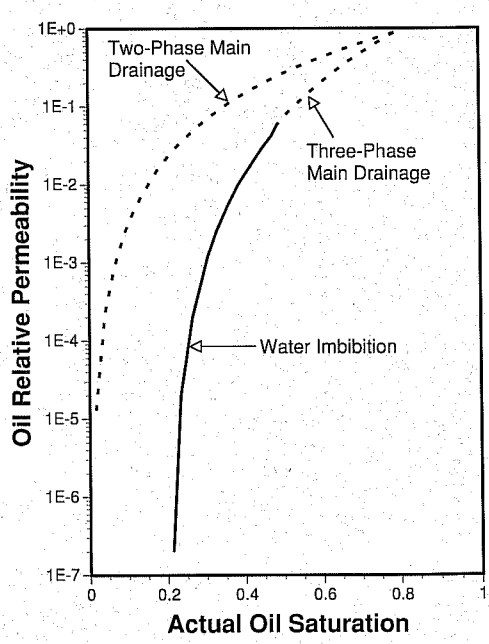

Figure 5. Predicted two- and three-phase oil relative permeabilities for the saturation path history of the first experiment.

Model Application

Continued from Page 3

pressure data very well, which suggests the model can be used to describe S-P relations in mixed-wet porous media. However, further investigations are needed to evaluate whether mixed-wet k-S-P relations should include algorithms for modeling nonwetting fluid entrapment.

Model Application

The Partnership's advanced mixed-wet k-S-P model was developed for use in oil reservoir simulators to predict multiphase flow behavior. Resulting simulations could be used to help explore alternative production scenarios and develop management strategies that minimize financial risks and maximize economic benefits. Initial results at PNNL suggest the mixed-wet k-S-P model may yield reasonable predictions of multiphase flow behavior; however, more rigorous tests are planed to verify these results.

Accomplishments

Accomplishments of the past three years follow:

- Two- and three-phase hysteretic capillary pressure/relative permeability theoretical models for mixed-wet reservoir were developed and tested against a variety of experimental datasets.
- Several two- and three-phase capillary pressure experiments were conducted in mixed-wet sand packs to test the theoretical model.
- Because virtually no consistent datasets were available in the literature, consistent laboratory datasets were developed. Programs were written to analyze the data and to compute mixed-wet model parameters. The model parameters computed from the laboratory data are consistent and make physical sense.
- Waterflood experiments were conducted to test the transient nature of the new theory. Experiments produced detailed quantitative data, which were used to test the implementation of the theory into the simulator. The model was able to predict cumulative oil production accurately.
- The full two-phase hysteretic theory was implemented into the simulator. The three-phase implementation has been initiated.
- Direct measurements of capillary pressure and relative permeability in single experiments were obtained using newly designed pressure cells. Unique and consistent datasets were obtained for water-wet mixed-wet systems. Results correspond to measured data.

Acknowledgment

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Salvo Researchers Win R&D 100 Award

Partnership researchers who created oil exploration algorithms won an R&D 100 Award in the annual competition for innovative technology sponsored by R&D Magazine. The researchers won presenting a 3D method to find oil that is superior to currently used 3D commercial packages.

Salvo is a code that produces higher quality seismic images than traditional methods. The winning researchers are Curt Ober, David Womble, and Louis Romero of Sandia National Laboratories (SNL), Ron Oldfield and Robert Gjersen, former SNL researchers, Charles Burch of Conoco, Inc., and Scott Morton of Amerada Hess Corporation. The research was conducted through the Computational Technology project, 3D Imaging of Complex Geologies: Remote and Rapid Processing of Terabyte Datasets.

"Most of the remaining oil and gas in the United States lies in regions of complex geologies where traditional seismic imaging methods are frequently unable to produce high-quality images, which increases the risks of drilling dry wells," the researchers wrote on their contest application. Wells frequently cost more than $10 million each to drill, and in cases of extreme difficulty can run as high as $50 million; thus, dry holes are expensive. Failure jacks up the overall cost of oil to consumers and can put small oil companies out of business by increasing operational costs. However, 3D seismic datasets can be terabytes in size, making them time consuming, therefore costly to process.

Salvo's algorithmic improvements, designed to use the power of massively parallel computers, result in time savings between 10 percent and 40 percent, compared to other programs.

Partnership News

Partnership Review

The Partnership completed the review of preproposals for FY00 in Drilling, Completion and Stimulation; Oil and Gas Recovery; and Diagnostics and Imaging. Approximately 40 preproposals were submitted. Based on the industry reviews, we are selecting preproposals to go forward to full proposals, and we are notifying the principal investigators. The full review of the new proposals and ongoing projects will be held in Houston (Drilling, Completion and Stimulation, November 16; Oil and Gas Recovery, November 17; and Diagnostics and Imaging, November 18).

ACTI

The Advanced Computational Technology Initiative (ACTI) has been one of the most successful components of the NGOTP. With the onset of ACTI, the Partnership greatly expanded in 1995, both in terms of the number of projects and the number of industry participants. Some ACTI projects have been highly successful on their own. For example, several R&D 100 winners have emerged from this program. In addition, these ACTI projects have provided the basis for traditional projects within the Partnership technology areas.

However, unless there are major changes in the proposed FY00 congressional budget, the Defense Programs (DP) and Office of Science (SC) contributions to ACTI will disappear. If this happens, we will see several significant programs in computational modeling disappear or be mothballed. Using the traditional new proposal and review process, the Partnership may decided to include evolutions or outgrowths of these projects in the coming years.

Publications

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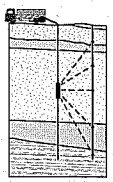
Project News



Diagnostic & Imaging Technology

Advanced Sensor Technology

Fabrication of the mechanical and micromachine electronics was completed. A design problem with the flex circuitry that feeds power and telemetry conductors to lower array levels was found. A delicate, long lead-time electronic component failed and reduced the number of array levels available for testing to two levels on each array. Four microholes (2 3/8" diameter, and 300'–500' deep) were drilled for installation of the arrays.

The arrays were sequentially installed and integrated into two seismic reflection lines. An inspection of field records shows signals with high noise, in comparison to data acquired from geophone spreads.

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Single-Well Seismic Imaging Technology

A good fit was obtained with a curving salt dome edge using velocities obtained in previous crosswell work. These results were used to model the sensitivity of the salt edge location as determined by means of a crosswell survey. Researchers found that full tomography would not locate the edge, but a simple zero offset crosswell would find it. They decided to perform a zero offset crosswell survey using one well inside and the other well outside of the dome.

Computational simulations of borehole seismic data previously acquired at the Bayou Choctaw Field test site, in Louisiana, were undertaken using a 3D elastic wave propagation algorithm. A parallel version of the algorithm was sited on a 32-node distributed memory cluster. The synthetic data provide a good match to crosswell P- and S-wave arrivals but have much stronger salt flank reflections/refractions than observed in the field data. More realistic geologic representations of the sediment/salt interface (curved, rugose, or transitional) are expected to diminish the computed reflection amplitudes.

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Seismic Imaging Behind Production Tubing

Travis Peak and Pettet formations (Chapel Hill Field, near Tyler, Texas) were selected to image the target reservoir formation with crosswell reflection imaging, with and without production tubing in the receiver well. This is a thin, highly productive sand which is not continuous between all wells in the area. Depth is approximately 8,200'. Two wells were selected in the field with a separation of approximately 1,520'.

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Large Downhole Sensor Array

Participants assembled the general-purpose, deep well pump. This wireline-deployed pump can be used to inflate bladders and operate actuators downhole. The pump is configured to allow reverse operation by reversing polarity, allowing the control to be accomplished via the power lines. The concept differs from other downhole pump/motor designs in an effort to improve technology.

The design team expects to have another magnetic-clamped geophone module completed in early September. This latest module uses temperature-resistant metal bellows to clamp the geophone module.

Researchers began the construction of a bellows-clamped module for its attachment to a coiled tubing segment. This module, which will not contain the geophones or electronics, would clamp to a section of tubing that does.

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Improved Prestack Kirchhoff Migration

The kinematic portion of the wavefront construction code is nearly complete. It was used to match first-arrivals in waveforms in finite-difference seismograms for a salt model. Arrival times were calculated using a two-point ray-bending algorithm.

Numerical modeling of wave propagation in the vicinity of a salt body showed that interface waves between the base of salt and surrounding sediments are strong at offsets far from the salt.

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Locating Geopressured Hydrocarbon Reservoirs

A curve-fit algorithm was developed for the dual minima gas solubility data. A near exact fit to the equation of state data proved not to be feasible, and instead, a piece-wise linear fit was used. The curve fit matches the charac-

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Project News (Continued from Page 6)

ter of the gas solubility data (two minima in temperature, increasing with pressure, etc.), and is therefore thought to be acceptable for testing the conceptual model.

Researchers investigated whether a thermal anomaly is associated with the West Cameron (WC) Block 66 Field. If multiple vapor-lock seals are formed around specific isotherms and an out-of-phase relationship exists between the seals, thermal anomalies are to be expected. Using the available well log data, temperature versus depth plots were constructed. Assuming multiple seal formation around 165° and 270°F, isotherm maps corresponding to those temperatures were constructed over the WC Block 66 Field. Based on earlier work, seal formation around these temperatures corresponds to a gas composition of 25 percent carbon dioxide and 75 percent methane.

When a NW-SE thermal cross-section is constructed based on the isotherm maps, a region of low thermal gradient is observed beneath the field location. The region lies in the depth range of 8,000' to 14,000'. The low gradient is due to an expanded depth interval between the two isotherms of interest. This expansion translates into an expanded depth interval between vapor-lock seals. This situation can create a possible travel-time anomaly for deep seismic reflectors below the field. The anomaly is a seismic "pull-up" in the two-way travel time. Like the model, deep reflector travel times measured beneath the WC Block 66 Field were found to exhibit a seismic "pull-up."

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The 3D Seismic Analysis Using SEG/EAGE Dataset

The cost-effective imaging technique that was recently developed (termed "common-azimuth migration") was refined through the use of more reference velocities. This yielded an image from the SEG-EAGE test dataset that is uniformly superior to the image obtained from Kirchhoff migrations. The goal is to develop a method that is nearly as fast as Kirchhoff, yet provides a better seismic image.

Analytical comparison of two imaging methods also showed that common-azimuth migration is more accurate than offset-plane-wave migration, even in a constant-velocity medium.

A new method was developed for systematically incorporating nonlinear uncertainties in the estimation of reservoir parameters. The method is being combined with ultrafast neural network learning to yield more accurate pseudo well-logs (gamma rays, resistivity, and porosity) from seismic data.

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Vertical Seismic Profiling While Drilling

Initial testing on a new noise attenuation operator for high-energy noise produced by various sources, such as ground-roll, burst-noise, and rig-noise, is very promising. Researchers will continue testing this operator on additional datasets.

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Oil & Gas Recovery Technology

Applied Production Technology (APT)

Artificial Lift Using Foam Pigs

DOE has submitted a patent.

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Optimizing Reservoir Production

Researchers tested renormalization and nonuniform coursening (RNC) scale-up for displacement processes through a number of different datasets, including data generated statistically and data obtained from actual reservoirs.

Researchers also examined the performance of RNC scale-up in the presence of gravity.

A number of modifications were made to the algorithm for calculating the upscaled relative permeabilities. An algorithm was tested earlier this year using novel boundary conditions, based on an analogy with electrostatics. It appears that these new boundary conditions are quite robust with respect to the grid coarsening algorithm. In many cases, excellent results are obtained without having to coarsen the grid nonuniformly. Researchers are comparing the two coarsening methods in a variety of flow scenarios.

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Extending Borehole EM Imaging

The focus of this project is time lapse crosswell electromagnetic imaging, often utilizing a single steel-cased well, located at a heavy oil pilot site in Lost Hills, CA. Two new observation wells, drilled in August, will provide core samples and well log information for this steel-cased crosswell imaging within a waterflood zone. Imaging is planned to begin in November.

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Improved Prediction of Multiphase Flow

Researchers are working on a parametric model that can be used to predict relative permeabilities, fluid saturations, and capillary pressures. (See the feature article, on Page 1.)

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Improved Waterflooding

At the University of Wyoming, researchers working with crude oil/brine/rock systems from the Powder River Basin of Wyoming (Minnelusa Formation), conclude that sandstone reservoirs containing clay offer the best prospect of improved oil recovery through choice of injection brine composition.

Participants completed the database search for additional historical field comparisons of the effect of brine composition on oil recovery. Because a limited amount of historical data is available, efforts are now focused on instituting a field pilot test to investigate the effectiveness of injection brine modification to improve oil recovery.

Laboratory studies focusing on a chalk outcrop (Stevens chalk) show that with synthetic reservoir brine as the connate brine, a change in the concentration of the invading brine had only a slight effect on oil recovery. This is the most realistic situation with respect to a reservoir.

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Development of a New Generation Petroleum Reservoir Simulator

The integrated parallel accurate reservoir simulator (IPARS) black oil model was validated using the Society of Petroleum Engineers' (SPE) comparative solutions, as well as by comparing the output to cases run using Eclipse. Some small improvements were added to the code, including a new, three-phase relative permeability model, and some new well models. The physically sound, 1-million-grid-block, three-phase black oil cases were constructed. Three years of simulation now run in five hours on 32 processors of a PC cluster linked with a Myrinet gigabit switch.

Based on recent success in applying ANL's ADIFOR tool (automatic differentiation in FORTRAN) to the IPARS compositional simulator, a new FORTRAN 90-based toolkit was begun and partially tested. When fully implemented, this new object-based toolkit will allow rapid evaluation of the robustness and efficiency of different formulations.

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Fluid Identification Acoustic Logging Tool

Researchers developed a comprehensive theoretical model for the cylindrical resonator sensor and now have experimental confirmation of the theoretical predictions. Recent experiments with this resonator show that immersing the sensor in the liquid bath does not degrade the sensitivity of the sensor in any way. Participants were able to differentiate liquids that have very close acoustic properties. (It would have no difficulty in discriminating between oil and brine.)

While determining the composition of a mixed-flow system consisting of gas, oil, and water, it was difficult to obtain an accurate reading of the composition because of the presence of the gas. To solve this problem, researchers developed an acoustic, phase-separator that first separates the gas from the mixed-phase system. Once separated, the composition of the oil+water system is determined separately from the gas volume.

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High-Resolution Reservoir Characterization

Researchers tested their algorithm against a conventional iterative pressure inversion method. Synthetic pressure datasets were generated and inverted using both approaches. The new approach, which utilizes the arrival time of the peak slope of the pressure transient, was found to be more than an order of magnitude faster than previously used methods. The new algorithm appears to be more robust than methods that directly match pressure amplitudes.

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Measuring Sucker Rod Pump Parameters Downhole

Instrumentation needs are being identified in order to test the clear plastic pump at the University of Texas (UT). An approach for mounting the pressure gauges was chosen.

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Project News

Drilling, Completion, & Stimulation Technology

Tiltmeter Hydraulic Fracture Imaging

Pinnacle Technologies successfully monitored a hydraulic fracture in a steamflood where the temperature in the tools was greater than 120°C (~250°F). There were no failures, and the fracture geometry was mapped successfully. They also mapped a frac in real-time using surface tiltmeters. Radio modems were used to collect the data as the frac progressed, which enabled the calculation of an azimuth five minutes after the pumping started.

Researchers retrieved the data from a pair of tiltmeters in a seismic vault near Elko, NV. The tiltmeters were set to record the tilt signal every four minutes, which is near the maximum sampling interval. Nearly a year of data is available for a long-term drift study.

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Advancing MWD into Ultra-Deepwater Drilling

Researchers are exploring alternative and simplified signal processing techniques to evaluate whether some of the constraints imposed on signal processing can be relaxed on real data.

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Directional Underbalanced Drilling and Microdrilling

Drilling and Completion Plan

A 1-11/16", outside diameter (OD), 5:6 lobe multistage mud motor was deployed on 1", OD coiled tubing with a release sub and check valve. This was assembled in a previously-drilled, shallow starter hole and completed with a grouted conductor pipe. An improved conductor pipe design and a near-optimum bit design for the less gummy clays in the basin sediments allowed the second two wells to be completed in two days. All wells were completed with 1.66", OD PVC flush-joint casing sealed with bentonite grout.

Coiled-tubing Micro-drill Rig

A unitized mud cleaning system was mounted on a trailer and transported to Fenton Hill (Los Alamos). A 2-3/8'-diameter, 60'-deep hole was drilled with a low-viscosity drilling fluid using the new mud-cleaning system and the coiled-tubing unit. The coiled-tubing unit and mud-cleaning system performed well at moderate drilling rates.

Instrumentation

Programming of the drilling data acquisition system on a Labview™ platform was completed, and the data acquisition system was successfully demonstrated during the Fenton Hill demonstration; however, the system failed before the first hole was completed. Several problems with the data system were identified before a total system failure took down the system.

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Perforation Dynamics in Geological Media

The third, computer-assisted tomography experiment (designed to measure the permeability in a Torrey Buff sandstone core subsequent to perforation) was performed at Pennsylvania State University. Torrey Buff is a tight, medium-porosity sandstone with an incipient permeability of 1–3 mD. It was found that, even with a 750 psi underbalance, a clean perforation was not obtained, and the tunnel was filled with damaged rock debris, explosive debris, and jet metal.

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Drill Cuttings Injection Field Experiment

The field work associated with this project was completed during early summer, through the final logging runs and survey work at the site. A total of four core holes were completed through the fracture zone. Characteristics of the fracture system were determined by examination of the core, analyses of imaging logs, detection of tracers in the injected materials, and comparisons of diagnostic techniques (microseismic and tiltmeter) with the observed fractures. Three papers were presented at the 1999 Rock Mechanics Symposium describing the overall field activities, the microseismic results, and the tiltmeter results. (See Publications, Page 5)

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Seismic Stimulation for Enhanced Oil Reservoirs

Drainage and imbibition tests were performed on a 1"-diameter sandstone sample, using 3 percent brine as the wetting phase and 10-weight oil as the

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non-wetting phase. Baseline and stress-stimulated production and fluid pressure drop data were obtained at constant flow rate as a function of saturation. Tests were performed with both zero and 300 psi fluid back-pressure. Mechanical stress stimulation was applied in three different ways: (1) continuous-wave 50-Hz oscillations, (2) broadband noise, and (3) a repetitive, one-minute frequency sweep from 20 to 200 Hz and back (30 seconds up and down).

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

Difference images of electrical resistivity tomography (ERT) field surveys obtained in March, and subsequently in May, show progressive changes in the electrical properties in the field, intensifying with respect to the February baseline data. These changes indicate the direction of steam and fluid movement across the field, intersecting a plane of horizontal production wells and approaching the location of the two high-resolution arrays.

The July difference image reveals changes in the field that are consistent with changes in field operations. The boiler operator reported repeated boiler outages prior to collection of this last dataset. The apparent increases in resistivity, revealed in the July difference image, are likely related to the decrease in steam injection rate, relative to the injection rate over the previous several months. The crosswell ERT data continue to indicate changes occurring in individual formation units, although less so during this time increment than the previous few months. This is also consistent with the reduced steam injection.

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3D Analysis for Induction Logging

The web site created to describe the project includes pdf files for downloading of recent articles, presentations, and publications generated from this project. The site can be found at **http://132.175.127.176/ngotp/induction/home.htm**.

Incorporation of anisotropy into the 3D finite difference code is progressing, with the following developments to report:

- A storage scheme was restructured for the preconditioning matrices in the forward code to better utilize FORTRAN libraries (SBLAS) for optimized matrix/vector operations; and
- A method was developed to simulate the propagation of low-frequency electromagnetic (EM) fields in media with arbitrary, anisotropic electrical conductivities. (Augmentation is under way on the existing modeling software which currently simulates propagation in isotropic conductors.)

The "low-frequency preconditioner" which significantly increases the rate at which forward models are evaluated was updated to account for EM induction in anisotropic conductors.

Researchers at the University of Wisconsin-Madison are analyzing the different analytical solutions available for modeling boreholes and anisotropic media.

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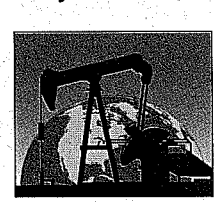

Upstream Environmental Technology

Monitoring of Particulate Emissions

The flow reactor in the SNL char laboratory was used to make simultaneous measurements of the temperature, size, and velocity of burning particles of coke formed during combustion of heavy fuel oil in spray flames in a boiler. Particles having the same size and velocity did not all have the same temperature, revealing that there are differences in reactivity among the particles produced from a given fuel under a given set of furnace conditions. The width of the distribution of oil coke reactivities was similar to that of a bituminous coal char, suggesting that reactivity differences may arise from differences in the thermal histories of particles during coke formation, as well as from differences in the composition of the heavy ends from which the coke is formed.

Measurements of particulate matter (PM) at natural, gas-fired sources used in upstream operations revealed that total PM, as determined by US EPA Method 5, was much greater than the sum of the individual components identified. Researchers used laser-induced breakdown spectroscopy for

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metals (iron, calcium, magne-sium, and sodium), a photoelectric aerosol sensor for polycyclic aromatic hydrocarbons, and a laser aerosol spectrometer for particles between 0.1 and 7.5 micrometers.

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Development of an In-Well Oil/Water Separator

Bench-scale testing is being conducted with a crude oil, designated Ladybug Crude, provided by Texaco. This is a Gulf of Mexico crude with an API gravity of 34.06°, a specific gravity at 60°F of 0.8547, a viscosity at 70°F of ~1030 centipoise (cP), and a viscosity at 80° F of ~217 cP. The tests were conducted at ambient conditions (70°–80°F).

Two problems were identified while operating with this crude: (1) the separator appears to be limited by the size of the heavy-phase and light-phase collectors, and (2) the shear created by the contact of the crude/water mixture with the outer surface of the rotor forms an emulsion that is difficult to break. The small size of the collectors resulted in both the aqueous and crude streams overflowing their respective collectors. This caused contamination of the crude effluent by the water and recycling of both the crude and water, back to the rotor inlet, which would reduce the throughput of the separator. A new housing was fabricated that increases the volume of the collector rings by approximately a factor of four. Tests with the new housing fed with TBP/dodecane and a dilute nitric acid solution indicated that the throughput of the separator was approximately doubled, while still being able to maintain <1 percent cross-phase contamination in both the aqueous and organic effluents from the separator.

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Stationary Source Emission Control

The plasma-assisted catalytic reduction process received two additional patents. Various aspects of the process are now covered by the following U.S. patents: "Plasma-Assisted Catalytic Reduction System." U.S. Patent No. 5,711,147, January 27, 1998; "Pre-Converted Nitric Oxide Gas in Catalytic Reduction System." U.S. Patent Number 5,891,409, April 6, 1999; "Catalytic Reduction System for Oxygen-Rich Exhaust." U.S. Patent Number 5,893,267, April 13, 1999.

Researchers completed installation of the piping between the full-scale plasma/catalyst aftertreatment device and the Cummins 6L, diesel engine generator set. The engine was operated at full flow. Researchers measured pressure drops across the major components and the temperatures at various locations for the full-flow case without insulation. Heated lines for chemical sampling of the exhaust gas are being installed. One line is being installed between the plasma and the catalyst to measure the plasma oxidation efficiency. The other line is being installed after the catalyst bed to measure the catalytic reduction efficiency.

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Reducing Chemical Use and Toxicity in Produced Water Systems

All data collection and analysis was completed on the use of nitrite to inhibit pitting corrosion. A new, composite-coated reference electrode was evaluated in the same pitting-corrosion test system. The electrodes have metals incorporated into a polymer coating that makes the surface conductive. Both silver- and molybdenum-coated electrodes were resistant to corrosion and thus would be useful as stable reference electrodes when used in very corrosive environments.

A new polished electrode concept was tested in a chemical-pitting cell. A positive correlation between the initial coupon surface preparation and pitting corrosion was demonstrated. A new test loop with seven metal coupons and three electrochemical noise probes was also constructed. Two different degrees of surface-polished coupons and electrodes were tested. The metal with the more polished surface (1 micron) had the greatest electrochemical noise pitting signal, as compared to the less smooth (600 grade) electrodes.

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Characterization of Soluble Organics

Members of the Petroleum Environmental Research Forum (PERF) met during the first week in October to finalize agreements on the specifics of oil and water sample selection and analytical protocol to identify their constituents. Regardless of sample origin, PERF members have requested that a number of characterization parameters be used to develop a model for predicting the toxicity of produced water during drilling operations. These include:

- crude oil,
- whole oil gas chromatography,
- deasphalting and liquid chromatographic separation,
- saturate fraction gas chromatography,
- thiophene analysis by gas chromatography with flame photometric detector,
- formation waters,
- major and minor cation analysis by inductively coupled plasma spectroscopy,

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- major and minor anion analysis by ion chromatography,
- light organic acid analysis by ion chromatography; and
- carbonate and bicarbonate by titration.

A summary of possible American Society for Testing Materials and Environmental Protection Agency methods was submitted to PERF staff for approval as analytical protocol for the required sample analyses. Analytical equipment is now being located and set up in anticipation of a sample submittal. Additionally, pressurized equipment is being acquired in the event that the PERF committee requests the preparation of simulants at high pressure and temperature.

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Sulfide Removal in Produced Brines

The investigation of additional sulfur sources for growth and maintenance of sulfide-oxidizing, nitrate-reducing bacteria is nearly complete. Researchers confirmed the utilization of thiosulfate and tetrathionate by what appears to be either a variant of Coleville Organism (CVO) or a closely related organism. Efforts are focusing on experiments to define the utilization of sulfide by these cultures after amplification on alternate sulfur sources.

In direct comparison to cultures of the original CVO isolate, the INEEL isolate can reduce nitrate (10 mM) and use thiosulfate (6 mM) fairly rapidly, and can use tetrathionate (3 mM) less rapidly. INEEL's isolate can oxidize sulfide in the presence of nitrate, although it is slower than the original CVO isolate. The original CVO isolate does not oxidize thiosulfate or tetrathionate.

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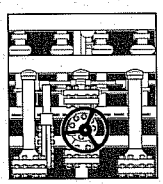

Downstream Environmental Technology

Bioprocessing of High Sulphur Crudes

Researchers configured a supercritical fluid bioreactor equipped with dual high-pressure sample valves. Initial system stability testing revealed some uncertainties associated with temperature control of components as assembled. Pressure control was satisfactory; therefore, modifications in the temperature-control system and reactor assembly are being made for improved stability and control. Researchers believe that isothermal system operation for sample introduction, treatment, and acquisition is functional. Solubility samples of dibenzothiophene (DBT) in supercritical carbon dioxide were obtained at 45°C from 900 to 2,900 psi.

Researchers fabricated a fiber optic-based absorption system for measurement of solute in supercritical fluids to be used to verify solubility measurements and sampling techniques. The fiber optic system is based on a constant volume static cell to minimize variations in fluid conditions between the dissolution and measurement regions. Multiple path lengths in a single cell will allow the determination of solubilities over a wide range of concentrations. The technique was evaluated and is reproducible. Absorption measurements for DBT in CO_2 at a series of temperatures and pressures were made. Solubility curves were generated for temperatures between 25° and 60°C, and pressures between 1,000 and 5,000 psi.

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Biological Upgrading of Heavy Oils

Cultures were tested for their ability to hydrogenate high-molecular-weight, polycyclic aromatic hydrocarbons (PAHs). Hydrogenation reactions occur, but yields are low. Low yields may be the result of poor reaction efficiencies, but it is also possible that the reaction is continuing past the desired product (dihydrodiol).

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Real-Time Characterization of Metals in Gas and Aerosol Phases

The field portable unit of a miniaturized laser-induced plasma spectroscopy system consisting of several advanced components (laser, detector, digital control, and aerosol beam-focusing device) was assembled. The final configuration of this prototype unit has a physical dimension of approximately 18" × 17" × 10" (L × W × H) and weighs ~50 pounds.

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

Researchers are assembling instrumentation and will plan for the various experiments required for evaluation of the terms in the mass balance equation.

Experiments will be performed in a "prototype" experimental house located at the Richmond Field Station of the University of California-Berkeley, as part of setup/calibration exercises and preliminary study before the SJV field studies.

Aerosol Dynamics initiated construction of double-cell systems for the simultaneous measurement of the concentration of indoor and outdoor $PM_{2.5}$ sulfates, nitrates, and carbonaceous aerosols. The systems are designed to yield 10-minute time resolution. Precision and accuracy testing and evaluation will occur this fall.

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Enzymatic Upgrading of Heavy Crudes via Conversion of PAHs

Enzymes active towards polycyclic aromatic hydrocarbon (PAH) conversion were modified with hydrophobic groups to make them active in organic solvents. Polyethylene glycol (PEG) and benzyl groups were attached to cytochrome c and its activity determined in organic media. Experiments were conducted in aqueous + aqueous-miscible solvent mixtures as well as with aqueous-immiscible solvents (toluene and decane). Results indicate improved activity of both modifications in aqueous-miscible solvent mixtures (up to 40 percent acetonitrile).

Enzymes require water to function; therefore, experiments with aqueous-immiscible solvents were conducted in the presence of water. Two different water contents were studied: ~0.1 percent and 5 percent. The activity of the enzyme was observed to be substantially lower in organic-immiscible solvent systems. The activity of PEG-modified cytochrome c, however, was found to be four times higher than the unmodified cytochrome c in a 95 percent decane - 5 percent aqueous buffer system with dibenzothiophene as the substrate.

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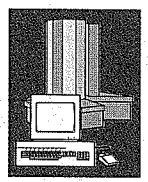

Defense Programs-Supported Computational Projects

Models for Deep Water Oil and Gas Production

VFLOW2D

The panel-to-point 2D fast solver was completed. For a simulation of a cylinder undergoing 20 diameters of motion, this improvement resulted in a speed-up of the total code by a factor of five. Workers continue to refine the wall-layer mesh to accurately resolve the boundary layer over a cylinder.

VFLOW3D

Improvements were made to the 3D fast solver to allow the fast multipole coefficients to be distributed across multiple processors instead of storing all coefficients on every processor. This improvement was verified, and the code is undergoing scaling performance testing for very large problems.

The code for 2D diffusion using the redistribution method was tested. The method was extended to 3D and is undergoing stability and performance analysis. Work is also continuing on convection and diffusion of the vorticity from the surface into the free stream. Two papers were presented. (See Publications, McBride, et. al., Page 5).

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Geologic Structure and Reservoir Mechanics

JAS3D was successfully coupled with the IPARS reservoir simulator. The coupling was two-way with pore pressures from IPARS internally passed to JAS3D and calculated porosities from JAS3D internally passed to IPARS. A simulation involving the surface subsidence resulting from four production wells was used as a demonstration calculation.

Improvements to the contact surface algorithm were implemented to handle numerical problems associated with multiple contact surface constraints acting on a node. The improvements made the algorithm more robust and allowed problems which were previously intractable to be solved.

Generalized finite-element (GFE) capability was added so that it is possible to enrich the interpolation in eight-node hexahedra, specifically for far-field problems. Two different classes of far-field problems were solved using the GFE approach.

A coupled fluid flow/geomechanics calculation was performed using the smooth, single-surface, cap plasticity

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model. This calculation repeated a calculation that looked at surface deformations in the South Belridge diatomite fields. The previous calculation used the extended Sandler-Rubin (ESR) cap plasticity model for the diatomite material behavior. The most important result from this comparison was that the calculation ran 3 1/2 times faster using the smooth model.

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3D Imaging of Complex Geologies

Researchers completed runs on seismic data for the SEG/EAGE salt model for line A-A'. These data were forward-propagated with absorbing boundary conditions at the surface. Thus, surface multiples are not produced in the data, which substantially reduces noise beneath the salt structure.

Salvo was announced as an R&D 100 winner on June 29 (See Page 4). The report for the Salvo users' guide was approved by the Partnership. The guide includes the manual for code use as well as complete documentation of the algorithms in Salvo.

Participants implemented and tested an absorbing layer in the current version of Salvo. Reflected energy from the side boundaries was greatly reduced, improving migrated images. Initial tests with the reduced-source migration show encouraging results.

Salvo was included as a "Cplant target application," and a series of performance studies on the Cplant architecture were done.

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Reducing Certain Seismic Data Acquisition Costs

Participants added shaped-charge experiments to their computer simulation activity. A series of four experiments is planned involving small (< 2 lb) high explosive charges detonated inside large concrete blocks. Researchers will compare the effects of a simple, cylindrical charge ("base case") to three other charges incorporating various shaped-charge features derived from computer simulations. Concrete is advantageous for its availability and well-characterized properties.

The final design of the experimental charges was completed, even though some details remain to be worked out.

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Coupled Rock/ Fluid Mechanics

Statistical techniques for assessing damage are further developed. In particular, the standard semi-variogram techniques are being utilized for damage characterization, and methods of texture analysis are being considered.

A histogram equalization algorithm was implemented to address the difficulty in normalization between scanning electron microscope image gray-scales when making statistical comparisons between the images. The algorithm changes the gray-level values in a given image so that the image histogram matches that of another designated image or any predefined histogram.

A semi-variogram analysis of shock recovery experiments is in progress. The statistics of the shock-recovered samples are being compared to the statistics of an undamaged sample.

Particulate Flow

Researchers are using the finite-element Navier Stokes solver, GOMA, to model the viscous resuspension of sediment (that removes the perforation damage) in an underbalanced perforating operation. Several improvements to the constitutive equation currently in GOMA were accomplished. Comparisons of model results to nuclear magnetic resonance data gathered in this project show that in some complex flows (those with significant curvature, for example) the original model did not predict the correct qualitative behavior. Improvements increased the types of flows for which the model is applicable.

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Near Wellbore Mechanics

MIMES is being used to model compaction zones often seen in highly porous sandstones, both in the field and in laboratory experiments. Compaction zones are regions of significant deformation caused by pore space crushing. Models of this phenomenon consist of an assemblage of particles of different sizes and shapes representative of sandstones. The particle assemblage is bonded at the contact points to simulate the effect of cement.

MIMES upgrades are now available at **http://mimes.mit.edu**, where a password-protected Zipped file can be downloaded. The web site also has sample problems available.

A MIMES training course was held for industry participants during May. The 2 1/2-day course had 11 participants who learned basic discrete-element modeling theory as well as code usage. MIMES was installed on the participants' own laptop computers, upon which they exercised the model on a wide variety of problems.

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Oil and Gas Data Infrastructure

The University of California-Santa Barbara started reporting the functionality of the Java™-based computer application. This data system was beta-tested extensively and subsequently installed in Sacramento in September.

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Advanced Reservoir Management (ARM)

The reservoir fluid-flow simulations show that two factors may be important to improve the past production match: porosity distribution and the presence of thief zones. Dynamic simulations demonstrate that the present geologic model may incorrectly account for reservoir storage capacity and original oil in place (OOIP). The dynamic match of water production history has been shown to be extremely sensitive to OOIP and to the existence of high-permeability zones or zones with high relative permeability to water. The dynamic modeling guided the reservoir study team to re-examine the existing geologic model and to reanalyze log data, particularly gamma and SP data, to improve calculations of shale fraction.

The data for geostatistical characterization of the Carpinteria Reservoir was imported into the RC2 software package. These data include six to eight well logs for each of more than 200 wells. Marker data, deviation survey data, and surfaces from marker distributions were also imported. Special core data exist for many of the wells, as do pressure test data.

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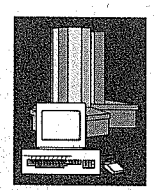

Office of Science-Supported Computational Projects

Subsalt Imaging with Marine Magnetotellurics (MT)

A new gravity-inverse algorithm was developed that is robust and suitable for incorporating into a joint MT-gravity-seismic inverse. The prototype joint MT-gravity inverse algorithm is working successfully under test conditions.

A consortium spawned the creation of a service company (Arnold Orange Associates), which provides MT surveys worldwide.

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Modeling and Processing Seismic Data

Researchers compared modeling results obtained using the extended local Rytov approach to results obtained using a finite-difference modeling approach. The Rytov approach models only one-way wave propagation and does not include reverberations. The finite-difference modeling approach models the complete wave equation. For media where backscattering is not important, researchers find that the Rytov approach gives traces that agree almost exactly with those obtained from finite-difference modeling.

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Optimal Fluid Injection Policy and Producibility

LBNL is developing an innovative set of computer-assisted-operations software tools and microsensors to promote higher, cheaper, and safer recovery from fractured, low-permeability oil fields. The following were demonstrated: (1) hydrofracture extension during water and steam injection is inevitable and can be catastrophic at times, (2) fluid flow is almost perpendicular to the growing fracture and can be approximated by a 1D model, and (3) average rate of fracture growth can be predicted from early injection data.

Researchers designed an optimal process-based injection controller. The controller inputs are the history of the injection pressure and cumulative injection, along with the fracture size. The output is the injection pressure; the control objective is the injection rate.

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Advanced Computational Analysis of Drill Cuttings

Work continued on implementation of software needed to convert 3D pore space images into a network on which numerical simulation of flow properties can be performed. Work has focused on transfering code between operating systems, debugging, and function checking each program segment. Initial processing was performed on a 3D, high-resolution x-ray CT image of one of the project reference rocks, Salt Wash North sandstone.

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