Development and Testing of Advanced Drilling Products

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Advanced technology continues to evolve at a rapid pace in the drilling industry. Technologies which are evolving include horizontal, underbalanced, and slim-hole drilling. Proper application of these technologies can reduce the cost of drilling and increase the productivity of natural gas wells. Very few tools have been available to operators to assist with the proper application of these technologies. An additional wide-spread problem in the industry is the inability to keep abreast of developments as they occur. This often results in a duplication of effort and wasted research funds that could be avoided with better technology transfer.

Introduction And General Objectives

Projects undertaken by Maurer Engineering Inc. for the DOE include the development of several drilling and engineering tools to take advantage of evolving technologies. These include the development of a high-power slim-hole drilling system consisting of a bit and downhole mud motor, a near-bit Measurement While Drilling (MWD) system, an advanced foam-drilling computer model, FOAM, and the development and testing of lightweight solid additives (LWSA) for drilling fluids that will facilitate underbalanced drilling. In addition, Maurer Engineering undertook an investigation of advanced Russian drilling technology, including the use of novel techniques and details of downhole motor systems used in the former Soviet Union. This investigation will help prevent duplication of research effort by U.S. engineers.

Phase I for each project, with the exception of the Russian technology study, included the basic design and laboratory testing of the systems, as well as yard- and bench-testing of the equipment or material developed.

In Phase II, the underbalanced drilling products and the high-power slim-hole drilling system are being field tested. The FOAM computer model will be validated using both surface and downhole pressure and temperature measurements recorded while a well is being drilling. The lightweight solid additives have been mixed in a conventional mud system to lower the density of the fluid. The slim-hole bit and companion high-power motor will be used to drill intervals in as many wells as possible, with comparisons then made to other slim-hole drilling techniques.

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Phase II for the near-bit MWD included re-design to accommodate a gamma ray detector, the addition of a data recorder to the receiver unit, and additional testing to ensure proper performance.

Descriptions of all four projects including results achieved to date follow.

Evaluate Advanced Russian Drilling Technology Project

Needs and Objectives

Since the 1950s and 1960s, much of the work performed in the world in novel and advanced drilling technologies has been carried out in Russia and the former Soviet Union. In fact, much of the advanced drilling research and development carried out in the United States during the last twenty years has been based on earlier work done in the former USSR.

Interest in advanced drilling techniques has multiplied in the U.S. over the past several years as major operating companies began to concentrate on reducing drilling costs in marginal reservoirs. However, many American engineers are unaware of the thousands of man-years spent and the major accomplishments made by Soviet engineers on advanced and novel drilling techniques. Without knowledge of the Russian work, much effort may be needlessly duplicated. This project was undertaken to familiarize American engineers with the work carried out in Russia and prevent a duplication of effort and the waste of potentially millions of research dollars.

Approach

A team of Russian Ph.D. engineers was assembled in Russia, led by Dr. Moisey Eskin, author of seventeen inventions and nearly fifty scientific publications, and coordinated by Dr. William C. Maurer of Maurer Engineering Inc. in the U.S. The team includes eight other Russian Ph.D. engineers and has a total engineering experience of over 300 man-years. This team performed a detailed review of all work done in Russia on novel techniques over the past 30 years. Joint funding for the review was provided by the U.S. Department of Energy, the Gas Research Institute, and Sandia National Laboratory.

Accomplishments and Benefits

Two volumes describing advanced technology research in Russia have been complied, edited and published. The first is a 446-page review of *Former-USSR R&D on Novel Drilling Techniques.* This volume was published in the fourth quarter of 1995. A second volume, containing approximately 450-500 pages, provides details of *Former-USSR R&D on Advanced Downhole Drilling Motors* and will be published in March 1997. These two volumes provided the basis of a Russian Drilling Technology Workshop held March 24, 1997 in Houston, Texas.

The dissemination of this material will prevent American engineers from researching technology and approaches to technology that have already been shown to be misdirected by earlier research.

It will also enable American engineers to select the most promising advanced systems for development in the United States, saving thousands of research dollars.

Future Activities

Other areas in which the Russians have invested much research in advanced drilling technology include Directional Drilling, Horizontal Drilling, and Advanced Drill Bits. Additional studies, similar to those carried out on Novel Techniques and Downhole Motors, are needed because much of this work is directly applicable to oil and gas drilling in the U.S.A. today. Some of the extensive R&D carried out in Russia will be helpful to U.S. service companies and operating companies in slim-hole, horizontal, coiled-tubing, and deep-drilling applications.

High-Power Slim-Hole Drilling System Project

Needs and Objectives

Over thirty years ago, more than 3,000 slim holes were drilled worldwide in oil and gas fields to take advantage of the reduced rig and tubular costs associated with this technique. With the increased emphasis over the past decade on reducing drilling costs, many companies are re-examining the application of slim-hole drilling.

Small diameter drill pipe used in slim-hole drilling is much more prone to twist-offs than conventional drill pipe because of the higher rotary speeds necessary and the thinner walls of the pipe. Another major obstacle to slim-hole drilling is the short life typical of small diameter tri-cone drill bits because of the inability of the bearings to withstand the bit weights required to drill at economical rates of penetration in slim-holes.

The overall objective of Phase I of this project was to implement and improve on new high-power slim-hole motors and TSP bits developed for slim-hole gas well drilling applications. The system was manufactured and bench tested in the laboratory in preparation for field testing.

During Phase II of the project, the objective is to take the designed system to the field and use it to drill wells under "real-world" conditions. An intermediate step was a drilling test carried out at Amoco's Catoosa test site near Tulsa, Oklahoma.

Approach

The power generated by a downhole mud motor is directly proportional to the speed at which it turns, the flow rate through the motor, and the torque required to turn the motor. The motor speed can be increased by increasing the flow rate through the motor or by reducing the pitch of the rotor. Torque can be increased by increasing the length of the rotor. Incorporating both these changes into a motor design will provide the maximum effect. Figure 1 shows how motor power is increased as these parameters are changed.

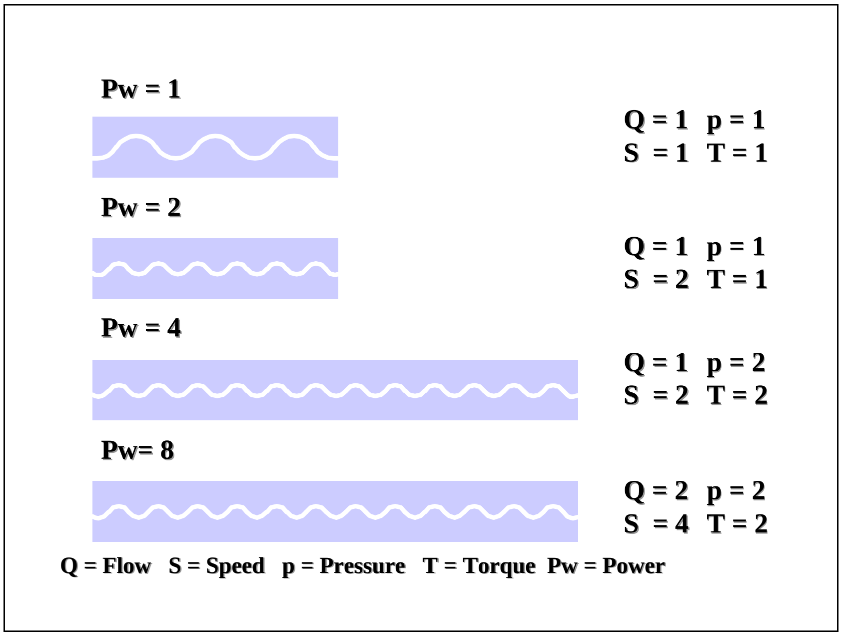

Figure 1. Moineau Motor Parameters Effect Motor Power

Results and Accomplishments

Phase I of the project was completed in the fall of 1995. A high-power 3-⅜ inch drilling motor was developed that delivers more power and drills faster than conventional motors. Additionally, two companion slim-hole bits were manufactured. Using a systems approach, the mud motor and TSP bit were matched to deliver maximum horsepower to the rock. The first bit developed utilizes large (5-mm) TSP cutters to drill hard rock at high rates. The second bit is a hybrid which utilizes both large TSP cutters and PDC cutters to increase run time in highly varying formations.

The high-power motor was manufactured by welding two conventional stator sections together, using a proprietary process, to form a single long power section. A special double-length rotor was machined to fit the longer stator and accommodate the increased horsepower available. The bearing pack is stronger than a conventional bearing pack and utilizes high strength metal-to-metal radial bearings, stronger roller thrust bearings, and a titanium flex shaft to transmit power from the rotor to the bit.

The high-powered slim-hole system has been fully tested in the laboratory with both dynamometer and drilling tests. Data from these tests have been analyzed in detail using Maurer Engineering computer software, and the results were used to help design applications for the Amoco Catoosa test site and additional field tests, one of which was conducted in Brazos County, Texas.

The first field test during Phase II was conducted at the Amoco Catoosa test facility in February, 1996. The DOE high-power slim-hole motor was combined with the hybrid PDC/TSP bit to drill from a depth of 619 feet to 1,446 feet. A variety of formations were encountered having compressive strengths of 4,000 psi to 29,000 psi. Figure 2 shows the High-Power Slim-Hole motor and bit hanging in the derrick of the test site rig.

Figure 2. High-Power Slim-Hole System at Catoosa Test Site

Softer formations were drilled at rates of 125 to 150 feet per hour (fph), comparable to conventional aggressive PDC bits. Conventional PDC bits cannot drill the very hard Mississippi Lime formation found near the bottom of the section at Catoosa, but the DOE hybrid bit and motor drilled 40 feet into the formation and were still drilling when testing time ran out. The TSP cutters in the hybrid bit allowed the system to drill the Mississippian at rates of up to 25 fph. The bit and motor held up throughout the entire test and stayed in the hole for the duration of the test. Figure 3 is a photograph of the TSP/PDC hybrid bit.

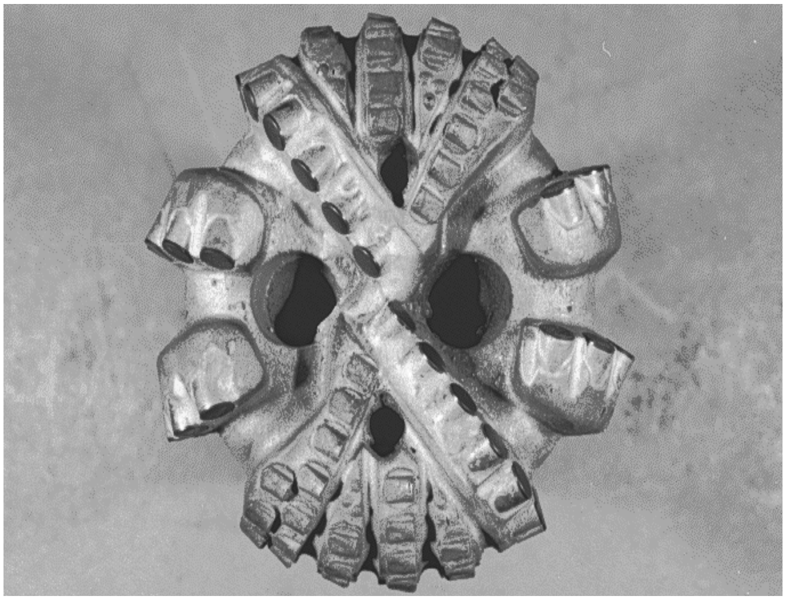

Figure 3. DOE TSP/PDC Slim-Hole Hybrid Bit

The rig crew and tool pusher were impressed with the system performance. Although the bit was slightly worn, it was not used up and could have continued to drill if testing time had not expired.

The post-test inspection of the disassembled motor revealed only one minor problem. A bellville spring sleeve O.D. was too large for the spring, resulting in an incorrect load distribution on the thrust bearing and causing one bearing race to wear excessively. The spring sleeves were redesigned, and a second motor was manufactured prior to additional field testing.

The first "real" field test of the high-power slim-hole system was conducted outside Bryan, Texas, about 90 miles northwest of Houston. This test was conducted in the Carroll-Biering Unit No. 1 well and consisted of a re-entry to drill a horizontal section in the Buda formation.

The kick-off and drilling of the curve sections of the well was carried out using conventional short directional mud motors. Once the horizontal section was reached, the conventional motor was pulled, and the DOE system was run into the well. Planned interval for the DOE system was a measured depth of 10,600 ft to 12,800 ft. (True Vertical Depth of 10,250 ft to 10,350 ft.) The operator had experienced success drilling this formation with a Hughes R382 bit and requested that this bit be used with the DOE motor.

The motor and the Hughes bit were run into the well at 10,447 ft measured depth and drilled for 33.5 hours to a measured depth of 11,020 ft. Overall penetration rate was 17.1 fph over the 573 ft interval drilled. Weight on bit ranged from 5,000 lbs to 8,000 lbs and flow rates through the motor ranged from 100 to 140 gallons per minute (gpm).

Initial hydraulic calculations for the test indicated an optimum flow rate of 150 gpm. This is 40 gpm higher than the recommended maximum flow rate through the motor. To compensate for the extra flow, a nozzle was placed in the rotor to by-pass 40 gpm at 1,000 psi pressure drop. However, the rig pumps were initially able to supply only 110 gpm at a pressure differential of 750 psi.

As the run progressed, the nozzle in the rotor washed out, allowing the flow rate to increase to 140 gpm, but preventing the pressure drop across the motor from exceeding 500 psi. The faulty nozzle and the incorrect assumptions about pump flow included in the calculations resulted in the motor operating at only 11 horsepower. The DOE motor would have run at 21-29 horsepower had correct hydraulics been provided prior to the test. Resultant performance at the increased power level would have been much improved.

Figure 4 shows the penetration rate and horsepower generated by the motor in the field test compared to conventional performance and projected performance with the improved hydraulics. The high-power motor, coupled with the TSP or hybrid bit can drill fast, but proper rig hydraulics and planning are the keys to success.

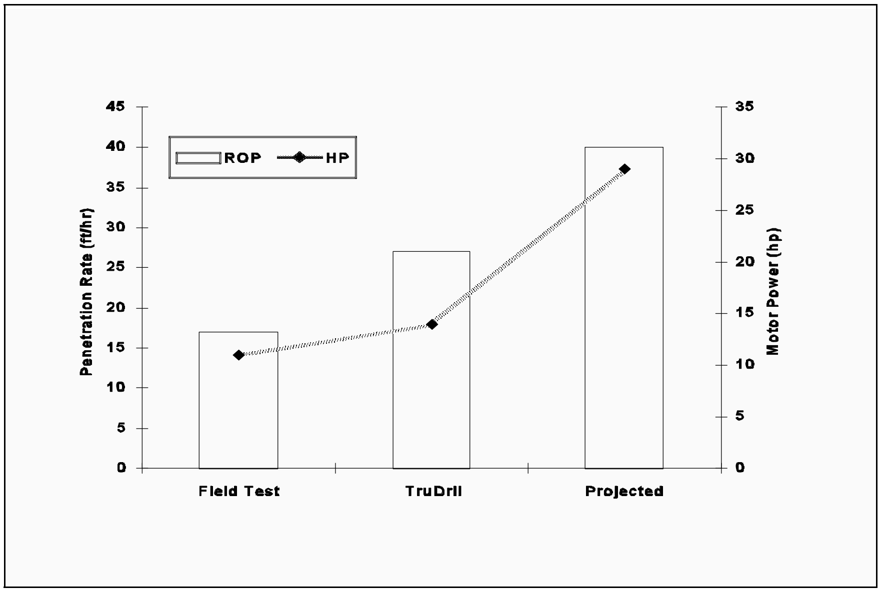

Figure 4. High-Power Slim-Hole Motor Performance In Field Test

Benefits

A high-power drilling system for slim-holes will reduce cost by improving penetration rates and reducing trip times compared to conventional drilling techniques. TABLE 1 shows the cost savings potential of using the high-power slim-hole system with optimum hydraulics in a well similar to the Carroll-Biering test case.

TABLE 1. Cost Comparison of High-Power Slim-Hole System to Conventional Drilling

COST COMPARISON			
	New Case	Base Case	Motor Breakeven
1. Bit Cost ($)	10,000	10,000	19,648
2. Rig Cost ($/hr)	600	600	876
3. Motor Cost ($/hr)	200	200	477
4. Rotating Time (hr)	29	37	16
5. ROP (ft/hr)	35	27	32
6. Trip Time (hr)	10	10	22
Footage Cost ($/ft)	38	48	

Future Activities

Remaining tasks for this project will concentrate on identifying appropriate opportunities to apply these products in the field. The methods used to capture field test opportunities to date will be evaluated and revised to focus future efforts on increasing field use for this advanced drilling product.

Near-Bit MWD System Project

Needs and Objectives

As horizontal and directional drilling and completion technology has improved with time, the length of horizontal sections has increased and the need for more accurate well bore placement has become more critical. Turning radii have decreased and acceptable target limits have become thinner. The impact of stand-off distance (the distance from the bit to the measurement point), has become correspondingly more important. Tools which examine formation properties and measure directional data 50-100 feet above the bit can result in missing thin targets, falling out of productive zones, dipping into water zones or gas caps, and significantly higher cost, especially if plugging back and/or sidetracking is required.

Combined directional and formation data measurements, or “geosteering” (a term coined by Schlumberger), allows improved well bore placement. When geosteering can be combined with minimized stand-off distance, optimum well bore placement will result, minimizing initial installation cost, improving well productivity, and lowering lifetime maintenance requirements.

The objective of this program was to develop a Near-Bit Measurement While Drilling (MWD) system which collects borehole directional and formation parameters directly at the drill bit-rock interface and transmits the information through an electromagnetic (EM) means to a receiver located 50-100 feet above the bit. The system is designed to work with positive-displacement downhole mud motors and bottom-hole assemblies from all manufacturers and to pass its data message to third-party steering tools and conventional MWD systems for subsequent transmission to the surface.

Approach

The basic design of the Near-Bit MWD system is based on the Guided Boring Systems (GBS) commercially successful AccuNav® EM MWD guidance system. This system is widely employed for under-river utility crossings and environmental remediation activities and is proven accurate and reliable in these applications. During Phase I the technical specifications were defined, and a first generation prototype was designed, fabricated, and tested in the laboratory. This prototype was configured with triaxial accelerometers (for direct measurement of borehole inclination), temperature, and pressure sensors.

During Phase II, the prototype developed in Phase I was redesigned to incorporate a formation-measuring sensor (specifically a gamma-ray measurement device), and the newly designed tool was tested in a series of experiments to assess system performance and reliability.

Results And Accomplishments

During Phase I, all technical specifications for the tool were prepared and described in detail. A first generation prototype tool was developed and tested in the laboratory to determine actual performance capabilities and system reliability.

In Phase II the mechanical components of the prototype were completely redesigned to incorporate the additional natural gamma-ray sensor. In addition, the power supply circuitry and software required considerable modification, and the near-bit receiver system was modified to increase data recording capability.

Figures 5 and 6 show the components of the Near-Bit system.

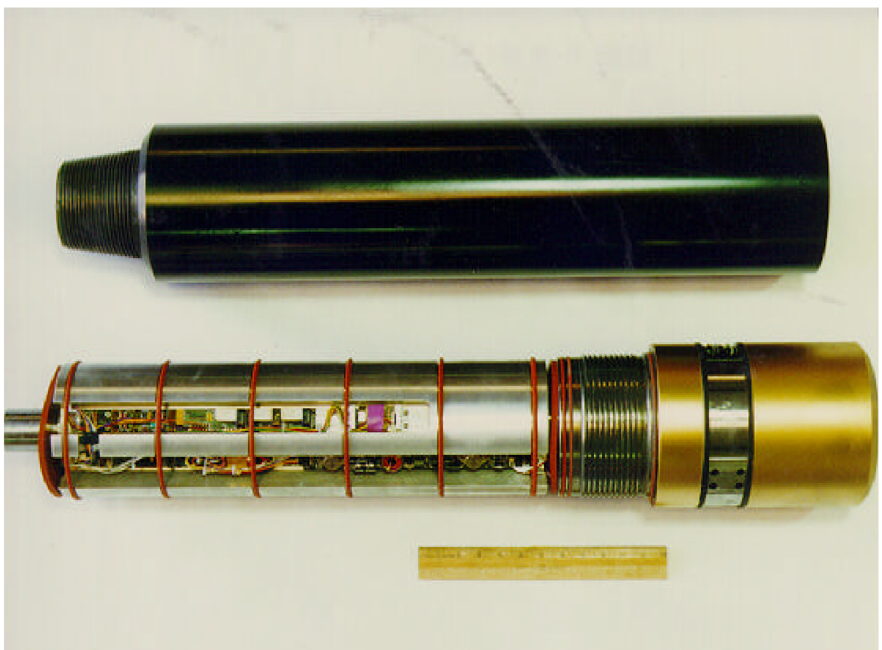

Figure 5. Near-Bit Transmitter

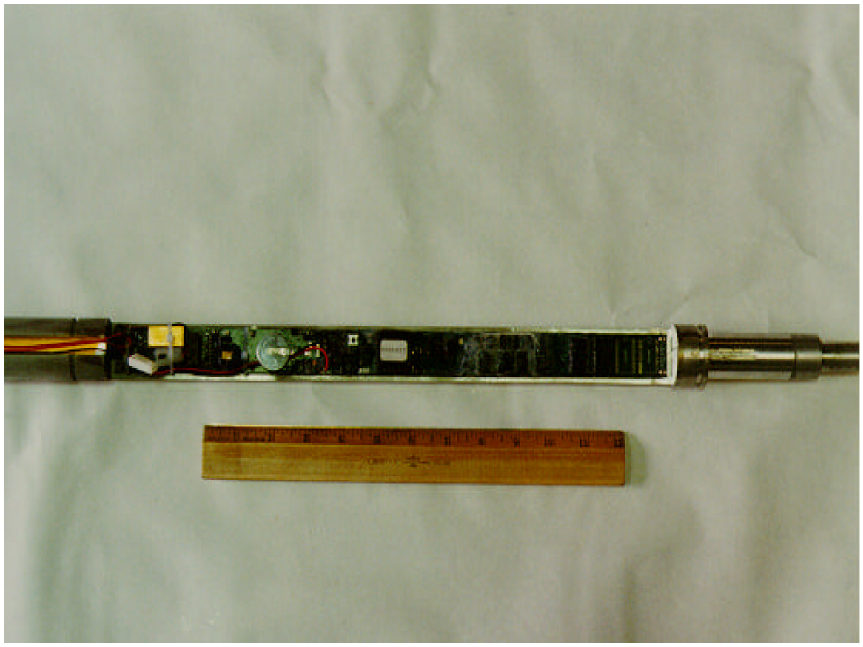
Figure 6. Near-Bit System Receiver

The complete system is designed for use with conventional 6-½ and 6-¾ inch multi-lobe mud motors. The transmitter-sensor sub is 6.500 inches in diameter, 42.5 inches long, and incorporates 4-½ inch API regular tool joints. All aspects of the triaxial accelerometer, temperature, and gamma-ray data collection routines are fully programmable. The transmitted message is received by a remote receiver located at a convenient distance from the transmitter in the drill string close to a third party wireline or steering tool. The message can be decoded and stored in buffered memory available for transfer to the MWD or wireline host for transmission to the surface.

A Near-Bit MWD system containing a natural gamma-ray sensor and triaxial accelerometer and temperature sensors has been successfully developed for use in short-, medium-, and long-radius directional drilling applications. The system can work in either cased- or open-hole sections of the wellbore. The operation of all electronics has been verified fully in laboratory and field environments.

<u>Benefits</u>

A fully configured near-bit MWD system will provide numerous benefits to the drilling industry. The system will make possible more accurate wellbore placement, resulting from real-time knowledge of the wellbore inclination angle and formation properties. The system (if pressure sensors are employed) will also improve well control by identifying kicks when they occur and optimizing response time. Penetration rates can be increased with a near-bit MWD system and downhole tool life can be improved by avoiding or minimizing detrimental operating conditions. Overall drilling cost can be reduced as a direct result of the combination of these benefits.

Future Work

The inclusion of additional sensors such as formation resistivity will further increase the commercial viability of the tool. Additional field testing is required prior to full commercialization to ensure the required level of reliability has been obtained. This field testing should be conducted in cooperation with service companies interested in commercializing the Near-Bit MWD technology.

Development and Testing of Underbalanced Drilling Products Project

Needs and Objectives

As horizontal drilling became increasingly important over the past decade, it became apparent that the effects of formation damage while drilling also increased. As productive formations are exposed to drilling fluids for longer periods of time in longer and longer horizontal sections, more opportunity exists for damage to occur. In order to prevent this damage and improve productivity, many operators began using underbalanced drilling techniques. The popularity of underbalanced drilling continues to grow, but is hindered by the lack of tools available to utilize the approach fully.

Drilling underbalanced in under pressured and depleted reservoirs often requires a fluid with a density lower than that of water ($SG<1.0$). Current underbalanced operations in these reservoirs can be carried out using air, mist, or foam. However, many operators are reluctant to drill underbalanced with foam because of the difficult hydraulic calculations required and the general lack of information and training relative to underbalanced drilling.

The DOE sponsored Maurer Engineering Inc. to develop a user-friendly PC-based foam-drilling model that can accurately predict pressure drops, cuttings lifting velocities, foam quality, and other foam-drilling variables. The model allows operators and service companies to easily and accurately predict pressures and required flow rates at the surface and under downhole conditions for foam drilling and work-over operations.

The addition of air or gas to the drilling fluid can also cause many problems, so a second objective of the project was to develop a lightweight, incompressible drilling fluid that will allow underbalanced drilling in low-pressure reservoirs without the limitations commonly associated with existing lightweight fluids. A new lightweight solid additive (LWSA) fluid was developed, and initial investigations of its properties were conducted during Phase I. Field tests of the drilling fluid are being conducted during Phase II.

Approach

A literature search was conducted to identify all available mathematical models related to the pressure and flow characteristics of foam fluids. Additional unpublished laboratory tests and mathematical models provided by Chevron and other sources were also reviewed. A PC foam-drilling model was constructed using the best available mathematical models. The model runs in a Windows environment.

At the same time, many candidate lightweight solid additives (LWSA) for drilling fluids were evaluated, and a microscopic hollow glass sphere was selected as the most appropriate for continued testing. Hollow glass spheres, with the capability of decreasing density, have been known to the oil and gas industry for years. Their application has primarily been for lowering the density of cement slurries to combat lost returns. The selected LWSA was tested extensively in the laboratory, as well as in a test-facility yard using conventional drilling rig equipment.

The LWSA was used to build both water- and oil-base muds. The rheological properties of the muds were measured, and the effects of various contaminants common to the drilling environment were investigated.

<u>Results And Accomplishments</u>

During Phase I the PC-based, user-friendly software, FOAM, was developed for planning and analyzing operational parameters during foam drilling projects and was made available for use by the oil and gas industry. The model calculates pressure responses and flow behavior of foam fluids. FOAM has been shown to be accurate by comparison with existing measurements and more cumbersome older computer models.

Any one of three rheology models may be selected by the user, and the model can handle any combination of liquids and gases injected while drilling. Data are input in a series of four input windows and includes a general well description, directional survey data, drill string and wellbore configuration, and drilling parameters such as injection rates of liquid and gas, injection fluid properties, drilling rates, and drill-cuttings descriptions.

After executing the program, FOAM tiles the output screens and the user is able to select individual output screens of interest by simply clicking with a mouse. Figure 7 shows an example of output data for a 7-⅞ inch wellbore drilled with foam to a depth of 5,000 ft.

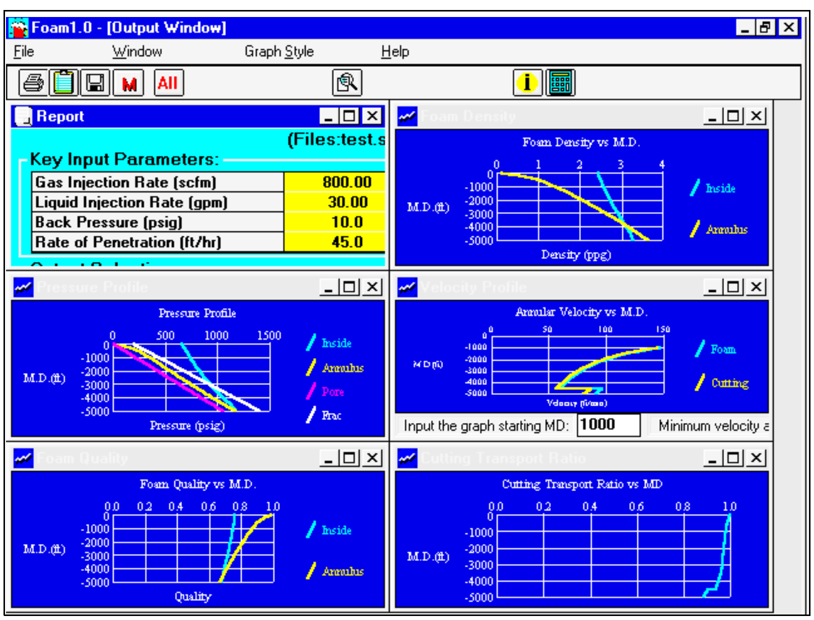

Figure 7. Tiled Output Screens From FOAM Computer Model

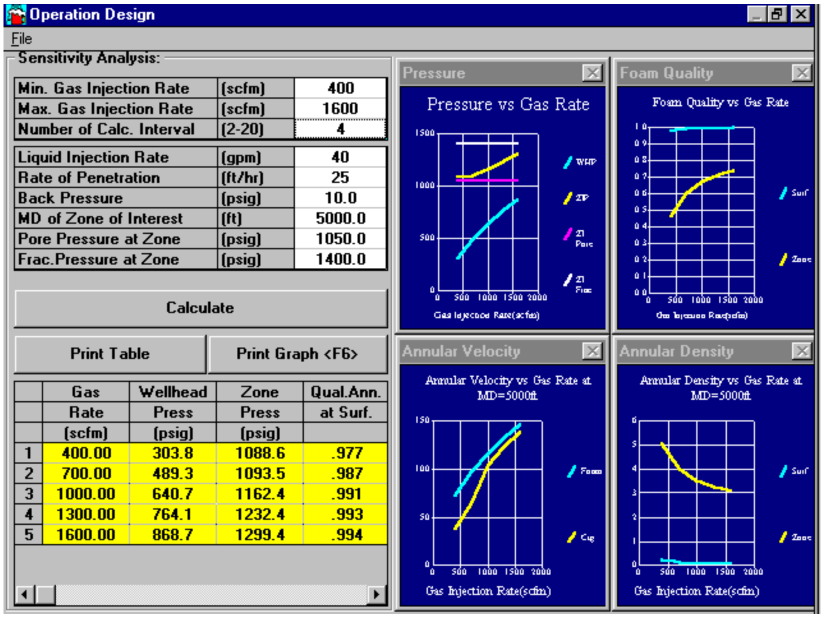

Figure 8. Operation Design Window From FOAM Computer Model

The user can perform an operation analysis or sensitivity analysis of the variable parameters involved in a foam drilling operation. Only four main parameters that effect pressure can really be controlled during an underbalanced drilling operation. These are gas injection rate, liquid injection rate, rate of penetration, and back pressure (or choke pressure). All four are included in the sensitivity analysis output shown in Figure 8 for the same 7-⅞ inch well at the hole bottom (5,000 ft).

The output from FOAM was validated by comparing it to other models, existing laboratory data, and actual field measurements. FOAM output matched other known models by an average of 8.6%. The model matched test well measurements made previously by Chevron by an average of 10.6%, and matched actual standpipe pressures measured on a Kansas foam-drilled well to within 4% (20-40 psi) as shown in Figure 9.

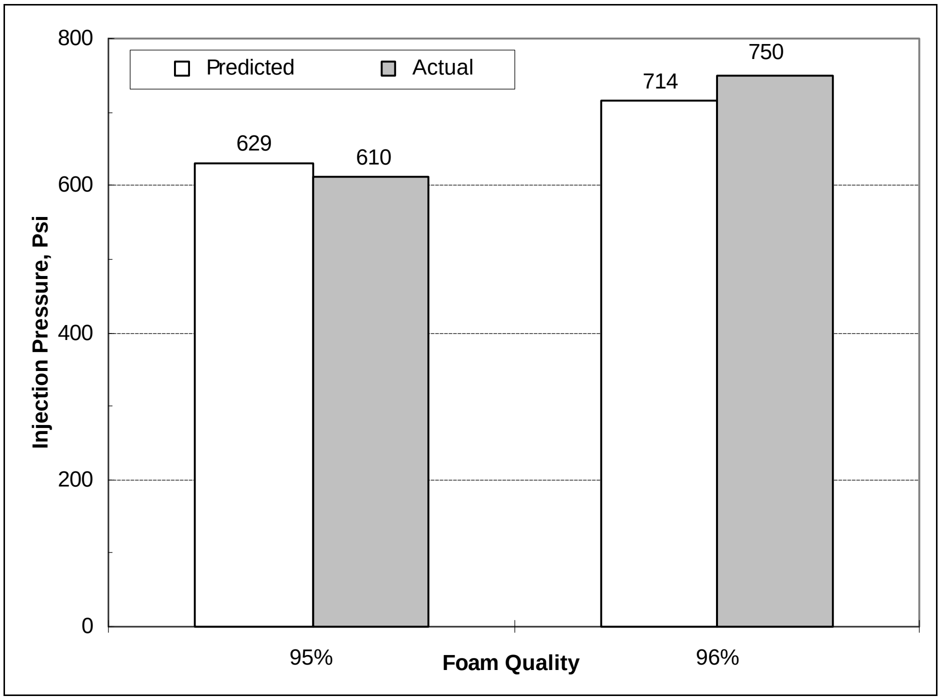

Figure 9. Comparison of FOAM Model to MEI Field Measurements of Injection Pressure

While the computer model was under development, work also continued on developing the lightweight drilling fluids. Lightweight, incompressible fluids were constructed using commercially available hollow glass spheres, and these muds were tested during Phase I in the laboratory and in a test facility yard using conventional rig-compatible solids control equipment. Figure 10 shows a microscope photograph of the spheres, which range in size from 5 to 75 microns.

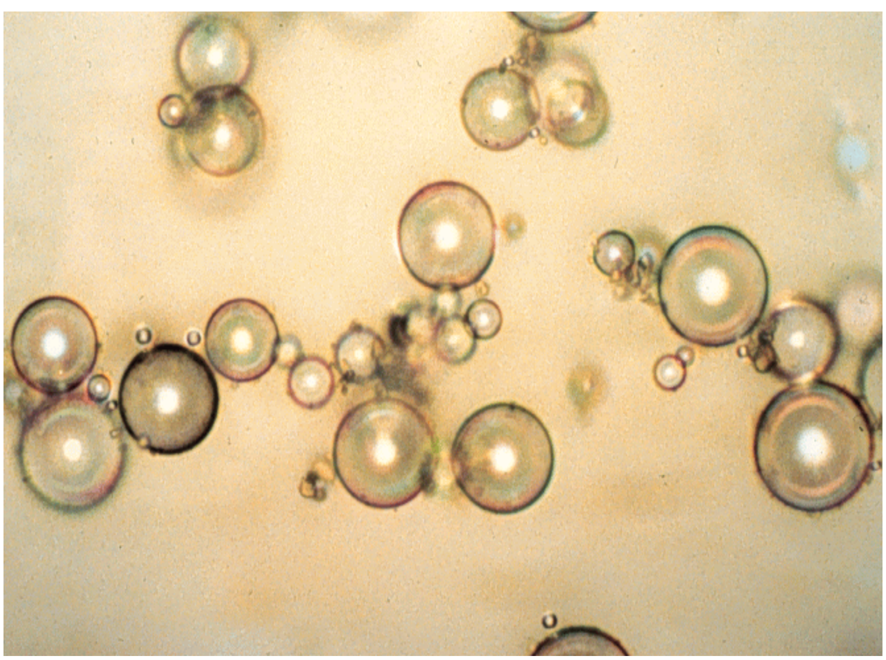
Figure 10. Microscope Photograph of Hollow Glass Sphere LWSA

At sphere concentrations below 40% by volume lightweight muds behave similarly to conventional drilling fluids. Figure 11 shows how Plastic Viscosity and Yield Point both increase as the concentration of spheres by volume increases.

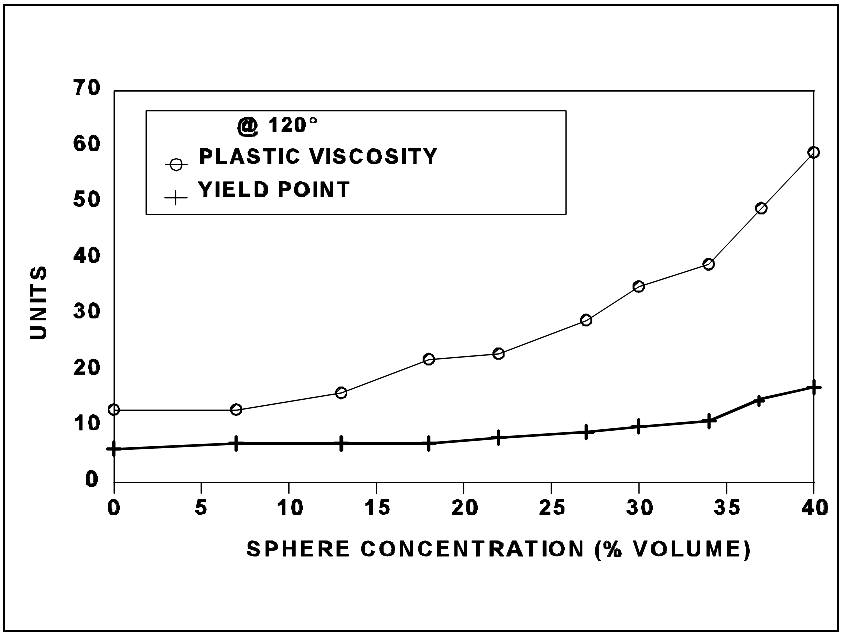

Figure 11. Lightweight Fluid Rheology

The effects of conventional solids control equipment on the glass spheres and on the whole mud were also measured with regard to sphere damage and recovery. The conventional equipment did not damage the spheres. Hydrocyclones proved to be the most effective equipment in maintaining the mud.

The LWSA has also been used successfully in two wells drilled near Bakersfield, California for Mobil Oil Company. The spheres were in the drilling mud at concentrations of up to 20% by volume

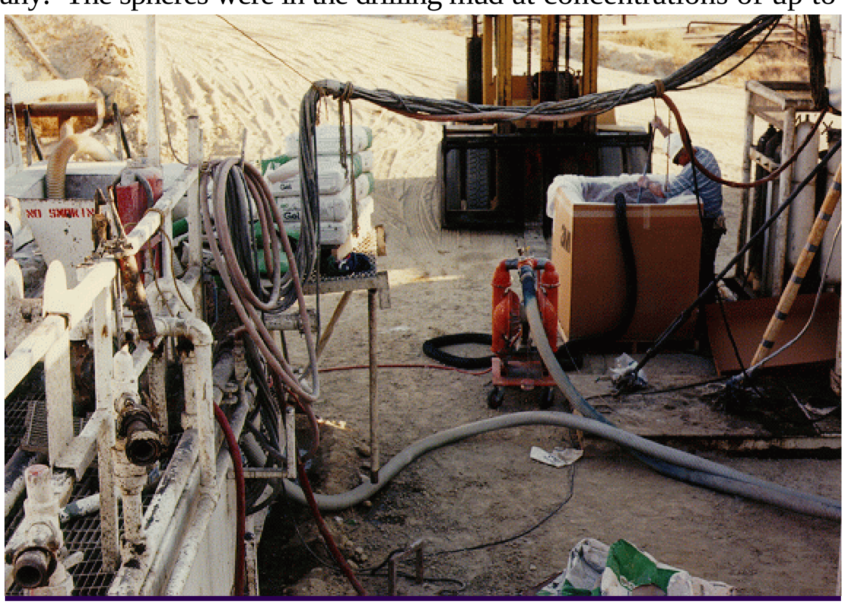

Figure 12. LWSA Field Test Mixing System

while over 3,000 feet of hole were drilled. A fresh-water base fluid was used, and the LWSA was added to the fluid system using a double-diaphragm pump. Figure 12 shows the pump in action as it draws the spheres from a 5 ft^3 box and sends them directly to the mud mixing hopper.

The spheres, being totally inert, are friendly to the environment. One of the biggest concerns was the possibility of a dust hazard while the spheres were being mixed in the mud, but no dust was seen during the four days of mixing. Figure 13 shows the spheres being added to the mud through the mud hopper.

Figure 13. LWSA Additions to Mud at the Mud Hopper

Figure 14 shows the calculated or theoretical mud weight compared to the actual mud weight at various depths in the second well in the field test. The agreement between theoretical and measured mud weight is excellent throughout most of the wellbore, indicating that no LWSA was being lost through attrition. Near the bottom of the well, the measured mud weight was higher than the calculated value, indicating that some LWSA was being lost.

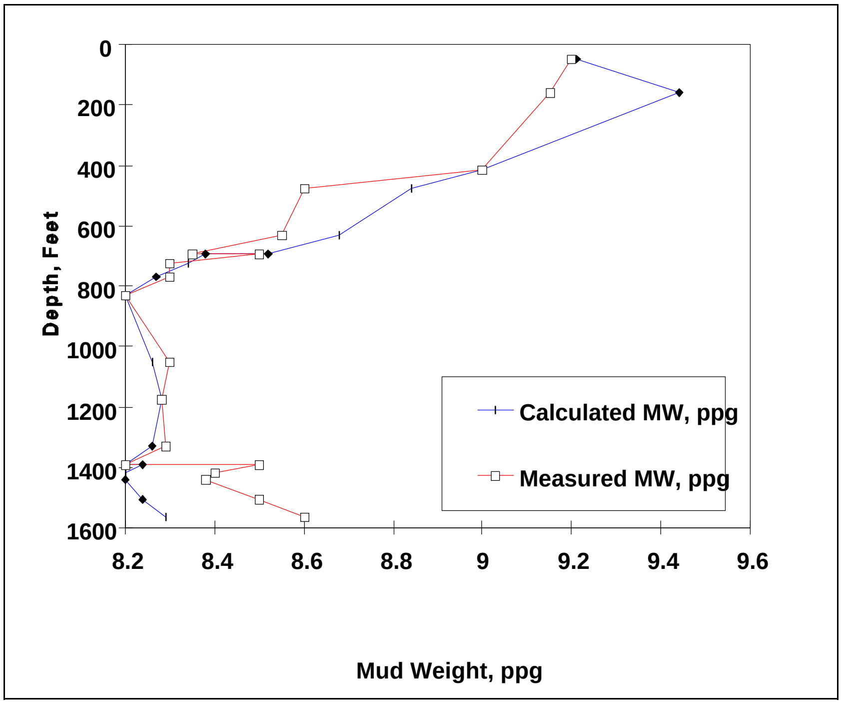

Figure 14. Effect of LWSA Additions on Mud Weight

This apparent LWSA loss is the result of three phenomena. The mud motor used to directionally drill the well was tripped out at that depth. Due to practices in place on the rig, 10-20 barrels of whole mud were lost during the trip and the volume was rebuilt at a higher mud weight. 10-20 barrels represents a significant portion of this entire mud system (about 5-10%), and would have a significant effect on mud weight overall. The pits were being diluted and the solids control equipment was kept running even though mud was not circulating. This dilution effect also altered the mud weight of the system. Finally, the calculated value for mud weight may not be a perfect match since some of the input parameters may not be known exactly.

The field tests so far have shown that LWSA can be mixed in the field and maintained in solution while drilling. The LWSA can also be circulated numerous times, even through a downhole mud motor, with minimal loss. Conventional rig equipment can be used in a LWSA operation with no detrimental effect on either the LWSA or the equipment.

Benefits

Widespread use of foam and LWSA drilling fluid technology for underbalanced drilling has the potential to significantly reduce capital expenditures and increase well productivity. In concert, these improvements will increase the net present value of drilling programs and extend the use of capital.

Expenditures can be reduced utilizing these technologies because rates of penetration for underbalanced drilling commonly are two to ten times higher than for conventional drilling. When drilling with foam, daily operating cost may increase 10-50%, depending on well depth, location, and other factors. To break even on cost using foam the rate of penetration increase required could be as little as ten percent. The FOAM software will make the decision to use foam drilling fluid much easier to make.

As described in the Phase I final report for the project, the use of LWSA drilling fluids would require a penetration rate increase of 20-25% in a typical well for cost to break even on this basis only. This is well within the realm of possibility. When the potential for improved productivity due to reduced formation damage is considered, the economics improve even more.

Future Activities

Remaining tasks on these two products will concentrate on identifying appropriate opportunities to apply the technologies in the field. Validation of the FOAM model will continue using both surface and downhole measurements of pressure and temperature as data are obtained. Real-time utilization of the program in the field is the ultimate goal. Additional field tests of the LWSA muds will concentrate on areas where lost circulation problems and low penetration rates can be improved by reducing the hydrostatic head imposed by the fluid column.

Conclusions

1. Four DOE projects involving advanced drilling products are at or near completion. Six drilling products have been developed in the course of this work.
2. Two source books describing advanced Russian drilling technology have been compiled, edited and published.
3. A high-power slim-hole mud motor was designed and tested and is ready for field use.
4. Two slim-hole bit designs, one utilizing TSP cutters and one utilizing hybrid cutter technology were developed, tested and are available for field use.
5. A near-bit MWD tool, capable of measuring hole inclination, temperature and natural gamma-ray response is available.
6. A new, lightweight drilling fluid for underbalanced drilling was developed and is undergoing field tests.
7. A FOAM software model for calculating the hydraulics of foam drilling and work-over fluids is available for industry use.
8. Additional work is required to identify appropriate field test opportunities for all drilling products.

Acknowledgments

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