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U.S. DOE R&D Efforts in Deep Gas Drilling Technology

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Abstract

To meet anticipated future demand for natural gas the U.S. companies will be challenged to develop unconventional reservoirs. Drilling economically under these conditions will require new technology. The development of economic drilling technology will play an increasingly key role in ensuring a dependable future supply of natural gas for the U.S. as well as worldwide.

The purpose of this paper is to summarize the current research and development effort in the U.S. DOE Fossil Energy (FE) Gas Exploration, Production, and Storage (GEPS) Program. The goal of the program is to develop the technology required to drill and complete unconventional and deeper, high temperature, and high-pressure gas reserves. Current emerging drilling technologies funded by the GEPS program and discussed in this paper are high speed telemetry or communication systems (>1MM bits/sec), metallurgical techniques to increase strength of steel, composite carbon drill pipe as strong as steel but 50% lighter, mud hammer optimization, high-pressure jet assisted drilling, high longevity PDC cutters, lightweight cements and new wellbore sealants, fracture diagnostics and optimization.

Introduction

Purpose of Program: The mission of the Gas Exploration, Production, and Storage Program is to partner with industry and others to develop environmentally friendly technologies that will steadily expand the nation’s economically recoverable natural gas resource base. This partnership will ensure that adequate supplies of reasonably priced natural gas are available to meet expected demand.

GEPS is part of The Strategic Center for Natural Gas (SCNG) at the National Energy Technology Laboratory (NETL). SCNG was created within the U.S. DOE Office of Fossil Energy three years ago to focus and integrate U.S. federal government efforts related to all aspects of natural gas as an energy source. The acronym of DOE will be used through out this paper to refer to the upstream gas program in NETL/SCNG. NETL partners with industry, universities, other laboratories, and private research organizations, and other federal and state agencies to develop technologies that will sustain the supply of natural gas in the United States.

The GEPS Product Line consists of four Program Areas designed to support the development and deployment of a steady stream of environmentally friendly products and technologies that will progressively expand the nation’s economically recoverable resource base and improve the efficiency of the gas storage system. Three areas in natural gas exploration and production (E&P) target the specific technologies needs of the near-term, mid-term, and long-term. The *Existing Fields Program Area* supports the full utilization of developed technologies in maximizing the near-term recovery efficiency of producing reservoirs. The *Unconventional Reservoirs Program Area* is designed to accelerate the development of evolutionary technologies to expand access to the nation’s vast, but currently sub-economic, resource base to support mid-term demand. The *Frontier Resources Program Area* targets revolutionary technology advances that will add fundamentally new resource elements to allow expanded gas usage to continue through the long-term. The *Gas Storage Program Area* will assure the effective utilization of this gas by addressing the efficiency of existing storage and the development of novel new storage concepts to enable the full utilization of domestic gas resources. Together, these programs will help industry ensure that natural gas is available and affordable until such time as the next generation of sustainable energy sources is developed. The focus of this paper is on the drilling and completions aspects of the unconventional and deep reservoirs.

Research and development (R&D) is widely recognized as a key to economic growth. Research and development spending by the petroleum industry continues to lag behind other industry sectors. The 2002 Interstate Oil and Gas Compact Commission (IOGCC) publication[1] concluded that the oil and gas industry players do not place as high a value on research and development as other industry sectors based on ratio of R&D expenditures to sales.

However, there are reasons as to why this prevails. Research that leads to proprietary products usually translates into high profit margins. In the free market system, developers of new technology must be compensated by a large segment of the industry where the technology is applied. Companies in the automobile, pharmaceutical, semiconductor industries, etc. can afford to obtain thousands of patents a year and spend billions of dollars a year on research because they receive adequate to substantial compensation in royalty and sales to others, as well as benefits realized within the company for the technology. However, in the petroleum sector the inability of operators and service companies to directly and quickly show a payback in R&D expenditures have caused less investment in R&D. Company stewards are unable to justify to their investors spending large sums of money for something that is largely donated to the public.

This market barrier along with mergers and entrenchment of the petroleum industry has resulted in substantial technological barriers to the continued development of new oil and gas resources in the United States.

Background

Why the Focus on U.S. Natural Gas?: Natural gas is expected to be the fastest growing component of the world's energy consumption portfolio. World natural gas consumption in 2020 is expected to total 162 trillion cubic feet, nearly double the 1999 total of 84 tcf. The largest increments in natural gas use are expected in developing Asia and North America. The United States is the dominant consumer of natural gas and its demand is expected to grow at 2.1 percent per year between 1999 and 2020. Total annual gas consumption in the U.S. is projected to increase from 22 tcf in 1999 to 34 tcf in 2020. Cumulative consumption would therefore be 607 tcf at the end of 2020 for the U.S and 2624 tcf for the world. Current U.S. reserves are estimated at 177 tcf and worldwide proved technically recoverable reserves were estimated at 5,421 trillion cubic feet as of January 1, 2002[2]. Most of these trends and increases toward the future demand for natural gas is a result of environmental impacts and concerns.

Historically to about the late 1970's, the U.S oil and gas industry's strategy was to find good acreage in the United States on which to drill for oil. Natural gas was widely viewed as less profitable than oil and, because of nationalization and wars in the Middle East, drilling overseas was widely viewed as overly risky. In the mid 1980s things began to change. Since then natural gas' share of worldwide well completions, has been increasing (**Fig. 1**). [3]

Deep Gas: The EIA, NPC[4], MMS[5], and others have stated that a growing share of the U.S. natural gas production will come from deep (20,000 feet and more) reservoirs. Large basins are known to exist at these depths with a few basins being exploited. Basins containing significant resources and reserves that are greater than 15,000 feet include the Greater Green River, Piceance, Wind River, Uinta, Anadarko, Permian, Gulf Coast, and Gulf of Mexico outer continental shelf (OCS). The USGS[6] estimates that 114 tcf of technically recoverable conventional deep gas remained to be discovered in the Rocky mountains (57 tcf), Gulf Coast (27 tcf), Alaska (18 tcf excluding Hydrates), and West Texas/New Mexico (4 tcf).[7] MMS5 estimates that below 15,000 feet and in less than 656 feet (200 meters) of water depths the OCS is relatively unexplored and could contain as much as 5 to 20 tcf with the most probable of 10.5 tcf of recoverable reserves.5

Most of these basins can be classified as high temperature and high-pressure reservoirs with many of the formations being low permeability reservoirs. Temperatures are >375ºF and many approach 400ºF and higher with pressures up to 20,000psi. Overall average drilling costs of deeper wells have been published at $5MM but many wells drilling at depths of 20,000 feet feet and beyond are currently costing from $17MM to over $35MM. These wells have cost profiles of 50% of the costs accruing in the last 10% of the well where the formations are hard, caustic, and hot. Though the risks are high the benefits can be tremendous. Of the tens of thousand of gas wells in the U.S. 5 wells in the Madden formation in Wyoming can produce 0.5 percent of the entire U.S. gas output. One well in the Tuscaloosa formation produced a record 92 MMCFD in 2000.[8]

Finding Costs: Finding costs are the costs of adding oil and gas proven reserves via exploration and development activities measured on a combined basis in units of dollars per barrel of oil equivalent (BOE). Conceptually they are all costs incurred in finding any particular proven reserves (i.e., measured as the ratio of exploration and development expenditures to proven reserve additions). The analysis presented here is a summary of the EIA report "Performance Profiles of Major Energy Producers 2001"[9] (the most current available) and is presented since the finding costs are important in developing a perspective of the industry's current and future resource development strategies and activities and where technology will need emphasis.

Costs to develop and replace offshore U.S. gas reserves through the drill bit have escalated in recent years and trended higher than foreign and onshore finding costs (**Fig. 2**). The offshore finding costs have declined since the 1980's but have generally been higher than the onshore and foreign costs. The 2001 three-year moving average of finding costs and single or annual costs indicate a reversal of this trend (see **Fig. 2** and **Fig 3**). In 2001 single year or annual U.S. onshore costs were higher than the other two regions (**Fig 3**). Single year finding costs give near term trends.

For the onshore U.S. finding costs, the three-year moving average (1999-2001) was $6.01/BOE a 22.8% increase over the previous three-year running average (1998-2000) while that of the offshore showed a 30.1% decline to $6.99. By contrast Canadian finding costs increased to $10.70 a 56.5%. John S. Herold Inc reported similar numbers.[10] EIA states that the costs outside the U.S. remained relatively flat at $5.25 and below that of North America

One interesting fact is that the three-year moving averages of the U.S. onshore and overall foreign finding costs are roughly converging. The offshore finding costs are declining and have yet to be seen if it will continue. The U.S. offshore finding costs have been rising for the last few years but the 2000 and 2001 three-year average finding costs show a plateau and a possible declining trend (**Fig. 2**). Though higher returns are expected from the Deep Water Gulf of Mexico and foreign projects they also have substantially more risk. Costs associated with an offshore prospect in the Deep Water Gulf of Mexico and elsewhere could exceed a billion dollars, substantially more than a decade ago and higher than onshore prospects. Portfolio development of a combination of high risk and low risk are evidenced for major energy players. This has resulted in an approximate 50-50 split of exploration and development investment portfolios between the U.S. and overseas opportunities (**Fig 4**).

Much of the trend reversal in finding costs between regions can be attributed to substantial increases in reserve additions offshore and less expenditures for unproved acreage. Development activity onshore Alaska and a number of higher cost deeper and exploratory gas wells being drilled onshore in the Overthrust Belt and Greater Green River Basin of Wyoming resulted in near term escalating trends in the U.S. finding costs.

To overcome these market, economic, and technological barriers the DOE sponsors long term, high-risk research of technologies for drilling and completion in low-permeability and deep reservoirs.

Emerging Technology

Rate of Penetration (ROP): Rate of penetration is one of the most critical problems in reducing drilling costs especially in deep, high temperature, high-pressure high-risk gas wells.[11] DOE is currently addressing this in three ways 1) Developing High Longevity PDC Cutters 2) Developing Drilling systems and tools to drill faster 3) Conducting studies to determine why rock at deeper depths and higher temperatures and pressures are so "difficult" to drill.

High longevity PDC cutters: Two projects are developing PDC cutters to increase the strength, durability, and longevity of PDC cutters used in harder formations. The projects use different technology to accomplish this.

Technology International Inc. uses a new treatment process involving ion beam implantation for strengthening and increasing the fracture resistance of the PDC cutters. The objective is to develop durable, thermally stable polycrystalline (TSP) diamond cutters that increase rate of penetration in hard abrasive rock formations. These cutters are being configured in unique TSP diamond drag bits and will be tested with industry support in deep drilling applications. The techniques being developed for these cutters include the use of new microwave and combustion synthesis brazing and a new shock absorption cutter design. Tests to date show increased diamond strength of 60% and fracture resistance of 40% over conventional PDCs.

The second cutter design project funded by DOE is to develop higher strength drill components, including cutters and improved processes for the manufacture of these components using microwave sintering technology of Tungsten Carbide-Cobalt based cemented carbides. This cutter has demonstrated improved abrasion resistance, improved erosion resistance, improved impact strength, and improved corrosion resistance over conventionally sintered carbide drill components. These advancements are possible due to the resulting fine grain structure of the microwave process, no grain growth inhibitors, and uniform cobalt distribution. The Pennsylvania State University developed the Microwave Technology and has partnered with Dennis Tool Company to commercialize the product.

Improved ROP from New Drilling Systems: Though the cutters and bits will allow additional advances to the ROP a systems approach will change the way we drill and possibly provide step changes in ROP. Again, the DOE has funded three projects to address different technologies in an attempt to significantly impact the costly drilling times in hard to drill formations. Two of these have the potential of also being used with Seismic While Drilling Energy Sources.

Jet Assisted Drilling: In 1997 Maurer Technology Inc. (MTI) was awarded a project under the advanced drilling systems solicitation to develop an advanced high-pressure coiled tubing drilling system. This project is in the demonstration phase to prove its effectiveness to increase ROP in the field. The project, however, has run into a couple of barriers preventing it from being commercialized.

The objective of this project is to develop and commercialize a high-pressure (10,000 psi) coiled tubing (HP-CT) jet-assisted drilling system that will increase ROP by as much as 2-to 4-fold and reduce drilling costs by up to 50 percent. The project was to be conducted in three phases. The first phase was to be a feasibility study. The second phase was to develop and define the system while the third phase was for field-testing and commercialization.

Jet-assisted drilling uses high-pressure, high velocity jets to cut slots in the rock, forming kerfs or ledges that are broken and removed by mechanical cutters (**Fig. 5**). This has been shown in both laboratory and field to increase penetration rates in many rock types compared to conventional tri-cone and PDC bit drilling by as much as 2-to 4-fold. Unlike cavitation jets, erosion jets do not have a depth limit.

The jet assisted drilling concept has been around since the 1960's. Work conducted by Shell in 1974[12] concluded that the threshold pressure for cutting rock is 5 times the rock's tensile strength irrespective of pressures or fluids used. However, in 1977 Exxon was able to effectively use jet-assisted drilling to depths of 8,000 feet.[13] Two reasons have caused the resistance to advance and acceptance of this technology. First, important pieces of equipment, such as motors, pumps, and bits have not been sufficiently robust for long-term operation at the high pressures. Second, jointed drill pipe in the past was not capable of sealing sufficiently at the tool joints causing leaks and resulting in washouts. These problems have been overcome with high-pressure pumps and motors, high-pressure extreme rated drill pipe, and coiled tubing.

CT drilling is still in its infancy and is primarily in smaller wells and in geographically specific wells. Initially the use of coiled tubing was thought to be the best solution to commercialize this technology since it eliminates the drill pipe and jointed connections. However, CT suffers from a significant increase in cycle fatigue at higher pressures. This technical barrier and current technological advances in jointed drill pipe make drill pipe a viable option. This introduces another barrier—the need for high surface pressure drilling rigs.

Current mud pumps are designed and built to effectively pump high-density muds at pressures up to 10,000 psi. However, there are very few drilling rigs designed for high pressure drilling onshore. One question that has not been effectively demonstrated that would make high-pressure rigs more acceptable is the effectiveness of significantly higher hydraulic horsepower and its positive benefit on increasing ROP.

The drilling system of high pressure motors and bits were designed, developed, and tested in phase II. Maurer Engineering Inc. (now MTI) designed bits incorporating carefully placed high-pressure nozzles for use with the high-pressure motors. Parameters tested include pressure drop, number and type of bearings, labyrinth seal design, and different types of drilling fluids. The effects of changes in these parameters were determined for motor performance in various rock types, including Glacier bluff Dolomite, Texas Cream Limestone, Sunset Red Sandstone, and Carthage Marble. ROPs of up to 1500 feet per hour were seen in atmospheric tests in dolomite and limestone but less in sandstones (**Fig. 6**). Another potential market for this system is to drill cement out of drill pipe or casing. Testing in this area showed that the system could drill oilfield cements at 1,200 ft/hr compared to 60 ft/hr with rotary drills. Thus reducing cement cleanout costs.

Hydraulic Pulse Drilling: Tempress Technologies, Inc. is developing Hydraulic Pulse Drilling. The objective of this effort is to test the feasibility, prototype development and commercialization potential of a drilling system that relies on mud driven suction pulses to enhance the rate of penetration in intermediate and deep wells. The system is expected to increase performance at depths beyond 5000 feet and to utilize the cyclic vibration of the system to serve as a seismic-while-drilling source. This equipment while still in the prototype development phase, has demonstrated the ability to drill at significantly improved ROPs in both closed loop surface and laboratory pressure vessel tests. Doubled ROP in pressure sensitive formations (shale and argillaceous sandstone) at low bit weight has been observed during tests. This technology is targeted to the hard to drill shale formations, which account for approximately 75% of rock drilled for oil and gas.

Steerable Mud Hammer: Also started in 1997, NOVATEK set out to develop a steerable drilling system (**Fig 7**) that would offer significant cost reduction and technical advantages over current drilling practice, particularly in deep, medium-to-hard rock formations. Improvements to drilling speed, formation evaluation, and data transfer from bottom to top of the well were identified as probable outcomes of this development effort. A yearlong paper study at the beginning of the project compared various candidate technologies and helped narrow the focus of the development program to those concepts most worthy of pursuit. This first phase of work was then followed by a second phase wherein candidate technologies were studied more closely and prototypes were built and tested. The purpose of this second phase was to identify and address practical and theoretical hurdles, and further refine designs to prepare them for eventual field use. A final field demonstration phase is scheduled but the project has not progressed sufficiently to move it into that stage. This project has been through several iterations of redesign. Current tests are in simulated borehole conditions at Tera Tek's drilling test facility in Salt Lake City, Utah.

This project also developed a pulsed jet hammer assisted shearing technology bit. Initially bit test runs were hampered by difficulties with the distributed high-pressure nozzles including blown nozzles, plugged nozzles, and washed/crack high-pressure passageways. However after repair the bit, final tests were run without bit failure. The high impact PDC cutters were free of damage and wear.

In hard rock tests at the high capacity rig at Terra Tek the hammer/PHAST bit system drilled without difficulty although inconsistent ROP were obtained. Two distinguishable drilling modes were observed in the Crab Orchard Sandstone at 3000-psi borehole pressure (**Fig. 8**);

- One where the rate of penetration increases steadily with bit horsepower
- The other where ROP is high to very high.

In the first mode penetration rates compare favorably to the ROP of a conventional rollercone bit under the same borehole pressure and at 40,000 lb WOB and 110 rpm. Increases of up to 45% over conventional method are achieved with the hammer system. These gains are primarily a function of input bit horsepower – in fact, if the data is plotted in terms of inches per revolution rather than total ROP, the graph becomes nearly horizontal, indicating that bit rpm is a major determinant of ROP.

Even greater gains, up to four times conventional, are seen in the second drilling mode. As noted above, though, these gains were inconsistently produced, suggesting that all key parameters were not controlled. These extraordinary data points were all noted to occur with low weight on bit, although not all low WOB situations gave the desired result. Such performance was not observed with a rollercone bit or with other hammer bits, and it was not as pronounced when drilling in Carthage Marble.

A parameter leading to the largest increases is hammer horsepower. The greatest improvement to second mode drilling comes with the greatest hammer input horsepower. Other parameters, including the effectiveness of the high-pressure jets in the PHAST bit, are unknown at this time and are deemed worth pursuing. Knowledge of such opens the door for deep hole application of percussion tools, and allows further pursuit of use of a jet assisted hammer as a steerable tool.

Mud Hammer Optimization: Terra Tek was funded by the Department of Energy and industry participants to put together an effort to test and optimize mud driven fluid hammers as one emerging technology that has shown promise to increase penetration rates in hard rock.[14] The thrust of this project has been to test and record the performance of fluid hammers in full scale test conditions including, hard formations at simulated depth, high density/high solids drilling muds, and realistic fluid power levels. Two 7-¾" diameter mud hammers with 8 ½" hammer bits were tested. A NOVATEK MHN5 and an SDS Digger FH185 mud hammer were tested with several bit types, with performance being compared to a conventional (IADC Code 537) tricone bit. Recently the Smith Fluid Hammer has been added to this project and benchmark tested at Terra Tek. However the test results have not been fully analyzed or released and are not discussed here.

The testing thus far has revealed that the two new generation mud hammers tested in this project have the ability to drill medium to hard rock (16,000 to 25,000 psi compressive strength) and operate in 10 to 15 ppg water base mud systems and demonstrated competitive ROP performance at or below 1000 psi borehole pressure but not at higher borehole pressures.

Interestingly, as a result of this testing, a new drilling mode has been identified for the NOVATEK mud hammer (see previous DOE project) while transitioning from low WOB to higher WOB. Performance improvement while drilling in this mode appears to be of significance. Drill bits designed to exploit both the rotary and impact components of the applied load, appears to provide better performance while there appears to be no advantage in the use of conventional IADC Code 537 tricone bits in conjunction with these tools. Future work includes the optimization of these or the next generation tools for operating in higher density and higher borehole pressure conditions and improving bit design and technology based on the knowledge gained from this test program.

These tests point to a need to address and understand more fully the measure and energy level required to break rock with percussion under downhole conditions. Both laboratory and modeling is needed. This same technology gap is known to exist in rotary drilling at greater depths also. The energy level and how rock is destroyed is not well understood.

Cementing: One of the most critical needs in well construction is cementing across sensitive and low pressured zones. The DOE has funded one project in developing advanced cements. Additionally, the DOE Fossil Energy has funded Argonne National laboratory to develop an oil field version of ceramicrete. Ceramicrete is a chemically bonded phosphate ceramic borehole sealant. This product shows promise but has not reached a field ready state and is not discussed any further here.

Ultra-Lightweight Cement Project: The objective of this project was to develop cementing systems using ultra-lightweight hollow spheres (ULHS) for deep water and other critical applications, test the physical performance of the cement slurry, and compare test results to the performance of conventional lightweight cements. Conventional lightweight cements have severe drawbacks as they achieve low compressive strengths and have difficulty providing long-term zone isolation under severe conditions. The impact of these failures is magnified when they occur in deepwater operations. In an effort to overcome the problems of conventional lightweight cements, Cementing Solutions, Inc. (CSI) with funding from the U.S. DOE has been developing new lightweight cement that will have long term durability, high strength, provide good bonding and long term zone isolation.

Technology advances in hollow spheres have aided in the development of new lightweight cements. Previously, lightweight hollow spheres could attain a specific gravity of 0.67, but they would collapse in high pressure applications, thus, limiting their use to shallow wells. Today hollow spheres are available that are ultra-lightweight and exhibit superior crush strengths of 3,000 to 10,000 psi. These new ULHS can also attain a specific gravity of as low as 0.32 to 0.46, while resisting wellbore pressures as high as 6,000 psi.

Like many of the projects funded by the DOE, an advisory council of industry experts was assembled to advise and periodically provide input to CSI. Over 5,000 data points from field jobs in the U.S. were supplied to the project from service companies. This data was used to determine the conditions under which lightweight cements were most commonly used and to define the type of operations currently being performed in deepwater wells. In addition to standard testing of cement slurries containing ULHS, a unique combination of tests to measure slurry's ability to withstand formation stresses over long periods of time. Other tests include applying a triaxial load to samples to simulation wellbore conditions, testing for Young's modulus and tensile strength, as well as stress cycling tests to ensure that the ultra-lightweight cement slurry could withstand the changes in temperature that occur in deepwater wells. The results from the testing demonstrated that ultra-lightweight cements exhibited high strength, low permeability, easy slurry designs, and durability.

The new ultra-lightweight cement has been field tested with encouraging results. The first field test was designed to ensure that the slurry could be easily blended, mixed, and pumped on location with little trouble. This test was performed on a South Texas well and the slurry was easily blended on location, and was mixed and pumped with no problems in a 7,000' well. The second field test was designed to test the slurry's performance in a land based well that closely resembled deepwater operations. The second test was performed in a well in the Rocky Mountains operated by the DOE and Rocky Mountain Oil Test Center (RMOTC) in Wyoming. The well had been previously cemented with foam cement and although there were problems with lost circulation, the well required high-strength cement and good zone isolation. One hundred barrels of the ultra-lightweight cement slurry (using 3M 6K ULHS beads) were mixed and pumped with no problems. The ULHS beads showed no breakage after one hour of conditioning at the surface. Ultrasonic logs performed on the well after the cement operation showed excellent application of the slurry, good bond properties, and good perforating qualities.

Future applications for the ultra-lightweight cement include: critical operations requiring the use of lightweight cements, wells with formation damage occurring from treatments with conventional cements, and coal seam wells. Because of its high strength, low permeability, and low density, this slurry will provide excellent bonding in deepwater offshore wells, or high temperature, high pressure land-based wells.

Tubulars: As the wells get deeper, hotter, and higher pressure the properties of the materials and rigs to drill and complete these wells are reaching their technical and economic limits. Developing innovative materials to increase the strength and/or decrease the weight of tubular products used in these wells is imperative. The DOE has two projects to develop lighter or stronger tubular products. Composite Pipe has progressed to an emerging technology stage. The other, microwave sintering, is a project that has just started under the Deep Trek program.

Composite Drill Pipe: Conducted by Advanced Composite Products Technology, Inc (ACPT), the objective of this project is to design and develop a composite drill pipe with a steel connection that is competitive with steel drill pipe in price and a significant technological advantage. The goal was to show improvement over steel pipe in three areas: 1) extended reach in horizontal drilled holes; 2) improving logging and measurement while drilling capabilities; and, 3) providing an enabling technology and cost savings in deep water drilling in the Gulf of Mexico.

During the first two years of this project, specifications for both 5-5/16 inch and 3⅜ inch composite drill pipe were finalized, materials for the composite tubing, adhesives, and abrasion coatings were selected based on laboratory testing, and a composite tube/metal tool joint interfacial connection was successfully tested. The efforts in the third year have focused on the production and testing of the full-scale pipe.

The composite drill pipe consists of a composite material with steel box and pin connections. The tube is manufactured by winding a composite material of graphite fibers and epoxy resin around a metal mandrel and the metal box and pin connections. The composite tube is then cured before being removed from the mandrel. The cured pipe is then finish machined and coated for abrasion resistance. Final preparation, which is normally done in the field, involves the addition of standard elastomeric centralizers before the pipe is run in the hole. Both the centralizers and the abrasive resistant coating can be repaired in the field, with the more extensive wear being able to be repaired at the factory.

The composite pipe offers advantages over conventional steel drill pipe. First, composite drill pipe is half the weight of steel drill pipe. This is extremely important for ultra-deepwater resource development and will allow the existing fleet of land rigs to drill to greater depths. The composite pipe is more fatigue resistant and flexible than conventional steel drill pipe. This technology will impact the industry in short radius drilling applications and may open up reservoirs once considered uneconomical. Other advantages include the ability to repair the composite pipe and to tailor or customize the mechanical properties of the pipe for its specific application. And finally, composite pipe has the potential to enable high-speed communications in the drill pipe because of the ease of placing cables within the body of the drill pipe.

During November 2002 a 3⅜ inch composite drill pipe was field tested in Tulsa, OK. The field test demonstrated the flexibility and reliability in a short radius curvature drilling application. The operator planned to drill a new lateral in an existing vertical well that had stopped producing in 1923. The lateral was kicked off at a depth of 1200 feet where a 70-foot radius curvature was drilled. Once the curved section was completed, the well was then drilled 1000 feet horizontally. The well was drilled into an oil-bearing zone, and the well was expected to produce 30 to 50 barrels of oil per day with a slow decline. During the test, the composite pipe remained in the curved section of the well and performed flawlessly. This test demonstrated the pipe's flexibility as well as reliability as the composite pipe was in a stressed state during the entire drilling operation.

The composite pipe will have a significant impact on the oil and gas industry, in the expensive deepwater offshore, but also could bring new life to thousands of idle wells drilled in the early 20th century which have oil and gas bearing zones once considered uneconomical.

Diagnostics While Drilling: The DOE program has funded several MWD, LWD, EM, and downhole data communication systems. Most of these have been successful at low temperatures <350°F. Above 350°F DOE has determined that current electronics are not sufficient to build the economic tools for any longevity.[15] DOE has funded a project that should give the industry a robust high-speed telemetry system.

Intellipipe Telemetry Project: In 1997 NOVATEK Engineering was funded by the U.S. DOE to develop a steerable Mud Hammer System (see NOVATEK Mud Hammer Project Previously described). As part of that research a high-speed data transmission system was needed. NOVATEK addressed that need and found that a substantial technology gap existed and would require substantial more resources than a supporting task would allow. Additionally in doing the research a better mode of data transmission was discovered. In 2001 the DOE partially funded NOVATEK to develop a high-speed downhole communications (telemetry) system now called Intelliserv®. Tests have been conducted in a 1000-foot well in Provo Utah and 2000 foot well at Catoosa test site. Data transmission rates are approaching 2 MM bits/sec

Currently, this project is finishing the last tasks of phase II and entering the third and final phase of activity. This final phase is to get a complete string into the field, establish high-speed communications with third party downhole tools, and prepare the system for commercial introduction. At the time of this writing the system is under field test to demonstrate operation of a bi-directional network in a 6,000-foot drill string under field drilling conditions.

This is one of the most enabling technologies to be developed recently for the petroleum industry. The impact is far reaching. The technological advancement offered are expected in the overall drilling process that will result in faster well drilling, thereby reducing well costs. The "smart pipe" itself is the building block of a downhole "internet system" that for the first time will allow high-speed bidirectional communication with various tools while drilling. One of the premier applications of the network is for seismic characterization of a reservoir during the drilling process.

Other potential applications of the network include feedback and control for downhole steering assemblies, real time data transmission to the surface, determination of stuck point, determination of excessive downhole make up of drill joints, drillstring vibration monitoring, pressure disturbances, etc.

Completions: Part of the DOE's program focus is to assist small operators preserve production and reserves from existing fields as well as tap the natural gas in emerging resources such as low-permeability sandstones. Developing completions technology is one way this is being done.

Real-Time Downhole-Mixed Stimulation Fracturing: The purpose of this project was to develop a new reservoir stimulation process that would allow the operator to control in real-time the proppant concentration and placement in the reservoir. This technology, being developed by Real Time Zone, Inc., includes the mixing of separate fluids downhole to create a composite fracturing fluid at the formation. Downhole-mixing is accomplished by dual injection of different fluids for admixture next to the perforated interval, via coiled or conventional tubing and the tubing-casing annulus. Downhole rheologic properties and proppant concentrations may be modified "on the fly" by adjusting surface pressure and rates.

This process can also be used to create different fracturing fluid phases and thereby induce realtime viscosity interfingering in the reservoir fracture or fractures, focusing proppant placement and facilitating control of proppant concentrations. The methodology may be combined with real-time fracture monitoring to enable an operator to change fracture propagation and improve resultant fracture geometries, and proppant concentration and placement.

Numerous advantages over conventional stimulations have been identified through the testing phase of this project. This process has been proven to have lower fluid-pipe friction pressure characteristics thereby reducing the treating pressure thus the horsepower required to pump the stimulation. Reducing the horsepower requirement results in a cost savings as well as reducing the exposure liability. The real-time enhanced fracture process also minimizes or eliminates some of the common reservoir stimulation problems including poor zonal isolation, excessive water production from stimulating out of zone, inefficient proppant placement in fractures and undesirable early treatment termination due to high pressures and/or premature screenout.

This technology was successfully demonstrated for the first time in a 12,300-foot Morrow gas well in the Sand Point field of Eddy County, NM. The treatment consisted of a methanol gel with 7,000 pounds of bauxite proppant pumped down the annulus and 40 tons of liquid CO_2 pumped down the tubing. The tubing pressure never exceeded 6,000 psi, and the casing side was never above 5,000 psi. In comparison, if the job had been pumped in the conventional manner, the pressures would have averaged closer to 10,000 psi. Originally scheduled for abandonment, the Sand Point well's post fracture production was 200-250 Mcfd. A post-fracture tracer log showed the treatment had been placed in the desired zone.

A second field test was performed in a Willow Lake well that was considered to be a dry hole. The Delaware sandstone showed about 40 to 50 feet of net pay at about a 5,000-foot depth, with a 40 to 50 foot wet zone directly below the pay and stratigraphic barriers. Most wells in the area produce at 60 to 90 percent water cut because the hydraulic fractures invariably grow out of zone and have fracture heights of 100 to 200 feet. In this field test, gelled lease oil and propppant were pumped down the tubing while pumping CO_2 down the annulus. The rates were carefully controlled to achieve appropriate mixing at the perforations. The result was an economic well that produces 8 to 10 BOPD at only 20% watercut.

This project is in its final phases of field-testing and the process has been licensed to Halliburton Energy Services. With further testing, downhole mixing of fracturing fluids could find increased application in a variety of treatments. When a job can be pumped with less pressure, less horsepower, and less fuel, it opens up opportunities for older wells with older tubing and lower incremental reserves to be stimulated economically. Additionally, the deeper wells can be stimulated at lower costs.

Future Effort

The ten summarized projects are a few of the R&D projects that the U.S. DOE has provided funding to ensure adequate supplies of natural gas for the U.S. These projects are some of the more significant emerging technologies in the drilling, completion, and stimulation area. There are a number of other projects in varying phases of development including but not limited to: high temperature LWD/MWD systems, long term R&D efforts in laser drilling and completions, Arctic Drilling/Production Platform, Dual density drilling, Underbalanced Drilling, non-damaging fluids, downhole fluid analyzer, and downhole power generation wireless communications, etc. Projects in Geological Hydrate Accumulations and Resources, Low Permeability Reservoirs, and Gas Storage Technology are also funded through the GEPS program.

Deep Trek Program: To help develop the high-tech drilling technology the industry needs to produce deeper reserves, the U.S. Department of Energy is sponsoring the Deep Trek Program. The goal is to make the production of deep oil and gas resources economically feasible. Technology development is focused on increasing the overall effective rate of penetration for deep drilling. The program kicked off on March 20, 2001 with a workshop in which industry needs were identified.

Included in the Deep Trek Program are the technology areas:

- Smart Drilling Systems
- Advanced sensors and monitoring systems
- Low friction, wear resistant materials and coatings
- Advanced drilling and completion systems
- New bit technology

The DOE is sponsoring a $10.4 million program to cost-share three phases of R&D: (1) feasibility and concept definition; (2) prototype development or research, development and testing, and (3) field/system demonstration and commercialization.

The solicitation was first issued in February 2002 and has had two round of proposals. In the first round five projects were awarded in September 2002.

Stimulation Technology for Deep Well Completions: The objective of the work is to review current and past stimulation activity and research results for deep HTHP well completions and stimulations in the United States. The information shall develop and extend the knowledge base for the DOE and industry in the U.S. and Gulf of Mexico (GOM). The results shall help reduce uncertainty and increase success in these areas. The project shall provide an assessment of 1) what is currently working in deep and HTHP formation stimulation and completion technology 2) what is currently not working in deep and HTHP formation stimulation and completion technology and 3) what needs improvement in deep and HTHP formation stimulation and completion technology. Pinnacle Technologies, Inc. is to accomplish this work.

Improved Tubulars for Better Economics in Deep Gas Well Drilling Using Microwave technology: The main objective of the proposed research program is to improve the rate-of-penetration in deep hostile environments by improving the life cycle and performance of coiled-tubing and/or drill-pipe, important components of a deep well drilling system for oil and gas development. This shall be accomplished by developing an efficient and economically viable microwave process to sinter continuously formed/extruded steel powder for the manufacture of seamless coiled tubing and drill-pipe and other oilfield tubular products. The goals of the project are to economically manufacture coiled tubing and other oilfield tubulars with improved performance under hostile underground and marine conditions. The Pennsylvania State University and Dennis Tool Company with Quality Tubing as advisory partner will develop this technology.

Electro-magnetic (EM) telemetry: The objective of this project is to develop a wireless, electro-magnetic (EM) telemetry system for use in deep natural gas and other high-temperature drilling applications beyond 20,000 ft. and up to 392º F (200ºC). The system shall be designed to facilitate MWD operations within a high temperature, deep drilling environment. E-Spectrum Technologies Inc. was awarded this project.

Deep Drilling Bits and Fluid Benchmarking: The project objectives are to benchmark drilling rates of penetration (ROP) in selected simulated deep formations and to significantly improve ROP through a team development of novel product drill bit and fluid system technologies. TerraTek Inc. will accomplish this study.

Drilling Vibration Monitoring & Control System: The objective of this project is to develop a unique Drilling Vibration Monitoring & Control System (DVMCS) to both monitor and control drilling vibrations in a 'smart' drilling system. This system has two primary elements: The first is a unique, multi-axis active vibration damper to minimize harmful axial, lateral and torsional vibrations, and thereby increase both rate of penetration (ROP) and bit life, as well that the life of other drillstring components. The hydraulic impedance (hardness) of this damper will be continuously adjusted using unique technology that is robust, fast acting and reliable.

The second component is a real-time system to monitor 3-axis drillstring vibration, and related parameters including weight-on-bit, torque-on-bit (TOB) and temperature. This monitor will determine the current vibration environment and adjust the damper accordingly. In some configurations, it may also send diagnostic information to the surface via real-time telemetry. APS Technologies will develop this tool.

These projects are typically one to three year projects. A second round of proposals has been submitted and is in the review process.

Nomenclature

BOE=Barrel of Oil Equivalent
CT=Coiled Tubing
DOE= Department of Energy
EIA = Energy Information Agency
FE=Fossil Energy

HP=High Pressure
HT=High Temperature
IADC=International Association of Drilling Contractors
LWD=Logging While Drilling
Mcfd= 1000 cubic feet per day
MMS=Mineral Mangement Service
MWD=Measurement While Drilling
NETL=National Energy Technology Laboratory
NPC=National Petroleum Council
OCS=Outer Continental Shelf
PDC=Polycrystalline Diamond Composite
PHAST= pulsed jet hammer assisted shearing technology
RMOTC=Rocky Mountain Oilfield Testing Center
ROP = drilling rate of penetration
Tcf=trillion of cubic feet
TSP=thermally stable polycrystalline
ULHS=ultra-lightweight hollow spheres
USGS=United States Geological Survey
WOB = weight on bit

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Figures

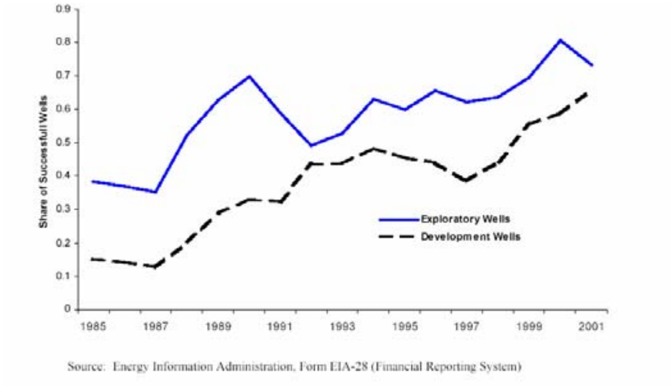


Figure 1: Natural Gas Share of Successful Exploratory and Developmental Oil and Gas Completions 1985-2001

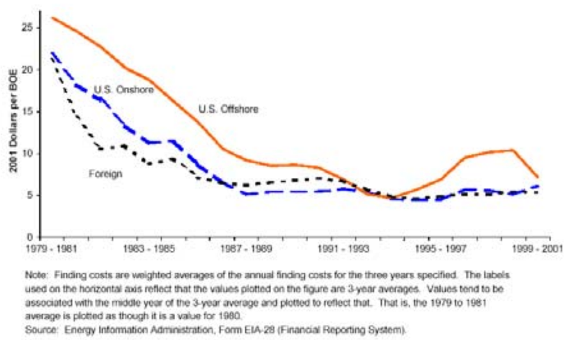


Figure 2: Three-Year Moving average Finding Costs 1979-1981 to 1999-2001

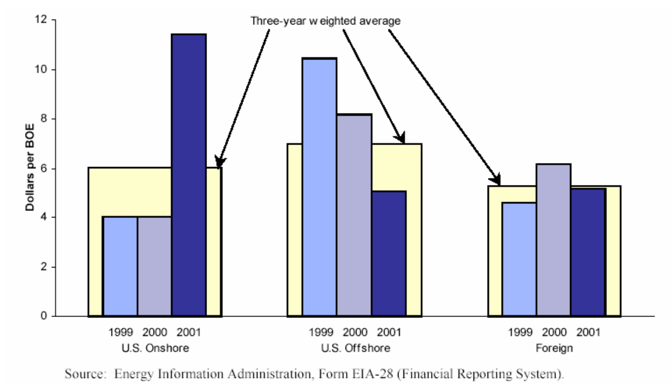


Figure 3: Annual Finding costs and Three Year Moving Average 1999-2001

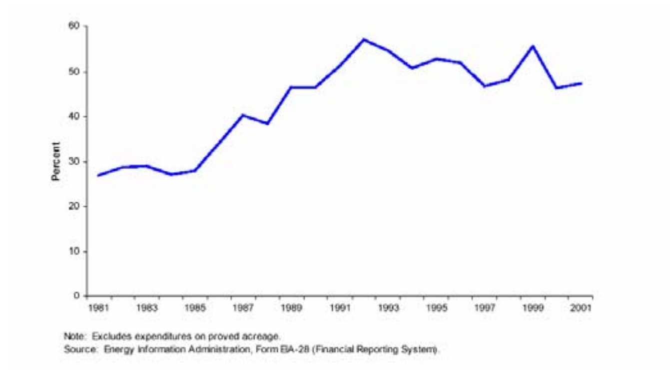


Figure 4: Expenditures Share of Worldwide Exploration and Development Expenditures 1981-2001

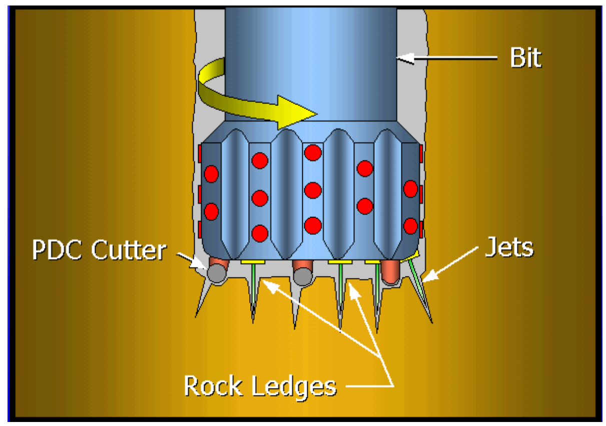


Figure 5: Concept of Jet Assisted Drilling

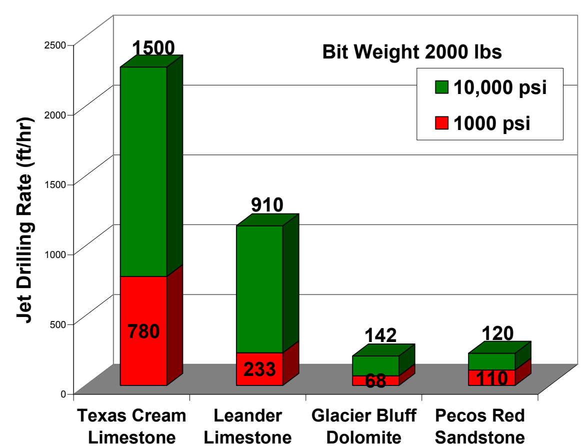
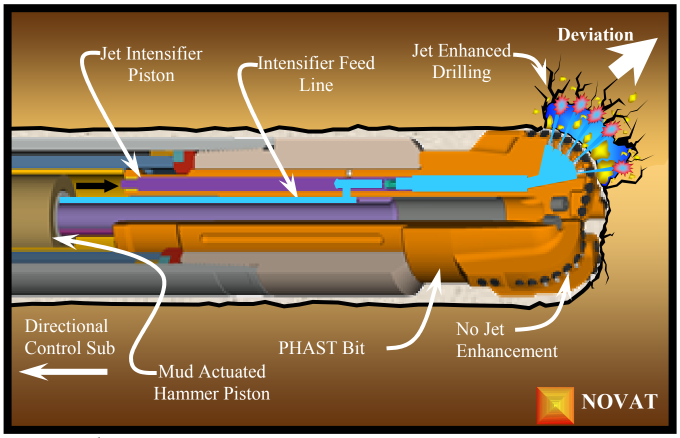


Figure 6: Jet-Assisted Drilling Rates



Patent Pending

Figure 7: Schematic of Steerable Mud Hammer

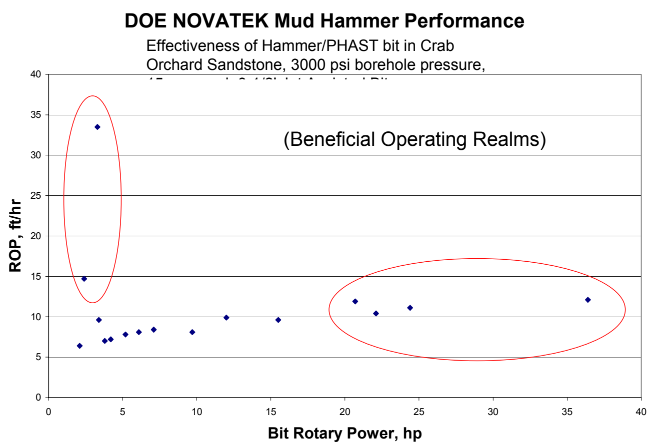


Figure 8: NOVATEK Hammer Performance in Crab Orchard Sandstone with possible transition areas delineated