Paper #2-23

SUSTAINABLE DRILLING OF ONSHORE OIL AND GAS WELLS

Prepared by the Technology Subgroup
of the
Operations & Environment Task Group

On September 15, 2011, The National Petroleum Council (NPC) in approving its report, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic and White Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic and White Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 57 such working documents used in the study analyses. Also included is a roster of the Subgroup that developed or submitted this paper. Appendix C of the final NPC report provides a complete list of the 57 Topic and White Papers and an abstract for each. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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* Individual has since retired but was employed by the specified company while participating in the study.

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Table of Contents

ABSTRACT

Although not always recognized or appreciated in the public arena, the technologies and practices of drilling oil and gas wells have followed pathways of continuous improvement for many decades. Motivations for improvements have been not only the tightening regulations for environmental protection but also geotechnical factors that have impeded the cost-effectiveness and production potential of resource-development projects. In almost every case, innovations driven by commercial factors also have brought substantial improvements in environmental safety and sustainability.

A critical area of focus in the drilling process is the proper management and disposal of drilling fluids and waste products. Drilling wastes can include drilling mud, produced water, or other byproducts that can have a harmful impact on the environment in the event of an uncontrolled release. The containment and disposal of the wastes is a main priority.

Specific findings include:

- Extended-reach drilling (ERD), and the associated technologies needed to support it, has contributed toward substantially reduced spatial footprints of drill pads by allowing multiple wells to be drilled and completed from a single pad. Not only is the required acreage needed for drilling significantly reduced, but collateral impacts likewise are reduced, including truck traffic, noise and air emissions. Development of emerging resources, such as shale-gas, will further drive optimization of multi-well pad practices.

- Muds and other fluids required to enable rotary drilling through rocks, are essential enablers of drilling and significant efforts have been made to reduce total fluid volumes as well as to reduce environmental incompatibilities in the fluid compositions. Recycling or re-use of fluids, involving a wide array of water-treatment technologies, has reduced the per-well magnitudes of disposal issues and spillage concerns.

- Construction and operation of drill rigs has benefited from evolving diesel-electric and all-electric options for powering drill-rig motors. Reduced dependence on diesel technologies has led to reductions of noise, petroleum fuel transportation and storage and air emissions at drill pads.

- Reliable construction and verification of well integrity has improved with advances in cementing technologies and with technologies for downhole logging of cement, casing and formation properties.

- Future drilling and delivery of onshore oil and gas wells will depend upon ongoing cooperation between operators and government regulators to find mutually agreeable solutions to overlapping commercial and environmental issues.

INTRODUCTION

A. Operations at an Onshore Drill Pad Site

The environmental impacts caused by the oil and gas industry are at the forefront of the public eye. What is less known and appreciated are recent advances in drilling technology that have provided the energy industry with the means to mitigate environmental footprints while simultaneously increasing production capabilities. The decrease of the industry's environmental footprint has primarily come from advances in pad-site design, extended-reach drilling, and multi-lateral technology.

A drill pad is a plot of land that is used to accommodate a drilling rig along with necessary supporting services, including water and waste storage, drill-pipe storage, field-services equipment, motor-vehicle parking and temporary office buildings. Drilling to create wellbores into hydrocarbon-bearing reservoirs always include at least one vertical section to achieve subsurface penetration but modern drilling increasingly emphasizes horizontal (sideways) completions to maximize recovery of unconventional oil or gas resources from geologic formations such as shales or similar tight-formation rocks of large lateral extent.

B. Advantages of Multi-Well Drill Pads

The importance of horizontal wells has driven efforts for footprint reduction toward the concept of multi-well pads. An analysis done for the US Department of the Interior on a horizontal vs. vertical well development concluded that a horizontal well will be able to drain roughly 4 times that of a vertical well. The analysis also found that the horizontal well would have only a third of the environmental footprint that a vertical well would have. This means a large number of horizontal wells placed on a singular pad could greatly decrease the number of disturbed acres (Arthur et al., 2009). A case study was recently done on the implementation of a 7-wellbore pad site in the Marcellus Shale. "Some of the main obstacles unique to the Marcellus shale for all operators are the topographical features limiting surface hole locations and water disposal and supply issues. Since many of the roads are restricted for heavy equipment and the area has limited pipeline capacity, drilling single wells pose significant challenges. For these reasons, many operators are moving to multi-well pads in the region" (Poedjono et al., 2010). By utilizing this multi-well site, the energy company was able to reduce the environmental impact by lowering the amount of additional acreage needed for extra pad sites.

Other advantages of multi-well pads include the reduced cost of future drilling operations which can be staged from a pad site already built. The overall life of the pad can also be extended by systematic completion of wells on the pad. And finally, by doing a multi-well pad the midstream infrastructure and operational requirements are made simpler, hence again lowering the amount of surface disturbance needed to successfully produce hydrocarbons.

When drilling operations begin on a pad site, there is already a pre-planned wellbore arrangement in place. This wellbore arrangement can contain anywhere from one to as many as 15 wellbores on a single pad site, including both vertical and horizontal developments. Using three-dimensional (3D) subsurface visualization technologies and abiding by anti-collision rules, multiple wellbore trajectories can be managed to create a singular multi-well pad site. That approach allows the operator to place multiple horizontal wells on a singular pad site.

REDUCING FOOTPRINTS OF DRILLING OPERATIONS

A. Extended-Reach Drilling (ERD)

Extended Reach Drilling (ERD) is the key technology for enabling multi-well pad sites and thereby reducing what otherwise would be a larger number of individual well pads. "The aim of ERD is either to reach a larger area from one surface drilling location, or to keep a well for a longer distance in a reservoir in order to maximize its productivity and drainage capability while at the same time reducing environmental footprints" (Agbaji, 2010). There are two common ways to technically describe what constitutes an ERD well. First, if the length of the departure is two times or more than that of the true vertical depth then it is considered to be an ERD. Second, it is considered ERD if the measured depth is a minimum of two times the true vertical depth.

The utilization of ERD can be seen in a case study of two ERD wells drilled offshore from Point Arguello in Santa Barbra, California. In this study a new ERD well and an ERD sidetrack were drilled off the Hidalgo drilling and production platform (the platform is located 6 miles offshore in 430 feet of water). The drilling team utilized a Rotary Closed Loop Steerable (RCLS) system, which allowed for communication to the rotary steerable system while maintaining rotation on bottom. Using the RCLS the tortuosity in the wellbores was kept to a minimum, allowing for easier liner-hanger and casing jobs to be performed. By drilling those two ERD wells, the environmental impact was substantially reduced, including avoidance of the need for a new drilling platform along with new surface or subsurface facilities (Hertfelder et al., 2008). Not only do ERD wells lower the environmental impact, they also increase the productivity of a field. An average ERD well can now contact over 60 times more subsurface area than a vertical well (Godec, 2009). The technology exists today to drill these ERD wells incredible distances. In May 2008, the longest horizontal well ever drilled reached a distance of 35,770 ft utilizing a relatively small rig package in the Al-Shaheen field in Qatar (Denney, 2009).

To further limit surface disturbances, the use of multilateral wellbores can be integrated into multi-well ERD pads. Building upon each other, the combination of these three technologies allows the energy industry to gain the most subsurface reservoir contact area while maintaining a minimal environmental impact. Multilateral wells can have a major positive impact on a company's overall performance. "This positive impact can be identified through higher production rates, through greater total production or ultimate recovery, by controlling or minimizing water and/or gas coning, by shutting off zones with water or gas encroachment, through greater reservoir understanding, and through minimizing facilities" (Oberkircher et al., 2002). Multilateral wells can be classified by a system known as Technology Advancement for Multilaterals (TAML). There are six levels to the TAML system, with levels 4, 5, and 6 having the ability for flow isolation. Current technology allows for "intelligent completion": an intelligent completion allows the operator to control flow downhole via real time data by manipulating the wellbore structure.

The utilization of these technologies in the current exploration and producing field has given operators the ability to limit their environmental impact while increasing their production capabilities. Advancements in all three fields have led to multiple industry successes, such as well site footprints are now 30% smaller than they were in 1970. Also, U.S. producers are able to add two times the amount of oil and gas per well than in the 1980s (Godec, 2009). Those successes, when coupled with the decrease in the environmental impact of operations, show the necessity of continued use and advancement of drilling technologies.

B. Built-for-Purpose Drill Rigs

A general concern to some people is the large padsite that needed to move a drill rig and the associated buildings. But the magnitude of that worry has been relieved significantly by new skid and walking rig systems. "The APEX Walking™ Rig's proprietary walking system moves the rig forward, sideways or in a circle with pipe racked back providing unrivalled flexibility for well layout or location constraints. Innovations in the electronic festoon system, flowline manifolds and mud system allow the rig to walk along well layouts in excess of 150' without the need to move any primary equipment beside the rig itself" (Patterson UTI Drilling, 2010). That skid/walking system allows for a more compact pad site with less environmental disturbance. Current rig skid/walking systems have seen much improvement. Current abilities include being able to skid in 8 directions, skid up to 40 ft/hr, 2.4 million pounds of lift capability, and most importantly no disassembly needed (Veristic Manufacturing, 2009). Not having to disconnect and reconnect hoses and lines allows for a safer and cleaner wellsite.

Electric top-drive systems, which are the motorized mechanisms used to turn and lift the drillstring and drillbit needed to create a wellbore, represent another technical improvement that can be utilized in built-for-purpose rigs. Current improvements now have given those top drives the ability to drill deeper and to deliver longer wells. With electric top drives currently having torque ratings of 35,000+ ft-lbs and hoisting capabilities of 500 tons, the length capability of current wells has been considerably increased (National Oilwell Varco, 2010). By utilizing those top-drive systems coupled with walking rig technology the environmental impact can be greatly reduced through the drilling of multiple ERD wells on a singular padsite. An auxiliary technology of importance to ERD is the improved capabilities of mud pumps which are the devices used to transmit drilling power through wellbores that bend from vertical to horizontal orientations. Those pumps are now allowing for transmission of higher pressures and greater flow rates which allow better hole cleaning in longer lateral wells.

Overall rig design is another aspect that drilling contractors can take into consideration. New generation rigs such as the FlexRig™ by Helmerich & Payne use a smaller padsite while maintaining the capability to drill to depths of 18,000 ft. FlexRig has been recognized by the Environmentally Friendly Drilling (EFD) program of the Houston Advanced Research Center (Rodgers, 2006). By combining smaller padsites with rig automation, the environmental impact is lowered while safety is increased. Nabors drilling has the capability of drilling to a depth of 10,000 ft while maintaining a padsite of only 195 ft by 80 ft on its coiled tubing rigs. Utilizing coiled tubing allows for a much smaller padsite while simultaneously allowing for slimhole drilling to capture hydrocarbons in lower depth zones. Those coiled tubing rigs can be moved in only twelve loads, reducing the amount of transportation needed as well (Nabors Industries Drilling, 2008).

The transportation of the rig from one site to another should also be taken into account with built-for-purpose rigs. For example, coiled tubing rigs can be moved in only twelve loads, thereby reducing the number of site-to-site transportation trips (Nabors Industries Drilling, 2010). Helicopter transport is becoming another valuable tool in the industry for rigs that can be broken down into sections manageable by heavy-lift helicopters. Helicopter transport options are especially crucial for remote-access locations that otherwise would entail substantial surface destruction by overland trucking.

C. Low-Emission Motors

The number one cause of air-emission issues associated with drill rigs is the dependence on diesel engines which historically have been the technology employed to provide power for the various motors that operate the rig. The easiest way to lower air emissions is to replace the diesel engines with alternative motors. Not only are the emissions of the rig lowered by avoiding diesel engines, but the amount of noise and petroleum fuel on location also are significantly reduced. Thos reductions further benefit the operator with a cleaner, smaller, and more environmentally friendly drill pad.

Drilling contractors can facilitate a more emission friendly rig by building/converting rigs that operate with a diesel-electric system. In a diesel-electric system, a rig's diesel engines provide power to the silicon controlled rectifier (SCR) house. From the SCR house the power is distributed to various locations on the rig, including a large electric motor that operates the drawworks. On power-type rigs, the drawworks are operated by two larger diesel engines which, on a diesel-electric rig, become unnecessary.

To further reduce dependence on diesel engines, the diesel-electric system can be replaces in some cases by connections to the regional electric-power grid. A case study of the effectiveness of grid power was done in the Barnett Shale when Chesapeake Energy teamed with TXU Energy and Rapid Power Management (RPM) to create a skid-based electrical system. The final system allowed for a single skid package to be brought onto location and connect directly from the electric utility lines to the SCR house. This skid designed by Rapid Power Management can be utilized in numerous different grid power systems and effectively provide reduced voltage harmonics and voltage notching. Not only are emissions lowered in this system, but the cost savings can be very large depending on current diesel prices. Chesapeake Energy saw a savings of $33,000 per well from the grid-power alternative, based on a diesel price of $2 per gallon; even greater savings could be expected if diesel prices were substantially higher. Although the operating savings were attractive, the Chesapeake-TXU-RPM project was driven by emission standards set by the Environmental Protection Agency (EPA) and the Federal Aviation Administration (FAA) (Shipley, 2009) which also were addressed successfully.

Another case study from south Texas on the Huisman LOC 250 rig showed the effectiveness of grid power coupled with the utilization of a flywheel kinetic energy recovery and storage (KERS) system. “It is the operator who pays for diesel and its transportation. Hence electricity as an alternate energy source with peak shaving technology is lucrative in terms of return on investment and operation cost. In addition it is emission free and environmentally friendly technology. A cost benefit analysis of the containerized system to transfer grid power to a rig, coupled with the KERS indicated that such a design had the potential to save more than $10,000 per week of drilling operations with significantly lower emissions, quieter operation, and smaller well pad. This system can eliminate the emissions during drilling and hence play a crucial role in environmental protection” (Verma and Burnett, 2009).

Drilling emissions is a solvable problem as seen in the two cases above. Not all rigs, especially the older ones, are capable diesel-electric conversion but future built-for-purpose rigs should be developed to run as diesel electrics as at least a convertible option that favors a “greener” exploration process.

D. Investments in Rig Conversions

For all of the environmentally-friendly technologies to be implemented, drilling contractors must either build new rigs or convert their older rigs. The cost of new and developing technology can be extremely high, so even modifying a rig, let alone building a completely new rig, can become an expensive endeavor. Without an economically-supportable plan and timeline for rig conversions, there is a risk of realizing a severe shortage of “qualified” drilling rigs as regulatory requirements overtake the technological basis of the national drill-rig fleets. Consideration should be given to incentivizing conversion and new-build construction of environmentally-friendly rigs through tax allowances or alternative credits made available to drilling companies at least as interim measures.

ADVANCED MANAGEMENT AND DISPOSAL OF DRILLING FLUIDS

A. Waste Handling

A critical area of focus in the drilling process is the proper management and disposal of drilling fluids and waste products. Drilling wastes can include drilling mud, produced water, or other byproducts that can have a harmful impact on the environment in the event of an uncontrolled release. The containment and disposal of the wastes is a main priority.

“Several new technologies are being applied to waste treatment such as: biological treatment (land spreading, composting, tank based reactors); thermal methods (thermal desorption and detoxification); chemical methods (precipitation, extraction, neutralization); and physical methods (gravity separation, filtration, and centrifugation)” (Rana, 2008). In addition, regulatory agencies and operators are working together to minimize drilling wastes as much as possible to improve environmental quality and reduce drilling costs.

The exploration and production of oil and natural gas is already regulated by a complex set of federal, state, and local laws that address waste management issues involved in the drilling process. Key federal regulations already in place to protect the environment include the National Environmental Policy Act, Clean Water Act, Safe Drinking Water Act and the Clean Air Act. Each of those acts, plus many more, hold operators accountable for damages to the environment and are enforced by governmental agencies like the Environmental Protection Agency or Bureau of Land Management. Failure to comply with those regulations can result in heavy fines and penalties. States also regulate drilling operations, including the management and disposal of waste and water, as well as underground injection, surface disturbances, wildlife disturbances and air emissions. Some municipal or local regulations also exist in certain communities. Especially in areas of urban drilling, like the Barnett Shale in north Texas, local authorities implement strict control through additional permits and ordinances.

One of the most influential technological advancements to achieve reduction of drilling waste has been the implementation of horizontal and directional drilling. The total length and volume of a horizontal well can be the equivalent of several vertical wells. Fewer wells drilled means less produced waste. Drilling multiple horizontal wells from a single site also lessens the amount of drilling waste produced by promoting the re-use of drilling mud and reducing traffic to and from the drilling location. Where it is feasible, air drilling also reduces the amount of drilling waste because it produces dry cuttings that are easier and more environmentally-friendly than wet or hydrocarbon-saturated cuttings.

Several options exist for waste treatment but recycling drilling fluids whenever possible is always a goal. "Discharges are not an alternative due to Environmental regulations. Thermal Desorption is a costly alternative to heat and evaporate all the water, although the oil will be recovered. Incinerations will have to add fuel to burn the fluids and do not recover any fluids and this becomes less cost effective." (Eia & Hernandez, 2006). Recycling drilling mud at the drill site in closed-loop systems makes waste management more cost-effective and practical. It is important to choose the best solids-control equipment to fit the needs of the wellbore, including selection among control equipment such shale shakers, desanders, desilters, and centrifuges to separate cuttings from the mud. The cuttings can be dumped into steel open-top tanks instead of large reserve pits to reduce the environmental footprint. From there the mud can be reconditioned and the cuttings can be hauled away by truck for proper disposal. As regulatory agencies adopt more zero-discharge policies, especially in environmentally sensitive areas, zero-discharge requirements will become operational necessities.

Leading industry service companies have developed new and improved ways of recycling and reusing drilling fluids and wastes both on and off the drilling location. For example, M-I SWACO's EnviroUnit is a wastewater- and slop-treatment system that can process wastes on the drilling location. "The EnviroUnit process allows the whole drilling fluid to be recovered without pre-separation into its individual components. The combination of physical and chemical treatment has been proven over the last 7 years onshore, where is has been shown that the waste stream for final disposal can be reduced up to 90%. The whole drilling fluids volume recovered can be as high as 36%" (Eia & Hernandez, 2006). The water recovered can then meet discharge regulations or be used for other rig operations. The system includes a monitoring system to control and prevent spills.

In addition to the EnviroUnit, M-I SWACO has developed a system called the EnviroCenter which is capable of more extensive and complex recycling techniques using an offsite configuration that is capable of processing drilling wastes from multiple wells. Drilling fluids thereby processed can be re-used as new drilling fluid or designated for the agriculture or construction industries. In a case study of the EnviroCenter, 150,000 Bbl of waste were processed to yield 44,000 Bbl of reusable drilling fluid, 91,000 Bbl of clean water, and only 15,000 Bbl of non-reusable waste that required disposal (Eia & Hernandez, 2006).

When it is not possible to recover or recycle drilling wastes, there are many options for the disposal. Traditionally, mud can be transferred to landfills or land treatment systems to be biologically treated. One of the newest methods is to transfer drilling waste to waste injection sites. Waste injection involves the pumping of drilling wastes into permeable and porous subsurface formations that can contain the waste in an environmentally safe manner. Ovalle et al. (2009) explain that "Waste Injection into subsurface formations has proven to be the most effective technology for final disposal of wastes from oil and gas drilling and production that provides a secure operation achieving zero discharge". Advancements in technology have made it easier to monitor and evaluate waste injection sites to reduce costs and lower risk. New software and simulators along with special monitoring equipment allow operators to identify and prevent potential risk that may jeopardize the injection operation and environmental integrity. It is important to monitor the process carefully because failure to do so can result in expensive remediation or clean-up costs.

B. Spill Prevention

In addition to all of the mentioned waste treatment options it is also important to manage risk by having a proper spill prevention plan. Operators and regulators can work together to determine the best way to monitor and prevent spills from occurring that can be harmful to the environment. Through the advancement of technology it has become easier to monitor operations where a potential for drilling fluids to spill exists. Sensors located in mud pits and tanks as well as pressure gauges throughout the drilling rig can provide real time data to the operator making it easier to prevent spills. Having a well designed plan in case a spill does occur can make the difference between a manageable accident and a larger incident.

C. Environmentally-Friendly and Cost-Effective Drilling Fluids

Perhaps the most important component of the entire drilling process is the drilling fluid, the preparation of which is crucial for delivery of a successful and environmentally safe well. As drilling becomes more difficult and less conventional, it is necessary to develop new and improved drilling fluids to meet the challenges that lie ahead. The industry has already seen great new technological advancements in this area that have particularly affected the ability of operators to drill multilateral and extended reach wells. Since it has become more necessary to focus on environmental impacts involved in the drilling process, the industry has responded with new and improved drilling mud that has very high environmental and cost savings upside. There is a wide variety of basic drilling mud types including water-based mud (WBM), oil-based mud (OBM), and synthetic mud (SBM) and each has different applications that can be tailored to fit the needs of the wellbore. Also, there are drilling fluids that can be easily reused or recycled to decrease environmental impacts and meet stricter governmental regulations. New drilling fluids coupled with better drilling fluid management processes have significantly enhanced drilling operations, lowered costs, and reduced the environmental impacts especially with respect to multilateral and extended reach drilling wells.

Several factors impact the success of a drilling fluid. Lubricity, hole cleaning, wellbore stability, and equivalent circulating density are important parameters. Also, if drilling in environmentally sensitive areas where certain fluids can be potentially harmful, the process of choosing the right drilling fluid can be extremely difficult. When drilling a multi-lateral and/or extended reach well, the drilling fluid will determine the success of the well. A major problem with ERD is the friction encountered along the drill string when drilling at great distances. This friction therefore hinders the ability of the drillstring to rotate freely causing a build-up of torque. Even though there has been a great capability gains in electric/hydraulic top-drive systems, the torque generated by the friction in the wellbore can become too much to overcome, thereby causing the system to stall. The friction in the wellbore can be overcome by the use lubricants in a WBM or using an OBM/SBM system. Choice of mud lubricant will depend on which fluids company is on location (each company has its own proprietary additive). Drilling beads constitute another lubricity product that can be used either in WBM or OBM. Beads sent downhole act to line the wellbore and thereby reduce the friction factor exerted by the wellbore walls. And with the use of a drilling-bead recovery system, the cost of using beads can be greatly reduced. Although oil-based and synthetic-based mud systems are the best for providing the needed lubricity, OBM often is disfavored in the public eye on the basis of environmental concerns. That false perception of OBM has spurred developments in, and the increased use of, SBM or high-performance WBM fluids. But with the proper handling and disposal techniques, OBM can be considered an environmentally safe fluid.

Because the drilling fluid used will always be relative to the needs of the wellbore it is hard to say one drilling fluid is superior to another in an absolute sense. However, the development of high-performance WBM may be ideal when considering the needs of an extended-reach or multilateral wellbore. OBM is not only more expensive but also harder to process after the well is drilled and can be potentially harmful to the environment if a spillage accident were to occur. New technologies have allowed the industry to develop environmentally safe chemicals that allow high performance WBM and SBM to more closely resemble OBM. For example, a high performance WBM that contains two novel chemicals, an amine polymer and an aluminum complex, was recently tested on an ERD well in the Liuhua field in the South China Sea. "Numerous experiments were conducted to evaluate the various properties of this novel water based drilling fluid. The experimental results indicate that it has excellent rheological properties, very low filtration rate, good lubricity, and strongly inhibitive character to shale, which are very close to the commonly used oil based drilling fluids" (Jienian et al., 2010).

Sometimes OBM is the only option when considering the well stability, friction, hole cleaning, and ECD requirements necessary to drill a successful well. Typically OBM costs significantly more then any other mud but offers a performance that will justify the expense. Like other drilling fluids, OBM has seen improvements and innovations to make them more effective thus allowing them to become more environmentally friendly. In the North Sea, anti-sag technology has been combined with clay-free, sub-micrometer weighting material to produce a more effective OBM system. "The low-solids, clay free system has a long history of reducing ECD and minimizing downhole losses while drilling, running casing, and cementing. The 17.9 lbm/gal fluid weighted with manganese tetraoxide material exhibits effective hole cleaning properties at lower viscosities than convention OBF's and shows no detectable sag tendency. Clay-free fluids also demonstrate excellent return permeability in a wide range of well types." (Carbajal et al., 2009). This particular system was used in an area where high-pressure, high-temperature wells and extended-reach drilling is required. It is also representative of innovations that are being done industry-wide to solve the challenges of unconventional drilling. Each drilling fluids company continues to produce unique and innovative OBM systems that boast improved performance but at an increased cost related to its hydrocarbon content. Determining which fluid will be the most cost-effective way to successfully drill a well often overrides other considerations. New technologies and innovations or incentives can allow operators to reduce costs while reducing environmental risk if operators and government regulators can work together to find acceptable solutions.

To combat the environmental concerns associated with OBM, SBM has been developed to provide a more environmentally safe product while maintaining the lubrication and other traditional attributes of OBM. While synthetic-based fluids have been mainly used for offshore drilling, tightening governmental regulations are making synthetic systems more attractive onshore. Technological advances such as reversible-emulsifier-package (REP) SBM allows the mud to switch from an invert emulsion to a direct emulsion while also switching wettability, thereby making SBM more attractive to operators (Friedheim & Patel, 1999). A study done in the Pedernales Field in Eastern Venezuela proved the capability of SBM. In that instance, the operator decided to use an invert mud (SBM) that could help reduce swelling clays and reduce filtrate invasion into the wellbore. The operator saw the elimination of stuck pipe, quicker trips, and enhanced bit performance which all helped offset the cost of the synthetic. "The utilization of a well-designed synthetic based fluid for drilling ERD wells in an environmentally sensitive area has advantages over both water base and conventional oil base systems. Field performance measures support the use of such systems on an economic basis alone. Other benefits such as reduced environmental impact, improved health and safety standards provide additional support for the use of synthetics" (Twynam et al., 1998).

The aforementioned examples are only a few of the technological advancements that are being made throughout the industry. The ultimate goal of drilling fluid technology is to move toward an effective drilling solution based on the needs of each individual wellbore while also creating an environmentally friendly and cost-effective fluid. If operators and government regulators can work together to advance the technology the environment will benefit.

ADVANCED CASING AND CEMENTING

Innovations and advancements in technology have given the industry the ability to manage risk and lessen environmental impacts with respect to well-bore integrity. The development and evaluation of appropriate casing and cementing programs with industry leaders and regulators has become crucial in meeting a more environmentally responsible goal. The key areas of focus with respect to well-bore integrity includes the achievement of zonal isolation with proper casing and cementing practices and ensuring correct evaluation of those practices. Several new and innovative technologies are already being used to better design fit-for-purpose solutions for each individual wellbore.

The ultimate goal of a successful casing and cementing program, especially from an environmental stand point, is creating reliable zonal isolation. Whether it is protecting the usable groundwater supply, sealing off a lost circulation zone, or targeting a producing reservoir the objective is the same. Industry service leaders such as Schlumberger and Halliburton have developed simulators, software, and cements to address challenges and meet the requirements for successful cement jobs. New simulators can help engineers design better cement jobs by predicting the outcome before the job is ever pumped. For example, Schlumberger and Halliburton have simulators that can help design a job by optimizing the rheology of spacers and slurries to avoid contamination, determining the correct volumes to be pumped, and providing the best centralization techniques to provide a better cement sheath. By inputting information such as cumulative wellbore stresses, wellbore geometry and trajectory, future stimulation treatments, and production/temperature cycling, current software programs can help develop the best cementing program for a unique challenge.

A. Cement Technologies and Practices

Custom cements have been a direct result of the various innovations in design programs. The cement sheath is critical because it provides the biggest contribution in extending the life of the well. Not only does it provide the zonal isolation required to successfully complete a well but it also serves as an impermeable seal to protect the casing from corrosion. Both of those objectives are important when considering the environmental sustainability of the well. As a result, creating the correct cement slurry to provide the best sheath has become a major priority.

Advancements in cementing technology have addressed the effects of CO2 and H2S and help achieve an environmentally friendly response to those potentially harmful gases. Halliburton's product, CorrosaCem™, is designed to withstand the corrosive environments found in some areas and achieves a stronger, longer-lasting seal. In the June 2009 issue of *E&P* magazine, a case study involving six wells in an area of high H2S content tested Halliburton's CorrosaCem™. Chemical integrity was maintained when the corrosion resistant cement was tested and observed over time. Also, geopolymeric slurries are being designed that reduce harmful greenhouse gases and water requirements while also exhibiting enhanced mechanical and chemical properties. This new environmentally friendly cement offers a variety of densities and thickening times, strong bonding to the formation and casing, enhanced elasticity and flexibility, compatibility with common additives, reduced CO2 and water requirements, and significant cost savings. In a separate case study, six wells were tested to determine the effectiveness of the geopolymeric cement and it was determined that the operators saw an average cost savings of 7.1%, a mix water reduction of 3.6% , and a CO2 reduction of 22.5% overall (Mahmoudkhani et al., 2008).

Another challenge that has driven cement technology is the inconsistency of cement jobs in lost-circulation zones which comprise depth intervals in a wellbore where fluids leak outward into mechanically weak or highly porous and permeable geologic units. Lost-circulation zones can be addressed with lightweight cements or foamed cements that are less dense, thus less likely to break down the formation or be lost to the problematic zone. Cement slurries with fibers also can contribute toward plugging lost-circulation zones. In 2006, lightweight slurries with reticular-fiber technology were tested in depleted reservoirs in southern Mexico. The lightweight slurries, combined with the plugging effects of the fibers, accomplished reliable zonal isolation (Romero et al., 2006). Lightweight slurries also can remove the need of doing a multistage cement job with DV tools (i.e., mechanical parts sent downhole to assist with cementing). Not only does that approach reduce the risk of unsuccessfully completing the primary job but it also increases the life of the well by providing a more uniform seal all along the interval.

Further advancements have been made in self-healing cements. As explained by Reddy et al., (2009), "A cement column in a wellbore is subjected to external and internal stresses beginning at the time a wellbore portion is cemented and throughout the well completion, production, perforation, stimulation, and remedial operations. Theses stresses have the potential to induce cracks in the cement column and create micro-annuli unless the cement is designed to withstand such imposed stresses. As a result, the cement sheath might lose the capability to provide the intended zonal isolation, resulting in problems, such as sustained casing pressure and interzonal communication". Extensive laboratory research has been done to develop a new elastomeric additive that allows set cement to seal cracks or fractures without depending on contact with a fluid. Currently, cement can swell to repair itself but only in the presence of a particular fluid, for example either oil or water, but this becomes a problem when it is unknown what fluids the cement may come into contact with over the entire life of the well. Additional research with respect to self-healing cements has been conducted in the field as outlined by Roth et al. (2008). Self-healing cements were tested in two gas wells in an area that typically had surface casing pressure leaks due to existing cementing practices. Careful testing and observation following the cement placement showed no signs of surface casing pressure leaks even more then a year later. Continued development of such an additive would have far-reaching cost and environmental benefits when considering reduced interzonal communication and fewer remedial operations.

Through extensive research and engineering, cement technology innovations are becoming more common and cost-effective. Better cementing practices and technologies will continue to focus on achieving efficient zonal isolation, not only to maximize production and minimize cost but also to protect the environment.

B. Wellbore Integrity Tests

In addition to efforts on advanced cementing technologies, further attention is needed on technologies and practices for reliably evaluating geologic formations and cementing results as applied in practice. Correctly evaluating the wellbore integrity can prevent or mitigate problems that can disrupt the drilling process or harm the environment. Incorporation of recent technological advancements and innovations has led to a better understanding of how best to evaluate the casing string and adjacent formations.

Testing the overall integrity of the wellbore is focused on two main attributes: casing integrity and formation integrity. The pressure integrity of both the casing string and formation must be evaluated to determine important drilling parameters such as mud weights, casing depths, and well-control factors. Correctly performing and interpreting formation strength tests can be the difference between the success and failure of a drilling project. The industry has already made steps in the right direction by working with government regulators to require integrity testing for each section of a well before the next can be drilled.

Formation strength tests have several purposes. Proper cementing procedures can be verified, maximum and minimum pressure are determined for an accurate mud weight window, and important formation stress data can be collected to predict lost-circulation or fluid-influx potential. Thanks to the incorporation of new technology, formation strength tests can be better performed and interpreted. Most notably, real-time test data acquired during drilling have largely improved the accuracy of formation strength tests. The most current downhole pressure tools are capable of transmitting data to the surface through mud pulsations that can be deciphered quickly and with a high degree of quality. The ability to observe test results in real time provides a large advantage by helping operators anticipate where the limits of the formation and casing might occur. Technology has allowed for a variety of different formation and casing shoe tests that leave provide the drilling engineer with choices of effective fit-for-purpose testing methods. Several innovative options exist to supplement these tests to achieve the minimum environmental impact.

To evaluate wellbore integrity with an even further degree of confidence and accuracy the latest well-logging abilities have proven to be very successful especially when used in addition to physical testing. Cement evaluation logging can be time-efficient and relatively cost-effective. Cement bond logging (CBL) and variable density logging (VDL) are not really new technologies but they can be effective if interpreted correctly. CBL and VDL tools provide an average volumetric measurement but at a low resolution. Ultrasonic imaging tools (USIT) provide a 360-degree view and higher quality resolution of the cement bond. As a consequence of contamination-lowered acoustic impedance levels, both conventional CBL and USIT logs can encounter difficulties when applied to cements with significant mud contamination. Industry leaders in logging such as Schlumberger, continue to develop new and innovative tools that can more effectively evaluate wellbore integrity. For instance, Schlumberger's new logging tool called an Isolation Scanner has a "cement evaluation service [that] provides more certainty by combining the pulse-echo technique with a new ultrasonic technique that induces a flexural wave in the casing with a transmitter and measures the resulting signals at two receivers. The attenuation calculated between the two receivers provides an independent response that is paired with the pulse-echo measurement and compared with a laboratory-measured database to produce an image of the material immediately behind the casing. By measuring radially beyond traditional cement evaluation boundaries, Isolation Scanner service confirms zonal isolation, pinpoints any channels in the cement, and ensures confident squeeze or no-squeeze decisions" (Schlumberger, 2009). That technology may not, in all cases, offer enough of an advantage over traditional logging methods to warrant the cost but it represents the progress the industry is making towards effective, economic, and environmentally beneficial technology upgrades.

Industry leaders and government agencies will continue to work together to determine the best cementing and casing practices in terms of operation and evaluation techniques. It is important to consider the far reaching effects that the new technologies and innovations being developed every day are having on the environment. The drilling industry has and will continue to achieve the highest wellbore integrity by avoiding remedial operations, providing cost-effective, fit-for-purpose solutions to each challenge, and reducing the environmental impact.

FINDINGS

Although not always recognized or appreciated in the public arena, the technologies and practices of drilling oil and gas wells have followed pathways of continuous improvement for many decades. Motivations for improvements have been not only the tightening regulations for environmental protection but also geotechnical factors that have impeded the cost-effectiveness and production potential of resource-development projects. In almost every case, innovations driven by commercial factors also have brought substantial improvements in environmental safety and sustainability. Specific findings include:

- Extended-reach drilling (ERD), and the associated technologies needed to support it, has contributed toward substantially reduced spatial footprints of drill pads by allowing multiple wells to be drilled and completed from a single pad. Not only is the required acreage needed for drilling significantly reduced, but collateral impacts likewise are reduced, including truck traffic, noise and air emissions. Development of emerging resources, such as shale-gas, will further drive optimization of multi-well pad practices.

- Muds and other fluids required to enable rotary drilling through rocks, are essential enablers of drilling and significant efforts have been made to reduce total fluid volumes as well as to reduce environmental incompatibilities in the fluid compositions. Recycling or re-use of fluids, involving a wide array of water-treatment technologies, has reduced the per-well magnitudes of disposal issues and spillage concerns.

- Construction and operation of drill rigs has benefited from evolving diesel-electric and all-electric options for powering drill-rig motors. Reduced dependence on diesel technologies has led to reductions of noise, petroleum fuel transportation and storage and air emissions at drill pads.

- Reliable construction and verification of well integrity has improved with advances in cementing technologies and with technologies for downhole logging of cement, casing and formation properties.

- Future drilling and delivery of onshore oil and gas wells will depend upon ongoing cooperation between operators and government regulators to find mutually agreeable solutions to overlapping commercial and environmental issues.

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