Paper #2-24

WASTE MANAGEMENT

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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ABSTRACT

Waste management technology is a critical element of successful drilling and production operations. Proper application of waste management principles is required for both efficient drilling operations and environmental protection. Use of any given waste-management approach will continue to be decided by the interplay of economic, technical and operational barriers.

During drilling the largest potential waste stream is used drilling fluids and cuttings that are produced while drilling the well. Options for handling the fluids and cuttings, or "muds", can be organized into a three-tiered water-management or pollution-prevention hierarchy:

- Tier 1 – Minimization: The generation of waste is minimized within the processes for drilling a well. This approach is mutually beneficial across all three objectives of minimizing the cost of drilling the well, meeting the technical of the drilling operation and minimizing the impacts on the receiving environment. When feasible, inhibitive drilling fluids and efficient mechanical solids-control equipment can often save money for operators and results in greater protection of the environment.

- Tier 2 – Recycle/Reuse: For the drilling fluid and cuttings that cannot be managed through water minimization approaches, operators can plan for reuse or recycling of drilling byproducts. The most common ways to reuse drilling fluids is to re-deploy them at another drilling location or at least to recover the most valuable constituents of the drilling fluids from one location and move them to another drilling location. Substantial efforts are ongoing to develop economic methods to treat drilling fluids and drill cuttings so that

- they can be beneficially reused in oilfield and non-oilfield applications.

- Tier 3 –Disposal: When drilling waste cannot be managed through minimization, reuse, or recycle, operators must dispose of it.

Four main lines of technology have been developed to address drilling waste management which is centered on handling muds that can include water, oil and certain chemical additives:

- Thermal treatment uses heat to separate more objectionable components from less objectionable components based on differences in volatility. It is a common process applied to oil-based mud and cuttings where centralized processing is feasible and disposal options are available for the objectionable residuals.

- Injection technology sends treated or untreated waste streams underground into geologic formations that can accept and safely isolate the waste. If geology and regulations permit, injection can serve to substantially simplify waste management while also reducing the surface footprint.

- High-order beneficial reuse on land comprises a combination of bioremediation and re-deployment of treated wastes as soil amendments. It is most readily applied to water-based muds although variations have been developed for some synthetic-based muds.

- Lower-order beneficial includes re-deployment as construction aggregates. The treatment criteria for aggregate use can focus more on stabilization rather than complete remediation so that the stabilized waste is rendered environmentally inert.

Future waste-management technologies and practices most likely will find growing attention on biodiversity protection; changing energy policy with increasing focus on greenhouse gas emissions; progressively more difficult drilling environments such as offshore deepwater, Arctic conditions and extended-reach wells; and reduced landfill space available for waste disposal with implied greater reliance on beneficial reuse options.

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THE ROLE OF WASTE MANAGEMENT IN OIL AND GAS EXPLORATION AND PRODUCTION

Waste management plays a role in the process of drilling a well as the drilling fluid circulates the cuttings from the wellbore, then as the fluid and cuttings are managed during and after their surface return and finally after the drilling has been completed and the cuttings and fluids are further processed or sent for disposal. As the evaluation of drilling waste has progressed, a larger view of drilling waste management has grown to incorporate a larger view of management activities. In addition to historical focus on drilling muds and cuttings management, the impacts on associated air pollution, resource management, and biodiversity protection has evolved waste management into a broad-based evaluation of all wastes associated with drilling and producing wells.

During drilling the largest potential waste stream is used drilling fluids and cuttings. During hydrocarbon production, the largest potential waste stream is produced water. The operational source of the drilling fluid and cuttings waste is the uphole return of drilling mud with entrained rock cuttings that are produced while drilling the well. The cuttings are generated by the drill bit and tend to break apart as they are transported to the surface. Drilling fluids are circulated downhole to capture and lift the cuttings to the surface where they are removed with mechanical separation equipment. The residual cuttings that cannot be removed from the drilling fluid become entrained into the drilling fluid as fine solids. In order to manage the buildup of fine solids, drilling fluids are diluted with fresh volume of base fluids. Excessive volumes of drilling fluids contaminated with fine solids become waste.

According to an American Petroleum Institute (API) waste survey, the exploration and production segment of the U.S. oil and gas industry generated more than 360 million barrels (bbl) of drilling wastes in 1985 (API, 2000). The report estimates that 28% of drilling wastes are sent to offsite commercial facilities for disposal (Wakim 1987). A similar API study conducted ten years later found that the volume of drilling waste had declined substantially to about 150 million bbl (API, 2000). While there are other sources of waste generated at the drill site, this paper will focus the generation and management of drilling fluids and cuttings from drilling operations.

BACKGROUND ON DRILLING WASTES

Before addressing the array of waste management strategies and technologies, it is important to understand the nature of drilling wastes and the process that generates the waste.

Drilling fluids, solids-control equipment and the drilling fluid circulation system all are critical parts of the drilling operation. Drilling fluids (sometimes call drilling mud) consist of a continuous liquid phase and additives which modify the properties of the fluid to achieve better performance. The critical functions of drilling fluid include removing cuttings from the well, maintaining wellbore stability, cooling and lubricating the bit and controlling subsurface pressure. Once the drill cuttings are carried to the surface by the drilling fluid, they are separated from the fluid using mechanical solids-control equipment. Once the drill cuttings are removed, the drilling fluid can be re-circulated down the drill pipe. Depending on the geologic formation, environment, application and well objectives, drilling fluid systems are customized to meet performance requirements.

Water-based drilling muds (WBMs) use water or brine as the continuous or external phase with the critical functions (density, viscosity, filtration, lubricity) achieved with the addition of various materials. Non-aqueous systems use non-water-soluble base fluid as the continuous phase with water (or brine) emulsified and dispersed in the base fluid. Non-aqueous drilling fluids (NAFs) include diesel, mineral oils, low-toxicity mineral oils (LTMOs), and synthetic base fluids. Studies in the North Sea and elsewhere in the 1980s, raised concerns about the environmental effects of the original high aromatic content of diesel fluids which drove the introduction of LTMOs and ultimately the development of synthetic-based muds (SBMs) in the 1990s. The SBMs were developed to have the same performance as oil-based muds (OBMs) but with a lower environmental impact and enhanced worker safety through lower toxicity, elimination of polycyclic aromatic hydrocarbons (PAHs), faster biodegradability, and lower bioaccumulation potential (Neff et al., 2000).

In selecting a drilling fluid one must consider the formations that are being drilled through (e.g., whether there are unstable shales present), the wellbore complexity (e.g., whether the hole is vertical, directional or extended reach), casing design, and pore pressure analysis. While WBMs maintain an important role in many drilling operations, NAFs offer a number of technical advantages over WBMs in difficult drilling situations (such as extended reach or drilling of high-temperature/high-pressure wells).

As compared to WBMs, NAFs inhibit shale hydration, consequently wellbore stability is maintained. NAFs are intrinsically lubricious; therefore, the ability to drill highly deviated (non-vertical) extended-reach and horizontal holes is enhanced over that with WBM use. In addition, NAFs are generally more stable in high-temperature applications such as those encountered in deep wells. Furthermore, NAFs are less susceptible to the formation of gas hydrates that might potentially occur during deepwater drilling operations. As a result of those characteristics, NAF use allows faster drilling rates and results in fewer drilling problems. Faster drilling also assures fewer rig days (less cost and emissions) and reduces health and safety risks to personnel. In addition, better wellbore maintenance with NAF use results in reduced quantities of waste solids.

Despite their high performance, there are limitations to NAF use. Those limitations include their cost, limitations on the fluid physical properties particularly in cold-water applications, reduced logging quality over WBMs, the high cost of lost circulation problems, and environmental concerns associated with NAF disposal.

Owing to the minimal technical demands, low-cost WBMs typically are used in the upper sections of most wells. As the well deepens, and/or becomes directional, the technical demands increase proportionately, necessitating displacement with either a specialized water-based system or a non-aqueous drilling fluid.

Environmental regulatory considerations play a significant role in both the selection of drilling fluids and the overall economics of drilling a well. The specific regulatory requirements of an area often dictate the technologies that can be used and what, if any, material can be discharged into the environment (EPA, 1999). This, in turn, influences what and how wells can be drilled. The ability to discharge NAF cuttings significantly expands the inventory of wells that can be economically drilled in an area.

While it is not possible to describe drilling waste using a single set of chemical properties and concentrations, several groups of constituents are present in most types of drilling waste. The major constituents of concern in produced water are:

- Salt content (expressed as salinity, total dissolved solids, or electrical conductivity).
- Oil and grease (this is an analytical test that measures the presence of families of organic chemical compounds).
- Various natural inorganic and organic compounds or chemical additives used in drilling and operating the well that may have some toxic properties.
- Solids generated from the drill cuttings.

DESCRIPTION OF THE TECHNOLOGY

A. Many Different Options for Managing Drilling Wastes

The characteristics of drilling waste water vary from location to location and over time. Different locales have different drilling conditions, regulatory/legal requirements, receiving environments, and infrastructure. As a result, no single waste management technology or technique is used at all locations. Many different technology options are available that can be employed at specific locations. Selection of a management option for waste management at a particular site varies based on:

- The nature of the technical requirements of the drilling operation.
- The economics of drilling the well and managing the associated byproducts.
- The environmental requirements for a receiving environment and regulatory structure perspective.

Much of the information for this paper is derived from the Drilling Waste Management Information System (DWMIS) website, developed by Argonne National Laboratory (ANL) for the US Department of Energy (DOE). DWMIS currently is housed as part of the website for DOE’s and ANLs information transfer system (ANL, 2011).

Drilling waste management technologies and strategies can be organized into a three-tiered water-management or pollution-prevention hierarchy (i.e., minimization, recycle/reuse, and disposal). Examples of technologies and practices for each group are shown in Tables 1-5.

Tier 1 – Minimization. In the waste minimization tier, the generation of waste is minimized within the processes for drilling a well. This approach is mutually beneficial across all three objectives of minimizing the cost of drilling the well, meeting the technical requirements of the drilling operation and minimizing the impacts on the receiving environment. When feasible, inhibitive drilling fluids and efficient mechanical solids-control equipment can often save money for operators and results in greater protection of the environment. Examples of waste minimization approaches and technologies are shown in Table 1.

Table 1.— Water Minimization Technologies.

Approach	Technology	Pros	Cons
	Drilling Mud and Cuttings		
Reduce the volume of drill solids entering the wells	Smaller diameter casing programs	Reduced cost of casing and less volume of drill cuttings	Difficult to use on deep holes where multiple casing strings are required. Less volume capacity for producing the well.
	Inhibitive water-based drilling fluids	Reduces degradation of cuttings and reduces wellbore instability. Increases rate of penetration. Use of advanced products encourages additional research	Shale inhibitor chemistry is expensive and adds either organics or salts to the drilling byproducts. Proprietary chemical ingredients generate public uncertainty about unknown potential hazards.
	Oil-based drilling fluids	Reduces degradation of cuttings and reduces wellbore instability. Increases rate of penetration.	Typically requires additional waste-management processing, Some OBMs contain toxic organics.
	Synthetic-based drilling fluids	Reduces degradation of cuttings and reduces wellbore instability. Increases rate of penetration.	Expensive base fluids and alternative internal phases are frequently cost-prohibitive.
Using Drilling Fluids and additives with lower environmental impacts	New drilling fluid products that remove a recognized environmental hazard such as heavy metals, salt or oil	Removal of environmental hazard from the product removes or deduces the concentration of the hazard in the drilling fluid waste.	Some constituents that have environmental hazards are extremely effective products that are required for efficient drilling.
	New drilling fluid systems targeting drilling fluid products that act together to achieve better performance	Can increase drilling efficiency, reduce cost and improve environmental performance	Can be cost-prohibitive. Proprietary chemistry can result in public concerns about unknown chemistry.
	Alternative weighting agents	Higher solids-control efficiency, lower trace metal	Increased cost.

Approach	Technology	Pros	Cons
	Alternatives to traditional use of barite either by changing the size of the particles or the chemical makeup	content.	
Improve mechanical solid control efficiency	Shale shakers	Advanced technology promotes high removal efficiency	Advanced performance is ineffective in situations where cutting size degrades in the wellbore
	Cuttings dryers and drying shakers	Secondary treatment for OBM and SBM cuttings reduce retention on cuttings	Ineffective on water-based mud cuttings due to shale hydration issues.
	Screens and screen selection	Improved removal of solids from drilling fluids	Screen improvements required new shale shakers to take full advantage of increased performance.
	Hydrocyclones, mud cleaners and other secondary solids-control equipment	Advanced technology promotes high removal efficiency	Advanced performance is ineffective in situations where cutting size degrades in the wellbore
	Centrifuges	Advanced technology promotes high removal efficiency	Low treatment volumes and removes drilling fluids additives along with the solids
	Mud tanks and reserve pit settling basins	Simple and low-cost alternatives	Inefficient and frequently generates large volumes of waste.
Closed-loop secondary treatment systems for drilling fluids	Chemically enhanced fine solids separation equipment	Recovers water from drilling fluid contaminated with fine solids	Requires additional equipment and costs
Drilling Practices			
Directional drilling	Extended reach, horizontal drilling multiple laterals	Reduced volume of cuttings and other waste by increasing efficiency	May be impractical in some locations and can increase cost.
Drilling smaller diameter wellbore	Closer spacing of successive drill strings, slimhole drilling, coiled tube drilling	Smaller wellbore produces less waste.	Reduces production volumes in some cases.
Pneumatic Drilling	Use of air or other gases to as the drilling fluid	Removes need for drilling fluid and reserve pit	Not applicable in many areas.
Advanced drilling fluid containment systems	Pipe wipers, mud vacuum systems, mud buckets designed to reduce spills on the rig floor.	Effective reduction of drilling fluid loss	Does not address fine solids buildup and can lead to contamination of drilling fluids.
Advanced	Reducing	Effective product delivery into	Advanced product delivery

Approach	Technology	Pros	Cons
drilling fluid product delivery systems	packaging waste though bulk product delivery systems reduces solid waste	mud systems improves efficiency. Packaging waste such as drums and empty sacks are a major waste stream	systems increase cost and are not applicable in some situations.
Advanced communication, analysis, and wellsite engineering	Effective and efficient use of available technology improves both drilling efficiency and waste minimization	Computer-based data acquisition improves information transfer and analysis so only the necessary products are used.	Over-reliance on technology diminishes sensitivity to onsite evaluation and action to address problems at the wellsite.

Tier 2 – Recycle/Reuse. For the drilling fluids and cuttings that cannot be managed through water-minimization approaches, operators can move next to the second tier, in which drilling byproducts are reused or recycled. The most common way to reuse drilling fluids is to reuse them at another drilling location. Another common technique is to recover the most valuable constituent of the drilling fluids with mechanical separation equipment (barite and base fluids) and reuse them on another drilling location.

Substantial efforts are ongoing to develop economic methods to treat drilling fluids and drill cuttings so that they can be beneficially reused in oilfield and non-oilfield applications. Some of those treatment options are also used for treatment prior to disposal of the residual byproducts which are discussed in the next section. Examples of water reuse and recycle management options and some of the specific uses are shown in Table 2.

Tier 3 –Disposal. When drilling waste cannot be managed through minimization, reuse, or recycle, operators must dispose of it. Table 3 lists water disposal technologies.

Table 2. Drill Cuttings Reuse and Recycle Management Option.

Management Option	Specific Use	Pros	Cons
Thermal Incineration	Rotary Kilns	Use of base fluid for energy No residual hydrocarbons on cuttings.	Limited application and transportation of cuttings to offsite treatment / use. No oil or energy recovery.
	Cement Kilns	Use base fluid for energy. Recovers energy and uses drill solids.	Limited slip stream to main cement production.
Thermal Desorption	Indirect rotary kilns	Thermal recovery of base fluid.	Dust from solids and thermal degradation of base fluids.
	Hot oil processors	Thermal recovery of base fluid, low operating temperatures.	Lower throughputs. Limited heat transfer.
	Thermal Phase Separation	Thermal recovery of base fluid, Better air emission controls than rotary kilns.	Cost of Unit.
	Thermo Mechanical Distillation using friction	Mechanical energy, compact size, limited process temperatures, off shore suitability.	Cost of Unit. Breakdown of cuttings from hammer mill results in solids carry over.
	Thermal Plasma Volatilization	High operating temperatures and volume reduction.	High Cost – experimental and no commercial applications yet.
Bioremediation and beneficial reuse in land application or wetlands application	Land Farming	Low treatment cost beneficial in some soil conditions.	Not effective for salt and heavy metals, requires available land area.
	Land spreading (one time)	Low treatment costs beneficial in some oil conditions. Aqueous solutions from reserve pits can help irrigate dry lands.	Not effective for salt and heavy metals, one-time use only
	Composting	Small footprint	Limited to temperate regions and requires water.
Vermiculture	Soil amendment production	Converts byproducts to beneficial soil amendment	Requires specialized drilling fluid and vermiculture experience.
Stabilization and use as a construction material	Road building sub base or surface	Has been demonstrated to meet specifications for road base.	
	Daily cover for land fills	Stabilized cuttings are an effective cover material	
	Other types of construction material	Can be used to develop drill pads	
Solvent Extraction using Super Critical CO2	Treatment of drill cuttings and recovery of oil	Ambient temps. Low energy consumption. High oil quality and recovery efficiencies.	Exploratory. No commercial unit available.

Table 3. Drill cuttings and drilling fluid disposal technologies.

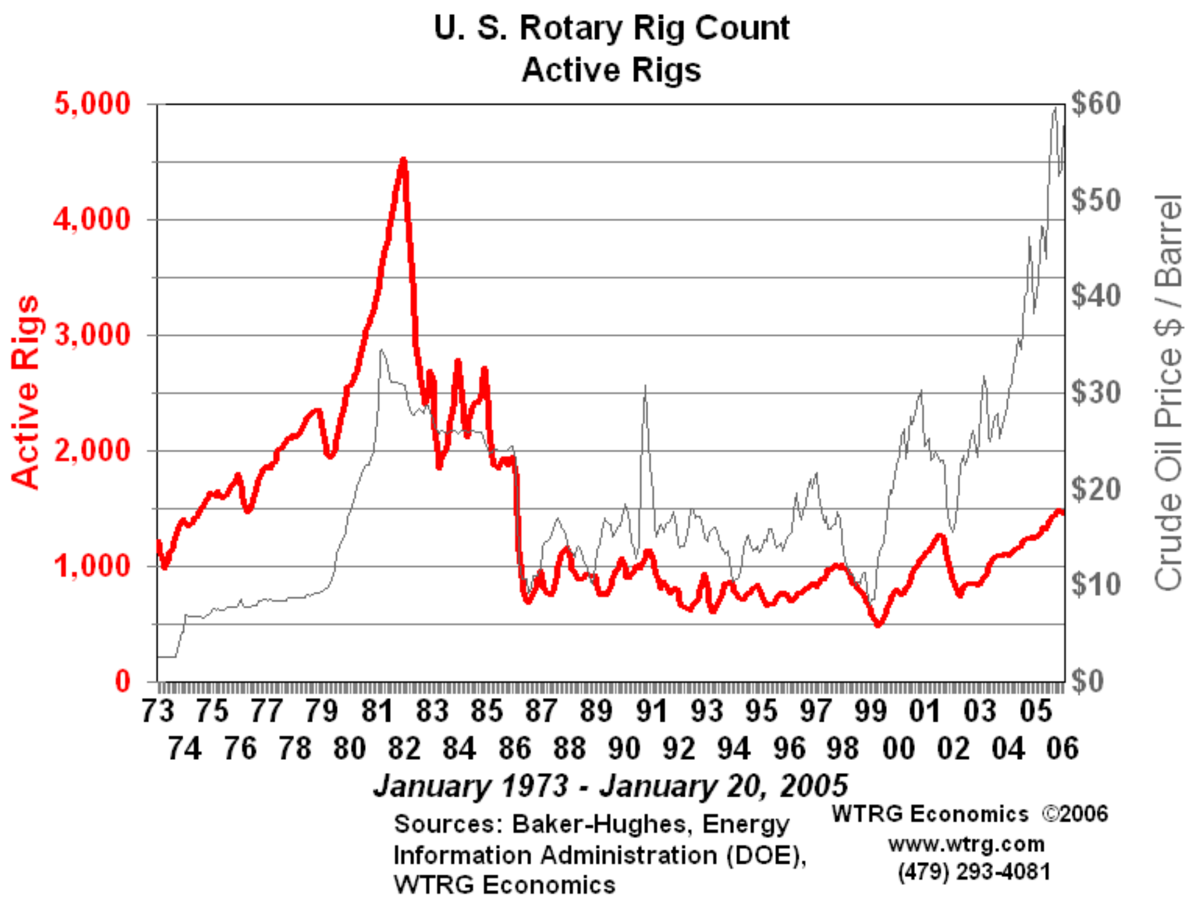
Technology	Pros	Cons
Onsite burial (Pits, Landfils)	Low cost and simple technique. Most common waste management method, low toxicity additives prevent environmental hazards.	If waste contains high concentrations of salts and hydrocarbons can leach from pit and create environmental hazards.
Discharge to Ocean	WBM and SBM cuttings can be disposed offshore with limited environmental impact.	Discharge of OBM cuttings can lead to cuttings piles that are slow to degrade under seafloor conditions.
Commercial disposal facilities	Offsite treatment and disposal allows effective and safe disposal of wastes that can not be disposed of onsite due to high concentrations of toxic constituents.	Requires transportation and associated air pollution. Reduces focus on waste minimization.
Slurry Injection	Onsite waste management.	Requires engineering studies to protect casing and drinking water supplies. Limited formations are available for injection.
Bioremediation / land application	Effective treatment of organics, safe management of drilling fluid constituents.	Not effective on wastes with high concentrations of salt and oil. Requires use of land areas.
Disposal in salt Cavern	Effective disposal in controlled conditions.	Requires transportation and associated air pollution. Reduces focus on waste minimization.

B. Historical Waste Management Technology Drivers

The history of development of oilfield waste management has several key drivers that continue to dominate the development and use of waste management strategies summarized in the previous sections. The first driver has been environmental compliance which has its own drivers of environmental science and regulatory development. Secondly, operational performance required to drill and produce wells has evolved driving forward new requirements for technology. Finally, economic performance of the waste-management technology and the overall exploration and production operation placed demands on technology.

Within this triad of performance, individual technologies are developed within a business environment that tends to by cyclic in nature. Frequently, when rig counts are high, service companies perform well financially and have resources to investing in research and new technology or new equipment. At other times, when commodity prices and rig counts are low, pricing for oilfield services collapses and the focus becomes using existing equipment and technology in the most efficient manner. Regulatory cycles can also impact the introduction of new technology. The need for new technology is sometimes created when a catastrophic event occurs. Other developments occur when discovery of an environmental hazard is revealed. Most commonly, a scheduled review of current practices requires systematic improvements in environmental performance. Figure 1 reviews the historical rig count for domestic operations compared with a key commodity driver, namely, the price of crude oil.

Figure 1. Variation of drill-rig activity with crude oil price



Even when economic conditions are stable and regulatory conditions are stable, new technology is sometime required to address operational targets for the drilling operation. Deeper drilling, high temperatures, lower temperatures, challenging shale formations, directional drilling. All of these conditions require higher performance and consequently, new technology to address the challenges. For offshore drilling operations, the major changes have been driven.

C. Timeline of E&P Waste Management

Table 4 summarizes the timeline of development of oil and gas drilling and associated waste-management technologies. In light of certain benchmark years, the timeline can be viewed as divisible into three main stages:

- Stage 1 (1859-1936): Creation of the industry and the earliest technologies
- Stage 2 (1939-1969): First availability of standardized drilling methods
- Stage 3 (1970-Present): Adoption of advanced and computer-assisted technologies

In Stage 1, simple methods for drilling were used. Early circulating systems in rotary drilling were focused on controlling sub-surface pressures and cleaning the cuttings from the wellbore. Water is the primary component of drilling fluids and the process of drilling the well entrains solids into the water providing viscosity to help lift the cuttings from the wellbore. Two key components of drilling fluids that were introduced in those early years were barite and bentonite. Those two key additives are commonly used today and into the foreseeable future because of their mud-enhancing properties. Barite is a heavy mineral that adds density to the drilling fluid and bentonite is a swelling clay that add viscosity and provides a slick wall cake on the wellbore. While neither barite nor bentonite were not selected for their environmental performance, as it turns out, both of those key additives have low environmental impacts. Also during those early years, shale shakers, desanders and centrifuges were introduced to help reduce the solids loading in the drilling fluid system. While the shale shaker was not introduced as a waste-management tool, its function to remove cuttings from the base fluid serves to significantly reduce the volume of drilling mud that must be disposed. While some attention had been made to drilling-fluid performance during the early years, the evaluation of drilling fluids was not uniform. Stage 1 ended with the introduction of a uniform practice of drilling fluid evaluation from API. Early environmental concerns focused on control of blowouts and production. Most waste management was conducted onsite and involved simple techniques such as storage in pits and burial

During Stage 2, drilling fluids and solids control evolved to meet new challenges. Those challenges generally evolved in two types of drilling environments. Along the Gulf of Mexico coastal region and in other areas, the drilling issues focus on drilling though geological shale formations that hydrate and cause drilling problems. Those formations have many technical descriptions but are known commonly as “gumbo.” In hard rock regions, the focus of improved drilling fluids focused on lowering the solids content in the drilling fluid so drilling could proceed faster. While new challenges continue to evolve, the basic structure of identifying issues and using drilling fluids and solids control to address them was set in place. Drilling waste management practices for exploration and production continued to focus on onsite management. Production equipment evolved to focus on maximizing production with more advanced storage tanks and separation equipment. As drilling moved from onshore to offshore, onsite discharge of spent drilling fluids, cuttings and produced water was discharged onsite.

Now within Stage 3, challenges continue to evolve and be resolved with both traditional and new technology. While environmental protection has always been part of E&P operations, during the 1970s intense efforts were made across all industries to review discharges for possible environmental hazards. Those efforts have become an important driver in all E&P activities, including evaluation of existing drilling fluids, solids control and waste management practices with particular focus on the discharge of drilling fluids, cuttings and produced water offshore. Many of those studies were in conjunction with regulatory development activities driven by the NPDES permitting system. Those extensive studies generally concluded that the traditional water-based drilling fluid components such as barite and bentonite did not pose a significant impact to the environment.

Table 4. Timeline of Technology Developments for E&P Waste Management.

Year	Drilling Technology	Drilling Fluid	SCE
Stage 1: Creation of the Industry and the Earliest Technologies			
1859	1859 Drake well dug by hand		
1870	First cable tool rig		
1887		Chapman patent	
1890	Rotary drilling developed		
1901		Spindletop, use of native clay fluids (gumbo)	
1922		Barite first used	
1928		Bentonite first used	
1929			Shale shaker introduced in California
1930		First proprietary agent for thinning mud.	
1931		Patent for dissolved salts to control shale heaving	Desander Introduced
1933	First whipstock for directional drilling		Centrifuge introduced
1935	First tri-cone bit	Introduction of sodium silicate muds to treat heaving shales, also shell began systematic research into oil based mud	
1936		API Standard Field Procedure for Testing Drilling Fluids	
Stage 2: First Availability of Standardized Drilling Methods			
1939	First horizontal well drilled (Havener Run field in Morgan County, OH)	Introduction of salt water muds and starch	
1942		First commercial oil based mud introduced.	

Year			
	Drilling Technology	Drilling Fluid	SCE
1943		Rise in popularity of quebracho (a tree bark extract), high pH muds to thin muds and manage drill solids along the gulf coast	
1946		Principles of Drilling Mud Control (training Manual)	
1947	First offshore directional wells drilled (Gulf of Mexico)		
1949		Patent for Calcium lignosulfonates	
1953	First truly multilateral well drilled		Decanting Centrifuge introduced, interest revived in desanders
1954	First hydraulic rotary rig		
	First directional drilling assembly		
1955	Craig-Geffen-Morse waterflooding model developed	Benefits of low solids muds recognized in hard rock drilling	
1956		First gyp-chrome lignisulfonate used for high temperature flow control prosperities	
1959			
1960		Bentonite extenders used to promote low solids drilling muds	
1961	First use of dynamic positioning	Chrome lignite, Chrome lignosulfonate widely used in Gulf Coast on deep wells and high temperatures.	
1963			Patent application for inhibitive properties of potassium based mud systems.
1965			General recognition of the importance of solids control led to the development of more effective solids control equipment.

Year			
	Drilling Technology	Drilling Fluid	SCE
1966	Computerized well data monitoring		
1967			Introduction of XC Polymer for low solids muds
1969	First coiled tubing rig job		
Stage 3: Adoption of Advanced and Computer-Assisted Technologies			
1971	Polycrystalline diamond compact bit introduced		
	2-D seismic prevalent, computers convert drill velocity data into geological information		
1972	Landsat satellite becomes available for remote sensing		
1974	3-D seismic data acquisition tested in Gulf of Mexico		API bulletin on Drilling Fluids Processing Equipment API Bulletin 13 C first edition
1975	First floating production system begins operation		
	First commercial 3-D seismic survey recorded		
1978	First measurement-while-drilling (MWD) system	MOBM	
1980	Cost of 3-D post time depth migration (PTDM) estimated at $8 million for 50 square miles		
1981	First offshore horizontal well (Rospo Mare field, offshore Italy)		
1983	Horizontal wells drilled from vertical shaft (Kern River, CA)		
1984	First steerable drilling system		
	New resistivity measurement devices		
1985	3-D vertical seismic profiling developed		

Year			
	Drilling Technology	Drilling Fluid	SCE
1986	Metal sealed-bearing roller cone bits		
	Neutron porosity measurement capability added to MWD		
1987	First logging while drilling (LWD) tool		
1988	Extended-reach drilling exceeds 60-degree radius		
	First horizontal well drilled from semisubmersible drill rig		
1989	Only 5% of Gulf of Mexico wells based on 3-D seismic data		
1990	Horizontal well achieves 14,585 linear feet		
1991	15,000-foot horizontal well drilled with directionally controlled coiled tubing		
1992	Slimhole horizontal well (3 3⁄8”) drilled 801 feet		
1993	3-D surveys worldwide cost $1 million for 50 square miles	First SBM in GOM	
	MWD tools advance—smaller, broader temperature range, pressure detection, geosteering		
1994	Digital image processing of 3-D		
1995	3-D seismic used for 75% of U.S. onshore surveys		
	4-D seismic emerges		
1996	80% of Gulf of Mexico wells based on 3-D seismic data		
	4-D seismic characterization methodology applied to previously recorded seismic surveys		

Year			
	Drilling Technology	Drilling Fluid	SCE
1997	Extended-reach drilling achieves 26,450 feet horizontal displacement in South China Sea		
1998	Magnetic resonance imaging begins on MWD		
2000	3-D PTDM cost reduced to $90,000 for 50 square miles by the year 2000		
2005	Deepwater GOM		
2010	Deepwater GOM		

A major focus of the NPDES permitting system was removal of conventional pollutants such as oil and grease. Therefore, the early permitting efforts in the 1970s for drilling fluids and cuttings discharges, the US EPA restricted and eventually prohibited the discharge of OBM and cuttings. Since the evaluation of WBM discharges did not result in a water quality or sediment quality issue the focus of regulatory developments shifted to technology standards which are pursued to minimize conventional, non conventional and toxic pollutants using a technology standard. Through a process of regional EPA offshore permits and eventually the effluent limitation guidelines, the US EPA issued effluent limitation guidelines for produced water, drilling fluids, drill cuttings and various other offshore discharges. The resulting limits set the technology criteria and structure for environmental performance for offshore drilling and production. While the evaluation of fluids and development of testing took many years and was not a surprise, when the technology-based toxicity limit of 30,000 ppm (of suspended-phase particulates as toxicants) went into effect (EPA, 1996), it was a steep learning curve for operators to adjust to a new limit on the drilling fluid additives they could use. Just like a mechanic who has had several tools taken from his tool box, adjustments were made to react to the technology-based limits that sometimes resulted in increased cost or alternative drilling practices. For example, traditional use of mineral oil as a lubricant and use of potassium chloride (KCl) for shale inhibition were stopped because they did not meet the technology-based limits. In their place, operators did more short trips and back reaming to control reactive shales and prevent stuck pipe. Since the mid 1980s drilling-fluid companies have continued to market wave after wave of specialized chemistry to address shale hydration and lubricity. The first systems for hauling drill cuttings and drilling mud were developed during that time, since not all drilling fluids and cuttings could be discharged (OBM and some WBM that failed the toxicity limit). Those systems typically used cuttings boxes which were transferred by barge or truck to shore for treatment and disposal. The cycle of OBM and WBM technology was broken in the early 1990s with the introduction of SBMs. Both the EPA and industry were challenged to find ways to appropriately use and regulate SBM technology. Eventually, a special set of effluent limitations were developed for SBMs and cuttings dryers were used to remove residual SBM from the cuttings.

During the 1970s on the other side of the Atlantic Ocean, the operators in the North Sea faced significant operational and drilling challenges. In order to address those challenges OBM was used and the drill cuttings were discharged. In the 1970s, those OBMs used diesel, however, as early environmental investigations revealed that diesel muds were toxic to marine life, lower-toxicity mineral oils were introduced. Continuing environmental investigations revealed that while mineral oils were not toxic, they tended to persist for many years due to their branched paraffin structure. Concerns about sediment quality resulted in SBMs, and many other advanced technologies to transport and treat OBM and SBM cuttings from 1969 though the current times.

During the same time frame of the 1970s though the current age, research into onshore impacts also developed along the lines of scientific research and regulatory development. As with offshore discharges, initial focus on traditional drilling fluid components focused on potential toxins and environmental impacts. As with offshore concerns the basic ingredients of barite and bentonite were found to be non-toxic and have low environmental impacts. Specialty additives such as XC-Polymer™ (based on xanthum gum) and starches that are commonly used in food products also were determined to be low environmental hazards, Consequently, the focus on shore became the use of inhibitive chloride salts ($CaCl_2$, NaCl and KCl) which were found to inhibit plant growth and also cause toxicity in freshwater supplies. Other specialty additives such as sodium bi-chromate used as an additive in high temperature wells were determined to be environmental hazards. Over a short period of time, the compounds that were identified as toxic environmental hazards in WBMs were removed from drilling-fluid products and replaced with less toxic components that fulfilled the same functional purpose. States had traditionally regulated oil and gas operations with organizations such as the Texas Railroad Commission and the Oklahoma Corporation Commission. As the science-based evaluations did not reveal the need for regulation under the federal Resource Conservation and Recovery Act (RCRA), states continued to evolve their rules for E&P waste to address the remaining issues associated with onsite and offsite waste management.

During Stage 3 of development, some advanced technologies have moved well beyond traditional waste management techniques. Those advanced technologies are further discussed in the next section to demonstrate how they evolved within the triad of environmental, operational and economic drivers.

VARIATIONS BASED ON RESOURCE TYPE AND LOCATION

Thermal treatment evolved as a treatment technology for OBMs. As previously discussed, OBMs were developed as a drilling-fluid technology because of the operational need to drill difficult formations at high temperatures. Thermal treatment is a common industrial process used to process slurries and sludge that share physical and chemical characteristics of OBM cuttings. During the evaluation of offshore drilling discharges, OBM cuttings were identified as an environmental discharge issue in the offshore environment. Thermal recovery of base fluids and the ability to treat a wide range of feedstocks resulted in several designs for thermal treatment. One such treatment approach was provided a demonstration permit in the Gulf of Mexico to treat mineral oil-based mud cuttings on-site and then discharge them if they met a 1%

residual oil content (ROC) limit. That technology demonstration did not meet the operational or cost targets and other onshore thermal-unit designs could not compete with the economics of commercial disposal that evolved in the Gulf of Mexico region. Thermal units achieved new life when the regulatory objective of a 1% ROC limit for all non-aqueous fluids was adopted in the North Sea in the year 2000. Several commercial onshore thermal units combined with landfill disposal of the residual solids operated successfully because they met the regulatory operational and economic needs of the region. Among the thermal units in use, the hammer mill technology became a standout and has continued to evolve into the current effort to place hammer mill thermal units on offshore rigs to meet the 1% discharge limits for non-aqueous fluids. The high processing rate, small footprint and recovery of base fluids are all positive attributes for thermal recovery technology. Because thermal processing is a treatment technology and not a disposal technology it must be combined with some type of onsite or offsite disposal of the residual solids, recovered water and oil. Thermal treatments face a range of technical, economic and environmental challenges. One reoccurring issue is the combination of high temperatures and flammable hydrocarbons, a safety issue that sometimes has resulted in thermal units being placed away from drilling operations. More importantly, thermal units are typically not very mobile and therefore must be set up in a centralized facility and then have the cuttings hauled to the treatment location. That lack of mobility means that, on top of treatment costs, transportation costs and disposal of residuals must also beat the cost curve for other waste-management options.

Injection technology evolved as a treatment technology to address issues in three areas. First, on the North Slope of Alaska, injection was introduced to address a lack of surface area for treatment and disposal. Use of conventional waste-management approaches like onsite disposal would have resulted in conversion of tundra to disposal site. In that situation, operator-controlled injection wells provided a successful waste-disposal technology with minimal footprint. Injection continued to see limited use in specialized areas until the market opportunity in the North Sea which resulted from the 1% discharge limit applied to OBMs. Injection technology practiced in the offshore environment allowed drilling and reinjection to occur without removing the drill mud and cuttings from the point of origin. The use of injection technology has a strong technical advantage because the application of injection technology is related to a strong understanding of underground formations. Clearly the exploration and production industry has a good pool of knowledge, experience and confidence to address complex problems associated with underground formations. In the case of fracturing formations and re-injection of the cuttings, specialized computer models help design planning and operation of injection sites to prevent unexpected results. Like all forms of waste management, injection technology has limitations. The most common limitation for injection technology can be lack of appropriate formations to receive the waste injections. Other common problems are limited injection rates which result in the need to store drilling cuttings and mud during periods of rapid generation of waste. Another significant challenge for injection technology is the difficulty of addressing technical failures of the technology. In the case of thermal units, if a batch of cuttings does not meet discharge limits the residual solids can be recovered and reprocessed. In the case of injection technology, a technical failure can result in waste being released into inappropriate formations and or creating breaches to the surface. In the failure-mode cases, the drilling waste cannot be recovered and if the accidental release is into a drinking water aquifer it is difficult to remove the contaminants from the affected formation. Consequently, continuing evolution of the technology has focused on the science of predicting and confirming that the injected waste is going where it is intended to go and staying where it is intended to stay. Injection technology has a strong presence in some areas as a commercial waste-disposal technology. In the Gulf of Mexico, injection of oilfield waste into salt domes is the current predominant waste management technique and is enjoying bother commercial and technical success. Other regions that do not have an established disposal infrastructure or have footprint constraints have successfully employed injection technology as a viable waste-management strategy (Veil and Dusseault, 2003; Puder et al., 2003; Geehan et al., 2006).

The third evolving technology is a combination of bioremediation, land application, and beneficial re-use as a soil enhancer. As with the other two technologies discussed, the process of biodegradation as a treatment technology developed initially to treat the oil in OBM cuttings. Land treatment has been a long-time practice to manage the low hazard aspects of WBMs. While the traditional focus of these techniques has been on appropriate management of the wastes, there was a recognition that some benefits to soil from the application of residual drilling-fluid components, Building on the positive aspects of this technique, both water-based and synthetic-based drilling fluids have developed product lines specifically targeted to provide beneficial residual properties to drilling fluids and cuttings so that instead of being approached as waste, the cuttings are approached as a byproduct with beneficial applications, In one specific region, cuttings were combined with other byproducts in a vermiculture application to generate a beneficial byproduct that could be used as a soil enhancer. In the case of bioremediation and beneficial reuse as a soil amendment, technical limitations frequently involve climate and land use. In cases where appropriate land areas or soil applications are available this is a viable technology. In areas such as the Alaska North Slope where the focus is on minimizing footprint, and the climate conditions also are not favorable for bioremediation, then other waste-treatment technologies have a technical and economic advantage (Growcock et al., 2002; Norman et al., 2002).

The fourth and final technology evolution for waste management is the use of stabilization and beneficial reuse of drilling waste as a construction aggregate. This approach has its origins in the stabilization of salts, heavy metals and hydrocarbons found in oil based mud cuttings. Rather than attempting to remove the unwanted constituents in OBM and cuttings, this technology focused on chemical stabilization and fixation to prevent leaching of contaminants into the environment. As both drilling fluids and treatment technology have evolved, the use of stabilization techniques can combine low levels of contaminants with other byproducts to generate construction aggregate that meets target properties. One of the key technical and economic challenges of this technology is generating sufficient quantities of construction aggregate to meet a sustained building program. Therefore, the current applications have been focused on the large centralized treatment facilities and used along with other available materials to create a viable construction aggregate.

ENVIRONMENTAL BENEFITS

In practice, the selection of a waste-management approach is influence by a combination of factors, including what is technologically possible as well as what is required or permitted by regulations. Among all factors, possible benefits to environmental quality are high-priority considerations although the exact benefits will vary with the waste-management approach that might be dictated by other limitations. If all other factors were equal in all circumstances, and environmental benefits were the main selection criteria, the comparison and contrast of different technologies would be as summarized in Table 5.

Table 5. Benefits Offered by Different Waste-Management Methods.

Technology	Air Discharge Benefits	Water Discharge Benefits	Land Disposal Discharge Benefits
Waste Minimization			
Product substitution to remove constituents of concern	Removal of contaminants	Removal of contaminants	Removal of contaminants
	Inhibitive water-based drilling fluids improves drilling efficiency and lowers drilling time.	Replacement of soluble salts with polymers and organic-based inhibition chemistry reduces pollutant loading on water sources	Replacement of heavy metals and diesel with other specialty products reduce pollutant loadings.
	New drilling fluid products that remove a recognized environmental hazard such as heavy metals, salt or oil	Removal of environmental hazard from the product removes or deduces the concentration of the hazard in the drilling fluid waste.	Some constituents that have environmental hazards are extremely effective products that are required for efficient drilling.
	New drilling fluid systems targeting drilling fluid products that act together to achieve better performance	Can increase drilling efficiency, reduce cost and improve environmental performance	Can also reduce all pollution loads that require land based disposal.
Improve mechanical solid control efficiency	Improved removal efficient increases penetration rates and reduces air discharges associated with motors.	Advanced technology promotes high removal efficiency and lower loading on water discharges offshore	Advanced performance is ineffective in situations where cutting size degrades in the wellbore and reduced discharges to land.
	Hydrocyclones, mud cleaners and other secondary solids control equipment reduce pollutant loads and shorten drilling time	Reduced pollutant loads reduce potential impact to water	Reduced pollutant loads reduce land disposal of residuals.
	Chemically enhanced solids	Recovers water from drilling fluid contaminated with fine	By minimizing dilution educed solids loading to land discharges.

Technology	Air Discharge Benefits	Water Discharge Benefits	Land Disposal Discharge Benefits
	separation equipment	solids	
Closed loop secondary treatment systems for drilling fluids Drilling Practices	Mud tanks and reserve pit settling basins	Simple and low cost alternatives	Inefficient and frequently generates large volumes of waste.
	Extended reach, horizontal drilling multiple laterals	Reduced volume of cuttings and other waste by increasing efficiency	May be impractical in some locations and can increase cost.
	Closer spacing of successive drill strings, slimhole drilling, coiled tube drilling	Smaller wellbore produces less waste.	Reduces production volumes in some cases.
	Use of air or other gases to as the drilling fluid	Removes need for drilling fluid and reserve pit	Not applicable in many areas.
Directional drilling	Allows for lower footprint and reduced number of wells and associated air discharges	Reduces number of wells and associated water discharges	Reduces number of wells and associated land discharges
Reuse and Recycling			
Thermal treatment	Greater drilling efficiency with the use of OBM and minimization of air discharged from treatment with recover of oil	Lower concentrations of contaminants in residual solids discharged offshore	Lower loading rates for land disposal
Bioremediation and beneficial reuse in land application or wetlands application	Greater efficiency of drilling reduces air pollutant loading, low energy treatment requirements reduce air pollutant loadings	Reduced pollutant loading to water discharges	Reduced pollutant loading to land.
	Daily cover for land fills	Stabilized cuttings are an effective cover material	
	Other types of construction material	Can be used to develop drill pads	
Stabilization and use as a construction material	Greater efficiency of drilling reduces air pollutant loading, low energy treatment requirements reduce air pollutant loadings	Reduced pollutant loading to water discharges	Reduced pollutant loading to land.
Water Disposal			

Technology	Air Discharge Benefits	Water Discharge Benefits	Land Disposal Discharge Benefits
Onsite burial (Pits, Landfils)	Reduced emissions related to hauling cuttings.	Protection of water supplies with appropriate design and operation of pits	Focus on pit constituents instead of pits themselves protects land use.
Discharge to Ocean	Reduced emissions related to hauling cuttings.	Protection of water supplies with focus on mud constituents	Reduced land disposal with onsite offshore disposal.
Commercial disposal facilities	Reduced treatment emissions	Protection of water supplies in a controlled treatment facility	Protection of land resources in a controlled treatment facility
Slurry Injection	Reduced emissions related to hauling cuttings	Protection of water supplies with appropriate design and operation of slurry injection	Reduction of land use with appropriate design and operation of slurry injection
Bioremediation/ land application	Reduced emissions related to hauling cuttings.	Protection of water supplies with focus on beneficial reuse	Beneficial reuse increases land value.
Disposal in salt Cavern	Reduced air emissions related to treatment of cuttings	Protection of water supplies in a controlled treatment facility	Protection of land resources in a controlled treatment facility

OUTLOOK FOR DRILLING WASTE MANAGEMENT

A. Innovation and Future Use

Innovation has been a continuous presence in the application of technology in the E&P industry. While some become frustrated in the slow pace of the introduction of new technology, field experience has demonstrated that many technologies that have been successfully applied in other industries struggle to perform in the harsh and often unforgiving conditions of the oilfield. Unlike conventional industries that operate in mature, populated locations under controllable conditions, oilfield technology must perform in remote and often extreme conditions. Consequently, new technology must be adapted to work in E&P applications and supported at the field level with experienced personnel.

Innovation is in response to challenges and the environmental, operational and economic challenges will continue to change as they have for the past 100 years. So far the discussion of technology has focused on treatment of contaminants. Equally important to addressing contaminants in the feed streams and by products are some of the critical innovations have occurred in the area of environmental assessments, including development of new tools to monitor and predict environmental performance. In the future, environmental performance evaluations will respond to new performance indicators on individual discharges and receiving environments and will evolve to life-cycle assessments, biodiversity protection, and multimedia assessments of environmental performance of operational and waste management technologies.

While the evaluation parameters will continue to evolve, the basic triad of issues will continue to balance environmental control technologies with operational and economic considerations of E&P operations.

B. Barriers and Opportunities

The opportunities and the barriers for new technology are the same three elements discussed for all of the past, present and future treatment technologies.

The first barrier is operational. Any pollution prevention, recycling or disposal technology must perform to meet drilling operational or product requirements. Not every well is successfully drilled, and not every waste-management technique is successfully applied. In many cases, it takes several attempts to identify and address the operational needs of the particular region. The application of technology is particularly difficult in the E&P industry due to environmental conditions and remote locations.

The second barrier is environmental. While economic and operational barriers are usually clearly understood, environmental challenges are frequently a mix of scientific, regulatory and legal requirements. In some cases regulations have exclusively focused on regulated existing technology with little or no room for addressing innovative technologies. In some cases the technologies listed above have been prohibited due to past issues but with no allowance for technology improvements. Consequently improvement in the development of regulations is an overall opportunity for future improvements. Technology associated with evaluation and protection of the environment is also a barrier to development appropriate limitations for technology and is an opportunity for future improvements.

Finally, economic barriers are a major impediment for application of new technology. There are three aspects of economic performance. One evaluation results in the ability of a technology to address a certain contaminants in a waste stream, A larger economic evaluation looks at the overall economic viability of an enterprise in the context of operational and environmental requirements, Still in a large economic view, energy and environmental policy and the resulting economic conditions can drive the need for oil and natural gas in the context of other energy sources with higher and lower end-use emissions.

C. Long-Term Vision

As described in the preceding sections, management of waste from oil and gas production is accomplished through many different technologies and practices. It is challenging to envision the future of water management with so many different operational and environmental settings.

Future waste management technologies are likely to focus on:

- Reduced treatment costs
- Reduced air emissions, including CO_2
- Minimizing transportation

- Minimizing energy inputs
- Capturing secondary value from the waste (extraction of minerals, power, or other factors)

FINDINGS

Waste management technology is a critical element of successful drilling and production operations. Proper application of waste management principles is required for both efficient drilling operations and environmental protection.

During drilling the largest potential waste stream is used drilling fluids and cuttings. The operational source of the drilling fluid and cuttings waste is the cuttings that are produced while drilling the well.

Environmental regulatory considerations play a significant role in both the selection of drilling fluids and the overall economics of drilling a well. The specific regulatory requirements of an area often dictate the technologies that can be used and what, if any, material can be discharged into the environment. This, in turn, influences what and how wells can be drilled.

Many different technology options are available that can be employed at specific locations. Selection of a management option for waste management at a particular site varies based on:

- The nature of the technical requirements of the drilling operation.
- The economics of drilling the well and managing the associated byproducts.
- The environmental requirements for a receiving environment and regulatory structure perspective.

Drilling waste-management technologies and strategies can be organized into a three-tiered water-management or pollution-prevention hierarchy (i.e., minimization, recycle/reuse, and disposal).

- <u>Tier 1 – Minimization</u>: The generation of waste is minimized within the processes for drilling a well. This approach is mutually beneficial across all three objectives of minimizing the cost of drilling the well, meeting the technical of the drilling operation and minimizing the impacts on the receiving environment. When feasible, inhibitive drilling fluids and efficient mechanical solids-control equipment can often save money for operators and results in greater protection of the environment.
- Tier 2 – Recycle/Reuse: For the drilling fluid and cuttings that cannot be managed through water minimization approaches, operators can plan for reuse or recycling of drilling byproducts. The most common ways to reuse drilling fluids is to re-deploy them at another drilling location or at least to recover the most valuable constituents of the drilling fluids from one location and move them to another drilling location. Substantial efforts are ongoing to develop economic methods to treat drilling fluids and drill cuttings so that they can be beneficially reused in oilfield and non-oilfield applications.
- <u>Tier 3 –Disposal</u>: When drilling waste cannot be managed through minimization, reuse, or recycle, operators must dispose of it.

Four main lines of technology have been developed to address drilling waste management which is centered on handling leftover drilling fluids or "muds" that can include water, oil and certain chemical additives:

- Thermal treatment uses heat to separate more objectionable components from less objectionable components based on differences in volatility. It is a common process applied to oil-based mud and cuttings where centralized processing is feasible and disposal options are available for the objectionable residuals.

- Injection technology sends treated or untreated waste streams underground into geologic formations that can accept and safely isolate the waste. If geology and regulations permit, injection can serve to substantially simplify waste management while also reducing the surface footprint.

- High-order beneficial reuse on land comprises a combination of bioremediation and re-deployment of treated wastes as soil amendments. It is most readily applied to water-based muds although variations have been developed for some synthetic-based muds.

- Lower-order beneficial includes re-deployment as construction aggregates. The treatment criteria for aggregate use can focus more on stabilization rather than complete remediation so that the stabilized waste is rendered environmentally inert.

Use of any given waste-management approach will continue to be decided by the interplay of economic, technical and operational barriers:

- Economic barriers for all waste management technologies are a combination of the cost of drilling and that value of the production. If the value of the production from a region is high then the economic stress on waste management techniques is reduced.

- Technical barriers are relative to the type of waste management technology employed. Two areas that continue to advance with combined environmental and waste management benefits are drilling fluids and solids-control equipment.

- Operational barriers continue to evolve as new areas of drilling challenges must address downhole geological conditions and the difficulty of adapting technologies for the rigors of oilfield applications.

Future waste-management technologies and practices most likely will find growing attention on biodiversity protection; changing energy policy with increasing focus on greenhouse gas emissions; progressively more difficult drilling environments such as offshore deepwater, Arctic conditions and extended-reach wells; and reduced landfill space available for waste disposal with implied greater reliance on beneficial reuse options.

REFERENCES

ANL (2011). Drilling Waste Management Information System. Argonne National Laboratory, US Department of Energy. http://web.ead.anl.gov/dwm/techdesc/commercial/index.cfm

API (2000). Overview of Exploration and Production Waste Volumes and Waste Management Practices in the United States. Based on API Survey of Onshore and Coastal Exploration and Production Operations for 1995 and API Survey of Natural Gas Processing Plants for 1995. Prepared by ICF Consulting for the American Petroleum Institute, May 2000, 112 p. plus tables. http://www.api.org/aboutoilgas/sectors/explore/waste-management.cfm

EPA (1996). 40 CFR Part 435. Oil and Gas Extraction Point Source Category; Final Effluent Limitations Guidelines and Standards for the Coastal Subcategory; Final Rule. US Environmental Protection Agency. Federal Register, 61 (242), December 16, 1996, p. 66086-66130. http://www.epa.gov/region6/6en/w/offshore/effluentguidelines-dec-16-1996.pdf

EPA (1999). Development document for proposed effluent limitations guidelines and standards for synthetic-based drilling fluids and other non-aqueous drilling fluids in the oil and gas extraction point source category (EPA-821-B-98-021). US Environmental Protection Agency, Washington DC, February 1999, 282 p. http://cfpub.epa.gov/ols/catalog/catalog_display.cfm?&FIELD1=SUBJECT&INPUT1=Chemical%20effluents&TYPE1=EXACT&item_count=37

ESRF (2004). Drilling Waste Management Recommended Best Practices. Prepared by Ellis & Associates Inc. for Environmental Studies Research Funds, Ottawa, Ontario, Canada, March 2004, 51 p. http://www.esrfunds.org/pdf/152.pdf

Geehan T., Gilmour A. and Guo Q. (2006). The cutting edge in drilling-waste management. *Oilfield Review, 18(4),* Winter 2006/2007, p. 54-67. http://www.slb.com/~/media/Files/resources/oilfield_review/ors06/win06/p54_67.ashx

Growcock F. B., Curtis G. W., Hoxha B., Brooks W. S. and Candler J. E. (2002). Designing Invert Drilling Fluids to Yield Environmentally Friendly Drilled Cuttings. Paper No. 74474-MS, IADC/SPE Drilling Conference, Dallas, Texas, February 26-28, 2002, 12 p. http://www.onepetro.org/mslib/servlet/onepetropreview?id=00074474&soc=SPE

Neff J. M., McKelvie S. and Ayers R. C. Jr. (2000). Environmental Impacts of Synthetic Based Drilling Fluids. OCS Study MMS 2000-064. Minerals Management Service, US Department of the Interior, August 2000, 132 p. http://www.gomr.boemre.gov/PI/PDFImages/ESPIS/3/3175.pdf

Norman M., Ross S., McEwen G. and Getliff J. (2002). Minimizing environmental impacts and maximizing hole stability– the significance of drilling with synthetic fluids in New Zealand. 2002 New Zealand Petroleum Conference Proceedings, February 24-27, 2002, 12 p. http://www.crownminerals.govt.nz/cms/pdf-library/petroleum-conferences-1/2002-nz-petroleum-conference-proceedings/norman-216-kb-pdf

Puder M. G., Bryson B. and Veil J. A. (2003). Compendium of Regulatory Requirements Governing Underground Injection of Drilling Wastes. Argonne National Laboratory, US Department of Energy, February 2003, 206 p. http://www.evs.anl.gov/pub/doc/reg-compendium.pdf

Veil J. A. and Dusseault M. B. (2003). Evaluation of Slurry Injection Technology for Management of Drilling Wastes. Argonne National Laboratory, US Department of Energy, February 2003, 110 p. http://www.evs.anl.gov/pub/doc/si-tech-report-1584.pdf

Wakim (1987). Wakim, P.G., "API 1985 Production Waste Survey, Statistical Analysis and Survey Results," American Petroleum Institute, Washington, DC, October 1987.