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Excellence Demonstrated on a Collaborative Team Approach to Deepwater GOM Completion Fluid Operations

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Abstract

The transition from drilling to completion activities is a discrete operation that requires specialized expertise and technology. The complexity of this transition is exacerbated in the Gulf of Mexico deepwater market due to operational and environmental conditions of water depth, subsea temperature and pressures, costs associated with non-productive time (NPT) and frequent use of costly, high density completion fluids. This paper presents lessons learned from a series of Gulf of Mexico deepwater projects where a suite of integrated solutions was utilized to deliver completion objectives on complex and challenging wells. All aspects of the job including collective pre-planning, brine facility operations, and successful execution of procedures on the rig culminated in wells free of debris, and without the occurrence of NPT.

The workflow began with an engineered displacement, where newly-developed chemistry was used to remove residual low-ECD, synthetic-based fluids (SBF) and position the wellbore and tubulars for displacement to high density, clear-brine completion fluids. A detailed wellbore cleanout and displacement procedure was prepared based on comprehensive hydraulic modeling. An optimum design of wellbore cleanup spacers was formulated specific to the well and rig surface fluid handling system, and was validated by extensive laboratory testing. The selection process for the completion fluid was conducted with consideration to compatibility, gas hydrate inhibition, true crystallization temperature (TCT), pressure and density. Additional solutions such as high-capacity filtration systems, advanced software modeling, and engineered wellbore cleanout tools were utilized to avoid NPT and increase operational efficiency.

Introduction

Deepwater drilling and completion operations in the Gulf of Mexico (GoM) have evolved in complexity as activities are conducted in ever-increasing water depths. These challenges include seismic acquisition, drilling operations, completion operations, subsea operations, production operations, distribution and logistics.[1,2] It is anticipated that developing technologies and capabilities towards supporting operations in water depths of 10,000 feet (3,048 meters) will become a requirement to participate.

Many of the prospects in the GoM have unique challenges, to include water depths approaching 10,000 feet, as well as high pressures (>10K psi) and temperatures (>350 °F BHT). Additionally, operators are challenged with drilling problematic formations (salt or tar zones) and to penetrate deep reservoirs (> 30,000 ft TVD), many of which are tight-sandstone formations (<10 md). Many GoM deepwater exploratory prospects are encountered at water depths ranging from 4,000 - 10,000 feet. Most of these are found within a subsalt environment, with salt canopies ranging from 7,000 - 20,000 feet thick and at target depths ranging from 25,000-35,000 feet TVD. A significant issue arising from deepwater operations is the hydrostatic head associated with these depths. For example, the hydrostatic head generated at water depths of 10,000 feet equates to a pressure in excess of 4,300 psi. These wells also are challenged with a declining geothermal gradient, with mud line temperatures often below 40° F (4° C). As a result, the highest pressure, and lowest temperature of a deepwater well typically occurs at the seafloor, the location of subsea blow-out preventers (BOPs).

As operational activities move from drilling towards completion, the challenges encountered from the operational environment require a collaborative, team approach as the reservoir is prepared for production. Focus on service quality, and flawless execution allow deepwater operators to realize the full potential of their reservoir assets through the provision of an array of reservoir-focused solutions. It is important to drill and complete the reservoir section with technologies engineered to protect the reservoir from damage, and maximize the productivity and injectivity of the reservoir asset.[3,4] A portfolio of integrated reservoir-focused solutions including wellbore cleanup (WBCU), high-capacity filtration, displacement modeling software, gas hydrate inhibition, clear brine fluids (CBF) and ancillary additives ensure the reservoir section is successfully drilled and prepared for completion.

Modern Completion Fluid Facility

Key enablers in the drilling and completion fluids value chain include facility placement, capability and capacity. Completion Fluid Facilities (CFF) are strategic offshore supply bases located near the operational area. Operators place importance on capacity, the ability to mix specialized fluids, to transfer fluids at high pump rates and to simultaneously mix, load and transfer fluids. Operational efficiencies are realized when leveraging the distribution and logistical benefits of best-in-class facilities, such as the newly commissioned offshore

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supply bases in Port Fourchon.[5] Distribution and logistical benefits are further enhanced with placement of drilling and completion fluids facilities in close proximity to one another. Figure 1 shows the front-view of the newly commissioned Completion Fluids Facility (CFF) in Port Fourchon, Louisiana. The facility was designed following Design for Manufacturing (DFM) concepts and processes such as process automation, Lean principles and Six Sigma process for reducing variability in preparing Completion Fluids. The facility operates within the framework of ISO 9001:2015 and API Q2 certified Quality Management Systems (QMS).

Figure 1 – Port Fourchon Completion Fluids Facility

Operators also place great importance on capacity and proximity of drilling and completion fluids facilities in Port Fourchon as means to drive logistical efficiencies. With this in mind, a new completion fluids facility has been constructed and commissioned to service the GoM market. The new facility can mix, store and blend customized Completion Fluids, as well as prepare special fluids such as wellbore cleanup (WBCU) displacement spacers. The footprint and capacity of the facility is quickly scalable to support multiple GoM deepwater completion fluids projects. Figure 2 shows an interior view of the facility with stainless steel pipes and valves.

Figure 2 – Interior View of Completion Fluids Facility

The facility was designed with prioritization and attention towards Health, Safety and Environmental (HSE) performance for facility workers. The facility design enables "hands-free" operations through the use of automated valves and radar-enabled tank level indicators, fully enclosed tanks, emergency shut-off devices, and low-elevation mixing platforms. Use of these features will reduce hand injuries, as well as injuries arising from working from heights. Use of enclosed tanks prevents debris entry into tanks and provides a safe atmospheric environment for facility staff when mixing high density brines.

Figure 3 – Radar-enabled, automated tank level indicators

The use of electrical pumps provides atmospheric and environmental benefits to include reduced carbon emissions, while the enclosed tanks reduce the possibility of contamination and waste. Automation enhances both consistency and repeatability of processes and activities at the facility. The radar-activated, and fully automated tank level indicators are located on all tanks within the facility and allow for precise, hands-free control. Tank volumes are displayed at a central control panel, providing workers with a visible means to quickly and accurately assess volumes while mixing and transferring fluids within the plant, and to offshore supply vessels. The electrical pumps, automated valves and tank level panel are shown below in Figure 4.

Figure 4 – Automation Features at Facility

Additionally, all mixing, and storage tanks are equipped with alarms and emergency shut-off devices (ESD) as shown below in Figure 5. Use of the ESD provide additional safeguards when transferring completion fluids within the plant, and to offshore supply vessels. Lastly, the facility has two load/offload stations to quickly transfer fluids to offshore supply vessels through 6-inch lines.

Figure 5 – Emergency Shut-off Device

Engineered Displacements – Rig Preparation

After drilling the reservoir to a planned total depth, operations move towards completions as the reservoir interval is prepared for completion activities. The initial phase of the completion operations is wellbore cleanup (WBCU), to include displacement (removal) of the incumbent SBF and residual materials from the wellbore, followed by placement of clear-brine completion fluid (CBF). Gulf of Mexico deepwater operators recognize that engineered displacements reduce operating costs and associated risks to subsequent completion operations. Additionally, these operators follow prescribed cleanout and displacement methods including the use of solvents, surfactants and mechanical tools in the WBCU process.

Wellbore cleanup of casing and open-hole sections require careful planning from chemical, rheological and mechanical perspectives. Poor displacements can create problems in the completions process to include stuck packers, corrosion of tubulars, formation damage, issues with setting completion tools and cement placement, increased filtration time and cost, increased disposal costs and the inability to deliver expected production.

For a WBCU operation to be truly successful, it must include a robust plan that incorporates mechanical cleaning, chemical cleaning and hydraulics modeling, as well as competent personnel to plan, execute, and support the operation. The cleaning process must remove all residual oils residual drilling fluid, thread compounds and chemical residues left on tubular surfaces from the drilling process. Most well-bore cleanup applications center on removal of residual emulsion fluids from the casing, and require that tubular surfaces are rendered to a water-wet state in advance of displacement to CBF.

Operations normally followed to ensure effective displacement of the incumbent SBF include: 1) circulating and conditioning the SBF; 2) short-tripping the work string to scrape the inside of the wellbore, riser and tubulars; 3) jetting the BOPs and wellhead to remove SBF, cuttings or scale debris; 4) pumping a series of displacement spacers through the well; 5) rotating and reciprocating the work string while pumping to facilitate the removal of SBF; and 6) filtering the completion fluid to the desired cleanliness and solids levels. Cleaning the pits, lines and handling equipment in contact with the completion brine, as well as preparing the displacement spacer train are also critical activities. Ideally much of this can be done during non-critical operations prior to making up the WBCU assembly.

Key performance indicators for the efficiency and effectiveness of the displacement design and execution include:

- Minimize rig time for pumping the displacement
- Minimize time required to circulate and filter the installed brine to the required specifications
- Minimized cross-contamination of the SBF and completion brine (i.e. SBF-spacer and spacer-brine interface)
- Minimize waste volumes and disposal costs
- Avoid HSE issues

Logistics planning is also important. The unique fluid handling system of each rig presents a set of advantages and disadvantages. Ideally, personnel knowledgeable in the proposed displacement visit and survey the rig and equipment, and then design a plan to most efficiently utilize the available equipment, tanks, space, and manifolds to successfully execute the planned displacement. A successful plan involves input and approval from the operator and service company personnel. In developing the plan, criteria discussed, evaluated, and reviewed typically includes:

- Requirement to maintain pumping throughout the displacement
- Responsibility to monitor barrels in/out to verify wellbore integrity
- Disposition, transfer, and storage of all fluids, including mud, brine, and all spacers/sweeps
- Identify “pinch points” that would slow down the displacement process
- Identify rig systems that are incompatible with the planned displacement process
- Identify personnel requirements, roles and responsibilities
- Identify additional equipment that could improve efficiency or remove barriers
- Identify operations that can be conducted off the critical time patch

Such information is evaluated, incorporated into the final displacement plan, reviewed and approved by the displacement team. The plan is reviewed at a pre-job meeting at which time any items identified for clarification are addressed.

Engineered Displacements – Hydraulics Software

The WBCU process requires use of engineering software for planning and execution of operational activities. These software programs allow for modeling the use of multiple fluids (SBF, displacement spacers and CBF) involved in the WBCU process. Wellbore displacement must be carefully designed to ensure the separation of the SBF from the CBF, while also meeting wellbore cleaning objectives. By computer-modeling the engineered displacement, potential problems can be identified before WBCU activities begin. This becomes critical in wells where the flow path and operational procedures are more complex. The appropriate modifications can then be made with the intent to reduce non-productive time (NPT).

The task of accurately modeling an engineered displacement is challenging due to varying trajectories, tubular configurations, circulating sub requirements, wellbore intervals, fluid properties and requisite pump rates. It is also important to model flow rates in the displacement process to ensure that annular velocities are sufficient to achieve flow regime requirements and debris removal. Without careful selection of mechanical and chemical clean up technologies, even an optimized hydraulics program, providing ideal flow rates, will not result in a clean wellbore.

A wellbore displacement software program was used to model placement, pump rates, flow profiles, riser boost, as well as annular coverage and contact times for each element of the spacer train for the GoM deepwater case histories presented in this paper. The software can model upwards of nine (9) flow paths and twelve (12) fluids used in a deepwater displacements. The software also allows the user to run animated, two-dimensional simulations of the displacement scenario. Circulating temperatures, pressures, ECD, volumes, horsepower, and fluid compressibility are calculated and graphically presented to facilitate delivery of a competent displacement process, leading to reduced operational costs and improved project economics.

Spacer Train Design

Failure to effectively displace the incumbent drilling fluid from the wellbore significantly complicates subsequent completion and tool operation. Important requirements for successful displacements include pre-displacement mechanical and chemical conditioning of the drilling mud, mechanical scraping of the casing, spacers, chemical washes, and pipe rotation and reciprocation during displacement. Advanced mechanical systems have been developed and are readily incorporated into today's displacement strategy, which includes brushes, magnetic subs, circulation subs, and junk baskets.[7]

Displacements are designed to achieve several outcomes, the first of which is effective removal of the incumbent SBF from the wellbore. Key to pumping a spacer train composed of multiple fluids is fluid-fluid compatibility. The design sequence of fluids pumped assumes that each fluid is compatible with its neighboring fluid in the spacer train. Laboratory analysis of fluid composition is required in order to verify fluid compatibility.

The primary objective of the transition spacer is to physically remove SBF from the wellbore. Design criteria for this spacer must consider the incumbent fluid, density requirements, wellbore internal pressure limitations, pump pressure and volume capacities, surface equipment limitations, service lines, and wellbore geometry. These push-pills are typically aqueous fluids, having densities and viscosity greater than the incumbent fluid, and often contain surfactants to ensure compatibility and cleaning of the incumbent SBF. The most significant factor to improve the efficiency of the displacement design is the density and volume of the transition spacer. Transition spacers having densities 1.0-1.5 lbm/gal above the incumbent fluid greatly enhance mechanical displacement efficiency. Typically, this pill should also cover at least 1,000 feet of the largest annular cross-sectional diameter.

It is generally accepted that flowrates during the displacement should be high enough for the cleaning spacers to be in turbulent flow to maximize cleaning efficiency. SBF used in deepwater operations have become increasingly complex and involve sophisticated chemistries to drive operational performance. Key to the performance of this spacer is selection of chemistries that best demonstrate the ability to clean and water-wet tubular surfaces. Contact times for cleaning spacers are generally designed for a minimum of five minutes. New displacement chemistries have been developed for these difficult field applications and will be discussed in the case history section of this paper.

The water-wetting capacity of the cleaning spacer is often measured through use of a mud residue threshold (MRT). The MRT measures the chemistries and concentrations required to provide wetting of metal surfaces for a given SBF. It is also important to estimate the anticipated residual mud volume (ARMV), which is the amount of SBF residue remaining on tubular surfaces prior to the arrival of the cleaning spacer. Factors known to reduce the ARMV are circulating and conditioning the incumbent SBF prior to displacement, use of mechanical WBCU tools and a properly designed transition spacer.

Finally, a high-viscosity spacer is pumped as a physical barrier between the cleaning spacer and the completion brine. Solids-free, high-viscosity spacers are typically formulated with the completion fluid and often utilized pre-activated HEC in divalent brines.

Pumping schedules are designed for each stage of the displacement process. Pumping adds energy to the process, assists in WBCU activities and provides a means to adequately scour wellbore surfaces, clean solid debris off pipe, casing and liner walls, and carry the debris out of the wellbore. Pump rates in the engineered displacement are designed to harmonize requirements for annular velocity, annular coverage, contact time and flow regime for each element of the spacer train.

Displacement Train Performance Tests

The performance of the cleaning spacer with the incumbent SBF is measured in the laboratory to determine compatibility and ensure cleaning efficiency prior to use. In these tests a 13.6 lbm/gal, low-ECD SBF field sample was shipped from the Port Fourchon supply base to the laboratory for displacement train performance testing. The SBF was weighted up to 14.2 lbm/gal for qualification for the two wells of interest. The transition spacers were weighted up to be 1.0 lb/gal heavier than the SBF.

Prior to running the standard displacement clean-up tests, the transition spacer compatibility test was performed between the weighted transition spacers and the SBF. To gauge the degree of compatibility between the SBF and transition spacer, the fluids are mixed together at various ratios and then a rheological test is performed. The test is run at ambient temperature with the primary focus being the 100 rpm dial reading of the 6-speed viscometer, ensuring there is no visual 'hump' occurring due to an incompatibility as shown below in Figure 6.

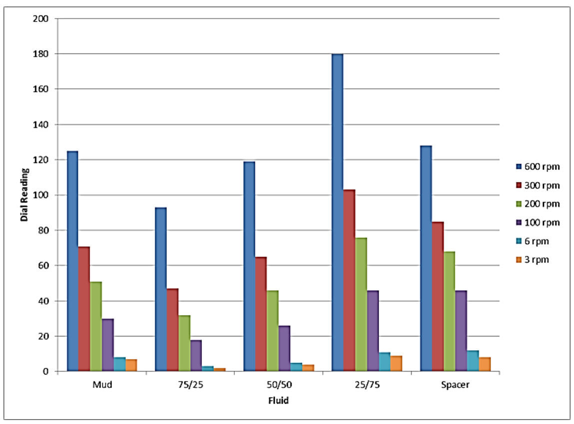

Figure 6 – Transition spacer compatibility test

A cleaning performance test was conducted utilizing a 6-speed viscometer equipped with a closed-end. The test utilizes a closed-end sleeve on the viscometer, one that has been blasted in order to remove the chrome coating and allow for the SBF film to more readily adhere to the sleeve. In addition to the standard displacement clean-up tests, the tests were repeated by contaminating each pill (i.e. the transition spacer was contaminated with 7.5% v/v of SBF and the cleaning pill was contaminated with 10% v/v transition spacer). This formulation yielded no incompatibilities during the compatibility test. For the 1st well, the clean-up efficiency is 99% for the uncontaminated test and 98% for the contaminated test, as shown below in Table 1. For the 2nd well, the clean-up efficiency is 99% for both the uncontaminated and contaminated tests.

Table 1 – Transition spacer compatibility test

	Uncontaminated Test	10% Contamination Test
Initial Mass of Sleeve, g	172	172
Loaded Mass of Sleeve, g	173.11	173.08
Final Mass of Sleeve, g	172.01	172.02
Mass of Mud Film, g	1.11	1.08
Loaded Mass – Final Mass, g	1.1	1.06
Clean Up, rpm	200	200
Exposure Duration Each Pill, min	5	5
Clean-Up %	**99%**	**98%**

The cleaning spacer displacement tests were conducted at ambient temperature, with and without contamination. The uncontaminated displacement test showed excellent cleanup after 5 minutes of cleaning pill exposure time. No residual material from the transition spacer or SBF was visible on the sleeve. The sleeve was allowed to dry in the oven for 15 minutes at 100°F and final cleanup efficiency was 99%. The contaminated displacement test showed excellent cleanup after 5 minutes of cleaning pill exposure time. No residual material from the transition spacer or SBF was visible on the sleeve. The sleeve was allowed to dry in the oven for 15 minutes at 100°F and the final cleanup efficiency was 98% as shown below on Figure 7.

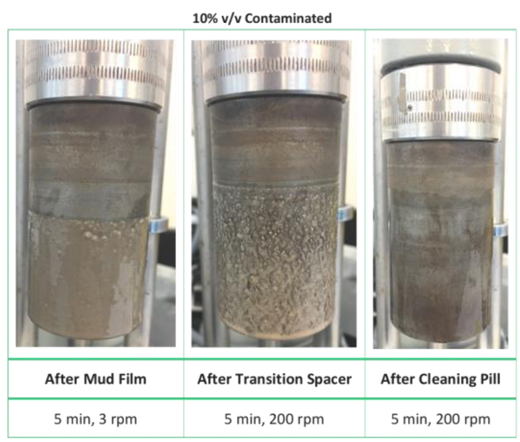

Figure 7 – Cleaning Spacer performance test

Post-displacement Analysis

The effective displacement of SBF to completion brine is an important operational outcome for deepwater completions. A poor displacement can cause production impairment, problems with a gravel pack, loss of mud or brine, and loss of rig time in addition to other complications. Metrics to determine the success or failure of the displacement operation have traditionally been based upon the clarity of the completion brine that follow the spacers, the interface volumes of mud and completion brine, a visual determination of the cleanliness of the WBCU tools pulled from the hole, and the time and materials required to filter the fluid. The most commonly used key performance indicators include:

- Clarity of the completion brine measured in either Nephelometric Turbidity Units (NTU) and Total Suspended Solids (TSS) immediately following the spacer circulation
- Number of filtration cycles (or quantity of filter media) required to achieve a target NTU
- Total volume of mud/brine interface created during the displacement
- Presence or lack of SBF on the WBCU tools when pulled from the hole either on the short-trip or after the displacement is finished

Displacements are most often evaluated on data gathered in the field based using the above indicators. Additional metrics involve the amount of circulating time and the volume circulated. A sharp interface between the spacers indicates effective displacement of the wellbore fluids and that the lack of SBF in the viscous tail spacer suggests that the wash spacer performed as anticipated.[8] Laboratory analyses on post-displacement fluid samples were used to determine the extent of interface between spacers, and to detect the presence of synthetic base-fluid and solids in the viscous lead spacer and of contaminants in the viscous spacer at the end of the spacer train.

Samples from the spacer train on the 2nd case history in this paper were collected from the rig as the spacer train sequence returned to surface at the flowline and shaker areas. An evaluation of these fluid samples was conducted to determine a possible model of the displacement and provide useful insight into the compatibility, isolation, and separation of the various wellbore fluids, chemical disposition of the spacers, and associated debris carried out of the well.

Pre-displacement samples of the spacers were collected on the rig, as well as 10 samples post-displacement. These samples were sent for evaluation to the Technology Center and evaluated following this procedure: 1) samples were mixed until homogenous using an overhead mixer equipped with a variable speed controller, then 2) a 50 ml aliquot was poured off into a properly labeled 50 ml centrifuge tube whereby the samples were centrifuged for 10 minutes at 5000 rpm, 3) after which, a photo (Figure 8) of the tube was take and an examination of the total volume of the sample in the tube, as well as, an approximation of the volumes of each layer in the tube was performed. The pH, density and rheological properties of the homogenous sample was then measured at ambient temperature.

Observations and measurements of the homogenized post-displacement spacers indicated that there were no base oil or surfactant residues found in the viscous spacer, which suggests that clear separation had occurred during the displacement.

Figure 8 – Pre-displacement samples after centrifugation

High Capacity Filtration

Filtration is the continual process of removing suspended materials (weighting agents, drilled solids, rust, perforating debris, scale, etc.) from the CBF prior to placement of the completion assembly. Following displacement into the well, the CBF is continually circulated and filtered until residual particles are removed and the cleanliness of the fluid falls within specified limits. Removal of these contaminants from the CBF is required, otherwise, residual materials can be carried into the formation or perforations, creating damage and negatively impacting production. There are two types of filtration equipment commonly used (filter press and dual-pod units) and the equipment is typically scaled to the size and complexity of the operation.

Figure 9 shows the high capacity filtration units that were used on the Gulf of Mexico deepwater projects in this paper. The units are designed to operate at flow rates upwards to 35 bbls/min. It is important to note the HSE features built into these filtration units. The units operate with electrical pumps, are hands-free with pressure relief valves (PRV) and a central control panel. From this panel the operator (top left) can remotely open/close valves, measure flow rates and dial in pump rates. The hand-rail system and walkways are designed to minimize risks associated with working from heights.

Figure 9 – High Capacity filtration units

Figure 10 presents and overview of the results arising from use of high capacity filtration units and experienced personnel in various stages of the displacement. NTUs are compared against specifications at each stage and are quickly brought within specifications.

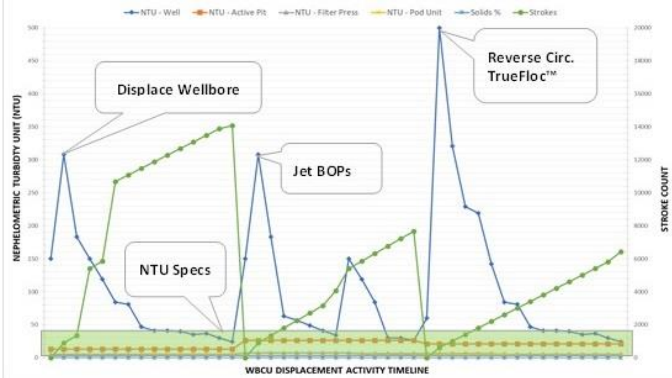

Figure 10 – Filtration performance – GoM Deepwater

Completion Fluid Selection

Choosing the right completion fluid is important because inappropriate fluids can have a significant impact on a project, not only during completion operations and startup, but also throughout the well's productive life. While sufficient density is needed to control formation pressure in any well, in deepwater wells it is also necessary to be able to modify the density without any adverse effect on crystallization and hydrate inhibition at seafloor temperature and maximum anticipated pressure. The completions fluid must be compatible with:

- reservoir matrix
- shale formations
- reservoir fluids
- subsea control fluids
- gravel- or frac-pack fluids
- stimulation chemicals and acids
- corrosion inhibitors
- packer fluid additives
- production tubular metallurgies
- fluid-loss control materials
- control line fluid; methanol
- production injection chemicals

The completion fluid selection process leans on two key operational parameters: density and crystallization temperature. For most deepwater Gulf of Mexico wells, temperature-related changes in density are insignificant (typically less than 0.1 lbm/gal), because reservoir temperature gradients are relatively low (1.2º F to 1.5º F per 100 ft). The density gain due to colder seafloor temperatures often offsets the loss from increased formation temperature. True crystallization temperature (TCT) of a brine is the temperature at which salt crystals begin falling out of solution at atmospheric pressure, given sufficient time and proper nucleation conditions. For single-salt brines, TCT depends on fluid density and cannot be adjusted. With multi-salt brines, TCT for a given density can be adjusted by varying the relative amounts of each salt. Generally, the lower the TCT, the more expensive the brine (a higher proportion of heavier salt is used) and the lower the hydrate inhibition (more "free" water in the solution).

With divalent brines made from calcium and zinc salts, the crystallization temperature increases with increasing pressure. In deepwater completion brines, the pressure-dependent crystallization temperature (PCT) is the definitive parameter due to colder temperatures and higher pressures at the seafloor. Applying 10,000 psi raises the crystallization temperature of divalent brines by 10 - 20º F and monovalent brines by only 1-5º F. In deeper water, crystallization is most likely to occur at the seafloor, as well as in the wellhead, subsea tree, blowout prevention (BOP) stack, and choke and kill lines. Choke and kill lines are most vulnerable because they can reach seafloor temperature within 30 minutes after circulation stops. Modeling can be used to predict temperature response.

Increasing or maintaining density by adding dry salt or volumes of a saturated "spike" brine can change the proportion of salts in a multi-salt blend, altering the brine's PCT. Hence, the common practice of slugging the work string with a spike fluid before tripping should be done with caution. Adding water to reduce density causes the hydrate equilibrium curve to shift, possibly increasing the risk of forming hydrates. Adding lighter salt brine or adding drill water along with a hydrate inhibitor might be safer options.

Gas Hydrates

Gas hydrates are products of a thermodynamic phenomenon where water and gas molecules combine to form crystalline solids. The crystal lattice structure of hydrogen-bonded water molecules provides a cage-like framework to host gas molecules.[9,10,11] Gas hydrate formation is a function of high-pressure, low-temperature, the composition of hydrocarbon gas present, and available free water. Gas hydrates form more readily at high pressure, lower temperature (exactly the conditions encountered at the BOP/wellhead of deepwater drilling/completion operations) with higher gravity gases, and in lower salinity waters. These conditions are often at temperatures much above the freezing point of water. In order for gas hydrates to form, there must be a large quantity of entrained gas in the drilling/completion fluid and the right combination of high pressure and low temperature. The temperature at which hydrates form is a direct function of pressure. As pressure increases with increased water depth, the temperature at which hydrates can form also increases. The hydrostatic head of the drilling/completion fluid column in the riser combined with the cold temperatures at the mudline create an environment conducive to gas hydrate formation.

Problems associated with the formation of gas hydrates in drilling/completion fluid include:

- Plugging of choke and kill lines, BOPs, and the riser from background or kick gas
- Plugging of flow lines where a kick has occurred
- Interference with drill string movement or BOP operation

- The liberation of large quantities of gas near the surface as the hydrates decompose or melt

Temperature, pressure, and gas composition determine conditions favorable for hydrate formation. Solidification occurs as the temperature decreases and/or the pressure increases. A light gas (methane) resists hydrate formation more than the heavier gases (ethane and propane).

As the temperature of the fluid is decreased and/or pressure is increased, seed crystals or hydrate nuclei are formed. At the critical pressure/temperature/gas combination, massive nucleation and encapsulation of gas into the hydrate structure occur. Elevated pressures and low temperatures specifically in deepwater drilling/completion operations promote hydrate formation. The gas hydrate crystals can plug subsurface and BOP equipment during drilling/completion fluid circulation. Conversely, as temperature increases, gas is released through dissociation such as gas breakout from oil mud. An uncontrolled sudden release of gas can become a kick.

The amount of inhibition required to prevent hydrate formation is determined by the difference between the water temperature at the wellhead and the hydrate formation temperature in fresh water

The formation of gas hydrates can be calculated by hydrate prediction modeling software. Requirements include seabed or mudline temperature and related reservoir and/or BOP test pressures. Various salts, alcohols, and glycol combinations can be mixed to suppress the gas hydration formation temperature. These are referred to as thermodynamic hydrate inhibitors. Thermodynamic inhibitors interact with the water phase to prevent the molecules from forming the hydrate crystal lattice. This increases the ‘severity’ of the conditions under which hydrates will form. Alcohols are seldom used due to toxicity and flammability. Glycols and salts are the most common thermodynamic inhibitors. Their effectiveness increases as their molecular weight decreases. Use of hydrate prediction modeling software is allows for a determination of the required concentration (wt.%) of thermodynamic hydrate inhibitor(s) to suppress gas hydrates. An example of the modeling outcomes of this software is show in Figure 11.

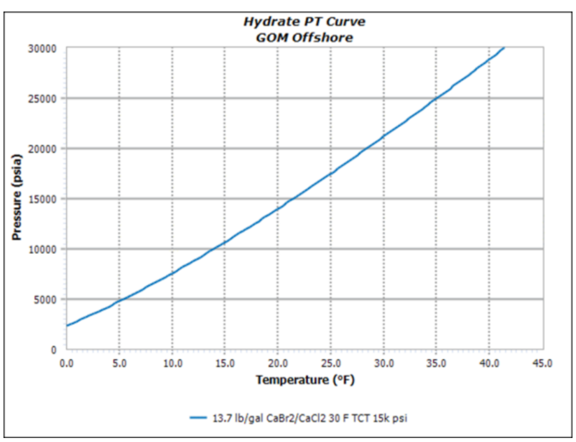

Figure 11 – Gas hydrate equilibrium curve

In some subsea trees, completion brine can mix with methanol and control fluid – used to operate subsea systems and the sub-surface safety valve (SSV) – just prior to landing the tubing hanger in a subsea tree. Lab tests confirm most heavy brines are incompatible with methanol and some brines are incompatible with certain control fluids. Precipitation of brine salts and separation of control fluid components occur immediately on contact. With some control fluids, contact with brine causes separation of the fluid’s dye package, lubricity package and corrosion inhibitor, suggesting a loss in control fluid performance. Salt precipitation, most pronounced with divalent brines ($CaCl_2$, $CaBr_2$ and $ZnBr_2$), can be sufficient to plug SSV control lines or block a chemical injection supply line or annulus bleed-off line. Precipitation appears to be less problematic with mixtures of monovalent brines and control fluids, although precipitation can occur when methanol is added. To avoid salt precipitation, sodium bromide has been successfully employed as a packer fluid, with the addition of ethylene glycol as needed for hydrate inhibition.[13,14]

Many completion teams and subsea tree suppliers have modified installation procedures to minimize the mixing of brine with control fluid and have eliminated opportunities for brine back-flow into control systems. However, intimate contact between brine, control fluid and methanol still occurs and cannot be avoided. Once the completion fluid has been selected, the following tests should be performed:

- measure the PCT of the specific brine composition with additives
- confirm the hydrate equilibrium curve
- confirm formation compatibility with brine and other completion fluids (fracturing fluid and acids) when iron is present
- confirm brine compatibility with reservoir fluids when iron is present
- measure corrosion rates on coupons of specific metals of the tubing and production equipment
- determine the necessary dosage of corrosion inhibitors, pH modifiers and oxygen scavengers
- Corrosion rates should be measured for a minimum of 28 days.

Case History #1

A GoM deepwater operator required a subsea decomplete intervention on a project in the Eastern GoM at a water depth of 4,500 feet. Decompletion operations were conducted from the ultra-deepwater drillship shown below in Figure 12. The completion fluids team developed a detail plan comprised of a robust engineered displacement program including chemical and mechanical WBCU solutions integrated through use of sophisticated displacement modeling software. High-level objectives involved displacing to brine, recovering tubing, and then displacing to SBF.

Figure 12 – Ultra-deepwater Drill Ship -Case History #1

The initial decompletion intervention procedure did not involve circulating brine below the mudline, which required additional volume built and delivered to location in a truncated timeframe after the rig arrived on location. Several CBF were required for operational sequences including the capture, isolation, and recovery of the packer fluid during intervention operations. The working fluid was a 13.5 lbm/gal $CaBr_2$/$CaCl_2$ blended CBF designed for a 30° TCT at 15,000 psi.

The rig surface fluid handling system was thoroughly cleaned of residual drilling mud while in transit from a previous well in preparation to receive completion fluid once on the new location. A comprehensive fluid management plan was outlined to handle multiple fluid interactions throughout the operation, which included six different fluid transitions. Berms used to control tubing debris from washing and thread cleaning activities from discharge into the GOM were utilized. Solids accumulation in the fluid were minimized using increasingly finer screen mesh sizes on shakers.

The operational team was able to effectively prepare and build all brine, spike fluid and associated additives without delays from the newly commissioned Fourchon completion fluids facility shown in Figure 13. This was the first project serviced from the new facility and personnel were able to support operations from the drill ship without interruptions.

Figure 13 – Support Facility

With less than 12 hours notice, the onshore and offshore fluids team quickly responded to the changes in work scope related to additional volume requirements. Timely delivery of the significant volumes of high density completion fluid and additives was managed through use of the Fourchon completion fluids facility. Personnel on board the rig successfully recovered the incumbent packer fluid with little to no density or volume loss and all logistics involved in the management of fluid during the decompletion occurred without the incidence of NPT. Figure 14 shows a brush/magnet tool following a successful offline riser cleanout operation.

Figure 14 – Brush/Magnet WBCU tool post run

Case History #2

An operator in the Gulf of Mexico required a solution to directly displace a 14.0 lb./gal low-ECD synthetic-based fluid (SBF) to a 13.7 lb./gal $CaBr_2/CaCl_2$ completion fluid on a deepwater subsea well. Operations were conducted from a dual-activity drillship, designed for operating at drilling depths of 40,000 feet shown in Figure 15 below. The total volume SBM to be displaced was 3,482 bbls at water depths of 4,500' (1,350 meters) with the well depth in excess of 27,000' (8,200 meters). The operator set completion fluid cleanliness specifications for the displacement at <30 NTUs out of the well and solids content at <0.05%.

Figure 15 – Ultra-deepwater Drill Ship -Case History #2

Laboratory tests were performed in advance of operational activities in order to qualify the proposed chemistry and to conduct performance tests of the spacer train formulation. Key aspects of the performance tests included spacer train compatibility and removal of SBF residue using the 6-speed viscometer test. Additionally, hydraulics modeling of the displacement process was done to satisfy requirements of contact, annular velocity, flow regime and annular volumes. This included use of mechanical wellbore cleanup (WBCU) tools that were sequenced and placed for physical cleaning of the wellbore and riser. Use of high-flow filtration equipment allowed for pump rates upwards to 30 bpm which kept pace while the riser was boosted.

The rig surface fluid handling system was thoroughly cleaned of residual SBF in preparation to receive completion fluid, while the fluid was circulated and conditioned to specifications prior to displacement. A spacer train was formulated with of a blended solvent/surfactant utilized in both the transition and cleaning spacers. These concentrations were customized to the specific drilling mud being displaced.

The choke, kill, and boost lines were first displaced to completion fluid at 5-10 bpm using base oil and cleaning spacers. The spacers were pumped down the work string at 6-9 bpm. The displacement spacer train was followed by 13.7 lb./gal $CaBr_2/CaCl_2$ completion fluid. The pump rates varied 14-18 bpm until the tail end of the viscous spacer passed above the BOP, at which point the remainder of the displacement occurred at flow rates of 25 bpm.

During the displacement, the work string and WBCU tool assemblies were rotated between 30-60 rpm. Similarly, the work string was reciprocated between 60-120 feet/minute once the displacement spacers were out of the work string. Photographs of the WBCU tools following completion of WBCU operations and laying down the BHA are shown below in Figure 16. From these, the performance of the chemistry in in removing SBF residue from the tubulars and WBCU tools is readily apparent. Due to the available pit space, all surface completion fluid was filtered prior to the displacement to avoid the need to filter while displacing. Once initial completion fluid returned to surface, a flocculant treated lead brine volume was reverse circulated around the well. The riser was then boosted. A short-trip was performed followed by the BOPs being jetted and the riser boosted a final circulation.

Figure 16 – WBCU tools post-displacement

The total displacement time from filling the service lines with brine to the fluid clarity endpoint was 17.75 hours, with 3.3 well volumes circulated. The final fluid clarity endpoint result was 17 NTUs and <0.01% solids out of the well, which exceeded the specified targets established by the operator. The performance of the high-capacity filtration units is presented in Figure 17. All spacers returned to surface as expected based on bbls/stroke calculations. The use of specific chemistries coupled with reliable hydraulics modeling, robust WBCU tools, and proper filtration resulted in a successful displacement.

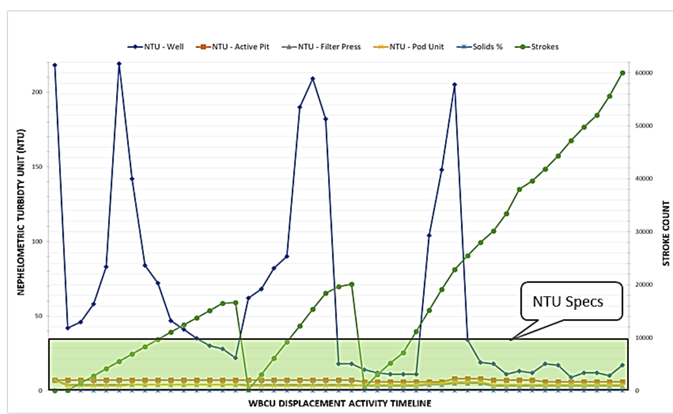

Figure 17 – High-capacity Filtration Performance

Case History #3

A deepwater operator in the Gulf of Mexico required a solution to directly displace a 14.1 lb./gal low-ECD synthetic-based fluid (SBF) to a 14.3 lb./gal pure $CaBr_2$ completion fluid on a deepwater subsea well. Operations were conducted from an ultra-deepwater, dual-activity drillship, designed for operating at water depths approaching 12,000 feet, and maximum drilling depths of 40,000 feet shown below in Figure 18. The total volume SBM to be displaced was 3,183 bbls at water depths of 4,498' (1,350 meters) with the well depth in excess of 29,000' (9,064 meters). The operator set completion fluid cleanliness specifications for the displacement at <30 NTUs out of the well and solids content at <0.05

Figure 18 – Ultra-deepwater Drill Ship -Case History #3

Laboratory tests were performed in advance of operational activities in order to qualify the proposed chemistry and to conduct performance tests of the spacer train formulation. Key aspects of the performance tests included spacer train compatibility and removal of SBF residue using the 6-speed viscometer test. Additionally, hydraulics modeling of the displacement process was done to satisfy requirements of contact, annular velocity, flow regime and annular volumes. This included use of mechanical wellbore cleanup (WBCU) tools that were sequenced and placed for physical cleaning of the wellbore and riser. Use of high-flow filtration equipment allowed for pump rates upwards to 30 bpm which kept pace while the riser was boosted.

The rig surface fluid handling system was thoroughly cleaned of residual SBF in preparation to receive completion fluid, while the drilling mud was circulated and conditioned to specifications prior to displacement. A spacer train was formulated with of a blended solvent/surfactant utilized in both the transition and cleaning spacers. These concentrations were customized to the specific drilling mud being displaced

The choke, kill, and boost lines were first displaced to completion fluid at 6-10 bpm using base oil and cleaning spacers. The spacers were pumped down the work string at 9.5-10 bpm. The displacement spacer train was followed by 14.3 lb/gal $CaBr_2$ completion fluid. The pump rate was 10 bpm until the tail end of the viscous spacer passed above the BOP at which point the remainder of the displacement occurred at 27 bpm.

During the displacement, the work string and WBCU tool assemblies were rotated between 30-60 rpm. Similarly, the work string was reciprocated between 60-120 feet/minute once the displacement spacers were out of the work string. Figure 19 shows images of the mechanical tools following completion of WBCU operations. The performance of the newly developed chemistries in the transition and cleaning spacers towards removing SBF residue is visually apparent.

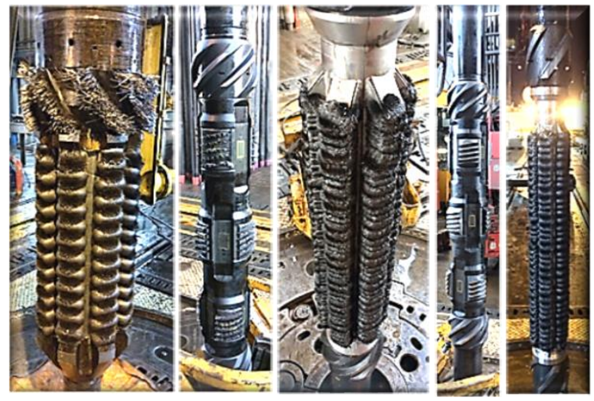

Figure 19 – WBCU Tools post-displacement

All surface completion fluid was filtered prior to the displacement to avoid the need to filter while displacing. Following initial returns to the surface, a flocculant treated lead brine volume was reverse circulated around the well. The riser was then boosted. A short-trip was performed followed by the BOPs being jetted and the riser boosted a final circulation.

The total displacement time from filling the service lines with brine to the fluid clarity endpoint was 22 hours, with 3.5 well volumes circulated. The final fluid clarity endpoint result was 24 NTUs and <0.01% solids out of the well, which exceeded the targets established by the operator. All spacers returned to surface as expected based on bbls/stroke calculations. The use of specific chemistries coupled with reliable hydraulics modeling, robust WBCU tools, and proper filtration resulted in a successful displacement. The performance of the high-capacity filtration units is presented in Figure 20.

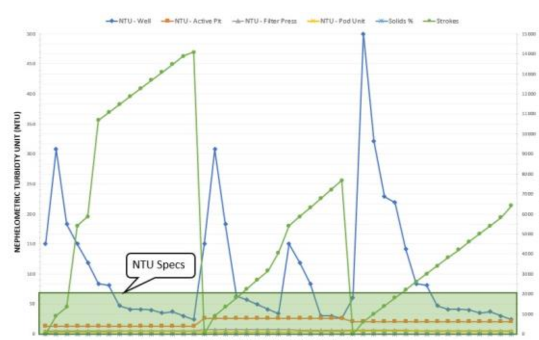

Figure 20 – High-capacity Filtration Performance

The operator requested that a calcium carbonate fluid loss control pill be formulated and readily available should losses occur following frac-pack operations. Using information such as reservoir properties, perforating information, fracture parameters, and screen and proppant information, a fluid loss control pill was developed and evaluated in the Technology Center. The pill was mixed as a contingency in the event of failure of the mechanical fluid loss control device to close properly.

Following completion of frac pack operations, the gravel pack service tool was engaged, however, it was observed that the fluid loss control device had failed to close properly. Initial rates of losses exceeded the threshold established by the operator, so the calcium carbonate pill was mixed within 30 minutes during non-critical rig operations. Subsequently, the pill was spotted and the well was monitored for losses over a 1.5 hour period. It was observed that losses decreased steadily until no losses were observed and the well was determined to be static. The calcium carbonate pill was 100% effective in preventing fluid losses for a period of 48 hours, which allowed the service tool to be pulled out of the well and the operator to run back in the hole to proceed with completion operations.

Results, Conclusions and Lessons Learned

- The GoM deepwater environment presents the potential for a variety of operational challenges.
- Gulf of Mexico deepwater operators recognize that engineered displacements reduce operating costs and risks
- Operational efficiencies in deepwater are improved when leveraging the distribution and logistical benefits of best-in-class facilities.
- A newly commissioned Completion Fluids Facility supports GoM drillship-based deepwater operations
- The facility was designed with focus towards automation in workflows, and HSE benefits to facility workers
- A new family of chemistries have been designed to deliver incremental value in GoM deepwater displacements
- Newly introduced WBCU displacement software can model upwards of 9 flow paths and 12 fluids used in deepwater displacements
- High-capacity filtration units with newly developed automated features drive operational and HSE performance
- Operational excellence and strong service quality demonstrated by integrating fluids, filtration and tools
- The ability and capacity to integrate services sets new standards of performance on challenging GoM deepwater completions

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Nomenclature

NPT – non-productive time, hours
ECD- equivalent circulating density, pounds per gallon
SBF – synthetic-based drilling fluid
TCT – true crystallization temperature, °Fahrenheit/Celsius
GoM – Gulf of Mexico
psi – pressure, pounds per square inch
F – temperature, degrees Fahrenheit
BHT – bottom-hole temperature
ft – feet
TVD – true vertical depth, feet/meters
md – permeability, millidarcy
C – temperature, degrees Celsius
BOP – blow out preventers
WBCU – wellbore cleanup
CFF – Completion Fluids Facility
DFM - design for manufacturing
ISO – International Organization for Standardization
API – American Petroleum Institute
QMS - quality Management System
HSE – health, safety and environmental
ESD – emergency shut-off device
CBF – clear brine fluid
lbm/gal – density, pounds per gallon
MRT – mud residue threshold
ARMV- anticipated residual mud volume
v/v- volume/volume
NTU – Nephelometric Turbidity Unit
TSS – total suspended solids
DE - diatomaceous earth
PRV – pressure-relief valve
PCT – pressure-dependent crystallization temperature
SSV – Sub-surface Safety Value
$CaCl_2$ *– Calcium Chloride*
$CaBr_2$ *– Calcium Bromide*
$ZnBr_2$ *– Zinc Bromide*
bpm – flowrate, barrels per minute

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