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Enhanced Spacer Designs and Displacement Modeling Enhance Wellbore Clean-Up in Gulf of Mexico and North Sea Completion Applications

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Abstract

Displacements of drilling or drill-in fluids to clear brine are critical for most completion operations. Without a well-planned displacement to the completion fluid, completion tool setting failures or wellbore damage may compromise a project's objectives. Wellbore clean up of casing and open-hole sections require careful planning from a chemical, rheological and mechanical perspective. In addition, the calculations required to accurately model an efficient displacement are multifarious because of varying trajectories, tubular configurations, circulating sub requirements, wellbore intervals, fluid properties and requisite pump rates.

Furthermore, in cases where geometry differences require varying pump rates due to multiple spacer systems, a single accurate planning tool helps the operator implement a safer displacement process. Using more accurate rheological models, such as the Herschel Bulkley model for drilling fluids, helps predict the pressure losses more accurately. Not withstanding these complexities, the displacement parameters must be modeled so that every operation, including cased and open-hole intervals, utilize the proper chemistry and mechanical energy to safely clean and remove unwanted wellbore debris.

This paper presents three case histories. Each case links its spacer chemistry with displacement modeling based rig design, well configuration and downhole tool selection and multiple spacer usage. Factoring in these parameter lead to excellent clean up of difficult to clean synthetic and oil base fluids in an efficient, safe and cost effective manner for three operators drilling in three separate worldwide locations.

Introduction

Unlike spacer designs typically used for ordinary clean up, today's displacement technology considers more than just removing one fluid from the wellbore and replacing it with another. Current wellbore displacement programs place added emphasis on rendering a wellbore free of oil and completely water-wet. In the case of cleaning a casing section, displacing an oil or synthetic-base fluid to a water-based fluid or clear brine presents different challenges. Displacement designs call for the hydraulic and mechanical removal of all solid particulates, the oil or synthetic-based drilling fluid and usually the chemical removal of residual oil.

The degree of oil removal depends on the application. Removing oily debris and mud from an open-hole and replacing them with clear brine may not require a complete and total removal of oil residues. For example, in gravel pack or stand alone screen applications, reservoir intervals drilled with invert emulsion fluids may only require a gentle cleansing action to prevent damaging emulsions from forming when contacted by clear brine. [1] Even in these cases, critical transport fluid velocities are required to fully remove solids and oily debris completely from the wellbore while maintaining the post drill-in oil wettability of the filter cake is desirable.[2, 3]

Most wellbore clean up applications of oil or synthetic-based fluids are performed in casing and require that nearly all the oil be removed and the casing rendered water-wet. When displacing these wellbores to clear brine, detailed procedures must be executed at the rig-site to avoid the formation of sludge potentiated by the contact between these dissimilar fluids. Without careful spacer selection, even an optimized hydraulics program providing ideal flow rates will not result in a clean wellbore, especially in the case of difficult-to-clean synthetic-based drilling fluids. Likewise, without proper hydraulic and mechanical lifting of cuttings beds and suspended solids in the drilling mud, properly formulated cleaning spacers may not render a wellbore clean. Thus, the process to achieve a clean wellbore requires the planning and coordination of all the aforementioned techniques.

The blueprint for a successful wellbore displacement and clean up process must consider a number of other critical variables including wellbore configuration, mechanical aides (scrapers, brushes, circulating subs, magnets, jetting tools), mud conditioning, multiple spacer rheologies, water depth, kill, choke and booster lines, forward versus reverse circulation, pump rates, rotation and reciprocation of clean up string, fracture gradients, effective surface cleaning and filtration needs. When these variables are input in the planning model and communicated to drilling personnel, a safe and cost effective displacement and wellbore clean up can be realized.

Proper execution of the displacement and the degree of cleanliness are obviously critical issues. However, the cleaning design must also consider waste volume reduction and be in strict conformance with local discharge regulations. For example, in many aquatic and onshore locations around the world, environmental regulations prohibit waste discharges of any nature. In these instances, clever methods of minimizing the waste volume without sacrificing clean up performance must be implemented. Similar volume restrictions are required when pit volumes are limited. Even in cases where pit capacity is not restrictive, the volumes could be large and any approved disposal volumes doubled or tripled.

In some drilling applications, such as the use of inland barge operations, cementing units, which are often used to pump spacers, are not housed on location. Predicting the required pump rates, expected pressures and hydraulic horsepower requirements makes it possible to plan for the proper cementing unit. Cementing units are usually rated at 7,000 or 10,000 psi. If a displacement requires 7,500 psi, a 7,000 psi unit would not be appropriate. The wrong unit would result in increase displacement time and possibly an unclean wellbore. Planning software that models the requirements of a displacement, especially when multi spacer systems are used, will prevent equipment misapplications and result in a cost savings to the operator.

In the discussion that follows three synthetic or oil-base fluid displacements and clean up case histories are detailed. Each of these case histories used modeling software to consider rig and wellbore limitations. In addition, these case studies included spacer chemistry and rheology, contact time and solvent saturation limits. Each operation resulted in a safe and cost effective removal of synthetic or oil-base fluid with minimal spacer volumes and waste disposal.

Displacement Planning

Proprietary displacement software for INTEQ Drilling Fluids (Displex^{SM}) was used for planning and executing the displacement operations detailed in this paper. Each displacement fluid (mud, spacer and brine) can be individually customized based on the rheological behavior. Available models to choose from are the Bingham Plastic, Power Law and Hershel Bulkley models. The individual characterization of each spacer allows for proper pressure management during the displacement process. Complex rheological models, such as Hershel Bulkley, seem to describe the rheological behavior of thixotropic fluids such as the drilling fluid and viscous push pills while the others, such as the Bingham model, do well with the Newtonian fluids.

A list of capabilities and benefits of this modeling software are given below:

- A detailed pressure analysis table enables the user to adjust the pumping schedule to achieve maximum displacement rates without exceeding the formation or fracture pressure.
- Flow-in and flow-out information is continuously available.
- ECD and pressure profiles with respect to time and depth are generated in tabular or in simulation mode.
- Pressure, ECD and flow profile information relative to time and volume is recorded.
- Forward and reverse circulation scenarios are available, including back pressure options.
- Up to nine (9) fluids in the annulus and drill string may be included.
- Five (5) different pump rates per spacer system are allowed, including separate fluids in the choke, kill and booster lines.
- Each fluid can have different flow properties and use a different rheological model.
- The model will show and account for free fall and allows for back pressure if needed to either control the free-fall or provide automatic calculation for maintaining the pressure for well control.
- A “circulation sub” in the workstring may be modeled for pressure and flow control.
- Minimum required pump rates calculated to move fluids in a turbulent flow regime.
- Color coding of the data allows for easy identification of problems.
- A full 2D, dynamic flow pattern simulator allows the user to visualize the simulation process.
- Last-minute changes in the displacement program are easily entered at the rig locations to account for any operational modifications or, in the case of pump failure, the pump schedule can be easily recalculated and adjusted for new parameters.
- Open-hole displacement modeling allows different cleanup spacers for both the open-hole and casing.

- Multiple fluid densities may be input to provide a safe overbalance. Animation features visually verified for fluid top during the entire process
- Models deepwater operations and provides flexibility for pumping multiple spacer systems at different rates to clean the casing and the riser. Choke, kill and boost lines can be used for either pumping down or taking returns as the process dictates.
- A volume calculator provides all the pertinent information about the wellbore. This reduces the planning time and possibility of error regarding contact time and spacer volumes.

Depending on the application, such as a deepwater or inland water application and specific wellbore conditions, input data will dictate which capabilities the modeling software will use. Because each of the case histories discussed below have completely different operating parameters, the output for each are also different and specific for each case.

Case History Discussions

Non-Aqueous Spacer System (1)

Case History 1: Deepwater GoM

This 20,800-ft deepwater displacement application in the Gulf of Mexico, which was drilled with an olefin-based synthetic base fluid, had a number of objectives, including a successful "one-pass" clean up of the casing string with a minimum of circulations to filter the 15.8 ppg $CaBr_2/ZnBr_2$ completion fluid to <20 NTU. Additionally, the operator required that the fluid volumes be managed at a minimum level to reduce pit and waste disposal.

To achieve these objectives, the operator chose a non-aqueous spacer clean up system because planning calculations indicated that only 125 bbl of spacers would be needed before pumping filtered completion brine.

The spacer sequence is shown as follows:

a. 25 bbl of synthetic-based oil
b. 25 bbl weighted, non-aqueous solvent spacer
c. 23 bbl neat non-aqueous solvent spacer
d. 25 bbl 5% seawater/surfactant water-wetting spacer
e. 25 bbl viscosified HEC in seawater

The total volume of the non-aqueous spacers was based on the saturation volume of the solvent and the total estimated surface area to clean. In most wellbore clean up applications, especially in deviated holes, turbulent flow is required for effective removal of solids and surface scouring. In this application, the base oil lead spacer and the non-aqueous, non-viscosified cleaning spacer were each programmed for turbulent flow. The software model calculated that 5.6 bbl/sec was possible without exceeding the pump limitations downhole pressure limitations (**Figure 2**). 5.6 bbl/sec exceeded the 300 ft/min minimum flow criteria for debris removal recognized by the industry. [4] Based on this flow rate, the spacer volumes were calculated for at least 10 minutes of contact time for the two non-aqueous solvent spacers combined.

While pumping the 125 bbl system down the work-string at a rate to allow 10 minutes of contact time (**Figures 1 and 3**), the pipe was rotated and reciprocated to allow the bristle brushes to scrape the casing ID. The workstring as placed on bottom when the first spacer entered the annulus. As the spacers returned to the surface, the base oil (~25 bbl) was isolated for reuse in the synthetic-based fluid system. The remaining 100 bbls of the spacer system were isolated for disposal. There were distinct visual differences noted between the clean up spacer interfaces. It was also reported that, as the clean up spacers returned to the surface, the concentration of oily debris diminished quickly to clear by the time the viscosified HEC spacer appeared at the surface.

After short-tripping with the bristle brush that had been placed near the end of the workstring and, after pumping a 20 bbl viscosified 15.8 ppg $CaBr_2/ZnBr_2$ HEC pill to surface, the completion brine was filtered.

In summary, only 100 bbls of used clean up spacers were shipped to the onshore disposal facility. This was attributed to non-aqueous spacer efficiencies and fluid velocities recommended by the hydraulic modeling program. A clean up operation using an aqueous spacer system would have required that an average of 525 bbl of spacers be collected and shipped to the onshore disposal facility. Furthermore, only 1.5 hours of circulating time were required to achieve a <20 NTU value or less. Previous aqueous spacer systems used by this operator required nearly 15 hours of circulating time to clean the wellbore and filter. Considering only spacer volumes, the disposal costs for the non-aqueous system was ~$1000. The disposal costs for an aqueous system would have been ~$5,250, regardless of the solvent concentration. Based on a $125,000/day rig, the savings realized while circulating (1.5 hr vs15 hr) to achieve <20 NTU was ~$70,000 (**Table 1**).

Non-Aqueous Spacer System (2)

Case History 2: Norwegian North Sea

Another effective but slightly different non-aqueous displacement method is used in the North Sea (Norwegian Sector). The spacer sequence for these displacements, like the system described in the first case history, ensures that the casing is cleaned before it has any contact with seawater or brine.

The main objectives for this application were to phase out environmentally unacceptable spacer additives and simplify the clean up procedures without compromising the clean up. The limited number of pills in this system's non-aqueous method has resulted in a number of operational improvements, including logistical handling.

The spacer sequence for this clean up system is listed below:

a. base oil lead pill
b. base oil soap pill (BOSP)
c. high-vis soap pill (HVSP) in seawater or brine
d. seawater followed by inhibited packer fluid

Generally, this technique is sufficient to reduce the NTU level to less than 80 and the solids content to less than 0.05% (v/v) after pumping only 1.5 to 2 times the wellbore volume. As with all displacements, low pump rates can extend the circulating time and encourage spacer intermingling which creates larger interfaces between pills. Low pump rates also may reduce the volume of recovered base oil to levels as low as 50%.

In a recent 11,760-ft TVD North Sea well that used the spacer sequence given above, the casing was successfully cleaned and water-wet as evidenced by the rusty appearance in the completion fluid after only two hours of pumping. This excellent clean up occurred despite the pump rate being limited to 11 bpm because of the limited injection capacity of the returned fluids.

The BHA for this clean up application consisted of a junk mill, motor assembly, 2 7/8” DP, PBR mill set, circulation sub, scraper, magnet sub and 5½” DP to surface. The entire string was reported to be totally cleaned when pulled out of the well.

The lead base oil pill was recycled into the oil-base drilling fluid system. The weak and unstable emulsion formed in the BOSP was separated upon being collected at the surface. On this operation 60% of the BOSP was reusable, but up to 80% of the BOSP has been reused on other operations where pump rates were higher.

From an environmental perspective, the surfactant added to the BOSP is rated 74% Green and 26% Yellow by the Norwegian Environmental Regulatory Agency. This component is also used in the high-vis soap pill. The other component used in this pill is 100% green. Despite having to formulate environmentally friendly spacers, their use in non-aqueous applications does not diminish their effectiveness (**Tables 2 and 3**).

On subsequent clean up operations, this new system has shown excellent performance due to improved displacement efficiency recommended by the modeling software. The improvements include reduced volumes of waste and increased volumes of recycled base oil.

The cost per meter and environmental comparisons using non-aqueous and aqueous spacer designs to clean up a typical 9-5/8” casing, can be found in **Tables 2-5.**

As noted in **Table 4**, the non-aqueous system’s cost in Offset 3 was 13% and 40% less per meter than the aqueous system’s cost for Offsets 1 and 2. In addition, the improvement occurred with a greater “green” content in Offset 3 compared to Offset 2 (45% versus 4%) and, on the first attempt, resulted in 211 bbl less waste generated. Of the waste volume generated from the non-aqueous spacer system, 50% of the recovered base oil was returned to the base oil storage tank and 50% to the OBM. The total recovery of base oil was calculated to be 74% of the original volume used. The aqueous system in Offset 2 only allow for 49% of base oil recovery for future OBM dilution (**Table 5**).

The advantages of applying aqueous and non-aqueous designs to *surface* cleaning are similar to wellbore and casing clean up operations. Based on the recommended concentrations of each surface clean up additive, the waste generated with the non-aqueous system was 49% less than the aqueous system (**Tables 6, 7 and 8**).

Aqueous Spacer System (1)

Case History: South Louisiana Inland Water

Inland water and other barge applications require accurate displacement modeling when planning spacer systems to effectively clean the wellbore and generate minimal waste. Inland water displacements pose problems that are easily overcome on normal offshore drilling and land rigs. Offshore drilling rigs have high capacity cement units available. On land locations, a replacement unit can be driven to location in a reasonably short period of time. Inland jobs require the units to be put on barges, thus making the proper equipment selection very important before it arrives to the rig. Modeling allows assists the use in identifying the annular velocity, hydraulic horsepower and pressure requirements of the displacement and allows the operator to determine if the rig pumping system is capable of performing the displacement. In this example, a direct displacement using forward circulation was chosen to minimize waste and allow pipe rotation and reciprocation during the displacement. This action provided key elements during the displacement not only mechanical cleaning but for efficient chemical contact time and proper annular velocity requirements for each hydraulic diameter.

The main objectives in this well were to reduce waste generation, coordinate spacer preparation on a rig with limited pits capacity, use the cementing unit as little as possible and minimize filtering time to reduce any operational non-productive time associated with the displacement. The limited number of pits required tight control of logistical handling. This project used the following aqueous spacer/brine sequence:

a. Base oil lead pill
b. Viscosified Oil Based Mud Pad
c. Pre-Mixed Cleaning and Water Wetting Spacer
d. High-Viscosity brine pill
e. Completion Fluid (brine)

This wellbore was displaced and the NTU level was less than 40 after the initial returns made it to surface. After a short trip to further mechanically clean the hole with the brushes and scrapers, the fluid was circulated one bottoms-up. The maximum NTU level was 75 and dropped to less than 18 before a second wellbore volume was circulated to surface.

The lead base oil pill and viscosified mud pad were recycled into the oil-base drilling fluid system. The pre-mixed cleanup pill was captured and reused to clean the remaining surface equipment resulting in an additional saving to the operator. The first 25 barrels of the viscosified brine pill were captured in the shale barge as a precaution. The remainder was fed back to the active system, treated with a breaker and used in the completion (**Table 9**).

The successful performance was due to improved displacement planning, efficient use of the spacer system, designing the entire process to reduce waste and non-productive time spent filtering fluid.

Conclusions

1. Displacement planning tools such as modeling software can be a valuable aid to ensure that spacer volumes and properties are adjusted to meet wellbore clean up needs.
2. Modeling software can be used to qualify rig equipment before a job starts.
3. Non-aqueous spacers can dramatically reduce the cost of the overall displacement by minimizing circulating and filtration time.
4. Non-aqueous spacers can improve cleaning efficiency and minimize waste disposal and increase recycling of base oil.
5. Non-aqueous surface clean up techniques reduce waste disposal volumes more than when using aqueous spacers.
6. Modeling software can improve the efficiency of less effective aqueous spacers by recommending more effective pumping schedules that also minimize waste disposal.

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GoM Clean Up Comparisons Case History 1		
	Aqueous	Non-Aqueous
Total Pill Volume, bbl	575	150
Disposal cost, $	5,250	1,000
Filtration Time, hr *	15	1.5
Filtration Time Cost, $	7,800	78,000
Rig time Savings, $	---	~70,200

* Filtration time (after last spacer circulated to surface)

Table 1 Clean Up Savings (Aqueous vs. Non-Aqueous)

Non-Aqueous Formulation Case History 2 - Norway Offset 3			
Components	Green	Yellow	Red
Cleaner A, liter	4,147	1,408	0
Cleaner B, liter	1,900	0	0
Xanthan Gum, liter	250	0	0
Base Oil, liters	0	6,359	0
Total Volumes, bbl	**39.6**	**48.8**	**0**

Table 2 Non-Aqueous Spacer Formulation

Aqueous Spacer Formulation Case History 2 - Norway Offset 2			
Components	Green	Yellow	Red
Cleaner C, liter	185	5,414	0
Xanthan Gum, liter	250	0	0
Base Oil, liters	0	5,962	0
Total Volumes, bbl	**2.8**	**71.7**	**0**

Table 3 Non-Aqueous Spacer Formulation

Norway Clean Up Comparisons Case History 2			
Aq = Aqueous		N-Aq = Non-Aqueous	
Spacer	Offset #1	Offset #2	Offset #3
Aq / N-Aq	Aq	Aq	N-Aq
T.Cost, $K	68.3	43.3	50.4
Vol., bbl	620	390	345
9-5/8”, m	2,478	2,284	3,086
Cost/m, $	**27.21**	**18.67**	**16.21**

* Base oil consumption not taken into account.

Table 4 Aqueous vs Non-Aqueous Cost Comparison

Pill Compositions and Recovery Case History 2 - Norway Offset 2 versus 3			
Non-Aqueous (3)		Aqueous (2)	
Description	bbl	Description	bbl
Base Oil Neat, 100%	50	Base Oil Neat, 100%	75
BOSP (Base Oil + 10%A)	145	HVSP Brine + 9%C	200
HVSP Brine + 10%A + 6%B	200	Low Vis Soap Brine + 9%C	225
Waste Recovery			
Net Waste Generated	252	Net Waste Generated	463
Oil Returned to OBM	133	Oil Returned to OBM	37

Table 5 Pill Composition and Recovery Comparison

Aqueous Formulation Case History 2 - Norway Surface Clean Up			
Components	Green	Yellow	Red
Cleaner D, liter	754	0	256
Base Oil, liters	0	5564	0
Total Volumes, bbl	**4.8**	**35**	**1.6**

Table 6 Non-Aqueous “Surface” Clean Up

Non-Aqueous Formulation Case History 2 - Norway Surface Clean Up			
Components	Green	Yellow	Red
Cleaner A, liter	754	256	0
Cleaner B, liter	600	0	0
Xanthan Gum, liter	100	0	0
Base Oil, liters	0	5,564	0
Total Volumes, bbl	**9.1**	**36.7**	**0**

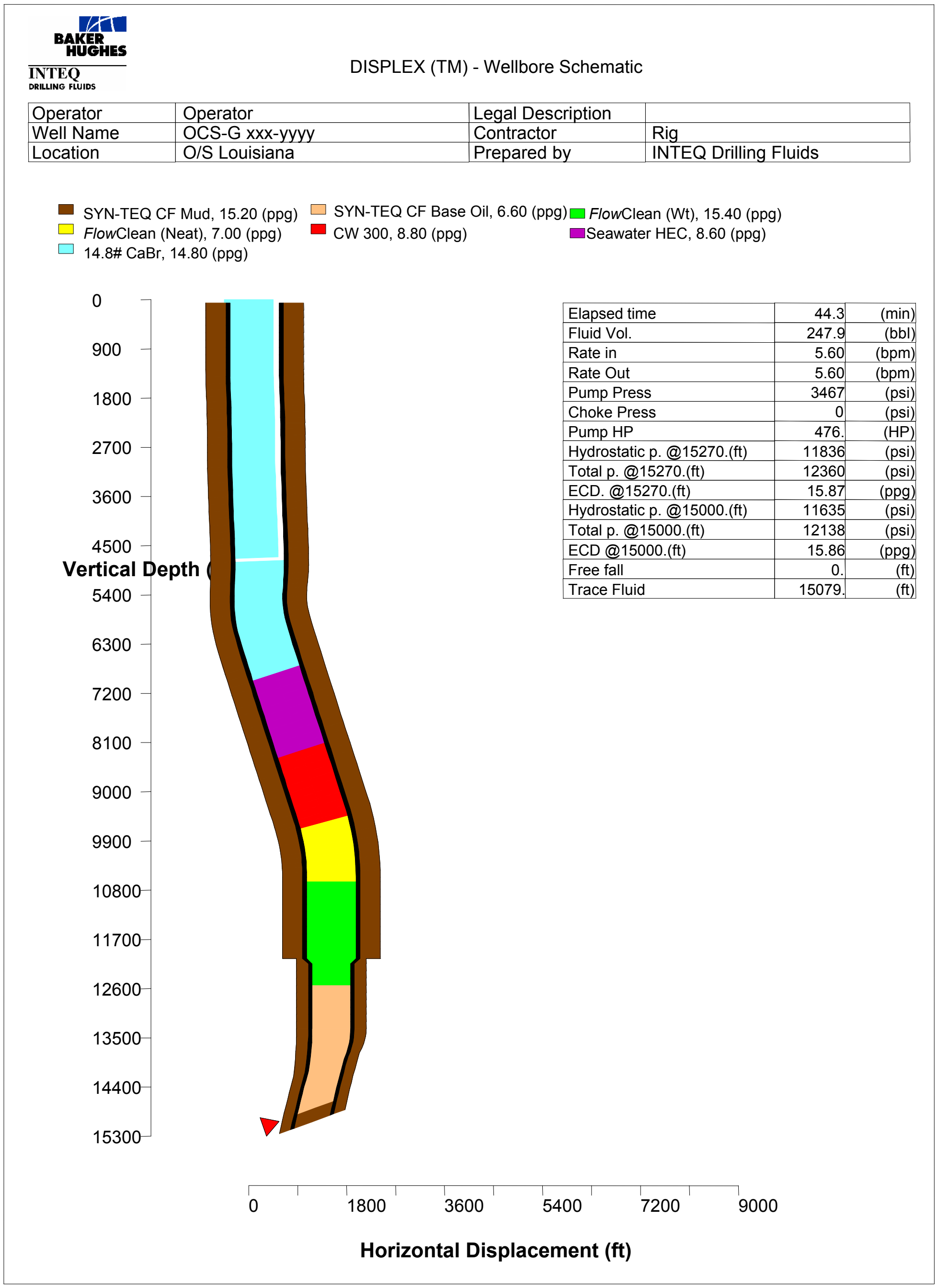
Table 7 Aqueous “Surface” Clean Up

Pill Compositions and Waste Volumes Case History 2 - Norway Surface Clean Up			
Non-Aqueous		Aqueous	
Description	bbl	Description	bbl
Base Oil Neat, 100%	35	Base Oil Neat, 100%	35
High Vis Soap Pill Brine + 10%A + 6%B	60	Surf. Cleaning Pill Brine + 4%D	150
Net Waste Generated	95	Net Waste Generated	185

Table 8 "Surface" Clean Up Waste Generation

Pill Compositions and Recovery Case History 3 South Louisiana Inland Water			
		Waste Generated	
Description	**bbl**	**Description**	**bbl**
Base Oil Neat, 100%	50	Base Oil –returned to fluid system	0
Viscosified Mud Pad	50	Viscosified Mud Pad-returned to active system	0
Pre-Mixed Cleanup System	75	Pre-Mixed Cleanup Spacer	75
Viscosified Brine	50	Viscosified Brine	25
Total Spacer Volume	225	Net Waste Generated	100

Table 9 Pill Composition and Recovery – Inland Water



Operator	Operator	Legal Description	
Well Name	OCS-G xxx-yyyy	Contractor	Rig
Location	O/S Louisiana	Prepared by	INTEQ Drilling Fluids

Elapsed time	44.3	(min)
Fluid Vol.	247.9	(bbl)
Rate in	5.60	(bpm)
Rate Out	5.60	(bpm)
Pump Press	3467	(psi)
Choke Press	0	(psi)
Pump HP	476.	(HP)
Hydrostatic p. @15270.(ft)	11836	(psi)
Total p. @15270.(ft)	12360	(psi)
ECD. @15270.(ft)	15.87	(ppg)
Hydrostatic p. @15000.(ft)	11635	(psi)
Total p. @15000.(ft)	12138	(psi)
ECD @15000.(ft)	15.86	(ppg)
Free fall	0.	(ft)
Trace Fluid	15079.	(ft)

Figure 1 Wellbore schematic showing spacer sequence and critical output parameters

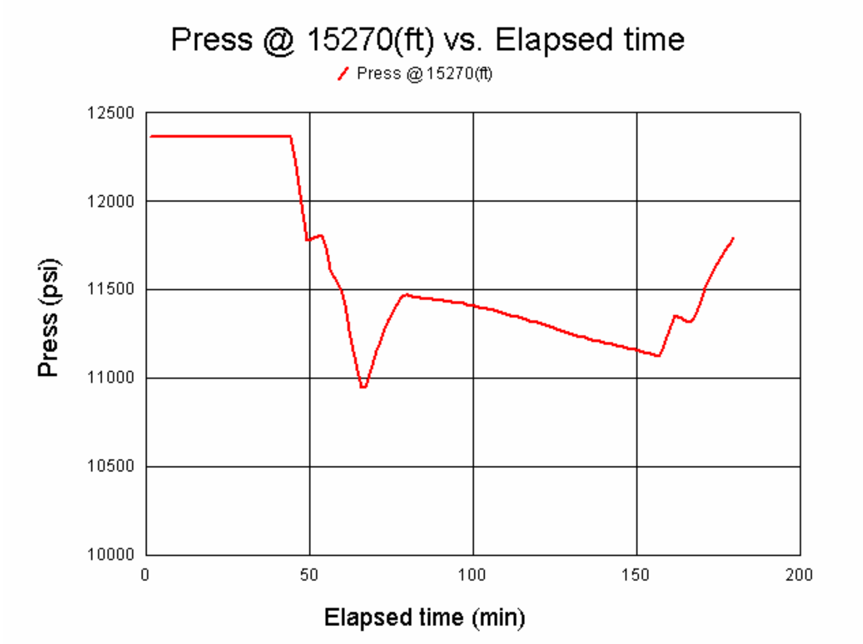


Figure 2 Pressure vs. Elapsed Time for Non-Aqueous Case History 1 - GoM

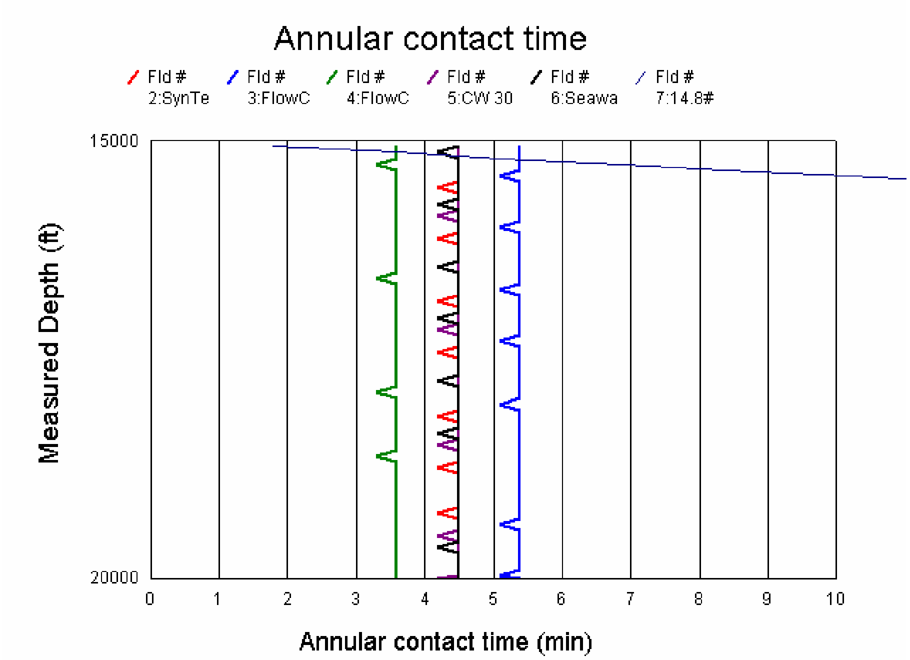


Figure 3 Annular Contact Time for Non-Aqueous Case History 1 - GoM