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Fundamental Understanding of Non-Aqueous Drilling Fluids Leads to Optimizing Seal Integrity while Reducing Design Time and Cost

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Abstract

Drilling with non-aqueous drilling fluid (NAF) maintains wellbore stability and reduces formation damage. However, NAF is detrimental to cementing operations and cement seal performance [1]. Fluid incompatibility can cause cement slurry to bypass drilling fluid in the annulus, leaving NAF fluid residue on casing that diminishes cement bond and seal effectiveness. Potential of incomplete NAF removal and reduced bond integrity significantly raise the risk of cement job failure, future operational problems, well control issues, and environmental damage.

Commercially-available cementing spacers and industry-accepted design protocols exist to mitigate the potential effects of these fluid incompatibilities[2], but the efficacy of current laboratory design methods is not thoroughly substantiated. Fundamental characterization of NAF-cement interactions on a molecular level is needed to deepen knowledge of related technical risks. Research Partnership to Secure Energy for America (RPSEA) targeted this objective and commissioned a two-year study of NAF-cement interactions related specifically to deepwater well cementing. The goal of this study is to develop technology resulting from this fundamental characterization into methods to assess and mitigate the technical risks of cementing wells drilled with NAF. Field-applicable design tests and best practices will improve cement seal placement and durability. Additionally, it is anticipated that modified design tests and criteria will reduce material cost and design time by directing design and operations focus onto attributes that most exactly affect performance and quantifying fluid compositions and volumes to optimize that performance.

Phase 1 of this two-phase study, presented here, involves fundamental analysis of NAF and cement interaction along with effects of spacers to mitigate incompatibility, aid in NAF removal, and affect wettability. The study combines traditional compatibility testing with rheological measurements of fluid mixtures to quantify flow behavior of NAF-spacer-cement systems. Wettability and surface film measurements include SSST, modified goniometer methods and a new quantitative fluorescence method to measure oil residue left on a steel surface. This knowledge is then translated into a laboratory evaluation method for quantifying NAF removal with bond strength of cement onto steel. This investigation includes various drilling fluids, spacer systems, and cements designed for representative deepwater well conditions. Complex well architecture and specific metallurgy of the tubulars are also considered. While developed specifically for deepwater wells, the method has application to any well drilled with NAF.

Introduction

The challenges of cementing in NAF are well known in the deepwater industry. NAF allows for stable drilling in high pressure high temperature (HPHT) and ultra-deepwater environments. However, NAF properties that were beneficial for drilling become detrimental to completions. Operators drilling deepwater wells in the Gulf of Mexico focus significant effort on designing fluid systems to mitigate detrimental NAF consequences, but design criteria do not all directly correlate to fluid performance. Spacer systems may be over designed for optimized application resulting in increased material and design cost.

Oil and water do not naturally mix. NAF interactions with cement or other aqueous-based completion fluid resulting from displacement, residue, fluid swapping, etc., can result in reduced compressive strength, channeling, downhole gelation and a poor cement bond [3]. This can in turn result in safety and environmental risks including job failure, future operational issues and loss of zonal isolation. Commercial products are available to assist with NAF displacement[4-5]. However, there is a need for fundamental characterization of NAF-cement interactions on a chemical level to improve the knowledge of related technical risks and the technology required for risk reduction and long-term well integrity.

The objectives of this project phase were to develop fundamental knowledge of NAF-cement interactions related specifically to deepwater cementing, to quantify risks associated with cementing in NAF, and to develop best practices and derive recommendations in order to reduce the recognized risks. This study analyzed the relationship between temperature, pressure, cement bond, degree of mud removal and its effect on zonal isolation in complex well architecture. A Project Advisory Group (PAG) composed of operator and service company engineers directly involved in all aspects of drilling and cementing deepwater wells directed the conduct of the investigation providing realistic conditions, design parameters, and current operational practices. Fluids under laboratory investigation included typical commercially available designs of cement slurries, NAF, and spacers with a focus on micro-particulate fluids and other new technologies. Planned benefits of the project include more meaningful and focused design method for cement and spacers used in deepwater wells drilled with NAF. Ultimately the improved design method is expected to require less engineering and testing time and to result in improved cement placement and bonding. Long-term wellbore integrity will be improved and environmental and safety issues, such as leaks from the formation and Sustained Casing Pressure (SCP), will be mitigated. The enhanced integrity of the cement will not only save operators from costly remedial work and additional rig time, but also increase productivity as well as reduce environmental and safety risks.

Deepwater Design Methods

Typically, the last three to four casing strings of a deepwater well drilled in the Gulf of Mexico are set in an NAF-drilled hole. Typical fluid and placement designs for cementing these strings, outlined below, have evolved over time to focus on wetted condition of the hole and casing surfaces, the density and rheological hierarchy of the NAF:spacer:cement fluid train, gelation or curdling of fluid mixtures, and placement rate limitation to prevent lost circulation. The fundamental drivers for this focus are thorough placement of cement into a well bore with surfaces prepared to adhere to the cement.

However, the testing, engineering, and design protocols for this cementing operation have drifted from performance-based methods. Wettability testing via goniometer, rod testing, tile testing, or SSST is not quantitative or directly relatable to bond quality. Rheology and fluid incompatibility evaluations are subjective with significant design effort devoted to rheological hierarchy. None of the design criteria or testing directly relates to cement performance as a well sealant.

Emphasis of the Study

Phase 1 study focused on development of more meaningful design criteria for spacers and cements for NAF application. It is anticipated that these criteria and associated test protocols will lessen design effort and result in broadened performance criteria for deepwater cementing operations which will in turn result in lowered cementing cost. This effort is concentrated on understanding fundamental Interactions between cement, NAF and spacers and identification of meaningful design criteria based on fundamentals and performance. The ultimate deliverable from a successful project would be a suite of performance-based wettability and compatibility design criteria and laboratory tests for cement and spacer used for deepwater wells drilled with NAF.

This volume of data and myriad of conclusions generated from Phase 1 are beyond the scope of this paper. A summary of major conclusions and observations supported by representative data sets and general evaluations is presented here. All data, procedures, and results will be published and publically accessible at completion of the project.

Study Materials and Conditions

Representative well conditions for testing were provided by the PAG and tabulated in Table 1.

A general cement composition with additives and properties representative of those usually applied in OCS applications was designed for fundamental compatibility testing. Three NAF drilling fluids were procured: two commercially available and routinely used in OCS operations and one designed from commercially-available materials in CSI's laboratory. A group of commercially available cement spacer fluids were also procured for testing. Several of these were obtained from commercial chemical suppliers and the rest were supplied by pumping service companies. Descriptions of all fluids tested in this investigation are tabulated in Table 2.

Evaluation Methods and Results

Wettability Fundamentals

The evaluation of successful displacement of drilling fluid from the casing and annulus, and properly conditioning those surfaces to bond with the cement slurry is paramount in primary cementing. For that purpose, the wettability of steel has been examined by various experimental techniques such as contact angle measurement, two phase separation, bubble pickup, micro-flotation, and vacuum flotation[6]. In this study, the wettability is investigated using a novel fluorescence technique to quantitatively evaluate the amount of residual drilling fluid on the surface of a steel tube following contact with the spacer.

To quantify the amount of drilling fluid left on the surface of the steel following exposure to the spacer, a hydrophobic fluorescence dye is mixed into the drilling fluid; after a pipe is exposed to the dyed drilling fluid followed by spacer, the residual drilling fluid in the pipe is flushed out with a solvent, and the fluorescence of that solution is measured by fluorescence spectroscopy.

The quantity of interest is the amount of oil that remains on the metal surface after displacement by the spacer. A fluorescent dye is chosen that is highly oil soluble, and highly water insoluble: Nile red. Nile red is also chosen because it is non-polar, and not likely to strongly interact with other additives in the oil-based drilling fluids. After the displacement experiment the dye is solubilized into tetrahydrofuran (THF), a water-miscible organic solvent. Tubes made of two types of steel, N80 and P110 which have 1.25 and 2 in diameter, respectively, were prepared.

Test procedures for sampling

Fig. 1 illustrates the test procedures used to obtain samples for fluorescence measurement. A carefully measured amount of hydrophobic fluorescence dye (e.g., 0.1 mg/mL) was mixed into the NAF and mixed together to make a complete blend. The dyed NAF was placed into the tube and stirred at 500

RPM (which corresponds to a shear rate of ~ 1500 s^{-1}) for 10 minutes. The NAF was then drained for 2 minutes. One of the spacer systems was placed into the tube and stirred at 500 RPM for 10 minutes to investigate its effectiveness at removing NAF.

After stirring, the spacer was drained for 2 minutes. Tetrahydrofuran(THF) was then added to the tube to dissolve residual oil from the tube surface. The sample was taken after shaking the tube by hand for 1 minute to complete dissolution of residual oil. The sample liquid was centrifuged to settle insoluble materials and the fluorescence of the liquid was measured to quantify the amount of NAF fluid removed from the tube. The thickness of the residual NAF was determined by performing a mass balance on the dye.

The relationships between fluorescence intensity and wavelength for experiments where NAF has been displaced using the three spacer systems are shown in Fig. 2. The control sample indicates that no spacer system was applied. Among three spacer systems, spacer D and E have very low fluorescence intensity, which means these two systems have good ability to remove drilling fluid from the tube. The spacer F system shows relatively small decrease of fluorescence intensity. Based on the results of dye concentration corresponding measured fluorescence intensity, the thickness of residual drilling fluid was calculated and shown in Table 3.

After flushing with spacer D or E, the thickness of the residual drilling oil film layer is reduced 30 fold. In case of spacer F, the reduction is only one third,. It shows that spacer D and E are excellent in their ability to remove the drilling fluid. Thus, the proposed fluorescence method can be used to quantify the efficiency of removing oil-based fluids from the metal surface.

Surfactant concentration

To evaluate the effect of concentrations of surfactant on wetting, three different concentrations of surfactant, 0.25, 0.50, 1.00 gal/bbl, added to spacer C were investigated. In addition, a commercial microemulsion system was tested to determine drilling fluid removal efficiency.

The relationships between fluorescence intensity and wavelength for those cases are shown in Fig. 3. The fluorescence decreases with increasing surfactant concentration, although the changes are not substantial. The microemulsion sample was marginally more effective than any of the surfactant formulations. The calculated thickness of residual drilling fluid is shown in Table 4. None of these systems is as effective as spacer D or E.

Metallurgy

Various specialty grades of steel are used in wellbore construction. The effect of material composition on the evaluation of wettability was investigated by using two representative steel types, N80 and P110. The spacer D was used to displace NAF. The calculated oil film thicknesses, Table 5, show that the drilling fluid thicknesses are quite similar for both control and spacer D cases, regardless of metallurgy.

Surface condition on wettability

Surface condition influences contact angles and wettability[7-11]. During the wellbore construction, the casing tube is weathered and may be significantly corroded. Thus, in this study, the effect of surface corrosion on wettability was investigated. The initially clean tubes were corroded by subjecting to atmospheric conditions until rust appeared. The clean tube was treated by sand blasting to prepare the control tube. The film thickness of the control sample, i.e. without spacer contact, is 20% thicker on the corroded surface, relative to the clean surface. With all three spacer formulations, the oil residue on the corroded surface is greater than on the clean surface Table 6. However, the increase in layer thickness is small in all cases.

For further investigation, the surface roughness of tubes was measured by profilometer to determine the relationship between the surface roughness and wettability. The 3D images of the clean and corroded surfaces are shown Fig. 4.

The surface contour of the corroded tube is rougher than that of the clean surface; so the marginally thicker oil film after exposure to the spacer fluids is possibly associated with local roughness on the surface.

SSST

The Spacer Surfactant Screening Test known as the SSST test is performed to determine the ability of the spacer and surfactants to convert the mixture to a water-external phase that is critical for water wetting[12]. Test apparatus and procedures are described in API Recommended Practice 10B-2[13]. This procedure does not address bulk displacement issues or quantify the degree of “water-wetting” by the spacer. Rather it identifies the required concentration of spacer added to NAF to render the mixture at least as conductive as 100% spacer. This point is indicative of a water-external 2-phase mixture that should render solid surfaces water-wet. Figure 5 below is an example of a spacer successfully achieving a water-external phase with the addition of 32% Spacer. A summary of results for all SSST tests appears in Table 7.

The test results in Table 7 indicate differences in performance of various spacers. However, interpretation of these results relating to cementing performance is unclear. No correlation of this wettability measurement to actual cement performance, such as bond strength, exists. This lack of performance correlation raises the question of the exact level of conductivity increase required to produce an adequate bond. Surfactant concentration to produce this result may actually be in excess of that required to optimize bonding.

Goniometer

The goniometer measures the water contact angle on coupon surfaces. By comparing the contact angle change before and after washing, the mud removal performances of surfactants or spacers can be evaluated. The model used in this procedure complies with ASTM D 724 and ASTM D 5946. Figure 6 shows the water droplets used by the goniometer.

This method was investigated as a result of industry interest from a Work Group under API SC10 in which the WG on Evaluation of NAF Removal & Water Wetting by Spacers is to evaluate and develop methods of determining the ability of spacer systems to remove a film of nonaqueous fluid from a surface and leave the surface water-wet. As a result of working with this API Work Group, inclusion of the goniometer method for this RPSEA project was a natural extension.

At the time of introducing the goniometer testing based on API results, use of metal coupons was being called into question, based on its inability to achieve a repeatable baseline contact angle. Testing for this study began with the use of glass coupons until a suitable metal coupon could be found. Early results of testing showed a high variance of contact angles on the glass coupons as well

Solids-laden NAF and spacers produced measurement errors of a very low contact angle caused by solids left on the coupons after treatment with the spacer. To remedy this situation, goniometer testing moved forward with testing of fluids without solids. Solids-free NAF was simulated by base oil, water, and emulsifiers. Solids-free spacers were formulated from water mixed with appropriate concentrations of surfactant. Solids-free cement fluids were obtained by filtering of mixed cements. Descriptions of the test methods used for the testing at Atmospheric and Stirred can be found in API SC10/WG01: Wettability.

Table 8 results illustrate that quantifiable surface wettability differences can be detected with the goniometer using the solids-free test method. Several of the spacers achieved water wetting with as low as 0.25gal/bbl surfactant added (Spacers E/F and I with Mud C) while others required higher doses. These linear quantitative results were encouraging, but still lack correlation to performance.

Shear Bond

A suite of tests described below was performed to assess the effects of controlled fluid washing of steel coupons on resulting bond strength of cement. With companion goniometer testing of wettability using solids-free fluid analogs to wash coupons, this testing method allowed direct comparison to wettability measurements by goniometer since the test substrates are identical.

This testing is designed to measure the shear bond strength of the metal coupon in set cement. After washing with NAF, spacer, and cement slurry, coupons are placed in cement slurry and cured. The bonding between the cement and coupon indicates the NAF removal performances of the spacers. Preparing the coupons starts with rotating the coupons mounted as shown in Figure 7 in a series of fluids starting with NAF, followed by spacer, and then cement slurry. Rotation speed can be controlled to mimic field shear rates. Conditioning/washing temperature can be controlled also. For HTHP applications, an API proposed washing method using a stirred fluid loss apparatus has been outlined and was used for this study. General test method consists of immersing coupons in each fluid and rotating coupon holder in the fluid for 10 minutes. After washing with cement slurry, the coupons are mounted in the shear bond fixture (Figure 8) which is filled with fresh cement slurry and cured. Shear bond is measured after curing.

To gather analogous wettability performance data, coupon wash testing was repeated with solids-free fluids. Table 9 presents representative results at room temperature and 255^{o}F. These data illustrate a strong general trend of wettability vs shear bond, However, outliers such as the results of Spacer I which yielded water-wet surface but low shear bond, indicate significantly more data are required to substantiate a correlation.

Rheology and Compatibility

Current deepwater well operators invest significant design effort into minimizing fluid incompatibility as measured by API Recommended Procedure 10B-2. All NAF:Spacer:Cement combinations were evaluated by this procedure. While too massive to present here, in summary, the fluid mixtures represented a wide range of compatibility. NAF:cement mixtures were all severely incompatible. Several of the spacers, notably Spacer B and Spacer C were not compatible with NAF while Spacers C and I exhibited incompatibility with the cement slurry. Additionally, several spacer formulations were more viscous than the cement while other spacers were less viscous than NAF, thus failing to follow the design criterion known as rheological hierarchy. This concept dictates that no fluid in the cement placement train can be more viscous than one following it. The rationale for this is that thicker fluids can more easily displace thinner ones. Therefore, while these fluids are all commercially available and recommended for use with NAF, they are not optimized according to current design criteria.

Placement Simulation

As with wettability, current deepwater operations invest significant effort into ensuring fluid compatibility and rheological hierarchy. Maximizing cement placement rate and displacement efficiency are desired outcomes. However, no quantitative relationship between compatibility, rheological hierarchy, and cement seal effectiveness was found. So, the next portion of the study focused on the effects that could be expected from non-optimized fluid train compatibility and rheology. A commercially-available numerical placement simulator was used for this evaluation. Simulation conditions corresponded to the Well 1 production liner listed in Table 1. Other inputs were rheological data for fluids and mixtures.

First, simulations of cementing with an idealized-rheology fluid train were run varying the displacement rate from the baseline 10 bpm. (At baseline displacement rate of 10 bpm 1000 ft of fill creates a contact time of over 10 minutes; so the spacer volume conforms to industry best practices guidelines.) Displacement efficiency at the end of treatment for each of these simulations is plotted in Figure 9. Note that displacement efficiency varies from 100% at the shoe for all cases to around 70% at the liner top with displacement efficiency increasing with increasing displacement rate. This outcome represents best-case displacement if ideal rheological hierarchy were achieved.

Figure 10 presents simulations of displacement simulation at 10 BPM for every NAF:Spacer combination for spacers A through E/F with cement. Note that predicted displacement efficiency falls into a narrow band for all fluids. No major reduction is observed for fluids falling outside the desired rheological hierarchy.

The simulator used for this study can accept a fluid train of up to 24 different fluids with varying rheology. This accommodation was used to assess placement efficiency changes from incompatible fluid mixtures. To evaluate effects of rheology and placement efficiency, a fluid train that exhibited both incompatibility and unacceptable hierarchy was chosen: Mud A:SpacerC:cement. The spacer was slightly incompatible with the NAF at low NAF concentrations and was incompatible with cement across the board. Simulation was performed using only single-fluid rheology. Then three more simulations were performed inserting actual rheology of each fluid mixture as a separate fluid in the train. To assess intermixed length's effect on placement efficiency, contaminated intervals of 50, 100, and 150 feet of annular fill for each mixture ratio were simulated. Results, presented in Figure 11, predicted virtually no effect on placement efficiency resulting from the contamination.

Friction pressure examination of how the higher-viscosity mixtures affected down-hole pressure indicated little pressure change produced by accounting for rheological effects of intermixing. Mixture rheology produced the highest simulated pressure increase for spacer C fluid trains. However, predicted ECD at TD was less than 0.1 lb/gal over that of the base case with ideal rheology hierarchy. Table 10 presents simulated pressures at TD of 26,000 feet for selected fluid trains at the point displacement rate is reduced prior to landing top plug.

Summary of Findings

Results from the wettability study produced notable information and relationships applicable to field operations. The analytical method using fluorescence to quantify residual oil film remaining on a metal surface provides a quantitative laboratory method of spacer's oil removal effectiveness. Relating the performance to bond development will confirm the method's utility. However, preliminary results are encouraging and actually indicate that a surface's wetted condition can be quantified. Preliminary results with varying metallurgy and roughness provide guidance for further refinement of wettability testing interpretation. Metallurgy appears to be of little consequence while roughness and surface condition may play a major role in bonding and cement seal. Expansion of this topic will produce more field-applicable results.

Goniometer testing results have demonstrated significantly improved understanding of the instrument as a tool to assess surface condition. With a long history of testing this method, the industry has been more or less at a standstill about how to perform testing or evaluate results. Results from this investigation, when shared with API Committee 10 Wettability Workgroup, served as a basis for the group's redirection and a new round of testing.

This investigation focuses on mechanical bond as the performance metric for spacer effectiveness. Initial work has uncovered interesting results concerning surface condition, shear rate and fluid composition. While it is too early to draw conclusions, the approach will prove meaningful in field application, and sufficient trends are observed to warrant further investigation of bond testing for relationships that can be quantified for field application.

Numerical modeling of intermixing effects on displacement efficiency and placement pressure indicates that incompatibility caused by intermixing may not be a significant detriment to cementing performance. This result is significant because it indicates that a lessened constraint of rheological hierarchy might be allowable for OCS cementing fluid train design. Additionally, degree of incompatibility as measured by mixture rheology may not be as detrimental as currently assumed. These indications are based on the assumption that the placement simulator provides accurate results, and this assumption will be evaluated in Phase 2.

Major design criteria for spacer application are all under investigation in this study. Initial results indicate that compatibility may be of lower importance than currently assumed for both displacement efficiency and placement pressure. Wall cleaning, effects of solids on bonding, flow rate, and flow regime all require additional study in addition to evaluation of newest spacer technology.

This investigation has called attention to the current well cementing design practices for wells drilled with NAF. All these were discussed above, and underlying fundamental technology required for improved understanding and performance are summarized here.

- Impact of incompatibility (gelation) on cement displacement efficiency.
- Required shear or hydraulic bond to provide competent annular seal
- Effect of metallurgy and surface roughness on bonding and seal effectiveness
- Quantitative relationship between surface wettability and bond
- Laboratory methods to meaningfully assess compatibility and surface cleaning/preparation.

Path Forward

Table 11 outlines comparison of current design attributes with potential improvements based on the results of this study thus far. A more in-depth description of each design attribute and discussion is presented below. Topics are presented in order of rank assigned by the PAG.

Currently, the only wettability testing sanctioned by API is the SSST which gives an indication of what volume ratio of spacer to mud is required to flip an OBM/SBM to a water-external phase. Other tests used by the industry include the tile test, the rotor test, the grid test, and the casing coupon or goniometer test. While several of these tests are widely used, evaluation of them is highly qualitative with little or no maximum or minimum thresholds in place. Goniometer testing in this study demonstrated the viability of goniometer testing as a means for wettability evaluation as well as demonstrating the relation between shear bond and surfactant loading. Correlating the contact angle to shear bond may be possible. Further Phase 2 testing will explore correlation of voltage readings from the SSST to effective water-wetting through goniometer testing and also to shear bond. Additional testing will investigate whether increased surfactant loading provides sustained or diminishing returns on effectiveness. Analysis from the testing performed in Phase 2 may influence the industry in choosing future tests to qualify a spacer for use. Additionally, future design criteria may include a maximum contact angle by goniometer testing to indicate a water-wet casing which will not adversely affect shear bond, quantitative analysis of the SSST, and maximum effective loading levels for surfactants.

Current design constraints on rheology require that each fluid be more viscous than the fluid it displaces and that the rheology of a mixture of the two adjacent fluids at various ratios should not exceed the rheology of the thicker of the baseline fluids. The theory of the rheological hierarchy is that by using a thicker fluid to displace a thinner fluid, the fluid intermixing at the interface is minimized. The compatibility testing helps to ensure that dramatic viscosification or instability will not occur at the fluid interface. Simulation of displacements that meet and do not meet these requirements showed minimal differences. In some cases, adjacent fluids that created highly viscosified mixtures increased the overall displacement efficiency of the job. Additionally, these cases did not exhibit substantial increases in ECD. Through additional modeling in Phase 2, a better understanding of the effects of rheology and compatibility on hole cleaning, displacement efficiency, and ECD can be gained. Some initial simulations indicate incompatible fluids—so long as they do not become unpumpable—may promote better displacement efficiency with minimal ECD consequence. Design criteria that effectively employ this strategy of mud removal may improve the overall quality of the cement bond, especially at or near the leading edge of cement. Future design criteria may also be able to more accurately predict the effects of fluid interface intermixing.

Conclusions

Phase 1 produced better understanding of important NAF-spacer-cement interactions and methods to evaluate them in the laboratory. Specific knowledge includes:

- Current lab tests of wettability are imprecise, subject to procedural errors, and difficult to relate to cement performance.
- SSST detects spacer volume to “flip” emulsion of OBM but does not reveal information about wettability or preparation of well surfaces for cement bonding.
- Goniometer method shows promise to provide quantitative assessment of spacer wash on surface wettability.
- Fluorescence tests provide a quantitative method for determination of NAF removal.
- Current lab tests of spacer effectiveness in NAF do not address the fluids’ effect on bond to well surfaces. Any lab evaluation method should be based on cement seal effectiveness.
- Effects of gelation of intermixed fluids on cement displacement efficiency and placement pressure do not appear to be as critical as currently believed. Better understanding of displacement efficiency and levels of intermixing is required to assess this completely.
- Performance and mechanical properties of intermixed cement-spacer fluids are not sufficiently examined in current design procedures.
- Based on Phase 1 results, the PAG charted direction for Phase 2. The target tasks, listed below, are currently underway.
    - Confirm laboratory design method for wettability based on performance through extended laboratory testing and FEA.
    - Correlate performance-based design method to goniometer and SSST results
    - Study fundamental relationship between surface wetted condition, cement adhesion, and bond toughness.
    - Assess intermixing during placement via analysis of field-collected samples and correlate to numerical placement model
    - Demonstrate field applicability of newly-developed design methods and performance standards through “shadow testing” of actual field materials form a deepwater well. Compare test results to actual job design and execution.

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Nomenclature

API = *American Petroleum Institute*
ASTM =*American Society of the International Association for Testing and Materials*
BPM = *barrels per minute*
°F = *degrees Fahrenheit*
ft = *feet*
gal/bbl = *gallons per barrel*
in = *inches*
μm = *micrometer*
mg/mL = *milligrams per milliliter*
nm = *nanometer*
OCS = *Outer Continental Shelf*

% = *percent*
lb/gal = *pounds per gallon*
ppg = *pounds per gallon*
psi = *pounds per square inch*
s^{-1} = *reciprocal second*
RPM = *revolutions per minute*

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Table 1: Well Properties

Well	Well 1			Well 2	
String	Upper String 1	Upper String 2	Production String	Upper String	Lower String
Casing Size	18 inch	16 inch	7 5/8 inch	16 inch	11 7/8 inch
Depth	16,000 feet	22,000 feet	30,000 feet	14,000 feet	24,000 feet
Pore/Frac	10.5 ppg / 15.0 ppg	13 ppg / 15.5 ppg	12 ppg / 13.5 ppg	11.2 ppg / 15.3 ppg	13.2 ppg / 15.8 ppg
Temperature	136°F	195°F	315°F	150°F	214°F

Table 2: Fluid Descriptions

Fluid	Description	Density
Cement	Class H	16.4 lb/gal
Mud A	Field Sample	12.7 lb/gal
Mud B	Field Sample	9.5 lb/gal
Mud C	In house formulation	11.9 lb/gal
Spacer A	Spacer no surfactant	16.0 lb/gal
Spacer B	Spacer w/ surfactant	14.5 lb/gal
Spacer C	Spacer w/ surfactant	14.5 lb/gal
Spacer D	In house formulation	14.5 lb/gal
Spacer E	Solvent Lead	14.5 lb/gal
Spacer F	Spacer Tail	14.5 lb/gal
Spacer G	Microemulsion	14.5 lb/gal
Spacer H	Microemulsion	14.5 lb/gal
Spacer I	In house formulation	14.5 lb/gal
Spacer J	Microparticulate	14.5 lb/gal

Table 3: Thickness of residual drilling fluid according to spacer systems

	Control	Spacer D	Spacer E	Spacer F
Thickness (μm)	30.0	0.9	0.6	11.4

Table 4: Thickness of residual drilling fluid according to spacer systems

Control		Spacer C			Spacer G
		0.25 gal/bbl surfactant	0.50 gal/bbl surfactant	1.00 gal/bbl surfactant	
Thickness (µm)	37.9	8.2	7.4	6.2	4.8

Table 5: Thickness of residual drilling fluid according to metallurgy

	N80		P110	
	Control	Spacer D	Control	Spacer D
Thickness (µm)	39	1.5	40	1.6

Table 6: Thickness of residual drilling fluid according to surface condition

	Control	Spacer D	Spacer E	Spacer F
Rusty (µm)	36.0	1.6	0.8	12.6
Clean(µm)	30.0	0.9	0.6	11.4

Table 7: SSST Results for NAF-Spacer Pairs with Mud A

Spacer	% Spacer for 100% Conductivity
Spacer B	75%
Spacer D	58%
Spacer F	32%

Table 8: Contact angle change after spacer contact

NAF-Spacer combination	Contact Angle (degrees) @ Surfactant concentration (vol gal/bbl)			
	0.25	0.50	1.0	2.0
Mud B-Spacer C	58	58	78	72
Mud B-Spacer D	42	55	58	60
Mud B-Spacer F	30	4	6	8
Mud B-Spacer G	76	79	62	6
Mud B-Spacer H	78	74	63	75
Mud B-Spacer I	46	37	1	3
Mud B-Spacer J	-	-	-	9
Mud C-Spacer C	36	44	6	4
Mud C-Spacer D	52	32	19	9

Mud C-Spacer F	12	8	4	12
Mud C-Spacer G	24	4	3	1
Mud C-Spacer H	68	62	49	4
Mud C-Spacer I	9	9	6	3
Mud C-Spacer J	-	-	-	11

Table 9: Shear bond vs contact angle (Mud B) at 80^{o}F and 255^{o}F. All Spacers contained 2.0 gal/bbl surfactant

Temp	Spacer	Angle after Spacer	Angle after Cmt	Shear Bond (psi)
80^{o}F	None	-	-	15
	C			30
	I	3	-	40
	G	10	-	75
	E/F	8	-	75
	Cement Only	-	-	85
255^{o}F	None	-	55	60
	I	15	4	155
	B	48	58	160
	G	21	16	350
	E/F	12	9	270
	Cement Only	-	45	

Table 10: Predictions of ECD and annular friction pressure for various compatible and incompatible fluid trains

Fluid Train	Friction Pressure (psi)	ECD at TD (lb/gal)
Ideal rheological hierarchy, no mixing	729	13.85
Mud A:Spacer C:cement, no mixing	744	13.86
Mud A:Spacer C:cement, 150 ft mixing interval	767	13.90
Mud A:cement, 150 ft mixing interval	477	13.59

Table 11: Proposed design attribute for investigation

Design Attribute	Current Limits or Practices	Potential Design Criteria
Placement Rate	• Placement rate is generally as high as reasonably possible while ensuring: o Friction pressure hierarchy is met. o ECDs do not compromise well integrity.	• Optimized placement rates based on: o Displacement efficiency. o Shear bond.
Seal Effectiveness	• No testing is currently in place to evaluate the impact of OBM/SBM on long-term seal effectiveness. • All testing done to simulate the thermal and pressure stresses for the life of the well are conducted assuming no contamination.	• Fundamental understanding of how contamination affects long-term seal effectiveness. • Thresholds for contamination to prevent long-term annular pressure build-up through cement sheath failure.
Mechanical Properties	• No testing beyond crush compressive strength is performed with contamination.	• Fundamental understanding of how contamination affects mechanical properties. • Thresholds for contamination levels across zones of interest.
Rheology and Compatibility	• Displacing fluids should be more viscous than the displaced fluid. • Mixtures of adjacent fluids should be no more viscous than the base fluids themselves.	• Improve fundamental understanding of the magnitude of the effects of rheological hierarchy. • Improve ability to predict effects of fluid interface intermixing.
Wettability	• Current testing includes: o SSST. o Tile Test. o Grid or Rotor Test. o Goniometer Test. • All evaluation is qualitative.	• Quantitative evaluation of testing such as: o Correlation between SSST, goniometer, and shear bond. o Minimum contact angle for effective bond.
Placement Simulation and Displacement Efficiency	• Model placement and displacement efficiencies. • Displacement efficiency models are often conservative in nature.	• Feedback from comparison of current simulators to each other, lab-scale testing, and real well applications can improve the displacement efficiency models.

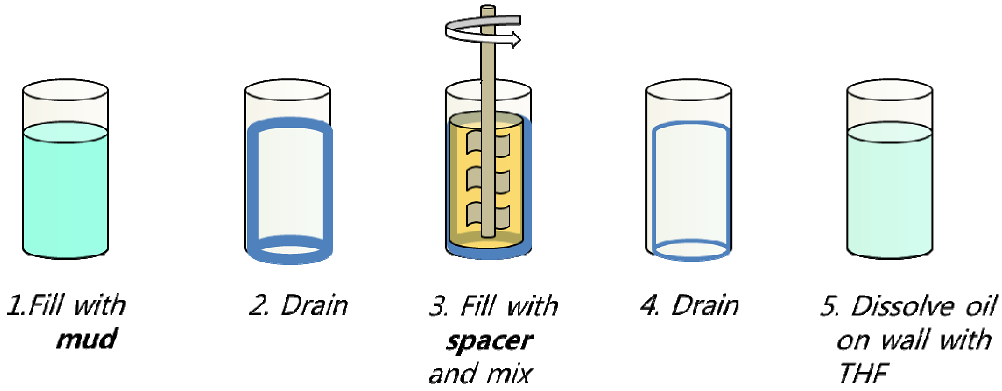


Figure 1: Test procedures for sampling

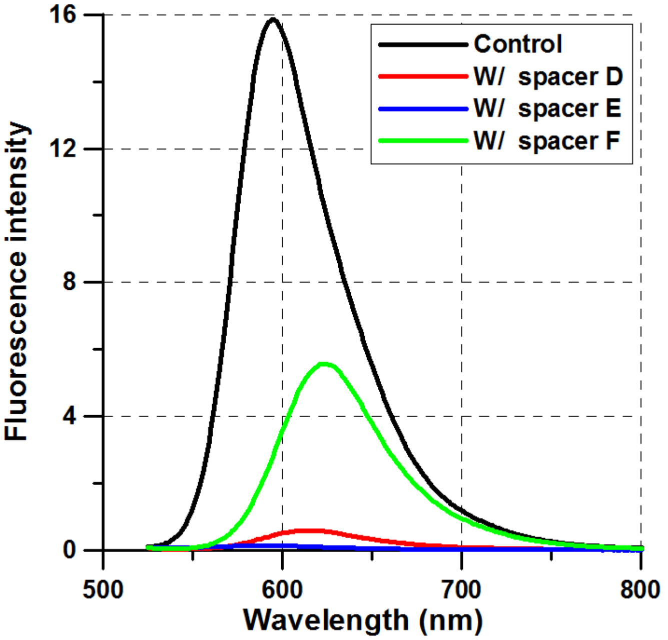


Figure 2: Fluorescence intensity according to spacer systems

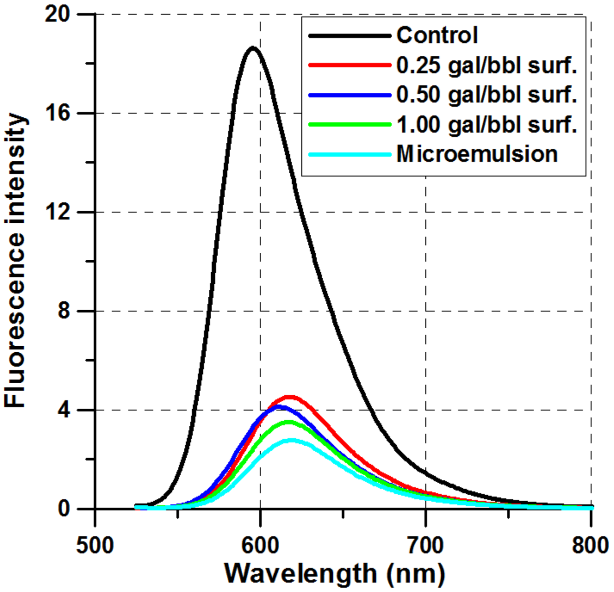
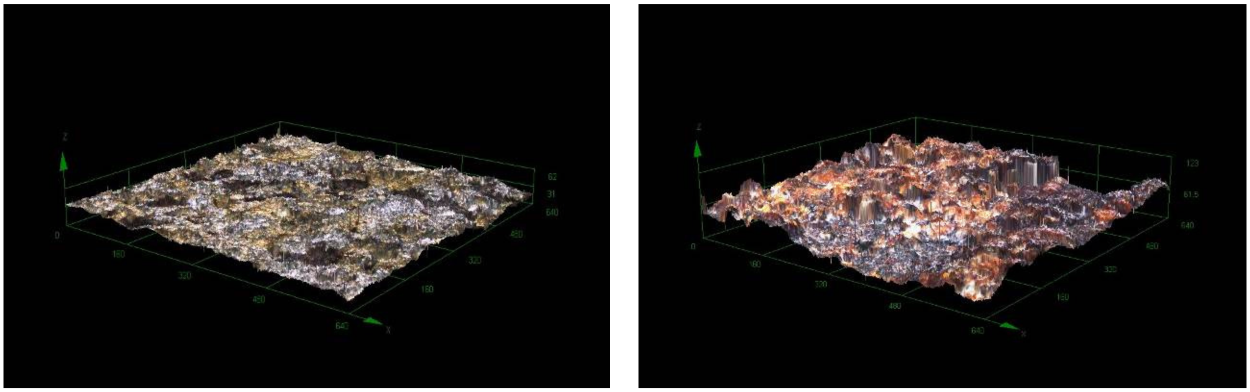
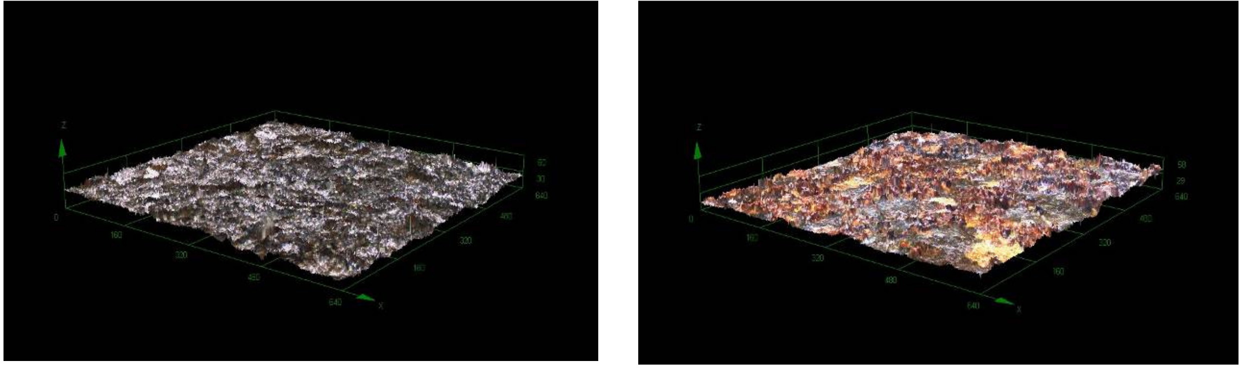


Figure 3: Fluorescence intensity according to spacer systems



(a) N80-Clean (b) N80-Rusty



(a) P110-Clean (d) P110-Rusty

Figure 4: 3D image of surface roughness

For the SSST test with Mud A and Spacer F the mixture successfully flipped at 32% addition of Spacer.

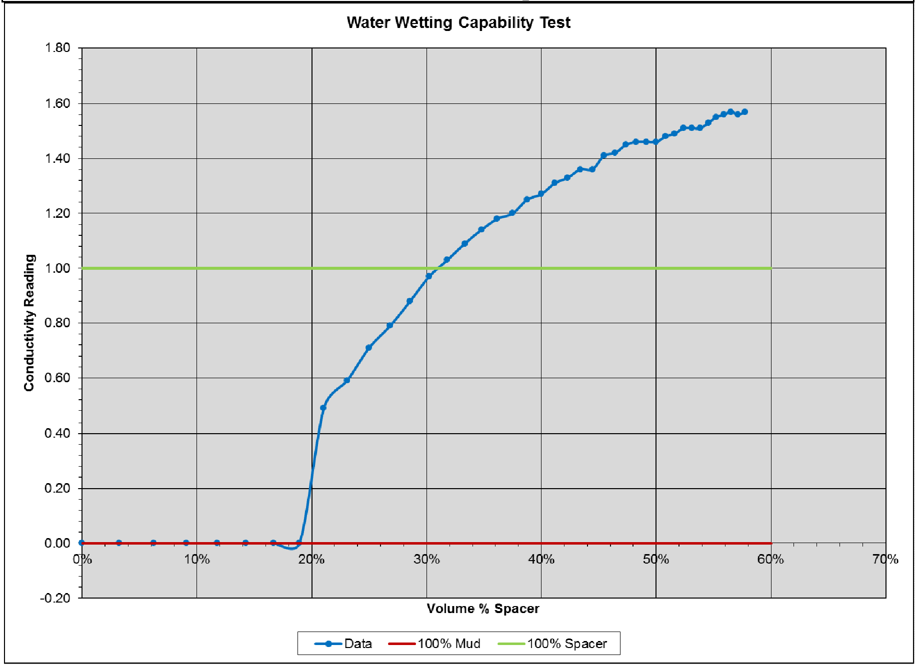


Figure 5: Representative SSST chart

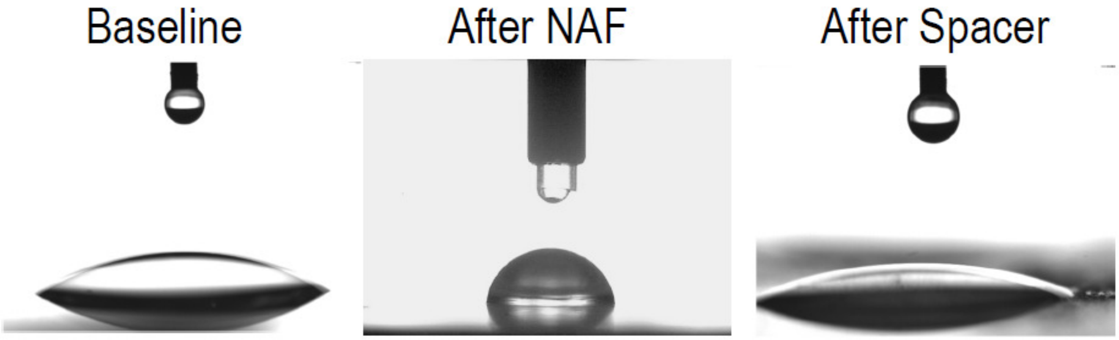


Figure 6: Water Droplets from the Goniometer

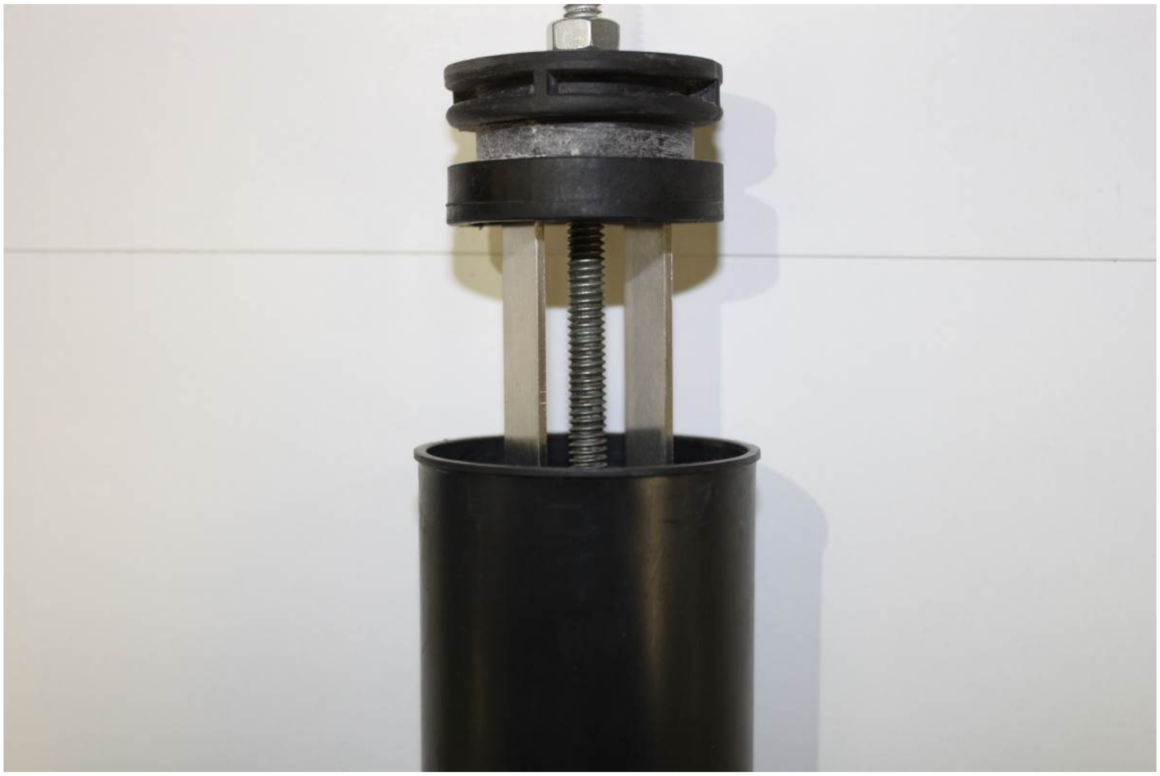


Figure 7: Coupons in atmospheric holder

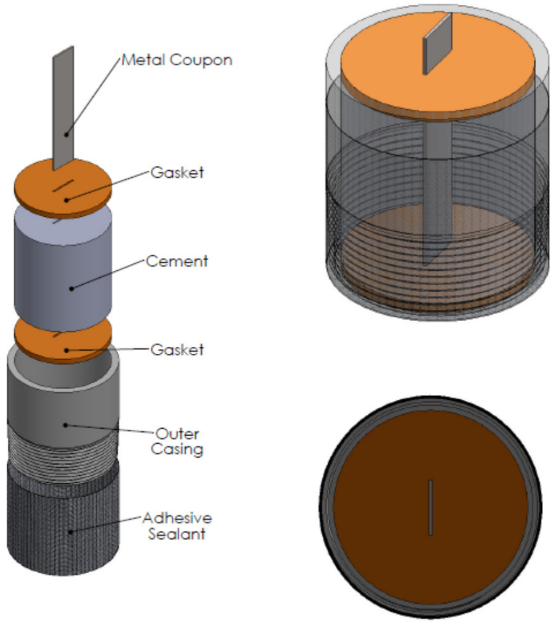


Figure 8: Shear Bond setup top view

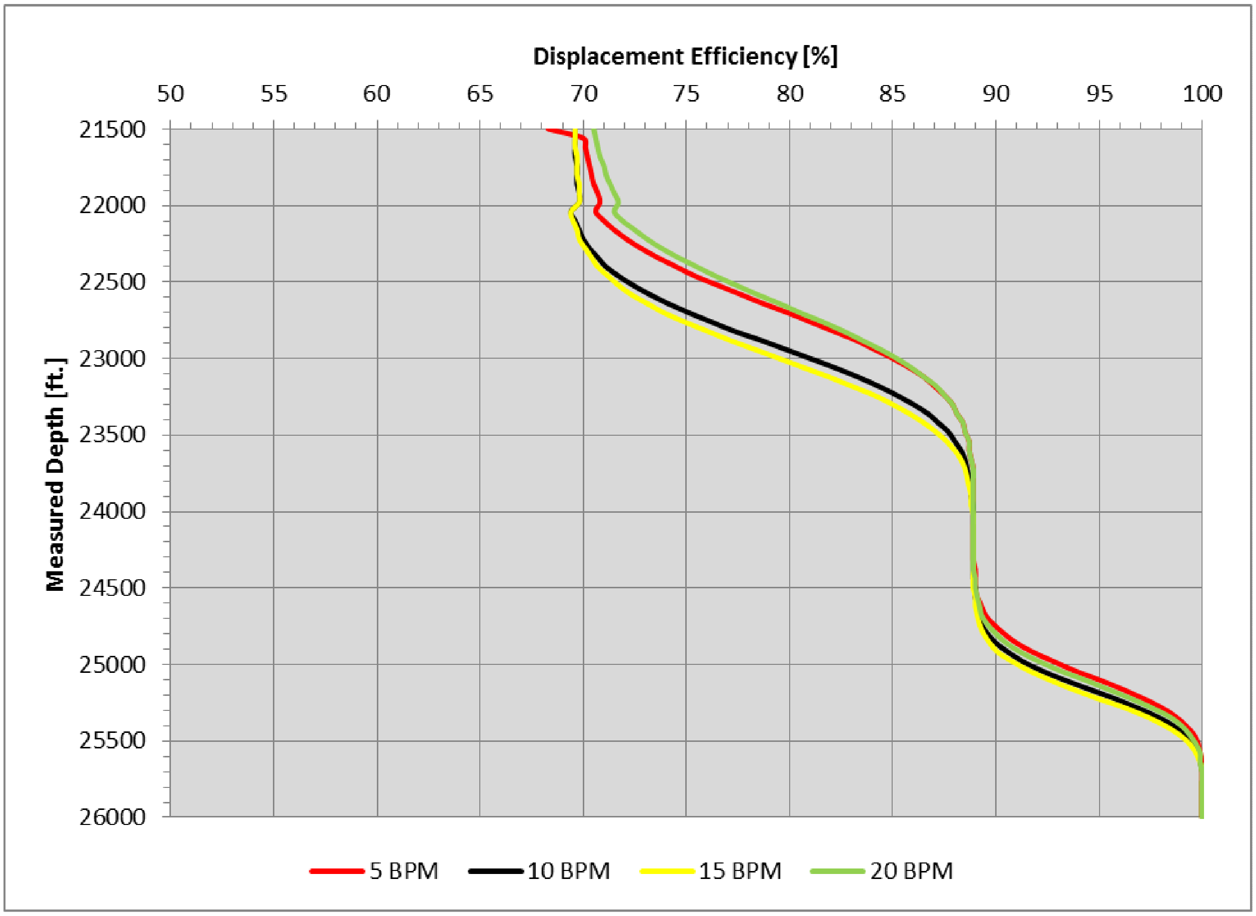


Figure 9: Rate vs. Displacement Efficiency for Ideal-Rheology Fluid Train

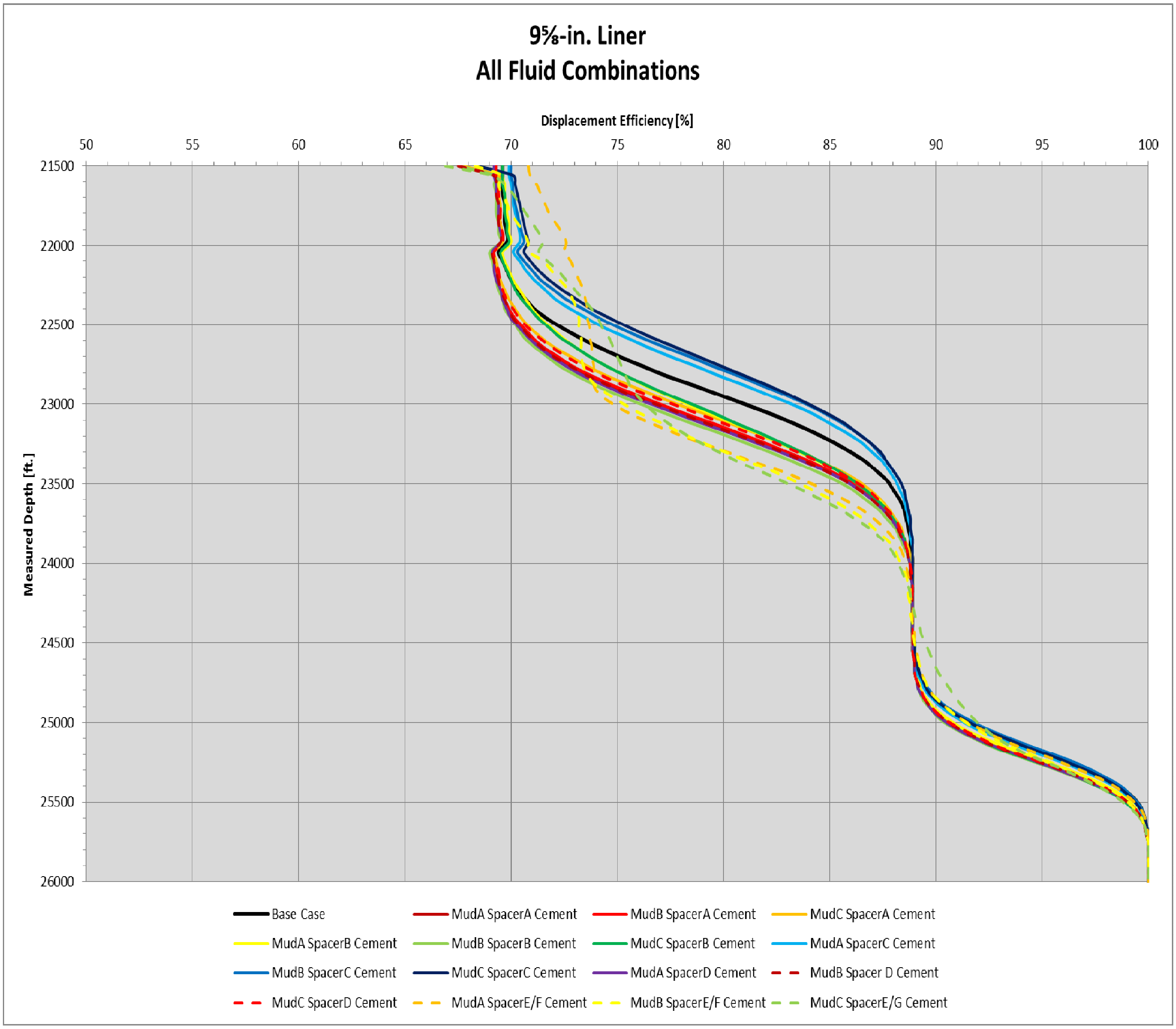


Figure 10: Base Case Displacement Efficiency for Spacers A through E+F with all Drilling Fluids

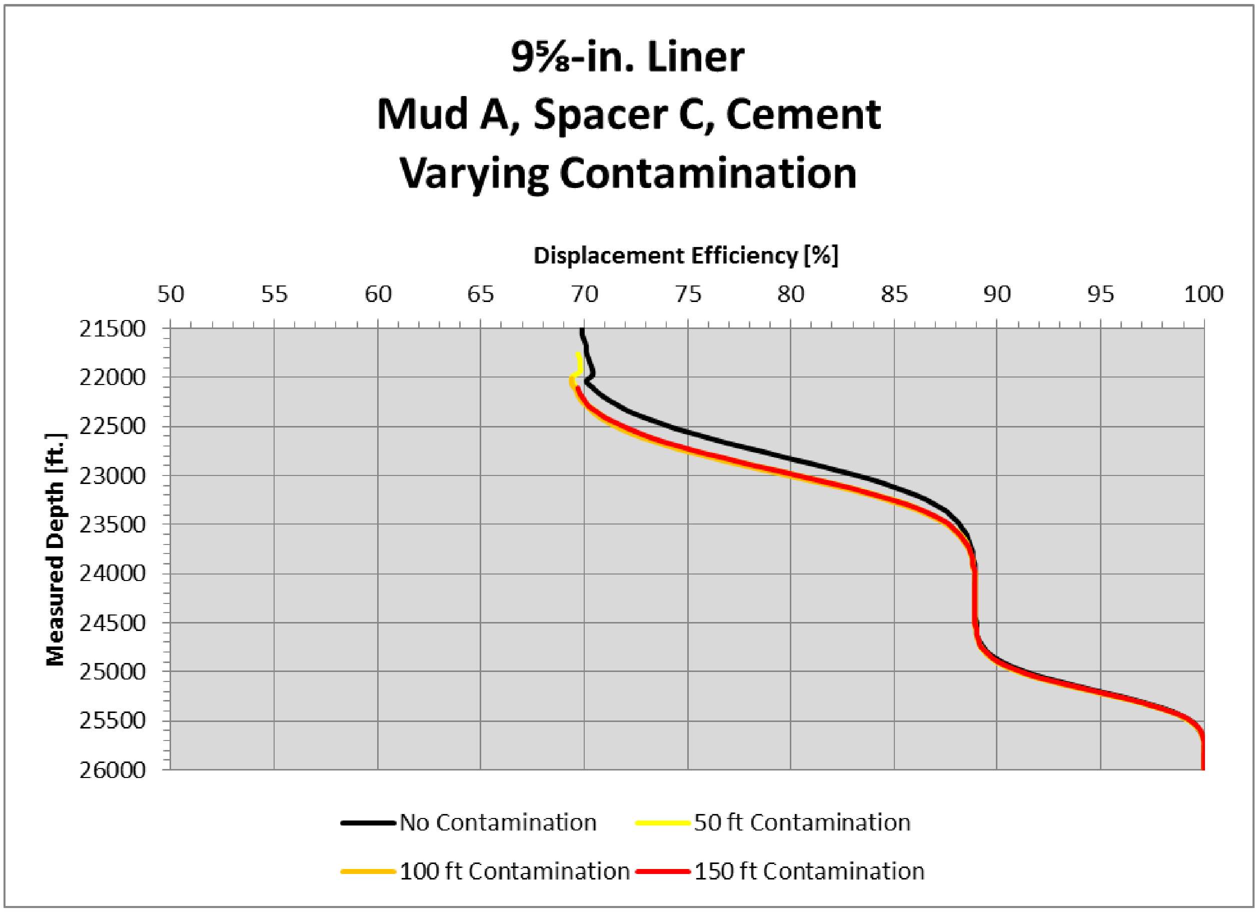


Figure 11: Varying contaminated intermixing lengths vs displacement efficiency for viscous spacer