

2nd Generation Low ECD Fluids for Narrow-Margin Deep- water Drilling: Meeting Future Challenges

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Abstract

Fluid-specific challenges for the design of Deepwater Non-Aqueous Fluids (NAFs) can be characterized as extreme with respect to:

- Temperature and pressure and their effect on rheology, which impacts frictional pressure loss.
- Temperatures can vary from 40° F to 300 +°F, with pressures from atmospheric to 20,000+ psi,
- Shear-rates, as defined by fluid velocities and geometries in the well can range from less than 5.11 sec-1 (3 rpm on Common 6-speed viscometer) to greater than 1022 sec-1 (600 rpm on Common 6-speed viscometer),
- Narrowing (to tenths of a ppg) ECD-FG (Equivalent Circulating Density – Fracture Gradient) margins for drilling and cementing without losses,
- Tight annular clearances and complex flow geometries for liners and tie-backs, and
- Requirement of low circulation rates or static conditions for extended periods, promoting barite sag,

The narrowing of the hydraulic window for well-construction activities is driving the industry to make the next step in progressing technologies to further reduce the margin between ECD and ESD (Equivalent Static Density) in critical well operations. These advancements will be key to safe operations and minimizing NPT in complex, deep-water wells as the effects of depletion progress.

A recent technical evaluation of potential GoM (Gulf of Mexico) suppliers' deep-water drilling fluid system offerings allowed BP to appraise the "state-of-the-art" in technical development of what we refer to internally as "2nd Generation" Low ECD Fluids. This paper presents observations and evaluation methods concerning key temperature/pressure rheology characteristics, time-dependent gel structure, and fluid stability. The measurement and evaluation of these key properties are proposed as a standard methodology by which to quantify the performance of these newer "Low ECD" fluids for our most challenging wells. In addition, it presents a general

method of evaluation of a prospective fluid's ECD reduction using a regionally tested hydraulics model.

Introduction

In early 2017, an evaluation of the Non-Aqueous Drilling Fluids (NAF) utilized for drilling deep-water wells in the Gulf of Mexico was initiated. The fluid formulations received were classified internally as either "Conventional" or "Low ECD", based on their intended application. These categories were defined in recognition that projected well construction activity would include both relatively standard and more complex wells from a hydraulic window management perspective. Advanced, or "Low ECD" fluids had recently and successfully been deployed in the region to manage the challenges of narrower ECD window applications. However, the supporting engineering and hydraulics modelling work performed during the applications underscored the desirability of opening the hydraulic window further. Thus, the intent of the evaluation was to appraise the "state-of-the-art" for deep-water NAFs, with emphasis on identifying the key fluid properties that differentiate performance of advanced "Low ECD" fluids from the conventional fluids. One conclusion from the initial evaluation work was that restricting fluid testing to conventional methods and parameters did not clearly reflect the reduction in pressure cycling observed in field applications with the more advanced fluids.

With acknowledgement of the above, a team was assembled to identify key characteristics/attributes of NAFs that would be required to achieve an improved low ECD invert emulsion synthetic-based mud using the following boundary condition assumptions:

- Water depth/Long Marine Riser (≥ 5000 ft.) and
- Seabed temperatures $\sim 40^\circ$ F
- Reservoir Temperatures of 275° F to $\geq 300^\circ$ F
- Multiple intervals/casing or liner strings below mud line
- Narrow Clearance (tight tolerance) Tubular restrictions – examples include:

- 18” Casing through 19.125” riser
- 11-3/4” through 13-3/8” or 13-5/8” contingency liners
- Complex flow geometries, long PBRs (Polished-Bore Receptacle), low TFA (Total Flow Area) liner equipment etc.
- Narrow Pore Pressure/ Fracture Gradient (PPFG) - hydraulic window constraints for drilling, tripping, running pipe and cementing.
- Situations where required zonal isolation is complicated by inclination, compromised stand-off and resultant rate limitations.

The team utilized regional experience, internal and third-party laboratory data, plus a review of industry publications to establish a suite of analytical tests and numerical evaluation techniques that could be used to evaluate fluid performance with respect to ECD management and fluid stability. To assure flexibility in development strategies, the team avoided being prescriptive concerning absolute values for key parameters – recognizing that novel chemistries, weighting agent strategies and theoretical approaches would be required to drive a step-change in ECD management. These testing requirements have been compiled into a single data-pack template with the intention of collecting fluid data and highlighting what the team consider to be the desirable *characteristics* for minimizing ECDs. As part of the evaluation the data provided is used to assess fluid performance using a standardized hydraulic software modelling protocol.

The major elements that are considered to influence fluid performance and their impact as discussed below.

Fluid Properties for Pressure Management

Base fluid Selection

The base fluid is the major constituent of any NAF, representing >50 vol% of a typical formulation. All non-aqueous fluids are sensitive to temperature and pressure effects to varying degrees. Consequentially, the selection of base fluid can have significant impact on overall performance of the drilling fluid.

The choice of base fluid in any given region is driven by several factors; availability, logistics, cost and regulatory requirements having the largest influence on this decision. Experience has indicated that most commercially available base oils can be used to formulate Low ECD NAFs, but that the choice of “chemistry” used to create the invert emulsion will likely be driven by the base fluid selected. Thus, a good understanding of the properties of the base fluid under temperature and pressure conditions is beneficial in guiding the selection of fluid components such as emulsifiers, wetting agents, rheology

modifiers, etc. Base fluids with lower kinematic viscosity and a flatter viscosity profile across the temperature range would be desirable, but may not always be practical due to other considerations, such as base oil availability, flash point, elastomer compatibility, etc.

A simple example of increased low temperature effects on viscosity is shown in **Figure 1**, which is a plot of Kinematic viscosity in cSt (centistokes) vs Temperature in °C at 1 atmosphere. In general, minimal increases in viscosity with lower temperature and higher pressure are desired. In this example, at a typical Gulf of Mexico seabed temperature of 40 °F (4.44 °C), Oil 2 is about 2.5 times more viscous than Oil 4.

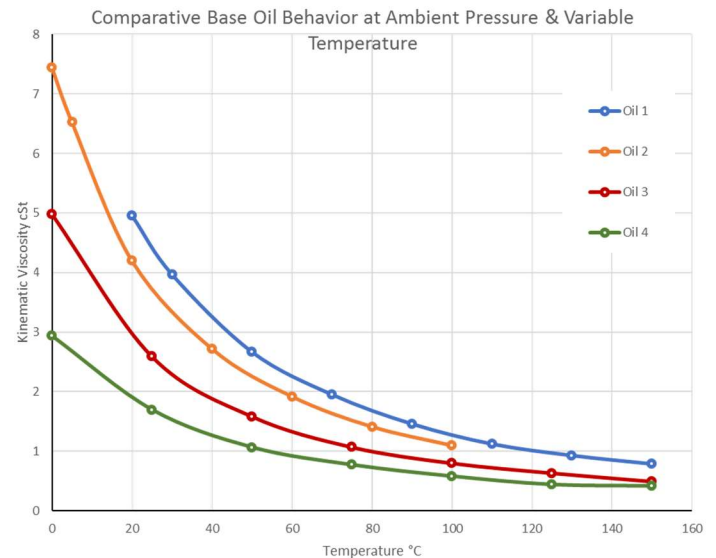


Figure 1. Base-Oil Viscosity as a Function of Temperature

The impact of this incremental difference in viscosity on bottom-hole pressure could be substantial, considering 5,000+ feet of colder riser fluid, as referenced above. In most deep-water operating theatres, such as Gulf of Mexico, the choice of base fluid is driven by environmental regulations, hence the opportunities to improve performance through change of base fluid are limited.

Rheology Trends Under Ambient Pressure Conditions

Fluid rheological properties under ambient pressure conditions provide a relatively simple means of identifying certain aspects of “low ECD” behavior. By varying the temperature of the test fluid using cooling baths and thermal cups, atmospheric rheology measurements can be made across a relatively broad range, from 40 – 150 °F, thereby simulating temperatures at the sea floor and deeper in the well. This testing protocol has the advantage of being simple enough to be run frequently at the

rigsite and is typically how we measure and manage fluid rheology in these operations today.

Although this test procedure is fairly basic and does not provide any indication of the impact of pressure on fluid performance, it is still capable of identifying significant trends in fluid behavior.

Figure 2 is a plot derived from common six-speed viscometer readings across a variety of mud densities and temperatures for the five Low ECD systems reviewed. The readings were plotted per temperature set, ranging from 40°F to 150°F. The densities used were 10, 12 and 14 ppg to incorporate the impact of weight material and cover the most common density ranges experienced in the field. What **Figure 2** represents is the average Low ECD dial reading percent increase when compared to the lowest profile recorded of the five. A trendline was then added for each temperature set.

Three aspects became noticeable from this evaluation. Firstly, there were wide variations in rheology profile across the Low ECD offerings, so the term ‘Low ECD’ probably needs some definition as to what it exactly means as it may not offer any type of guarantee regarding the rheological profile seen in the field. Secondly, the performance of the lowest rheological profile becomes distinctly better in the lower shear-rate ranges (e.g. 6 and 3 rpm speeds on the viscometer) as the percent deviation of the other Low ECD systems increases. This could be the performance aspect that delivers improved ECD response for deep-water wells as the low shear-rates have an impact on pressure loss experienced during circulation. Finally, the average deviations appear very similar at 80, 120 and 150°F, to the point where they become largely indistinguishable. However, at 40°F, there is a further step-up in deviation. Although it is not clear why this occurred it could be caused by differences in Low ECD systems chemistry regarding how they react to the colder temperature.

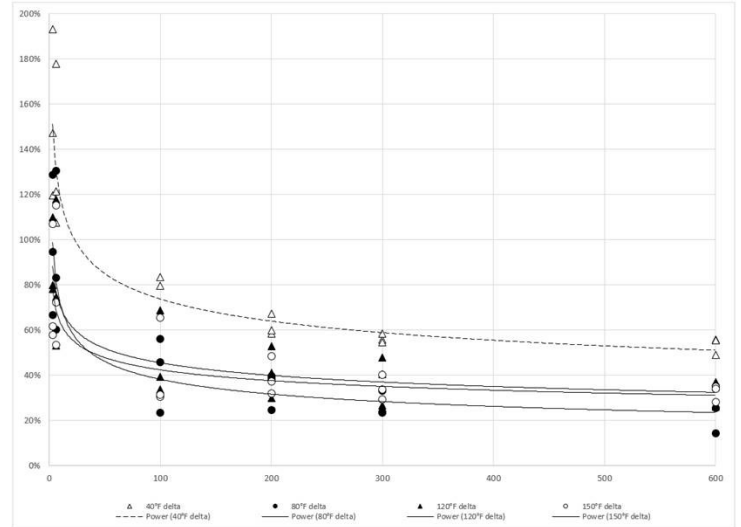


Figure 2. Ambient Pressure Rheology Changes across 10, 12, 14 ppg density Low ECD systems

Collectively, these observations suggest a greater degree of temperature sensitivity across the Low ECD systems than expected. As such, ambient pressure rheology data can be valuable in appraising fluids for challenging hydraulic window applications. However, as stated above, the deepwater drilling environment is characterized by extremes in temperature and pressure, having significant impact on rheology. This is addressed in the next section.

Rheology Under Downhole Pressure and Temperature Conditions

Knowledge of fluid rheology behavior under downhole temperature and pressure is imperative for an understanding of flow under extreme conditions. At any applied shear-rate, there should be minimum variance in the corresponding measured shear-stress as a function of temperature and pressure. This is shown in **Table 1** (Low ECD), and is highlighted at 600 rpm (1022 sec^{-1}) by the shaded, vertical column. For all shear-stress data collected over the range of temperatures and pressures tested, the values show minimum deviation. As shear-rate is ramped down within a temperature and pressure data set (shaded horizontal row), a relatively flat slope is beneficial, assuring a robust shear-stress measurement at 10.22 and 5.11 sec^{-1} (6 & 3 rpm respectively). These properties assure a minimum variation in viscosity in response to temperature and pressure and adequate low-shear properties for hole cleaning and sag mitigation. Also, they are comparable with standard ambient pressure rheology measurements facilitating a “tie-in” between field and laboratory data for input to hydraulics modelling.

Table 1. Grace M7500 Data for 12 ppg “Low ECD” NAF

Fluid: Low ECD (1st gen)
 Density: 12.0 ppg
 Mix: 16 hr hot roll at 250F
 Rheometer: Grace M7500

Temp (F)	Pressure (psi)	Dial Readings							PV (cP)	YP (lbs/100ft2)
		600	300	200	100	6	3			
40	15	117	73	55	39	15	14	44	29	
80	15	98	59	46	32	15	14	39	20	
120	15	85	53	42	29	15	13	32	21	
150	15	69	47	40	27	14	12	22	25	
40	3000	155	89	67	45	16	14	66	23	
80	8000	147	85	62	42	17	15	62	23	
120	12000	115	67	51	35	14	13	48	19	
150	15000	113	66	51	35	12	10	47	19	

The properties of a 12.0 ppg conventional system are provided below in **Table 2** for comparison. Note the significantly higher dial readings across all shear-rate ranges and the magnitude of temperature and pressure sensitivity as compared with the data in **Table 1**. The Plastic Viscosity of the conventional system at 40 °F and atmospheric pressure (125 cP) is approximately 3 times that of the “Low ECD” NAF (44 cP). Also note the incremental effects of pressure at any temperature. For example, comparing the 600 rpm shear-stresses (dial readings) at 40°F and ambient pressure with 3,000 psi data at the same temperature, a > 70 lb_f/100 ft² increase is observed (360=maximum dial deflection). In fact, one sees an approximate doubling (~2X) of the shear-stress measured at pressure vs. the ambient readings at 600 rpm in the “conventional” fluid.

Table 2. 12 ppg Conventional NAF Rheology at T & P

Fluid: Conventional SBM
 Density: 12.0 ppg
 Mix: 16 hr hot roll at 250F
 Rheometer: Grace M7500

Temp (F)	Pressure (psi)	Dial Readings							PV (cP)	YP (lbs/100ft2)
		600	300	200	100	6	3			
40	15	291	166	132	92	39	38	125	41	
80	15	157	96	76	57	27	26	61	35	
120	15	114	70	58	43	26	24	44	26	
150	15	98	70	56	41	26	24	28	42	
40	3000	N/R	230	169	117	45	45	-	-	
80	8000	368	190	140	97	32	33	178	12	
120	12000	254	139	108	69	26	25	115	24	
150	15000	225	122	91	59	30	30	103	19	

Thus, a key objective in formulating “low ECD” NAFs is to minimize the impact of pressure and temperature on viscosity in all shear-rate ranges.

Incremental Shear-stress with Pressure

To isolate and compare the magnitude of pressure effects, these data were analyzed at the same temperature, but at ambient (15 psi) and at elevated pressure. An **incremental shear-stress**

resulting from increased pressure (Tau/psi) was calculated for each fluid, as is shown in **Table 3**, which has been move to the end of the paper (p 8) for improved legibility. The ratio of the “conventional” to “low-ECD” shear-stress/psi result in a dimensionless “shear-stress - pressure multiplier” that quantifies the magnitude of the difference in pressure response between the two fluids.

While these trends have been observed in several fluids and to varying degrees, it is recognized that this type of analysis is speculative at this time. The incremental pressure for each temperature set is not constant, making it difficult to infer a trend as a function of temperature, although it appears that increased temperature dampens the pressure effects. However, it is striking that two fluids formulated with the same base fluid, oil-water ratio, density and weighting agent mineralogy exhibit a response to pressure with a variance of ~ 2.5X to ~5X at the same shear-rate. One can conclude that these fluids respond very differently to deformation under pressure, and it is possible that understanding this variance could influence the development of “Low ECD” Fluids.

Gel Strengths

Static Gel Strengths are also measured with conventional rheometers and are recognized as being a critical parameter for managing the hydraulic window. They are important for controlling pressures when breaking circulation, cuttings suspension during trips and mitigating weighting material sag. Gel strengths are usually measured at 3 rpm (5.11 sec⁻¹) after a static period of 10 seconds, 10 minutes and 30 minutes, although longer periods have been used. Temperatures can vary from ~ 40 -150 °F. **Table 4** illustrates what the authors believe are desirable gel strength and low-shear *trends*.

Table 4. Gel Strength Trends at 40 and 120°F

Test Temperature	Post Dynamic Age at 250°F for 16 hrs.	
	40° F	120°F
PV	63	26
YP	22	17
6 rpm	11	10
3 rpm	10	9
10 sec gel	11	10
10 min gel	20	17
30 min gel	23	18

Development of rapid gel structure at any test temperature that, after 10 and 30 minutes remains relatively consistent is preferred. This characteristic is evident in the 40° and 120° gel

data. Robust and consistent low shear-rate readings (6 and 3 rpm) are also desirable. Past guidance suggested the application of fixed ratios for gel strength values as a function of time with the intent of setting limits on the progressivity to manage performance. While this approach has proven to have been effective, concerns have been raised that this specificity limited the use certain chemistries and approaches¹. These concerns are based on our ability to correlate the measurement of gel strength with the pressure required to initiate circulation in a well.

Recent comparisons between simple pressure to break gels calculations, a commercial cementing simulator and actual well data indicate significant variability in results. Additionally, simple calculation methods assume a constant gel strength with depth, which is inconsistent with field observation. Despite perceived gaps, gel strengths and low shear (6 and 3 rpm) values will continue to inform our decisions concerning a fluid's fitness for purpose. However, this underscores an opportunity for the industry to improve its understanding of *longer-term* gel strength development, its measurement at pressure and temperature, and relate it to the pressure to initiate circulation in a wellbore.

Fluid Properties for Assuring Stability

The previous discussion has focused on template requirements for rheological properties that strongly influence frictional pressure losses and pressures to break circulation. This section discusses requirements that helps assure desired properties are sustained over time. Of primary importance is maintaining consistent density because fluids are a primary well control barrier during most well construction activities. It has been recognized that weighting material sag occurs under static and low shear-rate dynamic conditions², which are often protracted in complex deep-water operations.

Fluid Stability under Low Shear Conditions

The Step Down Test^{3,4} (Figure 3) utilizes a low shear-rate spindle viscometer to evaluate the suspension characteristics of a fluid under ultra-low shear-rate conditions by observing the resultant shear-stress³ response.

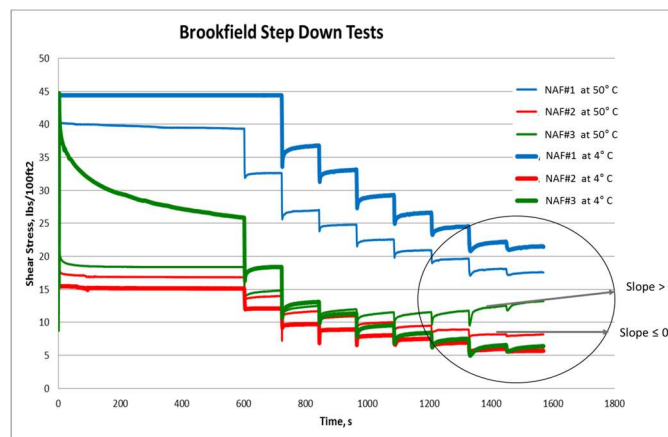


Figure 3. Step Down Test Results for Multiple NAFs at Two Temperatures

An encouraging result from this test is indicated by an increase in the shear-stress (Slope > 0) at the lower shear-rates after multiple cycles (inside circle). This response is not typically observed in “conventional” NAF formulations and is taken as an indication of a yield stress (τ_0) developing as shear-rate approaches zero. This is thought to be beneficial for suspension of weighting material. The results are also independent of the lower shear-rate measurements (6 and 3 rpm) made with a standard field viscometer which are often relied on for indications of suspension capability.

The Step Down Test is envisioned as a laboratory tool to support Low ECD NAF development. It is recognized that spindle viscometers of this type may not be readily available or practical for field use on mobile drilling units.

Fluid Stability under Low Shear Conditions – Field Tests

Monitoring fluid stability in the field is important to ensure that changes to actual fluid properties and/or composition do not significantly influence the ability of the fluid to support cuttings and weighting material. By their nature, field tests tend to be less detailed and perhaps less accurate than can be achieved with laboratory tests, however regular testing can help to identify trends and highlight increased risks of fluid instability⁴. Two industry test procedures have been incorporated into the testing protocol:

Sag Shoe Test

The Viscometer Sag Shoe Test (VSST) is a wellsite or laboratory test to measure weight-material sag tendency of field and lab-prepared drilling fluids under dynamic conditions^{5,6}. While not as sophisticated, the VSST measures an intrinsic fluid property must be combined with other test data and operational factors to identify risk of the occurrence of barite sag.

The method employs a standard rheometer to shear drilling fluid at 100 rpm (170 sec^{-1}) in a thermal cup for 30 minutes while collecting settled weighting material in a thermoplastic insert (sag shoe). **Figure 5** shows the standard equipment required to run a VSST.

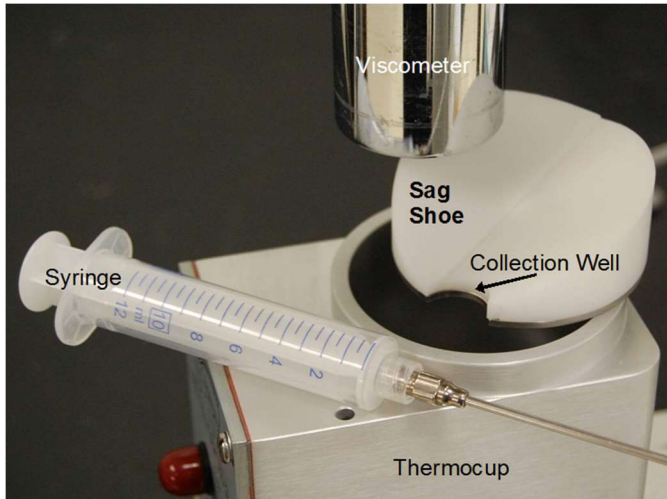


Figure 5. Basic Equipment for a Viscometer Sag Shoe Test (VSST)

The results of the VSST are reported in lbs/ gallon, and represent the change in fluid density due to dynamic settling in the thermal cup.

Sag Window

The Sag Window has been developed and used to define the boundary limits of viscosity required over a range of shear-rates to mitigate barite sag. The values of interest are normally from $0.1 - 1.0 \text{ s}^{-1}$. Measurements of viscosity at these low shear-rates requires more advanced viscometers than the standard six-speed versions that are typically used for field measurement, although variable shear-rate Couette coaxial cylinder rotational viscometers suitable for field use are available and becoming more widely used. Given the criticality of understanding flow properties over a broad range of shear-rates, this type of analysis is highly informative for development of a “Low ECD” NAF. **Figure 4** shows a representative Sag Window for a sample drilling fluid.

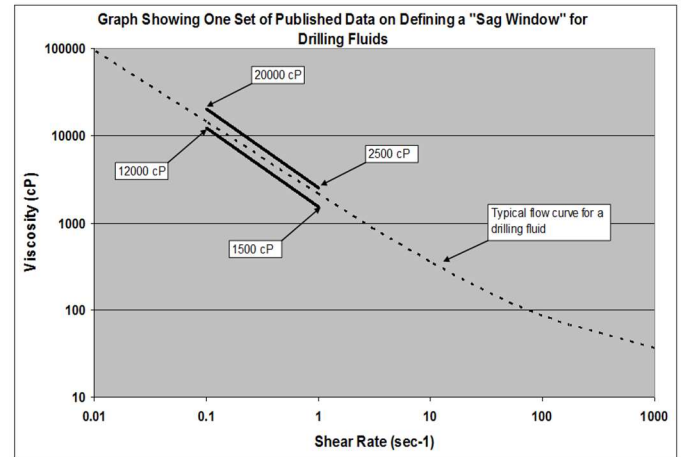


Figure 4. Sag Window example

Viscosity values which may be adequate to prevent sag of invert emulsion drilling fluids under dynamic field conditions have been proposed in the literature^{1,3,7}. The heavy solid “tramlines” on Figure 4 define the upper and lower limits of viscosity required to avoid sag between 0.1 and 1.2 sec^{-1} for this specific fluid.

It should be noted that the Sag Window tramlines for candidate “Low ECD” fluids may be influenced by novel chemistries, changes in grind-size/specific gravity of weighting material or other innovations employed to meet the frictional pressure loss and stability challenges discussed in this paper.

Fluid Stability Under Static Conditions

Fluid stability under downhole temperature conditions is usually conducted in the laboratory by ageing samples under static conditions (static ageing). The tests are typically performed using stainless steel ageing cells heated in an oven to at or near anticipated bottom hole static temperature. The ageing cells are flushed with an inert gas (typically nitrogen) and pressured to a head of $100 - 200 \text{ psi}$. Once ageing is completed, the density of the sample is measured across the column of fluid and any degradation of fluid (syneresis, barite settling) noted. While this is a simple test that can be used to run many test fluids and/or ageing parameters it is widely accepted that this test may not be totally indicative of fluid behavior in the field due to the low pressure applied.

The equipment to run long Static Sag Testing at downhole pressure as well as temperature is not widely available to the industry, however HPHT ageing cells have been designed and built at BP Fluids laboratory and may be used to validate the downhole stability of novel Low ECD Fluids.

Fluids Performance Evaluation – Software Modelling

This project was initiated due to recognition that for complex wells, any reduction in ECD without compromising operations increases options and further minimizes risk. This necessity was underscored by recent wells where highly detailed engineering was required to design and achieve the necessary flow rates, fluid and cement properties to navigate a complex flow geometry and successfully circulate and cement production liners without losses. This achievement was guided by extensive hydraulics validation modelling.

These experiences were used to inform the Standardized Hydraulics Model Example well that is utilized for benchmarking candidate “Low ECD” Fluids as part of the evaluation process. Results from one comparison of the ECDs while circulating a liner are illustrated in **Figure 6**.

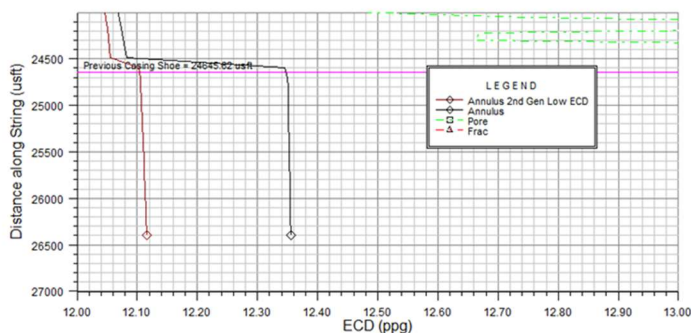


Figure 6: ECD Comparison of Low ECD Candidate vs. Benchmark

For this example, an incremental reduction in ECD with a “Low ECD” fluid as compared with the benchmark is 0.18 ppg at ~26,400 ft. This result serves to illustrate the scale of the challenge, as the demands of well design may require reductions in ECD in the range of 0.3 ppg or more over what has been achieved with more conventional fluids.

Conclusions

The testing procedures described in this paper are proposed as a comprehensive suite that would better define fluid behavior and provide a standardized means of benchmarking performance.

The challenge of drilling the narrow window between Pore Pressure and Fracture Gradient typical of deep-water wells is well understood within the industry. Furthermore, as the hydraulic window continues to narrow in more mature developed regions, the engineering of the drilling fluid to further reduce the degree of pressure cycling on the wellbore increases. As the challenges become greater, the

parameters that have historically been used to design and evaluate fluids for these wells require reassessment. An opportunity has been presented to consider alternative methods that could be used to define fluid performance and help drive further improvements to meet the challenges.

The authors maintain that the successful formulation of these Second-Generation Low ECD Fluids will require a “perfect marriage” of deep understanding of rheology and hydraulics with perhaps new and novel chemistries to develop stable, *low-friction* fluids at extreme conditions.

A fundamental premise of the work presented in this paper is that, if the physics is not fully considered, finding the correct chemistry to meet the challenge becomes incrementally more difficult. It is hoped that the work presented here will encourage engagement with the wider Fluids community around how to define success under these conditions with the ultimate goal of achieving fluid performance that is not just better, but also more predictable.

Acknowledgments

The authors would like to thank the BP Gulf of Mexico Drilling Team for its support, with special recognition to Rafael Flores for his guidance and input concerning hydraulics modelling. We also recognize our fluids contractors for their continued interest and engagement in this pursuit.

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7. API Recommended Practice – Wellsite Monitoring of Weight-Material Sag

Table 3. Isothermal Incremental Shear-Stress due to Pressure

Temp F	Pressure psi	600-rpm reading		Differentials (Pressured minus ambient)				Incremental lbs/100ft ² per psi		Multiplier / Factor
		Low ECD	Conventional	Temp	Pressure	600-rpm Low ECD	600-rpm Conventional	Low ECD	Conventional	
40	15	117	291	0	2985	38	n/r	0.01273	n/r	---
40	3000	155	n/r							
80	15	98	157	0	7985	49	211	0.00614	0.02642	4.30612
80	8000	147	368							
120	15	85	114	0	11985	30	150	0.00250	0.01252	5.00000
120	12000	115	264							
150	15	69	98	0	14985	44	127	0.00294	0.00848	2.88636
150	15000	113	225							