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Digital Drilling Fluids and Lab Automation Lead to Optimal Deepwater Drilling Solutions

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Abstract

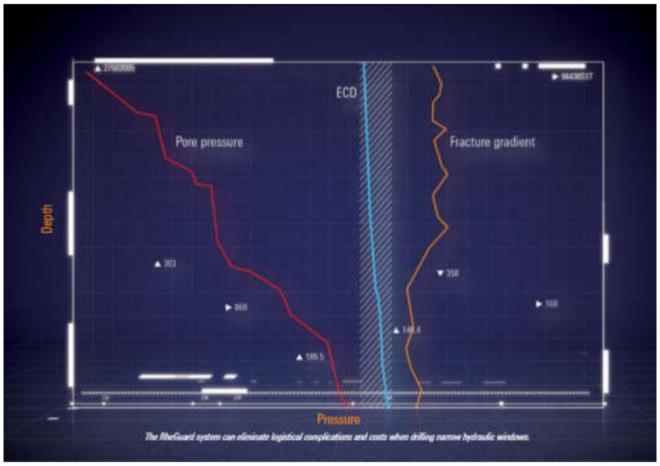
The complex and demanding set of requirements for high-pressure, high-temperature (HPHT) deepwater environments is a big challenge for drilling fluid formulation[1,2]. A variety of functional additives[3] are used to tune fluid properties based on qualitative understanding of the composition-property relationships. Despite increasingly stringent specifications for drilling fluids, traditional formulation strategies have not changed in many decades. Formulation and optimization are typically done by trial and review, usually adjusting one factor at a time.

To address the challenges of HPHT drilling fluid development, we devised a novel strategy combining automation and a data-driven approach. Fit-for-purpose automated drilling fluid rheometers were developed to remove a bottleneck in testing and to improve reproducibility and repeatability of data. Design of experiments (DOE) was used to systematically evaluate and quantify the property-composition response surface of the fluid. The outcome of this approach was development of a mathematical model of a fluid and the digitalization of fluid chemical interactions to create a digital drilling fluid avatar.

With a digital fluid model, we can predict fluid response and adjust formulations accordingly to meet specific job requirements. Digital fluid optimization is reducing the need for further lab experimentation, shortening the development cycle to meet complex specifications, and improving response time if specifications change. This approach now has a proven track record in delivering solutions to the field at an accelerated pace.

Introduction

With more challenging drilling operations and the need to drill through heavily depleted formations, there is an increasing demand for fluids that meet a stringent set of specifications. Low viscosity is needed when the window between pore pressure and formation fracture gradient is small. This requirement is illustrated in Figure 1 where, with increased depth, the safe drilling window between the formation pore pressure and fracture gradient is narrow.

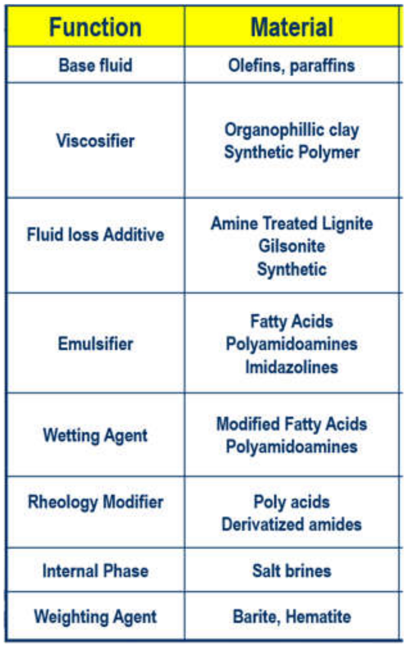


The RheGuard system can eliminate logistical complications and costs when drilling narrow hydraulic windows.

Figure 1. Low-viscosity fluids for GoM.

Requirement of a thin fluid can be challenging because to achieve viscosity targets the fluid needs to be thin at ambient conditions and under pressure, yet there are other conflicting requirements such as acceptable low-shear-rate viscosity for effective cuttings removal and low gels for low breaking circulation pressure. Furthermore, these low-viscosity fluids need to be able to suspend barite and low gravity solids (LGS) under static and dynamic conditions, maintaining their rheological properties for extended durations while exposed to high temperatures. Further compounding the issue, the complexity of the deepwater HT wells means that well plans may require a well plan revision that changes the requirements of a drilling fluid. Together these challenges present a complex problem to a drilling fluid formulator.

Fluids of choice for these applications are typically invert-emulsion drilling fluids. Figure 2 shows a typical set of fluid components of a synthetic-based mud (SBM) with a description of the main function for each type of additive. However, each component changes multiple fluid properties simultaneously albeit to a different degree. These products are not fully interchangeable and typically a given product cannot reliably serve multiple functions. Furthermore, many types of products are available under each category, and product concentrations can also be changed. To screen all possible permutations of these factors, hundreds of tests are usually needed, which is impractical. While institutional knowledge may be used to a certain extent to reduce the formulation space, for fluids that push the boundaries and rely on new additives and complete reformulation there is little prior knowledge of what works and what does not.



Function	Material
Base fluid	Olefins, paraffins
Viscosifier	Organophillic clay Synthetic Polymer
Fluid loss Additive	Amine Treated Lignite Gilsonite Synthetic
Emulsifier	Fatty Acids Polyamidoamines Imidazolines
Wetting Agent	Modified Fatty Acids Polyamidoamines
Rheology Modifier	Poly acids Derivatized amides
Internal Phase	Salt brines
Weighting Agent	Barite, Hematite

Figure 2. Minimal number of components necessary to create a drilling fluid and description of common chemistry used and respective function.

Automation Equipment

Successful, accurate, and reliable fluid formulation effort requires a set of simultaneous improvements to the old workflow of fluid formulation. Currently, a lot of testing protocols are highly manual in nature and require a lot of time at the bench. Manual tests cannot be left unattended and rely on the skill of the operator to produce accurate reproducible data. Combined, these issues create a substantial bottleneck for the formulation effort. The other aspect of improved formulation workflow is to improve data utilization with application of design of experiments, as discussed in subsequent sections.

Primary automation effort was focused on automating rheology measurements that are required for each formulation generated for fluid development. Rheology measurements are a routine low-skill task that, nevertheless, requires a lot of time and attention from the operator. Specifically for deepwater drilling fluids, rheology is measured at several temperatures—40 degF, 100 degF, 150 degF. The industry workhorse for rheology measurements is a 6-speed Couette rheometer that is operated manually to cycle through each speed (shear rate) and for gel measurements up to 30 min per temperature as necessary. It is a reliable but simple device that lacks data recording capability or ability to control sample temperature.

These shortcomings lead to potential sources of error in recording and sharing of data and in measured values themselves. Manual recording of data is inefficient and is prone to human error. Lack of automated temperature control and dependence on the skill of the operator can lead to deviations in actual vs reported mud check temperature and, as a result, inaccurately measured rheological parameters. Measurements at 40 degF are particularly challenging because small changes in temperature around 40 degF can result in a large change in drilling fluid viscosity. For example, high-shear-rate viscosity of drilling fluids depends on base oil viscosity that, in turn, has a strong temperature dependence around 40 degF (Figure 3). Small deviations from temperature target within API standard specifications (+/- 2 degF) can significantly affect measured rheology.

To address these challenges, we developed an automated drilling fluid rheometer with fully automated temperature control capabilities both for heating and cooling. With the automated rheometer, rheology measurements for the entire suite of temperatures do not require human intervention, allowing the operator to focus on other value-added tasks. Measurement results are recorded digitally, making the data easy to process and share. Furthermore, the ability to monitor and control temperature in the 40–180 degF range increases the accuracy of rheological measurements due to superior temperature control during measurements.

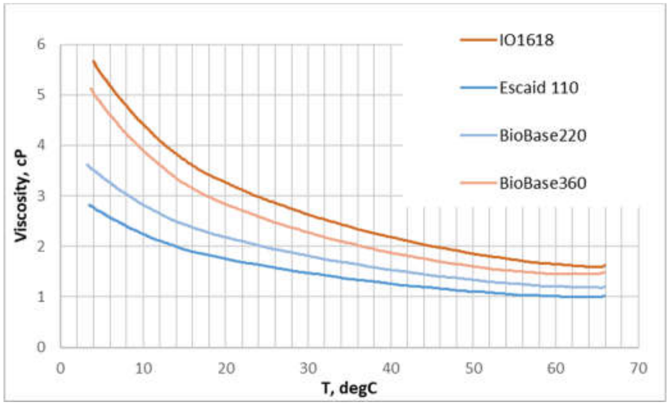


Figure 3. Viscosities of various base oils as a function of temperature. Viscosity changes fast at 4 degC (40 degF).

Design of Experiments

With the development of automation and increased data generation rate, data analysis, rather than data generation, may become a bottleneck. Here, improvement of data utilization is necessary. With many components in a drilling fluid and many responses that are typically recorded per sample and many samples being tested it becomes more difficult to determine the optimal formulation without software-based data analytics.

Previously, formulation efforts would include selecting an initial formulation and changing one component or concentration of a component at a time until specifications are met. There are several challenges with this approach:

- A stack of results sheets are created but property-composition patterns are difficult to identify.
- Concise communication of information from entire body of work is difficult, hence data utilization is poor.
- If the proposed final formulation has challenges, additional formulation efforts are needed to address the challenges without affecting the good properties.
- It is difficult for the developer to change more than one component at a time and keep track of changes and their effects.

A more rational approach to a complex fluid formulation problem of this type is to generate a property-composition response surface using well established DOE methods. This approach allows us to analyze the effect of many factors such as multiple components and concentration variations simultaneously. This is beneficial since it may be possible that two components act in synergy and it takes two or three simultaneous changes to formulate a fluid that meets requirements. With a response surface model, we can model multiple changes, observe trends, and communicate findings more effectively, perform numerical optimization for a formulation based on multiple variable changes at once. Overall, experimental design is an excellent way to address the complexities of the fluid formulation.

The response surface approach enables digital prediction and optimization of fluid properties. Using minimal amount of experimentation, a wide range of fluid compositions is covered. Once models are completed, they largely remove the guesswork of understanding the response of fluid properties to formulation changes. Furthermore, digital fluid models also enable a quick response to changing fluid requirements. Plausible compositions that meet any particular set of requirements can be instantly generated digitally for testing in the lab.

A typical DOE workflow is shown in Figure 4 and consists of design setup (digital), implementation (hands-on lab testing), and data analysis (digital), resulting in a property-composition response surface, which is effectively a digital model of the fluid. The most laborious and time-consuming part of the process is lab testing (Step 3, Figure 4). Steps 2 and 4 are performed in the DOE software with some input from the user. Design-Expert software (StatEase, Minneapolis, MN) was used in this work. The model is generated based on least-squares fit and statistical analysis methods and is accompanied by model-quality metrics (fit statistics). For creating a digital fluid model, each mud property of interest requires its own model generated from experimental data.

Response surfaces designs can vary based on the system from simple flat planes to very intricate shapes. The more complicated the response surface is more data points are required to create an accurate model. The challenge for the experimenter is to balance the quality of the model with the amount of work it takes to create it. For drilling fluid optimization, some factors are immutable requirements that will remain fixed, such as the type of base oil and fluid density. Other factors may be adjusted such as brine type and salinity, but typically one common brine is used for development, such as 25% $CaCl_2$. For the remaining components of the drilling fluid formulation it is up to the researcher which variables should be tested.

Figure 5 presents a minimal number of components that are necessary to create an invert-emulsion drilling fluid. The variables included in the model were based on prior knowledge and on fluid requirements. Including remaining variables such as organoclay, lime, or brine concentration as variables in the study would be possible but would increase the amount of work required to create a model.

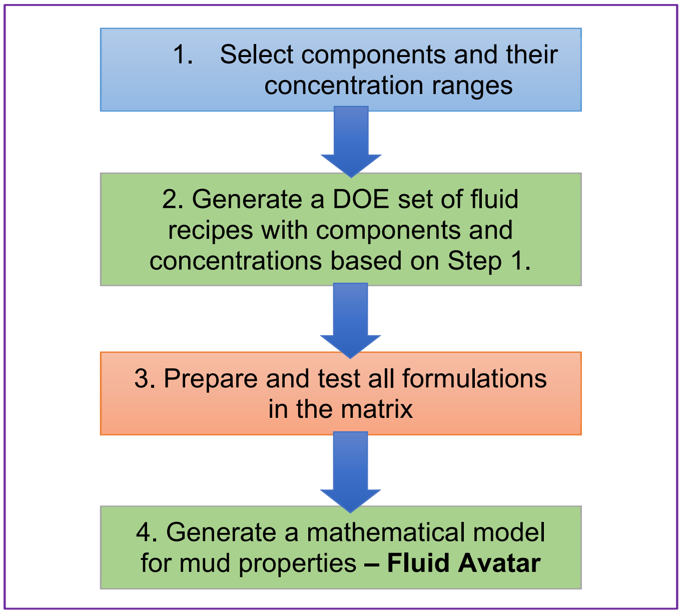
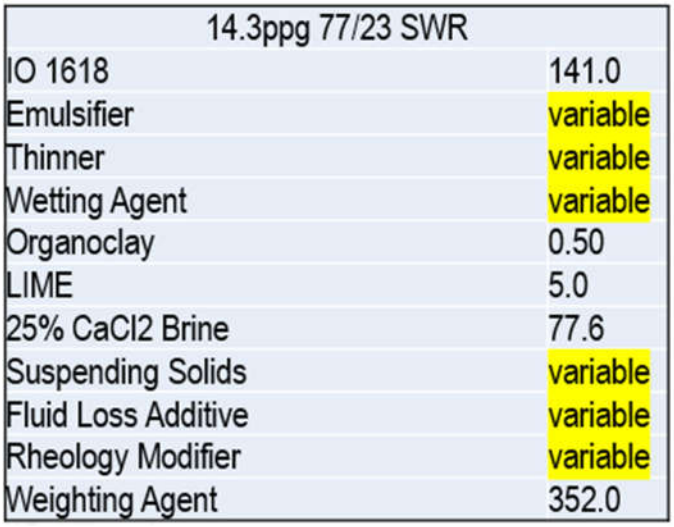


Figure 4. A typical workflow for building a response surface model of a drilling fluid.



14.3ppg 77/23 SWR	
IO 1618	141.0
Emulsifier	variable
Thinner	variable
Wetting Agent	variable
Organoclay	0.50
LIME	5.0
25% CaCl2 Brine	77.6
Suspending Solids	variable
Fluid Loss Additive	variable
Rheology Modifier	variable
Weighting Agent	352.0

Figure 5. Components of a drilling fluid used for low rheology formulation. Components for property and composition response surface analysis are highlighted in yellow.

In addition to including or excluding certain components to vary in the model, one can include categorical factors, i.e., more than one type of product such as two different organoclays or more than one emulsifier.

The expected complexity of response surface profile has a strong effect on the amount of work it takes to complete the study and there is a certain amount of art and knowledge required to design this type of study. Even with automated rheometers that we introduced, the amount of work needed to complete the effort should be carefully considered. For example, for six selected components in Figure 5, only six formulations are required to create a response surface if there is no interaction between components (highly unlikely). However, if two-component interactions are important, a minimum of 22 fluid recipes need to be tested. If additional complex phenomena are occurring, such as minima or maxima in property dependencies on some components, the model must include quadratic factors, which changes the matrix to 28 tests. For even higher complexity, such 3-way interaction (three components in synergy), the model will require substantially more testing to complete.

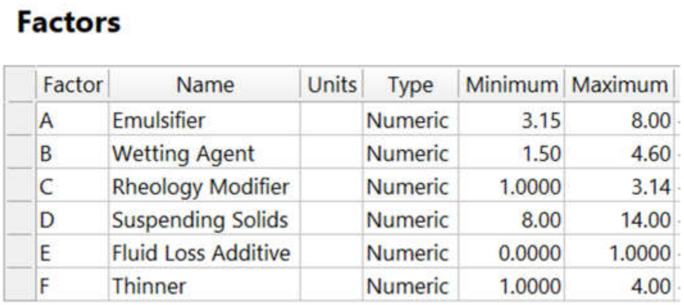
From our extensive efforts on developing response surfaces for drilling fluids, we determined that two-factor interactions are common. However, we found that a larger number of datapoints is typically required to obtain adequate signal-to-noise ratio from our measurements and create a model with good predictive ability. Thus, typically enough data points to generate a quadratic model is usually generated and measured, and the actual surface type is typically analyzed once all experimental data have been obtained.

Creating a Drilling Fluid Model

The aim of this task was to generate a fluid formulation for deepwater drilling in the Gulf of Mexico meeting a set of stringent requirements on rheology, HPHT fluid loss, high-temperature stability, and low sag. The requirement on high-temperature stability at 280–325 degF AHR and ASA allowed to narrow down the scope of additives suitable for this formulation. This effectively excluded any ester-based additives or any salts based on fatty amines and fatty acids (usually reaction product RMs). Prior tests showed that these can survive high temperature briefly but cannot meet the requirement after 7-day static aging at 280 degF. On the other hand, concentrations of suitable additives (Figure 5) were varied over a range wider that institutional knowledge would suggest for two reasons:

- Explore the design space to ensure optimal drilling fluid formulation
- Determine the tolerable practical ranges for engineering guidelines

Ranges for factors used in the study are shown in Figure 6.



Factors

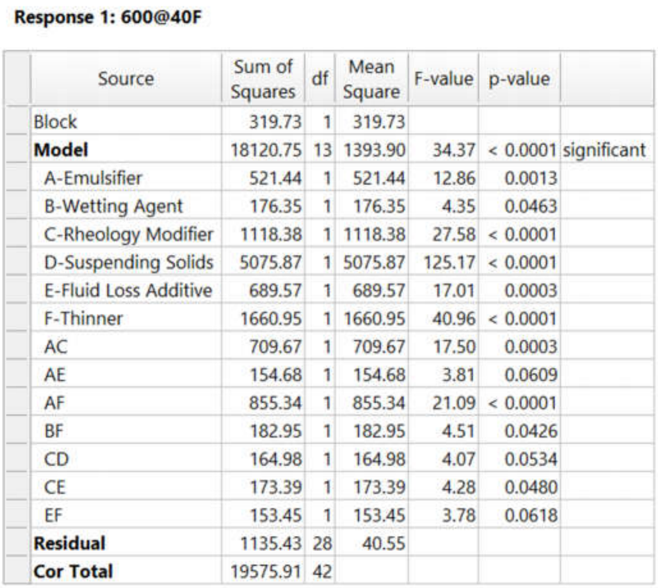
Factor	Name	Units	Type	Minimum	Maximum
A	Emulsifier		Numeric	3.15	8.00
B	Wetting Agent		Numeric	1.50	4.60
C	Rheology Modifier		Numeric	1.0000	3.14
D	Suspending Solids		Numeric	8.00	14.00
E	Fluid Loss Additive		Numeric	0.0000	1.0000
F	Thinner		Numeric	1.0000	4.00

Figure 6. Factors and ranges used in the study.

For reasons previously stated in this paper, we started with a 22-test model to test for two-factor interactions but later augmenting the model to a matrix of 45 tests. This was necessary because of complex and very specific requirements for the project.

Analysis of Model

Model analysis has shown that most properties of interest are adequately described by equations that only consider two factor interactions (Figure 7).

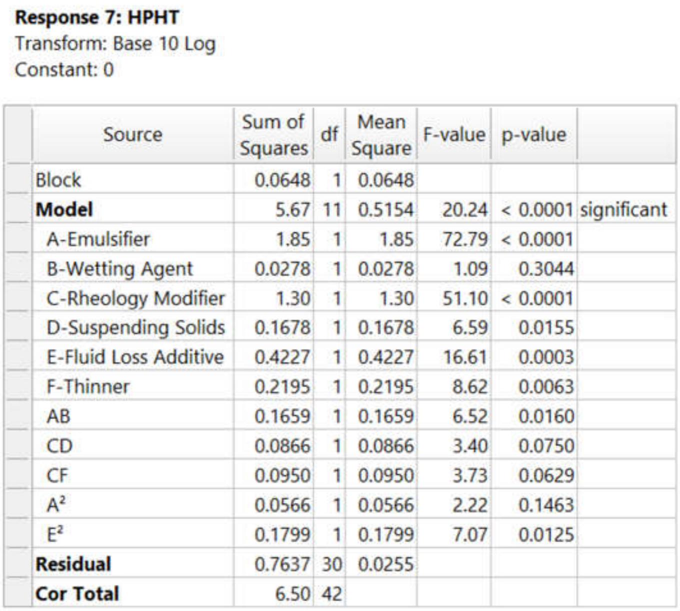


Response 1: 600@40F

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Block	319.73	1	319.73			
Model	18120.75	13	1393.90	34.37	< 0.0001	significant
A-Emulsifier	521.44	1	521.44	12.86	0.0013	
B-Wetting Agent	176.35	1	176.35	4.35	0.0463	
C-Rheology Modifier	1118.38	1	1118.38	27.58	< 0.0001	
D-Suspending Solids	5075.87	1	5075.87	125.17	< 0.0001	
E-Fluid Loss Additive	689.57	1	689.57	17.01	0.0003	
F-Thinner	1660.95	1	1660.95	40.96	< 0.0001	
AC	709.67	1	709.67	17.50	0.0003	
AE	154.68	1	154.68	3.81	0.0609	
AF	855.34	1	855.34	21.09	< 0.0001	
BF	182.95	1	182.95	4.51	0.0426	
CD	164.98	1	164.98	4.07	0.0534	
CE	173.39	1	173.39	4.28	0.0480	
EF	153.45	1	153.45	3.78	0.0618	
Residual	1135.43	28	40.55			
Cor Total	19575.91	42				

Figure 7. Example of ANOVA for 600@4 0degF. Note that model does not go beyond the 2-factor interaction.

One exception to this rule was the HPHT fluid loss testing result and this only occurred because of the large range of surfactant that we selected for the study. This was partially done to find the engineering limits of the system and partially to test if DOE approach can describe a system with complex behavior (Figure **8**).



Response 7: HPHT
Transform: Base 10 Log
Constant: 0

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Block	0.0648	1	0.0648			
Model	5.67	11	0.5154	20.24	< 0.0001	significant
A-Emulsifier	1.85	1	1.85	72.79	< 0.0001	
B-Wetting Agent	0.0278	1	0.0278	1.09	0.3044	
C-Rheology Modifier	1.30	1	1.30	51.10	< 0.0001	
D-Suspending Solids	0.1678	1	0.1678	6.59	0.0155	
E-Fluid Loss Additive	0.4227	1	0.4227	16.61	0.0003	
F-Thinner	0.2195	1	0.2195	8.62	0.0063	
AB	0.1659	1	0.1659	6.52	0.0160	
CD	0.0866	1	0.0866	3.40	0.0750	
CF	0.0950	1	0.0950	3.73	0.0629	
A^2	0.0566	1	0.0566	2.22	0.1463	
E^2	0.1799	1	0.1799	7.07	0.0125	
Residual	0.7637	30	0.0255			
Cor Total	6.50	42				

Figure 8. ANOVA for HPHT fluid loss at 280 degF. Tests conditions: duration 30 min, pressure differential 500 psi, paper disks.

The complex behavior of variable factors vs HPHT response is visualized in Figure 9.

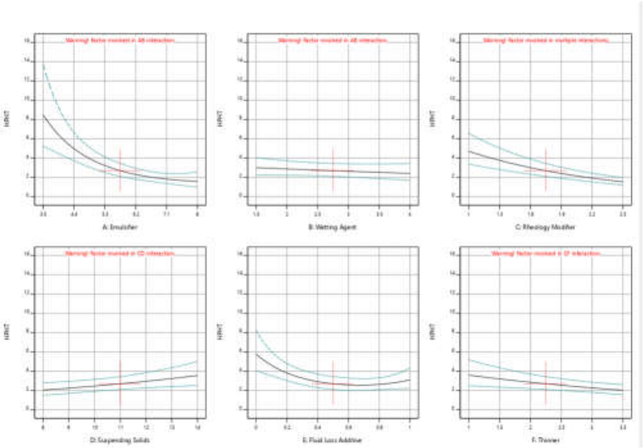


Figure 9. Factor interaction for HPHT fluid loss.

Here we can see a steep drop off in HPHT fluid loss with increased emulsifier content from 3 ppb to 5 ppb, and a steady value at higher emulsifier concentrations. Alternatively, a 3-D map can be evaluated for effect of multicomponent changes (Figure 10).

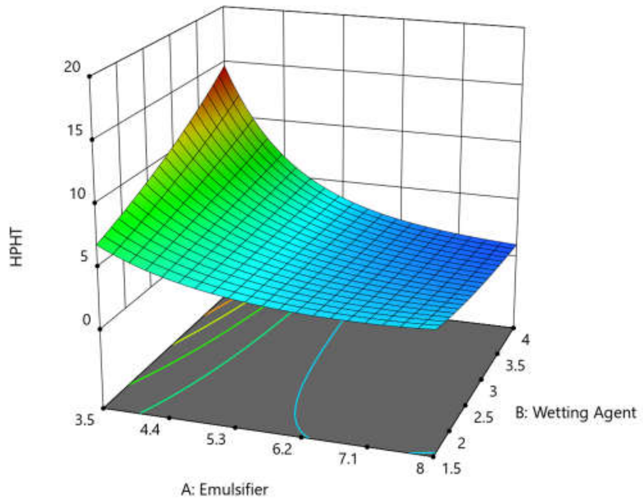


Figure 10. HPHT fluid loss response surface for emulsifier and wetting agent concentrations.

It can be observed that at high concentration of emulsifier, there is little effect from the wetting agent and, similarly, at high concentration of wetting agent the emulsifier has little effect on the fluid loss test. Most likely the underlying explanation for this effect is that surfactant adsorbs on solids and below some minimum quantity there is not enough surfactant in solution to stabilize the emulsion. However, successful application of DOE demonstrates that it is not necessary (albeit helpful) to thoroughly understand the underlying chemistry and physics to create a good drilling fluid formulation from a selected set of components. Furthermore, with a visual representation of fluid behavior as shown in Figure 9, one can create more effective engineering guidelines for the drilling fluid. An example of such a guideline can be to run a fluid with excess emulsifier and accept higher rheology as a trade-off for a system tolerant to drill solids that it picks up or to run with low emulsifier for thinner fluid but be ready to treat as drill solids and cuttings removal will deplete the system off emulsifiers.

With a model in hand there are several benefits that become immediately obvious compared to the typical trial-and-error formulation approaches. One benefit is ease of communication of information. For example, Figure 11 shows color-coded correlation of additives on properties of interest.

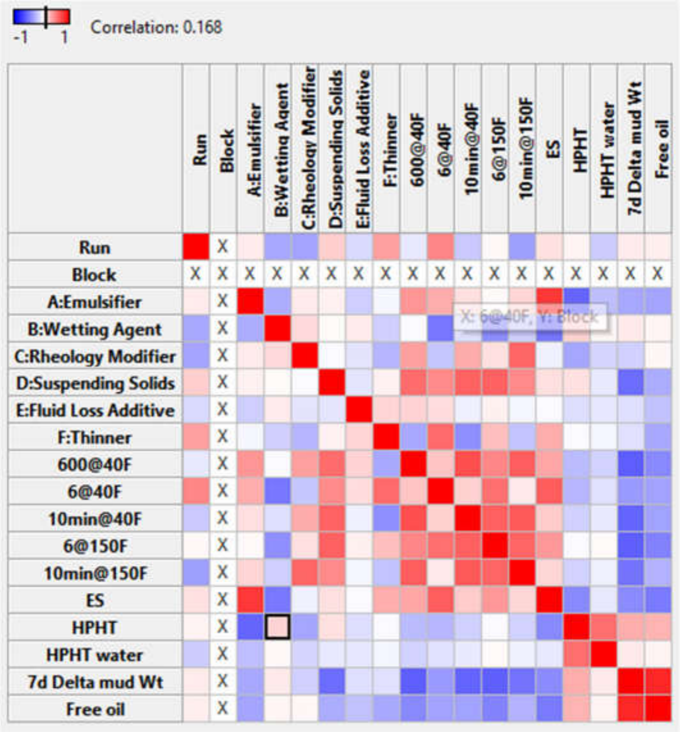
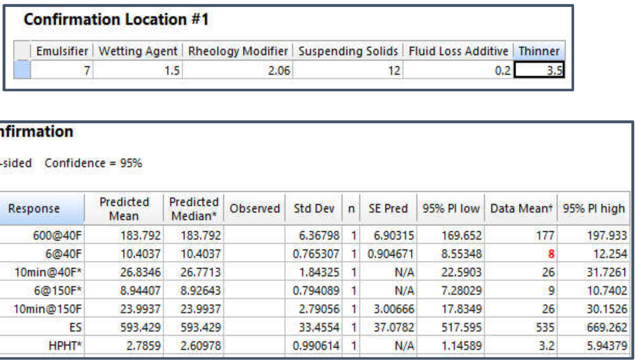


Figure 11. Heat map of additives and their effect on properties of interest. Red–increase in response value. Blue–decrease in response value.

Correlation is coded by positive or negative and magnitude; this is a useful educational tool to share a large amount of information in an easy-to-understand format. Another example is presented in Figure 9 showing how a particular property changes when component concentration is adjusted; as part of the software package, one can do virtual formulations and change the concentration of any given component and then observe how the system responds. One example of this dynamic analysis that is impossible by other means is to observe effect of surfactants on fluid loss.

Numerical Optimization of a Fluid Formulation Based on DOE Model

Data analysis, as described above, is applicable to understand trends as a function of one or multiple variable changes; however, an optimized fluid a combination of all factors fitting the requirements to the best of our ability. With a DOE model we can optimize multiple parameters at once. Figure 12 (top chart) shows a computer-generated solution based on input requirements for low viscosity 14.3 ppg 77/23 OWR fluid, bottom chart shows predicted results and actual measured results. As shown in the chart, the only property outside the predicted range is 6 rpm at 40 degF and that is most likely related to poor temperature control of the sample and resolution of FANN 35 that we address with introduction of automated rheometer.



Confirmation Location #1

Emulsifier	Wetting Agent	Rheology Modifier	Suspending Solids	Fluid Loss Additive	Thinner
7	1.5	2.06	12	0.2	3.5

Confirmation

Two-sided Confidence = 95%

Response	Predicted Mean	Predicted Median*	Observed	Std Dev	n	SE Pred	95% PI low	Data Mean†	95% PI high
600@40F	183.792	183.792		6.36798	1	6.90315	169.652	177	197.933
6@40F	10.4037	10.4037		0.765307	1	0.904671	8.55348	8	12.254
10min@40F*	26.8346	26.7713		1.84325	1	N/A	22.5903	26	31.7261
6@150F*	8.94407	8.92643		0.794089	1	N/A	7.28029	9	10.7402
10min@150F	23.9937	23.9937		2.79056	1	3.00666	17.8349	26	30.1526
ES	593.429	593.429		33.4554	1	37.0782	517.595	535	669.262
HPHT*	2.7859	2.60978		0.990614	1	N/A	1.14589	3.2	5.94379

Figure 12. Model prediction of components to be used to achieve a thin fluid meeting a complex set of requirements. Data Mean is measured values based on actual mixed fluid from a computer recommendation (top chart).

An additional advantage of a model is that if the fluid that is computer-generated fails some type of test or job-specific requirement we can apply institutional knowledge and force constraints on the fluid to come up with a better formulation. For example, using lower emulsifier dosage is preferred to get a thinner system; as previously discussed, using ultra low emulsifier means the fluid will experience issues sooner without treatment as drill solids start to accumulate. Based on this type of knowledge, and specifics of a drilling operation it may be advisable to accept rheology compromises in a fluid that means the fluid demands less monitoring. Alternatively, a highly tuned fluid can be created that will require more attention from the mud engineer to maintain mean performance.

Another benefit of DOE digital models is increased ability to reject erroneous measurements or results from prepared fluids. Occasionally, when remixed a formulation that was previously deemed acceptable generates spurious results. In this case, the formulator ends up with two different sets of data from the same fluid without knowing which data set is correct. Consequently, troubleshooting is required to determine the root cause of the deviation and additional replicates are created and results are compared. These activities are generally un-planned and result in delays when coming up with a fluid recommendation.

With DOE, it is easier to spot the outlier to the general trend. In Figure **13**, the outlier is indicated by the red arrow. With a substantial data set fitting a pattern, it is now easier to dismiss an erroneous result and avoid chasing false leads or discard promising directions when optimizing a fluid formulation.

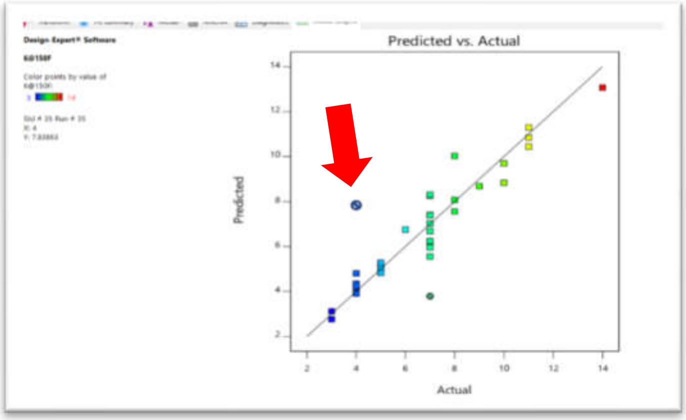


Figure 13. Data points for the model showing good correlation between predicted and actual values vs a questionable data point (actual four, predicted eight).

Conclusions.

Experiment design and automation have been successfully used to accelerate drilling fluid development via increasing throughput, more accurate measurements, and better data utilization. The digital fluid model obtained via design of experiments and response surface method is accurate across a wide range of conditions, helps clearly communicate property-composition trends and dependencies, and has an excellent predictive ability for formulation of optimized fluids.

Realizing synergies of digital modeling and automated measurements, we produced exceptionally stable fluid systems and successfully tested them to 325 degF. Comprehensive optimization of all components simultaneously decreased the complexity of the fluid by reducing the number of components and yielded a high-performing mud system with lower OWR than was previously possible for improve cost structure.

Digital models of drilling fluids are a part of the digital enablement strategy to enable automated drilling operations in the future. The surface response maps created in the lab will be combined with real-time mud measurement data to create accurate recommendation of a fluid maintenance plan to achieve desired drilling performance.

Acknowledgments

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Nomenclature

HPHT – high pressure high temperature
RSM – response surface methodology
DOE – design of experiments
OWR – oil water ratio

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