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The Missing Pressure Factor in Deepwater SBM

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Abstract

Synthetic-based invert drilling fluids (SBM) with desired rheological properties are used in deepwater drilling to manage downhole ECD and meet other complex challenges. The traditional approaches include fluids with low organophilic clay content and rheological modifiers to reduce the viscosity at 40 °F (mud line) and increase viscosity at elevated temperature to achieve a constant profile downhole. It certainly brings benefits such as low gel strength in riser after shut-in; however, constant rheology is difficult to achieve practically as drill solids affect the overall clay content. The reduction in use of additives can lead to unstable emulsions. More importantly, the pressure effect is sometimes not quantitatively considered in fluid design process although it impacts downhole rheological properties dramatically.

This paper presents a unique composition-temperature-pressure 3-dimensional approach to design a deepwater SBM. The ratios between the selected additives were found to be a key in responses to temperature and pressure ranges from 40 °F to 300 °F and ambient to 30,000 psi. The combination of laboratory formulations, HTHP rheological measurement and hydraulic modeling has led to the development of a new generation synthetic-based deepwater drilling fluid. It was designed specifically to provide a downhole rheological profile that minimizes dynamic pressure loss through the ranges of deepwater temperatures and pressures while meeting all other critical parameters such as fluid loss and filter cake quality, contaminant tolerance, emulsion stability and environmental compliance. In combination with the hydraulic software, it provides a reliable solution for drilling deepwater wells, especially in a tight equivalent circulation density (ECD) window environment.

Introduction

Since the 1980's, the advancement of drilling fluids has become an essential part of deepwater oil and gas exploration. The harsh environment poses unique requirements for the fluid properties. Although the definition of deepwater varies, it normally means a water depth of 1,000 feet or more, which means the mud line (ML) temperature can reach sub 40 °F, significantly lower than the surface temperature. The water depth also affects the subsurface geopressure profile which leads to a narrow drilling envelop between pore and fracture pressure (1) or mud weight/fracture gradient window. Therefore, accurate control and prediction of ECD is critical to minimize risks of lost circulation in low pressure zones and potential safety hazards (uncontrollable blow out) in high pressure zone. The rheological properties of drilling fluids determine the ECD and other drilling performance. Surge and swab pressures, and gel-breaking pressures are other important aspects to consider.

In offshore drilling, the fluid and cuttings have to be compliant with current environmental regulations. In the Gulf of Mexico (GoM), the U.S. Environmental Protection Agency (EPA) governs discharge of drilling cuttings with SBMs. In GoM, it requires that the base fluid contain less than 10 ppm poly-aromatic hydrocarbons (PAH), create no visual sheen on the water surface and pass kill tests with Mysidopsis Bahia shrimp and Leptocheirus Plumulosis amphipod. Water-based mud (WBM) does have environmental advantages but it often shows limited performance (2), such as hydrate formation; therefore, invert emulsion drilling fluids are preferred. Internal olefin (IO), IO/LAO (linear alpha olefin) blends and esters are the fluids of choice in toxicity and biodegradation tests. IO16-18 has been mostly used in GoM in the last two decades.

Temperature and Pressure Effect on SBMs

Like any fluid, synthetic-based muds (SBM) is affected by temperature and pressure in terms of physical and rheological properties. The physical properties are relatively easy to predict based on the available PVT data of the base fluid and internal phase, as they make up the majority of the fluid. On the other hand, the rheological properties are more complicated to predict. As seen in the analysis shown in figure 1, the rheological properties are governed by the fluid composition especially viscosifiers, emulsifiers and rheology modifiers. In the field, shearing history changes the rheological properties as well. More importantly, the rheological properties vary dramatically with temperature and pressure. Figure 2 shows a qualitative analysis of temperature and pressure effect on SBM rheological properties.

In deepwater environments (such as GoM), temperature ranges from sub 40 °F up to 350 °F and pressure can be up to 30,000 psi. In general, SBM thins with temperature. For conventional SBMs with organophilic clays, the viscosity and gel strength become very high at cold temperature (40 °F), which is the limiting factor for using conventional SBMs in deepwater. Certainly, SBMs can also get thick when exposed to temperature exceeding 350 °F where the additives, especially emulsifiers, undergo chemical reaction or degradation leading to gelation. The effect of pressure is relatively straight forward, as viscosity increases with pressure as the fluid density increases. However, it is complex to predict the fluid rheological properties in a deepwater environment where temperature and pressure change simultaneously. As shown in figure 2c, with the depth of a deepwater well, the fluid temperature can reach 40 °F at mud line. Below the mud line, the fluid temperature goes up with the formation temperature. At the same time, the pressure continuously increases with the true vertical depth (TVD).

Constant or flat rheology SBM

One approach the industry has taken in the last two decades was the development of constant (3) or flat rheology (4) SBM. The main concept is to minimize or eliminate the detrimental effect of organophilic clay at cold temperature. One approach is to reduce the use organophilic clay and compensate it with a rheology modifier (4), while the other way is to replace organophilic clay completely with a polymeric or solid viscosifier (5).

The emergence of constant or flat rheology fluids has been successful especially in GoM in terms of mitigating the temperature effect and reducing operational challenges with conventional fluids; however, there are both pros and cons (6,7).

- The development criteria often require a strict flat yield point (YP) profile from 40 °F to 150 °F, which can be an overkill as other properties are sacrificed.
- Yield point values do not relate directly to consistent ECD. Low shear-rate yield point (LSYP) is a better indicator for optimizing ECD, hole cleaning, barite sag and surge and swab pressures (8).
- The rheological properties beyond 150 °F are often underestimated.
- Although the temperature effect is more predominant than pressure (9) especially above mud line where pressure is normally less than 5000 psi, the pressure effect has to be addressed also.
- The surface pressure viscosity is often used to predict downhole behavior, which can be misleading.
- An overcorrection on temperature effect can lead to higher viscosity especially when pressure exceeds 10,000 psi.
- The interactions between the additives in an invert fluid are complicated. There are synergistic and antagonistic interactions. More additives can make it difficult to maintain and predict.
- The minimum use of clay is practically hard to maintain with effect of drill solid.

Development of a 3-D SBM

The analysis above leads to the demand for a new generation of deepwater SBM. Although the effect of pressure on deepwater fluids are usually monitored and discussed in the industry, it has not been quantitatively used in the fluid formulation development. A composition-temperature-pressure 3-dimentional approach is utilized here to develop the new generation deepwater SBM. The innovation was to employ HTHP viscometer analysis and hydraulics modeling in the process of developing SBM formulations in order to optimize the interactions of the chemicals to balance the temperature and pressure effect, as shown in Figure 3.

The development took place in steps that includes selecting proper chemistry and products, investigating interactions between components by monitoring the fluid properties with both conventional and HTHP viscometers, using hydraulic modeling to obtain the downhole fluid behaviors (ECD) and then further optimizing the fluid chemistry. The key was in identifying the direct relationship between the chemistry and fluid downhole behavior.

Being an invert emulsion with abundant solids, SBM has been studied extensively in the industry (10). For instance, there was a recent study that indicated the relationship between the response to temperature of the interfacial tension to the flat rheological properties of SBMs (11), but it is still not possible to develop a clear structure-performance relationship due to the complexity of the system. The emulsion stability is determined by the physico-chemical behavior of the compounds, more specifically the molecular structure of the surface active reagents or emulsifiers and the interactions at the liquid and solid interfaces. As the continuous phase (base oil) is viscosified by either organophilic clay or polymeric viscosifier, it affects the overall fluid properties dramatically especially the sensitivity to temperature and pressure. A slight change in the component can result in unpredictable downhole behavior. Therefore, the best approach is to measure the rheological properties under simulated downhole conditions to provide direction for formulation modification.

Parameters for a typical GoM deepwater well were received from a customer and used as the base for the temperature and pressure matrix and hydraulic calculation. The temperature and pressure at 5 depths were selected and incorporated in the HTHP viscometer matrix to evaluate the fluid behavior under downhole conditions. The HTHP viscometer data were used to develop a 3-dimensional rheology-pressure-temperature data cube that enumerated the effect of temperature, pressure, and shear rate on the shear stress. A 3-D interpolation technique was then used to curve-fit the temperature-pressure data, and was used to determine the downhole rheological property at any given combination of temperature and pressure. A sophisticated transient temperature profile model was developed and utilized to determine downhole temperatures under circulating and static conditions. A numerical integration approach was taken to determine downhole pressures based on a PVT-compositional model that separately analyzes the temperature and pressure effects on the density of the liquid phases in the mud. Circulating pressures were

calculated considering temperature and pressure dependent density and rheology.

Figure 4 shows the three phases of the development, as represented by SBM A, SBM B and 3-D SBM. The corresponding LSYP and ECD are shown in figure 5. In phase 1 development (SBM A), the target was set to develop a constant rheology fluid using the common industry standard of minimum change from 150 °F to 40°F (< 20% variation in yield point at surface). The fluid certainly behaves better than conventional SBMs in terms of cold temperature viscosity and ECD but the trend downhole was of concern as the pressure overcorrected the thinning effect due to temperature. The organophilic clay content was kept at a minimum level and compensated by a rheology modifier. In phase 2, the criteria were modified slightly to allow more variation on the fluid viscosity under ambient pressure. The downhole LSYP curve remains fairly constant with improvement on the overall ECD. It was demonstrated that constant rheology at ambient pressure does not provide constant downhole rheology. Allowing for some variation with temperature was actually beneficial in terms of balancing the temperature and pressure effect. HTHP viscometer analysis and hydraulic simulations were both closely used in phase 1 and phase 2 and resulted in the development of 3-D SBM in phase 3. The downhole fluid behavior was found to be sensitive to not only the dosage of the additives but also the relative ratios, as each additive responds differently to temperature and pressure. By controlling the ratios in the fluid formulation, the downhole rheological properties remain fairly constant for the simulated deepwater well. The overall ECD was improved significantly. The basic properties of a 12 lb/gal 3-D SBM are shown in tables 2 and 3. One point to note is that the YP and LSYP are not strictly flat at ambient pressure.

As shown in figure 5, 3-D SBM shows significantly improvement over SBM A and SBM B in terms of downhole LSYP and ECD. The delta LSYP and delta ECD were calculated as the difference between maximum and minimum values, which indicates how constant fluid properties were downhole. The LSYP curves indicate the perfect balance in 3-D SBM formulations that accounts for temperature and pressure effect simultaneously. The surface density was 12.0 lb/gal and the ECD increased to 12.46 lb/gal in both SBM A and B, while the increase was reduced by 22% for the 3-D SBM. The improvement is significant in a deepwater well with very narrow mud weight/fracture ingredient window.

Certainly, the rheological behavior at cold temperature (40 °F) cannot be underestimated. Figure 6 shows the comparison between a conventional SBM and the 3-D SBM under shut-in condition. The simulated temperatures and pressures are marked along with depth. Data were collected setting the HTHP viscometer to the indicated temperature and pressure values for an extended period of time. At 40 °F and 5500 psi (simulated mudline), PV, YP and LSYP of 3-D SBM were significantly lower than the conventional SBM. Long term gel strength were also investigated and it was confirmed that 3-D SBM has non-progressive gels (over 1-hr).

The 3-D SBM can be formulated up to 17 lb/gal without losing constant downhole properties under temperature and pressure. The fluid is also tolerant to drill solid, carbon dioxide, seawater and cement contamination. The downhole behavior was not significantly impacted by contaminants as confirmed by HTHP viscometer analysis and subsequent hydraulic simulations. Emulsion stability and barite sag were investigated as well and the fluid showed excellent performance. The fluids shows good stability to 350 °F. The oil separation at 250 °F and 15,000 psi was seen to be minimum after static aging for 168 hours.

Environmental and cost aspects

The 3-D SBM developed is fully compliant with current GoM regulations. It passes the 96-hour LC50 test, 10-day sediment toxicity test and the sheen test at a certified third party lab. As the ratio of the additives are well defined in the fluid, it provides simple field guideline and procedures, and ensures compliance when formulations have to vary to meet changing requirements.

The current downturn has proven to be severe and is reshaping the industry. Calling for more cost-effective products is almost a must and it will be the same for deepwater drilling fluids. The 3-D SBM utilizes very cost-competitive products and contains limited numbers of additives to maintain simplicity for field application, which will be a key to assure a smooth and safe deepwater drilling.

Conclusions

The harsh operational and geological environment requires constant rheological properties for drilling fluids. A lot of effort has been focused on minimizing the cold temperature viscosity, while the pressure effect has not drawn sufficient attention especially on how to balance the temperature and pressure effect in order to control the downhole properties.

SBMs with constant or flat rheology has been the fluid of choice over the past two decades for deepwater but the constant behavior at ambient pressure does not equate to a constant downhole behavior.

A new generation 3-D SBM was developed by incorporating extensive HTHP rheology measurement, hydraulic simulation and formulation designs. The 3-D SBM does not show a strict constant profile at ambient pressure but provide a constant downhole behavior, which results in much better ECD control.

The 3-D SBM is simple to employ and maintain in the field while fully compliant with GoM regulations.

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Nomenclature

Define symbols used in the text here unless they are explained in the body of the text. Use units where appropriate.

SBM = *Synthetic Based Mud*
LSYP =*Low-Shear Yield Point*
YP =*Yield Point*
PV = *Plastic Viscosity*
ECD = *Equivalent Circulation density*
WBM = *Water Based Mud*
ML = *Mud Line*
ppg = *Pounds Per Gallon*

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Table 1. Components of the 3-D SBM

	Function	Concentration
IO 16-18	Continuous phase	As Required
Surfactants	Primary Emulsifier / Wetting Agent	6-15 lb/bbl
Rheology modifier	Rheological Modifier	< 2 lb/bbl
Organophilic Clay	Viscosifier	As required
Polymeric fluid loss reducer	HTHP filtrate reducer	< 3 lb/bbl
Calcium Chloride brine	Internal phase	As required
Lime	Alkalinity Control	As required
Viscosifier	Temporary Viscosifier	As needed

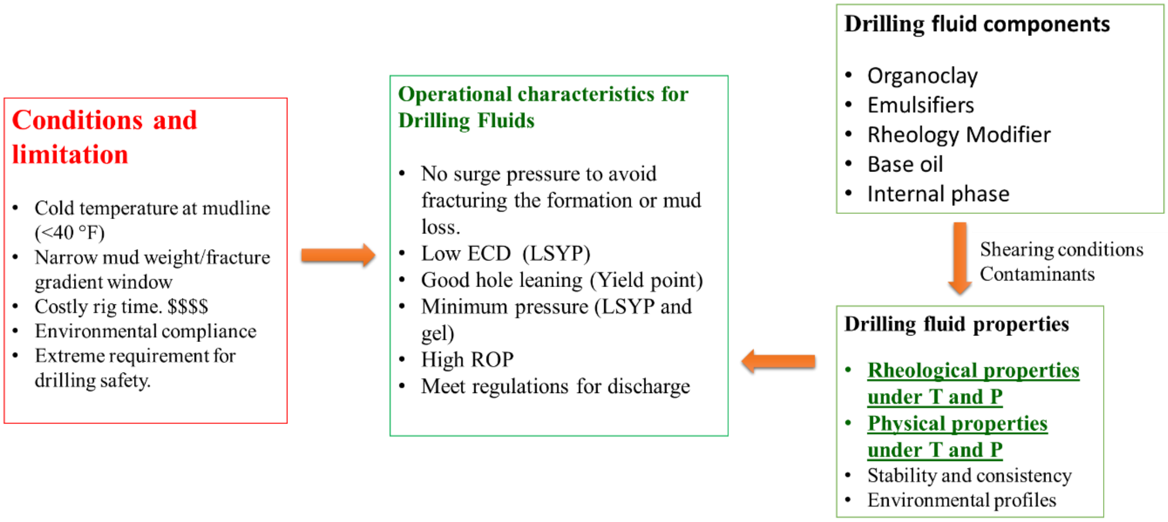
Table 2 a typical rheological profile at ambient pressure of the 3-D SBM

Rheology Temp. @°F	40	100	120	150
Pressure (psi)	0	0	0	0
600 rpm reading	101	64	56	46
300 rpm reading	58	40	35	28
200 rpm reading	43	31	26	20
100 rpm reading	27	21	18	14
6 rpm reading	10	10	8	6
3 rpm reading	9	9	7	6
Plastic viscosity, cP	43	24	21	18
Yield point, lb/100 ft^2	15	16	14	10
LSYP	8	8	6	6
10-sec Gel, lb/100 ft^2	11	12	11	10
10-min Gel, lb/100 ft^2	18	17	13	9
30-min Gel, lb/100 ft^2	20	16	15	11

Table 3 Fann-77 data on the 3-D SBM

Rheology Temp. @°F	43.2	43.2	43.2	66.7	66.7	66.7	101.1	101.1	101.1	153.7
Pressure (psi)	0	5249	8056	0	2211	5091	0	5266	8282	5258
600 rpm reading	96.1	170.6	204.5	61.8	85.3	101.3	52.2	69.9	83.2	52.6
300 rpm reading	63.6	100.8	119.4	47.5	52.7	61.8	37.6	46.2	53.6	34.6
200 rpm reading	50.7	74.1	87.3	37.6	41.9	49.3	31.3	36.9	42.4	27.7
100 rpm reading	37.2	47.1	54.1	24.9	29.9	34.6	21	25.6	29.2	19.4
6 rpm reading	15.7	18.7	19.5	12.3	14.7	16.3	10.5	11.7	12.5	10.5
3 rpm reading	15.2	17.6	17.8	11.6	14.1	15.6	9.6	10.9	11.5	10.2
Plastic viscosity, cP	33	70	85	14	33	40	15	24	30	18
Yield point, lb/100 ft^2	31	31	34	33	20	22	23	23	24	17
LSYP	15	17	16	11	14	15	9	10	11	10
10-sec Gel, lb/100 ft^2	11	11	11	12	12	12	12	12	12	10
10-min Gel, lb/100 ft^2	18	18	18	19	19	19	17	17	17	9
30-min Gel, lb/100 ft^2	20	20	20	22	22	22	16	16	16	11

Rheology Temp. @°F	153.7	153.7	204.5	204.5	204.5	255	255	255	304.2	304.2	304.2
Pressure (psi)	9327	12929	8118	10085	15205	12603	15258	20095	18179	20255	25072
600 rpm reading	62.5	72.5	46.6	55.6	64.8	49.6	53.9	60.4	49.6	51.7	56
300 rpm reading	41.4	48.2	31.5	35.1	42.6	31.6	34.8	40.4	33.5	35.3	39.3
200 rpm reading	32.7	37.9	25.4	27.9	33.5	25.6	28.1	32.3	28.1	29.1	32.5
100 rpm reading	22.4	25.5	18	19.5	23.1	18.5	20.1	22.9	21.3	22.3	24.3
6 rpm reading	11.2	11.7	10.7	11.2	12.1	11.4	11.9	12.6	10.3	10.8	12
3 rpm reading	10.6	10.8	10.4	10.7	11.4	10.6	10.9	11.7	8.3	9.1	9.9
Plastic viscosity, cP	21	24	15	21	22	18	19	20	16	16	17
Yield point, lb/100 ft^2	20	24	16	15	20	14	16	20	17	19	23
LSYP	10	10	10	10	11	10	10	11	6	7	8
10-sec Gel, lb/100 ft^2	10	10	10	11	11	12	12	12	13	13	13
10-min Gel, lb/100 ft^2	9	9	10	11	11	12	12	12	13	13	13
30-min Gel, lb/100 ft^2	11	11	11	12	12	13	13	13	14	14	14



Conditions and limitation

- Cold temperature at mudline (<40 °F)
- Narrow mud weight/fracture gradient window
- Costly rig time. $$$$
- Environmental compliance
- Extreme requirement for drilling safety.

Operational characteristics for Drilling Fluids

- No surge pressure to avoid fracturing the formation or mud loss.
- Low ECD (LSYP)
- Good hole leaning (Yield point)
- Minimum pressure (LSYP and gel)
- High ROP
- Meet regulations for discharge

Drilling fluid components

- Organoclay
- Emulsifiers
- Rheology Modifier
- Base oil
- Internal phase

Shearing conditions
Contaminants

Drilling fluid properties

- **Rheological properties under T and P**
- **Physical properties under T and P**
- Stability and consistency
- Environmental profiles

Figure 1 Analysis of deepwater drilling fluid

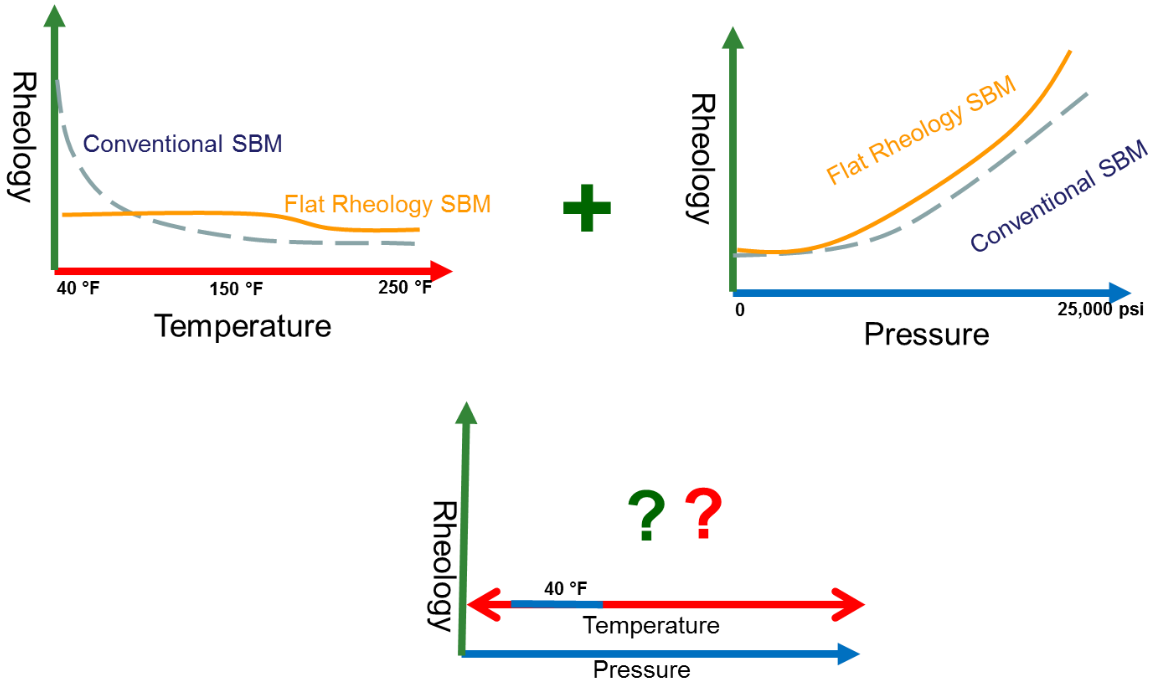


Figure 2 Trends of temperature and pressure effects on SBM rheological properties

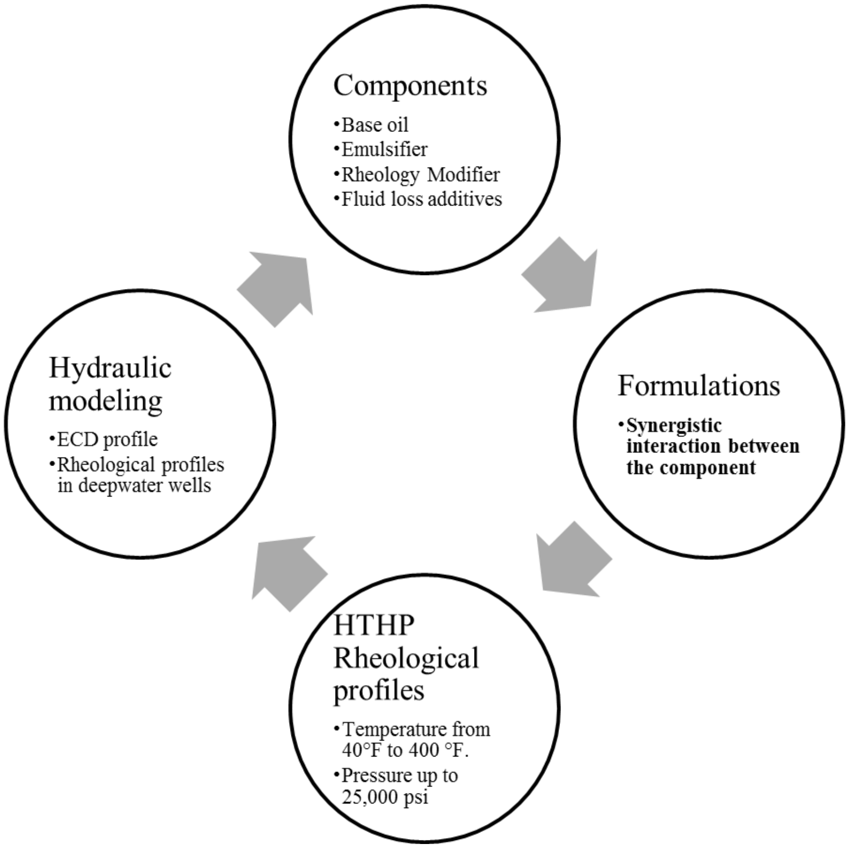


Figure 3 Development strategy of a 3-D SBM

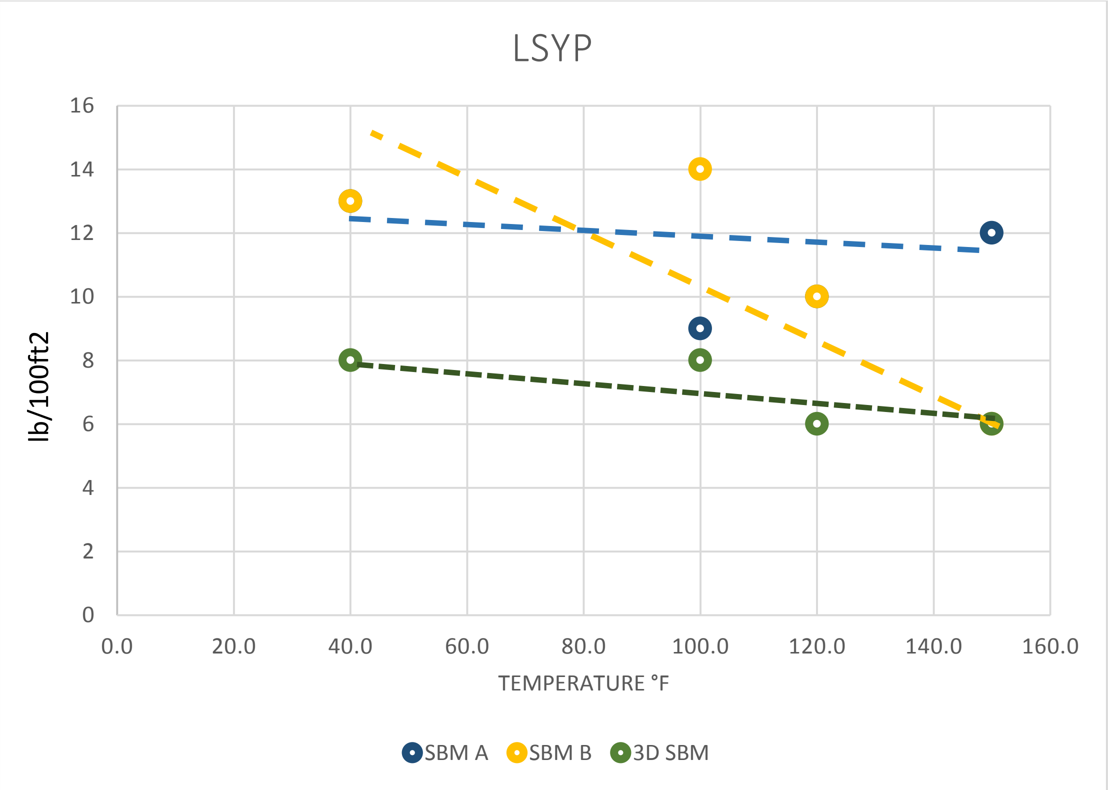
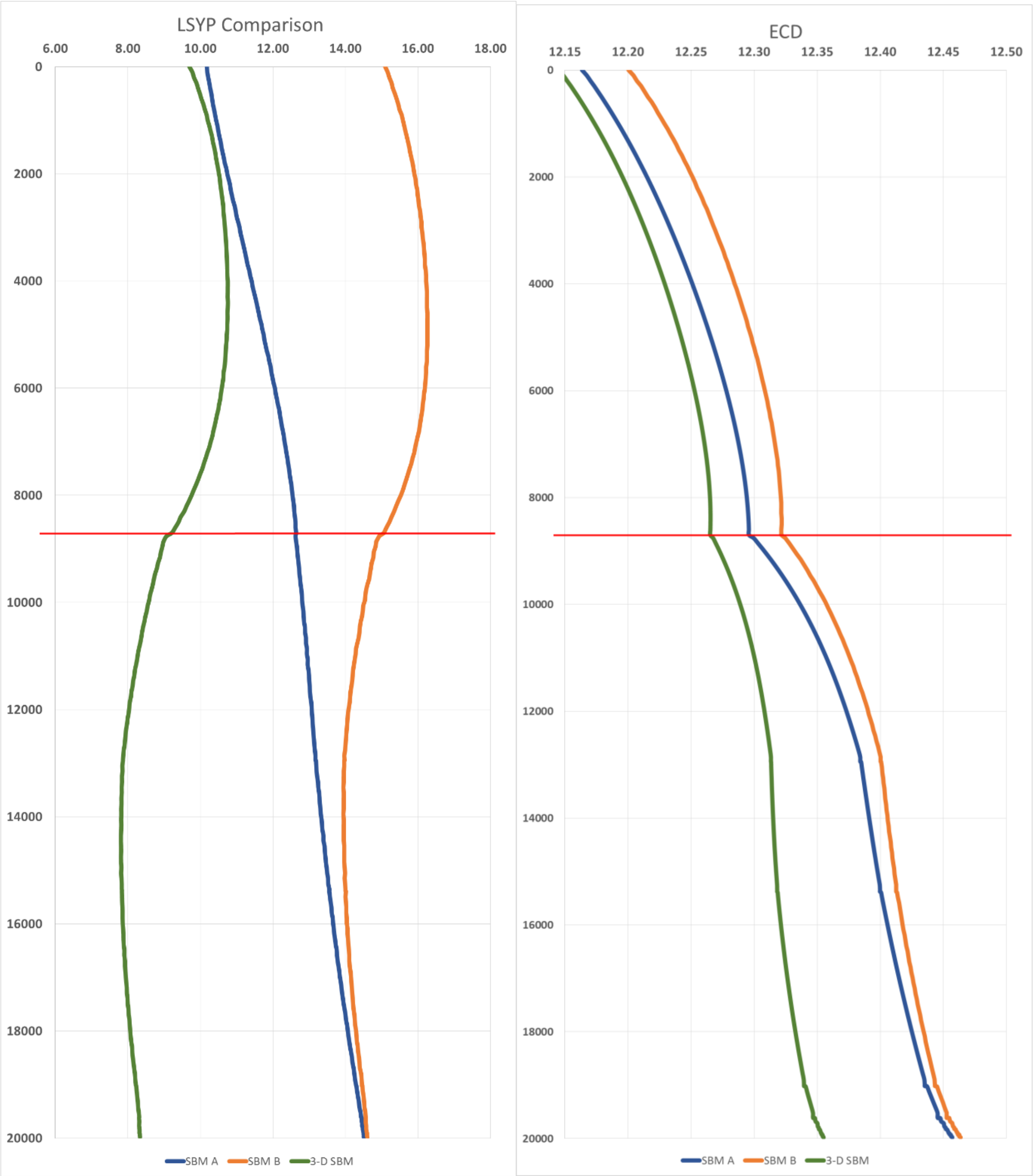


Figure 4 LSYP of SBM A, SBM B and 3-D SBM



SBM A	
Surface Density =	12 lb/gal
Δ LSYP =	4.34
Δ ECD =	0.29
Max ECD =	12.46

SBM B	
Surface Density =	12 lb/gal
Δ LSYP =	2.32
Δ ECD =	0.26
Max ECD =	12.46

3-D SBM	
Surface Density =	12 lb/gal
Δ LSYP =	2.95
Δ ECD =	0.21
Max ECD =	12.36

Figure 5 LSYP and ECD in a GoM deepwater well under circulation.

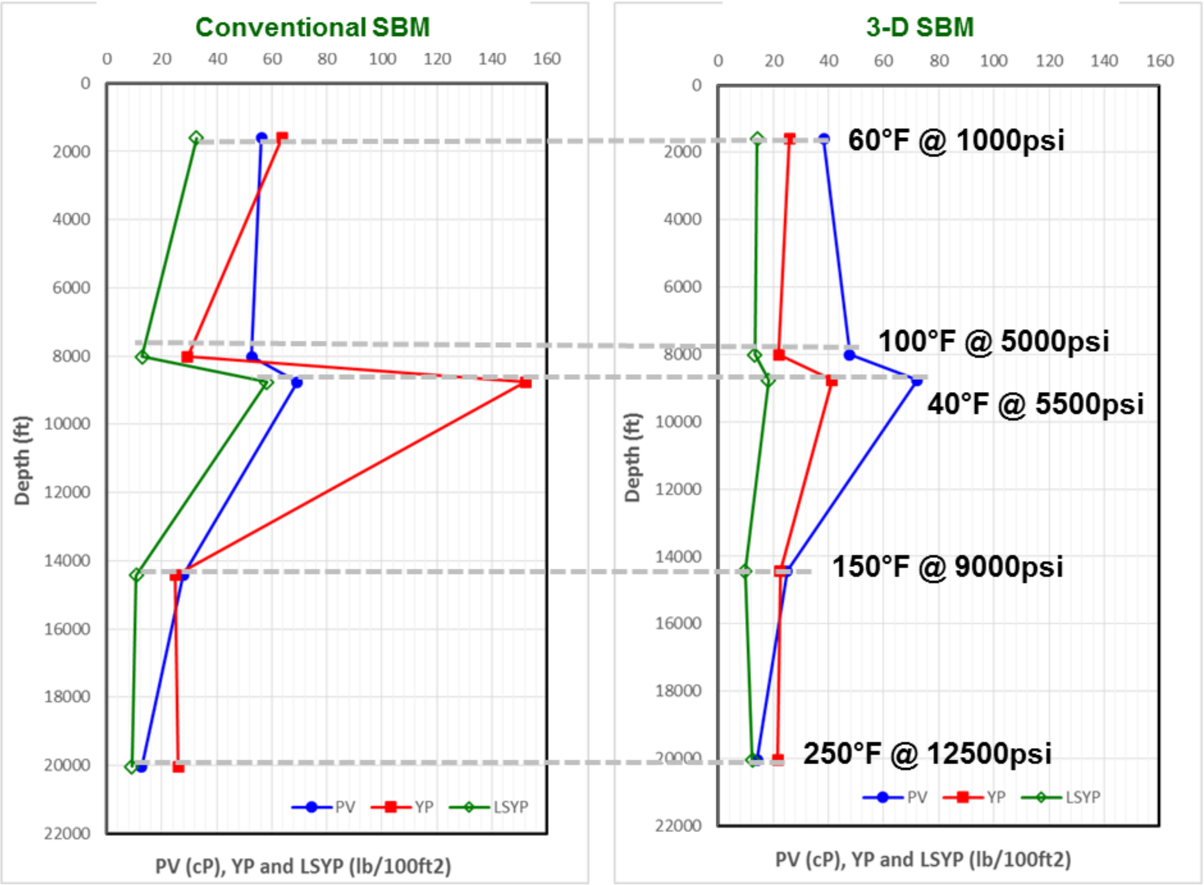


Figure 6 PV, YP and LSYP in a GoM deepwater well in comparison to a conventional fluid (Simulation data)