

Engineered Offshore Displacements: Description, Tools, and Field Results

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Abstract

A critical phase of preparing the well for the completion operation is the wellbore cleanup (WBCU) and displacement, which is done to transition the well from a drilling fluid to completion brine and remove residual material from the wellbore. The displacement performance can significantly impact the completion operations, and thus the wellbore productivity. Operators and service companies alike generally recognize that engineered displacements reduce operating costs, decrease non-productive time, and minimize the risk of failure for subsequent completion operations.

A successful displacement requires not only an appropriate spacer train design, but also optimization of the operational parameters. The contribution of these factors to the overall displacement performance can be categorized into three aspects: chemical, hydraulic and mechanical. In most cases, the operational parameters are limited by the well design and rig equipment.

Engineering software for WBCU operations model pump rates, flow profiles, annular velocity, coverage and contact times for elements of the spacer train. This paper presents and discusses use of the software in the development and field applications of engineered displacements for Gulf of Mexico deepwater completion operations, compares predictive models with field data from two wells, and discusses common practices for spacer train design.

Engineered Displacement

An engineered displacement involves following best practices based on prior successful experience, chemistry for the transitional fluids specific to the displacement being designed, selecting the appropriate equipment, evaluation using software for hydraulics calculations, and collaboration between the operator, service providers, rig personnel, and material/tool vendors. Poorly designed displacements can compromise subsequent completion operations due to issues associated with stuck packers, corrosion of tubulars, formation damage, issues with setting completion tools and cement placement, increased filtration time and cost, increased disposal costs and the inability to deliver expected production. Typical elements of an effective engineered displacement include: 1) circulating and conditioning the drilling fluid; 2) short-tripping the work string, 3) pumping a series of displacement spacers through the

wellbore, 4) rotating and reciprocating the work string and WBCU tools and 5) filtering the completion fluid to the desired cleanliness and solids levels. Failure to effectively displace the incumbent drilling fluid from the wellbore significantly complicates subsequent completion and tool operation. The approaches taken towards the hydraulic, chemical and mechanical elements of engineered displacements vary between open and cased hole displacements. Cased hole displacements center on removal of debris and residual drilling fluid, water-wetting tubulars, minimizing contamination waste volumes and filtration time. The objectives of open hole displacements are to clean the wellbore, permit installation of the lower completion assembly and removal of the reservoir drill-in fluid (RDF) filter cake.

Additionally, the type of displacement varies between direct and indirect displacements, with both forward and reverse circulation pathways. Direct displacements are commonly used on wells using non-aqueous fluids (NAF), with high daily costs. A typical example of a direct, cased hole displacement would be a Gulf of Mexico, deepwater displacement.

Best Practices for Direct Displacements

The focus of this paper is the engineered displacement, more specifically direct, cased hole displacements with NAF. To disseminate what are, in the authors' experience, some helpful rules of thumb for spacer train designs, some general best practices are now presented. Advantages of the direct displacement include shortened displacement times, reduced rig time and wastes generation, improved logistics and improved pressure profile. The primary downside to a direct displacement is the risk of poor displacement design, and the resultant cost implications for waste, rig time, fluid treatment and disposal. The term "engineered" displacement is often used to describe the direct displacement because the hydraulic, chemical and mechanical levers of the displacement must be effectively designed, integrated and executed in an engineered manner.

There are typically 4-5 fluids considered in an engineered, direct displacement. These are the: a) incumbent drilling fluid, b) base oil spacer (with NAF), c) transition spacer, d) cleaning spacer, e) viscous (tail) spacer and f) the completion fluid. An engineered displacement is designed to harmonize requirements for annular velocity, annular coverage, contact

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time and flow regime for each element of the spacer train.

Most direct displacements are pumped in the forward circulating direction, meaning the displaced fluids are pumped down the work string and up the annulus, with pressure applied to the drill string. This is the most commonly used pumping direction, with benefits around lowering differential and pump pressures, as well as minimizing the potential for plugging the bit. Reverse circulation is often used in pickling operations, when pumping flocculant pills or installing packer fluids. The displaced fluids are pumped down the annulus and up the work string, with pump pressure applied to the annulus.

The hydraulic design focuses on annular velocity and coverage, fluid types, contact time, flow direction and flow regime. Chemistry of the spacer train is important to ensure compatibility of neighboring spacer train elements, removal of residue, water-wetting and viscosity. Mechanical considerations include the use of specialized WBCU tools, filtration and pipe rotation and reciprocation.

Lastly, a high viscous tail spacer serves as a barrier between the cleaning spacer and the completion fluid. This tail spacer also finishes cleaning the wellbore, removing the remaining non-completion fluids, debris and particle residue. A 500 ft column in the largest annular cross section is often considered enough.

Spacer Train Design - Chemistry

The spacer designs require that each element is compatible with its neighboring fluid and this is verified via laboratory testing. The primary function of the transition spacer is removal of the incumbent drilling fluid from the wellbore. This spacer also functions as a physical barrier between the drilling fluid and spacer train. The transition spacer should have a column height between 500 to 1,500 feet in length along the largest annular cross section, which is typically the riser in a deepwater displacement. It is important that the density of the transition spacer, often referred to as a weighted transition spacer, is 1.0 – 2.0 lbs/gal higher than the incumbent drilling fluid. The rheological properties are adjusted to allow the transition spacer to act like a push pill, helping to break the gel strength of the mud and initiate movement of the residual drilling fluid. Due to the rheological properties and high density, this spacer is pumped in the laminar flow regime.

The role of the cleaning spacer is removal of drilling fluid residue from tubular surfaces, and to render those surfaces to a water-wet state. The cleaning spacer volume should be enough to allow for contact time of 5-10 minutes at the flow rate of interest, and with annular velocities ranging from 150-180 feet per minute. Additionally, the flow regime of the cleaning spacer should be in turbulent flow at this flow rate.

The final spacer is a high viscosity tail spacer. The tail spacer is designed with high suspension characteristics to sweep any remaining debris out of the well. This spacer is pumped in the laminar flow regime. Following the tail spacer, the completion brine is circulated into the wellbore.

Spacer Train Design - Hydraulics

Both offshore rigs for the wells presented in this paper had enough pumping capacity for the engineered spacer train project execution. The figure below shows an example rig pump for deepwater displacements.



The main considerations for rig pumps are the desired rates, the overall pressure limitations, and friction pressure losses predicted. Often the design includes a pump for the choke and kill lines, a pump for the boost line, and two pumps for the drill pipe. While the first displacement presented in this paper had two rig pumps available for the drill pipe, one of the pumps available for the second displacement (well #2) was offline during the displacement. After rerunning the hydraulics calculations, it was determined that the lead and cleaning spacers could still be pumped in turbulent flow and the jobs proceeded as planned with no issues.

Proper engineering analysis of downhole operations often requires software modeling due to the large number of complex calculations to consider. When evaluating the impact of a range of variables, such as rheological or density values, software becomes even more necessary. While the base calculations for frictional pressure losses, flow regimes, hydrostatic pressure, and other considerations for multiple density fluids present in the wellbore simultaneously is complex, the structure of the software is also critical.

A wellbore displacement software program has recently been developed to model placement, pump rates, flow profiles, riser boost, as well as annular coverage and contact times for each element of the spacer train. The software can model upwards of nine (9) flow paths and twelve (12) fluids used in a deepwater displacement. It also allows the user to run animated, two-dimensional simulations of the displacement scenario. Circulating temperatures, pressures, ECD, volumes, horsepower, and fluid compressibility are calculated and graphically presented to facilitate delivery of a competent displacement process, leading to reduced operational costs and

improved project economics.^{1,2,3}

In collaboration between the completion fluid service company and the hydraulic software provider, the best practices for spacer train design were added to the hydraulics software to assist with job planning (**figure 1**). An example of the design window used to assist in determining appropriate volumes of spacers for the spacer train is also shown in **figure 2**.

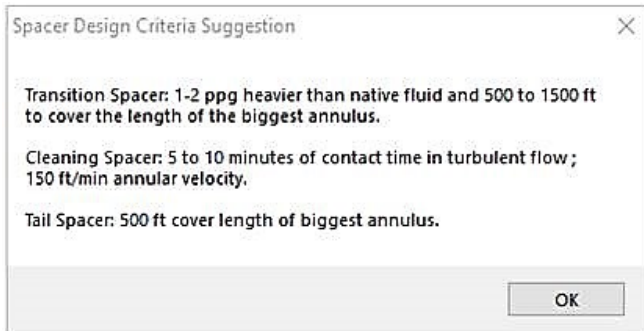


Figure 1: Spacer Train Design Best Practices

Fluid	Criteria	Ann. Vol. (bbl)	From (ft)	To (ft)	Ann. Len. (ft)	Top MD (ft)	Contact (min)	Ann. Vel. (ft/min)	Q (bpm)	Vol. (bbl)
1 base oil	Length				1500.0	2182.0				489.674
2 weighted transition	Length				1500.0	3682				320.986
3 chemical wash	Contact					5182	10	150	7.19	71.862
4 viscous spacer	Length				500	5198				23.954
5 brine	Ann. Vol. %	150								3354.938

Figure 2: Spacer Train Design Window

An existing hydraulics software using calculations tested over two decades was selected to plan the displacements. Extensive field validation conducted for pressure matching and the ability to model complex scenarios such as pressure and temperature dependent rheology and density changes were technical requirements. To facilitate proper planning and simplify the design process for complex flow paths common to offshore displacements, easy to use menus were developed as shown below (**appendix A**).

Deepwater engineered displacements are complex and require the WBCU software that can accurately model the hydraulics of the circulating system when displacing. Additional features to the software, to include intermixing/contamination calculations, have been developed for use in the WBCU software. Additionally, rotation and reciprocation calculations have also been established and validated to consider their impact on pressure losses and ECD during the displacement. Animations representative of the fluid paths and timing are also critical to the engineers' ability to verify the software inputs are the same as intended, and that the software is therefore running the appropriate calculations (**appendix B**).

Collaboration

Planning at all stages was collaborative between the operator, completion fluids provider, and various product vendors to ensure appropriate quality, availability, and correct use of all materials and tools. Completion engineers witnessed and evaluated the proposed spacer chemistry and testing methods at the lab testing facility. Modifications were also implemented to the hydraulics software to improve workflow and clarity for engineers during the job design process.

Collaboration for the engineered displacements involved training for the service company representatives involved in the job planning and execution. Though the personnel involved were experienced, the training was used as a refresher and an opportunity to plan the displacements. The specific chemistry of fluids involved was discussed by lab personnel and software training was conducted to ensure appropriate use of the calculation and planning tool available.

Job Design

Both wells considered for planning and post-job pressure matching with the hydraulics software were offshore wells in the Gulf of Mexico (GOM). The two wells were drilled and completed at a water depth approaching 4,500 feet, and with inclinations ranging from 10°-30°. Both wells were drilled using a drill ship capable of operating in water depths approaching 12,000 feet.

The pumping schedule for well #2 is shown below:

Stage 1 – Displace the incumbent SBF from the choke and kill lines with 15 bbls of base oil, followed by 15 bbls cleaning spacer, followed by 90 bbls brine at flow rates of 10 bbl/min.

Stage 2 – Direct displacement of the low-ECD SBF with 150 bbls of base oil, followed by 350 bbls weighted transition spacer, 300 bbls chemical wash, and 80 bbls viscous spacer, all at 13 bbl/min. This was followed by circulating approximately 3,000 bbls of completion fluid pumped at 13 bbl/min. Additional completion fluid was circulated down the pipe at 4.8 bbl/min while also boosted via the kill and boost lines to the riser at 10 bbl/min.

[Jet BOPs]

Stage 3 - Reverse circulated 100 bbls of flocculant-treated completion brine down the annulus and up through the kill line at 10 bbl/min. This was followed by circulating approximately 1,500 bbls of completion fluid at 10 bpm.

Field Data Comparison

Well #1

The pressure prediction vs. the field values were very close, with the trends accurately following the changeover to different density fluids, changing flow rates, and other parameters. Two hours into the displacement, the rig began rotating and reciprocating the work string while pumping, which had not been factored into the hydraulic simulation. The steady difference of roughly 1,500 psi due to pipe movement can be seen from 120 minutes through the end of that stage (**figure 3**).

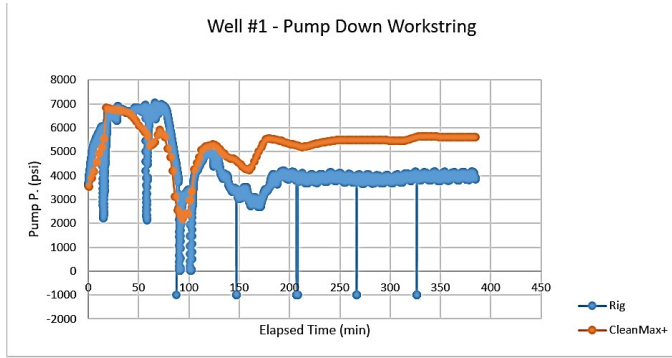


Figure 3: Pressure Match Well 1; Stage 1

From the hydraulic software, the predicted pump pressure through the drill pipe starts out at 2,000 psi until approximately 120 minutes, at which time the chemical wash enters the annulus and the pressure drops to approximately 1,400 psi by 180 minutes into the job. At this point the chemical wash enters a larger annular space, resulting in a further drop in pump pressure, albeit at a lower slope, to approximately 1,200 psi by 240 minutes into the job.

The pump requirements for boosting were lower as an additional pump was used. The pump pressures predicted were very similar to that seen during this stage of the displacement.

There were some problems with gathering pump information from the rig, resulting in the end pressures as the only known pressures for comparison. As the end pressure for this stage of the displacement match almost identically, and this is the only field value acquired, the pressure prediction was considered successful (figure 4).

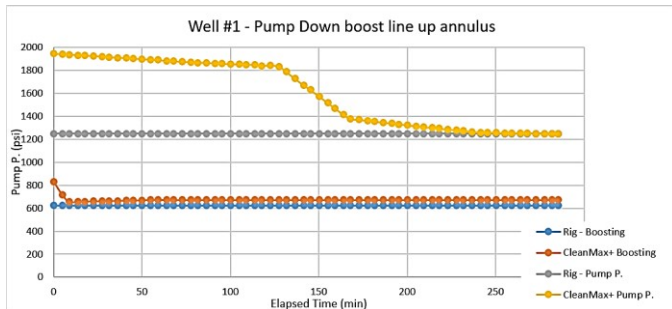


Figure 4: Pressure Match Well 1; Stage 2

Well #2

Reverse circulating pressure predictions in well #2 provided a slightly more conservative initial value that was reached by the rig pump within 20 minutes. This is also considered an excellent match (figure 5). The source of the initial difference in pump pressures is not known, though there are numerous downhole events that are difficult to measure. In the authors' experience, these slight differences are not uncommon.

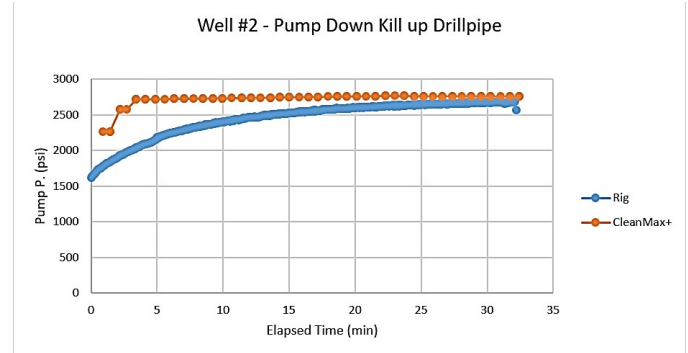


Figure 5: Pressure Match Well 2; Reverse Circulation

The engineered displacement software shows a clear increase in required pump pressure as the heavier fluid enters the annulus, though the rig pressures were only captured for the end of this stage. This predictive matching attempt was not as successful as most of the other stages. In this instance the hydraulic software predicted approximately 20% higher than the end value for the rig (figure 6).

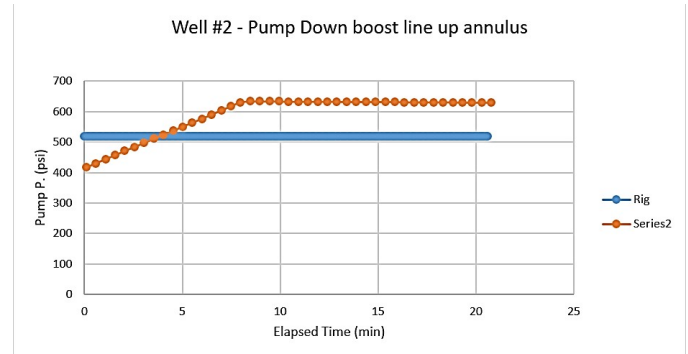


Figure 6: Pressure Match Well 2; Annulus

Pumping down the drill pipe while circulating the completion brine provided a very close match with the rig data, within a tolerance of 5% (figure 7).

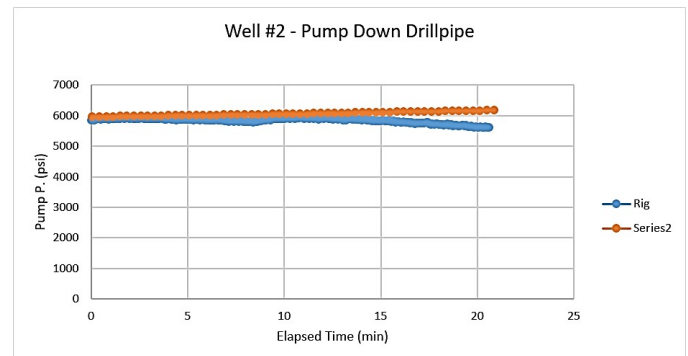


Figure 7: Pressure Match Well 2; Drill Pipe

Conclusions

There are many different aspects to appropriately engineering a deepwater displacement from an in-situ drilling fluid to a completion brine. Using the appropriate tools is a prerequisite for success. Appropriate training, collaboration, and planning are also critical to using those tools correctly.

Hydraulics software is a needed tool for complex wellbore cleanup operations, and there are programs available that can handle the challenges of multiple different densities through various combinations of flow paths. Software can also be customized and streamlined to allow for use in specific applications, like offshore displacements, to aid in the design and application process when designing spacer trains to successfully run in the turbulent flow regime, contact the annulus for a specified period of time, and other important design criteria.

In the case of the two offshore wells evaluated, pressure prediction was very accurate. The only significant difference was related to pipe movement, which has been noted and can be accounted for. Based off this experience in the GOM, correctly engineered displacement calculations can be trusted with a reasonable degree of accuracy to predict rig requirements and the ability to pump at the required rates to successfully clean and displace the wellbore.

Nomenclature

WBCU – wellbore cleanup

RDF – reservoir drill-in fluid

NAF – non-aqueous fluid

SBF – synthetic-based fluid

lbs/gal – density, pounds per gallon

ft – feet

ECD – equivalent circulating density

GoM – Gulf of Mexico

bbls – volume, oilfield barrels (42 gallons)

bbl/min – flowrate, barrels per minute

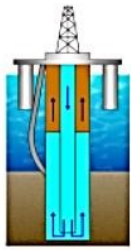
BOP – blow-out preventer

psi – pressure, pounds per square inch

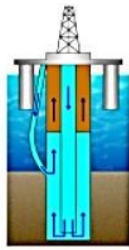
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3. Detiveaux, C., Gray, L., Kratzer, M., Chabaud, G., Smith, S., Riker, R., DeFrees, A., “Excellence Demonstrated on a Collaborative Team Approach to Deepwater GOM Completion Fluid Operations” AADE-20-FTCE-098, presented at the 2020 AADE Fluids Technical Conference and Exhibition held at the Marriott Marquis, Houston, Texas, April 14-15, 2020.

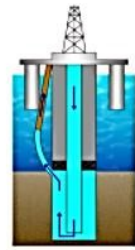
Appendix A: Flowpath Selection Window



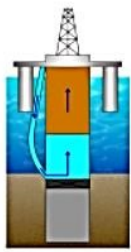
Forward - take return through riser



Forward and pump down CKB lines



Forward - take return through CK lines



Pump down CKB lines to clean up riser - Single line



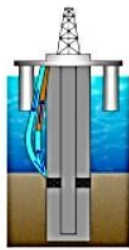
Pump down CKB lines to clean up riser - Multiple lines



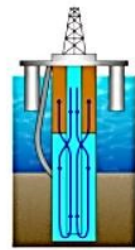
Reverse - pump down CK lines - Single line



Reverse - pump down CK lines - Multiple lines

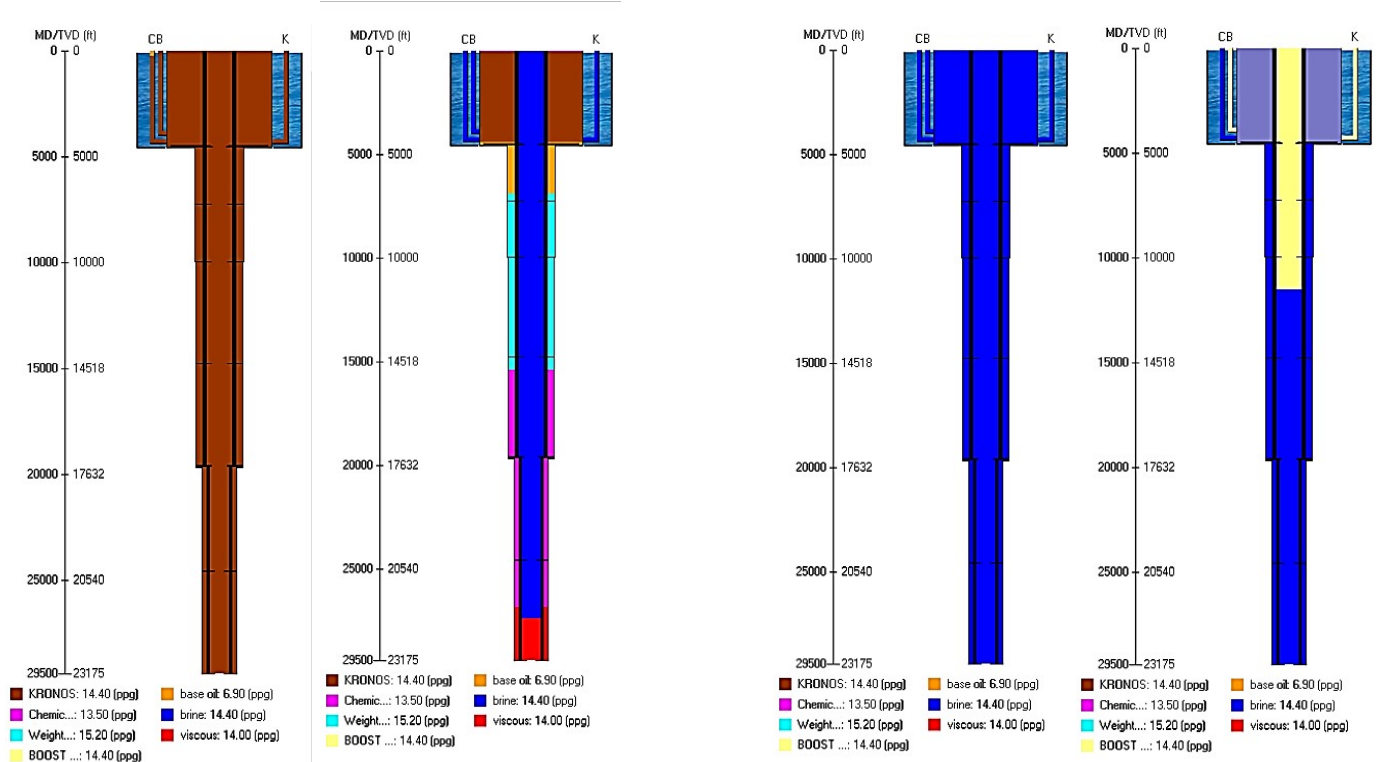


Pump down one CKB line and return through another



Gravel pack

Appendix B: Software Animation Well #1

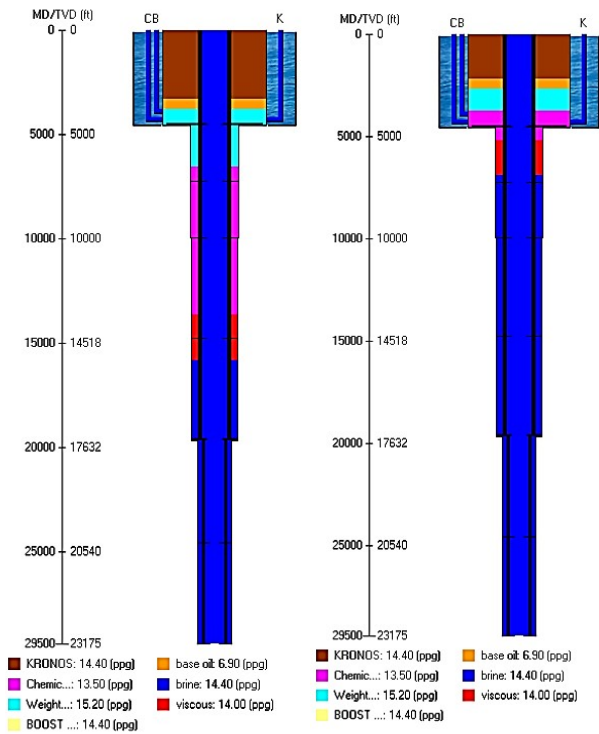


Original wellbore fluid (left) and Spacer Train (right)

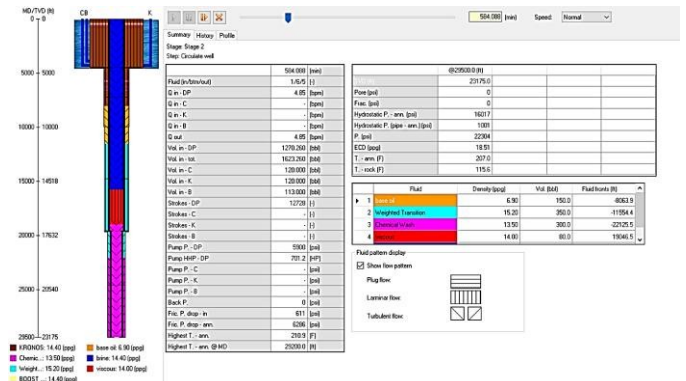
Brine Circulation Pre-Boosting (left)

Brine Circulation and Boosted Fluid (right)

-the brine pumped during boost is shown both in the choke/kill lines and in the pipe as yellow; the mixed boosted brine and previously pumped brine is shown as a grey color



Spacer Train and Initial Brine Displacement (both)



Representative output window with animation fluid schematic, tubular values, and flow regime visually represented. Numerous tabular or graphical displays of different variables are available.