AADE–02-DFWM-HO-10

Using Static "Rainbow" Charts to Design Dynamic Completion-Fluid Displacements

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Abstract

A completion-fluid displacement is an important well operation that can be complicated by various physical conditions and constraints. As such, this dynamic process can be difficult to plan without practical means to manage and synchronize key parameters. Described in this paper is an innovative displacement-design tool known as "rainbow" charts, so-called because of their distinctive graphical look. The charts are used in conjunction with standard graphs to display and analyze on a single sheet of paper the hydrodynamic aspects of a completion-fluid displacement. For comparison purposes, the method is applied to a Gulf of Mexico displacement that was originally designed using an effective, but more conventional spreadsheet approach.

A rainbow chart is a continuous plot of the position of each fluid in the annulus and work string throughout the displacement. Pressure and flow-rate curves positioned directly above or superimposed on a rainbow chart permit a vertical line drawn though all the graphs to precisely define key parameters at any specific time. Also, design overlays drawn on a rainbow chart assist in detailed analysis of certain parameters (such as flow regime) in any part of the well during any part of the displacement.

Perhaps the most important benefit of rainbow charts is that their framework makes it possible to address other pressing issues, such as the combined hydrodynamic and chemical effects related to wellbore cleaning. Comments on these issues and enhancement opportunities also are included in this paper.

Introduction

The first, and one of the critical steps in the completion process, is the displacement from drilling mud to clear-brine completion fluid. The objective of this operation is to provide a clean brine in a water-wet wellbore devoid of whole mud and mud film. This requires a properly designed and executed plan of hydrodynamic parameters, as well as chemical factors, particularly if synthetic or oil-based fluid are involved.

Displacement design[1] can be complicated by various physical conditions and constraints. Among these are multiple spacers and washes, persistent and tenacious synthetic-based mud films, wide differences in fluid density and viscosity, directional profiles, complex geometry configurations, and pressure, horsepower, and flow-rate limitations. Analysis of this dynamic process is particularly difficult without practical means to manage and coordinate key parameters. Conventional graphical techniques using computer spreadsheets have provided a step improvement in the displacement design process. However, this approach has inherent limitations.

The subject of this paper is an innovative tool that works in conjunction with standard graphics to optimize completion-fluid displacements. Known as "rainbow" charts because of their distinctive graphical appearance, their purpose is to synchronize key parameters on a single sheet of paper or static computer display. Currently, the charts are linked to basic hydrodynamic factors, including flow rates, volumes, and pressures (surface and downhole). Chemical factors also can be addressed; but this is under development and discussion in this paper is limited.

Engineered displacements using rainbow-chart examples are presented to show how the design process can be improved, simplified, and clarified. Much of this paper is based around a Gulf of Mexico displacement case history. Illustrative examples generated by a fit-for-purpose computer program also are included to demonstrate the flexibility of the overall rainbow-chart concept. However, the intended focus here is on the rainbow-chart concept and not the details of the software.

Displacement Design Using Conventional Graphics

A 10,770-ft (10,020-ft TVD) well from Vermilion 363 completed in 1997 was selected to illustrate use of the rainbow charts. **Table 1**, captured from the original spreadsheet, summarizes pertinent well data. The completion operation involved displacing 17.0-lb/gal water-based mud to 17.0-lb/gal $ZnBr_2$ completion brine in a wellbore having open perforations within the target sand interval. The spacer package consisted of (a) 50 bbl of 17.5-lb/gal viscosified, barite-weighted spacer followed by (b) 25 bbl of 8.6-lb/gal surfactant wash and (c) 50 bbl of 11.6-lb/gal viscosified $CaCl_2$. A 4.5-in. by 3.5-in. work string was installed inside 7.625-in. casing.

Pore pressure in the target BN-1 sand at 10,020 ft was 8,720 psi (16.74-lb/gal equivalent). Maximum allowable bottomhole pressure was estimated at 9,275 psi (17.8-lb/gal equivalent). Because of the dynamic hydrostatic-pressure profiles created by fluids of different density, the well had to be circulated on choke to keep the bottomhole pressure within the 555-psi operating window. Concurrently, the flow rate had to be as high as possible to promote proper wellbore cleaning by the wash spacer, without exceeding the bottomhole-pressure limit.

Two areas of particular concern are identified in **Table 1**. As seen in **Fig. 1**, the first one occurs at about 183 bbl when the low-density wash spacer reaches TD. The flow rate reduction from 2.25 to 1.5 bbl/min is required to keep the bottomhole pressure within range. Also at that point, the annular hydrostatic pressure begins to decrease rapidly as the wash spacer enters the annulus. Back pressure is required to keep the bottomhole pressure above the pore pressure from there forward. The second concern is from 422-497 bbl, the period over which the heavier, viscous spacer first reaches the surface until the wash spacer is circulated completely out of the well. It is during this period that the choke pressure is at its highest values.

Actual displacement followed the plan; however, the operation was somewhat difficult and lengthy, complicated by the low flow rates and narrow operating window.

The Rainbow-Chart Concept

The displacement plan described in the previous section would be easier to follow if it were possible to quickly visualize the downhole fluid locations and accurately coordinate them with flow rates and resulting pressures. These are precisely the primary advantages of rainbow charts.

A rainbow chart is a continuous plot that shows the position of each fluid involved in the displacement as it circulates through the annulus and work string. The independent axis can be pump strokes or cumulative fluid volume pumped. When used with flow-rate and pressure curves, either superimposed or positioned directly above, a vertical line drawn through all the graphs at any specific fluid-volume value can precisely define key parameters, including:

1. Position and length of each fluid in the annulus and work string
2. Hydrostatic pressures in the annulus and work string
3. Hydrostatic pressure differential at TD
4. Bottomhole pressure
5. Flow rate
6. Pump pressure and hydraulic horsepower
7. Choke or Back pressure (if required to maintain bottomhole pressure within specified limits).

Clearly, other data curves can be added, space permitting on the hardcopy or computer screen. However, the focus in this paper is on the hydrodynamic variables listed above.

The rainbow-chart method is illustrated by the computer-screen capture in **Fig. 2** for the Vermilion example. The two multi-colored rainbow charts are synchronized vertically with the volume of fluid pumped and laterally with the well geometry. The upper geometry and rainbow-chart pair applies to the work string. The lower pair for the annulus has been "unfolded" downwards to prevent overlapping the work-string chart. (*Note*: This figure and others like it are computer screen captures. This accounts for the crowded, "flat" look. These charts are designed to be printed in portrait mode.)

Fig. 2 might look somewhat daunting at first glance; however, the red vertical line placed at 170 bbl helps put all into focus. In a real setting, the vertical line can be moved interactively using a mouse on a computer screen or a straight edge on a hardcopy printout. The data set in the upper left-hand corner of **Fig. 2** matches conditions after pumping the 170 bbl. Additional data at selected fluid-volume points from a more detailed matrix are listed in **Table 2**. Clearly, the graphics make it easier to review and evaluate the displacement.

The basic construction of a rainbow chart is best explained by first visualizing the red vertical line as a very narrow, fluid-filled slot. Each fluid (identified under "Displacement Design") is represented by a different color within that slot, as shown in **Fig. 3**. A multitude of the slots placed side-by-side and blended together would then become a rainbow chart.

Design Overlays

"Design overlays" add another level of usefulness to the combined graphics in **Fig. 2**. These overlays act as templates that when superimposed over rainbow charts permit evaluation of various design parameters. For example, the wash spacer ideally should be in turbulent flow to maximize wellbore cleaning and help achieve water-wet surfaces.[1] Even for wells with complex geometry and a variable flow-rate schedule, the overlay method allows immediate inspection of the flow regime for each fluid throughout the displacement.

A design overlay essentially is a large matrix or data grid. As expected, rows are depth-based and columns are pump-strokes or volume-based. **Fig. 4** illustrates a single-column overlay superimposed over a schematic of a fluid-filled slot like those shown in **Fig. 3**. Grid mesh size can be 50-500 ft by 1-5 bbl depending on the application.

Each cell in the data grid can contain records of valuable information such as those listed in **Fig. 4**. Some of the records already are considered, while others are reserved for future enhancements. The most promising of these are related to more detailed hydrodynamic analyses and chemically related issues, of which wellbore-cleaning analysis is perhaps the most critical.

The significance of the records in the data grid is that each can be compared to a pre-set condition. A flag (true or false) is set depending on the result of the comparison defined by a single or complex SQL-type interrogation. An example condition might be “turbulent flow and velocity < 100 fpm”. If the comparison flag is set in a particular cell, a thin vertical line is drawn corresponding to the position of the cell in the data grid. The collection of thin lines constitutes the final overlay template.

Fig. 5 shows a design overlay applied to **Fig. 2**. The selected design criterion is flow regime. Cross-hatching is indicated wherever the regime in not laminar (turbulent or transitional flow). Note that the wash spacer (Fluid B) is turbulent throughout the displacement (work string and annulus). Recall that the flow-rate schedule was 2.25 bbl/min for 183 bbl and 1.5 bbl/min for 25 bbl before returning to 2.25 bbl/min. The viscosified 11.6-lb/gal $CaCl_2$ (Fluid C) is turbulent in the work string except for the small period (indicated by the arrow in **Fig. 5**) where the flow rate was lower and the pipe diameter was larger. The overlay indicates that the $ZnBr_2$ completion fluid is turbulent throughout the work string and laminar throughout the annulus. Maximum hydrodynamic values for the entire displacement are listed in the upper left-hand corner of the figure.

Design Options

Several design options are available to help optimize certain displacements. Some of these are software features and are not discussed here. However, two options that are central to the rainbow charts concept are illustrated in **Figs. 6-8**.

The screen capture in **Fig. 6** shows the Vermilion example design if displaced using reverse circulation. On close inspection, the design, as is, would impose a higher-than-desired bottomhole pressure after pumping around 335 bbl when the wash spacer enters the work string. Clearly, a correction is possible, but this is not pertinent to this paper.

The second design option is related to staged displacements. A different 19,472-ft (16,010-ft TVD) well was selected to illustrate how rainbow charts could be effectively used to evaluate and design an indirect displacement. For simplicity, displacement to seawater is planned for two stages (whereas a three-stage displacement probably would be more appropriate). **Fig. 7** gives stage-one results with the tapered work string at 9,250 ft; for stage two the work string is at TD in **Fig. 8**. Additional design criteria include maximum pump pressure of 4,500 psi, and maximum and minimum flow rates of 4.0 and 0.5 bbl/min, respectively. The ability to set practical boundary conditions such as these is an important time-saver for design engineers. The final displacement to $ZnBr_2$ is not illustrated.

Enhancements and Opportunities

The rainbow-chart framework is such that finite-difference methods are available for advanced applications. Among these are detailed hydrodynamic analyses and chemically related issues such as wellbore cleaning. Generally speaking, these opportunities can be realized by enhancing existing data grids, or superimposing additional grids that focus on particular technologies. The following are some opportunities for hydrodynamic-related issues:

1. *Adjustments for temperature and pressure effects on downhole rheology and density*. The framework already is in place and tools[2] are available, but considerable uncertainties and complexities can be involved. For one, additional information required on the drilling mud formulation is sometimes not available to the completion operation. Also, circulating temperature profiles are not easily defined.
2. *Allowances for fluid-fluid interfaces and their effects on localized density, viscosity, and chemical makeup (surfactants)*. Some research already has been conducted in this area, and results are promising. Validation with field data will be critical.
3. *Advanced displacement mechanics*. This is very computer-processing intensive, but numerical methods fit within the rainbow-chart scheme. The impact of eccentricity on pressure loss and wall shear stress is an area of special interest. Also, improved techniques for predicting flow regime (especially in eccentric annuli) are critical for evaluating hydrodynamic effects on mud-film removal.

Perhaps the greatest opportunities exist when combining hydrodynamic and chemical factors to accurately predict wellbore cleaning, especially when a synthetic-based mud is involved. Model developments are in progress, and, as before, implementation lends itself to the rainbow-chart framework already in place.

Conclusions

1. The design and execution of complex displacements from drilling mud to clear-brine completion fluid can be improved, simplified, and clarified using an innovative tool known as “rainbow” charts. The technology is applied to the displacement plan of a Gulf of Mexico Vermilion 363 well that was originally designed using conventional spreadsheet analysis.
2. Static rainbow charts, when combined with conventional pressure and flow-rate graphics, provide a complete view of a dynamic completion-fluid displacement on a single sheet of paper or static computer screen.
3. The process allows design engineers to quickly

visualize downhole fluid positions, accurately coordinate them with pressures and flow rates, and evaluate options.

4. Superimposed “overlays” turn rainbow charts into powerful design tools by indicating when and where given parameters fall within specified ranges.
5. The rainbow-chart framework has application for more advanced uses, including detailed hydrodynamic analyses and critical chemically related issues such as wellbore cleaning.

Nomenclature

A, B, C… – *spacer fluids*
BHP – *bottomhole pressure, psi*
dHP – *delta hydrostatic pressure, psi*
HHP – *pump hydraulic horsepower, hhp*
P_{ann} – *annular pressure loss, psi*
P_{choke} – *choke pressure loss, psi*
PhAnn – *annular hydrostatic pressure, psi*
PhWS – *work-string hydrostatic pressure, psi*
P_{pump} – *pump pressure, psi*
P_{ws} – *work-string pressure loss, psi*
SQL – *structured query language*
$ZnBr_2$ – *zinc bromide completion fluid*

Acknowledgements

The authors thank Samedan Oil Corp. and M-I *L.L.C.* for supporting this effort and for permission to publish this paper.

References

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Vermilion 363 Mud Displacement with spacers and ZnBr2

BN-1 Sand **Pore pressure = 8,720 psi @ 10,020' TVD**

Casing **10,770'** **7 5/8" 29.7, 33.7#, 39# P110** **Drill Pipe** **7,200'** **4 1/2" 15.5# P110 PH6** **Max Allow. BHP = 9,275 psi (17.8 ppg EMW at 10,020' TVD)**

(wt'd ave. 6.725" ID) **3,570'** **3 1/2" 9.3# P110 BTS8**

Ann Volume		bbls/ft	**bbls**	**D.P. Volume**		bbls/ft	**bbls**
4.500	7,200	0.024272	**174.76**	**4.500**	7,200	0.014230	**102.5**
3.500	3,570	0.032000	**114.24**	**3.500**	3,570	0.008700	**31.1**

Spacers :	**A**	**50 bbls**	**17.5 ppg Visc Spacer**	**PV 45, YP 140**
	B	**25 bbls**	**8.6 ppg Wash Spacer**	**PV 1, YP 1**
	C	**50 bbls**	**11.6 ppg Visc CaCl2**	**PV 25, YP 2**

Mud & Zinc :
17.0 ppg Mud - PV 50, YP 15
17.2 ppg ZnBr2 - PV 20, YP 2 (17.0 ppg ave. density)

Annulus	**Cum.**	Fluid placement	**Rate**	Static	Static	Static	Static Csg	Annulus	**Ann.Circ'g**	**Circ BHP**	**Req'd**	**Circ'g Ann.**	Frac Grad	**Circ'g BHP**	BHP
Stage	**BBLS**		**BPM**	H.H.	SICP	H.H.	vs SIBHP	friction	**BHP**	**vs. SIBHP**	**Choke**	**BHP thru**	BHP Limit	**vs. F.G.**	pore
	Pumped			DP	if SD pmp	CSG	@ zone	pressure		**@ zone**	**press.**	**choke**	(17.8 ppg)	**Press limit**	press
				0 psi SP	CP vs DP	0 psi SP									
							8720 psi			**8720 psi**					
@ 10,020'	**0**	17.0 ppg mud	**2.25**	8,858	0	8,858	138	234	9,092	372	**0**	9,092	9,275	(183)	8,720
	50	A in DP	**2.25**	8,949	(91)	8,858	138	234	9,092	372	**0**	9,092	9,275	(183)	8,720
	75	A,B in DP	**2.25**	8,180	678	8,858	138	234	9,092	372	**0**	9,092	9,275	(183)	8,720
	125	A,B,C in DP	**2.25**	7,193	1,665	8,858	138	234	9,092	372	**0**	9,092	9,275	(183)	8,720
	133	A at MS	**2.25**	7,210	1,648	8,858	138	234	9,092	372	**0**	9,092	9,275	(183)	8,720
1	**183**	A in Csg; B at MS	**1.50**	6,864	2,021	8,885	165	390	9,193	473	**0**	9,193	9,275	(82)	8,720
2	**208**	A,B in Csg; C at MS	**2.25**	7,689	975	8,664	(56)	382	9,046	326	**0**	9,046	9,275	(229)	8,720
3	**258**	A,B,C in Csg; Zn at MS	**2.25**	8,858	(512)	8,346	(374)	419	8,765	45	**150**	8,915	9,275	(360)	8,720
4	**422**	A at Surface	**2.25**	8,858	(739)	8,119	(601)	370	8,489	(231)	**430**	8,919	9,275	(356)	8,720
5	**472**	B at Surface	**2.25**	8,858	(779)	8,079	(641)	73	8,152	(568)	**770**	8,922	9,275	(353)	8,720
6	**497**	C at Surface	**2.25**	8,858	(438)	8,420	(300)	77	8,497	(223)	**430**	8,927	9,275	(348)	8,720
7	**547**	Zn at Surface	**2.25**	8,858	0	8,858	138	63	8,921	201	**0**	8,921	9,275	(354)	8,720

Bordered areas are periods during the displacement of underbalance to pore pressure or approaching safety margin to pressure limit at hole in casing interval.

Table 1 – Engineering data set for the Vermilion case-history well developed using spreadsheet-style analysis.

Vol	Flow	A	A	A	A	B	B	B	B	C	C	C	C	ZnBr	ZnBr	PhAnn	PhWS	dHP	BHP	Ppump	HHP	Pann	Pws	Pchoke
bbl	bbl/min	bbl	Lead	Tail	Length	bbl	Lead	Tail	Length	bbl	Lead	Tail	Length	bbl	Length	psi	psi	psi	psi	psi	hhp	psi	psi	psi
0.0	2.25	0	0 P	0 P	0	0	0 P	0 P	0	0	0 P	0 P	0	0.0	0	8847	8847	0	9226	611	34	379	231	0
20.0	2.25	20	1406 P	0 P	1406	0	0 P	0 P	0	0	0 P	0 P	0	0.0	0	8847	8885	38	9226	696	38	379	354	0
36.7	2.25	37	2579 P	0 P	2579	0	0 P	0 P	0	0	0 P	0 P	0	0.0	0	8847	8916	69	9226	766	42	379	455	0
40.0	2.25	40	2813 P	0 P	2813	0	0 P	0 P	0	0	0 P	0 P	0	0.0	0	8847	8921	74	9226	778	43	379	473	0
60.0	2.25	50	4219 P	703 P	3516	10	703 P	0 P	703	0	0 P	0 P	0	0.0	0	8847	8614	233	9226	1132	62	379	519	0
80.0	2.25	50	5626 P	2110 P	3516	25	2110 P	352 P	1758	5	352 P	0 P	352	0.0	0	8847	8063	784	9226	1665	92	379	502	0
80.3	2.25	50	5648 P	2132 P	3516	25	2132 P	374 P	1758	5	374 P	0 P	374	0.0	0	8847	8063	784	9226	1665	92	379	502	0
86.7	2.25	50	6095 P	2579 P	3516	25	2579 P	821 P	1758	12	821 P	0 P	821	0.0	0	8847	7925	922	9226	1799	99	379	498	0
100.0	2.25	50	7032 P	3516 P	3516	25	3516 P	1758 P	1758	25	1758 P	0 P	1758	0.0	0	8847	7669	1178	9226	2047	113	379	490	0
111.7	2.25	50	8268 P	4337 P	3931	25	4337 P	2579 P	1758	37	2579 P	0 P	2579	0.0	0	8847	7439	1408	9226	2361	130	379	574	0
120.0	2.25	50	9226 P	4923 P	4303	25	4923 P	3165 P	1758	45	3165 P	0 P	3165	0.0	0	8847	7285	1562	9226	2583	142	379	641	0
140.0	2.25	50	10556 A	6329 P	4655	25	6329 P	4571 P	1758	50	4571 P	1055 P	3516	15.0	1055	8851	7186	1665	9253	2773	153	402	706	0
160.0	2.25	50	9906 A	8076 P	3559	25	8076 P	5977 P	2098	50	5977 P	2461 P	3516	35.0	2461	8862	6997	1865	9328	2823	156	466	493	0
161.7	2.25	50	9851 A	8268 P	3421	25	8268 P	6095 P	2173	50	6095 P	2579 P	3516	36.7	2579	8863	6959	1904	9336	2836	156	473	459	0
180.0	2.25	50	9255 A	10375 P	1910	25	10375 P	7501 P	2875	50	7501 P	3868 P	3633	55.0	3868	8874	6852	2022	9404	2710	149	530	158	0
200.0	1.50	50	8604 A	10231 A	1627	25	10231 A	9801 P	1509	50	9801 P	5274 P	4526	75.0	5274	8717	7436	1281	9155	1790	66	438	71	0
220.0	2.25	50	7954 A	9580 A	1627	25	9580 A	10394 A	813	50	10394 A	6681 P	4466	95.0	6681	8575	7922	654	9088	1334	74	513	168	0
240.0	2.25	50	7303 A	8930 A	1627	25	8930 A	9743 A	813	50	9743 A	8651 P	3146	115.0	8651	8445	8454	9	8947	672	37	502	179	0
260.0	2.25	50	6467 A	8279 A	1812	25	8279 A	9092 A	813	50	9092 A	10719 A	1627	135.0	10821	8302	8847	546	8915	261	14	563	193	51
278.8	2.25	50	5648 A	7667 A	2019	25	7667 A	8480 A	813	50	8480 A	10107 A	1627	153.8	11433	8242	8847	605	8915	261	14	630	193	43
280.0	2.25	50	5600 A	7628 A	2028	25	7628 A	8442 A	813	50	8442 A	10068 A	1627	155.0	11472	8236	8847	611	8915	261	14	633	193	45
300.0	2.25	50	4793 A	6902 A	2109	25	6902 A	7791 A	889	50	7791 A	9418 A	1627	175.0	12122	8135	8847	712	8915	261	14	641	193	140
320.0	2.25	50	3986 A	6031 A	2045	25	6031 A	7120 A	1089	50	7120 A	8767 A	1647	195.0	12773	7988	8847	859	8915	261	14	580	193	348
328.8	2.25	50	3631 A	5648 A	2017	25	5648 A	6737 A	1089	50	6737 A	8480 A	1744	203.8	13060	7951	8847	896	8915	261	14	557	193	407
340.0	2.25	50	3179 A	5196 A	2017	25	5196 A	6249 A	1053	50	6249 A	8116 A	1867	215.0	13424	7923	8847	924	8915	261	14	545	193	447
353.8	2.25	50	2622 A	4639 A	2017	25	4639 A	5648 A	1009	50	5648 A	7667 A	2019	228.8	13873	7891	8847	956	8915	261	14	528	193	496
354.9	2.25	50	2579 A	4596 A	2017	25	4596 A	5605 A	1009	50	5605 A	7632 A	2027	229.9	13908	7888	8847	960	8915	261	14	526	193	501
360.0	2.25	50	2384 A	4389 A	2006	25	4389 A	5398 A	1009	50	5398 A	7466 A	2068	235.0	14074	7880	8847	967	8915	261	14	517	193	518
380.0	2.25	50	1622 A	3582 A	1961	25	3582 A	4591 A	1009	50	4591 A	6684 A	2093	255.0	14856	7869	8847	978	8915	261	14	475	193	571
400.0	2.25	50	859 A	2776 A	1916	25	2776 A	3784 A	1009	50	3784 A	5814 A	2029	275.0	15726	7888	8847	959	8915	261	14	434	193	593
403.8	2.25	50	715 A	2622 A	1908	25	2622 A	3631 A	1009	50	3631 A	5648 A	2017	278.8	15892	7891	8847	956	8915	261	14	427	193	596
404.9	2.25	50	674 A	2579 A	1905	25	2579 A	3588 A	1009	50	3588 A	5605 A	2017	279.9	15935	7891	8847	956	8915	261	14	424	193	600
420.0	2.25	50	97 A	2003 A	1905	25	2003 A	2977 A	975	50	2977 A	4995 A	2017	295.0	16545	7907	8847	940	8915	261	14	410	193	598
422.6	2.25	50	0 A	1905 A	1905	25	1905 A	2874 A	969	50	2874 A	4891 A	2017	297.6	16649	7906	8847	941	8915	261	14	400	193	609
429.9	2.25	43	0 A	1626 A	1626	25	1626 A	2579 A	953	50	2579 A	4596 A	2017	304.9	16944	7909	8847	938	8915	261	14	355	193	651
440.0	2.25	33	0 A	1241 A	1241	25	1241 A	2193 A	953	50	2193 A	4188 A	1995	315.0	17352	7901	8847	946	8915	261	14	289	193	725
460.0	2.25	13	0 A	478 A	478	25	478 A	1431 A	953	50	1431 A	3381 A	1950	335.0	18159	7897	8847	950	8915	261	14	159	193	858
472.6	2.25	0	0 A	0 A	0	25	0 A	953 A	953	50	953 A	2874 A	1922	347.6	18666	7911	8847	936	8915	261	14	81	193	923
479.9	2.25	0	0 A	0 A	0	18	0 A	674 A	674	50	674 A	2579 A	1905	354.9	18961	8033	8847	814	8915	261	14	83	193	799
480.0	2.25	0	0 A	0 A	0	18	0 A	669 A	669	50	669 A	2574 A	1905	355.0	18966	8033	8847	814	8915	261	14	83	193	799
497.6	2.25	0	0 A	0 A	0	0	0 A	0 A	0	50	0 A	1905 A	1905	372.6	19635	8326	8847	521	8915	261	14	87	193	502
500.0	2.25	0	0 A	0 A	0	0	0 A	0 A	0	48	0 A	1812 A	1812	375.0	19728	8346	8847	501	8915	261	14	87	193	482
520.0	2.25	0	0 A	0 A	0	0	0 A	0 A	0	28	0 A	1050 A	1050	395.0	20490	8561	8847	286	8915	261	14	86	193	268
540.0	2.25	0	0 A	0 A	0	0	0 A	0 A	0	8	0 A	288 A	288	415.0	21252	8773	8847	74	8915	261	14	85	193	57
547.6	2.25	0	0 A	0 A	0	0	0 A	0 A	0	0	0 A	0 A	0	422.6	21540	8847	8847	0	8932	277	15	85	193	0
547.7	2.25	0	0 A	0 A	0	0	0 A	0 A	0	0	0 A	0 A	0	422.6	21540	8847	8847	0	8932	277	15	85	193	0

Table 2 – Displacement-data matrix for Vermilion example showing position of each fluid and pressures at selected values for volume of fluid pumped. The labels “P” and “A” refer to pipe and annulus, respectively, under “lead” and “tail” headings. These identify the beginning and end position in terms of measured well depth for each fluid.

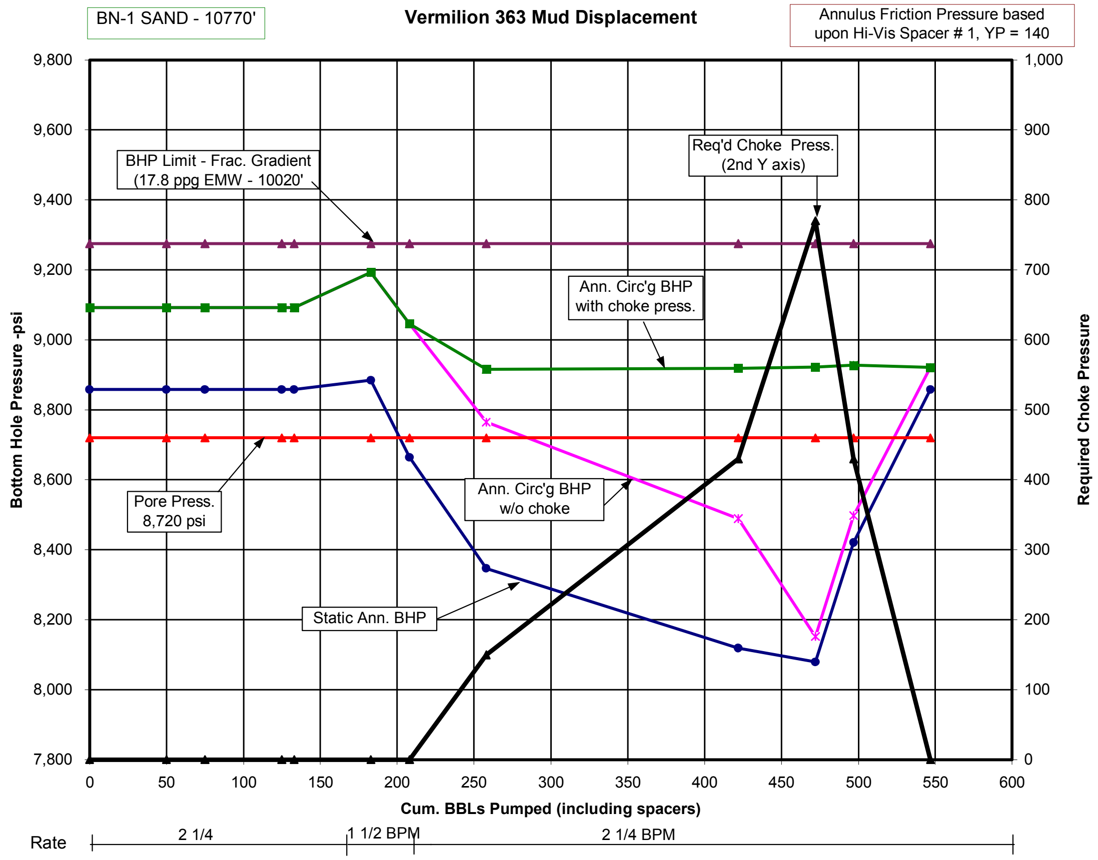


Fig. 1 – Pressure curves for Vermilion 363 displacement example summarized in **Table 1**.

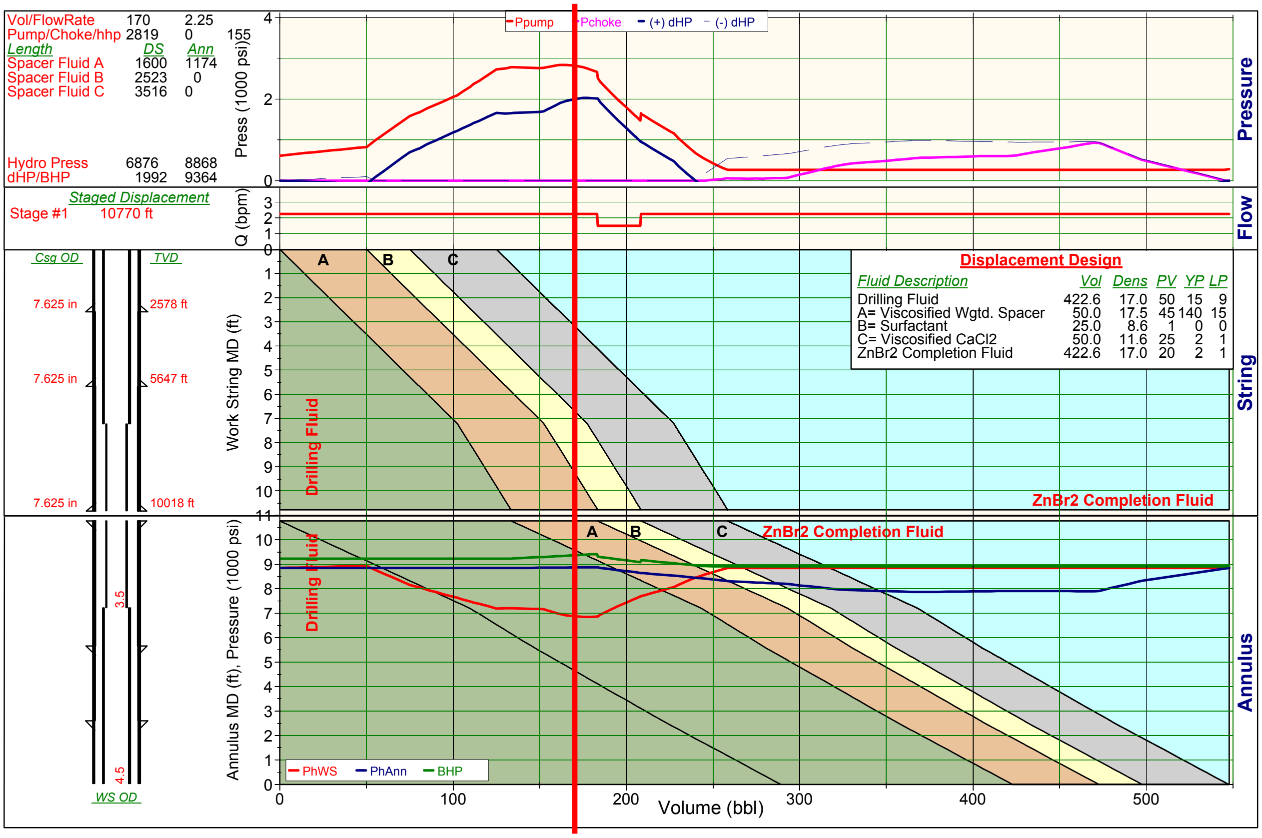


Fig. 2 – Rainbow charts application for the example shown in **Fig. 1**.

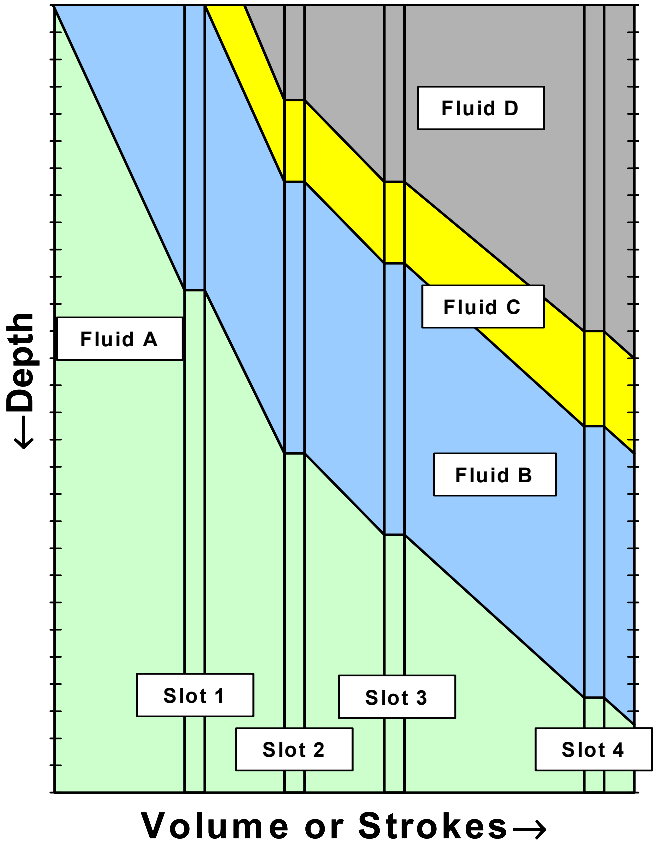


Fig. 3 – Schematic illustrating rainbow chart construction using a multitude of individual fluid-filled slots placed side-by-side.

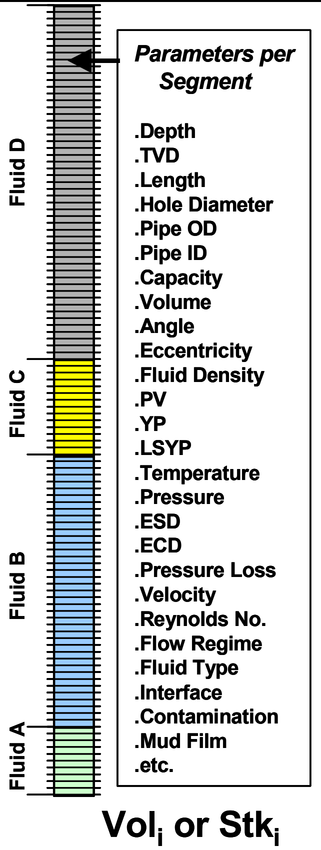
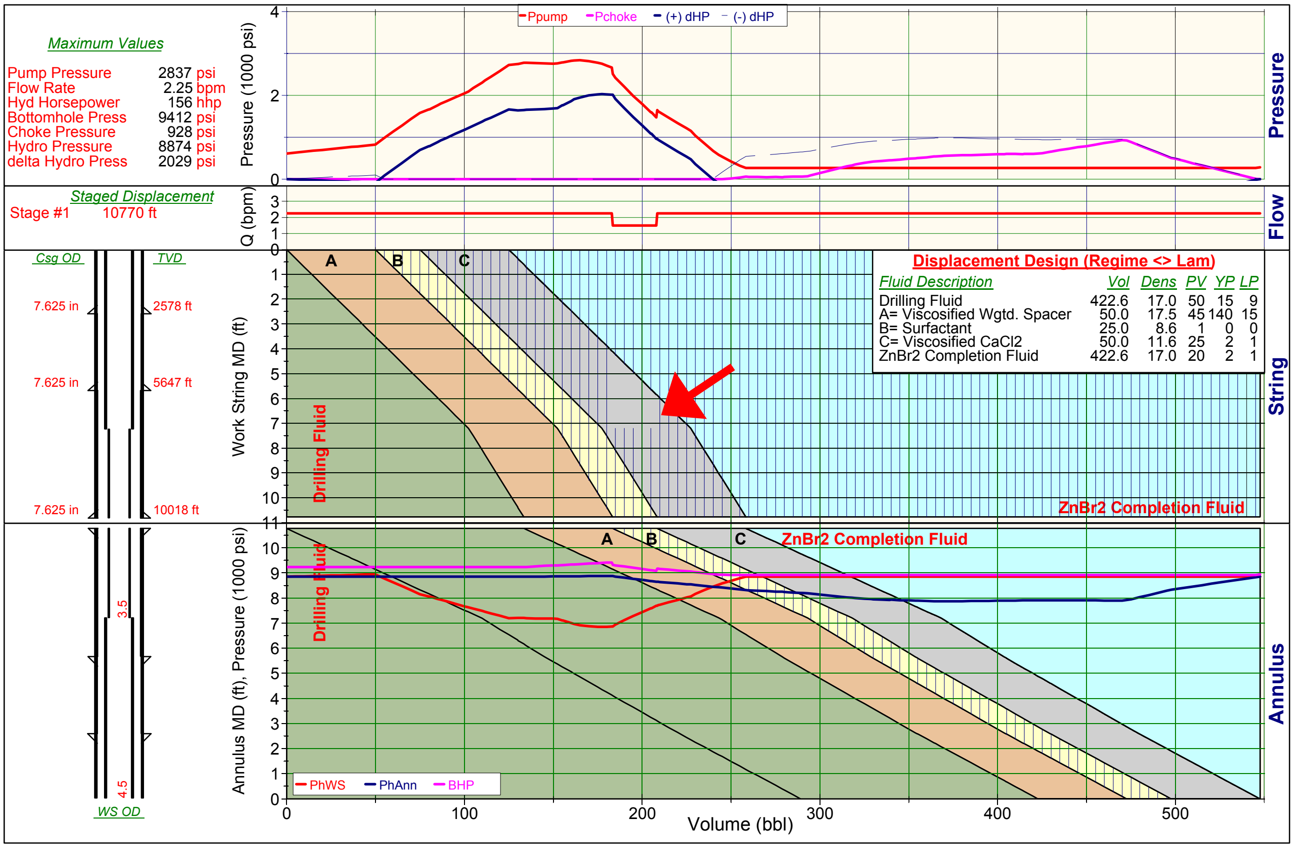


Fig. 4 – Overlay grid showing parameters defined for each element at a given volume or stroke.



Maximum Values

Pump Pressure	2837	psi
Flow Rate	2.25	bpm
Hyd Horsepower	156	hhp
Bottomhole Press	9412	psi
Choke Pressure	928	psi
Hydro Pressure	8874	psi
delta Hydro Press	2029	psi

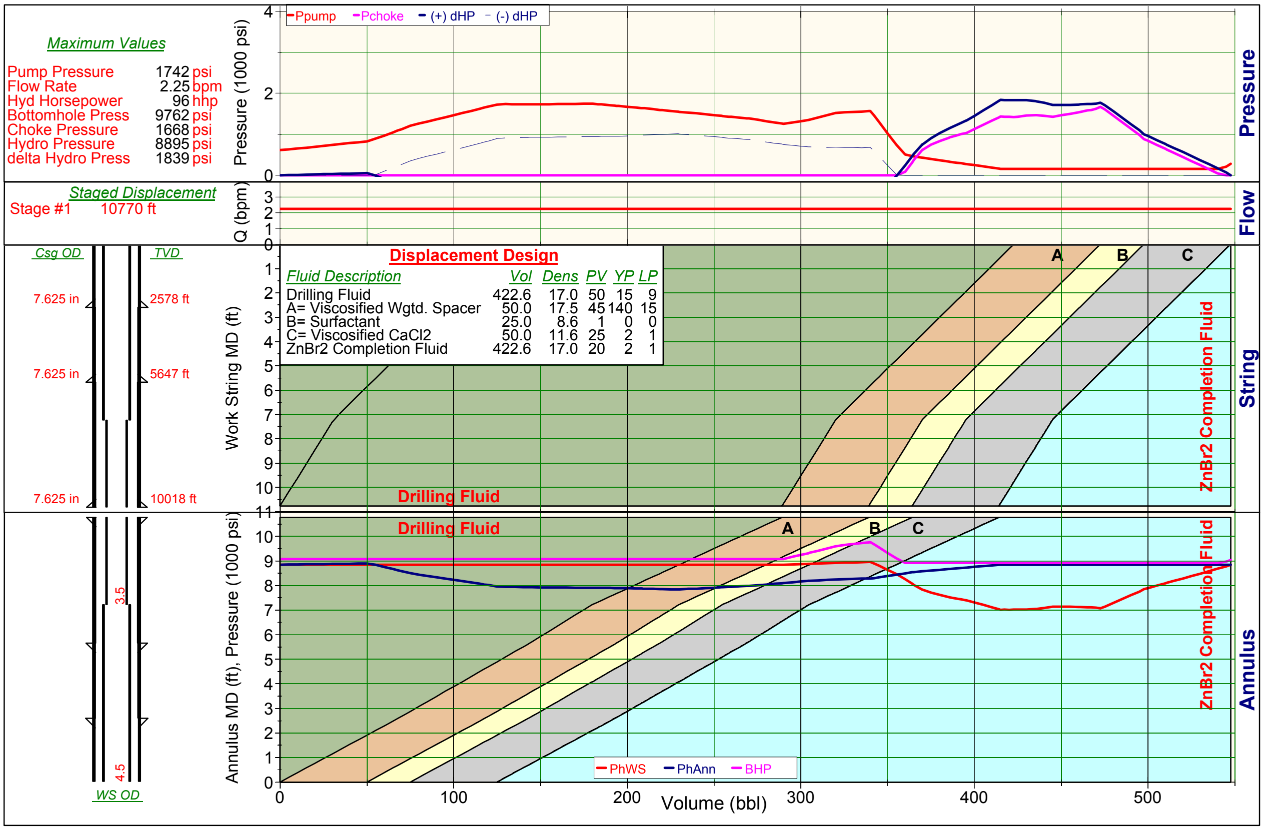
Staged Displacement

Stage #1 10770 ft

Displacement Design (Regime <> Lam)

Fluid Description	*Vol*	*Dens*	*PV*	*YP*	*LP*
Drilling Fluid	422.6	17.0	50	15	9
A= Viscosified Wgtd. Spacer	50.0	17.5	45	140	15
B= Surfactant	25.0	8.6	1	0	0
C= Viscosified CaCl2	50.0	11.6	25	2	1
ZnBr2 Completion Fluid	422.6	17.0	20	2	1

Fig. 5 – Design overlay applied to **Fig. 2**. Cross-hatched areas indicating where flow regime is not laminar. The arrow points to an area where Fluid C is in laminar flow in the work string.



Maximum Values

Pump Pressure	1742	psi
Flow Rate	2.25	bpm
Hyd Horsepower	96	hhp
Bottomhole Press	9762	psi
Choke Pressure	1668	psi
Hydro Pressure	8895	psi
delta Hydro Press	1839	psi

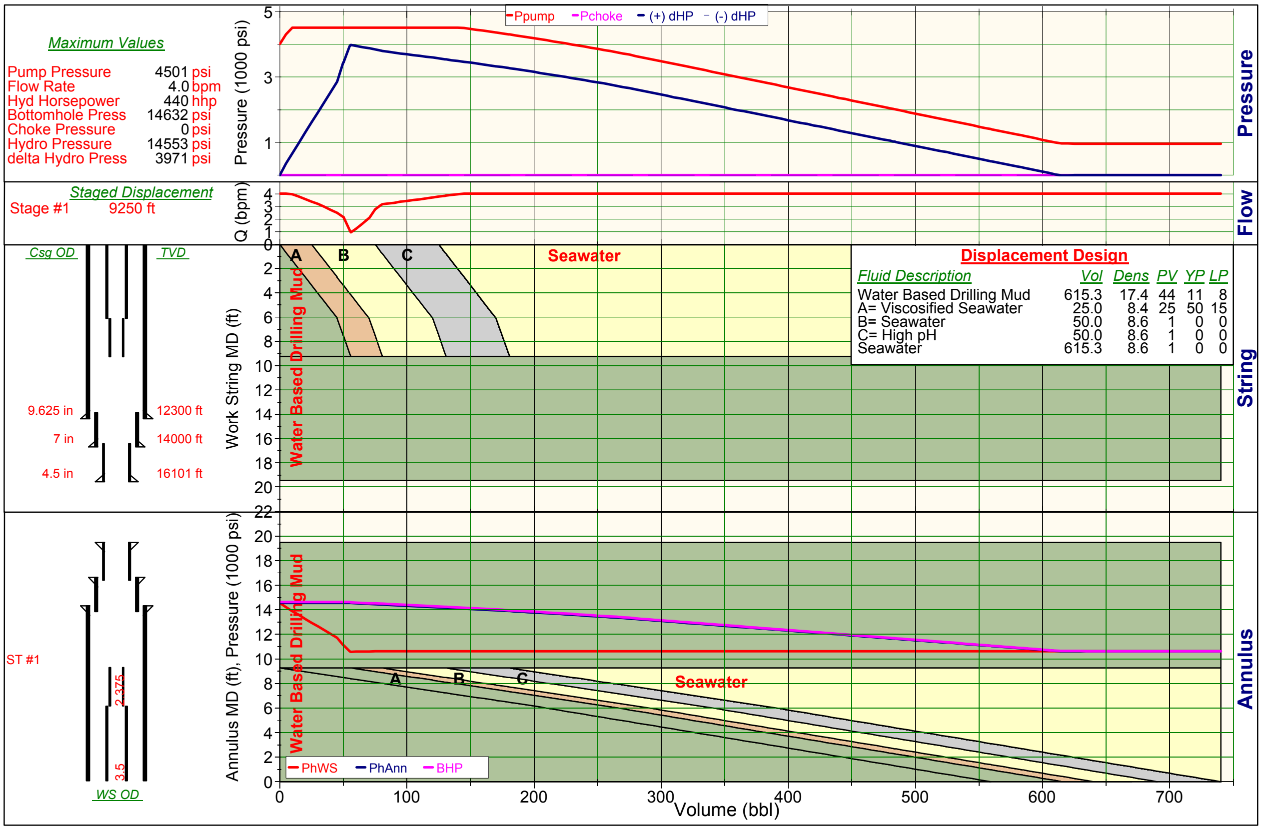
Staged Displacement

Stage #1 10770 ft

Displacement Design

Fluid Description	*Vol*	*Dens*	*PV*	*YP*	*LP*
Drilling Fluid	422.6	17.0	50	15	9
A= Viscosified Wgtd. Spacer	50.0	17.5	45	140	15
B= Surfactant	25.0	8.6	1	0	0
C= Viscosified CaCl2	50.0	11.6	25	2	1
ZnBr2 Completion Fluid	422.6	17.0	20	2	1

Fig. 6 – Vermilion 363 example design if displaced using reverse circulation.



Maximum Values

Pump Pressure	4501	psi
Flow Rate	4.0	bpm
Hyd Horsepower	440	hhp
Bottomhole Press	14632	psi
Choke Pressure	0	psi
Hydro Pressure	14553	psi
delta Hydro Press	3971	psi

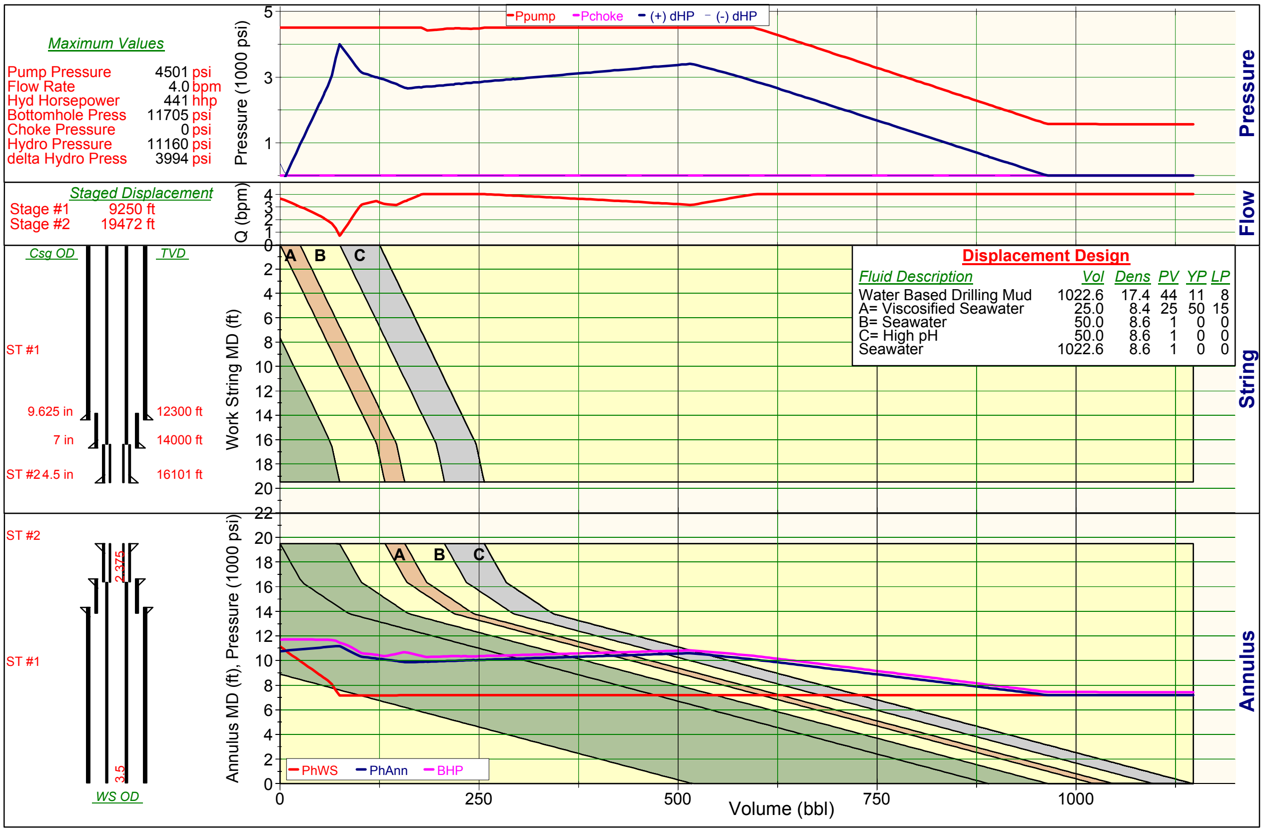
Staged Displacement

Stage #1 9250 ft

Displacement Design

Fluid Description	*Vol*	*Dens*	*PV*	*YP*	*LP*
Water Based Drilling Mud	615.3	17.4	44	11	8
A= Viscosified Seawater	25.0	8.4	25	50	15
B= Seawater	50.0	8.6	1	0	0
C= High pH	50.0	8.6	1	0	0
Seawater	615.3	8.6	1	0	0

Fig. 7 – First part of a two-stage indirect displacement for a well with complex geometry. Work string is at 9,250 ft.



Maximum Values

Pump Pressure	4501	psi
Flow Rate	4.0	bpm
Hyd Horsepower	441	hhp
Bottomhole Press	11705	psi
Choke Pressure	0	psi
Hydro Pressure	11160	psi
delta Hydro Press	3994	psi

Staged Displacement

Stage #1	9250 ft
Stage #2	19472 ft

Displacement Design

Fluid Description	*Vol*	*Dens*	*PV*	*YP*	*LP*
Water Based Drilling Mud	1022.6	17.4	44	11	8
A= Viscosified Seawater	25.0	8.4	25	50	15
B= Seawater	50.0	8.6	1	0	0
C= High pH	50.0	8.6	1	0	0
Seawater	1022.6	8.6	1	0	0

Fig. 8 – Second part of a two-stage displacement for a well with complex geometry. Work string is at TD (19,472 ft).