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Drilling Research Projects

Study on Effective Hole Cleaning Using "Sweeps" in Horizontal Wellbores

(Progress Report)

Sandeep Valluri, University of Tulsa, Drilling Research Projects,
Masters of Science, Oil & Natural Gas Engineering, A&M, Kingsville, B.E. Chemical Engineering DSCE, India.

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Abstract:

This is the third report being presented for this project. This report presents experimental results obtained from the tests conducted on the Low Pressure Ambient Temperature flow loop as well as results from the preliminary tests conducted on the Elevated Pressure Elevated Temperature flow loop. Based on results from previous "sweep" tests conducted, subsequent "sweep" tests were conducted according to a modified Test Matrix. A detailed analysis of the experimental data obtained is presented. The effect of parameters such as, rheology, flow rate & drill pipe rotation on volumetric cutting concentration removed, bed heights and pressure drop are presented. The modified mechanistic model for the critical re-suspension velocity for cutting in yield-power law fluid is presented. The focus of this report will be on the results obtained from the "sweep" tests.

Project Status

Literature Review	95%	
Flow Loop Training	L.P.A.T. (*)	E.P.E.T. (**)
	100 %	100%
Modeling	90%	
Experiments	L.P.A.T. (*)	E.P.E.T. (**)
	100%	100%

(*) L.P.A.T. (low pressure ambient temperature loop), (**) E.P.E.T. (Elevated Pressure Elevated Temperature loop)

Introduction:

This project focuses on the particular technique termed as "sweeps", in which circulation of specific fluids specially formulated to remove the cuttings beds, are periodically necessary. In vertical and near vertical wells these fluids are devised to add to the lifting of the cuttings to the surface. In "deviated" wells they are designed to add to the shear forces on the top layer of the cuttings bed, thus adding to the "erosion" of the cuttings bed.

Problem Statement:

Poor cuttings transport in deviated and extended reach wells has warranted the need for novel techniques to clean the wellbore of cuttings bed that have been formed by the deposition of cuttings that are generally fines and smaller sized cuttings. Drilling fluid "sweeps" are used in order to clean the borehole from cuttings that are not removed by ordinary drilling fluid circulation. There has been a lack of certainty of the sweep type selection in the field. In addition there is not much information pertaining to use of the "sweeps", a sign that this particular area of research has not received its due attention. Therefore a rigorous experimental and theoretical analysis of the "sweeps" to quantify the "efficiency" of the drilling fluid "sweeps" needs to be performed. To our knowledge this is the first study on the "sweeps" in a controllable lab scale environment.

Generally in practice the sweep fluids are injected in addition to the drilling mud that is already present in the well-bore. The sweep fluid "displaces" the base fluid out of the drill-pipe as well as the well-bore while contributing to the bed erosion process. The stability of the interface between the base fluid and the sweep fluid is of concern. The stability of the interface may have some influence on the efficiency of sweep as it may affect the rheology of the sweep fluid due to mixing etc. Various models [1], [2], [3], [4] allow a careful investigation of individual effects of various parameters that effect the displacement efficiency. The major parameters that effect the displacement are the fluid rheology, fluid density & the fluid yield stress.

Literature Review:

1. Mechanistic modeling of critical re-suspension velocity of cutting in yield-power law fluid.

Ramadan Ahmad[5] presented the moment balance based on the cuttings rolling mechanism for horizontal and highly inclined wellbores. The critical state for a cutting's movement on a cuttings bed is when the resultant moment with respect to the contact point, P, equals zero. (Figure 1. presented in the appendix)

$$\Gamma = d_p /2 \, [F_L \cos\phi + F_D \sin\phi - F_g \sin(\alpha+\phi) - (F_b+F_p)\cos\phi] = 0$$

Mingqin Duan [6] presented a modified moment balance for small size cuttings, specific sizes used were 0.45 mm (1/56 inch) and 1.4 mm (1/18 inch). He included the Van der Waals dispersion forces, F_{van},

which are colloidal forces existing between any neighboring particles in the moment balance, in the original moment balance equation as shown in figure 1 presented in the appendix .

$$\Gamma = d_p /2\ [F_L\cos\phi + F_D \sin\phi - F_g \sin(\alpha+\phi) - (F_b+F_{vanR})\cos\phi] = 0$$

A detailed procedure to calculate the C.R.V for cutting in power-law fluid was also presented [6]. This procedure was modified to calculate the C.R.V. for cutting in yield-power law fluid.

a. Drag Force:

Calculations [7] were performed for a sphere moving in a viscoplastic fluid with the Polyflow finite-element software from Fluent Inc. Their study determined the drag coefficient of a sphere in a Herchel-Bulkley viscoplastic fluid in an infinite medium by means of numerical modeling. They showed that the fluid flow produces a drag force F_D, defined by:

$$F_D = \frac{C_D \pi K U^n D_p^{2-n}}{4}, \tag{1}$$

Where:

$$C_d = [A_1 - A_2(1-n)^2 + A_3(1-n)] + B_1[1 + B_2(n - B_3)Od^{-\beta}$$

$$\beta = (n + B_4)/B_5 \quad , \quad Od = \frac{\tau_0}{K(U/D_p)^n}$$

with, A_1= 8.00, A_2 = 5.354, A_3 = 8.589, B_1 = 9.731, B_2 = 1.059, B_3 = 0.130, B_4 = 0.196, B_5 = 2.017

b. Plastic Force:

Although the porosity of small cuttings bed is quite small, space does exist between neighboring particles. Stagnant fluid is filled within these spaces despite the fluid flowing above the particles. Since most of the commonly used drilling fluids are not Newtonian fluid, the fluid gel strength will generate a force to pull back the particle when it has a tendency to move. This force is the "plastic force" F_p. After Angle of Repose correction, Clark and Bickham's [8] approximation of plastic force, Fp can be expressed as:

$$F_p = \frac{\pi d^2}{2}\tau_y[(\frac{\pi}{2} - \phi) + \phi\cos^2\phi - \sin\phi\cos\phi] \tag{2}$$

c. Near Bed Velocity Profile

Both C_D and C_L are functions of particle Reynolds number, R_{ep}, and the dimensionless shear rate, η. In order to get R_{ep} and η, the local velocity, V_r , and the velocity gradient, $\frac{dV_r}{dy}$, must be obtained.

The velocity profile in the viscous sublayer which is closest to the cuttings bed takes the following form[9],

$$u^+ = (y^+ .X)^{1/n} \qquad (y^+ \leq \delta) , \tag{3}$$

Where δ is the thickness of the laminar sublayer[10].

$$\delta = \frac{5D_{hyd}}{\mathrm{Re}_{gen}}(2/f_{bed})^{0.5}$$

Where u^+ is dimensionless local velocity, $u^+ = V_r/U_f$, y^+ is dimensionless distance from the mean bed surface, $y^+ = y^n U_f^{2-n}(\frac{\rho_f}{K})$ for yield power law fluid, y is the distance from the mean bed surface, U_f is bed friction velocity, $U_f = (\tau_{bed}/\rho_f)^{0.5}$, and τ_{bed} is average bed shear stress, all in SI units.

Substituting u^+ and y^+ into above equation and rearranging it yields

For the laminar sub-layer: ($y^+ \leq \delta$)

$$V_r = y(\frac{\tau_{bed}X}{K})^{\frac{1}{n}} \tag{4}$$

$$\frac{dV_r}{dy} = (\frac{\tau_{bed}X}{K})^{\frac{1}{n}} \tag{5}$$

Where $X = [1 - \frac{\tau_O}{\tau_{bed}}]$

For the turbulent core: (($y^+ > \delta$)

$$u^+ = A + B.\ln X + B\ln y^+$$

A = 3.8/n, B = 2.78/n

d. Friction Factor:

Reed and Pilehvari [11] proposed an equation for non-Newtonian turbulent flow in a rough pipe; it reads,

$$\frac{1}{\sqrt{f}} = -4\log(\frac{0.27\varepsilon}{D_{eff}} + \frac{1.26^{N^{-1.2}}}{(R_{e,gn}f^{(1-N/2)})^{N^{-0.75}}}) , \tag{6}$$

Where ε is absolute pipe roughness. Treating ε as the mean bed roughness, this equation can be used to approximate the bed fiction factor. The mean bed roughness, ε, is expressed as a function of the angle of repose, ϕ, and particle diameter, d_p.

Past Work:

The following is a list of the various stages of this research project. Figure 2, shown in the appendix lists the various components that comprise this research project.

This study consists of two main stages:

I. **Experimental Stage (Details of each part are provided in section named "Experimental Stage")**
   1. **Fluid Characterization:**
      a. Fluid Design
      b. "Temperature effects"
   2. **L.P.A.T "Sweep" Test:**
      a. Type I
      b. Type II
      c. Type III
   3. **Preliminary E.P.E.T "Sweep" Tests**

II. **Theoretical Stage: (Details of each part are provided in section named "Theoretical Stage")**
   1. **Literature review on "fluid-fluid" displacement.**
   2. **Mechanistic modeling of critical re-suspension velocity of cutting in yield-power law fluid.**

Experimental Stage:

The details of the different parts of the experimental stage are as follows:

1. Fluid Characterization:

Before the "sweep" tests could be conducted, fluid characterization was performed for the following reasons:

1. To design fluids with a mixture of appropriate quantities of PAC (Polyanionic Cellulose) & X.C.D (Xanthum Gum), to obtain the required rheological properties.
2. To study the effect of temperature on the rheology of the designed fluids.

3. The rheological properties of all the fluid used in the different stages of the experimental stage are listed in the Table 1, provided in the appendix. The fluids and their properties have been presented in the order of use in the different stages of this study.

2. L.P.A.T "Sweep" Test:

a. Type I:

The difference between the different "Types" of sweep tests is the use of different "base" fluids and "sweep" fluids. Type I "sweep" tests were conducted by using water as the base fluid and highly viscous fluids, A, B & C as the sweep fluids.

An initial test matrix required flow rates of the sweep of 100, 200 & 300 gpm. The results from these tests indicated that the 100gpm sweep tests were ineffective and would not aid in drawing any tangible conclusions from the "sweep" tests. The test matrix was modified to incorporate sweep tests with higher flow rates. The preliminary tests were designed to quantify the sweep efficiency based on the volume of the sweep.

The higher flow rates would require high volumes of the "sweep" fluid and we did not have the required facilities to run these high volume sweeps. Thus the "sweep efficiency" was modified to be quantified based on time rather than volume. All the sweep tests have been designed for two minutes sweeps in the test section, irrespective of the flow rate.

Based on this design the modified test matrix is listed in table 2:

Base Fluid	**Sweep Fluid**	**Flow Rate, G.P.M., (m^3/s)**	**Drill Pipe Rotation, RPM**	**Bed height**	**Test Time, mins**
Water	Fluid A	200, 300, 400 (0.0126, 0.189, 0.0252)	0, 50, 100	40-50% of Section	2
Water	Fluid B	200, 300, 400 (0.0126, 0.189, 0.0252)	0, 50, 100	40-50% of Section	2
Water	Fluid C	200, 300, 400 (0.0126, 0.189, 0.0252)	0, 50, 100	40-50% of Section	2

Table 2: Type I Test Matrix

A total of 36 tests were conducted in the Type I sweep tests. The results from these tests have been presented in the previous reports. The key results from these tests will be presented in the results and discussion section of this report.

b. Type II

After the detailed analysis of the results obtained from the "Type I" sweep tests, two additional types of sweep tests were proposed, i.e "Type II" & "Type III". The "Type II" tests were conducted by using high viscous fluid "Fluid F" as the base fluid and comparatively less viscous fluid "Fluid D"& water as the sweep fluids. The main idea behind these tests was to study the effect of the less viscous fluids on the cuttings bed height in the test section. Results from these tests are presented in this report. A total of 18 tests were conducted in Type II. The test matrix for these tests is listed in the table 3:

Base Fluid	Sweep Fluid	Flow Rate, G.P.M., (m^3/s)	Drill Pipe Rotation, RPM	Bed height	Test Time, mins
Fluid F	Fluid D	200, 300, 400 (0.0126, 0.189, 0.0252)	0, 50, 100	40-50% of Section	2
Fluid F	Water	200, 300, 400 (0.0126, 0.189, 0.0252)	0, 50, 100	40-50% of Section	2

Table 3: Type II Test Matrix

c. Type III

The Type III tests were conducted with water as the base fluid and high-viscous high-density fluid as the sweep fluid. The main idea behind these tests was to study the influence of the change in density of the fluid on the sweep efficiency. Results from these tests are presented in this report. A total of 9 tests were conducted in Type III.

The test matrix for these tests is listed in the table 4 below:

Base Fluid	Sweep Fluid	Flow Rate, G.P.M., (m^3/s)	Drill Pipe Rotation, RPM	Bed height	Test Time, mins
Water	Fluid E	200, 300, 400 (0.0126, 0.189, 0.0252)	0, 50, 100	40-50% of Section	2

Table 4: Type III Test Matrix

3. Preliminary E.P.E.T "Sweep" Tests:

As mentioned earlier under the fluid characterization, the effect of temperature on the rheological properties was studied and presented in earlier reports. Results indicated that temperature had a significant effect on the rheological properties of the fluids. Results indicate that:

When the temperature is raised, for the fluids tested:

- The flow behavior index n increases.
- The consistency index K decreases.
- The yield point decreases.

Literature review indicated that previous cuttings transport tests [12] conducted at the Elevated Pressure Elevated Temperature (E.P.E.T) facility at the University of Tulsa have shown the substantial effect of temperature on cuttings transport. The second stage of the project would thus be the experimentation in the Elevated Pressure Elevated Temperature flow loop to study the effect of temperature on the sweeps. Thus based on the results obtained from the fluid characterization and literature review conducted, preliminary "sweep" tests were conducted in the E.P.E.T. flow loop. The results obtained from these tests are presented in this report.

The test matrix for these tests is presented in the table 5 below:

Base Fluid	Sweep Fluid	Temperature, ^{0}F, (^{0}C)	Pressure, psi	Flow Rate, gpm, (m3/s)
Water	Fluid A	80 ^{0} , (26.6)	150-200	100 & 200, (0.0063, 0.0126)
		120 ^{0} , (48.8)	150-200	
	Water	180 ^{0} , (82.2)	150-200	

Table 5: E.P.E.T. Test Matrix

Experimental Section:

The appendix contains figure 3, which shows the schematic diagram of the current flow loop with the modifications made to incorporate the "Sweeps". The experimental section of the LPAT flow loop is 90 ft long and consists of an 8-in. inner diameter transparent casing with 4.5 in. outer diameter drill pipe. The drill pipe can be rotated up to 120 rpm (revolution per minute R.P.M.). A 75 H.P. centrifugal pump

(maximum tested capacity is 650 g.p.m.) is used to pump fluid into the flow loop. The cuttings are injected at the inlet of the annular test section where they merge with the test section.

As mentioned earlier, the test matrix needed to be modified to incorporate higher flow rates of the "sweep". The higher flow rates would require high volumes of the "sweep" fluid and we did not have the required facilities to run these high volume sweeps. Thus the "sweep efficiency" will be quantified based on time rather than volume. All the sweep tests have been designed for two minutes sweeps in the test section, irrespective of the flow rate. The test procedure for the L.P.A.T. sweep tests is provided in the appendix.

Sweep Test Results:

L.P.A.T. Sweep Test Results:

Thirty six, eighteen & nine sweep tests were performed in Type I, Type II, Type III sweep tests respectively. As mentioned earlier these tests differed from each other in the base fluid and sweep fluids used. The effect of different drilling parameter i.e. the fluid rheological parameters, drill pipe rotation and flow rate on cuttings removal is presented in this report.

The analysis of the data obtained appears to indicate that it is not sufficient to focus on one drilling parameter, i.e. the rheological parameters of the fluid alone to clean the wellbore. Tests clearly show that, a proper combination of these drilling parameters is required for efficient hole cleaning. All the figures mentioned in this section are found in the appendix.

Effect of Rheological Parameters:

"Type I"

Three different fluids with yield points of 20, 30 & 40 lb/100ft^2 were prepared to study the effect of rheology on the bed erosion and cutting removal process. The tests indicate that it is not sufficient to only use a more "viscous" sweep to efficiently "erode" the cuttings bed. Figure 4 shows the plot of dimensionless bed height, before and after sweeps, for water and fluids with yield points of 20, 30 & 40 lb/100ft^2 at 400 gpm, without any drill pipe rotation. Dimensionless bed height is defined as the ratio between the calculated bed height and the inner diameter of the casing. This figure clearly shows that change of rheological parameters alone from 20 to 40 lb/100ft^2 have almost no effect on the "erosion" process or the cuttings removal. Figure 4 also shows that water appears to have the most effect on the

reduction in bed height. A comparison of the flow conditions, as shown in the table 6, for the fluids shows that the viscous fluids are in laminar flow as compared to water which is in turbulent flow.

"Type II"

The idea behind these tests was to study the effect of less viscous sweep on the cutting removal process. The rheological properties of the fluids used, i.e. Fluid F (base fluid used to build the initial bed) & Fluid D (sweep fluid) is presented in table 1. Figure 5 shows the plot of dimensionless bed height versus distance from injection end, for Fluid D and water at 300 & 400 gpm without drill pipe rotation and figure 6 shows the plot of dimensionless bed height versus distance from injection end, for Fluid D at 200, 300 & 400 gpm without drill pipe rotation We see that Fluid D has a considerable effect on the erosion process even in the absence of drill pipe rotation. Indicating that the less viscous sweep is more effective than a high viscous sweep, within the given flow rate range. Again the study of the flow conditions for the less viscous sweep indicates that they approach turbulent flow, when the flow rate is increased from 200 to 400 gpm.

"Type III"

The idea behind these tests was to study the effect of a comparatively higher density sweep on the bed erosion process. Although an attempt was made to maintain a relatively low viscosity for this fluid, due to the addition of large quantities of barite, it was the most "viscous" fluid used. The rheological parameters of this fluid are presented in table 1. When we study figure 7, plot of Dimensionless bed height versus distance from injection end, for Fluid E at 200, 300 & 400 gpm without drill pipe rotation we see that this fluid has no visible effect on the bed reduction process in the absence of drill pipe rotation. Thus the high density sweep which was highly viscous proved ineffective in bed erosion. This gives further proof that increasing the viscosity alone, does not improve the erosion process.

When we study the figure 17, plot of weight of cuttings versus fluid type, it allows an analysis based on the quantity or the amount of cuttings removed from the test section by the sweep fluids in the absence of drill pipe rotation. The figure clearly indicates that fluid A, B, C & E (highly viscous fluids) remove a very small amount of cuttings from the test section, in the absence of drill pipe rotation. But in contrast, fluid D & water remove large quantities of cuttings from the test section in the absence of drill pipe rotation.

Effect of Flow Rate:

"Type I"

Figure 8, plot of dimensionless bed height for fluid with yield point of 20 Lb/100ft^2 at flow rates of 200, 300 & 400 gpm. The figure shows that an increase of the flow rate from 200 to 400 gpm does not have any noticeable effect on the bed height. This is also indicated by figure 9, plot of volumetric cuttings concentration removed, for fluid with yield point of 30 Lb/100ft^2 at flow rates of 200 300 & 400 gpm without any drill pipe rotation. But in comparison when we look at figure 10, i.e. plot of dimensionless bed height for water at flow rates of 200 300 & 400 gpm, there is a large difference in bed heights. This is also indicated by figure 11, plot of volumetric cuttings concentration removed, for water at flow rates of 200 300 & 400 gpm without any drill pipe rotation. In the case of the viscous fluid the circulating fluid appears to take the path of least resistance and simply flow over the cuttings bed, i.e. the space between the cuttings bed and the casing.

"Type II"

Figure 12, plot of cuttings volumetric concentration removed, for fluid D at flow rates of 200, 300 & 400 gpm without any drill pipe rotation. Both this figure & figure 6 plot of dimensionless bed height for fluid D at flow rates of 200 300 & 400 gpm, indicates that fluid D is effective in cuttings bed reduction, when the flow rate is increased up to 400 gpm.

"Type III"

Figure 13, plot of cuttings volumetric concentration removed, for fluid E at flow rates of 200, 300 & 400 gpm without any drill pipe rotation. Both figure 13 and figure 7 indicate that fluid E is ineffective in cuttings bed reduction, even when the flow rate is increased up to 400 gpm.

Effect of drill pipe rotation:

It has been shown [13] that drill pipe rotation has a significant effect on hole cleaning during directional drilling. All the tests that incorporate drill pipe rotation showed that it has a considerable effect on cutting removal. This is indicated by figure 14, plot of dimensionless bed height for fluid with yield point of 30 Lb/100ft^2, with drill pipe rotational speed of 50 rpm and different flow rates of 200, 300 & 400 gpm & figure 12, plot of volumetric cuttings concentration removed for fluid with yield point of 30 Lb/100ft^2, with drill pipe rotational speeds of 0, 50, 100 rpm and a flow rate of 300 gpm. Other plots [14] have also shown that, under the influence of drill pipe rotation, the increase of flow rate of the viscous fluid

improves cuttings removal. The drill pipe rotation agitates the cuttings and helps lift them into the stream of the sweep fluid, thus facilitating the cuttings removal.

One of the drawbacks of using water as the sweep fluid was the uneven cuttings bed heights at the end of the sweep, which is seen clearly under the influence of drill pipe rotation. For this, we study figure 16, plot of dimensionless bed heights in the lower end with water & fluid with yield points of 20, 30 and 40 Lb/100ft^2, with flow rate pf 300 gpm and rotational speed of 50 rpm. We see that when the fluid is water, the bed height tends to be higher than the bed before the sweep test, on the lower side of the test section.

When we study figure 19, plot of dimensionless bed heights versus distance from injection end, for fluid D (less viscous) with flow rate of 300 gpm and rotational speed of 0, 50 & 100 rpm, we see that the bed height reduction is uniform throughout the test section.

When we study the figure 18, plot of weight of cuttings versus fluid type, it allows an analysis based on the quantity or the amount of cuttings removed from the test section by the sweep fluids with 50 rpm drill pipe rotation. The figure clearly indicates that in the presence of drill pipe rotation all the fluids perform well, including the highly viscous fluids. This provides additional evidence that drill pipe rotation has a significant effect on the cuttings bed reduction.

Effect of different parameters on differential pressure:

To study the effect of different parameters on pressure we study figure 20, plot of measured differential pressure versus time (duration of the sweep, two minutes) for water at different drill pipe rotational speeds of 0, 50 & 100 rpm. Measured differential pressure reflects the frictional pressure drop along the test section. As depicted in the figure, the pressure drop generally decreases with increase in pipe rotation with time during the sweep tests. This is because the higher pipe rotation results in less cuttings concentration in the test section and thus a larger flow area. At 50 rpm, the pressure decrease due to cuttings removal appears to be compensated by the increase in pressure due to the turbulence caused by drill pipe rotation. But at 100 rpm, the pressure decrease is quite noticeable. The same can be seen in figure 21, differential pressure versus time for fluid with yield point of 30 Lb/100ft^2 with drill pipe rotational speeds of 0, 50 & 100 rpm and flow rate of 300 gpm.

Next we study figure 22, the plot of the differential pressure versus time for fluid D without any drill pipe rotation at different flow rates of 200 gpm, 300 gpm & 400 gpm. We see that at 400 gpm the pressure drop reduces considerably with time. It can be further concluded that, if the sweep time were

increased the pressure drop would further reduce to finally reach a steady value. At 200 gpm and 300 gpm again, the pressure drop is not noticeable.

E.P.E.T. Preliminary Sweep Test Results:

Previous tests in other research projects [12] conducted at the Elevated Pressure Elevated Temperature flow loop have indicated that temperature has a considerable effect on cuttings transport.

The influence of temperature on the rheological parameters of the fluids has been described in detail in previous reports. Nine tests were conducted to study the influence of temperature on the bed erosion process, by using water as the base fluid and fluid A as the sweep fluid.

Since the E.P.E.T. flow loop does not have a transparent test section the cuttings bed reduction or cuttings removal is quantified based on the concentration of cuttings removed from the test section based on the densitometer reading changes and the pressure drop change during the two minutes of the sweep.

We first study figures 23 & 24, plots of pressure drop versus time (two minutes of sweep) for water and for fluid A at different temperatures, i.e. 80^0, 120^0 & 180^0 F at 200 gpm. The effect of the change in temperature is evident from both these plots. We observe that as temperature is increased from 80^0 to 180^0 the measured pressure drop reduces for both water and for fluid A. This change in pressure drop is attributed to the reduction in "apparent viscosity" for fluid A and the reduction of the viscosity of water. This change has also been reported by previous investigators.[12]

The next step is to understand the effect this change in temperature has on the bed reduction. For this we study three different figures 25, 26 & 27. All three figures are plots of densitometer (densitometer 1 & densitometer 2, shown in figure 32 presented in the appendix) reading versus time (duration of sweep, two minutes) for fluid A at 200 gpm. Each of these plots are at different temperatures, i.e 80^0, 120^0 & 180^0 F respectively. From these plots we see that although at 80^0 & 120^0 we do not see a difference in the densitometer readings with time, close observation of figure 27, i.e. plot at 180^0 F indicates that, as the cuttings are removed from the injection end of the test section, densitometer 2 readings reduce with time. A study of the flow conditions presented in table 7 in the appendix reveals that at 180^0 the fluid approaches turbulent flow. The figure also indicates that, the carrying capacity of the polymer has been reduced as densitometer 1 readings do not appear to reduce with time. Which indicates that the cuttings removed from the injection end are carried a short distance and deposited at the other end of the test section. Thus from the preliminary tests conducted at elevated temperature elevated pressure conditions we may say that an increase in temperature could effect the sweep efficiency due to its effect on the rheological properties of the sweep fluid.

Theoretical Stage:

As mentioned earlier a detailed procedure to calculate the C.R.V for cutting in power-law fluid was presented.[6] This procedure was modified to calculate the C.R.V. for cutting in yield-power law fluid. The following are the modifications made to the original procedure:

1. The plastic force was added to the moment balance presented [6], represented by equation 2 presented in the literature review section.

$$F_p = \frac{\pi d^2}{2}\tau_y[(\frac{\pi}{2}-\phi)+\phi\cos^2\phi-\sin\phi\cos\phi] \quad (2)$$

2. The drag force equations were modified specifically for yield-power law fluids using equation 1 presented in the literature review section.

$$F_D = \frac{C_D \pi K U^n D_p^{2-n}}{4} \quad (1)$$

3. The equations for the velocity profile to calculate the local velocity v_r and the local velocity gradient dv_r for yield-power law fluid represented by equations 3 through 5 respectively presented in the literature review section were incorporated.
4. The modified equation to calculate the friction factor represented by equation 6 presented in the literature review section was used.

$$\frac{1}{\sqrt{f}} = -4\log(\frac{0.27\varepsilon}{D_{eff}} + \frac{1.26^{N^{-1.2}}}{(R_{e,gn} f^{(1-N/2)})^{N^{-0.75}}}) \quad (6)$$

Figure 33 presented in the appendix shows the different steps involved in the procedure[6] to compute the C.R.V.

Effect of rheological parameters on C.R.V.:

The following results were obtained from the computer program developed to calculate the C.R.V. for cutting in yield-power law fluid. Figure 28, plot of the critical flow rate required for cuttings re-suspension predicted by the program versus the fluid type, i.e the three fluids termed as the high viscosity fluids, fluid A, B & C indicates that the flow rate reduces as the “viscosity” of the fluids increases. To understand this in terms of the specific rheological parameters, i.e fluid behavior index n, consistency index K and yield points of the respective fluids, we use three figures, i.e figures 29, 30 & 31 presented in the appendix.

From these plots we see that the program predicts that the critical re-suspension velocity decreases when:

- The flow behavior index n decreases.
- The consistency index K increases.
- The yield point increases.

Conclusions:

1. Increasing yield stress from 20 lb/100 ft2 to, 30 lb/100 ft2 & 40 lb/100 ft2, i.e a highly viscous fluid does not have any significant effect on the bed erosion process, within the test conditions.
2. Drill pipe rotation has a significant effect on bed erosion.
3. In the absence of drill pipe rotation water and fluid D (less viscous) proved to be more effective than the highly viscous fluids.
4. The high viscous high density sweep proved to be ineffective. The higher viscosity of the fluid may be the cause for this.
5. Water although very effective in the "bed erosion" process, has the draw back of being unable to carry the cuttings for a long distance.
6. The effectiveness of the less viscous sweep and water is attributed to the flow regime, the two fluids are in turbulent flow at the effective flow rates as opposed to the high viscosity fluid being in laminar flow.
7. Temperature has a significant effect on the rheological parameters of the fluids.
   When the temperature is raised for the fluids tested:
   - The flow behavior index n increases.
   - The consistency index k decreases.
   - The yield point decreases.
8. The effect of temperature was evident from the E.P.E.T. tests. At 180^0 F, the densitometer readings specifically DM2 reduced with time. Thus indicating that it had an effect on the concentration of the cuttings in the test section and hence an effect on the cuttings bed.
9. Mechanistic modeling of cutting re-suspension velocity of cuttings in yield power law fluid, indicates that C.R.V reduces when:
   - The flow behavior index n decreases.
   - The consistency index k increases.
   - The yield point increases.

Recommendations for Field Applications:

1. Drill pipe rotation in conjunction with a highly viscous fluid, in the range of 40 to 80 rpm is recommended for practical applications in order to efficiently reduce bed heights and transport cuttings.
2. Highly viscous fluids are not recommended for cuttings bed erosion in horizontal wellbore conditions and in low pump rates, in the absence of pipe rotation.
3. In the absence of drill pipe rotation, to clean cuttings out of a wellbore when drilling is stopped, use water or low viscosity mud instead of high viscosity mud.

Recommendations for Future Studies:

1. Further experimentation on the sweep study is recommended, with focus on fluids with lower "viscosity" and comparably high densities. The flow conditions need close attention; an attempt must be made to conduct experiments in which the "sweep" fluids are in turbulent flow conditions.
2. Close attention must be paid to all the rheological parameters, i.e. fluid behavior index n, consistency index K and yield stress of the fluids.
3. Mechanistic modeling for the "sweeps" should primarily focus on the "near bed" velocity profile. Accurate predictions of flow profiles are essential to accurately quantify the different forces acting on the cuttings.

PROJECT TIME TABLE:

	2004			2005		
	Spring	Summer	Fall	Spring	Summer	Fall
Literature Review						
Literature Review & Modeling						
Experiments						
Model Verification						
Final Report						

Future Work:

1. Final Thesis

References:

1) Raymond W. Flumerfelt, "Laminar displacement of Non-Newtonian fluid in parallel plate narrow gap annular geometries." S.P.E. 4486, April 1975.
2) Robert M. Beirute, and Raymond W. Flumerfelt, "Mechanics of the displacement process of drilling muds by cement slurries using an accurate rheological model." S.P.E. 5801, 1977.
3) D. Nguyen and S.S. Rahman, "A mathematical model for laminar displacement of one Non-Newtonian fluid by another in horizontal concentric annuli." Chem. Eng. Comm. 2000.
4) Ahmadi Tehrani, John Ferguson and S.H. Bitttleson, "Laminar displacement in annuli: A combined experimental and theoretical study." S.P.E. 24569.
5) Ramadan, A., "A Mechanistic Model to Determine the Critical Flow Velocity Required to Initiate The Movement of Spherical Bed Particles in Inclined Channels." Chemical Engineering Science 58 pg. 2153-2163, presented at Norway, 18 June 2002.
6) Mingqin Duan, University of Tulsa, Master of Science Dissertation "An Experimental Study of Small Sand –Sized Cuttings Transport in Horizontal And High Angle Boreholes", 2005.
7) Benjamin M., Pascal J. & Albert M. "Sphere Drag in Viscoplastic Fluid", AIChE Journal, October 2004 Volume 50, No. 10.
8) Clark, R.k. Bickham, 1994. "A Mechanistic model for cuttings transportation, S.P.E. 28306, 69th Ann. Tech Conf., New Orleans.
9) SEDM Desouky, M.A. Al Saddique, King Saud University "Turbulent Pressure Loss of Yield-fluids in Pipes", 1999.
10) B, Mck Torrance, Mechanical Engineer, "Friction Factors for Turbulent non-Newtonian Fluid Flow in Circular Pipes." November 1963.
11) T. Reed and A. Pilehvari, "A New Model for Laminar, Transitional, and Turbulent Flow of Drilling Muds", SPE 25456, Production Operations Symposium held in Oklahoma City, OK, USA, March 21-23, 1993.
12) L. Zhou, R.M. Ahmed, S.Z. Miska, N.E. Takach, M. Yu & M.B. Pickell, "Experimental Study & Modelling of Cuttings Transport with Aerated Mud in Horizontal Wellbore at Simulated Down hole Conditions.
13) Sanchez, R.A. et al.: "The Effect of Drillpipe Rotation on Hole Cleaning During Directional Well Drilling." Paper SPE, presented at Amsterdam, 4-6, March 1997.
14) Sandeep Valluri May 2005 TUDRP Progress report "Study on Effective Hole Cleaning using "Sweeps" in Horizontal Wellbores".

Nomenclature:

A_1 : Equation Constant used in equation for drag coefficient

A1 : Equation Constant used in equation for drag coefficient

A2 : Equation Constant used in equation for drag coefficient

A3 : Equation Constant used in equation for drag coefficient

B : Log constant

B_2 : Equation Constant used in equation for drag coefficient

B1 : Equation Constant used in equation for drag coefficient

B2 : Equation Constant used in equation for drag coefficient

B3 : Equation Constant used in equation for drag coefficient

B4 : Equation Constant used in equation for drag coefficient

B5 : Equation Constant used in equation for drag coefficient

C_D : Drag coefficient

C_L : Lift coefficient

CRV : Critical re-suspension velocity (m/s)

d : Drill Pipe Diameter (m)

D : Wellbore Diameter (m)

Deff : Effective Diameter

d_p : Particle diameter (m)

f_{bed} : Bed friction factor

F_b : Buoyancy (N)

F_D : Drag (N)

F_g : Gravity (N)

F_L : Lift (N)

F_{vanR} : Resultant Van der Waals Forces on a particle on a cuttings bed (N)

g : Gravitational acceleration (m/s^2)

K : Fluid consistency index ($Pa \cdot s^n$)

n : Fluid behavior index

Od : Oldstrom Number

Q : Liquid flow rate (gpm)

Re,gn : Generalized Reynolds Number

R_{ep} : Particle Reynolds number

U : Average fluid velocity in an annulus (m/s)

U_f : Bed friction velocity (m/s)

u^+ : Dimensionless local velocity

V_r : Local velocity at the particle center along fluid flow direction (m/s)

X : Equation Variable.

y : Distance above the mean bed surface (m)

Y.P. : Yield Point

Greek letters

α : Hole angle from vertical (degrees)

β : Direction angle of eccentricity (degrees)

ρ_f : Fluid density (kg/m^3)

ε : Absolute bed roughness (m)

Γ : Moment applied to a particle on a cuttings bed (N·m)

θ : Dimensionless hole angle

φ : Cuttings angle of repose (degrees)

τ_o & τ_y : Both used for yield stress, lb/100 ft ^2

η : Dimensionless Shear Rate

APPENDIX:

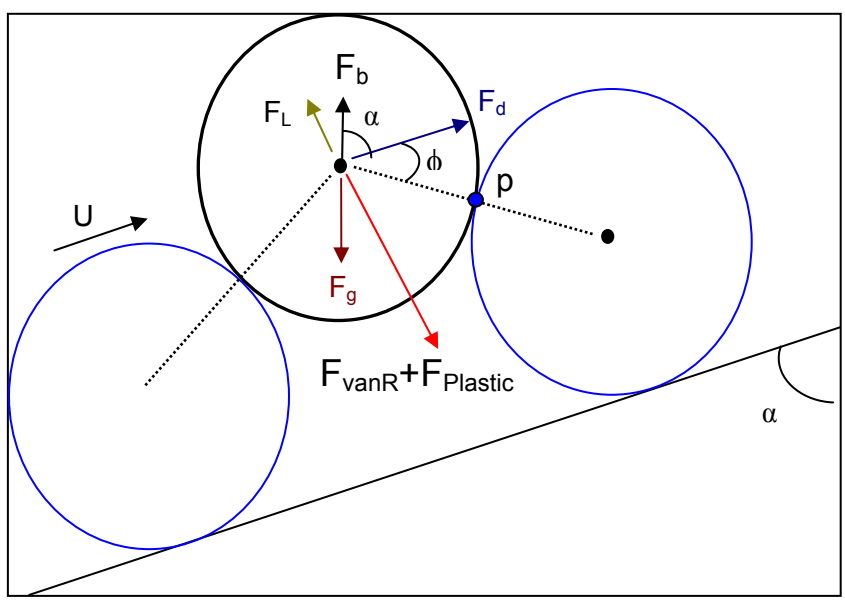

Figure 1: Moment Balance of a Particle Resting on Its Neighbors [6]

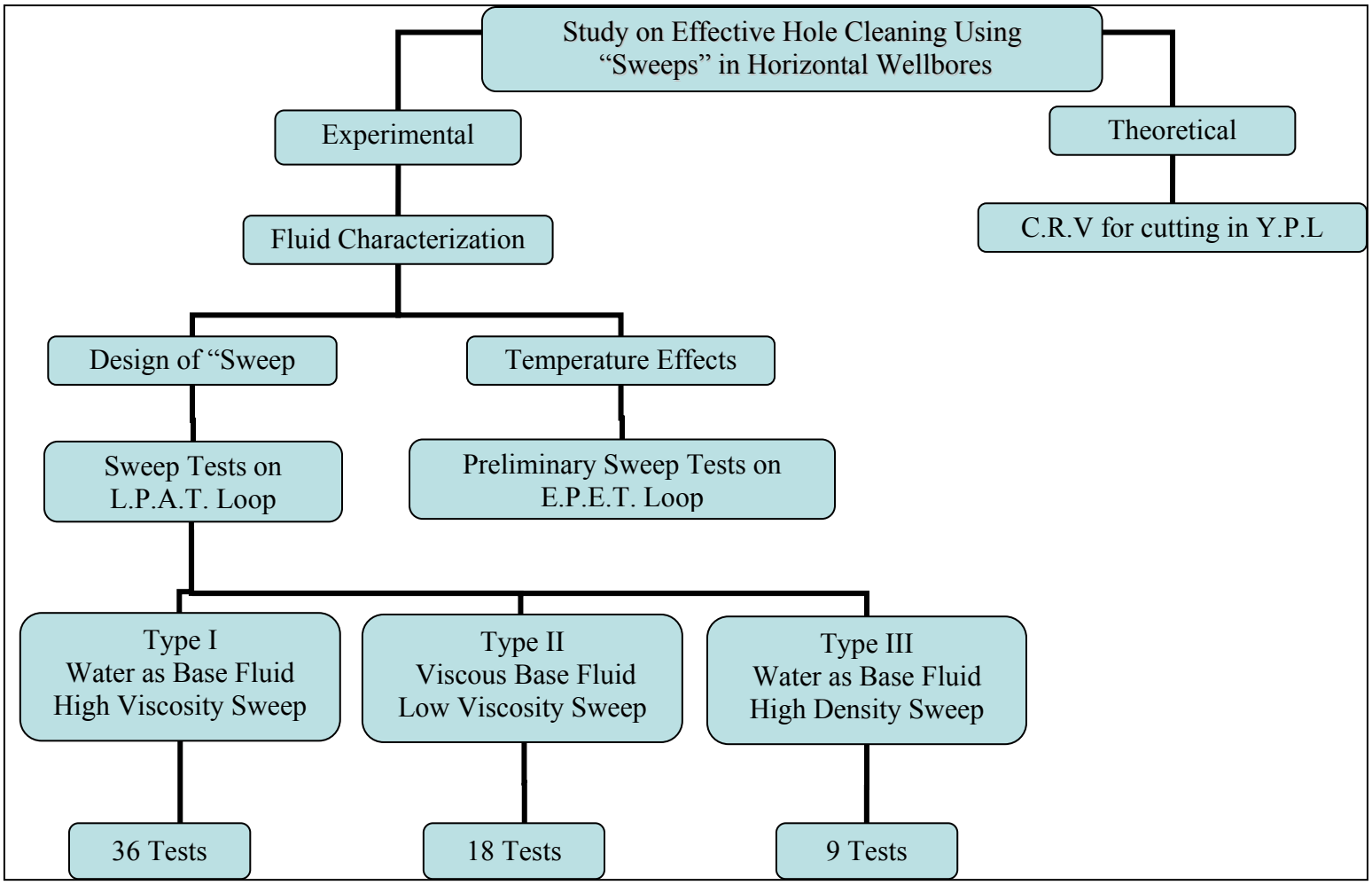

Figure 2: Schematic of different stages of research project

Fluid Label	Composition			Fluid Type	Fluid Properties					
					API (Bingham Plastic)		Yield-Power Law Model Parameters			Density, lb/gal
	P.A.C. lb/bbl	X.C.D. lb/bbl	Barite, lb/bbl		Plastic Viscosity	Yield Point, lb/100ft^2	Consistency Index, K, lbfs^n/100ft^2	Flow Behavior Index, n	Yield Stress, ty, lb/100ft^2	
Fluid A	1.5	1	0	High Viscosity	12	20	1.74	0.48	5	8.3
Fluid B	1.5	1.5	0	High Viscosity	15	30	2.94	0.33	8	8.3
Fluid C	1.5	2	0	High Viscosity	18	40	4.14	0.17	11	8.3
Fluid D	0.5	0	0	Low viscosity	-	0	0.21	0.75	0	8.3
Fluid E	1.5	1	234	High-Viscosity High - Density	13	50	11	0.16	21	12
Fluid F	1.5	0	0	High Viscosity	-	-	0.46	0.69	0	8.3
Water	0	0	0	Newtonian	-	-	0.002	1	0	8.3

Table1: Fluid Label, composition, rheological parameters & density.

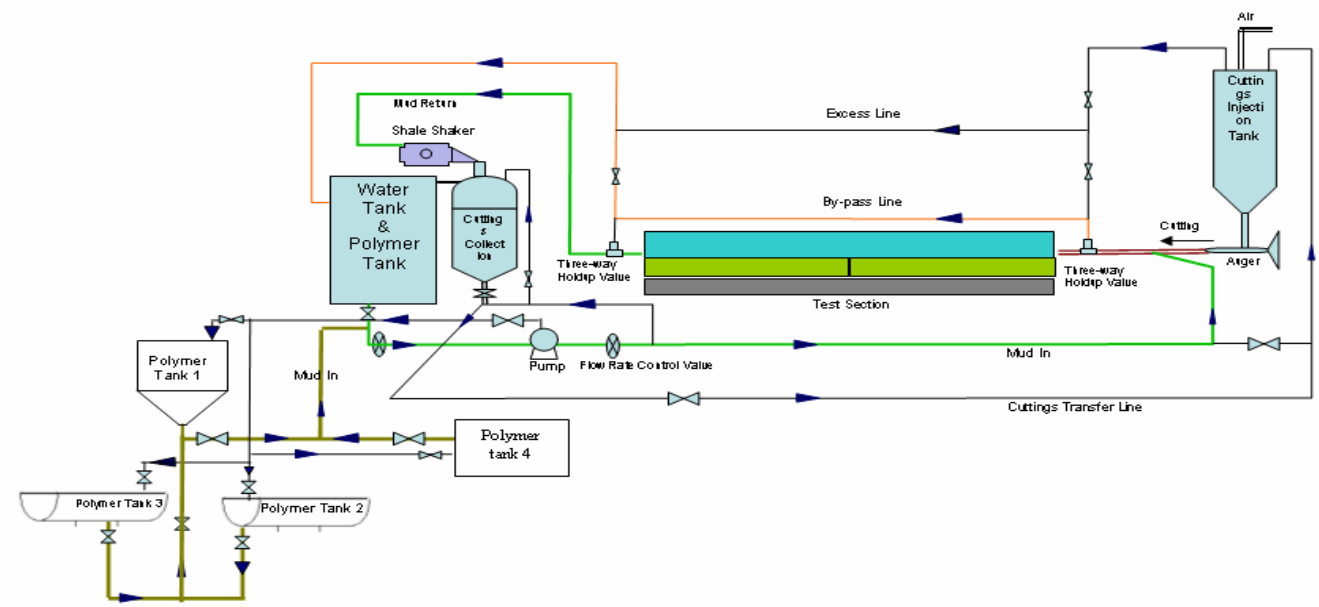

Figure 3: Current L.P.A.T. (Low pressure ambient temperature flow loop with modifications).

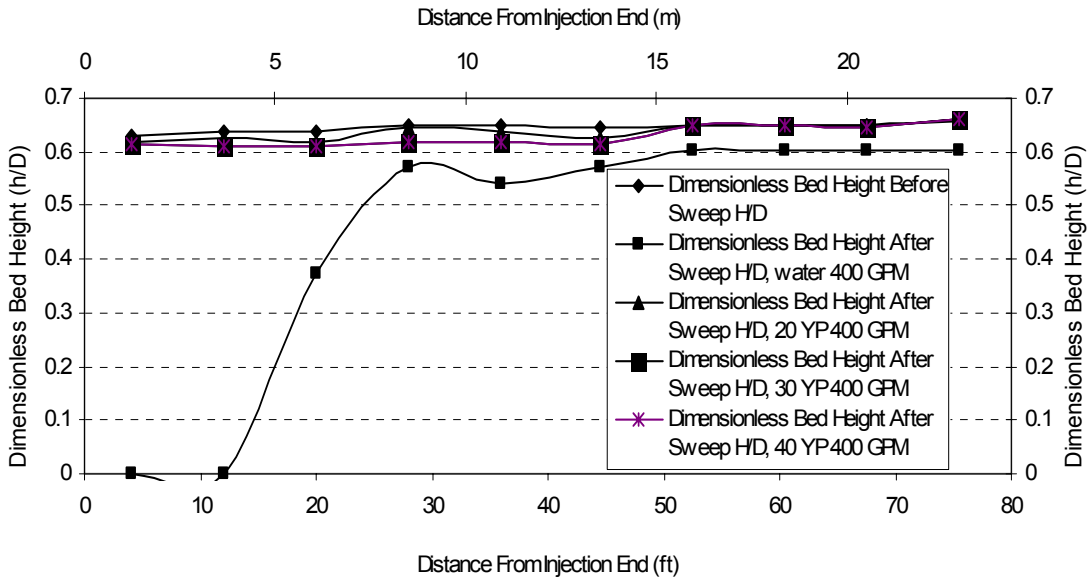

Figure 4: Dimensionless bed height, before and after sweeps, for water and fluids with yield points of 20, 30 & 40 lb/100ft^2 at 400 gpm, without any drill pipe rotation.

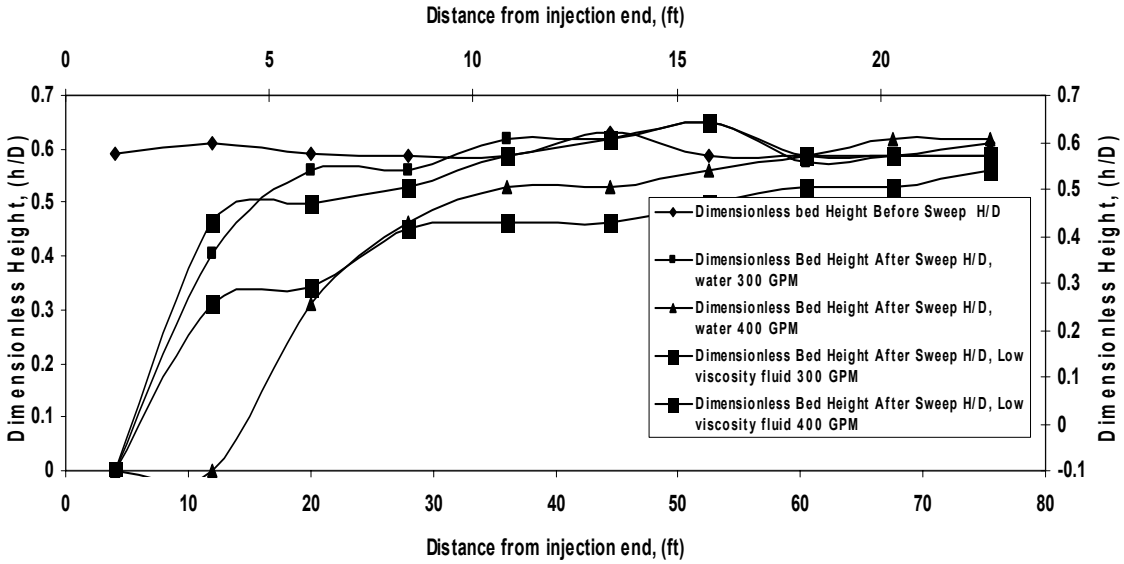

Figure 5: Dimensionless bed height for bed built with highly viscous fluid and using "sweeps" of water and fluid D

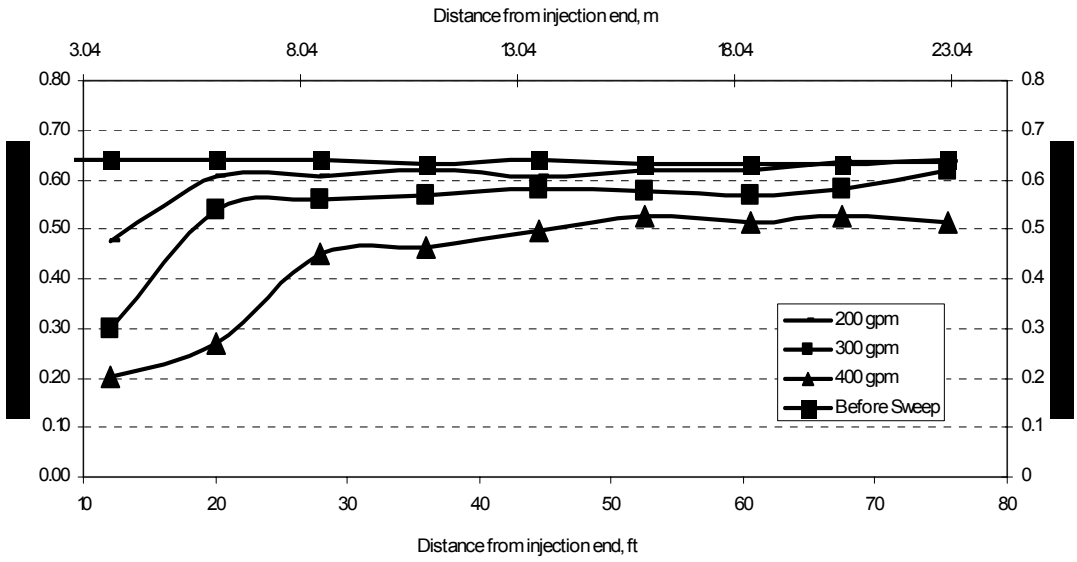

Figure 6: Dimensionless bed height, before and after sweeps, for fluid D at 200 gpm, 300 gpm & 400 gpm, without any drill pipe rotation.

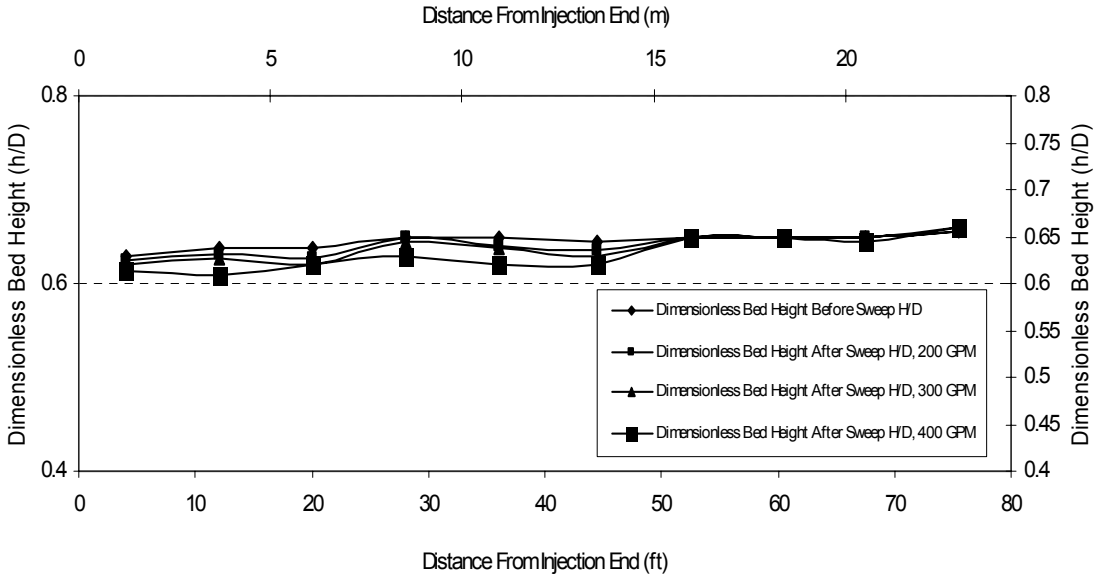

Figure 7: Dimensionless bed height, before and after sweeps, for high density high viscosity fluid at different flow rates without any drill pipe rotation.

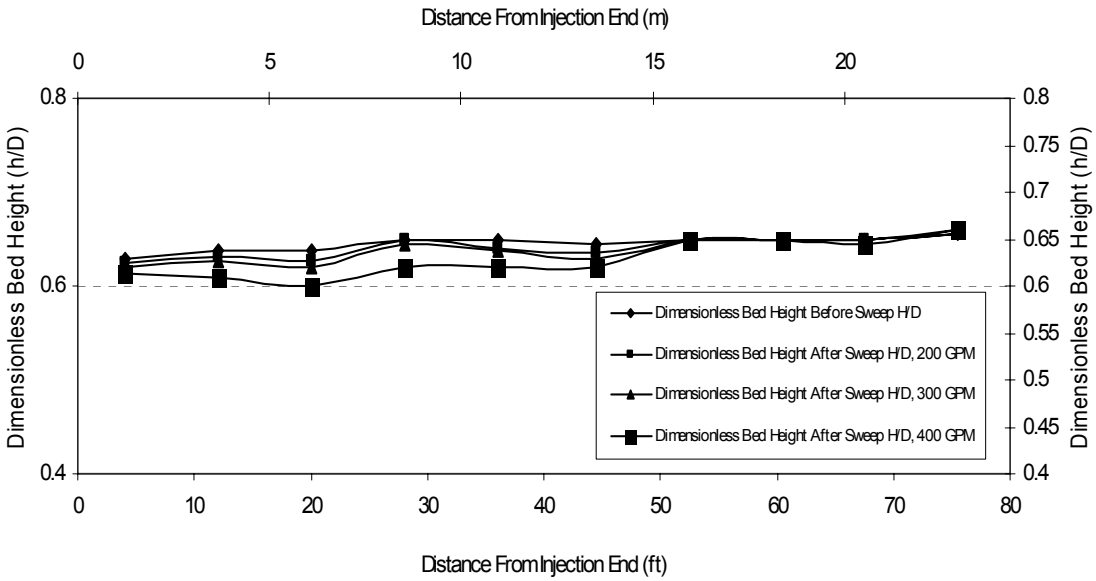

Figure 8: Dimensionless bed height for fluid with yield point of 20 Lb/100ft^2 at flow rates of 200 300 & 400 gpm.

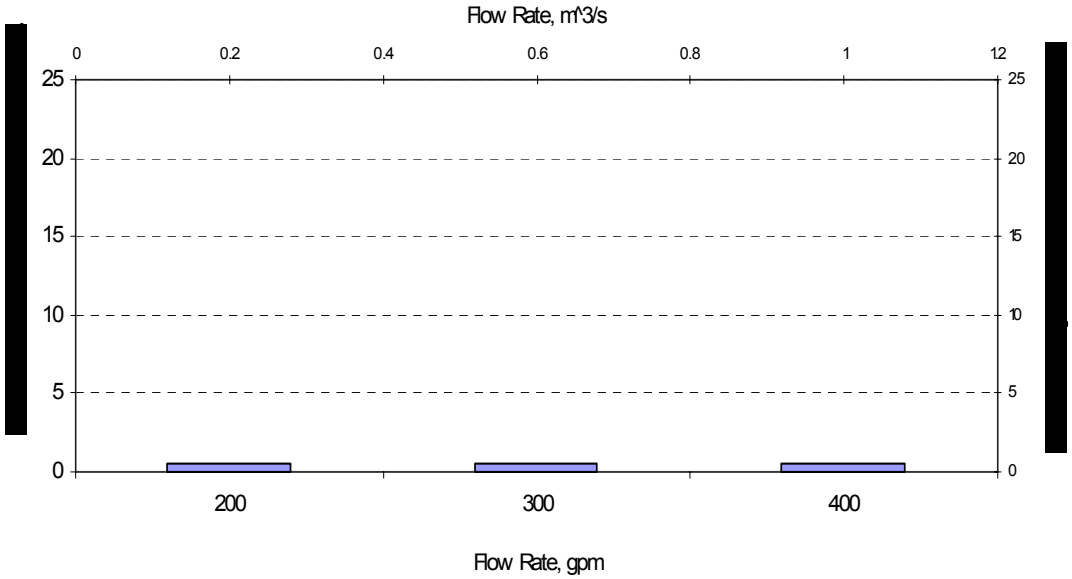

Figure 9: Volumetric cuttings concentration removed comparison of 200, 300 & 400 gpm, for fluid with yield point of 30 lb/100ft^2 & no drill pipe rotation.

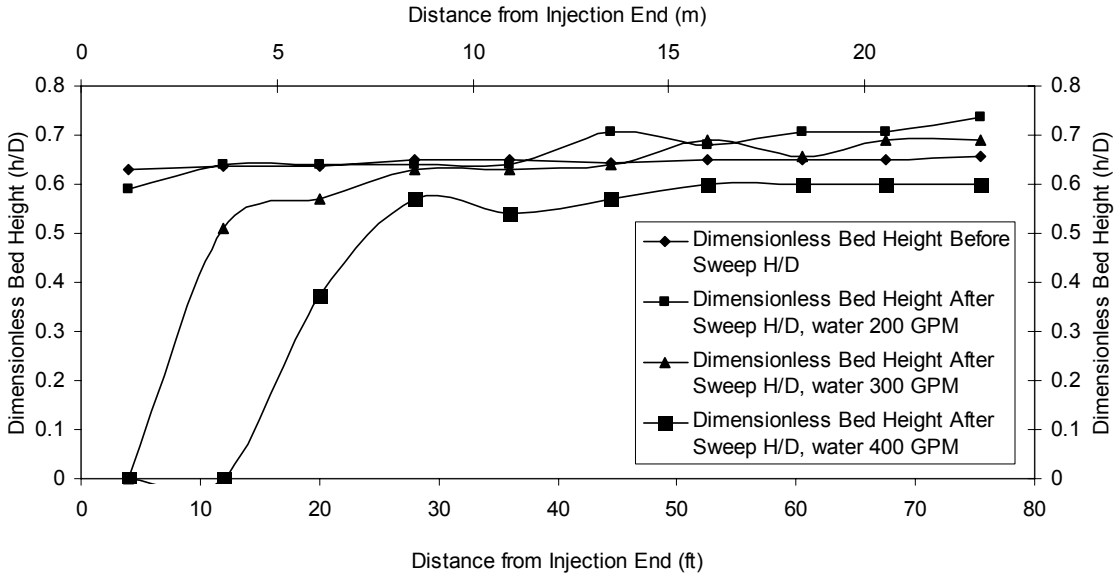

Figure 10: Dimensionless bed height for water at flow rates of 200 300 & 400 gpm

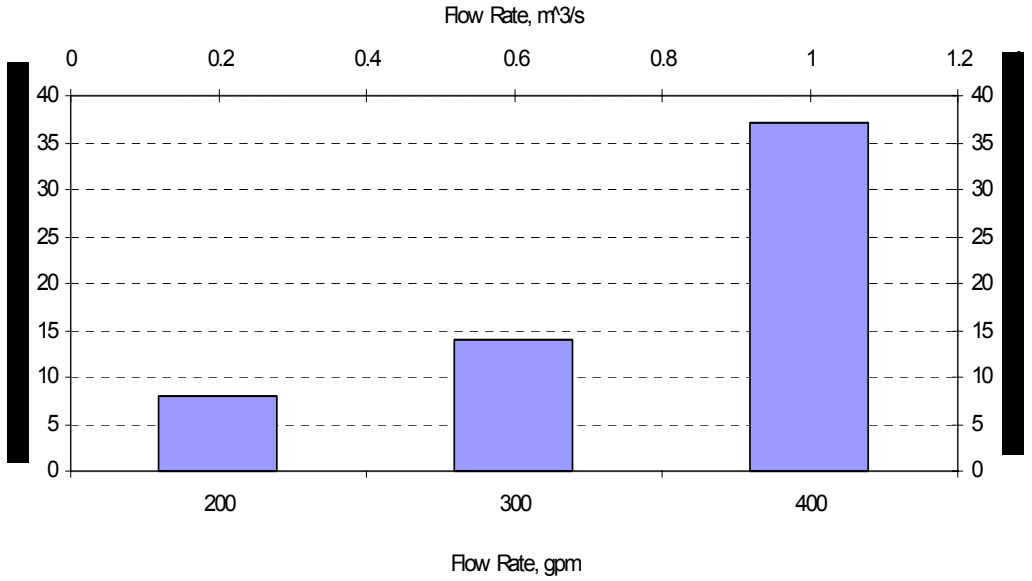

Figure 11: Volumetric cuttings concentration removed comparison of 200, 300 & 400 gpm water, in the absence of drill pipe rotation

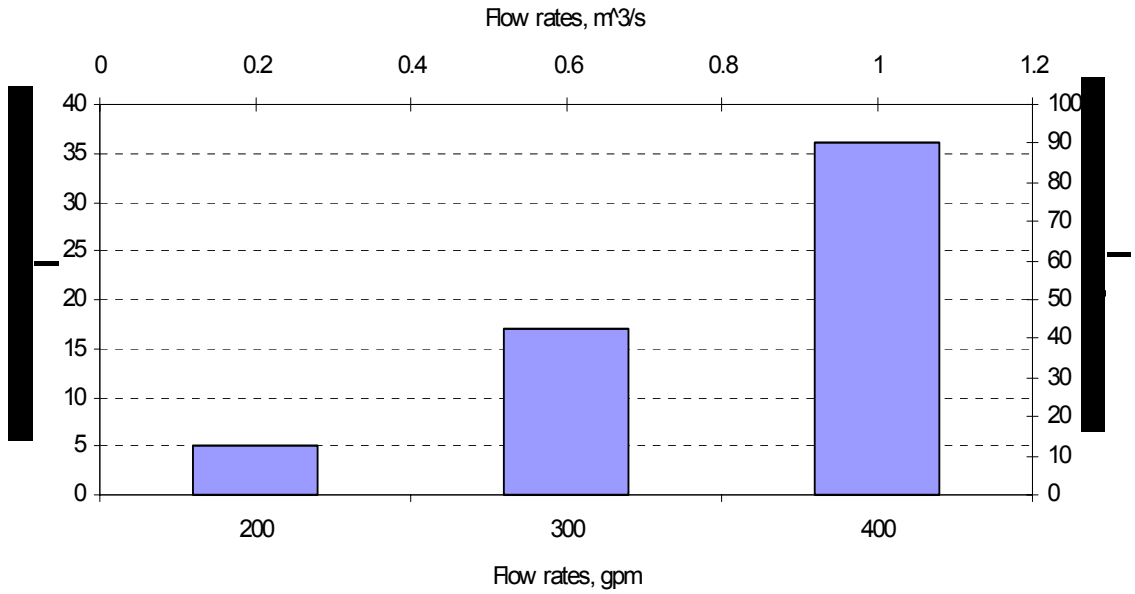

Figure 12: Volumetric cuttings concentration removed comparison of 200, 300 & 400 gpm, fluid D, and no drill pipe rotation.

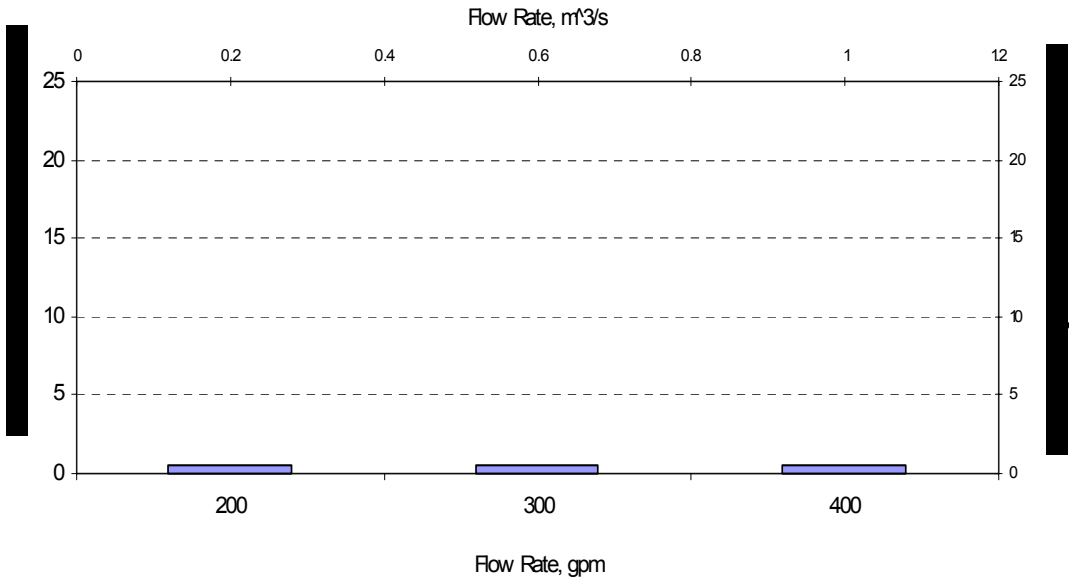

Figure 13: Volumetric cuttings concentration removed comparison of 200, 300 & 400 gpm, for fluid with yield point of 30 lb/100ft^2 & no drill pipe rotation.

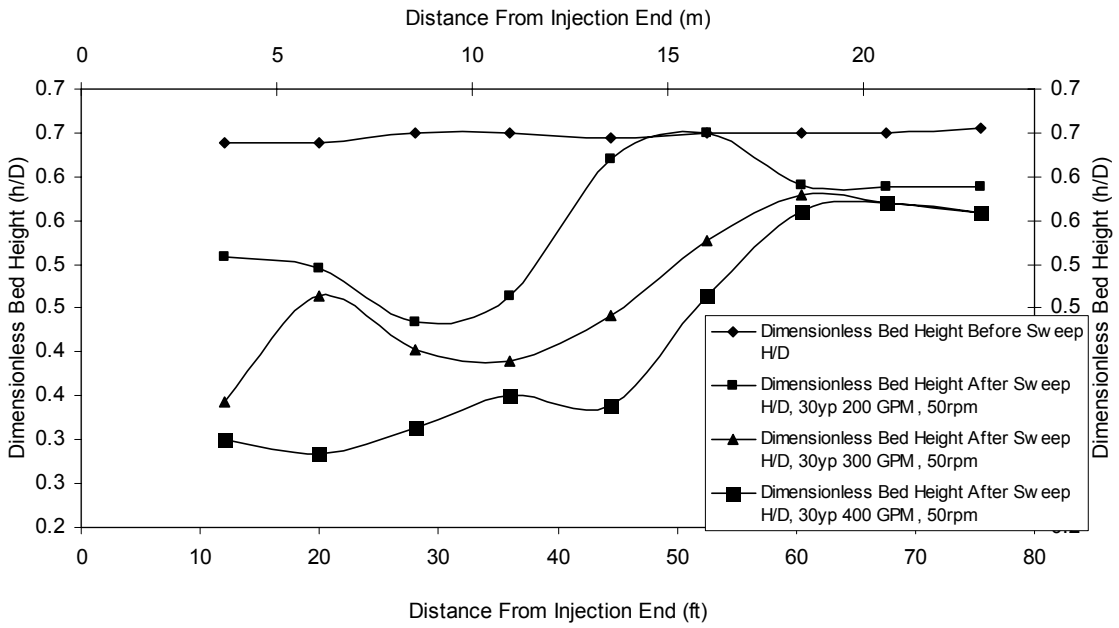

Figure 14: Dimensionless bed height comparison of fluid with yield point of 30 lb/100ft^2 with flow rates of 200, 300, and 400 gpm & drill pipe rotational speed of 50rpm

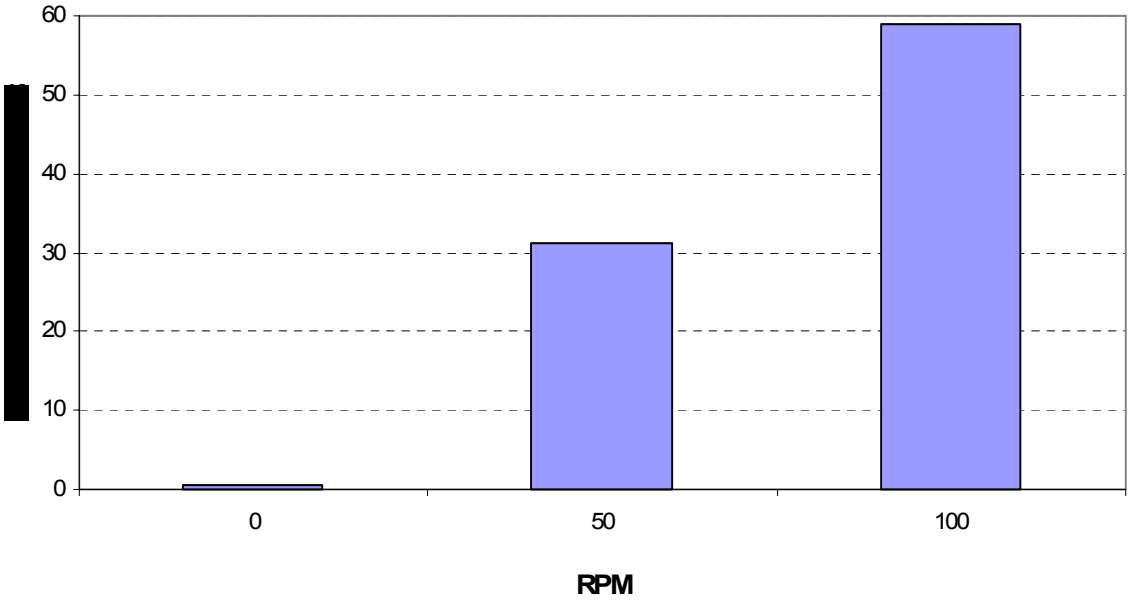

Figure 15: Volumetric cuttings concentration removed comparison of 300 gpm for fluid with yield point of 30 lb/100ft^2, 0, 50, 100 rpm

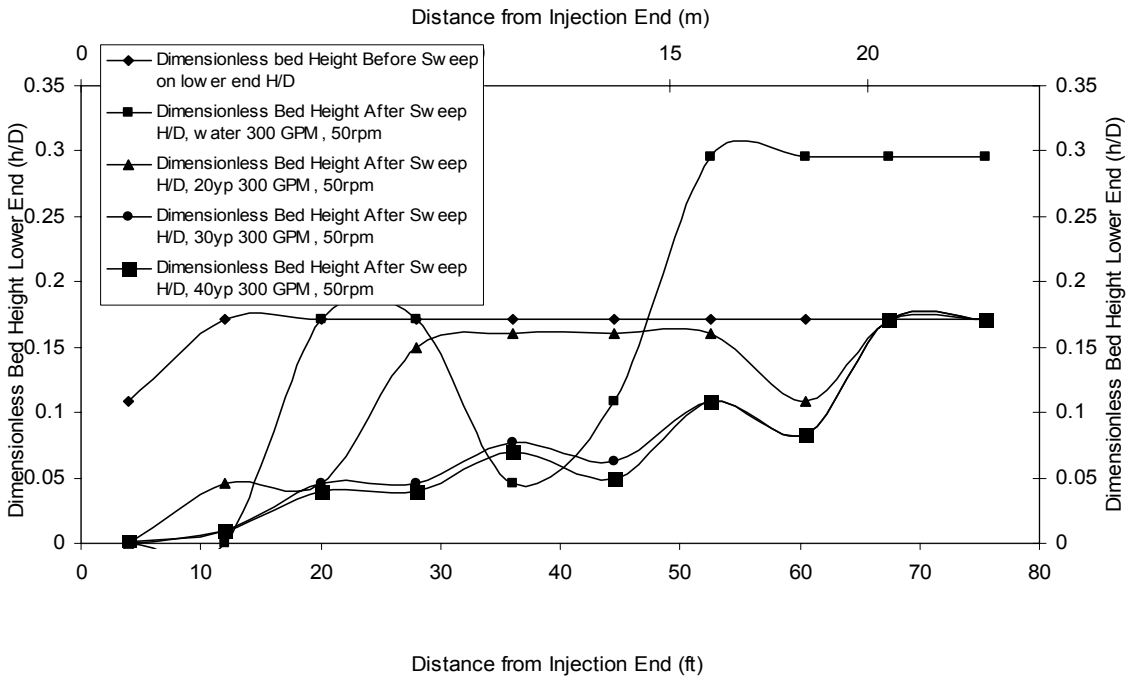

Figure 16: Dimensionless bed height comparison of bed heights in the lower end with, water & fluids with yield points of 20 lb/100ft^2 , 30 lb/100ft^2, 40 lb/100ft^2 fluid, 300 gpm & 50 rpm.

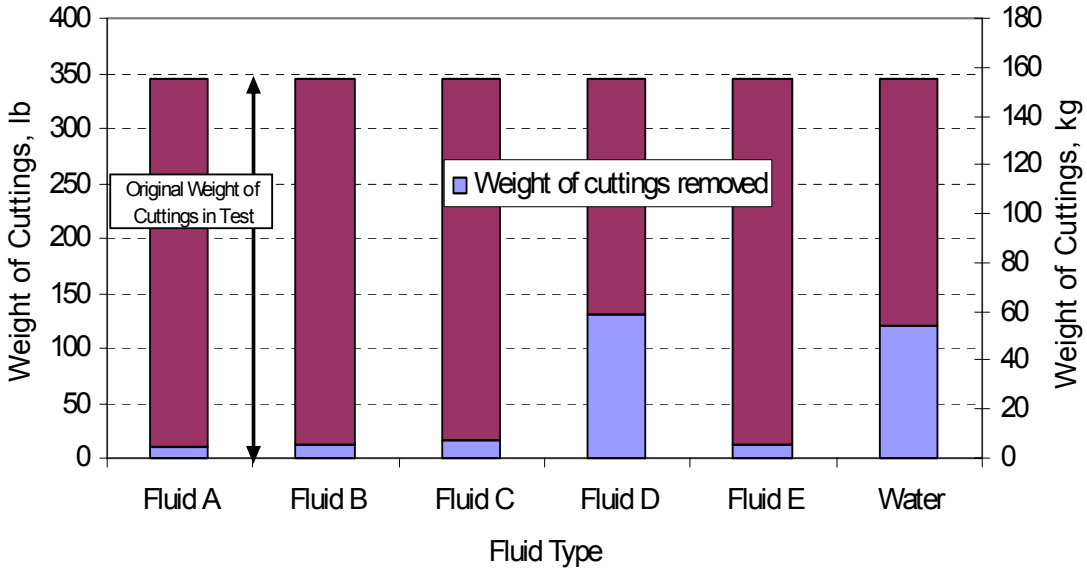

Figure 17: Weight of Cuttings versus fluid Type, in the absence of drill pipe rotation & flow rate of 400 gpm.

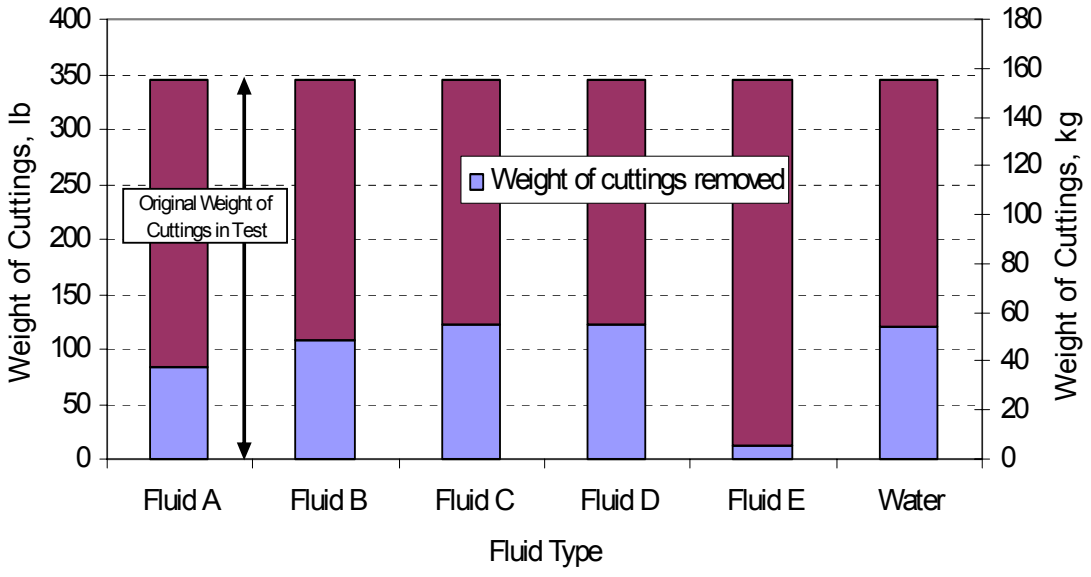

Figure 18: Weight of Cuttings versus fluid Type, with 50 rpm drill pipe rotation anf flow rate of 300 gpm

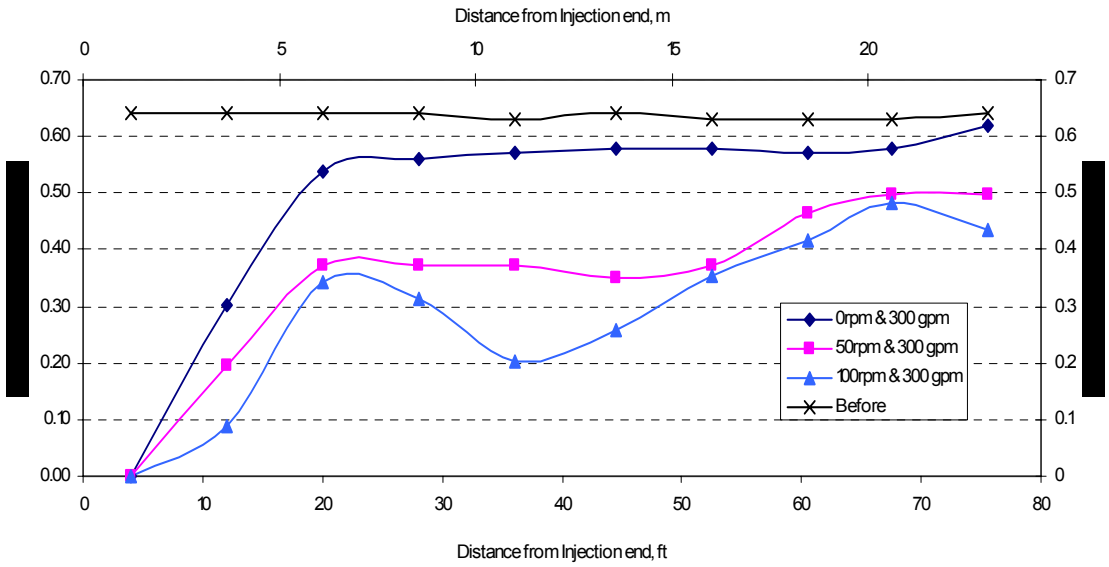

Figure 19: Dimensionless bed height comparison of bed heights for fluid D (Less viscous) at different drill pipe rotational speeds of 0, 50 & 100 rpm at flow rate of 300 gpm.

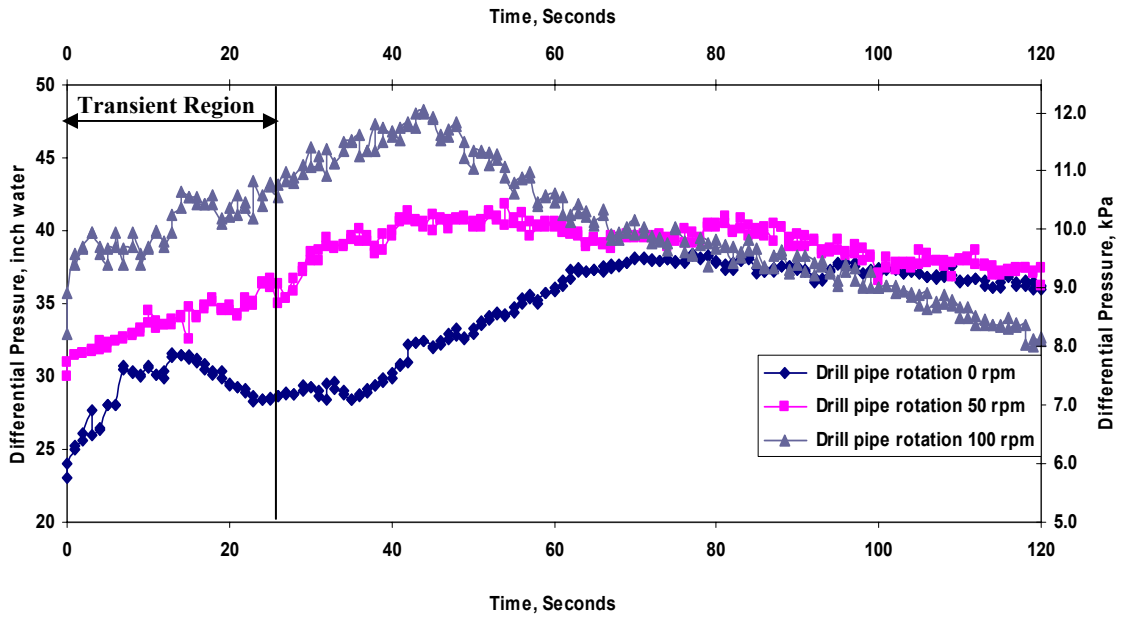

Figure 20: Differential Pressure versus time for water with different drill pipe rotational speeds of 0, 50 & 100 rpm at 300 gpm.

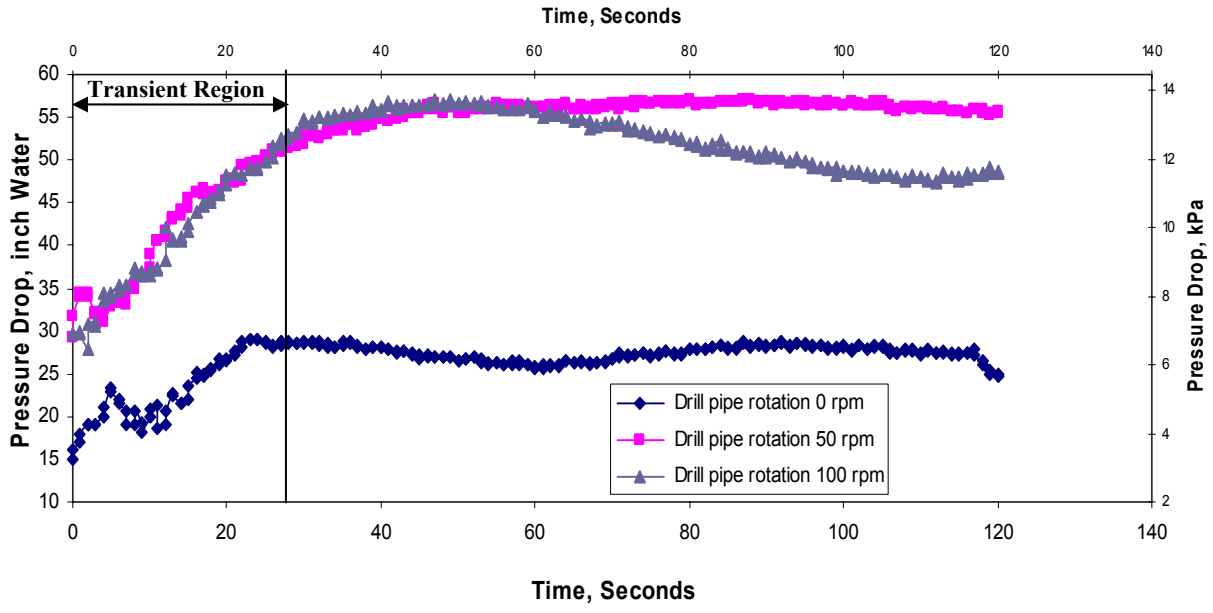

Figure 21: Differential Pressure versus time for fluid with yield point of 30 Lb/100ft^2 with drill pipe rotational speeds of 0, 50 & 100 rpm and flow rate of 300 gpm.

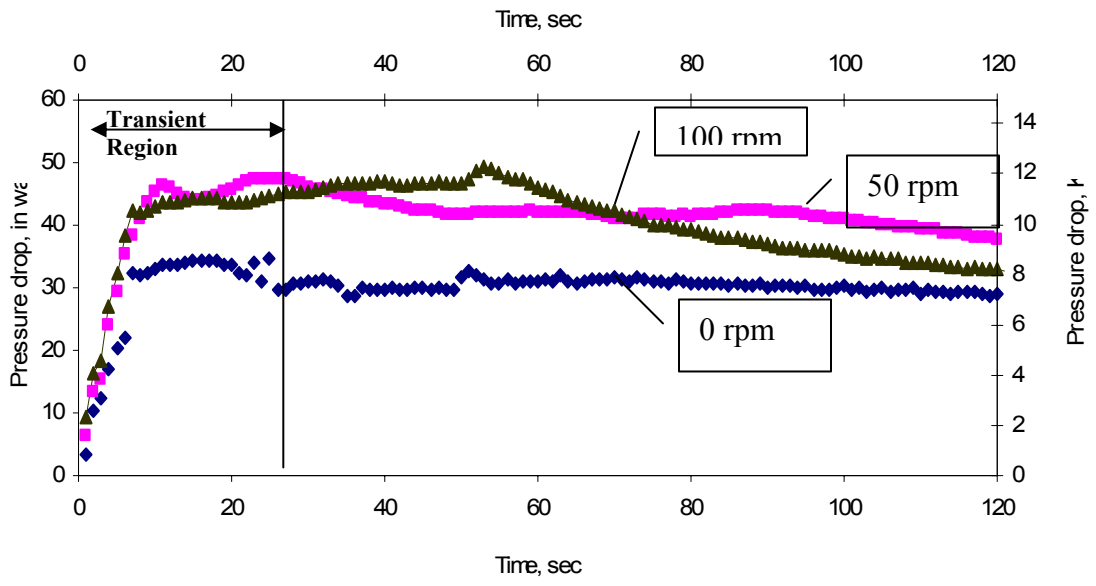

Figure 22: Differential Pressure versus time for fluid D(Less Viscous) with different drill pipe rotational speeds of 0, 50 & 100 rpm at 300 gpm.

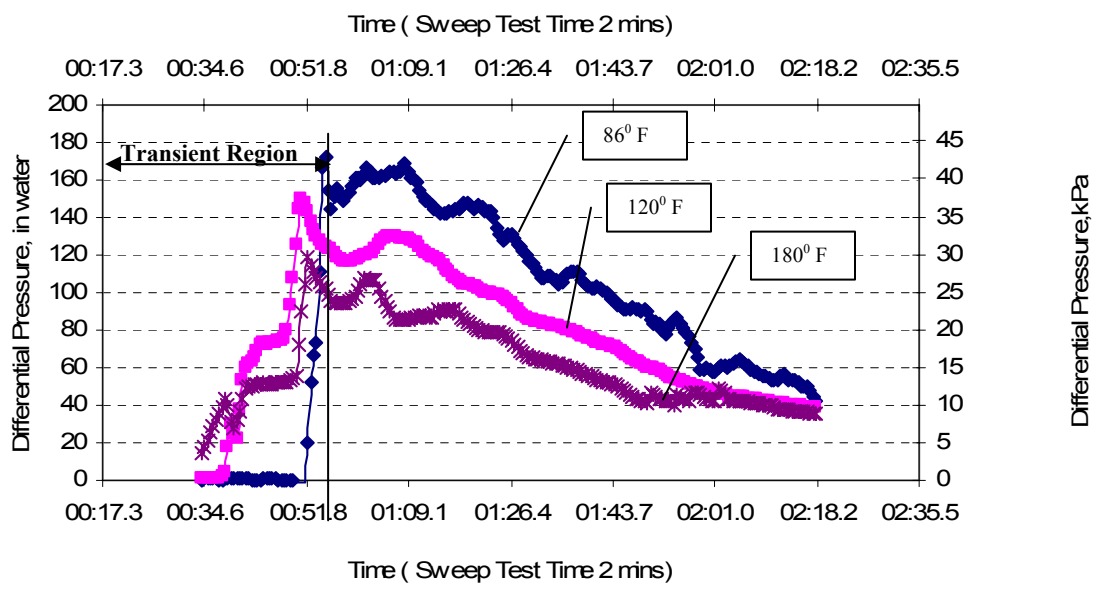

Figure 23: Differential Pressure versus time for water at 200 gpm at different temperatures, i.e. 86^0, 120^0 & 180^0 F

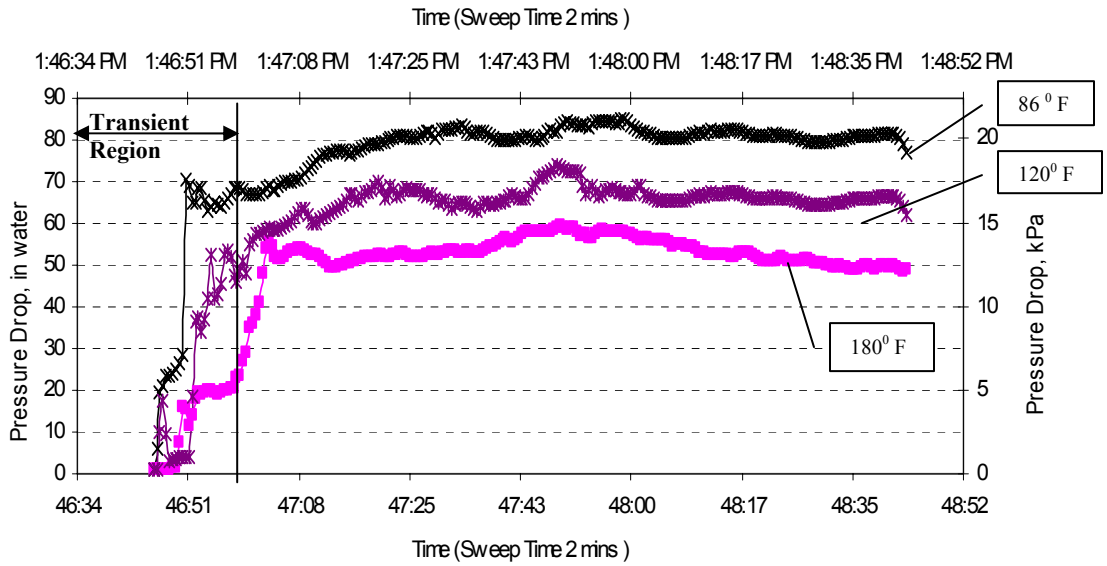

Figure 24: Differential Pressure versus time for fluid A at 200 gpm at different temperatures, i.e. 86^0, 120^0 & 180^0 F

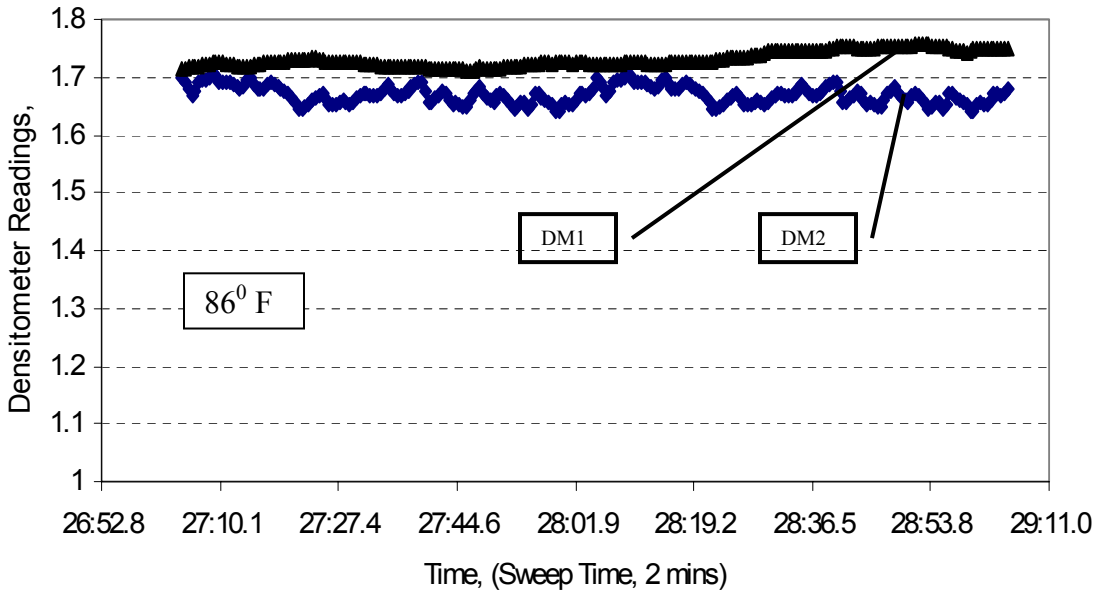

Figure 25: Densitometer Readings (Densitometer 1 & Densitometer 2) vs. time (Sweep time 2 mins), for fluid A at 200 gpm at 86^0 F.

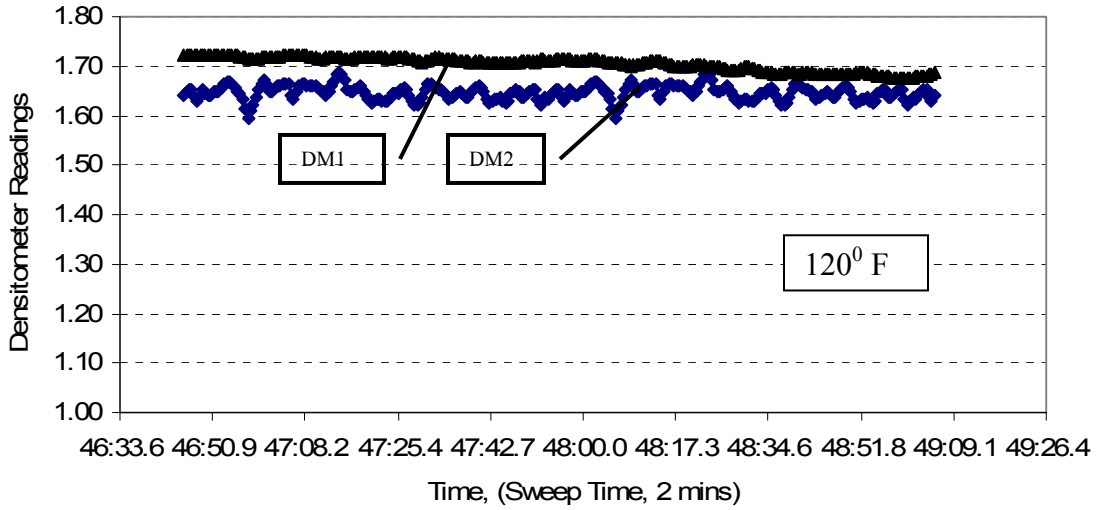

Figure 26: Densitometer Readings (Densitometer 1 & Densitometer 2) vs. time (Sweep time 2 mins), for fluid A at 200 gpm at 120^0 F.

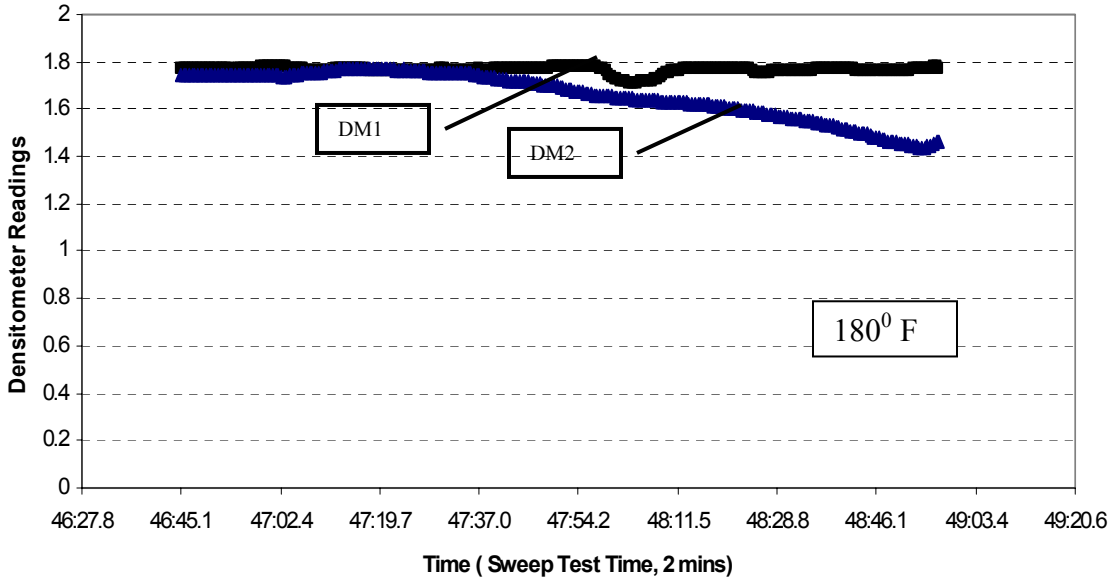

Figure 27: Densitometer Readings (Densitometer 1 & Densitometer 2) vs. time (Sweep time 2 mins), for fluid A at 20 gpm at 180^0 F.

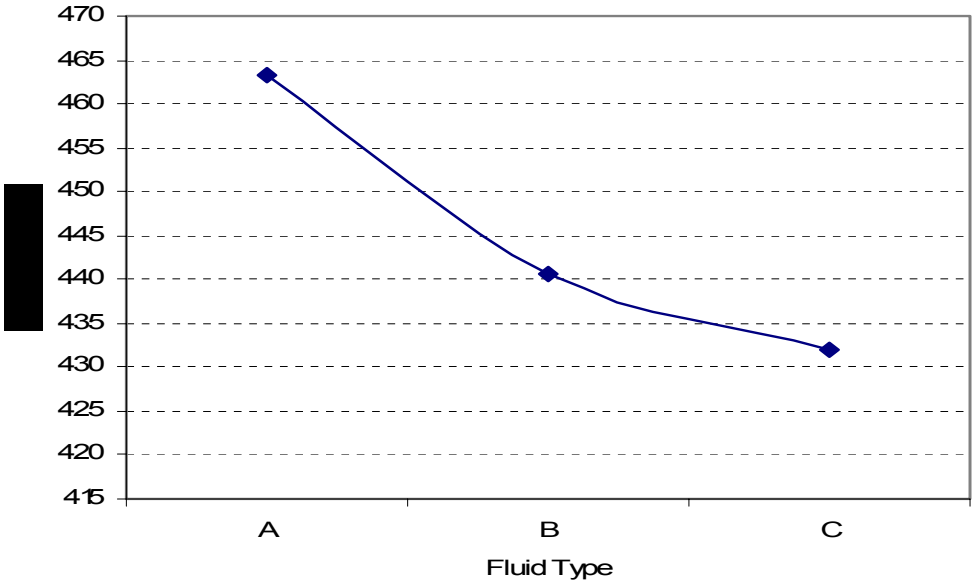

Figure 28: Critical flow rate required for cuttings re-suspension predicted by the program required for cuttings re-suspension versus Fluid Type A, B, C.

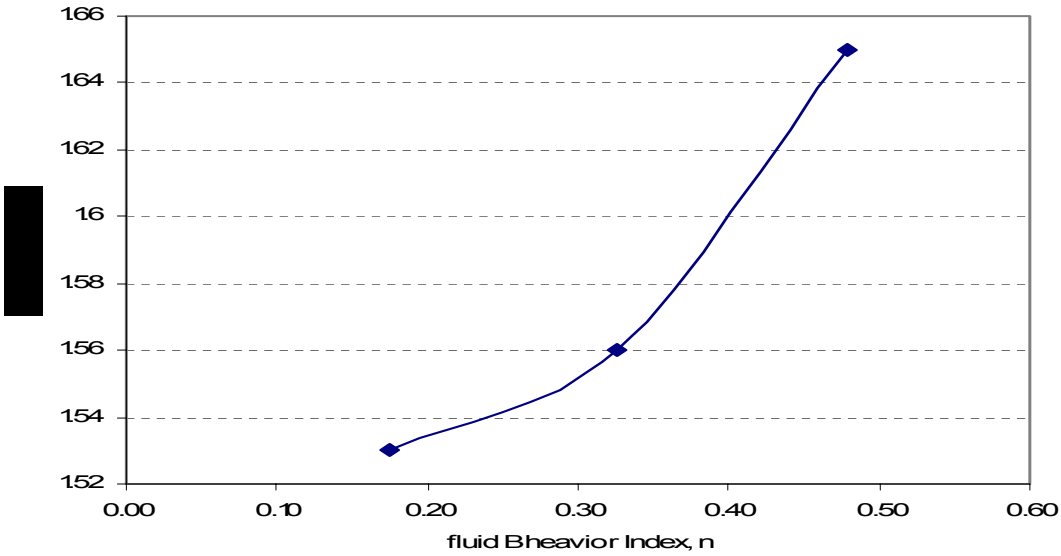

Figure 29: C.R.V predicted by the program versus flow behavior index n.

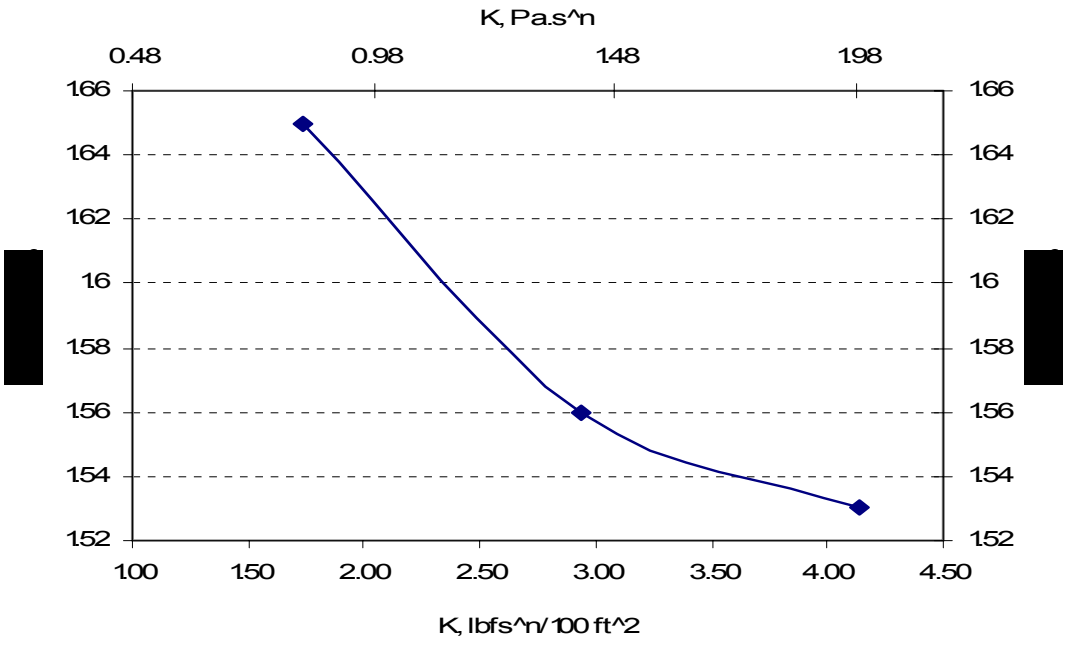

Figure 30: C.R.V predicted by the program versus Consistency Index K

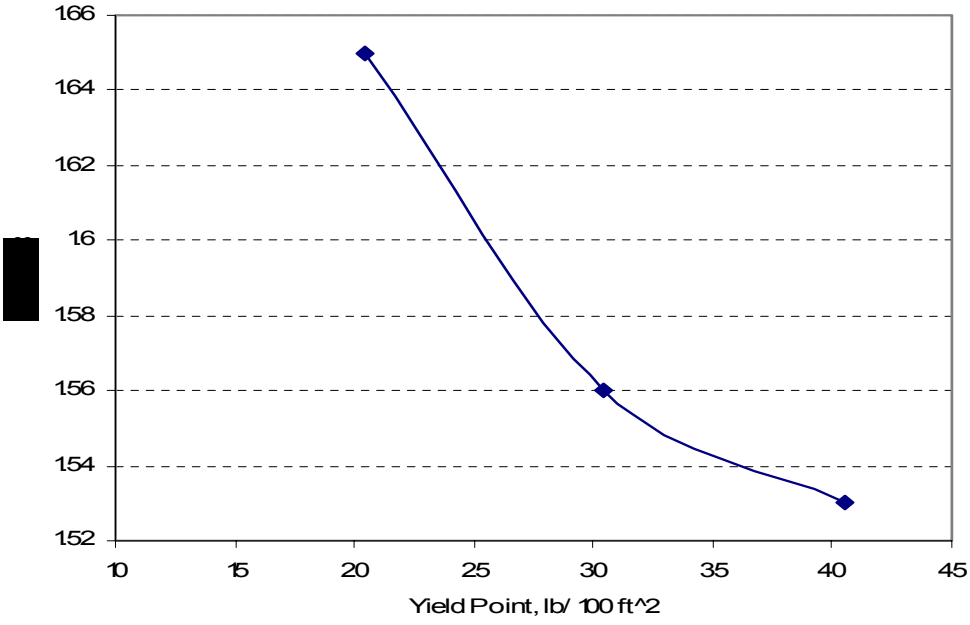

Figure 31: C.R.V. predicted by the program versus Yield Stress.

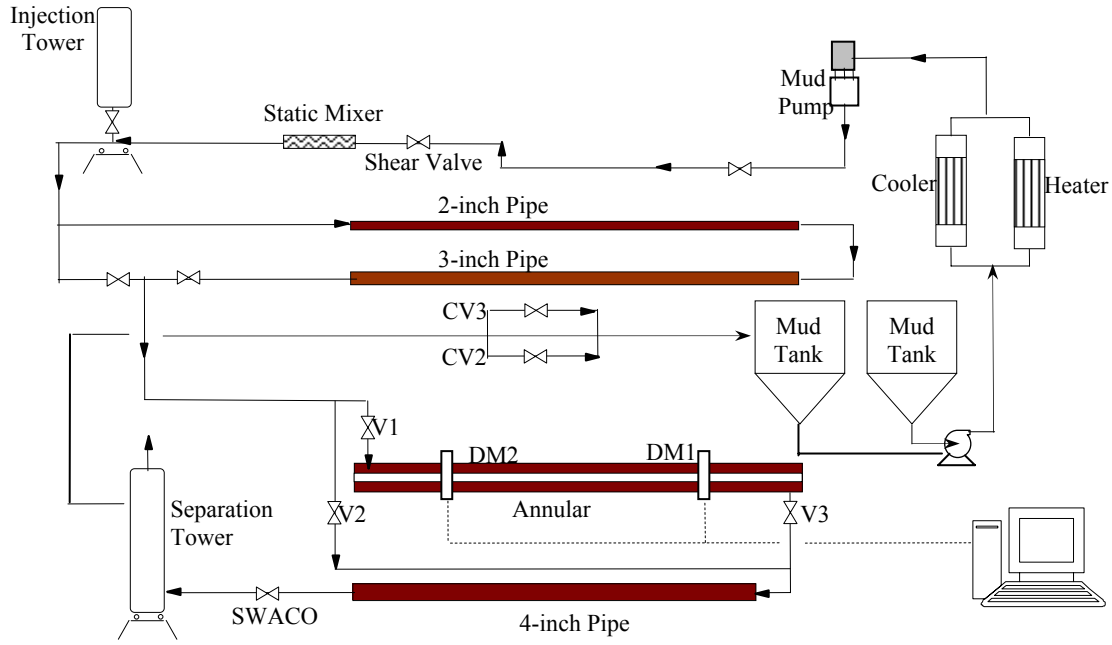

Figure 32: Current E.P.E.T. (Elevated pressure Elevated temperature flow loop with modifications).

Fluid	Flow Rate (Gpm)	(Nre)	Fluid	Flow Rate (Gpm)	(Nre)
Fluid A (20 Lb/100ft^2)	200	173.9	**Fluid C (40 Lb/100ft^2)**	300	216.3
Fluid B (30 Lb/100ft^2)	200	120.9	**Fluid D (Water)**	300	58208.1
Fluid C (40 Lb/100ft^2)	200	102.7	**Fluid A (20 Lb/100ft^2)**	400	571.5
Fluid D (Water)	200	38805.4	**Fluid B (30 Lb/100ft^2)**	400	408.6
Fluid E (Low viscosity)	200	1852	**Fluid E (Low Viscosity)**	400	4740
Fluid A (20 Lb/100ft^2)	300	349.8	**Fluid C (40 Lb/100ft^2)**	400	365.1
Fluid B (30 Lb/100ft^2)	300	247.4	**Fluid D (Water)**	400	77610.8

Table 6: Reynolds Number for different fluids at different flow rates

Temperature	Fluid A(Yield Point @ Given Temperature)	Flow Rate (gpm)	Nre
80^0 F	20 lb/100 ft^2	100	425
81^0 F	20 lb/100 ft^2	200	1100
120^0 F	12 lb/100 ft^2	100	600
120^0 F	12 lb/100 ft^2	200	1800
180^0 F	2 lb/100 ft^2	100	1200
180^0 F	2 lb/100 ft^2	200	4100

Table 7: Elevated Pressure Elevated Temperature Reynolds Numbers

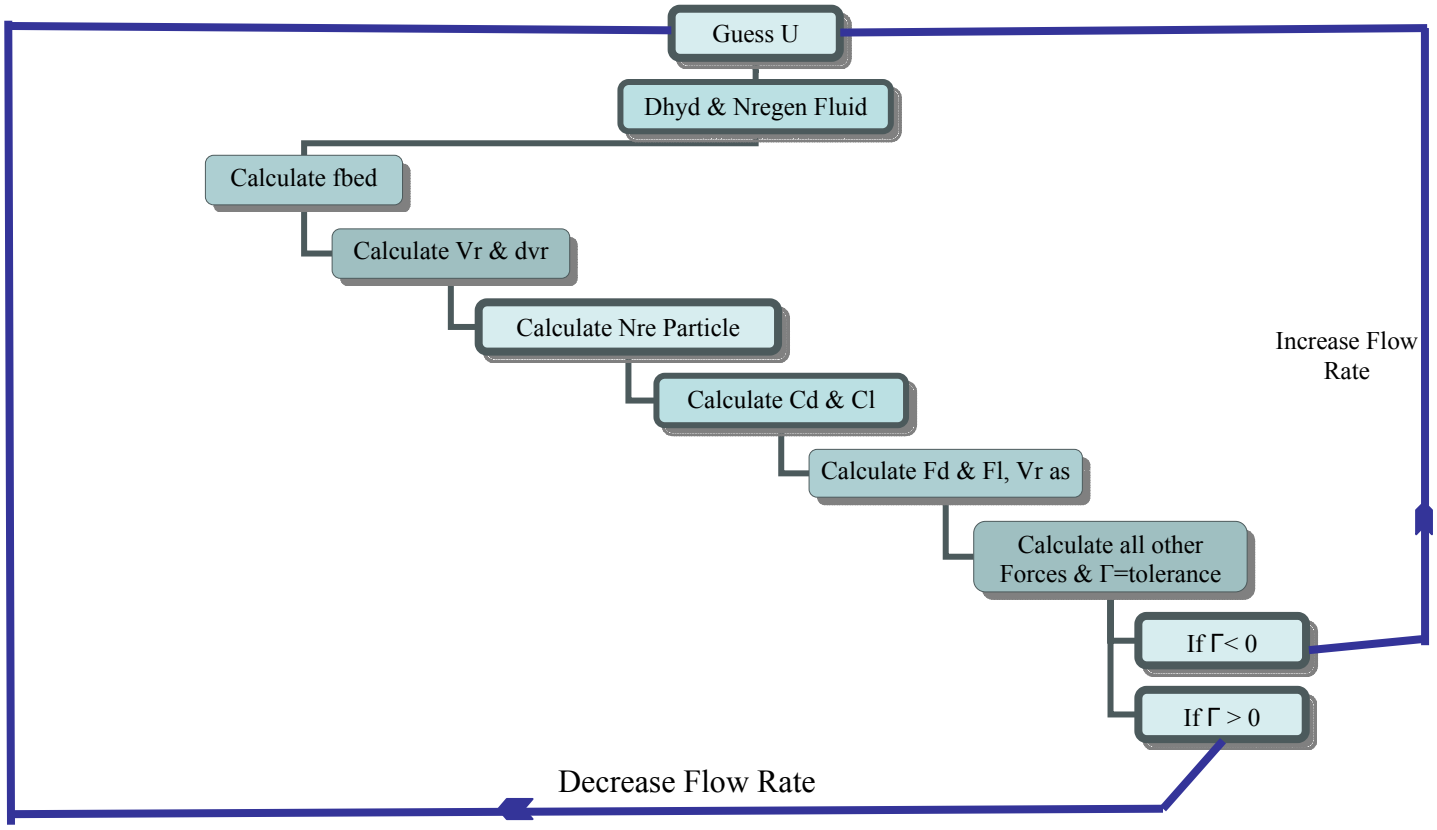

Figure 33: Procedure [6] to computer critical re-suspension velocity.

LPAT "Sweep" Test Procedure

A standard procedure is followed for conducting the experiments, the steps of which are provided below. For any successful run, it is necessary that steady-state conditions be reached in the test section before data acquisition can be initiated.

1. The test fluid is prepared, by adding the required amount of both PAC (Poly Anionic Cellulose) and XCD (Xanthum Gum) to water in the primary tank indicated by 2 in figure1.
2. Prime the centrifugal pump if the primary tank indicated by 2 in Figure1 is emptied and filled with a new fluid.
3. Once the fluid is prepared, measure the rheology of the fluid and then transfer this fluid to the secondary tanks indicated by 3, by switching the valves indicated by 7 with the help of the centrifugal pump.

4. Check the rheology of the fluid again after the fluid has been transferred to the secondary tanks to ensure that the fluid has maintained the desired rheologic properties.
5. Clean the primary tank with water, to ensure there is no contamination of the base fluid, i.e. water with polymer. Fill the primary tank with water to begin tests.
6. Start LabView on the computer terminal (create a new file for every experiment run)
7. Open up the main mud valve at least 30%.
8. Start the mud pump to establish flow rate of water through the test section indicated by 1.
9. Once a steady flow rate has been established and circulation of the drilling fluid has been ensured, start the cuttings injection auger indicated by 9, from both the LabView interface as well as the control panel switch.
10. Adjust the valve lever on the injection tank indicated by 5, to establish a steady ROP (cuttings injection). At this time, cuttings will start falling into the flow stream and will be pushed into the test section by the auger.
11. Start the shale-shaker indicated by 4 from the control panel.
12. Carefully observe the dP-12 and dP-13 plots on the LabView interface. These curves will increase at first and then level off when steady state has been achieved. At the same time, observe the ROP plot on the interface. The ROP plot should remain steady around an average value during a run. The average value will be the effective cuttings injection rate during the experiment and can be changed by altering the valve position on the injection tank or changing the auger speed.
13. Close the hold-up valve, to isolate the test section, and divert the flow into the bypass line indicated by 8, by opening the bypass line valve. Cuttings will be trapped inside the test-section by doing so; the weight of these cuttings has to be determined.
14. Close the cuttings injection valve and turn off the injection auger both from the control panel as well as the LabView interface. This will stop further injection of cuttings into the test section. Stop the centrifugal pump.
15. Close the main water inlet and open the secondary mud tank valve.
16. Start the centrifugal pump and allow the “sweep” fluid to run in the by-pass line.
17. Once the desired flow rate is obtained, open the hold-up valve and close the by-pass valve, allowing the fluid to “sweep” the test section. Note down the start time of the test. The end time of the test is two minutes after the start time.
18. Start pipe rotation if required by the test.

19. Continue data logging. A complete data sheet is provided in the appendix for reference. This data sheet contains the records maintained in addition to the ones kept using the Lab View interface.
20. As soon as the "sweep" is complete, open the by-pass valve and close the hold-up valve simultaneously. Turn off the centrifugal pump and stop pipe rotation.
21. Switch the valves again from the secondary tanks to the primary tank and start the centrifugal pump to clean the by-pass and test section with water.
22. Increase the flow rate in order to clean the bypass line and the hoses. This step is also called the 'first flush'.
23. If required, start drill-pipe rotation from the control panel switch. Adjust the drill-pipe rotational speed with the knob on the control panel and read the current rpm from the display.
24. When the weight of the collection tank becomes steady, open the hold-up valve while simultaneously closing the bypass line valve. This step is termed the 'second flush'. Note down the collection tank weight prior to opening the hold-up valve in this step.
25. When the test section has been flushed completely and all the cuttings are removed note down the collection tank weight. The difference between the collection tank weights before and after the second flush gives the weight of the cuttings inside the test section at steady state. This cuttings' weight is used for computations and analysis in the later part of the report.
26. Proceed to shut off the mud pump and the shale-shaker
27. On the LabView interface, press 'STOP' to save and close the data file.