PREVENT POOR CEMENTING RESULTS BY THE USE OF BOTTOM CEMENTING PLUGS

T. J. Griffin, Jr., Schlumberger Dowell
P. P. Valko, Texas A&M University

Abstract

The objective of primary cementing is to support the pipe and achieve a seal so that the desired fluids can be produced from the well. Although a lot of effort is spent in designing for effective fluid displacement in the annulus, displacement in the pipe is frequently overlooked. When fluids are being circulated down the pipe, the balance of forces is not correct for efficient displacement. The heavier fluid is on top, displacing the lighter fluid below it, with buoyant forces causing the heavier fluid to tend to fall through the lighter fluid. Wiper plugs are available to prevent this, but in practice, bottom plugs frequently are not used.

When bottom plugs are not used, the cement may bypass the spacer. The cement may then mix with or bypass mud, resulting in poor displacement, leading to poor isolation of various well intervals. Other problems include interfacial mixing resulting in high permeability cement and exposure of pipe to corrosive fluids, or high displacement pressures due to high viscosity of mixes of incompatible fluids.

An investigation of the physics of fluid displacement in pipes was undertaken. The study combines the effects of density and rheology and defines the condition which exists when wiper plugs are not used to separate fluids flowing down the pipe. A computer model provides a qualitative evaluation of the efficiency of the displacement process and indicates the possible instability of the displacement front. Case histories are given which demonstrate the effects of contamination or of one fluid bypassing another and the results of the use of bottom plugs.

Background

During recent investigations of operational failures, it became obvious that contamination of cement slurries in the casing may have been a contributing factor. This contamination is caused by ineffective displacement and interfacial mixing of mud and spacer or spacer and cement or even mud and cement. Such contamination occurs because no bottom wiper plug is used (or possibly only one) and buoyant forces cause the fluid to "fall through" the fluid ahead of it.

Realizing that the importance of using wiper plugs is not always appreciated, we initiated a project to define the fluid mechanics of a heavier, top fluid displacing a lighter, bottom fluid when flowing downward in the pipe. An additional purpose was to develop computer software for the calculation of the efficiency of this displacement.

Theory

The mechanics of the displacement process is described in a report by Valko[1]. The work is based on that of Flumerfelt[2,4] and Beirute-Flumerfelt[3] in which they described the upward displacement of a lighter fluid by a heavier fluid. The flow profile is related to the rheological properties of the fluids, their densities, the geometry of the flow channel, and the velocity of flow.

Since we were interested in the displacement while the fluids are inside the casing, we changed the direction of flow to downward (Figure 1). Unlike the case in the annulus where the higher density of the displacing fluid improves displacement efficiency and causes all flow to be in the primary direction, in our situation, with the heavier fluid on top, it is possible that the heavier fluid can flow downward due to gravity, allowing the lighter fluid below it to flow upward to replace it. Whether and the degree to which this occurs depends on a number of variables (see later discussion of sensitivity). Thus, we allowed the flow to be either positive (down) or with a negative component (up) (Figure 2). In the figures, the arrows represent the velocity component along a radial position at a position along the length of the pipe (depth). In order to compute the shape of the interfacial boundary, we make this computation at positions along the entire length of the pipe. The inflection point (see Figures 1 & 2) defines the interfacial boundary between the pair of fluids at the chosen depth. The composite of such calculations at all depths defines the interfacial boundary of the pair of fluids along the length of the pipe.

Computer Software

We used a software called Mathematica[5] (version 2.2.3 from Wolfram Research) to derive calculations of the displacement. A routine calculates the efficiency of displacement versus time and the position of the interfacial boundary at various times in the displacement. To make the calculations, the routine uses the properties of the fluids (density, ρ; yield value, Ty; and plastic viscosity, PV), the length and diameter of the pipe and the pump rate. A number of assumptions and constraints are made when making such calculations. These include:

- Pipe is vertical.
- Flow is laminar.
- Fluids behave as Newtonian although Bingham Plastic parameters are input and are used to approximate the Newtonian rheology at the appropriate shear rates.
- There is no interfacial mixing, therefore there are no rheological changes at the interface.

Figure 3 shows the shape of the interfacial boundary between pairs of fluids as computed by the software. Depending on the properties of the fluid, the pipe diameter and the velocity, the interface may be "stable" and approach the shape of a parabola, as shown in Figure 3a; it may have an outer ring in which the lighter, bottom fluid is static with the heavier top fluid flowing down through it in a similar internal parabola, Figure 3b; or it may have a ring in which the lighter fluid is flowing counter to the primary direction of flow i.e. the lighter fluid is flowing upward, Figure 3c. Although this plot can be made at any time in the displacement process, those shown are for the time at which the leading edge of the interfacial boundary reaches the end of the pipe. The wire frame of the drawings is a distorted representation of the shape of the pipe, with the wire length representing the length and its diameter representing the diameter of the pipe.

In addition to the shape of the interfacial boundary, the software plots the theoretical displacement efficiency versus time.

Figure 4 shows the calculated fractional efficiencies for the three cases shown in Figure 3. Time is normalized to the time at which the leading edge of the interfacial boundary reaches the end of the pipe (one on the time scale). As one would expect, the efficiency is best when there is a stable interface as shown in Figures 3a and 4a. In such a case, the efficiency may approach 80 - 90% for extended times.

If a "static" region exists, as shown in Figure 3b, the efficiency may approach 40 - 60% for extended time. The condition with reverse flow causes the poorest displacement efficiency (Figures 3c and 4c). In this case, efficiency may be only 10 - 20%. Note that there is some instability in the calculation as represented by the upward pointing cones in the center of the interfacial boundary plot and by the declining efficiency in the plot of efficiency vs. normalized time. It should be noted here that the use of these calculations can only be assumed to be qualitative. The purpose is to demonstrate the severity of the problem of displacement of a lighter fluid by a heavier fluid when displacement is downward and to emphasize the need for bottom plugs.

Note that all of these conditions assume that there is no interfacial mixing. If the reverse flow situation exists, the forces acting to cause the lighter fluid to flow upward will likely cause extreme mixing with the displacing fluid (in the configuration of cementing oil and gas wells, the fluid cannot flow upward as indicated here, since the top of the pipe is enclosed by a cementing head). Of course, intermixing can occur with any of these scenarios. Obviously, degrees exist between each of the cases described above.

Sensitivity Study

The software was used to make a sensitivity study of the parameters which we thought might have a bearing on the shape of the interface and the efficiency of displacement. The parameters studied were

- Pipe diameter
- Density difference

- Yield point difference
- Plastic viscosity difference
- Average velocity

A base case for the sensitivity study was: pipe ID = 6.276 inches (7 inch, 26 lb/ft), density difference = 2.8 lb/gal, Ty = 15/10 lb/100 ft^2, PV = 20/80 cps, velocity = 131.6 ft/min. Table 1 lists all the variables and results of the sensitivity study.

Pipe Diameter - Figure 5a shows the effect of increasing pipe diameter on the efficiency of displacement while holding all other properties constant (note the non-linear scale on the efficiency plots). The lower curve shows the efficiency at the time that the leading edge of the interfacial boundary reaches the end of the pipe. As the size of the pipe increases, the displacement efficiency decreases. The condition is very unstable (reverse flow of the lighter fluid) in the larger size pipes under the conditions studied (complete data are shown in Table 1). The upper curve shows the displacement efficiency at the time that a full pipe volume has been pumped. Note that in the best case (4 $^1/_2$ inch casing) the displacement is far below 100%.

Density Difference - Figure 5b shows the influence of density difference on displacement efficiency. This study was made with 7 inch pipe. As one would expect, efficiency decreases as the density difference increases. Note that even with a very small density difference, 0.3 lb/gal, the displacement efficiency is only 70% at the time a full pipe volume has been pumped (theoretical 100% displacement).

Ty Difference - Figure 5c shows the displacement efficiency versus the yield point (Ty) for fluids with a 2.8 lb/gal density difference in a 7 inch pipe. Under the conditions chosen for this study, there is a major improvement in displacement efficiency when the Ty changes from a negative to a positive Ty difference between the bottom and top fluids (negative Ty difference means the Ty of the displacing fluid is less than that of the fluid being displaced). Again, however, note that this improvement flattens out and additional increases (within the range of practical limits) are not likely to reach 100% displacement efficiency.

PV Difference - Figure 5d shows that at the low shear rates and other conditions chosen for this study, PV difference has little effect on the displacement efficiency.

Velocity - Figure 5e shows the effect of increasing the velocity on the displacement efficiency. This study was conducted for 7 inch pipe with a 2.8 lb/gal density difference. The efficiency increases as the velocity is increased from 130.5 to 522.2 ft/min (5 to 20 bpm). Again, 100% efficiency is not reached by increasing the velocity.

Sensitivity Summary - When the conditions are modified to the most efficient for each parameter from the above study (4 ½ inch casing, 9.2 lb/gal fluid displaced by 9.5 lb/gal, Ty of 15 and 50 lb/100 ft^2 and PV of 20 and 80 cps, respectively), the calculated displacement efficiency is only 60% at the time that the leading edge of the interfacial boundary reaches the end of the pipe, and it is 80% at the time a volume equal to the pipe volume has been pumped. As can be seen from the analysis of the effects of the parameters studied and this combined result, practical modification of any of these parameters will not assure complete displacement in the casing. Even with a small difference in densities, rheological effects still cause displacement to be far from perfect. Additionally, modifying any of these would reduce the mud removal efficiency in the annulus.

Well Problems Associated With Incomplete Displacement

In well cementing, a number of problems can result from the incomplete displacement of fluids in the pipe. These include:

- Contamination of the leading edge, or entire spacer.
- Failure of the spacer to perform its mud removal/separation function.
- Contamination of the leading edge, or entire cement slurry.
- Failure of the cement to set, or extremely long setting time of cement due to retardation of the cement by the spacer.
- Complete bypassing of one fluid by another.
- Poor isolation of various well intervals.
- Failure of the cement to provide a seal at the shoe after drill out.
- Lack of hard cement in the "shoe track" during drill out.
- Failure in placement of squeeze cement (over-displacement) and subsequent unsuccessful squeeze.
- Low strength kick-off plug

Most of these problems are considered by well operators as a "bad" cement job, or soft or unset cement.

Although some contamination of spacer may occur during displacement in the annulus, the effects described previously can result in a major amount of mixing in the pipe. This may result in inefficiency of mud removal by the spacer. This mixing may be so complete that it may also result in mixing of the three fluids; mud, spacer, cement. In some cases, such a mixture can have extremely high viscosity, causing high friction pressures. The mixture may also be incompatible enough that there is the appearance of a premature set. On a liner, it could cause stuck drill pipe. Some slurries are extremely incompatible with the drilling fluid. Intermixing of these fluids can have disastrous results.

Contamination of the leading edge, or entire cement slurry can result in a change in the rheological properties of the cement, which may be apparent from increases in friction pressures during displacement. Contamination of the cement may also appear as retardation due to components of the spacer or the mud. This may appear as an apparent "lack of cement" on sonic or ultrasonic evaluation logs. In some cases, the intermixing may be only the leading edge of the slurry and it may appear as a lower than expected cement top, or very "ratty" or low strength cement at the top. It is also possible for the cement to fall or flow completely through the spacer or for the tail slurry to flow through the lead slurry. In that case, the log may have evidence of good cement through part of the interval with poor cement at the bottom, where the good, strong, tail cement should be. There may also be spotty occurrences of strong and low strength cement.

Two very common problems are failure of the cement to provide a seal at the shoe after drill out and lack of hard cement in the "shoe track" during drill out (commonly referred to as a "wet shoe"). The failure of the shoe during a "shoe test" (or leak-off test - LOT) may be more related to the characteristics of the formation in which the casing is set than to the quality of the cement job. However, there may be occasions if bottom plugs are not run and the cement bypasses the spacer and mud, that the top wiper plug could then push the bypassed spacer/mud into the shoe joint and even on the outside around the bottom joints of casing. A wet shoe may also prevent a successful casing test without the use of a packer.

Even when bottom plugs are run, there still may be a problem in the shoe track. If the tendency is for the cement to bypass the spacer, then obviously, a wiper plug will not help in the shoe track, since the plug stops at the float collar. An added problem is that the shape of the orifice in the float collar establishes a thin jet of the cement through the fluid in the pipe below the collar. This action may compound the already difficult situation. There has been some work in recent years to change the geometry of flow out of the float collar. With these changes, and by the use of bottom wiper plugs, it may now be possible to shorten the length of the shoe track, achieving a benefit by reducing the amount of hole that has to be drilled.

Case Histories

Offshore Gulf of Mexico

A mixed string of 9 $^5/_8$ x 9 $^7/_8$ inch intermediate casing was set to 12,673 ft. Two days after cementing, an attempt was made to test the casing to 5,000 psi. Just before reaching 5,000 psi, the pressure suddenly dropped to near zero. After testing the casing with a packer and finding it to be sound, the shoe was drilled out (no cement). Four days after the cement job, a squeeze job was attempted and the well was circulated. Cement evaluation logs indicated no cement with any strength.

After extensive testing, over-retardation by cement additives was ruled out as a cause. Although the software developed during this project was not available at the time of the investigation into the cause of this failure, mixing of the cement and spacer and retardation by the spacer was suspected as a cause. Lab tests on mixes of spacer and cement showed that minor amounts of spacer could cause severe retardation. Additionally, mixes of the cement with mud were even more retarded.

Even though a bottom plug was run, it was run between the mud and spacer, thus allowing the cement to fall or flow through and mix with the spacer. Figure 6 shows the shape of the interfacial boundary between the spacer and the cement and the displacement efficiency versus normalized time. Table 2 gives the properties of the fluids. Note that the densities of fluids in this case were relatively closely matched, yet the results were poor.

Most likely, a bottom plug between the cement and spacer would have prevented this problem.

Indonesia

In Indonesia, a very long 7 inch liner was cemented with two slurries, a lead at 12.5 lb/gal and a tail at 15.8 lb/gal. The top of the liner was at 2240 ft and the bottom was at 9844 ft. During displacement, extremely high friction pressures were encountered, so high that the job had to be terminated, leaving cement in the liner. The properties of the fluids are shown in Table 3.

Evaluation of the displacement of these fluids in the liner showed that there is a high likelihood that the lead cement fell through the spacer and the tail fell through the lead slurry. The shapes of the interfaces of these two fluids with the fluids ahead are shown in Figure 7.

Note the great tendency for reverse flow of the lower, lighter fluid in each case. The displacement efficiency is 20% or below for each. Such a condition makes mixing of the fluids likely and even makes the potential for mixing of three fluids high. Such mixing of three fluids could result in highly viscous mixes with the combination of fluids used on this well. Such incompatibilities were demonstrated in the lab and verified the results.

Discussion

Although there is surely a certain amount of interfacial mixing, its influence on the displacement process is not well understood and has not been included in the model. The properties of the mixed fluids at the interface may have a major influence on what happens during displacement. If there is no viscosification when the fluids mix (or the mixed fluids are intermediate or lower in viscosity), the interfacial boundaries may resemble the results demonstrated here.

Perhaps a zone of pseudo-stable mixed fluids develops. This zone may act like a long fluid plug between the respective fluids. If there is viscosification at the interface, however, the viscosification may have the effect of limiting the amount and severity of the mixing zone (acting something like a wiper plug). In that case, the results expected from the phenomena described here may not be realized.

Another possible scenario is that a more viscous layer will develop and the thinner displacing fluid will "channel" through it. This will result in a layer of the fluid mixture on the inner surface of the casing. When the top wiper plug passes, it will collect this mixed layer and deposit it in the shoe track and, depending on the volume, around the shoe joints, resulting in a "wet shoe."

Conclusions

1. There is a strong likelihood that bypassing of mud and spacer by the cement can occur in the casing or in drillpipe.
2. There is little that can be done to change the properties of the fluids to prevent this bypassing without impairing the mud removal efficiency in the annulus.
3. Even if the densities of the fluids are nearly matched, rheological effects cause the efficiency of displacement in the pipe to be poor.
4. Bypassing of fluids in the pipe can result in a variety of problems including, but not limited to: wet shoes, seal failure in the annulus around the shoe, poor quality cement due to intermixing, and extreme pressures due to mixing of cement and mud.
5. These problems can exist no matter what the fluids, including the tail slurry bypassing the lead.
6. Bypassing can be a problem in plug and squeeze cementing as well as in casing cementing.

The best way to avoid problems created by the bypassing of fluids in the pipe is to use bottom wiper plugs for casing (or liner) cementing. Similar wiper plug employment can be used for setting cement plugs and for squeeze cementing by the use of special tools in the drill pipe.

References

1. Valko, Peter, "Fluid Displacement in Pipe," Texas A&M University, Petroleum Department, October 30, 1994.
2. Flumerfelt, R. W., "Laminar Displacement of Non-Newtonian Fluids in Parallel Plate and Narrow Gap Geometry," *Society of Petroleum Engineers Journal*, pp. 169-180, April, 1975.
3. Beirute, R. M., and Flumerfelt, R. W., "Mechanics of the Displacement Process of Drilling Muds by Cement Slurries Using an Accurate Rheological Model," SPE 6801, (1977).
4. Flumerfelt, R. W. in Ullman's Encyclopedia of Industrial Chemistry, Ed. B. Elvers, Volume B1, Part 4, p. 4-35, VCH, Weinheim, (1990).
5. Wolfram, Stephen, *Mathematica® A System for Doing Mathematics by Computer*, Second Edition, July 1993, Addison-Wesley Publishing Company.

Appendix - Derivation of Velocity Profiles

In the core region, Newtonian Poiseuille flow theory provides the velocity distribution[4]:

$$u_1 = C_{21} - \left(-\frac{dp}{dz} + g \times \rho_1\right) \times r_v^2/(4 \times \mu_1) + C_{11} \times ln(r_v)/\mu_1$$

and in the outer region, similarly,

$$u_2 = C_{22} - \left(-\frac{dp}{dz} + g \times \rho_2\right) \times r_v^2/(4 \times \mu_2) + C_{12} \times ln(r_v)/\mu_2$$

where r_v is the radius *variable*. The terms μ_1 and μ_2 represent Newtonian viscosities approximating the Bingham viscosity at equivalent shear rates. The pressures, and hence, the pressure gradients, respectively, are the same in the two phases.

There are four integration constants in the above two equations. They can be determined from the following constraints:

(1) the velocity at the boundary, r_c, should be the same in the two phases
(2) the stress (velocity derivative multiplied by viscosity) at the boundary, r_c, should be the same in the two phases
(3) the velocity is zero at the wall (no slip)
(4) the velocity at the center is finite.

The latter requirement results in $C_{12} = 0$.

The flow rates in the separate phases can be obtained by integrating the velocity profiles. The sum of the two phase flow rates is known and equals the prescribed flow rate:

$$Q = q_1 + q_2$$

The aim is to obtain the individual phase velocities and flow rates, in addition to the location of the phase boundary and the common pressure gradient. Technically this is done by writing the constraints in the form of mathematical equations and eliminating the integration constants.

The derivative of the velocity distribution with respect to the radius is (in the outer region)

$$du_1/dr_v = C_{11}/(\mu_1 \times r_v) - \left(-\frac{dp}{dz} + g \times \rho_1\right) \times r_v/(2 \times \mu_1)$$

and the flow rate is the integral of $(2 \pi r_v u_1)$ between the limits r_c and r:

$$\begin{aligned}
q_1 = {} & \pi \times r^2 \times (-4 \times C_{11} + 8 \times C_{21} \times \mu_1 + \frac{dp}{dz} \times r^2 - g \times r^2 \times \rho_1 + 8 \times C_{11} \times ln(r))/(8 \times \mu_1) - \\
& \pi \times r_c{}^2 \times (-4 \times C_{11} + 8 \times C_{21} \times \mu_1 + \frac{dp}{dz} \times r_c{}^2 - g \times r_c{}^2 \times \rho_1 + \\
& 8 \times C_{11} \times ln(r_c))/(8 \times \mu_1)
\end{aligned}$$

The same expressions for the displacing, inner phase, are as follows. The derivative is:

$$du_2/dr_v = -((-\frac{dp}{dz} + g \times \rho_2) \times r_v)/(2 \times \mu_2)$$

and the flow rate is given by:

$$q_2 = C_{22} \times \pi \times r_c{}^2 + \pi \times r_c{}^4 \times (\frac{dp}{dz} - g \times \rho_2)/(8 \times \mu_2)$$

The following equations have to be satisfied:

$$eq_1\text{:} \quad C_{21} - r^2 \times (-\frac{dp}{dz} + g \times \rho_1)/(4 \times \mu_1) + C_{11} \times ln(r)/\mu_1 = 0$$

$$\begin{aligned}
eq_2\text{:} \quad & C_{21} - r_c{}^2 \times (-\frac{dp}{dz} + g \times \rho_1)/(4 \times \mu_1) + C_{11} \times ln(r_c)/\mu_1 = \\
& C_{22} - r_c{}^2 \times (-\frac{dp}{dz} + g \times \rho_2)/(4 \times \mu_2)
\end{aligned}$$

$$eq_3\text{:} \quad \mu_1 \times (C_{11}/(\mu_1 \times r_c) - r_c \times (-\frac{dp}{dz} + g \times \rho_1)/(2 \times \mu_1)) = -(r_c \times (-\frac{dp}{dz} + g \times \rho_2))/2$$

$$\begin{aligned}
eq_4\text{:} \quad & C_{22} \times \pi \times r_c{}^2 + \pi \times r_c{}^4 \times (\frac{dp}{dz} - g \times \rho_2)/(8 \times \mu_2) + \\
& \pi \times r^2 \times (-4 \times C_{11} + 8 \times C_{21} \times \mu_1 + \frac{dp}{dz} \times r^2 - g \times r^2 \times \rho_1 + 8 \times C_{11} \times ln(r))/ \\
& (8 \times \mu_1) - \pi \times r_c{}^2 \times (-4 \times C_{11} + 8 \times C_{21} \times \mu_1 + \frac{dp}{dz} \times r_c{}^2 - g \times r_c{}^2 \times \rho_1 + \\
& 8 \times C_{11} \times ln(r_c))/(8 \times \mu_1) = Q
\end{aligned}$$

Explicit expressions for the 3 non-zero constants are given in Valko's report[1].

Nomenclature

C_{11}		integration constant
C_{21}		integration constant
C_{12}		integration constant
C_{22}		integration constant
g	m/s^2	acceleration of gravity
k	m^2	permeability
L	m	length of pipe
p_b	Pa	pressure at the bottom
p_t	Pa	pressure at the top
$\frac{dp}{dz}$	Pa/m	pressure gradient
Q	m^3/s	flow rate
q_1	m^3/s	flow rate of fluid 1
q_2	m^3/s	flow rate of fluid 2
r	m	pipe (inner) diameter
r_v	m	radial location
r_c	m	radial location of the interface
u_0	m/s	nominal fluid velocity, Q/A
u_i	m/s	velocity of an the interface point
u_1	m/s	velocity of fluid 1
u_2	m/s	velocity of fluid 2
z	m	depth measured from top
μ_1	Pa·s	viscosity of fluid 1
μ_2	Pa·s	viscosity of fluid 2
μ_e	Pa·s	equivalent Newtonian viscosity
ρ_1	kg/m^3	density of fluid 1
ρ_2	kg/m^3	density of fluid 2
τ_y	Pa	yield stress
μ_p	Pa·s	plastic viscosity (PV)

Table 1
Displacement Sensitivity

			Original Fluid				Displacing Fluid				Efficiency		
ID (in)	Q (bpm)	Velocity (ft/min)	ρ (lb/gal)	Ty (lb/100ft^2)	PV (cps)	N_{Re}	ρ (lb/gal)	Ty (lb/100ft^2)	PV (cps)	N_{Re}	t=1	100%	
Casing Size													**Casing**
3.958	2	131.6	9.2	15	20	407	12	10	80	490	40	60	4.5
6.276	5	130.5	9.2	15	20	430	12	10	80	577	28	42	7
12.347	19.3	130.3	9.2	15	20	458	12	10	80	692	15	15	13.375
Density Difference													$\Delta\rho$
6.276	5	130.5	9.2	15	20	430	9.5	10	80	456	50	70	0.3
6.276	5	130.5	9.2	15	20	430	10.5	10	80	504	38	62	1.3
6.276	5	130.5	9.2	15	20	430	12	10	80	577	28	42	2.8
Ty													**ΔTy**
6.276	5	130.5	9.2	50	20	144	12	10	80	577	23	36	-40
6.276	5	130.5	9.2	15	20	430	12	10	80	577	28	42	-5
6.276	5	130.5	9.2	15	20	430	12	30	80	253	40	62	15
6.276	5	130.5	9.2	15	20	430	12	50	80	164	40	68	35
PV													**ΔPV**
6.276	5	130.5	9.2	15	20	430	12	10	80	577	28	42	60
6.276	5	130.5	9.2	15	60	357	12	10	80	577	27	41	20
6.276	5	130.5	9.2	15	140	279	12	10	80	577	27	40	-60
Velocity													**Velocity**
6.276	5	130.5	9.2	15	20	430	12	10	80	577	28	42	130.5
6.276	10	261.1	9.2	15	20	1550	12	10	80	1748	34	52	261.1
6.276	20	522.2	9.2	15	20	5321	12	10	80	4768	38	61	522.2

Note: Efficiency is percent of original fluid displaced at the indicated time. "t=1" represents the time at which the leading edge of the interfacial boundary reaches the end of the pipe. "100%" represents the time at which a full pipe volume of the displacing fluid has been pumped.

Table 2
Properties of Fluids
Gulf of Mexico Case History

	Density	Ty	PV
Mud	16.5	5	54
Spacer	17.0	15	50
Cement	17.6	3	94

Table 3
Properties of Fluids
Indonesia Case History

	Density	Ty	PV
Mud	9.1	19	23
Spacer	9.5	6.5	16.5
Lead Slurry	12.5	2.5	44
Tail Slurry	15.8	3	51

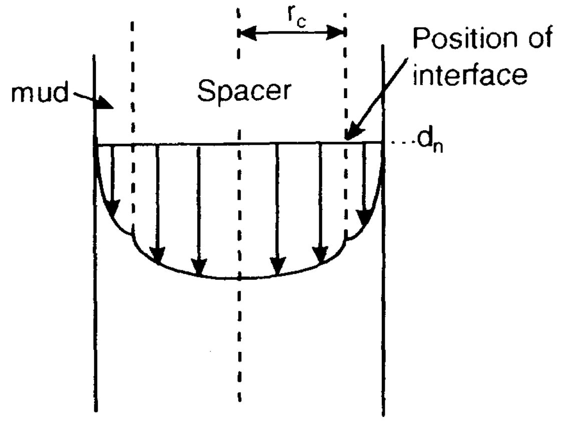

Figure 1 - Velocity refile and interfacial boundary for downward flow using the Beirute-Flumerfelt concept of two-phase displacement. The interface is located at radius r_c which varies with the vertical location $\mathbf{d}_n$.

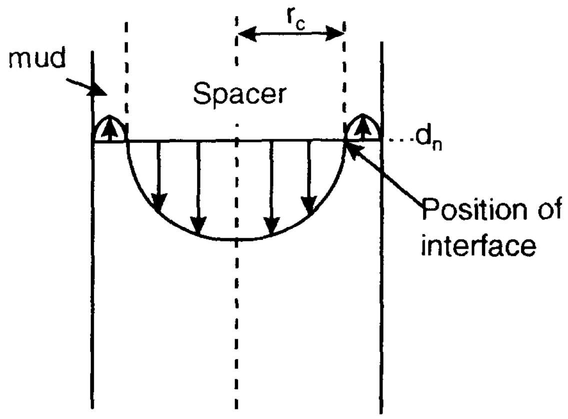

Figure 2 - Reverse flow near the wall of the pipe. The heavier displacing fluid occupies the central region.

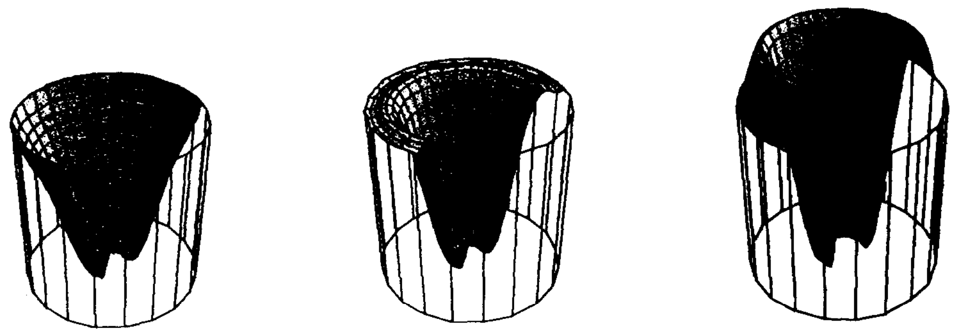

Figure 3a - Stable Interface

Figure 3b - Static region

Figure 3c - Reverse Flow

Figure 3 - Shape of the interfacial boundary at the time that the leading edge of the interface reaches the end of the pipe.

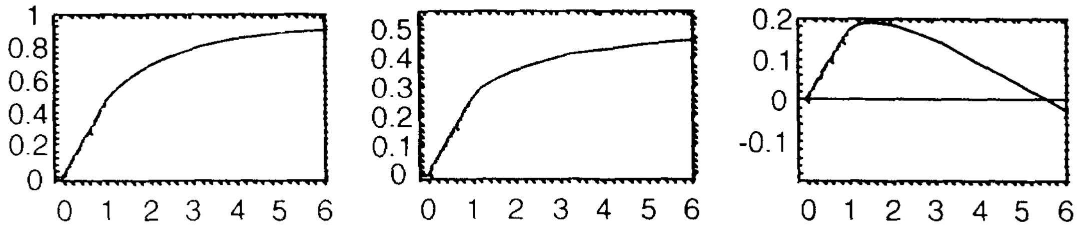

Figure 4a - Stable

Figure 4b - Static Region

Figure 4c - Reverse Flow

Figure 4 - Plot of displacement efficiency versus normalized time

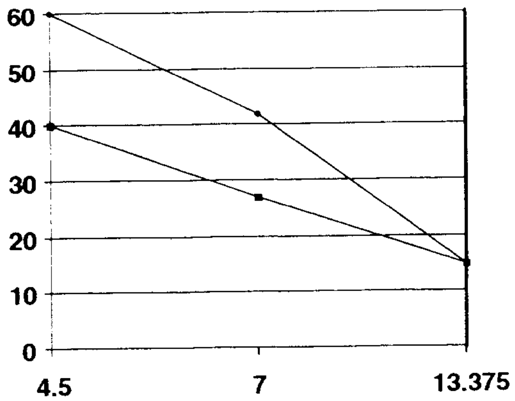

Figure 5a - Casing Size (in)

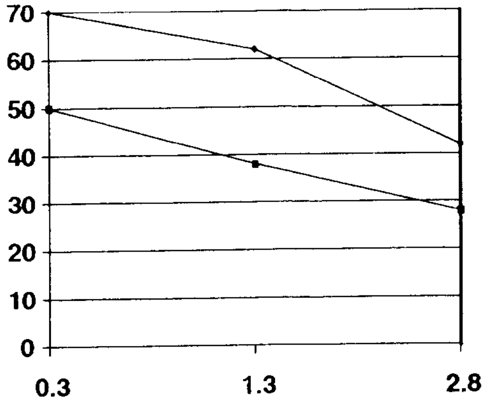

Figure 5b - Density difference (lb/gal)

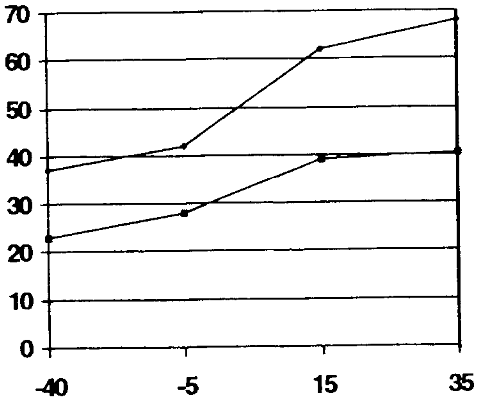

Figure 5c - Ty difference

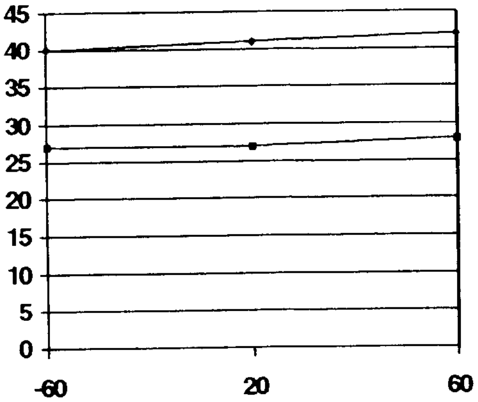

Figure 5d - PV difference

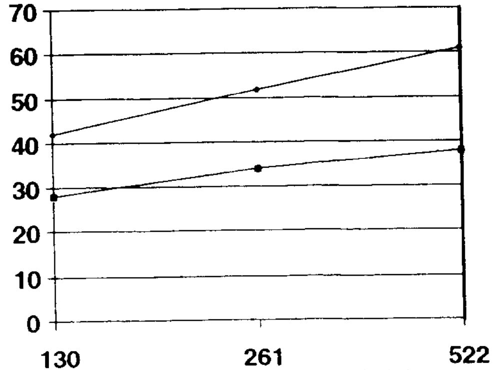

Figure 5e - Velocity (ft/min)

Figure 5 - Influence of variables on the efficiency of displacement. The lower curve is the efficiency at the time at which the leading edge of the interface reaches the end of the pipe. The upper curve is the efficiency at the time that a theoretical 100% displacement should occur, i.e., the time at which a full pipe volume of the top fluid has been pumped.

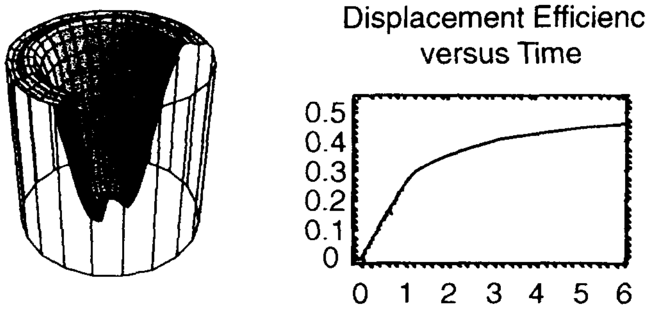

Figure 6 - Displacement of spacer by cement in Offshore of Mexico intermediate casing.

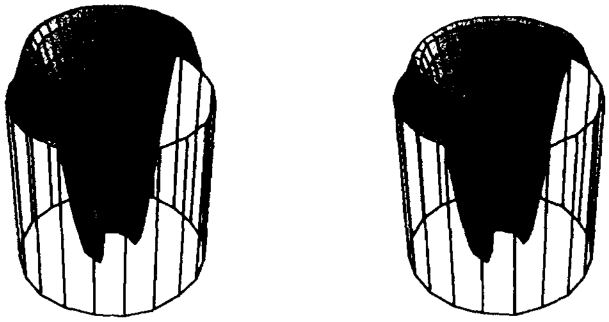

Figure 7a - Spacer/Lead Slurry Figure 7b - Lead Slurry/Tail Slurry

Figure 7 - Interfacial boundary for Indonesia liner fluids.