



A New Polymer Sealant for Curing Severe Lost Circulation Events

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This paper was prepared for presentation at the AADE 2006 Fluids Conference held at the Wyndam Greenspoint Hotel in Houston, Texas, April 11-12, 2006. This conference was sponsored by the Houston Chapter of the American Association of Drilling Engineers. The information presented in this paper does not reflect any position, claim or endorsement made or implied by the American Association of Drilling Engineers, their officers or members. Questions concerning the content of this paper should be directed to the individuals listed as author/s of this work.

Abstract

Conventional lost circulation materials (LCMs) are challenged at their limits of effectiveness to achieve the goals of sealing severely fractured, vugular and cavernous formations.¹⁻⁹ LCMs that are capable of such feats under ideal conditions may be hampered in performance by the temperatures and chemistries encountered in many real-world applications. This work introduces a polymer-based technology that offers a new method for controlling severe lost circulation events. The new technology offers a fast reaction time, which can allow for the rapid sealing of vugular openings and fractures. The temperature range of application is from 32°F to in excess of 400°F.

The efforts expended to develop an effective treatment included studies to further understand how yield point, mixing energy, velocity, and rheometer testing can be used to predict mechanical strengths of the new sealant. Experiments focused on the performance of candidate materials over a wide range of temperatures, pH, and salinity values for both aqueous and non-aqueous drilling fluids. The appropriate spacers, wetting agents, and densities needed for delivering these inverse emulsion polymers are also addressed.

Introduction

Conventional lost circulation materials (LCMs) are often composed of materials in a range of particle sizes. These LCMs are very good at sealing off micro or smaller fractures downhole. However, this novel polymer-based technology offers a new method for controlling severe lost circulation events. The new technology offers a fast reaction time, which can allow for the rapid sealing of vugular openings and fractures, even in temperatures in excess of 400°F.

Conclusions

A successful field trial for using inverse emulsion polymer as a new LCM is described. The technology presented opens up a new avenue to cure severe lost circulation such as that resulting from vugular openings and fractures, and provides the high performance expected from state-of-the-art lost circulation materials.

Anionic inverse emulsion polymer/oil disperse polymer is a new polymer sealant for curing severe lost circulation events. The new LCM reacts with water to form an effective seal for severe lost circulation events. The polymer sealant is easy to displace and spot, and is fast acting, resulting in a minimum of drilling non-productive time. The product is easy to transport and apply.

Unlike some other polymeric LCMs, this new LCM exhibits equivalent performance whether in fresh water, seawater, and 24% NaCl solution or other brine combinations, adding to its versatility and range of applications. Once activated, the material forms a cohesive sealant, which can be used in the harshest drilling conditions, including high temperature and high density situations.

Results and Discussion

To seal off severely vugular and cavernous formations, a polymeric material can be employed with good success. As with any new technology, the treatment should be easily delivered downhole, have a fast reaction time, be effective over a broad temperature range and in both low and high salinity environments. In this investigation, three different classes of inverse emulsion polymers – anionic, cationic and non ionic inverse emulsion polymers – were investigated. In general, anionic polymers proved to be the most cost effective due to the developed manufacturing technology. The polymer belongs to an established class of materials that are super absorbent polymers. Non ionic and cationic polymers normally are 3 to 10 times more expensive than anionic polymers due to the more complex process chemistry. In this investigation, a commercially available anionic inverse emulsion polymer (AIEP), cationic inverse emulsion polymer (CIEP) and non-ionic inverse emulsion polymer (NIEP) samples were obtained for testing.

The initial screening test for three classes of inverse emulsion polymers was a simple dilution test. The procedure was to dilute the sample with as much liquid (water or 1 % NaCl solution) as possible while remaining a paste. The data from **Table 1** summarizes this preliminary investigation, which identified the AIEP as

the best performer.

Following dilution testing, we proceeded with extrusion rheometer testing. To find out the optimal mixing ratios for the AIEP, to understand how this new inverse emulsion polymer behaves as an LCM, and to compare those behaviors with the existing commercial LCM (a deformable, viscous and cohesive material (DVC)), data, such as rheology measurements on the extrusion rheometer, yield point, plastic viscosity, mixing energy and Baglay's coefficient were obtained. However, only the data from the extrusion rheometer and Baglay's coefficient are analyzed in detail here.



Figure 1. Extrusion rheometer core

One of the main components of the extrusion rheometer is a core, which has a slit opening of 1 mm, 2 mm or 3 mm (**Figure 1**). The core itself can be 2, 4 or 6 inches long. The rheometer is filled with the material to be tested. Pressure is applied to push the material out of the core. Forces vary in pushing different materials through the same core under identical conditions (**Figure 2**). This force is measured in pounds. By comparing these results/forces, we can predict how the material might behave downhole (e.g., the initial pressure required to push the material into the vugular, cavernous formations; the higher the force, the more pressure required). From this data we also can predict the shear stress of the material (Baglay's coefficient plot), how easily the same material can be replaced by pressure (Baglay's coefficient), and indications of the mechanical strength of this material (the higher the force

required to push the material, the stronger the material can withstand the pressure).



Figure 2. Extrusion rheometer

Table 2 summarizes the extrusion rheometer data for a commercial LCM and AIEP in different solutions. Different sizes of core were used in the test. However, only one set of data (6 INL X 3 MMW, Table 2) was obtained with the existing commercial LCM due to time constraints. The three force readings for the commercial LCM were: 606, 481 and 492 lb respectively. The average was 526 lb. The standard deviation was 69 and the coefficient of variance (COV) = 13.1%. The reproducibility for commercial LCM was not very good. The other characteristic feature of the commercial LCM was its initial pressure, which surged and then dropped, as illustrated in **Figure 3**. That is the initial pressure required to push the commercial LCM into the vugular, cavernous formations. There were no such pressure drops for the AIEP sample (**Figure 4**).

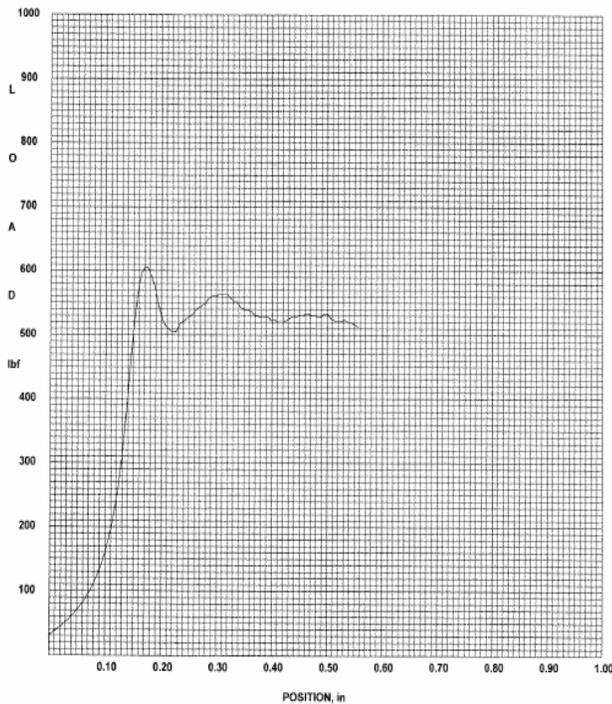


Figure 3. Commercial LCM profile for the extrusion rheometer run using 6INLX3MMW core

More tests were conducted using higher concentrations of AIEP: 1% NaCl and seawater (both 1:3). In the end it was found that the optimal formulation was 1:3 (AIEP: 1% NaCl). It was in this formulation that the AIEP paste had an acceptable mechanical strength compared with the commercial LCM (Figures 3 and 4).

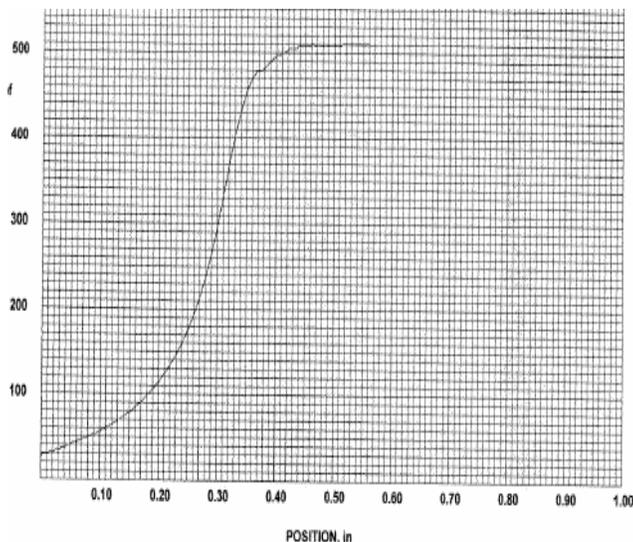


Figure 4. AIEP:1% NaCl (1:3) profile for the extrusion rheometer run using 6INLX1MMW core

No drop in pressure after the peak injection value occurred, as shown in Figure 4, in contrast to Figure 3. This data indicates that AIEP is more efficiently placed downhole than the commercial LCM. The standard deviation and COV for the AIEP were much better than the commercial LCM (Table 1).

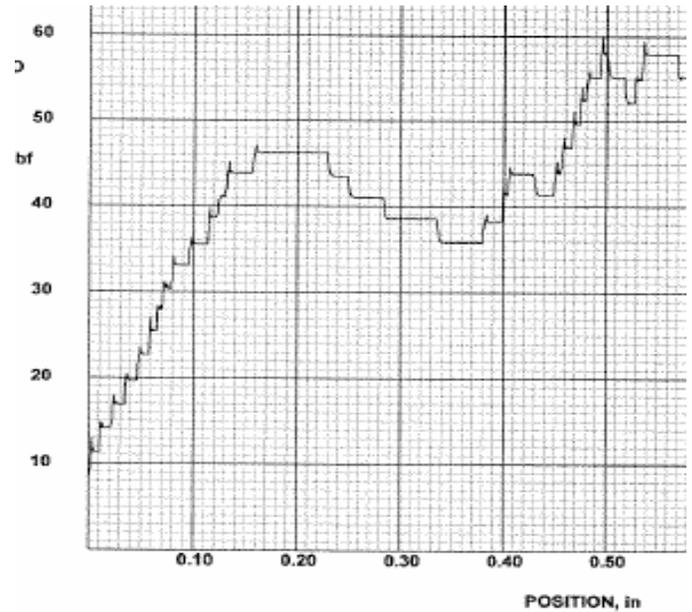


Figure 5. Commercial LCM: Oil-based mud (3:1) profile for the extrusion rheometer run using 6INLX1MMW core

Figure 5 was the profile of an extrusion rheometer experiment using commercial LCM (DVC) with 12 ppg oil-based mud (3:1). It is important to point out that the same size of core was used for both Figures 4 and 5. However, the dilution factors were different in these two experiments. The dilution factor for AIEP was 1:3 (AIEP: 1% NaCl) and 3:1 for the commercial LCM (oil-based mud). Surprisingly, the average force was only 72.2 lb (Figure 5) compared with 517 lb for AIEP (Figure 4). Furthermore, if commercial LCM was mixed with only 25% oil-based mud, the force decreased tremendously (Figures 3 and 5). In Figure 3, a 3 mm slit was used and in Figure 5, a 1 mm slit was used. If a 3 mm slit was used for Figure 5, the value would be lower than shown in Figure 5 for the 1 mm slit. If we take into consideration the proportion of AIEP used in the experiment, only 30% was active material, and the force was still 517 lb. The mechanical strength for Figure 4 was better than Figure 5. Thus, the results show that AIEP is a very effective LCM especially on low concentration compared with the commercial LCM.

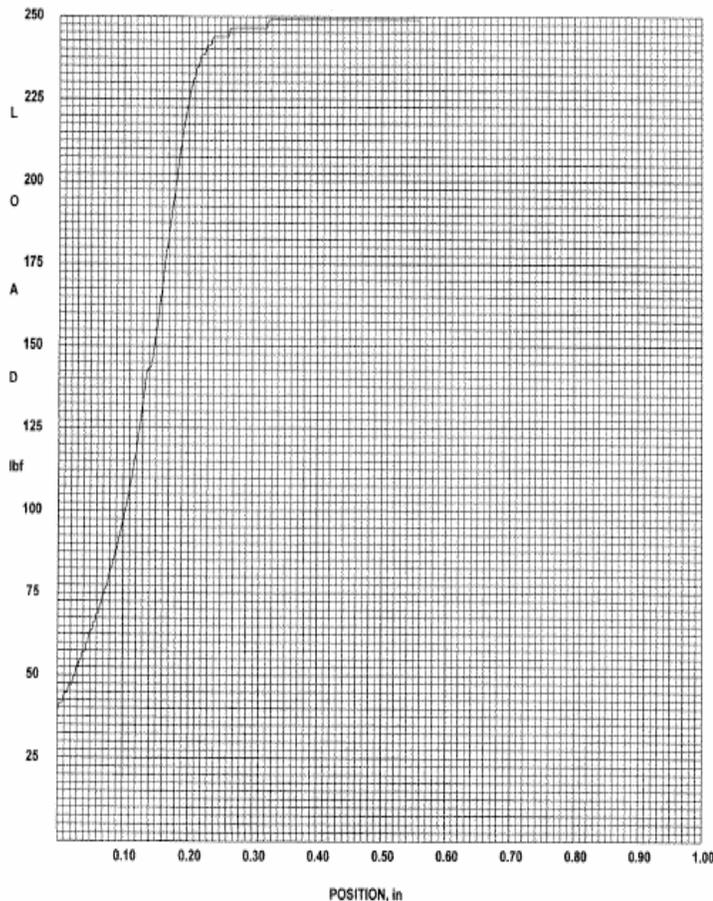


Figure 6. AIEP: Seawater (1:3) profile for the extrusion rheometer run using 4INLX1MMW core

AIEP formulated with seawater also was investigated.

Figure 6 shows the profile of the seawater experiment. In contrast to the data in Table 2, the values determined for seawater were lower than for 1% NaCl solution. Yet these values were still acceptable.

From the extrusion rheometer data, the Bagley factor could be derived. To derive the Bagley factor, the width of the slit was kept constant, and different forces were measured while changing the lengths of the core under the same conditions, as illustrated in **Figure 7**.

Bagley Coefficient is defined as: Bagley factor = F_0 / F_{L2} .

F_0 is defined as the force when X , the length of the core, equals 0. This value is extrapolated from the force extrusion graphs as seen in **Figures 7 through 9**. F_{L2} is defined as the force obtained using the 4 inch core in this particular case. In general, the smaller the Bagley

coefficient number, the lower the pressure it requires for placing the LCM to the fracture. However, the smaller Bagley coefficient also means the weaker the mechanical strength the LCM has. For most LCM tested, the Bagley coefficient falls between 0 and 80%.

For the commercial LCM (DVC) used in this investigation, the Bagley coefficient was between 25 to 80%. Based on past experiments, the Bagley coefficient optimal range was 35 to 55%, which is based on the balance between the mechanical strength and pressure range to place the commercial LCM downhole.

As **Figures 7, 8 and 9** show, the Bagley coefficients for the AIEP are lower than the commercial LCM. The Bagley coefficients were 10%, 13.4% and 25.7% respectively for the AIEP, rather than the 25 to 80% for the commercial LCM. Thus it is easier to push the AIEP and 1% NaCl mixture into the fracture formations.

The Bagley coefficients are lower than those traditionally viewed as optimal. This lower value might indicate that the anionic polymer could be easily replaced by other fluids and may not seal fractures relative to the commercial LCM material as well. The dislodgement experiments seemed to confirm this possibility with the relatively low values measured (10 psi for the 1% NaCl mixture and 9 psi for the seawater mixture). However, it is important to note that the traditional LCM is based on sized solids, while this new LCM material is polymeric in nature. It is thought that the amount of solids in the system effect the test outcome. The amount of solid in the AIEP and 1% NaCl mixture was small compared to the commercial material. After the polymer material is heated overnight, the paste decreases in size. Thus the dislodgement pressure was low. However, AIEP behaved differently in water- or oil-based muds, indicating that the material may not be easy to dislodge or may lack sufficient strength to perform as an effective LCM. Note the data presented later in **Figures 13 and 16**.

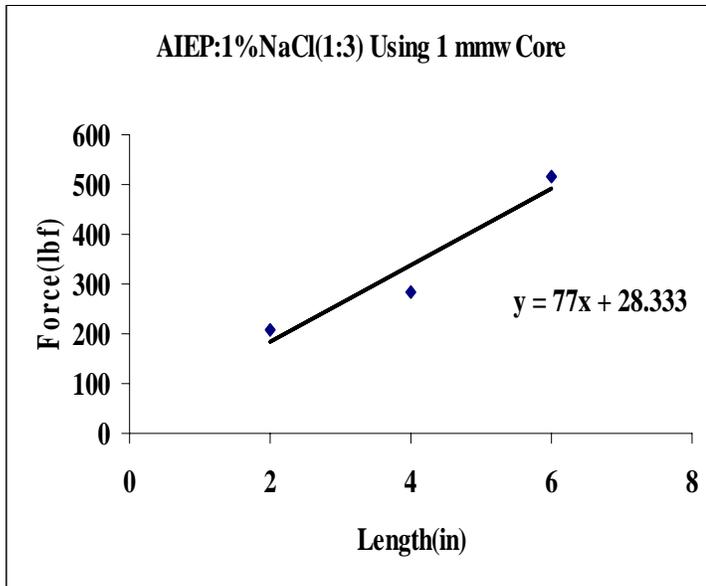


Figure 7. Bagley Coefficient = $F_0 / F_{L2} = 28.33 / 283 = 0.10$ or 10%

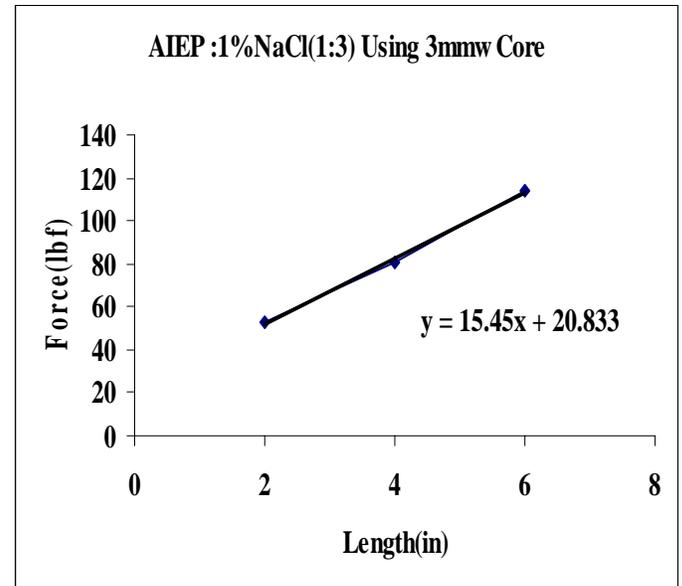


Figure 9. Bagley Coefficient = $F_0 / F_{L2} = 20.83 / 80.9 = 0.257$ or 25.7%

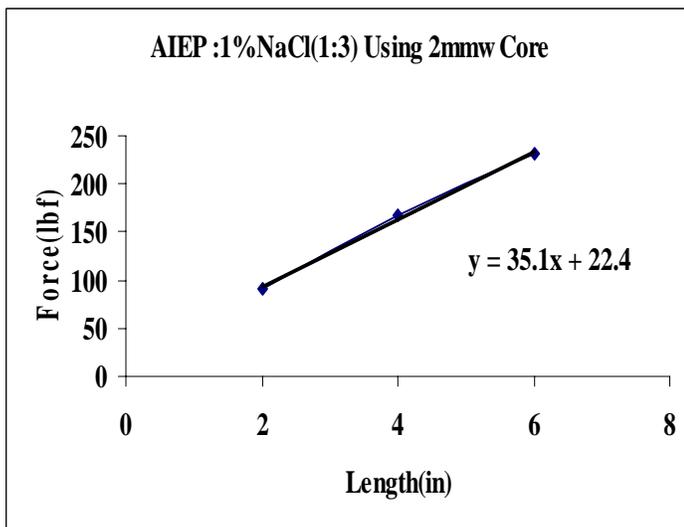


Figure 8. Bagley Coefficient = $F_0 / F_{L2} = 22.4 / 166.8 = 0.134$ or 13.4%

Yield point, mixing energy and flow rate were also obtained for this new AIEP. The results were compared with commercial LCM. The AIEP showed great potential as a new lost circulation material. For the AIEP to become a successful new commercial product, details concerning methods on how to use the AIEP would need to be investigated. It was necessary to investigate how different drilling fluids affect the performance of the AIEP. It was also important to find out the appropriate spacers and wetting agents to deliver the AIEP downhole. All the initial test results obtained with the AIEP were either in DI water or seawater. To see if the AIEP could work well with different drilling fluids, water- and oil-based muds were tested. Lignosulfonate mud (**Table 3**) was one of the water-based muds tested. After hot rolling in a 150°F oven for 16 hrs, different concentrations of the AIEP in the mud were tested. Even with the dilution factor of 1:30 (AIEP: mud), the solid formed from the mixture of the two was a cement like slurry paste (**Table 4**).

One aspect that requires more detailed discussion is the effect of salts on the reactivity of AIEP and how the super absorbent works, since we will refer to this phenomenon a number of times.^{10, 11}

Super absorbing polymers typically contain polyacrylamide and polyacrylate functionality. **Figure 10** shows that when super absorbent polymer comes in contact with water, the polymer backbone containing hydrophilic functional groups, interacts with the solvent accompanied by an energy decrease and an entropy

increase. Hydration and the formation of hydrogen bonds are two sources for such polymer/solvent interactions. The polymer chains also tend to disperse in the given volume of solvent. This leads to a higher number of allowed configurations for the system, which is equivalent to a higher degree of entropy.

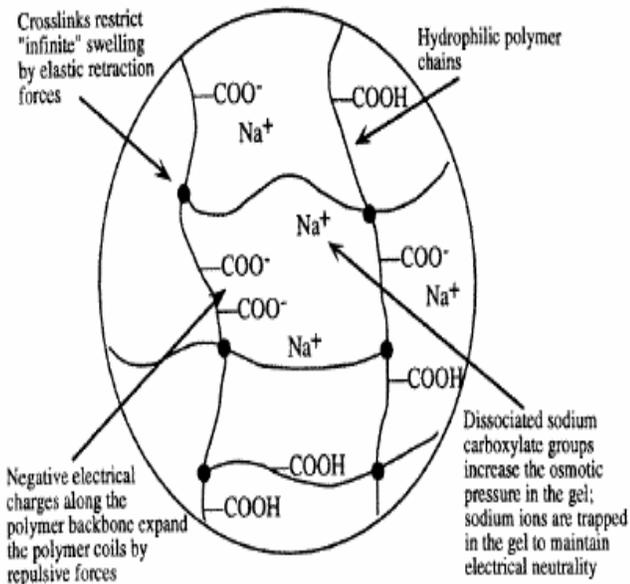


Figure 10. Mechanism of swelling of superabsorbent polymers

Due to the presence of the cross-linked polymer, chains are restricted in swelling by elastic retraction forces of the polymer network. The more chains separate from each other, the more stiffened the originally coiled polymer chains become. This causes a decrease in the entropy of the chains. Finally, there is a balance between the trend toward infinite dilution of the chains and retractive forces of the polymer matrix.

When the polymer comes into contact with water, the solvent diffuses into the polymer network and solvates the sodium ions. Water, with its high dielectric constant, lowers the attractive forces between the sodium ions and the negatively charged carboxylate groups. As in solutions of simple salts, the sodium ions are released and freely move within the polymer gel. Hence they contribute to the osmotic pressure. But, it is impossible for them to leave the gel region due to the attraction forces of the negative charges, which are fixed along the polymer backbones. The sodium ions therefore behave as if trapped by a semi-permeable membrane. The driving force for swelling is then the difference between the osmotic pressure in and outside of the gel. Increasing the salinity and the osmotic pressure of any

external aqueous solution lowers the absorption capacity of the gel for that fluid.

In view of the absorption mechanism, we can discuss the results of the investigation of the seawater version of the lignosulfonate mud with the AIEP. The dilution factor decreased to 10 from 20 when using the seawater version of the lignosulfonate mud (Table 4). The cations in the seawater (e.g., Na^+ , K^+ , Ca_2^+ , Mg_2^+ , etc.) affect the performance of the AIEP. This phenomenon is known as salt poisoning. The salt poisoning effect was more pronounced for Ca_2^+ relative to Na^+ . To correct the problem, soda ash (Na_2CO_3) was added to the mud to remove the Ca_2^+ . The results were excellent. The dilution factor became 20, just as in the case with fresh water muds, and the texture of the solid resembled the fresh water mud, too.

Figures 11 through 13 show how AIEP reacts with lignosulfonate mud. Note the paste-like texture of the final mixture in Figure 13.

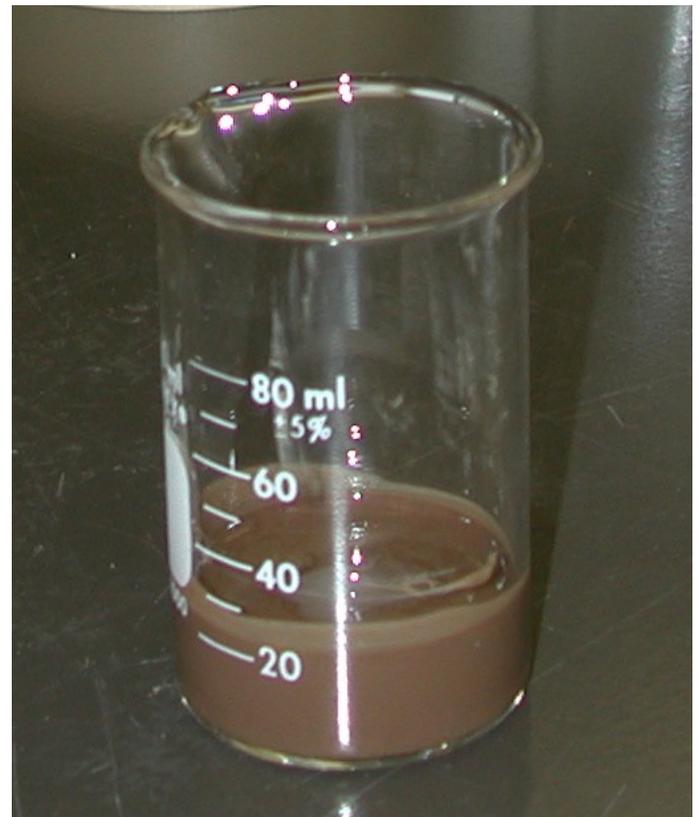


Figure 11. Lignosulfonate mud (fresh water)



Figure 12. AIEP : Lignosulfonate mud (fresh water)
(1:20)



Figure 13. After 1 min. mixing time (AIEP:
lignosulfonate mud)(1:20)

Thus, it becomes important to find out how the salinity, pH and density affect the performance of the AIEP. Different salinity, pH and density muds were formulated (**Table 5**). All the muds from Table 5 were hot rolled at 150°F for 16 hrs, and pH measurements were taken.

Density played an important role with respect to the solid quality mixing with the AIEP. It also determined the amount of AIEP required. If we examine the data in **Table 6**, under the same conditions, the lower the density, the more AIEP is required to form the solid (4 mL of AIEP for D = 10 ppg vs. 2 mL AIEP for D = 16 ppg, that is 50% decreasing in vol.). It is worthwhile to point out that the solid formed using mud with a density of 16 ppg is noticeably thicker and stronger compared with the mud having a density of 10 ppg. Alternatively, the effects of pH on AIEP are not as obvious as density. Under the same conditions, comparing the mud with pH = 7.66 and 11, it takes 1.5 min. to form the solid at pH = 7.66 vs. 1 min. for pH = 11. There is no obvious difference when the pH is changed from 9 to 11.

Salinity had a greater effect on the performance of AIEP than pH. The fresh water mud from **Table 7** was the best in terms of the amount of AIEP used and the quality of the solid after mixing. Again, with more cations in the solution, more AIEP was needed to form the solid. Therefore, more AIEP was needed when the salinity increased (Table 7). To find out if the presence of KCl would affect performance, two experiments were done. The results indicated that there were no problems forming solid regardless if it was 10% KCl solution or 24% NaCl with 3% KCl solution, as long as there was enough AIEP in the mixture (in this case, 3 mL AIEP) (Table 7). If high salt problems were encountered in the field, diluting the mud with 20 – 30 % fresh water helped. If the high salt problems can be predicted, dilution of the mud before adding AIEP is recommended.

The AIEP showed such promising potential as a new LCM, especially when used in conjunction with water-based mud. We applied the same technology to the oil-based mud. The oil dispersed polymer (ODP) went through the same vigorous testing procedures with oil-based muds as the water-based muds. After many lab tests, it was found that the ODP worked well with both water- and oil-based muds. The following pictures show ODP mixed with oil-based mud before and after hot rolling.



Figure 14. ODP: Internal olefin oil-based mud:
soda ash water (2:1:4) mixture



Figure 16. Before and after hot rolled

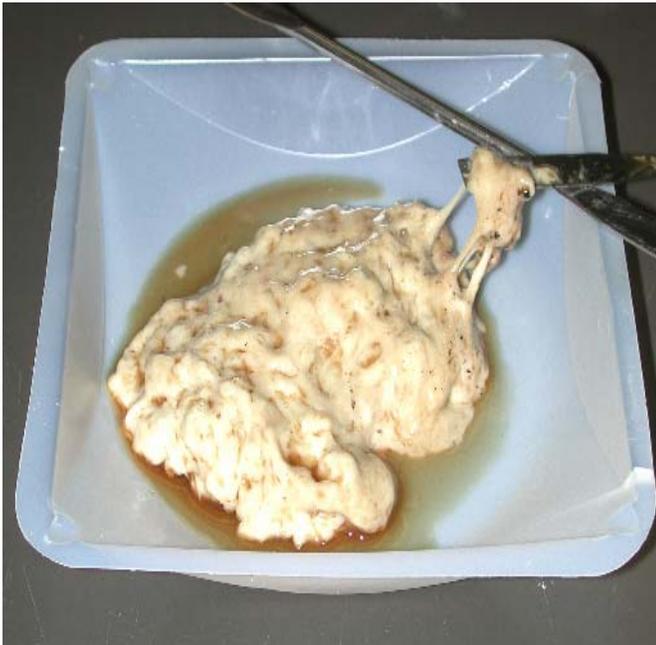


Figure 15. The mixture from Figure 14 was hot rolled
in 400°F oven for 16 hrs

Figures 14 to 16 illustrated the effect of temperature on the mixture of ODP / internal olefin oil-based mud and soda ash water. The 400°F temperature not only did not destroy the polymer paste, but it afforded a more uniform and sponge like polymer plug. After seeing these pictures, one can surmise that such material can seal off the fractures downhole fast and easily.

Summary of laboratory results

Serial tests were performed on both water- and oil-based mud with AIEP and ODP. The purposes/goals of these tests were to determine whether AIEP/ODP could be used as a new lost circulation material for both water- and oil-based mud. This paper documented the process of how a LCM was discovered. AIEP/ODP was also investigated for how they behaved under different pH, salinity and density, and how to apply this new technology in the field. Here are the summaries:

- ODP is the best candidate as an inverse emulsion polymer in lost circulation control for both water- and oil-based mud based on lab tests.
- Excellent results can be obtained using ODP with fresh water, seawater, 10% NaCl and even 24% NaCl mud. ODP can still have great results in 10% KCl solution, and 24% NaCl plus 3% KCl solution. In the high salt solution/mud,

more ODP is needed to achieve the same performance.

- For ODP to achieve the same performance as with fresh water, high Ca_2^+ content should be treated with soda ash. Soda ash can be added directly to any combination of the mud, a spacer, or the ODP.
- ODP works better with high density mud. Additional solids such as resilient graphitic carbon-based material, barite or drill solids will always enhance the performance of ODP as a LCM. ODP can be weighted up to 20 lb/gal with barite.
- pH has no significant impact on the performance of ODP.
- Using ODP in oil-based mud bears many similarities to water-based mud, such as treating out the Ca_2^+ ions with soda ash and adding solid such as resilient graphitic carbon-based material to enhance the performance of ODP. The soda ash can be added to any combination of the spacer or ODP. The big difference between oil-based mud and water-based mud is that more ODP will be needed in oil-based mud to achieve the same goal.

Field trial

The investigations in the lab for the ODP in this report demonstrated the great potential it has as a new LCM for both oil-and water-based mud. However, the data from the initial field trial demonstrated how this new LCM cured total losses in a long openhole section on the first attempt.

Hutchinson County, Texas, is notorious for its lost circulation problems. Conditions range from bad to disastrous. Practically every LCM known has been tried. When Latigo Petroleum was drilling on the Gladys Harvey A61 No. 1 well after setting 9 5/8" casing at 1,628 ft, it encountered a drilling break at 9,197 ft, followed by complete loss of circulation. The 9.2 lb/gal active mud system was carrying 18-20 lb/bbl of LCM when the drilling break occurred. The decision was made to raise the LCM concentration in stages up to 34 lb/bbl after losing circulation. Pills containing 50 lb/bbl of various sized LCM also were pumped.

Short trips resulted in regaining circulation at almost any point above the loss zone. After approximately 48

hours of attempting to cure the loss, Latigo decided to drill to a competent formation and possibly perform a cement squeeze. After dry drilling 191 feet with no changes in formation or drill rate, it was decided to once again attempt to stop the losses and log the hole.

Several types of LCMs were mixed in the system, and two 80 bbl pills containing 50 lb/bbl of LCM were mixed and pumped. After approximately one day of dry drilling, circulation could not be regained until the pipe was pulled to approximately 2,600 ft. Cumulative mud losses to this point were estimated at approximately 5,000 bbl.

Personnel from Halliburton recommended spotting the new rapid-set LCM product (ODP). A pump truck was called out. Two totes totaling 11 bbl of ODP were put in one tank, and 5 bbl of diesel was placed in another tank.

The drill pipe was run open-end to a depth of 9,172 ft. The pumping sequence and procedure is shown below:

1. 5 bbl of diesel spacer.
2. 11 bbl of ODP.
3. 5 bbl of diesel in the ODP tank on the fly to help clean and flush the pumps.
4. 11 bbl of water treated with two 50 lb sacks of soda ash.
5. As soon as the water with soda ash was pumped into the drillpipe, the operator switched to the rig pumps to place the pill. The pump rate was maintained at 5-6 bbl/min.

When the treated water cleared the pipe followed by 2-3 bbl of mud, there was no noticeable change in the pump pressure. Pumping was stopped and the pipe was pulled to 5,860 ft.

Before the application of the ODP, this well was expected to be a total loss. After the application, full circulation was regained at 5,860 ft and the mud was conditioned. After observing bottoms up, the operator staged in the hole to 7,277 ft and repeated circulating bottoms up with full returns. After bottoms up at 7,277 ft, the operator staged in to 8,038 ft and pumped for 20 minutes with full returns. The operator continued running into the hole to 9,020 ft.

The last joint took a little weight. When the driller broke circulation, the pump pressure rose to 1,800 psi immediately before dropping back. This may have been a bridge or possibly some of the LCM ODP pill. Full circulation was maintained for two hours, after which Latigo decided to trip out and log the hole. Logging was completed and the decision was made to sidetrack the hole.

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Table 1. Preliminary lab test results for three classes of inverse emulsion polymers

Sample	1:1(v/v)	1:3	1:6	1:9	1:10	1:20	1:30
AIEP in DI	Thicken within 1 min. Took 45 min. to dissolve.	Thicken within 1 min. Took 20 min. to dissolve.	Thicken within 1 min. Took 18 min. to dissolve.	Thicken within 1 min. Took 7 min. to dissolve.	Thicken within 1 min. Took 7 min. to dissolve.	Thicken after 2 min. Took 7 min. to dissolve.	No stiff polymer formed. After overnight, not pourable.
AIEP in 1% NaCl	Thicken within 1 min. Took 45 min. to dissolve.	Thicken within 1 min. Took 30 min. to dissolve.	Thicken within 1 min. Took 12 min. to dissolve.	After 30 min still two phases (solid and liquid). After overnight it hardened. Took 10 min. to dissolve.	After overnight still two phases (solid and liquid).	After overnight still two phases (solid and liquid).	N/A
CIEP in DI	Thicken within 1 min. Took 45 min. to dissolve.	Thicken within 1 min. Took 45 min. to dissolve.	Thicken within 1 min. Took 40 min. to dissolve.	Thicken within 1 min. Took 25 min. to dissolve.	Thicken within 1 min. Took 20 min. to dissolve.	Thicken within 1 min. Took 12 min. to dissolve.	Thicken within 1 min. Took 6 min. to dissolve.
CIEP in 1% NaCl	Runny at first, but after two hrs it thickened. It took 30 min to dissolve.	Runny at first, but after overnight, it thickened. It took 10 min to dissolve.	Runny even after overnight.	Runny	Runny	Runny	Runny
NIEP in DI	Thicken within 1 min. Not completely dissolve even after overnight.	Thicken within 1 min. Took 25 min. to dissolve.	Thicken After 2 hrs. Took 10 min. to dissolve.	N/A	N/A	N/A	N/A
NIEP in 1% NaCl	Runny	Runny	Runny	N/A	N/A	N/A	N/A

Table 2. Extrusion rheometer test results for AIEP in DI, 1% NaCl solution and in seawater.

Sample	2INL X1M MW†	4INLX 1MMW	6INL X1M MW	2INLX 2MMW	4INL X2M MW	6INLX 2MMW	2INLX 3MMW	4INLX 3MMW	6INLX3MM W
Commercial LCM	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	Ave: 526* SD**: 69 ***COV: 13.1%
AIEP:DI water (1:9)	N/A	Ave: 134.7 SD: 5.67 COV: 4.2%	N/A	Ave: 46.1 SD: 2.61 COV: 5.7%	N/A	N/A	N/A	N/A	Ave: 57.2 SD: 8.9 COV: 15.6%
AIEP:1% NaCl (1:6)	N/A	Ave: 136.3 SD: 5.7 COV: 4.2%	N/A	Ave: 41.3 SD: 3.27 COV: 7.9%	N/A	N/A	N/A	N/A	Ave: 62.1 SD: 1.19 COV: 1.9%
AIEP:1% NaCl(1:3)	Ave: 209 SD: 2.38 COV: .1%	Ave: 283 SD: 1.15 COV: 0.5%	Ave: 517 SD: 6.56 COV: .3%	Ave: 90.6 SD: 1.88 COV: 2.1%	Ave: 166.8 SD: 2.15 COV: .3%	Ave: 231 SD: 4.85 COV: 2.1%	Ave: 52.6 SD: 3.01 COV: 5.7%	Ave: 80.9 SD: 1.87 COV: 2.3%	Ave: 114.4 SD: 8.34 COV: 7.3%
AIEP: seawater (1:3)	N/A	Ave: 248 SD: 1.16 COV: 0.5%	N/A	Ave: 82.0 SD: 1.76 COV: 2.1%	N/A	N/A	N/A	N/A	Ave: 108.8 SD: 7.82 COV: 7.2%

†2 INL X 1 MMW means the core used is 2 inches long and the slit opening is 1 mm wide.

*Tests are done using extrusion rheometer, the units are in lb.

** SD: Standard deviation

***COV = SD/\bar{X}_{Ave} (coefficient of variance).

Table 3. Lignosulfonate mud formulation

Sample, (lb/gal)	14.0
Fresh water, bbl	0.76
Gel viscosifier, lb/bbl	20
Thinner, lb/bbl	6
NaOH, lb/bbl	3 (pH ~11 - 11.5)
Filtration control, lb/bbl	4
Drilled solid, lb/bbl	30.0
Barite, lb/bbl	271.6

Table 4. Preliminary lab test results of AIEP with lignosulfonate mud

Sample	1:1(v/v)	1:2	1:10	1:20	1:30	1:50
AIEP with lignosulfonate mud (with freshwater)	Thicken within 1 min. Forms loose solids.	Thicken within 1 min. Forms clay like solids.	Thicken within 1 min. Forms clay like solids.	Thicken within 1 min. Forms clay like solids. Slightly wetter than 1:10.	Slightly slurry, more cement like.	Slurry and watery.

Sample	1:5(v/v)	1:10	1:15	1:20
AIEP with lignosulfonate mud (with seawater)	Thicken within 1 min. Forms rubbery clay.	Thicken within 1 min. Forms clay like solids.	Slurry at first, then hardens after 1 hr.	Slurry at first, then hardens after 1.5 hr.

Table 5. High performance water-based mud formulations

Sample, (lb/gal)	Fresh water	10% (w/w) NaCl	24% (w/w) NaCl			
	13	13	10	13	13(w/o NaOH)	16
Fresh water, bbl	0.826	-	-	-	-	-
10%(w/w), NaCl, bbl	-	0.845	-	-	-	-
24%(w/w), NaCl, bbl	-	-	0.994	0.875	0.875	0.756
NaOH, lb	0.25	0.25	0.25	0.25	-	0.25
Suspension agent/viscosifier, lb	0.75	0.75	1.0	0.75	0.75	0.25
Filtration control agent, lb	4.0	4.0	4.0	4.0	4.0	4.0
Shale stabilizer, lb	3.25	2.75	2.0	2.0	2.0	2.0
Flocculant (active), lb	0.50	0.5	0.5	0.5	0.5	0.5
Shale stabilizer, lb	4.0	4.0	4.0	4.0	4.0	4.0
Barite, lb	256.3	228.3	81.5	183.2	183.2	358.3

Table 6. How density and pH affect the performance of AIEP

	24% (w/w) NaCl				
Density, (lb/gal)	10	13	13	13	16
Mud vol. (mL)	10	10	10	10	10
pH	9.05	7.66	9.06	11.0	9.05
AIEP (mL)	4	3	3	3	2
Observations	It needs the most AIEP to form polymer paste/solids. The texture of the paste is also the most loose one among all other samples.	It takes the longest time (1.5 min. vs. ~ 1 min.) to harden, compared with all other muds with the same density, but different pH.	It takes the same amount of AIEP to form solids/paste when the density is the same, regardless the differences in pH.	There is no significant difference when pH changes from 9 to 11.	It only takes 2 mL of AIEP to form paste/solids. The texture/strength of the solid formed also is the best.

Table 7. How salinity affects the performance of AIEP

	Fresh water	10% (w/w) NaCl	24% (w/w) NaCl
Density, (lb/gal)	13	13	13
Mud vol. (mL)	10	10	10
pH	9.03	9.05	9.06
AIEP (mL)	1	2	3
Observations	It needs only 1 mL AIEP to form polymer paste/ solid. The texture of the paste is also the best among all other samples.	The texture and strength of the solid is between fresh water and 24% (w/w) NaCl.	AIEP still works in 24% NaCl (w/w) mud. It just needs more AIEP to form solid/paste.

Sample	10% KCl	3% KCl + 24% NaCl
AIEP (3mL) : Salt solution (10 mL)	Forms solid	Forms solid