

OIL PRODUCTION AFFECTED BY ASP AND GELATION TECHNOLOGIES

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Проведено аналіз впливу технологій внесення інгібітору корозії ASP і технологій огелювання на рівень нафтовидобутку. Показано, що технології огелювання були розроблені для забезпечення більш ефективного вертикального розгортання для затоплення природно тріщинуватих повід-колекторів нафти. Наведено результати аналізу ефективності використання комбінації цих двох технологій, які, на думку автора, могли б розширити застосовність лужного поверхнево-полімерного заводнення.

Ключові слова: інгібітор корозії ASP, технологія огелювання, нафтовидобування

Проведен анализ влияния технологий внесения ингибитора коррозии ASP и технологий огеливания на уровень нефтедобычи. Показано, что технологии огеливания были разработаны для обеспечения более эффективной вертикальной разветки для затопления естественно трещиноватых пород-коллекторов нефти. Представлены результаты анализа эффективности использования сочетания этих двух технологий, которые, по мнению автора, могли бы расширить применимость щелочного поверхностно-полимерного заводнения.

Ключевые слова: ингибитор коррозии ASP, технология огеливания, нефтедобыча

Gelation technologies have been developed to provide more efficient vertical sweep efficiencies for flooding naturally fractured oil reservoirs or more efficient areal sweep efficiency for those with high permeability contrast «thief zones». The field proven alkaline-surfactant-polymer technology economically recovers 15% to 25% OOIP more oil than water flooding from swept pore space of an oil reservoir. However, alkaline-surfactant-polymer technology is not amenable to naturally fractured reservoirs or those with thief zones because much of injected solution bypasses target pore space containing oil. This work investigates whether combining these two technologies could broaden applicability of alkaline-surfactant-polymer flooding into these reservoirs.

Aluminum citrate-polyacrylamide, resorcinol-formaldehyde, and the silicate-polyacrylamide gel systems did not produce significant incremental oil in linear core floods. Both flowing and rigid flowing chromium acetate-polyacrylamide gels and the xanthan gum-chromium acetate gel system produced incremental oil with the rigid flowing gel producing the greatest amount. Higher oil recovery could have been due to higher differential pressures across cores. None of the gels tested appeared to alter alkaline-surfactant-polymer solution oil recovery. Total water flood plus chemical flood oil recovery sequence recoveries were all similar.

Keywords: corrosion inhibitor ASP, gelation technologies, oil production

Introduction

Gelation technologies provide more efficient vertical sweep efficiencies for flooding naturally fractured oil reservoirs or more efficient areal sweep efficiency for those with high permeability contrast «thief zones». Field proven alkaline-surfactant-polymer technology economically recovers 15% to 25% OOIP more oil than water flooding from swept pore space of an oil reservoir. However, alkaline-surfactant-polymer technology is not amenable to naturally fractured reservoirs or those with thief zones because much of the injected solution bypasses target pore space containing oil. This work investigates whether combining these two technologies could broaden applicability of alkaline-surfactant-polymer flooding.

Executive Summary

Chromium acetate-polyacrylamide gel used to close fractures and divert fluid into the matrix maintains diversion capability after injection of an alkaline-surfactant-polymer solution. Linear core floods indicate that the chromium acetate-polyacrylamide gel integrity is maintained after

injecting alkaline-surfactant-polymer solution at 72, 125, and 175 °F. Xanthan gum-chromium acetate gels on the other hand were only stable at 72 and 125 °F. Numerical simulation of applying a gel treatment to a Minnelusa reservoir with two sands separated by shale indicates that prior treatment of the higher permeability sand with gel will recover additional oil. Water flood oil recovery is improved by 196,000 bbls with gel treatment. Alkaline-surfactant-polymer flood oil recovery is improved by 596,000 bbls with prior gel injection.

Experimental

Evaluations performed at 72°F used Big Sinking crude oil supplied by Bretagne in Lexington, Kentucky. Big Sinking crude oil is a 42° API gravity, 3 cp crude oil. It's characteristics have been described elsewhere. Evaluations at 125°F and 175°F used a 19.4° API gravity crude oil with a viscosity of 30 and 13 cp at the elevated temperatures, respectively. Polymers used in the linear core floods are listed in Table 1. Chemicals were dissolved in 1.0 wt% sodium chloride.

Table 1 – Polymers Used in Gelation Linear Core floods

| Polymer Name | Type/Degree of Hydrolysis | Supplier |
|-----------------|---------------------------|--------------------------|
| Flocon 4800 | xanthan gum | SNF Floerger |
| Alcoflood 1275A | polyacrylamide/30% | Ciba Specialty Chemicals |
| HiVis 350 | polyacrylamide/30% | Tiorco, Inc. |
| Watercut 204 | polyacrylamide/7% | Tiorco, Inc. |

Table 2 – Berea Core Properties

| 100% NaCl Brine Saturated Permeability ---Oil Saturation--- Core flood | K _T , abs(md) | Porosity(%) | Soi(Vp) | Sor(Vp) |
|---|--------------------------|-------------|---------|---------|
| Fractured Core Linear Core flood Cr ⁺³ - PHPA rigid – NaOH (prior to cutting fracture) | 595 | 22.8 | 0.562 | 0.349 |
| 175 ⁰ F Linear Core floods Cr ⁺³ -XG rigid - NaOH | 290 | 22.6 | 0.609 | 0.236 |
| Cr ⁺³ - PHPA rigid - NaOH 125 ⁰ F Linear Core floods | 425 | 23.1 | 0.582 | 0.211 |
| Cr ⁺³ -XG rigid - NaOH | 502 | 22.8 | 0.791 | 0.382 |
| Cr ⁺³ - PHPA rigid - NaOH | 555 | 23.3 | 0.712 | 0.336 |
| Radial Core floods dual core, common well bore, same core holder | | | | |
| Cr ⁺³ -PHPA rigid flowing – NaOH | 631 | 23.0 | 0.541 | 0.284 |
| Cr ⁺³ -PHPA rigid flowing - Na ₂ CO ₃ | 58 | 17.9 | 0.510 | 0.355 |

Linear core floods were performed using 2 inches diameter by 5 inches long, unfired Berea sandstone. Radial core floods used 6 inches diameter by 2 inches high, unfired Berea sandstone. Table 2 lists the core properties. Fractured linear core was developed by chisel etching a straight line cut along the length of core sides and faces. Continual light tapping of the chisel along the etched line eventually created a fracture.

So_i and S_{oR} are initial and water flood residual oil saturation, respectively. PHPA is partially hydrolyzed polyacrylamide, and XG is xanthan gum. Single core linear core flood injected fluid sequence is listed below. Core floods were performed at designated temperature.

1. Saturate core with 1.0 wt% NaCl by evacuation and determine porosity and pore volume;

2. Inject 1.0 wt% NaCl and determine the absolute permeability to water (k_{abs});

3. Inject crude oil to immobile water and determine the effective permeability to oil at immobile water (k_{orw});

4. Inject 1.0 wt% NaCl at 12 ft/day fluid frontal advance rate to residual oil and determine the effective permeability to water at residual oil (k_{orw});

5. Inject gel fluids at 12 ft/day;

6. Stop injection. Pull core holder apart, clean gel out of injection and production lines. Fill injection lines with 1.0 wt% NaCl before assembling core holder;

7. Re-assemble core holder and allow gel to form overnight with no flow;

8. Inject 1.0 wt% NaCl at 12 ft/day to stable pressures;

9. Inject 1.0 wt% NaOH plus 0.06 wt% active ORS-46HF plus 1300 mg/L Alcoflood 1275A at 12 ft/day. Inject 5 to 10 pore volumes;

10. Shut-in overnight;

11. Resume ASP solution injection at 12 ft/day. Inject 1 to 2 pore volumes;

12. Inject 1.0 wt% NaCl at 12 ft/day for 5 to 10 pore volumes to get stable pressures and determine permeability change from step 8.

Differential pressures were measured from the core injection face to one inch from the injection face, and from injection face to production face. Differential pressure from one inch behind the injection face to production face of the core was calculated by difference between the two measured values. Single fractured core linear core flood injected fluid sequence is.

1. Repeat steps 1 through 3 of the single linear core flood procedure.

2. Remove core from core holder and fracture core.

Table 3 – Gel Chemical Compositio

| Gel | Polymer | mg/L | Cross Linking Agent (Bulk) | |
|--------------------------------------|--------------|-------|----------------------------|-------|
| | Type | | Type | mg/L |
| 72 ⁰ F Core floods | | | | |
| Cr ⁺³ -Xanthan Gum | Flocon 4800 | 5,000 | Watercut 684 | 3,250 |
| Cr ⁺³ -PHPA rigid flowing | Watercut 204 | 7,500 | Watercut 684 | 2,425 |
| 125 ⁰ F Core floods | | | | |
| Cr ⁺³ -Xanthan Gum | Flocon 4800 | 5,000 | Watercut 684 | 3,250 |
| Cr ⁺³ -PHPA rigid flowing | Watercut 204 | 5,000 | Watercut 684 | 1,590 |
| 175 ⁰ F Core floods | | | | |
| Cr ⁺³ -Xanthan Gum | Flocon 4800 | 2,000 | Watercut 684 | 950 |
| Cr ⁺³ -PHPA rigid flowing | Watercut 204 | 3,000 | Watercut 684 | 1,430 |

3. Place fractured core into core holder. Put overburden pressure on core and inject Big Sinking crude oil and determine k_{orw} .

4. Inject crude oil to immobile water at 30 ft/day and determine the effective permeability to oil at immobile water (k_{orw}).

5. Inject 1.7 pore volumes of 1.0 wt% NaCl at 4 ft/day fluid frontal advance rate to residual oil and determine k_{wro} .

6. Inject at 4 ft/day 0.5 pore volumes of Marcit gel (7500 mg/L WaterCut 204: 2425 mg/L WaterCut 684 or 250 mg/L Cr⁺³).

7. Inject 0.05 pore volume of 1.0 wt% NaCl. Stop injection. Clean out injection and production lines. Fill injection lines with 1.0 wt% NaCl. Do not take the core holder apart.

8. Shut-in for two days.

9. Inject 1.0 wt% NaCl at 4 ft/day for 7.4 pore volumes to get stable pressures, flush gel from core, and get resistance factor.

10. Inject 7.1 pore volumes 1.0 wt% NaOH plus 0.06 wt% active ORS-46HF plus 1300 mg/L Alcoflood 1275A at 4 ft/day.

11. Inject 1.0 wt% NaCl at 4 ft/day for 6.5 pore volumes to get stable pressures and flush ASP-gel from core.

Differential pressures were measured from the core injection face to production face. Dual individual core radial core flood with a common manifold injected fluid sequence is listed below. Separate radial core holders were used in steps 1-3.

1. Saturate core with 1.0 wt% NaCl and determine porosity and pore volume.

2. Inject 1.0 wt% NaCl and determine the absolute permeability to water (k_{abs}).

3. Inject Big Sinking crude oil to immobile water and determine k_{orw} . Place core in stacked core radial core holder. A piece of cellulose paper was placed between the cores to facilitate capillary continuity. An O-ring was placed on the outer edge of the cores at their junction that will seal to the annulus edge to facilitate separate collection

of fluids from each core. Place an overburden of 1000 psi on the cores. Stacked core injection steps 4-10 - fluid frontal advance rates are summed height, average porosity, and average diameter for two cores.

4. Stack cores so that a common well bore is present.

5. Inject 1.0 wt% NaCl at 5 ft/day fluid frontal advance rate to residual oil saturation and determine k_{orw} for each core.

6. Inject gel fluids at 5 ft/day 0.7 pore volumes of the high permeability core and monitor injection pressure.

7. Inject 0.05 pore volumes of the high permeability core of 1.0 wt% NaCl at 5 ft/day.

8. Stop injection and allow gel to form for two days.

9. Inject 1.0 wt% NaCl at 5 ft/day for 5 pore volumes and determine resistance factor.

10. Inject 1.0 wt% NaOH plus 0.10 wt% active ORS-60HF plus 1300 mg/L Alcoflood 1275A solution at 5ft/day and monitor injection pressure.

11. Inject 1.0 wt% NaCl at 5 ft/day for 5 pore volumes and determine residual resistance factor.

Produced fluids were collected in test tubes on a fraction collector. Resistance factor for all core floods was calculated according to

$$RF_i = \frac{(\Delta P / q)_i}{\Delta P / q}$$

, where ΔP is differential pressure, psi, and q is injection rate, ml/hr. Baseline values are after 1.0 wt% NaCl injection at S_{orw} and before initial chemical injection.

Oil saturation is determined by mass balance of injected and produced fluids. Final oil saturation was cross-checked by extraction of fluids by hot toluene. Gel chemical compositions are listed in Table 3.

Gel solutions were mixed in a 1.0 wt% NaCl solution in an injection tank as a single solution just prior to injection.

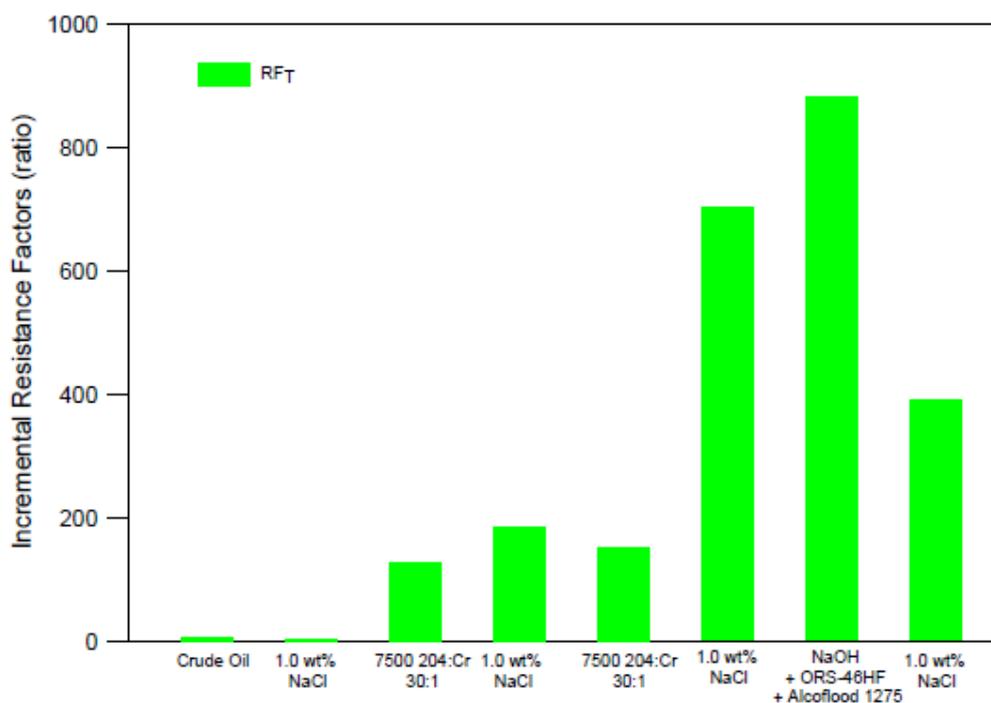


Figure 1 – Ending Resistance Factors for a Rigid Polyacrylamide-Chromium Acetate Gel followed by NaOH-ORS-46HF-Alcoflood 1275A Linear Core flood, RF_T (green) shown

Alkaline-Surfactant-Polymer Solutions

A 1.0 wt% NaOH plus 0.06 wt% ORS-46HF plus 1300 mg/L Alcoflood 1275A solution was used with Big Sinking oil in the 72°F core floods. ORS-46HF was supplied by OCT, Inc. Interfacial tension between the alkaline-surfactant-polymer solution and Big Sinking crude oil was 0.191 dyne/cm. A 1.0 wt% NaOH plus 0.10 wt% ORS-60HF plus 1300 mg/L Alcoflood 1275A solution was used with the 19.4° API gravity crude oil in the 125°F and 175°F core floods.

Interfacial tension between the alkaline-surfactant-polymer solution and 19.4° API crude oil was 0.001 dyne/cm.

Results and Discussion

Fractured Core Polyacrylamide-Chromium Acetate Gel Linear Core floods/ Fractured core linear core floods are a continuation of the prior study to determine if gel solutions placed in a fracture are stable to subsequent injection of an alkaline-surfactant-polymer solution [2]. Injected gel mixture was 7500 mg/L Flopaam 4800 plus 250 mg/L Watercut 684 as Cr^{+3} . Alkaline-surfactant-polymer solution injected was 1.0 wt% NaOH plus 0.06 wt% active ORS-46HF plus 1300 mg/L Alcoflood 1275A.

Figure 1 depicts resistance factor changes measured from the injection face to the production face of the core. Residual resistance factors after gel injection and before alkaline-surfactant-polymer solution indicated gel was placed uniformly in the fracture as well as in the core. Residual resistance factors after alkaline-surfactant-polymer injection following gel injection were maintained and of the same order of

magnitude as prior to alkaline-surfactant-polymer injection. Polyacrylamide-chromium acetate gels used to plug fractures are stable to subsequent NaOH alkaline-surfactant-polymer solution injection. Permeability changes are summarized in Table 4.

Elevated Temperature Gel Stability Testing

A series of polyacrylamide-chromium acetate, xanthan gum-chromium acetate, and resorcinol plus formaldehyde gel matrices were mixed and incubated at either 125°F or 175°F with varying pH alkaline-surfactant-polymer solutions to determine if gel systems were stable to alkaline-surfactant-polymer solutions at elevated temperature.

Gels were allowed to sit for 1 to seven days to allow gels to form. Once gels were formed, alkaline-surfactant-polymer solutions were layered over the top of the appropriate gels. Alkaline-surfactant-polymer solutions pH varied from pH 9.2 to 12.9 as reported earlier [3]. Gels were incubated at 125°F and 175°F and visually evaluated at 0, 1, 3, 7 days. Consistent with prior results, gel stability to alkaline-surfactant-polymer solutions was

- Aluminum-polyacrylamide gels were not stable to alkaline-surfactant-polymer solutions with pH values ranging from 9.2 to 12.9.
- Chromium-polyacrylamide gels were stable to alkaline-surfactant-polymer solutions with pH values ranging from 9.2 to 12.9.
- Chromium-xanthan gum gels were stable to alkaline-surfactant-polymer solutions with pH values ranging from 9.2 to 12.9.
- Resorcinol-formaldehyde gels were stable to alkaline-surfactant-polymer solutions with pH values ranging from 9.2 to 12.9.

Table 4 – Berea Sandstone Physical Parameters Chromium Acetate – Polyacrylamide Fracture Core Linear Core flood

| NaOH-ORS-46HF-Alcoflood 1275A – 22.8% Porosity | Permeability (md) K_T |
|--|-------------------------|
| Pre-Fracture Absolute Permeability to 1.0 wt% NaCl, K_{abs} | 630 |
| Pre-Fracture Effective Perm to Oil at Immobile Water, K_{orw} | 355 |
| Post-Fracture Effective Perm to Oil at Immobile Water, K_{orw} | 33,500 |
| Post-Fracture Effective Perm to Water at Residual Oil, K_{wro} | 23,000 |
| Post-Fracture, Post-Gel Sequence, K_{wro} | 33 |
| Post-ASP Solution, K_{wro} | 60 |

| Type | Concentration | Crosslinker Polymer: Crosslink ratio |
|------------------------------|----------------|---|
| | (mg/L) | |
| Polyacrylamide: Aluminum | 1:1 | Watercut 677 |
| Polyacrylamide: Aluminum | 1:2 | Watercut 300 and 500 |
| Polyacrylamide: Aluminum | 1:3 | HiVis 350 |
| Polyacrylamide: Aluminum | 1:4 | HiVis 350 |
| Polyacrylamide Chromium | 30:1 | Watercut 684 |
| Polyacrylamide Chromium | 35:1 | Watercut 204 |
| Polyacrylamide Chromium | 40:1 | Watercut 204 |
| Polyacrylamide Chromium | 45:1 | Watercut 204 |
| Polyacrylamide Chromium | 50:1 | Watercut 204 |
| Xanthan Gum:Chromium Gels | 8:1 | Watercut 684 |
| Xanthan Gum:Chromium Gels | 10:1 | Flopaam 4800 C 4,000 and 6,000 |
| Xanthan Gum:Chromium Gels | 12:1 | Flopaam 4800 C 4,000 and 6,000 |
| Xanthan Gum:Chromium Gels | 15:1 | Flopaam 4800 C 4,000 and 6,000 |
| Xanthan Gum:Chromium Gels | 18:1 | Flopaam 4800 C 4,000 and 6,000 |
| Xanthan Gum:Chromium Gels | 20:1 | Flopaam 4800 C 4,000 and 6,000 |
| Polymer | Resorcinol wt% | Formaldehyde wt% |
| Resorcinol/formaldehyde gels | 1.0 | 0.85 |
| Resorcinol/formaldehyde gels | 1.0 | 1.71 |
| Resorcinol/formaldehyde gels | 2.0 | 1.71 |
| Resorcinol/formaldehyde gels | 2.0 | 3.42 |
| Resorcinol/formaldehyde gels | 3.0 | 2.56 |
| Resorcinol/formaldehyde gels | 3.0 | 5.12 |

pH of resorcinol/formaldehyde gel solutions were adjusted to pH 9 with NaOH.

Elevated Temperature Linear Core floods

Linear core floods evaluating the polyacrylamide-chromium acetate gel and the xanthan gum- chromium acetate gel were evaluated at 125°F and 175°F to determine if the gels were stable to an alkaline-surfactant-polymer solution at elevated temperatures. Two pairs of linear core floods were performed to evaluate if the polyacrylamide-chromium acetate gel and the xanthan gum- chromium acetate gel were stable to alkaline-surfactant-polymer solutions at elevated temperatures in core. Figures 2 and 3 depict the resistance factor changes for the polyacrylamide-chromium acetate gel at 125°F and 175°F, respectively. Table 5 summarizes core permeability changes.

Polyacrylamide-chromium acetate gels were stable to subsequent injection of a 1.0 wt% NaOH plus 0.10 wt% active ORS-60HF plus 1300 mg/L

Alcoflood 1275A solution. Figures 4 and 5 depict the resistance factor changes for the xanthan gum-chromium acetate gel at 125°F and 175°F, respectively. Xanthan gum-chromium acetate gel was stable to subsequent injection of a 1.0 wt% NaOH plus 0.10 wt% active ORS-60HF plus 1300 mg/L Alcoflood 1275A solution at 125°F but not at 175°F. The latter is due primarily to the instability of the gel at the higher temperature. Table 5 summarizes core permeability changes.

Gel sequence and alkaline-surfactant-polymer injection recovered additional oil. Table 6 summarizes oil production with each step.

Significant incremental oil was produced by gel injection and subsequent alkaline-surfactant-polymer solutions.

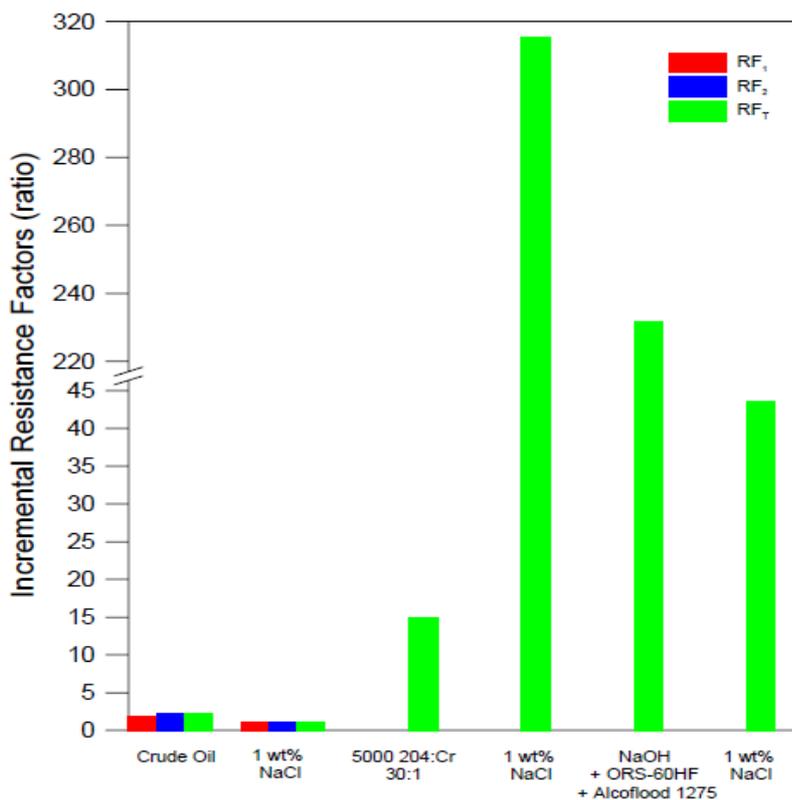


Figure 2 – Ending Resistance Factors for Polyacrylamide-Chromium Acetate Gel followed by NaOH-ORS-60HFAlcoflood 1275A Linear Coreflood at 125°F, from left to right each set of histograms is RF1(red), RF2(blue), RFT(green)

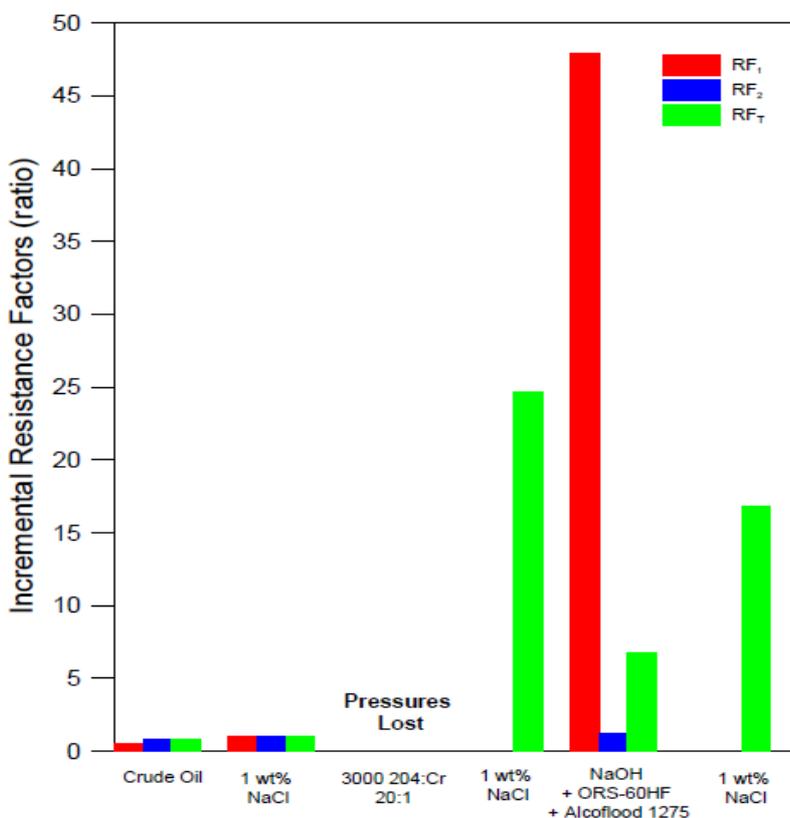


Figure 3 – Ending Resistance Factors for Polyacrylamide-Chromium Acetate Gel followed by NaOH-ORS-60HFAlcoflood 1275A Linear Coreflood at 175°F, from left to right each set of histograms is RF1(red), RF2(blue), RFT(green)

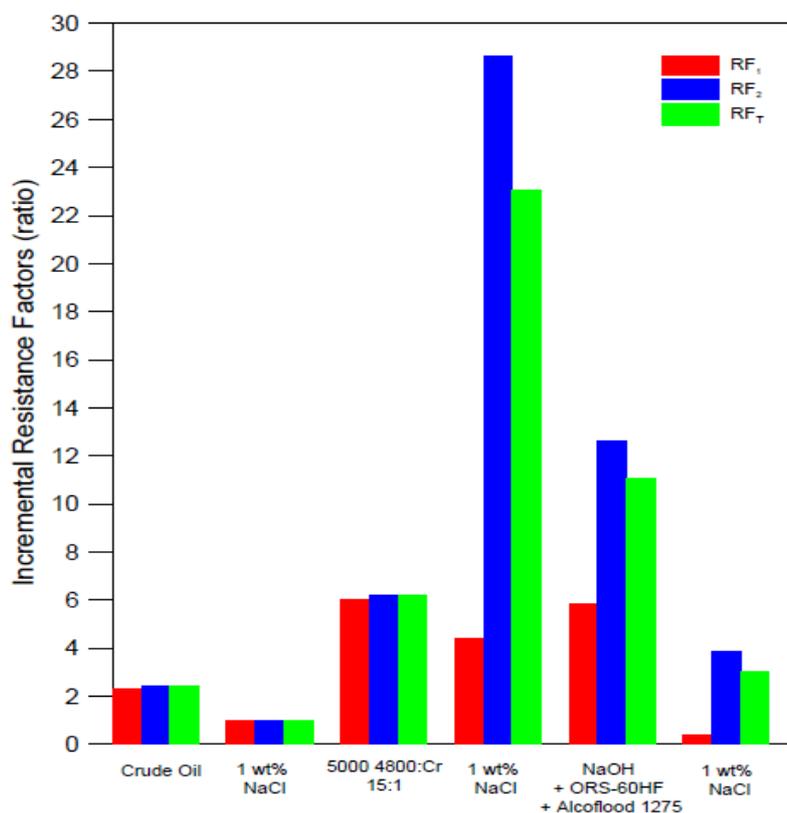


Figure 4 – Ending Resistance Factors for Xanthan Gum-Chromium Acetate Gel followed by NaOH-ORS-60HF-Alcoflood 1275A Linear Coreflood at 125°F, from left to right each set of histograms is RF1(red), RF2(blue), RFT(green)

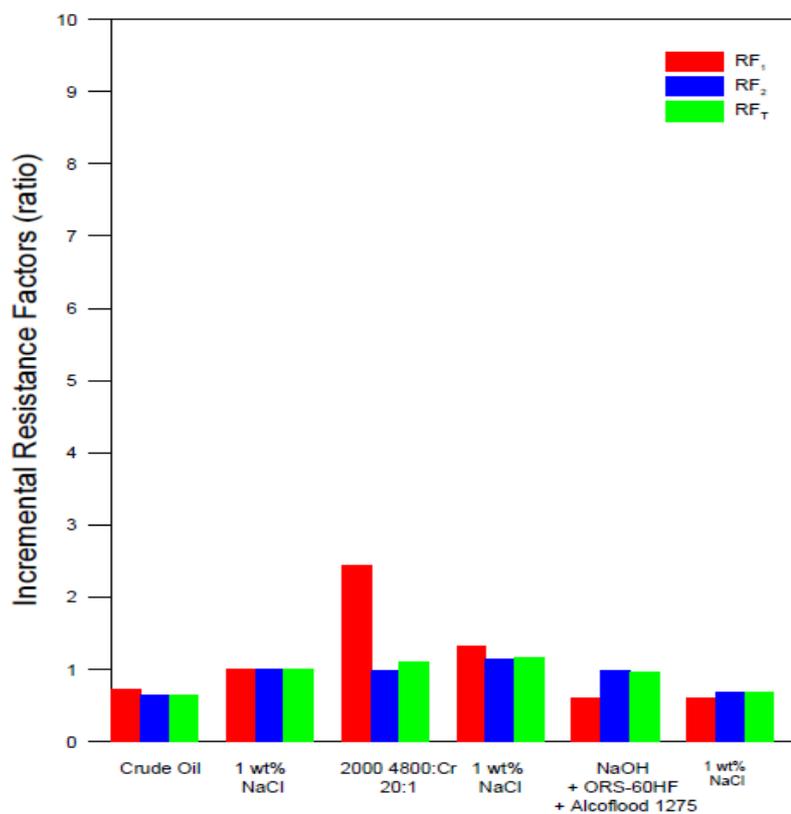


Figure 5 – Ending Resistance Factors for Xanthan Gum-Chromium Acetate Gel followed by NaOH-ORS-60HF-Alcoflood 1275A Linear Coreflood at 175°F, from left to right each set of histograms is RF1(red), RF2(blue), RFT(green)

Table 5 – Berea Sandstone Physical Parameters Polyacrylamide and Xanthan Gum-Chromium Acetate Gel Linear Core floods

| Permeability (md) | K ₁ | K ₂ | K _T |
|---|----------------|----------------|----------------|
| Polyacrylamide-Chromium Acetate Core floods NaOH-ORS-60HF-Alcoflood 1275A – 23.3% Porosity – 175°F | | | |
| Absolute Permeability to 1.0 wt% NaCl, K _{abs} | 282 | 772 | 555 |
| Effective Perm to Oil at Immobile Water, K _{orw} | 547 | 267 | 300 |
| Effective Perm to Water at Residual Oil, K _{wro} | 17 | 40 | 24 |
| Post Gel Sequence, K _{wro} | - | - | <0.1 |
| Post ASP Solution, K _{wro} | - | - | 0.3 |
| NaOH-ORS-60HF-Alcoflood 1275A – 23.1% Porosity – 125°F | | | |
| Absolute Permeability to 1.0 wt% NaCl, K _{abs} | 473 | 414 | 424 |
| Effective Perm to Oil at Immobile Water, K _{orw} | 646 | 320 | 353 |
| Effective Perm to Water at Residual Oil, K _{wro} | 13 | 6 | 7 |
| Post Gel Sequence, K _{wro} | -- | -- | 0.2 |
| Post ASP Solution, K _{wro} | -- | -- | 0.3 |
| Xanthan Gum-Chromium Acetate Core floods NaOH-ORS-60HF-Alcoflood 1275A – 22.8% Porosity – 175°F | | | |
| Absolute Permeability to 1.0 wt% NaCl, K _{abs} | 346 | 280 | 291 |
| Effective Perm to Oil at Immobile Water, K _{orw} | 528 | 262 | 288 |
| Effective Perm to Water at Residual Oil, K _{wro} | 15 | 4 | 5 |
| Post Gel Sequence, K _{wro} | 8 | 2 | 3 |
| Post ASP Solution, K _{wro} | 18 | 5 | 6 |
| NaOH-ORS-60HF-Alcoflood 1275A – 22.6% Porosity – 125°F | | | |
| Absolute Permeability to 1.0 wt% NaCl, K _{abs} | 514 | 499 | 502 |
| Effective Perm to Oil at Immobile Water, K _{orw} | 535 | 535 | 535 |
| Effective Perm to Water at Residual Oil, K _{wro} | 32 | 21 | 22 |
| Post Gel Sequence, K _{wro} | 8 | 2 | 3 |
| Post ASP Solution, K _{wro} | 32 | 6 | 8 |

Table 6 – Oil Recovery of Polyacrylamide and Xanthan Gum-Chromium Acetate Gel Core floods

| Cumulative Oil Recovery, % OOIP | | |
|--|------------------|------------------|
| Injected Solution | 125°F-Core flood | 175°F-Core flood |
| Polyacrylamide-Chromium Acetate Core floods | | |
| 1.0 wt% NaCl - Water flood | 52.8 | 63.7 |
| Gel Sequence and NaCl flush | 75.2 | 74.0 |
| ASP Solution and NaCl flush | 95.6 | 98.4 |
| Incremental Oil Recovery, % OOIP | | |
| Gel Incremental Oil Recovery | 22.4 | 10.3 |
| Gel+ASP Incremental Recovery | 20.4 | 24.4 |
| Xanthan Gum-Chromium Acetate Core floods | | |
| 1.0 wt% NaCl - Water flood | 51.7 | 61.2 |
| Gel Sequence and NaCl flush | 69.4 | 68.4 |
| ASP Solution and NaCl flush | 92.4 | 92.2 |
| Incremental Oil Recovery, % OOIP | | |
| Gel Incremental Oil Recovery | 17.7 | 7.2 |
| Gel+ASP Incremental Recovery | 23.0 | 23.8 |

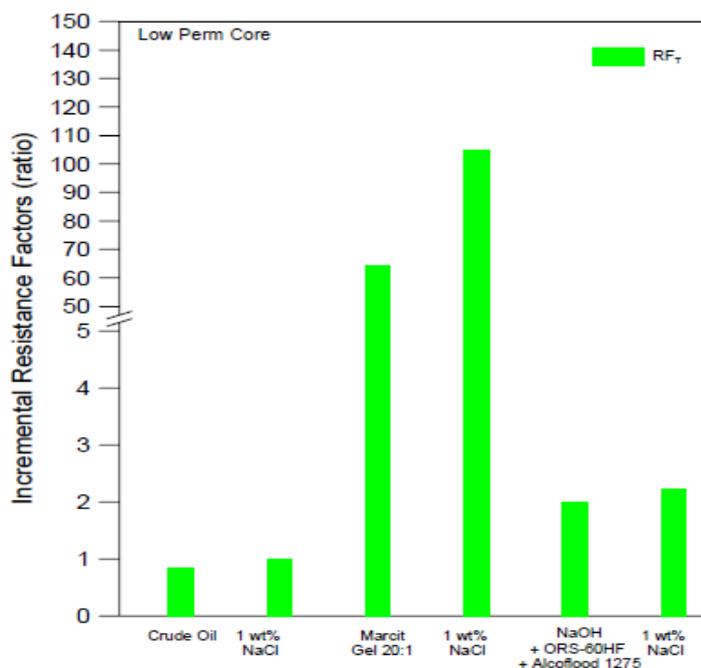


Figure 6 – Low Permeability Core, Ending Resistance Factors for the Rigid Chromium Acetate-Polyacrylamide Gel followed by NaOH-ORS-60HFAlcoflood 1275A, from left to right each set of histograms is RFT(green)

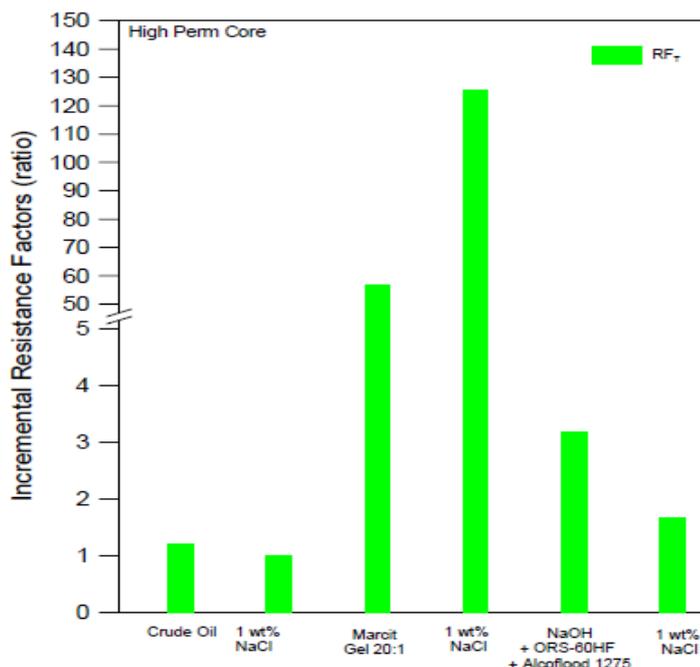


Figure 7 – High Permeability Core, Ending Resistance Factors for the Rigid Chromium Acetate-Polyacrylamide Gel followed by NaOH-ORS-60HFAlcoflood 1275A, from left to right each set of histograms is RFT(green)

Elevated Temperature Chromium Acetate-Polyacrylamide Gel Dual Stacked Core, Common Well Bore Stacked Radial Core floods

A dual stacked core pair with a common well bore core flood evaluated the stability of a chromium acetate-polyacrylamide gel to subsequent alkaline-surfactant-polymer injection at 175°F. In this case, cross flow was possible. Injected gel mixture was 3000 mg/L Watercut 204 plus 150 mg/L Watercut 684 as Cr^{+3} . Polymer and

chromium ion concentrations were lower than previous reported 72°F core flood² to permit gel to be injected prior to developing rigidity. Injected alkaline-surfactant-polymer solution was 1.0 wt% NaOH plus 0.06 wt% active ORS-60HF plus 1300 mg/L Alcoflood 1275A. Crude oil was the 19.4° API gravity crude oil.

Figures 6 and 7 depict resistance factor changes for the both core. Chromium acetate-polyacrylamide gel reduced the permeability of

Table 7 – Berea Sandstone Physical Parameters – Chromium Acetate-Polyacrylamide

| Dual Stacked, Same Well Bore 175°F Radial Core flood Permeability (md) | K1 | K2 | KT |
|---|-----|-----|------|
| NaOH-ORS-60HF-Alcoflood 1275A | | | |
| High Permeability Core – 23.0% Porosity | | | |
| Absolute Permeability to 1.0 wt% NaCl, K_{abs} | 535 | 458 | 508 |
| Effective Perm to Oil at Immobile Water, K_{orw} | 105 | 90 | 90 |
| Effective Perm to Oil at Immobile Water, K_{orw} (after stacking core) | - | - | 108 |
| Effective Perm to Water at Residual Oil, K_{wro} | - | - | 3.7 |
| Post Gel Sequence, K_{wro} | - | - | 0.03 |
| Post ASP Solution, K_{wro} | - | - | 2.2 |
| Low Permeability Core – 18.5% Porosity | | | |
| Absolute Permeability to 1.0 wt% NaCl, K_{abs} | 45 | 82 | 52 |
| Effective Perm to Oil at Immobile Water, K_{orw} | 28 | 18 | 23 |
| Effective Perm to Oil at Immobile Water, K_{orw} (after stacking core) | - | - | 26 |
| Effective Perm to Water at Residual Oil, K_{wro} | - | - | 0.6 |
| Post Gel Sequence, K_{wro} | - | - | 0.01 |
| Post ASP Solution, K_{wro} | - | - | 0.3 |

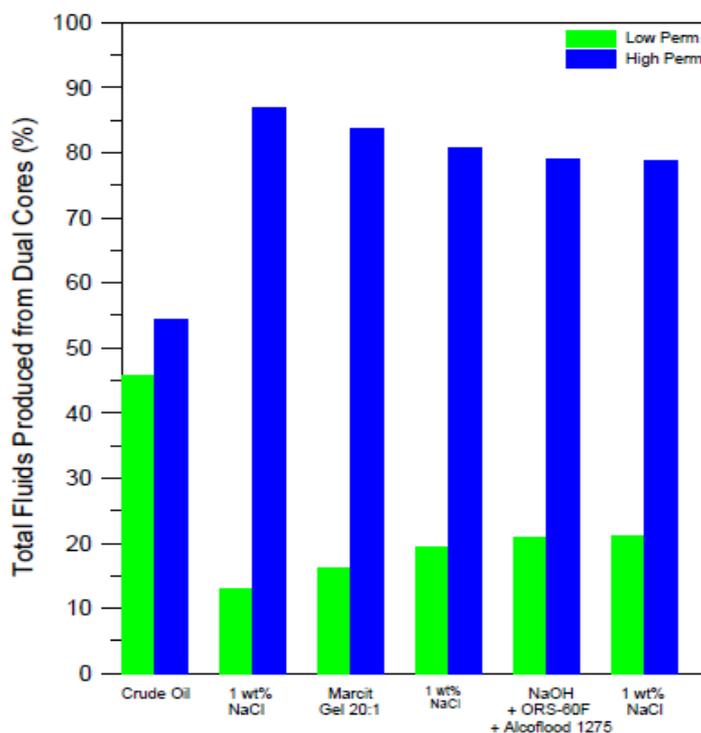


Figure 8 – Flow Distribution between High and Low Permeability Cores, Dual Stacked Radial Coreflood, Chromium Acetate-Polyacrylamide Gel, green is low permeability and blue is high permeability

each core with the high permeability core permeability reduction being slightly greater during and after gel injection. Permeability changes were maintained after alkaline-surfactant-polymer injection but not to the same degree as previously reported possibly due to injection of a more fluid gel and gel syneresis. Permeability

changes for dual, stacked core chromium acetate-polyacrylamide core flood are summarized in Table 7.

Change in flow distribution due to chromium acetate-polyacrylamide gel injection into the stacked radial core configuration is shown in Figure 8. Flow distribution was 87% flow through

Table 8 – Oil Recovery of Chromium Acetate -- Polyacrylamide Gel Dual Stacked, Same Well Bore 175°F Radial Core flood

| Cumulative Oil Recovery, % OOIP | Injected Solution High K - Core | Low K - Core |
|----------------------------------|---------------------------------|--------------|
| 1.0 wt% NaCl - Water flood | 47.5 | 30.4 |
| Gel Sequence and NaCl flush | 59.1 | 38.0 |
| ASP Solution and NaCl flush | 93.0 | 52.1 |
| Incremental Oil Recovery, % OOIP | - | - |
| Gel Incremental Oil Recovery | 11.6 | 6.6 |
| Gel+ASP Incremental Recovery | 33.9 | 14.1 |

the high permeability core during initial water flood. Flow distribution was reduced to 80% through the high permeability core during the water flush subsequent to gel placement, indicating gel was diverting injected water from the high permeability core into the low permeability core. Injected alkaline-surfactant-polymer solution did not alter the flow distribution.

Oil recoveries from the chromium acetate-polyacrylamide gel stacked radial flood are summarized in Table 8. Incremental oil was produced during gel injection from each core.

Alkaline-surfactant-polymer injection produced a significant volume of incremental oil from both core.

Numerical Simulation of a Crosslink-Alkaline-Surfactant-Polymer Flood

A Minnelusa reservoir with an «A» sand and a «B» sand with common production and injection wells was simulated to demonstrate improvement of oil recovery after gel treatment followed by an alkaline-surfactant-polymer flood. A and B sands are separated by a shale layer. GCOMP numerical simulation software was used [4]. GCOMP is a black oil numerical simulation package with a chemical flood option.

The flood consists of one injection well (34X-10) and two production wells (43-10A and 15-11). Wells 44-10, 14-11, 43-10, and 34-10 were either dry holes or were lost prior to contemplating alkaline-surfactant-polymer injection. Figure 9 depicts the well orientation.

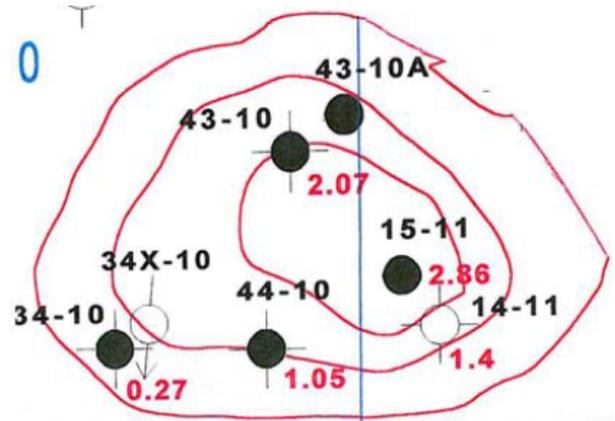


Figure 9 – Minnelusa Field Well Orientation

Reservoir and Model Definition

A 20 by 14 grid model consisting of seven layers with the top two layers A sand and bottom five layers presenting the B sand was defined. Table 9 lists individual layer parameters.

Initial oil saturation was 0.805 V_p and water flood residual oil saturation was 0.335 V_p .

Figure 10 depicts the water displacing oil relative permeability curve. Initial reservoir pressure was 2685 psi. Reservoir temperature was 133°F. The Minnelusa Field produces a dead crude oil with an API gravity of 21.5° with a viscosity of 29 cp at initial reservoir pressure and temperature. Formation volume factor was 1.02. Bubble point was 175 psi. Fluid and rock compressibilities used in the model are water

Table 9 – Numerical Simulation Layer Parameters

| | Layer | Pay (ft) | Porosity (%) | KXY (md) | KZ (md) | Pore Volume (bbls) |
|--------|-------|----------|--------------|----------|---------|--------------------|
| A Sand | 1 | 4.3 | 20.2 | 224 | 184 | 1,286,600 |
| | 2 | 10.5 | 19.9 | 381 | 312 | 3,136,523 |
| B Sand | 3 | 14.8 | 20.0 | 302 | 248 | 4,423,123 |
| | 4 | 1.3 | 21.0 | 506 | 415 | 18,469 |
| | 5 | 0.5 | 18.5 | 79 | 65 | 4,995 |
| | 6 | 9.4 | 17.7 | 807 | 662 | 2,259,435 |
| | 7 | 6.5 | 12.1 | 565 | 463 | 909,069 |
| | 8 | 17.7 | 17.3 | 626 | 512 | 3,191,968 |

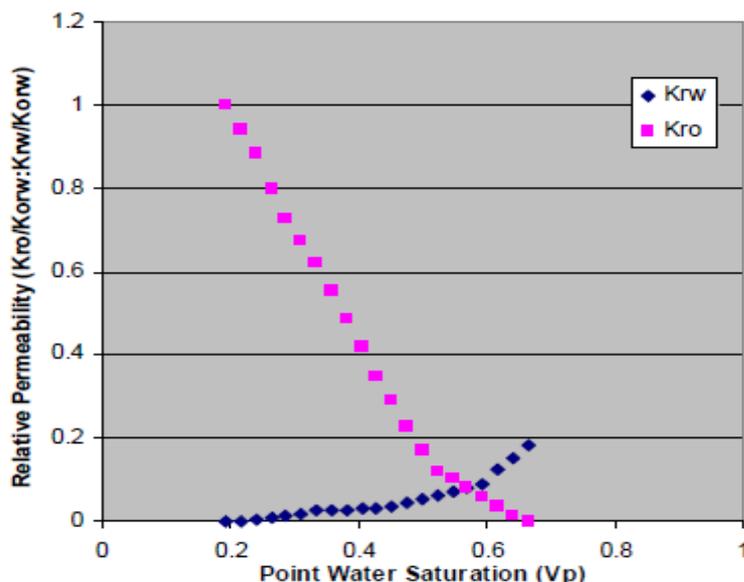


Figure 10 – Minnelusa Oil-Water Relative Permeability Curve

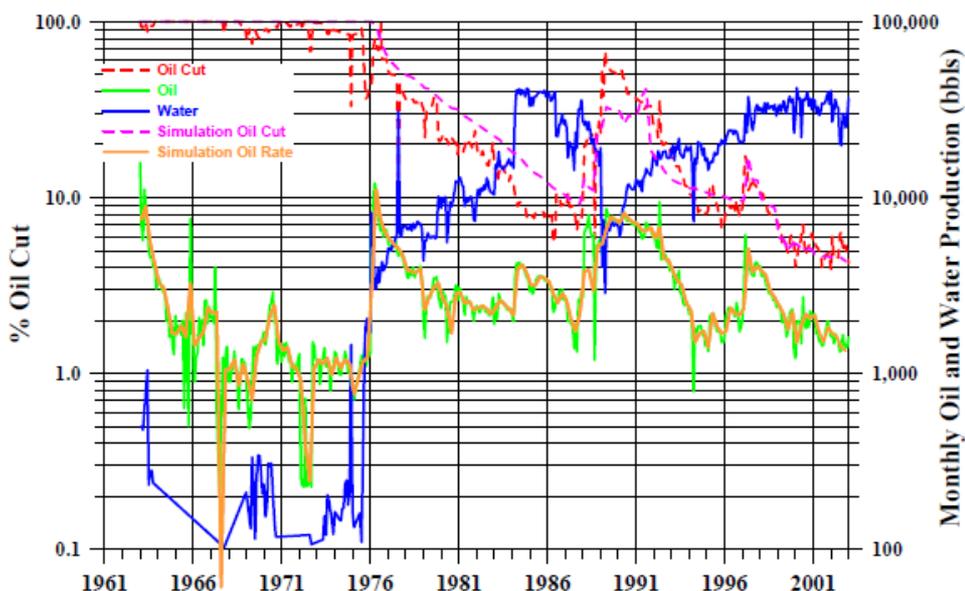


Figure 11 – History Match – Primary/Waterflood Production

2.95E-06 psi⁻¹, crude oil 5.79E-06 psi⁻¹, and rock 2.7E-05 psi⁻¹. Transmissivity between the layers was equal to 82% of the horizontal transmissivity.

History Match - Model Validation A production water flood history match was performed by fixing the oil rate from each well and allowing water rate and oil cut to vary. History match was from 1961 to 2003. Figure 11 shows oil rate, water rate, and oil cut match for the wells. Injection matched historical values exactly.

Core flood History Match - Chemical Model Validation

An alkaline-surfactant-polymer radial core flood was history matched to calibrate model

chemical option. Core flood used reservoir crude oil, produced water, and reservoir core. Chemical system used was 1.00 wt% NaOH plus 0.1 wt% ORS-46HF plus 1300 mg/L Alcoflood 1275A. Linear core flood data was used to develop adsorption isotherms and polymer rheology data. Interfacial tension values used in the model are from laboratory measurements.

Radial core flood model consisted of a 5 by 1 radial grid system with 2 layers. Initial oil saturation was 0.805 Vp. Initial reservoir pressure was 2685 psi. PVT characteristics were such that the viscosity of the crude oil was 28 cp at 133°F at 2685 psi. No water-oil or gas-oil contacts were present. PVT characteristics and relative permeability curves from the field history match were used in the core floods match. Core flood history match was achieved by changing

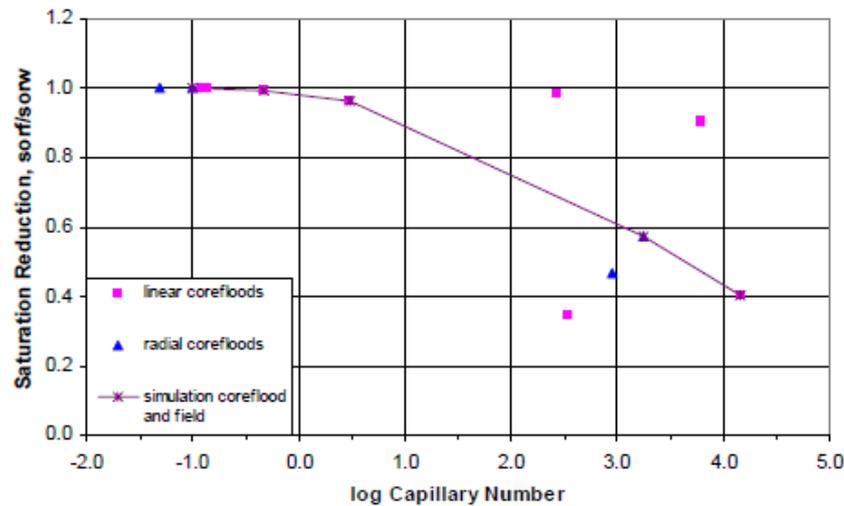


Figure 12 – Oil Saturation Reduction versus log Capillary Number

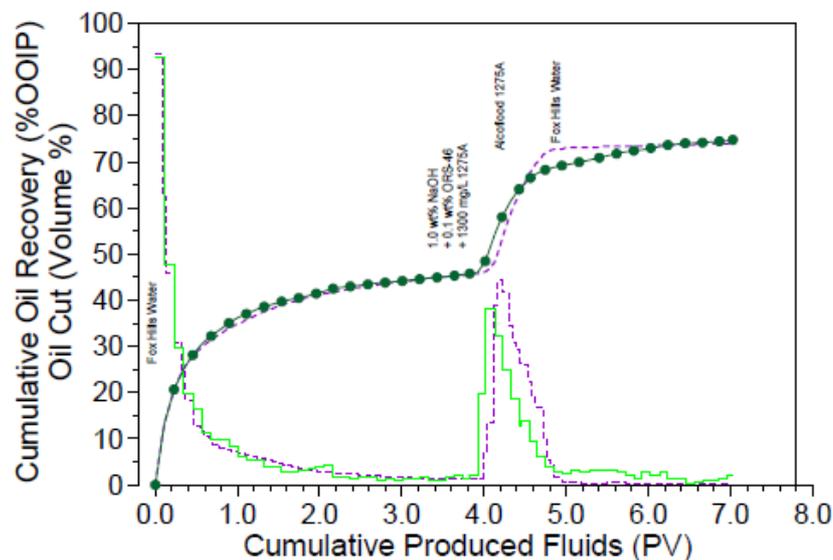


Figure 13 – Oil Cut and Cumulative Oil Recovery Radial Coreflood History Match

permeability and capillary number desideration curve. Final permeability distribution was 14 md for both layers. This compares to 13.6 and 16.3 md for the effective permeability to oil and effective permeability to water, respectively. Figure 12 shows the capillary de-saturation curve required to match the core flood. Note, the capillary number - desideration correlation matched core flood values during water flood. As capillary number increased due to chemical injection, linear core flood data facilitated a match better than radial core flood data.

Figures 13 and 14 show oil recovery and oil cut history match, and produced chemical match for the alkaline-surfactant-polymer radial core flood. Both the water flood and chemical flood oil recoveries are duplicated by the numerical simulation indicating the relative permeability and capillary number calculation accurately depict the water flood and the alkaline-surfactant-polymer flood for the Minnelusa oil, water, and rock system. Produced chemicals were similarly matched.

Alkaline-Polymer and Alkaline-Surfactant-Polymer Forecasts

Five forecasts were made:

1. Water flood through 2020;
2. Crosslink B Sand in 2003 followed by water through 2020;
3. No Crosslink, ASP Flood: B Sand - 0.262 V_p ASP followed by 0.278 V_p polymer drive followed by water to 2020 (0.972 V_p); A Sand - 0.024 V_p ASP followed by 0.076 V_p polymer drive followed by water to 2020 (0.049 V_p);
4. Crosslink B Sand and inject chemical over the same time as case 3: B Sand - 0.091 V_p ASP followed by 0.110 V_p polymer drive followed by water to 2020 (0.885 V_p); A Sand - 0.036 V_p ASP followed by 0.098 V_p polymer drive followed by water to 2020 (0.087 V_p);
5. Crosslink B Sand and inject chemical until approximately 0.25 V_p of ASP solution has been injected into the B Sand: B Sand - 0.239 V_p ASP followed by 0.152 V_p polymer drive followed by

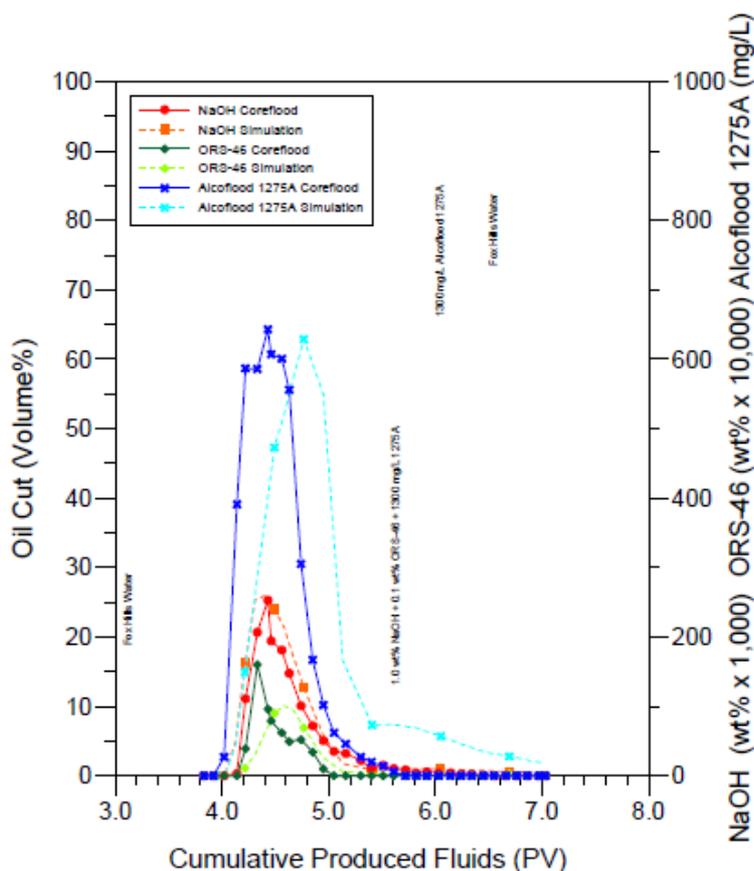


Figure 14 – Produced Chemical Radial Coreflood History Match

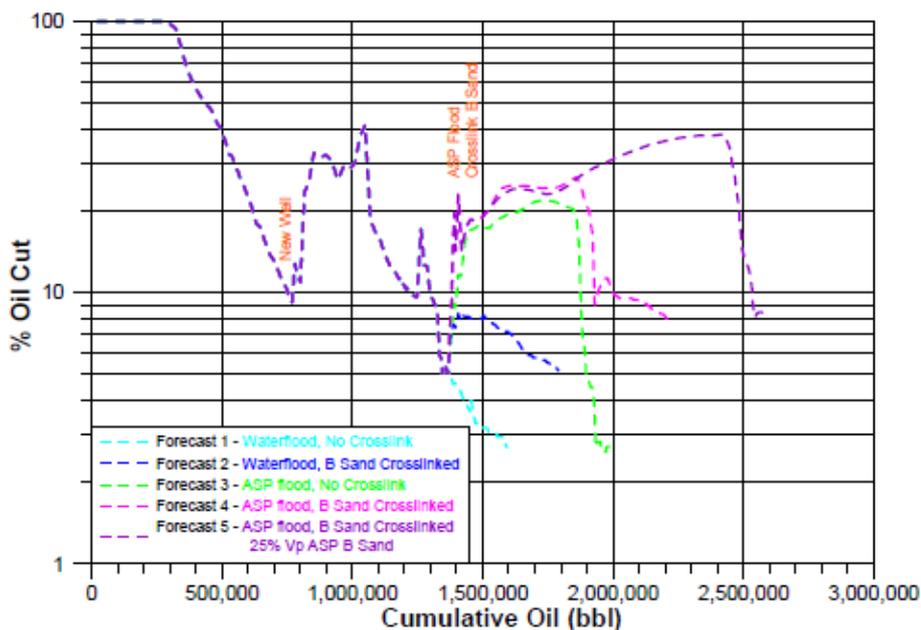


Figure 15 – Oil Cut versus Cumulative Oil Produced for the Five Forecast Cases

water to 2020 (0.315 V_p); A Sand - 0.124 V_p ASP followed by 0.126 V_p polymer drive followed by water to 2020 (0.027 V_p).

Figure 15 depicts the oil cut as a function of cumulative oil production and Figure 16 depicts cumulative oil as function of cumulative total fluids produced. Crosslinking of the B Sand was simulated by decreasing the X, Y, and Z transmissivity of the B Sand to 20% of the

original value, corresponding to a resistance factor of 5. Note in Figure the volume of fluids produced and, therefore, injected decreases when either the B Sand is crosslinked or viscous ASP solution is injected. Total fluid produced volume and, therefore, injection volume decreased by up to 2,800,000 bbls. Table 10 summarizes incremental oil produced.

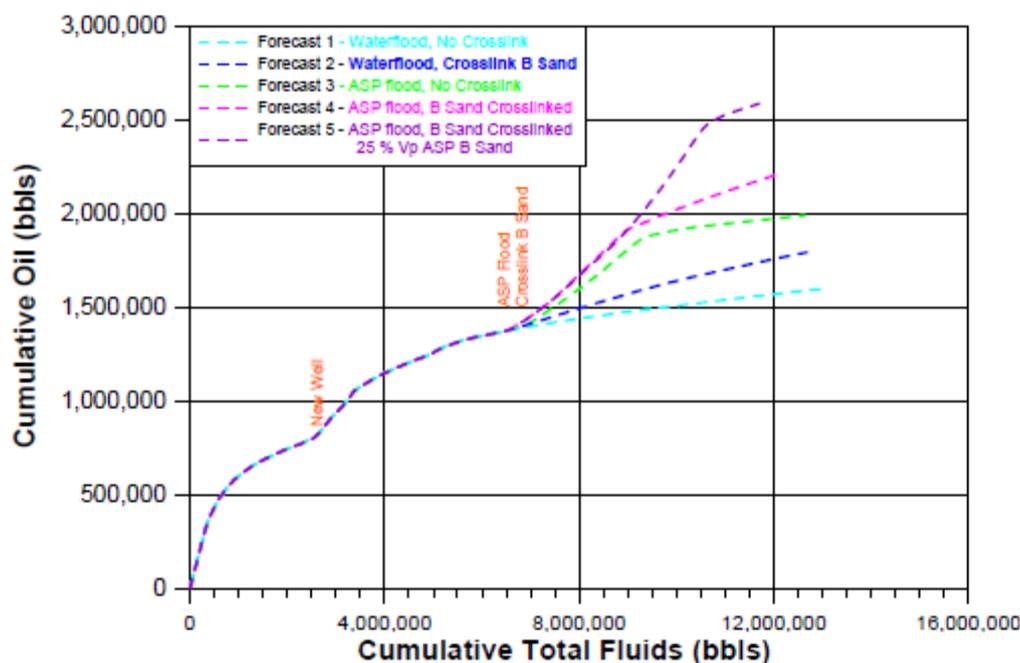


Figure 16 – Cumulative Oil Produced versus Cumulative Total Fluids for the Five Forecast Cases

Table 10 – Water flood and Alkaline-Surfactant-Polymer Flood Forecast Incremental Oil Production

| Incremental Oil Production (bbls) | | |
|-----------------------------------|------------------|-----------------------------|
| | Over Water flood | Over no Crosslink ASP Flood |
| B Sand Crosslink Water flood | 196,144 | ----- |
| No Crosslink ASP Flood | 392,656 | ----- |
| B Sand Crosslink ASP Flood | 619,988 | 227,332 |
| B Sand Crosslink 25% Vp ASP Flood | 989,090 | 596,436 |

Conclusions

Chromium-polyacrylamide gels are stable to injection of an alkaline-surfactant-polymer solution from 72°F to 175°F.

Injection of a gel sequence prior to an alkaline-surfactant-polymer solution will divert injected fluid into lower permeability core, resulting in higher oil recoveries.

Gels used to seal fractures are stable to subsequent alkaline-surfactant-polymer solution injection, if gels are stable to alkaline-surfactant-polymer solutions in other applications.

Numerical simulation indicates placement of a gel into a higher permeability section of a reservoir will improve water flood recovery and alkaline-surfactant-polymer flood oil recovery compared to the same injection fluid without a prior gel treatment.

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2 Pitts, M., Qi, J., Wilson, D., Stewart, D. and Jones, B.: Semi-annual Technical Progress Report, Coupling the Alkaline-Surfactant-Polymer Technology and the Gelation Technology to Maximize Oil Production, September 30, 2004 to April 1, 2005, submitted to the Department of Energy, Award Number De-FC26-03NT15411.

3 Pitts, M., Qi, J., and Wilson, D.: Semi-annual Technical Progress Report, Coupling the Alkaline-Surfactant-Polymer Technology and the Gelation Technology to Maximize Oil Production, October 1, 2003 to April 1, 2004, submitted to the Department of Energy, Award Number De-FC26-03NT15411.

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