# DEVELOPMENT OF WATERFLOOD PROFILE MODIFICATION USING BRIGHTWATER TECHNOLOGY

by
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## I. INTRODUCTION

Water flooding, in many mature fields is facing a common problem of low sweep efficiency in the late production period. The breakthrough of injection water is very early when high permeability streaks or thief zones exist in the formation, and resulted in excessive water production. Two kind of technologies commonly are used to modify the permeability streak i.e. MPM (Microbial Profile Modification), and polymer gel with cross linkers material.[1,2]

A new technology which is called BrightWater has been intensively studied. BrightWater is capable of in-depth placement into high permeability streaks in the reservoir.

To improve the water flood sweep efficiency, studies of examination a fluid injection design have been evaluated. The objective of this study is to setup core flooding tests and to determine the effectiveness of the BrightWater to reduce the permeability, and also include optimization of BrightWater formulation, resistance factor determination, and gelling time evaluation.

## II. BRIGHTWATER TECHNOLOGY

BrightWater is a chemical system, which was firstly formulated by a joint research project of an Industry Consortium such as BP, Chevron Texaco and Ondeo Nalco Energy Services. BrightWater mainly consists of polymeric "kernel" particles these are capable of "popping" under the influence of elevated temperature and time. The expandable particles can then provide resistance to fluid flow in porous media.[3]

The kernel micro particles are prepared using an inverse emulsion polymerization process to ensure a pre-selected particle size range. The original particle diameter of the polymeric micro particle can be made ranging from about 0.1 to about 3 microns. The kernels particles were supplied as a 30% active dispersion in light mineral oil. This was dispersed into the formation brine with high shear rate intended to simulate the field makeup of the products. The required level of dispersing surfactant was added to avoid the particles from aggregation.

Figure 1 and 2 present the comparison of the initial condition of BrightWater and after expansion of kernel micro particles at elevated temperature. It looks that swelling is approximately 10 xs bigger than the initial size.[4]

## III. VISCOSITY TESTS

Two set of bottles had been prepared in this experiment. The first set bottles tests was in the neutral condition of pH = 7, while the second one was the basic solution at pH = 9. Both have a variety of concentrations ranging from 1000 to 4500 ppm. Beside that, one bottle of 1500 ppm at acid condition of pH 6 was also tested. All of the bottles were store in the oven at temperatures of 205oF. Next, their viscosities were measured at various intervals time to determine the BrightWater popping performances.

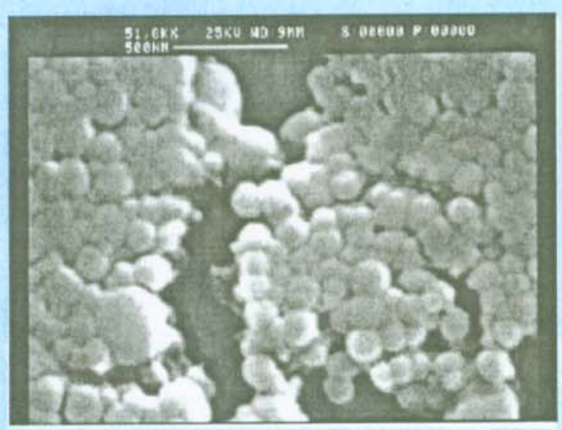

**Figure 1**
**X10 Magnification, before expansion**
**(Scale is 0.5 uM) (After Pritchett J. et all., 2004)**

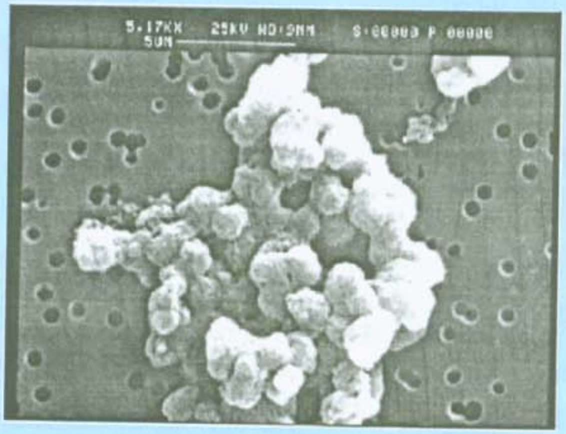

**Figure 2**
**X1 Magnification, after expansion (scale is 0.5 uM) (after Pritchett J. et all. 2004)**

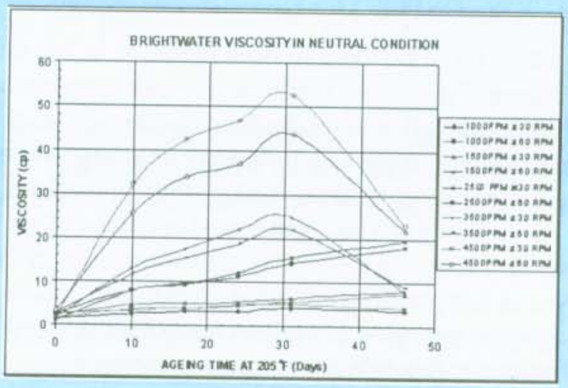


**Figure 3**
**BrightWater viscosity in neutral condition**

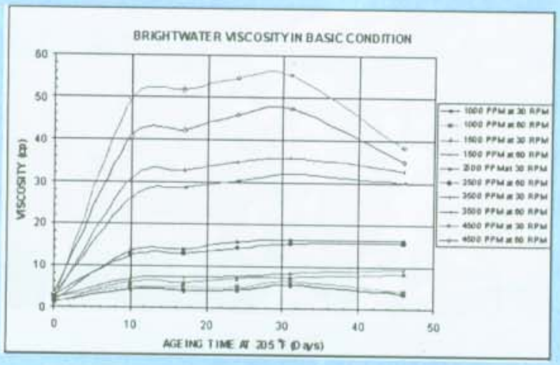


**Figure 4**
**BrightWater viscosity in basic condition**

The result of the viscosity test is shown graphically in Figure 3 for neutral condition and Figure 4 for basic condition. The viscosity lines of the neutral condition have similar trends. They initially increase gradually with time and after reaching the optimum value they fall down slowly. The only difference is the number of days the lines approaching the optimum number. For example, the lines of 1000, 3500, and 4500 ppm approach the optimum viscosities of 5, 22, and 43.70 cp respectively at day 31. The line of 1500 and 2500 ppm reach the optimum number of 8.3 and 18.1 cp after 46 days of ageing. Based on the results of these tests, 1500 ppm of BrightWater has been considered to be used on flow resistance tests.

## IV. BASE LINE TESTS

These tests were done to determine the effects of produced water quality on permeability of the core, prior conducting injectivity tests and flow resistance tests. Core plug no. 12 (470 mD) represents medium permeability zone, while plug no. 2 (868 mD) represents of high permeability zone had been used in this experiment.

The experiment was done as follows: Firstly cores were Injected with filtered formation water at constant rate 2 cc/minute for several pore volumes, then increase the rate to 5 cc/minute, and finally, increase it to 10 cc/minute until the total injected fluid approximately 100 pore volumes; Lastly, inject unfiltered formation water for both cores for about 100 pore volume and measure the changes in permeability; Then, calculate PRF (Permeability Reduction Factor), which can indicate the degree of the permeability reduction. 100% indicates totally blocking and 0% indicates no damage at all. The formula for PRF is written as follow:

$$PRF = \frac{K_w - K_{obv}}{K_w} \; x \; 100\%$$

Where:

Kw : Permeability to synthetic water
Kobv : Observed permeability

The results of base line tests are shown in Figure 5. The increasing injection rate on Core no.2 from 2 to 5cc/minute did not change the permeability so much. However, the increased injection rate of 10cc/minute resulted in the gradual permeability reduction. The initial permeability to water is 264 mD and decrease down to around 184 mD, or approximately 28.4% of PRF. Furthermore, the permeability decreased steadily after unfiltered formation water was injected continuously into the core. The reduction is approaching 105 mD after totally of 80 pore volume injected. This is similar to PRF of 59.1%. The second test result of Core no.12 is almost similar to the first one.

## V. INJECTIVITY TESTS

The purpose of these tests is to evaluate the effects of polymer injection on permeability. Core plug nos. 1 (832 mD) and 9 (380 mD) were used for these experiments. The BrightWater solution was made up for 2000 ppm, a little bit higher concentration compared to the concentration used for flow resistance tests of 1500 ppm to make sure the flow resistance tests will run as expected.

The procedures of the tests are describes in the following paragraphs: Firstly synthetic brine injection was run at 10 cc/minute for nearly 50 pore volume; Then, BrightWater injection (2000 ppm polymer) of similar rate for around 100 pore volumes; Next, Inject 50 pore volumes of synthetic brine and investigate changes of the permeability.

The result of injectivity test on core plug no.1 is presented in Figure 6. This figure indicates that the initial permeability is 503 mD, but the injection of BrightWater had reduced the permeability drastically down to 176 mD or PRF of 65%, and it gradually decreased down to the level of 85 mD (83% PRF), after totally of 100 pore volumes BrightWater have been injected. The following synthetic brine injection did not improve the permeability significantly. Therefore, to recover the permeability a reverse flow was conducted, where the result shows a small increase on the permeability from 94 mD to 154 mD, or the PRF is at the level of 69.4%.

Figure 7 shows the results of injectivity test on core plug no.9. This figure has almost similar characteristics to core plug no.1. The only different is that the permeability reduction occurs from the beginning of the injection due to high injection rate of 10cc/minute. The permeability steadily dropped from initially 191 mD down to a level of 40 mD (79% PRF) after 50 pore volume of synthetic brine and 100 pore volumes of BrightWater have been injected. After that, although 50 pore volumes of synthetic brine had been injected could only slightly improve the perme-

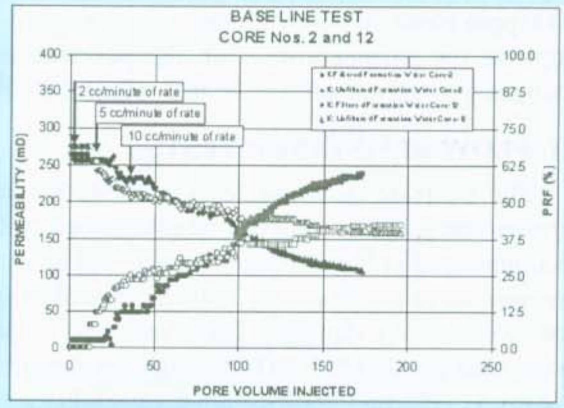


**Figure 5**
**Base line tests**

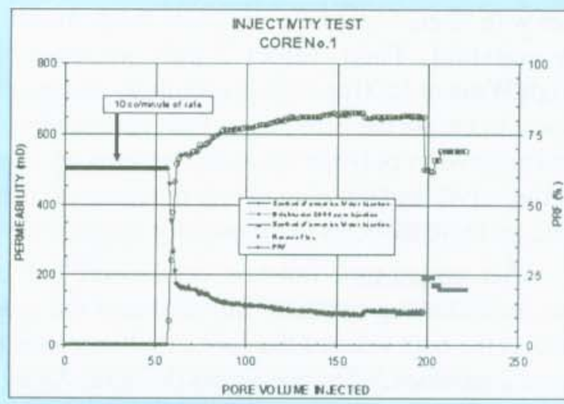


**Figure 6**
**Injectivity test on core No.1**

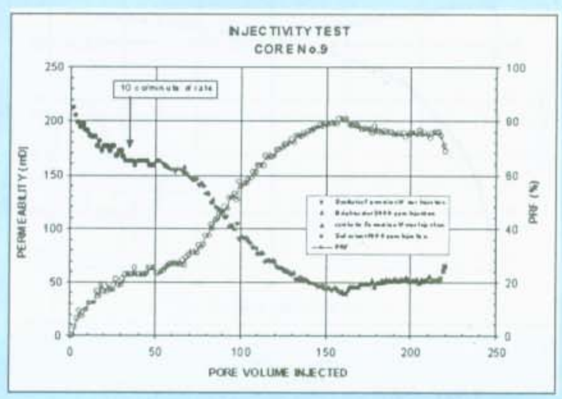


**Figure 7**
**Injectivity test on core No.9**

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ability to the level of 51 mD (73.3% PRF), it only improved about 5.7%. Then, a surfactant injection of 1000 ppm about 30 pore volumes was performed to improve the permeability. But, the permeability changes was only small; i.e. 76 mD (60.21% PRF).

## VI. FLOW RESISTANCE TESTS

The purpose of these tests is to determine whether the polymer plug can be established at the recommended polymer concentration, and at what pressure level the plug may still stay stable in the core without any damage. These tests were done using core no. 3 (1527 mD) the high permeability, and no. 11 (701 mD) for medium permeability tests. The blocking tests were run using 1500 ppm of BrightWater.

The detailed works are explained as follows : Prepare BrightWater of 1500 ppm and 1000 ppm polymer solutions; Next, Measure the permeability of the core with filtered synthetic brine until the permeability constant; Then, Inject 2 pore volumes of BrightWater of 1500 ppm. This volume should be sufficient to ensure the core plug is fully saturated with the BrightWater polymer solution; furthermore, close all the valves and put plug tightly to ensure no fluid leakage, leave the cores in the oven for about 60 days.

After ageing time finished, do the core one by one the following scenario: Slowly bleed the pressure on the both sides of the core simultaneously, to avoid a pressure difference across the core; Apply a differential pressure of 1 psig and hold for 20 minutes; If fluid flow is not detected, increase the pressure by 2, 4, 6, 9, 12, 15, 20, 25 psig respectively and hold each time for 20 minutes. After this, decrease the pressure 4 psig, and then 2 psig for several minutes; if the fluid flow is detected at any pressure level as listed above, it would indicate the polymer plug has yielded and the maximum pressure can not hold the flow anymore. At the first stage, the measurable fluid flow is observed (it may even be the first stage), continue to flow at this pressure. Develop a plot of permeability versus cumulative pore volume injected. Compare this permeability with the filtered formation water; If the flow rate becomes too small to be measured readily, then move to the next higher pressure step to make the permeability measurements.

Two kind of equations will be introduced here that can be used to measure the reduction of the permeability during the flow resistance tests. Firstly, it is called PRF (permeability reduction factor) and secondly RsF (resistance factor). The first has been written down previously, while the second equation is given as follows:

$$R_s F = \frac{1}{1 - PRF/100}$$

### A. *Flow Resistance Test of Core No. 3*

The initial BrightWater injection on Core no. 3 has resulted in the decrease of permeability down to

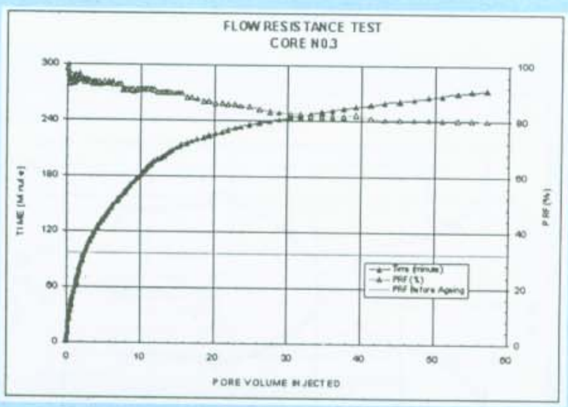


**Figure 8**
**Time-PRF vs pore volume injected flow resistance test on core No.3**

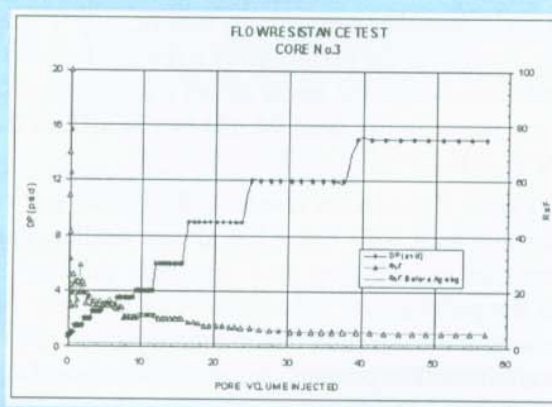


**Figure 9**
**DP-RsF vs pore volume injected flow resistance test on core No.3**

312 md, from initially of 460 mD (32% PRF). After Ageing, then flow resistance tests are demonstrate in Figures-8, and 9 respectively. Figure 8 shows the relationship between time, and PRF versus pore volume of injected fluid. Lastly, Figure 9 displays the differential pressure across the core and RsF.

Core number 3 is actually a high permeability core sample. Figure 8 shows that the value of PRF is almost flat above 80%, compare to PRF before ageing at the level 32%, and is still meaningful. Figure-9 also explains that RsF during testing is always above the value before ageing, especially at the beginning of the flow resistance test having infinite RsF for some times. The RsF value ranges from 70.64 to infinite. Then, it drops gradually with increasing injection pressure to a level of 5 at a high rate of 17.25cc/minute. The core was almost totally blocked only at the beginning of 25 minute with 0.1 cc/minute injection rate or 1.0 psig injection pressure. Afterward the rate increases with increasing injection pressure.

### B. *Flow Resistance Test of Core No.11*

The first BrightWater injection on Core no. 11 had reduced the permeability down to 109 mD. Test after ageing on Core number 11 shows a better RsF result, due to lower permeability core sample. The results are presented in Figures 10, and 11 respectively. Figure 10 shows the relationship for time, and PRF versus pore volume of injected fluid. Lastly, Figure 11 exhibits the differential pressure across the core during testing and RsF.

The result indicates that the permeability at initial injection pressure of 1 psig is very low and almost totally blocking for approximately 12 minutes. At this condition the permeability closes to zero and the RsF approaches infinite. After that the flow of fluid becomes obvious even though the injection pressure is still 1 psig. Next, the permeability gradually increases with the increasing injection pressure. Reverse flow at the end of the test has resulted in higher permeability. This indicates that the BrightWater particles might be flown out of core.

The time and PRF lines in Figure 10 proves that the flow resistance is very clear at the beginning of the test for nearly 80 minutes until the injection pressure levels approach to 4 psig. At this circumstance the production of fluid becomes apparent at the range of 1.0 cc/minute. PRF is ranging from 100 to 95% at

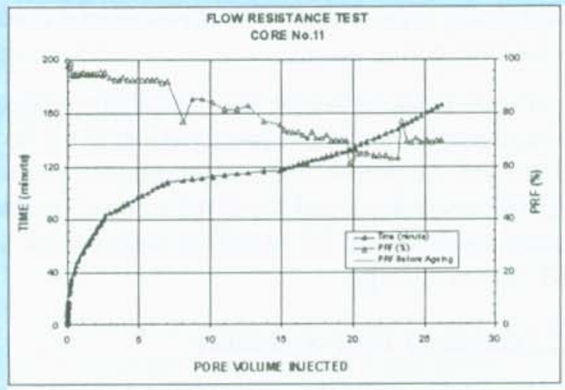


**Figure 10**
**Time-PRF vs pore volume injected flow resistance test on core No.11**

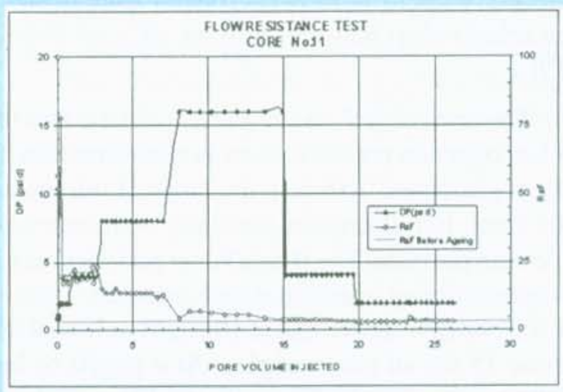


**Figure 11**
**DP-RsF vs pore volume injected flow resistance test on core No.11**

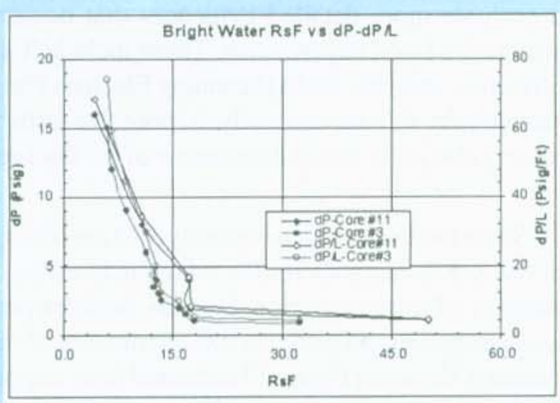


**Figure 12**
**RsF vs dP and dP/L**

the injection pressure up to 4 psig, above this value it drops slowly to the level of 70%. This number is similar to the PRF before ageing.

Figure 11 shows that the RsF line initially achieves infinite number and subsequently stable at the level of 20 until 2.6 pore volume of fluid injected, afterward it moves down steadily to the value of residual resistance factor of 3.3, which is the same as the RsF before ageing.

### C. *Analysis of Flow Resistance*

In addition to the above flow resistance tests, new figures are presented containing the combination of the test results of core number 3, 11. These figures may be easier to understand how big is the magnitude of the RsF needed for reducing permeability in the reservoir and giving the impact on directing the injection water to the unswept zones. Figure 12 shows the relationship between RsF vs. dP and RsF vs. dP/L.

The lines of RsF vs. dP present the evident that at low injection pressure, there is almost no flow for all core samples. RsF is in the range of infinite and 20. Then, RsF decreases gradually with increasing injection pressure. The BrightWater particles may be swept out during injection at high pressure. The lines of RsF vs. dP/L prove that at 10psig/ft or less, RsF is above 15 for all core samples. At 4 psig/ft or less, RsF is greater than 30. Normally, the differential pressure across the reservoir is below 4psig/ft during injection period, except near the injection well.

## VII. ADDITIONAL ANALYSES

Several additional analyses also have been done to evaluate more detailed evidences that occurred during core flood experiments. These include X-ray diffraction analysis, SEM (Scanning Electron Photomicrograph), thin section analysis, pore size distribution and also particle size distribution of the fluid content

Some kaolinites (approximately 3%) are obtained on the X-Ray analysis results which may cause the tendency of fines migration. Overlay between pores size distribution and particles size distribution of fluid content is shown in Figure 13 indicated fines trapping may occur in the pore throat. However, the average pore size having a diameter is 7 times more than the average particles size of the fluid content. In general,

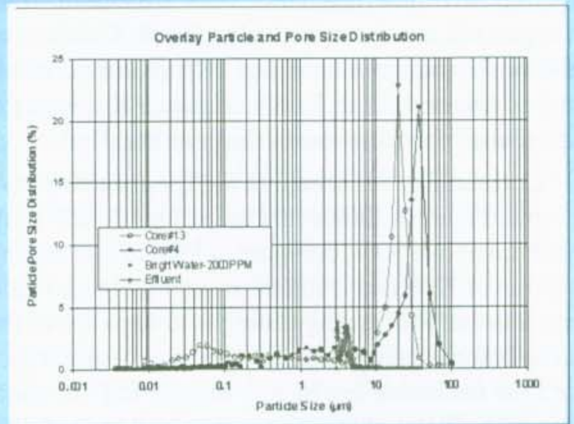


**Figure 13**
**overlay particles and pore size distribution**

the particles will pass through the pore throat, except for the larger particles will be trapped at the small pores throat. This possibly occurred in the core flood experiments causing the permeability reduction.

## VIII. CONCLUSIONS AND RECOMMENDATION

Based on the results of the several kinds of laboratory tests, and numerous of additional tests to find out evident to support the most likely reasons why some phenomenon occur in the experiments, the following highlights can be observed:

1. The viscosity of 1000 ppm and 1500 ppm of the basic conditions are almost similar to the neutral conditions. The optimum viscosity of 1000 ppm of basic condition is approximately 5.6 cp and in neutral condition is 4.1 cp, while at 1500 ppm 8.4 cp in basic condition and 7.8 cp in neutral condition.
2. Base line test with formation water at low rate have no effect on formation damage even for a medium permeability core. However, at very high rate causes some degree of permeability reduction.
3. BrightWater Injectivity tests have significant effects on permeability reduction to the level of 82% of PRF both of medium and high permeability cores. This is likely a result of fines migration triggered by surfactant in the BrightWater solution. Later experiment with addition of a clay stabilizer appeared to solve this problem.

4. BrightWater solution of 1500 ppm is able to generate sufficient flow resistance in medium as well as high permeability cores.
5. RsF testing using 1500 ppm BrightWater are in the range of 30 to 50 at initial flow resistance tests for all tests. At 4psig/ft or less, RsF is greater than 30 indicating sufficient degree of flow restriction to divert the injection water to the lower permeability zone.
6. Tendency of fines migration may occur due to the existence of kaolinite and other fines material such as detrital matrix and pseudo matrix.
7. To scale up the laboratory findings in the real reservoir condition, a reservoir simulation has been completed for designing BrightWater treatment in the field that show significant incremental oil using the RsF results.

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