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Systematic Extensive Laboratory Studies of Microbial EOR Mechanisms and Microbial EOR Application Results in Changqing Oilfield

Dejun Deng, Chenglong Li, Quanyi Ju, Pingcang Wu, Changqing Petroleum Administration Bureau and F. L. Dietrich, SPE, Z. H. Zhou, SPE, Microbes, Inc.

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Abstract

Microbial EOR was extensively laboratory tested to evaluate microbial affects on fluid properties and oil recovery then successfully applied in Changqing Oilfield. Fourteen different items were evaluated in 271 different tests to better understand the mechanisms of microbial EOR. Testing included core flooding, mobility improvement, crude compositional changes and microbe metabolite production and affects. Results are that the facultative anaerobic microbes can degrade the alkanes in crude into shorter chain alkanes and produce beneficial metabolites including carbon dioxide, surfactants and organic acids. The lower oil viscosity and beneficial metabolites are effective at increasing oil production rate and recovery. The lab testing is very complete and systematic leading to performance evaluation of the treatments in twenty-seven wells. Microbial EOR increased production 17.5 tons/day or eighteen percent.

Introduction

The use of microbial EOR (MEOR) is attractive for the Changqing Oilfield because of the technology's low cost, easy implementation and suitability to Changqing reservoirs [1, 2 and 3]. However, before implementing MEOR it was decided to investigate the claims made for the microbe products and enhanced recovery mechanisms. The ability of the microbes to grow with oil containing normal alkanes as their sole carbon source as well as their ability to produce the stated byproducts of solvents, acids and surfactants is investigated. Much of the Changqing Oilfield is maturing under waterflood, so the microbes' ability to reduce waterflood residual oil is of special interest. The question of microbe performance in the field is investigated though evaluation of individual production well treatments, with many lab tests on field crude oil and water samples. The testing generally confirmed the claims made in previous papers and the commercial field application proved technically and economically successful. The laboratory testing together with the field pilot forms a complete evaluation of microbial EOR effectiveness.

Laboratory Studies of Microbial Metabolism and EOR Mechanisms

Microbes can improve oil recovery by

1. Generation of gases that increase reservoir pressure and reduce oil viscosity,
2. Generation of acids that dissolve rock improving absolute permeability,
3. Reducing permeability in channels thereby improving displacement conformance,
4. Altering wetability,
5. Producing bio-surfactants that decrease interfacial tension, and
6. Reducing oil viscosity by degrading long-chain saturated hydrocarbons [3].

The microbe products used are mixed cultures of facultative anaerobes. They are motile and capable of using normal alkanes as their sole carbon food source. These products are designed to penetrate the reservoir, not to plug, so mechanism 3 above is not germane to these cultures. The predominate mechanisms at reservoir conditions are believed to be 5 and 6.

Laboratory studies include microbe growth rate, gas generation amount and composition, organic acid production, surfactant production, crude composition changes and core flooding effectiveness. Some of these tests were done on samples inoculated in the laboratory and some from samples taken before and after inoculation of wells in the field.

Growth Rate

In the laboratory, Products #1, #4, #5 and #6 as well as a blend were cultured, inoculated in paraffin and crude oil as food source. The microbe grew vigorously. After culturing 24 hours the microbe concentration increased over 10^3/ml (Figure 1) and CO_2, H_2, N_2, NH_4 and lighter, C_6- alkane gases were

produced (Table 1 and Table 2). The microbe concentration remained steady after growing to a count of 10^6/ml in three to five days. The quantity of produced gas was 30 to 60 ml per liter of culturing liquid.

The microbe-produced CO_2, H_2 and lighter alkane gas serves an important function in diluting crude oil and improving the crude oil mobility in formation. If a great deal of gas were produced causing crude swelling oil would be driven out from reservoir in field application. In the field pilot project natural gas production increased in one well, B189 of Maling Block.

Effects on Water

Organic matter was analyzed in produced water and crude oil samples before and after treating the wells with a blend of the four microbes products tested above (Table 3). Organic acid was produced in the field metabolizing process and this acid decreased the pH value of the water. Spectrographic analyses showed carboxyl acid generated, in which acetic acid is main constituent. After field inoculation, organic acid content increased 13% to 169% for the six wells tested.

Interfacial tension changes in produced oil and water were tested on six wells before and after field inoculation (Table 4). A general decrease occurred, caused by surfactant and alcohol in the metabolites. Decreased interfacial tension significantly improves the mobility of oil relative to water in the formation and enhances oil recovery.

Effects on Oil

After the formation was inoculated the growing microbes degraded paraffin molecules, increasing short-chain hydrocarbon components (Table 5). This reduction in long-chain waxes and corresponding increase in solvent reduced the freezing point and cloud point temperatures of the oil in a manner similar to adding paraffin dispersing agents and solvents. The viscosity, paraffin content and solidifying point of the produced crude oil all decreased in varying amounts. The change of saturated hydrocarbon alkane content in crude oil is the primary desired effect of microbe treatment. Paraffin content obviously decreased after MEOR treatment, down 40% compared to before treatment. Most MEOR-treated wells decreased in paraffin content and all wells decreased in solidifying (freezing) temperature.

Hydrocarbon C_{16-} content increased by 8 to 10% in Wells Z306 and S32-15 from chromatographic analysis (Figure 2 and Figure 3). These changes further verify that paraffin is a carbon resource for MEOR microbes and explain that incremental oil production and recovery result from crude oil lightening. (C_{16-} represents C_2 to C_{16}, and C_{17+} represents C_{17} to C_{32}).

Core Flooding

To understand the effects of microbes on EOR in the reservoir, an oil formation core from Maling Oilfield was selected for a MEOR core-flooding test. The Maling middle zone formation water was used for the test ($CaCl_2$ type, from the Luohe Zone). The viscosity of simulated oil was 2.55 mPa.s. Test steps were:

a) The core was evacuated, then saturated with formation water. The pore volume and effective porosity were determined. The effective permeability was measured by water flooding at 100% S_w.
b) Simulating oil was used to drive water out and the irreducible water left was measured. Saturated oil volume was recorded and the original oil saturation was calculated.
c) Water was injected to drive out oil until no more oil could be recovered, and the recovery rate was recorded (which is over 40%, the average water drive recovery in Maling is also about 40%). The produced oil and the residual oil saturation were calculated.
d) Two pore volumes of microbe-laden fluid (the injection water mixed with 1% microbe product blend) were pumped into the core. The core was kept under steady temperature (50°C) and steady pressure for 24 hours.
e) Microbes-laden fluid of 20 PV (the injection water mixed with 0.6% microbe product blend) was used to drive oil to reach steady state (no oil flow out). Then produced oil and the ultimate recovery factor were calculated.

The results (Table 6 and Figure 4) show that MEOR treatment increased ultimate oil recovery rate by 4.2% of original oil in place in two different cores. The increase over waterflood recovery was eight to ten percent.

Microbial EOR Pilot Project

Producing wells were treated in two stages in 1996 and 1997 by pumping microbes in batch treatments down the tubing-casing annulus of these rod-pumped wells. Twenty wells and twelve wells were initially selected for the first and second stages respectively. Due to operational problems and difficulties in establishing reliable baselines on some wells, the final number used for evaluation is 16 in the first stage and 11 in the second stage. The pilot wells were scattered in Plant 1, Plant 2 and Plant 3 in many different zones.

Reservoir and Fluid Characteristics

The main data of the treated wells in Changqing Oilfield are:

Formation	Sandstone reservoirs, Jurassic Y7, Y9, Y10 and C6
Effective Thickness	2.6 ~ 29.6 m
Porosity	11.0 ~ 17.8 %
Permeability	1.66 ~ 149.2x10^{-3} μm^2
Temperature	43 ~ 54 °C
Solidifying Point of Crude	5.0 ~ 24.0 °C
Viscosity (at 50°C)	4.29 ~ 6.58 mPa·s
Paraffin Content	4.40 ~ 12.98 %
Water Cut	4 ~ 76 %
Salinity	17.13 ~ 104.4 g/L

Treatment Design

The microbe product selection and treatment design and operation were determined by the vendor/consultant for the Changqing oil field MEOR pilot test. Product selection was based on the results of vendor lab viscosity testing as an indicator of product effectiveness on crude oil and water samples from throughout oil field [1, 3]. A microbe product blend composed of 30% #1, 20% #4, 20% #5 and 30% #6 was determined. Based upon well and reservoir information the first MEOR treatments were designed to use 24 m^3 of microbe-laden fluid per well, containing138 liters of microbe product blend. The displacing fluid was 6 ~ 12 m^3 of clean water. After the initial treatment, the volume of microbe-laden fluid was 50% of that for the first treatment, at the same microbe concentration. Periodic microbial EOR treatments were applied to the project. Wells in the first stage were treated 3 to 6 times and in the second stage were treated 2 to 3 times. The interval between treatments was nominally one month.

Analysis of Results

Both Stage 1 and Stage 2 of the Changqing Oilfield MEOR pilot resulted in significant incremental oil production (Table 7). On a typical well with good MEOR response the increase was immediate and sustained, coupled with a reduction in water cut (Figure 5).

While not every well responded as well as this example well, Nan 32-15, oil production increased 18% overall, 15% for Stage 1 and 21% for Stage 2. Fluid production also increased, but not as much as oil, indicating a slight decrease in total water: oil ratio. Fluid production increased 11% overall, 7% for Stage 1 and 15% for Stage 2.

From reviewing the complete production data, the following general observations can be made:

a) Some of the effective wells had effective period exceeding 30 days for a treatment. The effective period of a few wells was as high as 58 days for a treatment, such as Well S32-15. But most of these wells had effective period of 15 ~ 30 days after each treatment, and then dropped to the level as before the treatment.
b) For the ineffective wells, their daily produced fluid and oil showed no obvious increase. Although some wells increased at first, the increase was not maintained. Analysis of the production curves shows that the main reason MEOR did not increase production was the overall depletion, not caused by microbes squeezing.
c) MEOR treatments had a slight positive effect on water cut. Water cut kept steady or had a slight drop in the effective wells, but water cut rose in most of ineffective wells. For the 10 MEOR-treated wells in Maling Oilfield, average water cut before treatment was 39.9% versus 39.4% after the 1st treatment and 37.4% after the 5th treatment. Several MEOR-treated wells had water cut increases in Ansai Oilfield. Before treatment, the average water cut of these 10 wells was 42.9%, rising to 51.2% after the 1st treatment. After 2nd treatment, the average water cut decreased gradually and the average water cut was down to 46.6% after the 4th treatment. The main reason was that most of oil wells in Ansai have lower fluid production, 6 m^3/d normally. Some time was necessary to produce the 20 to 32 m^3 of treatment fluid squeezed into each well, and water cut deceased after most of squeezing fluid was produced.

The increase in incremental production in Stage 2 is attributable to applying the experience gained in Stage 1. Stage 1 indicated better performance on wells with higher permeability, so for Stage 2 wells were selected with permeability greater than $50x10^{-3}$ μm^2. Also only wells with a viscosity reduction of at least 30% in laboratory tests were selected. Extra care was taken to select wells with a better-defined baseline. In addition, the treating procedure was modified. The tubing wing valve was opened until after pumping microbes-laden fluid for a time determined according to production fluid level and pump setting depth. This allowed the fluid in the annulus to be displaced around the downhole pump and out the tubing, rather than pushed into and possibly damaging the formation. Then the wing valve was closed and the microbe treatment was slowly squeezed into the formation.

For Stage 1 cumulative incremental oil was 1413 tons and net profit was ¥348,500. For Stage 2 cumulative incremental oil was 1138 tons and net profit was ¥344,000. Total net profit for the two-year project was ¥692,500, or about $83,000 US.

Based on encouraging production and laboratory results, at the end of 1998 an independent block with 5 injectors and 13 producers was selected for a MEOR water flood test. At present, the project is under way and its effectiveness is being monitored.

Conclusions

1. Inoculation of paraffin and crude oil with microbes generated CO_2, H_2, C_{6-} gas, organic acid, and surfactant. Crude oil became lighter.
2. Microbes reduced interfacial tension.
3. Crude oil mobility and the relationship between oil and water were improved resulting in enhanced oil recovery as proven by core flooding and pilot production response.
4. Correct well and product selection and operating procedure are important to achieve effective treatment.
5. According to the laboratory tests, well monitoring, and analyses of treatment results, wells having higher fluid production, water cut in the range of 25 ~ 60%, higher paraffin content, higher viscosity and higher permeability will have better treatment effectiveness.

SI Metric Conversion Factors

acre-foot × 1.233 489	E+03	= m^3
barrel × 1.589 873	E-01	= m^3
foot × 3.048*	E-01	= m
md × 9.869 233	E-04	= μm^2
psi × 6.894 757	E+00	= kPa
U.S. Gal × 3.785 412	E+00	= L
°F (°F-32)/1.8		= °C

* Conversion factor is exact.

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2. Streeb, L. P., and Brown, F. G.: "MEOR - Altamont/Bluebell Field Project" paper SPE 24334 presented at the SPE Rocky Mountain Regional Meeting, Casper, Wyoming, May 18-21, 1992.
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Tables

Table 1 – Analysis of Gas Produced by Microbes from Paraffin (1 g paraffin + 8 ml products)

Item	Prod. #1	Prod. #4	Prod #5	Prod #6	Product Blend
CO_2 (%)	52.27	26.23	32.42	34.58	23.55
H_2 (%)	0.06	9.427	44.30	29.16	0.137
N_2 (%)	47.65	64.33	23.38	36.25	76.31
Specific Gravity	1.255	1.027	0.748	0.896	1.096
Air content (%)	1.97	10.08	0.841	0.566	19.23
Threshold pressure (Mpa)	5.466	4.265	3.757	4.164	4.361
Threshold temperature (K)	219.2	164.1	142.77	160.7	167.94

Table 2 – Analysis of Gas Produced by Microbes from Crude Oil (at 30°C with oil from Well Zhong 306, 1.0% Product for 22 days)

Item	Prod. #1	Prod. #4	Prod #5	Prod #6	Product Blend
CH_4 (%)	0.010	0.661	2.196	0.008	0.372
C_2H_6 (%)	0.098	1.161	4.546	0.138	0.532
C_3H_8 (%)	0.570	6.198	24.937	0.793	2.642
iC_4 (%)	0.147	1.599	6.100	0.202	0.645
nC_4 (%)	0.246	2.717	10.478	0.334	1.097
iC_5 (%)	0.066	0.761	2.839	0.088	0.292
nC_5 (%)	0.057	0.661	2.483	0.075	0.253
iC_6 (%)	0.025	0.311	1.004	0.028	0.100
nC_6 (%)	0.012	0.180	0.536	0.015	0.053
iC_7 (%)	0.001	0.002	0.043	0.002	0.004
nC_7 (%)	0.002	0.007	0.245	0.002	0.007
Alkene (%)	0.001	0	0	0	0.003
CO_2 (%)	44.45	34.14	24.24	9.531	32.73
H_2 (%)	0	1.028	0	0	0.050
N_2 (%)	54.32	50.58	20.91	88.78	61.22
Specific gravity	1.223	1.260	1.539	1.034	1.192
Air content (%)	3.981	0.277	13.16	31.70	0.526
Paraffin (%)	1.235	14.257	54.842	1.684	6.00
Methane coefficient	0.008	0.046	0.040	0.004	0.062
Threshold pressure (Mpa)	5.171	4.780	4.595	3.832	4.741
Threshold temperature (K)	208.1	217.0	289.9	146.93	197.4
Volume of produced gas (ml/L)	56.0	60.0	36.0	4.0	30.0

Table 3 – Organic Acid Content in Produced Water (main component is acetic acid, 190 to 300 nm)

Well #:	Z302	Z306	Z311	W14-26	W19-15	W25-3
Before treatment (ppm)	52	49	80	53	109	53
After treatment (ppm)	140	120	90	120	130	138
Increase (%)	169	145	13	126	19	160

Table 4 – Interfacial Tension of Produced Oil Before and After Microbial EOR

Well #:	S30-16	Z302	Z306	W19-15	W25-3	W14-26
Before treatment (mN/m)	43.04	41.5	56.5	60.8	60.1	55.8
After treatment ((mN/m)	36.0	36.4	44.2	44.3	50.1	44.0

Table 5 – Changes in Produced Crude Oil Before and After Microbial EOR Treatments

Plant	Well #	Time	Freezing point (^{0}C)	Viscosity (MPa. S) (50 ^{0}C)	Wax content (%)	C_{16-}/C_{17+} (%)
Maling	Z306	Before:	19	6.58	9.60	57.77/42.23
		After:	2	5.78	4.66	65.18/34.82
	Z302	Before:	20	5.81	6.85	60.15/38.85
		After:	3	6.11	4.11	52.88/47.93
	S28-19	Before:	16	5.39	10.94	59.03/40.97
		After:	6	6.10	4.20	52.88/47.12
	S32-15	Before:	14	5.34	9.44	49.13/50.87
		After:	8	6.58	5.09	59.50/40.50
Ansai	W17-14	Before:	24	5.68	9.64	49.72/50.28
		After:	20	6.18	6.32	58.35/41.65
	W14-26	Before:	24	6.01	7.45	51.81/48.19
		After:	18	5.39	6.61	57.72/42.28

Table 6 – Core Flooding Test Results (see text for description of procedure)

Core # Well XZ 14	Φ (%)	Vp cm^3	K $10^{-3}\mu m^2$	Soi (%)	Sor (%)	Water drive Vow (ml)	Water drive Ewf (%)	Microbe drive Vom (ml)	Microbe drive Em (%)	Last Recovery E (%)
9-3	14.0	5.256	5.63	68.1	40.5	1.45	40.50	0.12	4.19	44.69
9-4	14.0	5.334	6.537	66.9	37.8	1.55	43.42	0.15	4.18	47.60

Table 7 – Pilot Production

Pilot Stage	Well #	Baseline			Average During MEOR			Improvement					
		Liq. /d	Oil /d	Water cut	Liq. /d	Oil /d	Water cut	Liq. /d	Oil /d	Water cut	Liq % Incr	Oil % Incr	WC % Decr
		(m3)	(t)	(%)	(m3)	(t)	(%)	(m3)	(t)	(%)	(%)	(%)	(%)
1st Stage	W15-12	8.26	2.01	71	6.59	2.11	68	-1.67	0.10	3	-20	5	4
	W24-6	3.14	1.23	36	3.38	1.58	53	0.24	0.35	-17	8	29	-47
	W17-14	5.77	1.28	74	6.53	1.37	79	0.76	0.09	-5	13	7	-7
	W9-28	2.29	1.05	40	2.63	1.17	56	0.34	0.12	-16	15	11	-39
	W24-3	4.58	3.21	16	6.13	4.19	32	1.55	0.98	-16	34	30	-96
	W19-15	2.89	1.36	24	2.75	1.42	49	-0.14	0.06	-24	-5	4	-99
	W14-010	9.97	3.26	61	10.54	4.46	58	0.57	1.20	4	6	37	6
	Z306	10.20	5.09	33	8.99	5.11	43	-1.21	0.02	-10	-12	0	-32
	Z302	3.55	2.03	33	5.07	3.01	41	1.52	0.98	-8	43	48	-25
	Z311	8.83	3.03	59	8.46	3.06	64	-0.37	0.03	-5	-4	1	-8
	N197	5.78	1.98	59	7.11	2.33	67	1.33	0.35	-8	23	18	-14
	N189	3.87	1.67	48	4.42	2.10	53	0.55	0.43	-4	14	26	-9
	N63-2	3.21	1.51	44	3.92	1.60	59	0.71	0.09	-16	22	6	-36
	S28-19	13.51	7.89	31	15.27	8.67	43	1.76	0.78	-12	13	10	-39
	S32-15	18.43	9.30	41	24.18	11.22	54	5.75	1.92	-13	31	21	-32
	S30-19	17.04	7.80	27	13.75	8.45	39	-3.29	0.65	-12	-19	8	-44
2nd Stage	189	2.13	1.11	38	3.56	1.92	36	1.43	0.81	-1	67	73	4
	197	6.57	1.21	76	7.61	2.59	59	1.04	1.38	-1	16	114	21
	302	7.42	4.08	35	8.26	4.43	36	0.84	0.35	0	11	9	-5
	306-3	11.26	6.35	33	12.63	7.18	34	1.37	0.83	-1	12	13	-5
	116-2	3.07	1.75	32	1.17	0.63	35	-1.90	-1.12	1	-62	-64	-7
	5-1	6.17	3.65	30	12.38	5.85	44	6.21	2.20	-3	101	60	-46
	10-13	9.48	5.35	33	13.71	6.4	46	4.23	1.05	-1	45	20	-39
	32-15	19.1	7.47	54	25.18	11.18	48	6.08	3.71	-4	32	50	11
	121-7	21.9	5.89	70	15.39	4.63	65	-6.51	-1.26	1	-30	-21	8
	173-2	2.17	1.57	20	4.28	2.61	28	2.11	1.04	-1	97	66	-44
	173-3	12.6	6.36	45	13.2	6.74	38	0.60	0.38	-1	5	6	16
	1st Stage	121.32	53.70		129.71	61.83		8.39	8.13		7	15	
	2nd Stage	101.87	44.79		117.37	54.16		15.50	9.37		15	21	
	Total	223.19	98.49		247.08	115.99		23.89	17.50		11	18	

Baseline production is month preceding MEOR start unless that month was an inaccurate representation of the well's performance, then a more accurate projection was made using a decline curve.

Figures

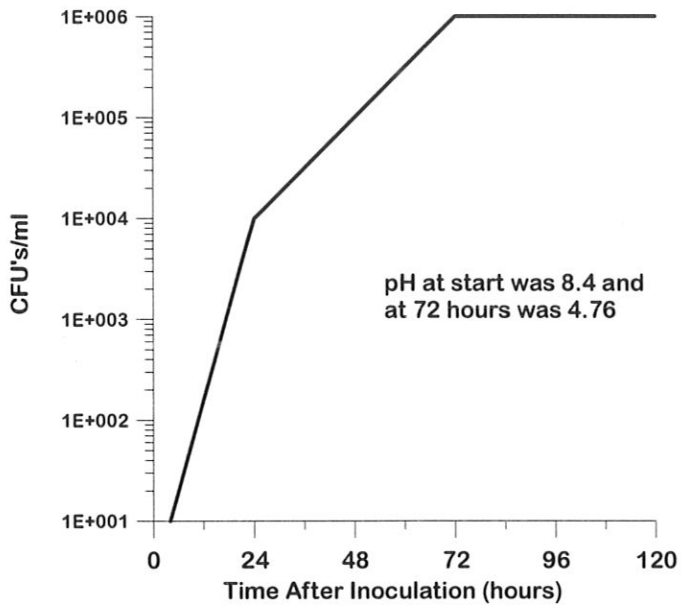

Figure 1 – Microbe Growing Test. Started with 0.1% at 30°C. In several tests with wax and crude oil the concentration always reached a maximum in 3 to 5 days.

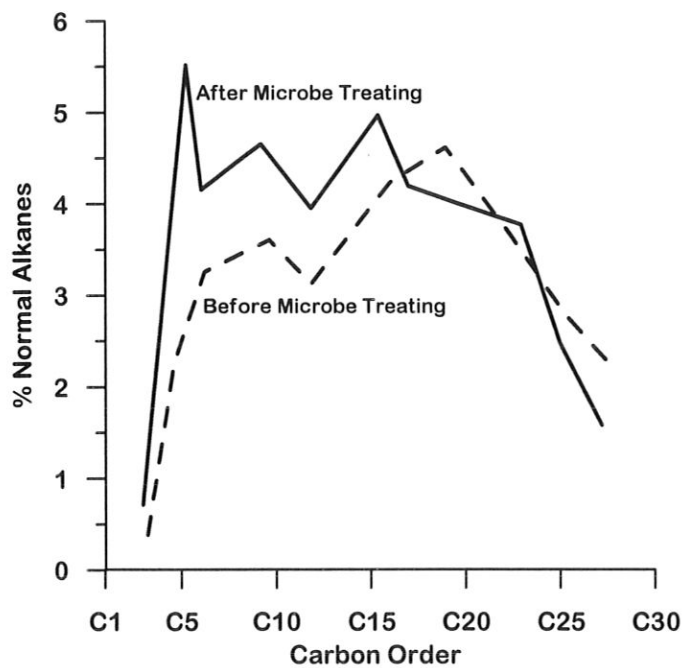

Figure 2 – Chromatograph of Oil from Well S32-15 Before and After Microbe Treatment. Note the increase in the C_{16-} components and the decrease in the C_{16+} components.

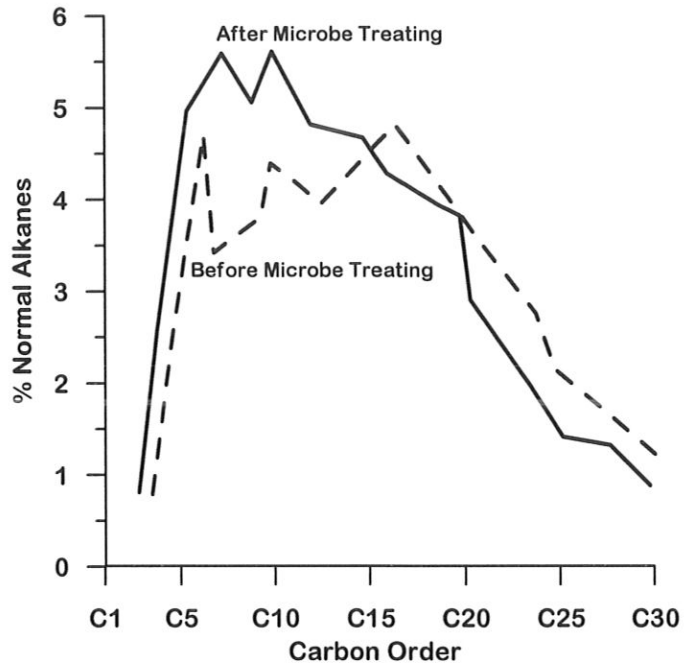

Figure 3 – Chromatograph of Oil from Well N189 Before and After Microbe Treatment. Note the increase in the C_{16-} components and the decrease in the C_{16+} components.

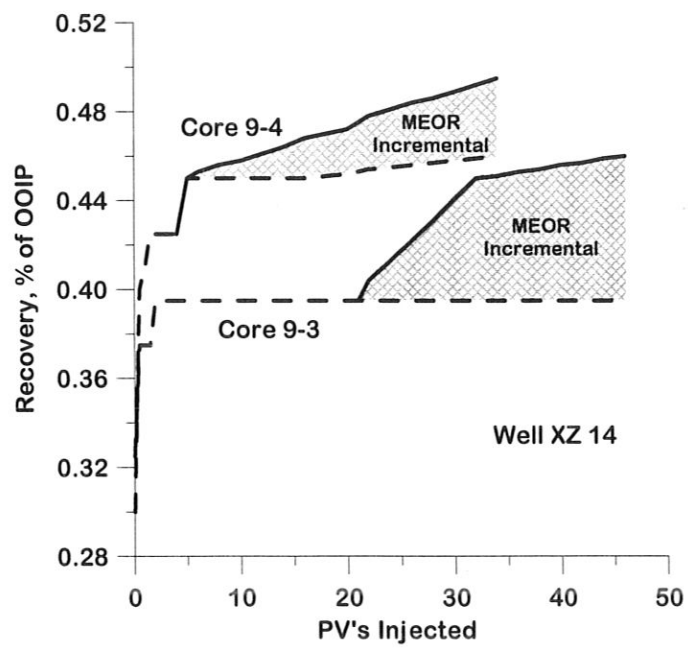

Figure 4 – Core Flooding Test. Additional recovery averaged 4.2% of OOIP for an 8% to 10% increase over waterflood recovery.

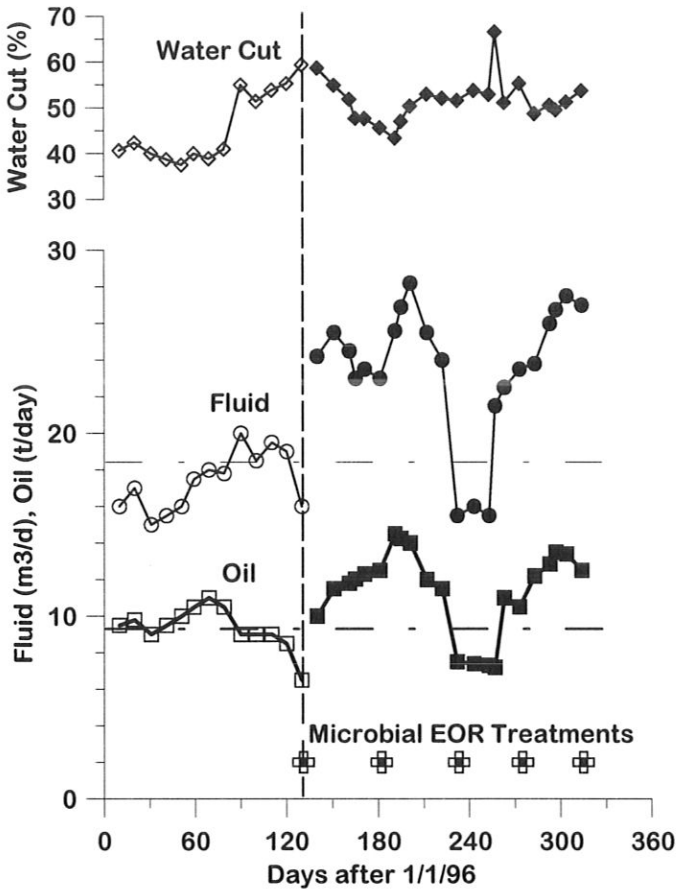

Figure 5 – Nan 32-15, an Example Well with Good MEOR Response. Note the increase in oil production and the decrease in water cut.