

Microbial Pilot Test for the Control of Paraffin and Asphaltenes at Prudhoe Bay

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Abstract

The following paper describes a six month pilot test for the control of paraffin and asphaltene deposition at the reservoir level using naturally occurring microorganisms. For the course of the paper, paraffin will be defined as pentane soluble hydrocarbon precipitates. Likewise, asphaltene will be defined as hydrocarbon deposits which are pentane insoluble and toluene soluble. The microbial project was conducted on four wells in the Eastern Operating Area of the Prudhoe Bay oil field. The microorganisms were selected based upon their ability to metabolize long hydrocarbon chains into lighter components.

Data collected from the project reflects the impact on total fluid production and crude oil physical and chemical properties i.e. API gravity, viscosity, and sulfur content.

Operation and maintenance costs for the microbial treatments versus alternative methods are shown and proven to be favorable on certain well types. The advantages of growing the microbes on site and increasing the variety and type of microbial functions is presented. The treatment techniques for effective microbial application along with candidate selection are discussed.

Introduction

Prudhoe Bay is located on the central north slope of Alaska. The oil field was discovered in 1968; development began in 1977. Production to date from the Prudhoe Bay field is in excess of 9 billion barrels. The field depletes the Sadlerochit reservoir which is characterized by four different zones: Zulu, Victor, Tango, and Romeo (type log in figure 1). Each zone is characterized by a different lithology, thickness,

porosity, permeability, etc. The reservoir drainage mechanism is dependent upon gas cap proximity. Where a gas cap is present, the field is depleted by a gravity drainage mechanism supported by gas cap injection. Where there is limited gas cap support, the field is depleted by water flood (WF) and enhanced oil recovery (EOR) mechanisms.

The microbial treated wells are located in the southeast peripheral corner of Prudhoe Bay. All treated wells are located in the same WF/EOR pattern. Three of the four wells (A, B, and D) have corner locations in a loosely fitted inverted five spot pattern. The remaining well, C, occupies the only developed side well location in the pattern. Well spacing varies from 80-160 acres.

Reserve depletion in the treated pattern is supported by alternating injection of water and MI (miscible injectant). Water injection began in 1984 using sea water as the displacement medium. In 1994 sea water was replaced with recycled produced water. MI injection was introduced in 1993 as an enhanced oil recovery mechanism to the existing water flood. To date, 15 MM bbls of water (80% sea water) and 1 Bcf of MI have been injected into the treated pattern. Recovery to date from the treated wells totals 8.5 MMBO.

All the treated wells are completed in the Zulu formation. Top of structure averages 8975' TVD with an average sand thickness of 80 feet. Reservoir temperature is approximately 196 °F while the reservoir pressure is estimated at 3400 psi. Table 1 lists reservoir statistics for the treated wells.

Well	Porosity (%)	Permeability (md)	Gross Sand Thickness (ft)
A	19.7	65	96
B	20.4	78	41
C	20.7	122	109
D	19.6	50	71

Table 1: Reservoir characteristics for wells treated in the pilot program.

Crude oil API gravity prior to treatment averaged 24 degrees, ranging from 21 to 26 degrees. Proceeding northwest from the treated pattern, oil quality improves. Crude oil API gravity in neighboring patterns averages 26 degrees. One component of the improved oil quality is a decrease in the asphaltene concentration. Asphaltene

concentration tends to increase with proximity to the southeast periphery. Average asphaltene concentration in the treated wells was 9.2 wt% (5.8-15.8 wt%) while adjacent patterns averaged 5.8 wt% (3.4-11.9 wt%). Coinciding with the increased concentration of high MW hydrocarbons is an increased crude viscosity.

The effect of crude oil composition has a significant impact on productivity in the treated region. High crude oil viscosity has contributed to regionally low gross well fluid rates of less than ~1000 bbls/day. For two of the treated wells, B and D, low fluid rates in conjunction with heat losses through the 2000 ft thick arctic permafrost, contribute to the deposition of heavier crude constituents as well as gas hydrate formation. Well production occasionally ceases due to the formation of a hydrate or paraffin plug. To return wells to production, the plugs are mechanically and thermally removed by jetting hot oil with a coil tubing unit. The operations associated with hydrate/paraffin formation resulted in unfavorable economics for wells B and D. Various treatments (conventional hot oil treatments, solvents, surfactants, etc.) were tested in an effort to increase production and/or reduce operating costs. The wells showed favorable responses to the treatments, but the economics did not meet acceptable hurdles.

In addition to production impacts, paraffin/asphaltene deposition can increase routine well work costs. As a result of the deposition of high MW hydrocarbons, hot oil treatments are often required during routine well operations. The treatment removes the paraffin/asphaltenes preventing successful execution of the associated down hole well work. The remaining treated wells, A and C, fell into this category.

As a result of (1) the aforementioned operational and production impacts and (2) positive responses from an earlier small microbial pilot³, the expanded microbial pilot program was initiated. Four wells were treated: A, B, C, and D. Well A has produced since 1981 while the remaining wells were drilled in the early 1990's. All the treated wells have been stimulated with fracture treatments. Table 2 lists pre-treatment production statistics for the treated wells.

Well	Cumulative Oil Production (MBO)	Liquid Rate (blpd)	Water Cut (%)	Formation Gas Rate (Mscfd)
A	7126	1400	70	1000
B	610	800	69	<500
C	559	2450	81	500
D	225	900	69	<500

Table 2: Pre-treatment production statistics for wells in the pilot program.

Technology

Enhancement of petroleum production through the

application of microbiology began more than fifty years ago. Various mixtures of yeast, molasses, beer, etc., have been introduced into oil wells in an attempt to solve production problems and/or enhance well productivity. Since these early beginnings, the use of microbes for biodegrading and enhancing paraffinic oils has been shown to be a viable technique.^{1,2} More recently, supplemental nutrients have been injected into reservoirs to "feed" the indigenous microflora. The additional nutrients are supplied in an attempt to increase the bacterial activity and thereby accelerate the natural crude oil biodegradation process.

Injection techniques for well inoculation vary among annular batch treatments, continuous annular and tubing injection, and various forms of full bore squeeze procedures.

The type of recent biological products also varies. Freeze dried products, enzymes, microbial blends, and microbial concentrates have been tried in domestic and remote locations throughout the world.

Environmental factors affecting bacterial application include temperature (down hole and surface), acidity, existing chemical treatments, and toxic formation materials. Pressure has not been seen as a detrimental factor to date with some known pressures to be in excess of 12,000 psig. Acceptable pH can vary from 4.0 to 9.0, although actual short term pH values up to 11.5 have been documented without damage to the culture. Down hole temperatures from 65 degrees F to 270 degrees F are acceptable.

The bacteria colonize at the oil-water interface and move through the reservoir in the connate water. Therefore an important prerequisite for successful microbial application is a preexisting water source.

Bacteria effective against asphaltenes are a new and very promising development in the enhanced recovery of asphaltene based crudes. Recent successful results in the microaerophilic degradation of asphaltenic tars in Southern California oil fields has spurred interest in reservoir level application to improve crude characteristics and well productivity.

Microbial History at Prudhoe Bay

Initial experience with bacterial products at Prudhoe Bay was obtained from a small scale pilot program in 1992.³ Two producing wells with a lengthy history of paraffin deposition were targeted for microbial treatment in an effort to reduce operating costs by eliminating or decreasing the frequency of hot oil treatments. The targeted wells typically required coil tubing hot oil treatments every 4 to 6 weeks at a cost of approximately \$7,000/month/well. The primary objectives of the early microbial tests were to verify the effectiveness of microbial treatments and target a 50% reduction in the costs of hot oil treatments.

Results of the initial pilot appear to confirm microbial treatments can have a positive effect on well productivity.

Compositional changes in the crude included an increase in the API ° gravity, reduced pour point, and reduced viscosity. Treatments in the initial pilot resulted in incremental rate increases of 150 and 300 bopd for the two treated wells. The ability to discern the effect of the bacteria on the produced crude was complicated by changes in producing characteristics. Increasing GOR (gas to oil ratio) from gas cap encroachment posed the potential for stripping off the lower molecular weight components and altering the crude composition thereby masking the bacterial compositional changes. The preliminary results from the early trials offered encouragement to proceed with a larger microbial test on additional wells. Operational costs of the initial test indicated potential cost savings of \$1,900 a month per well.³

Microbial Application

Prudhoe Bay due to its remoteness and environmental extremes offers a unique challenge for biotechnology. Bacteria are primarily composed of water and are subsequently susceptible to freezing in the arctic environment. In addition to freezing, water mass creates bulk and weight which increases shipping and handling costs. In the interest of cost reduction, the bacteria for the pilot project were cultured in on-site portable fermenters.

In order to design an appropriate treatment program, each well history was reviewed and produced fluids were analyzed. Table 3 typifies the produced fluids.

Constituent	Measurement
pH	6.2
Bicarbonate, mg/L	2132
Chlorides, mg/L	13,000
Sulfate, mg/L	915
Calcium, mg/L	320
Magnesium, mg/L	238
Silicon, mg/L	25.8
Potassium, mg/L	127
Sodium, mg/L	8720
Iron, mg/L	3.4
Oil Viscosity, SUS 180 °F	44
Sulfur in crude, Wt. %	0.93
Asphaltenes, Wt. %	8.58
Paraffin, Wt. %	8.7
Formation Temperature, °F	180

Table 3: Produced fluid example from a treated well.

Twelve species of commercially available, naturally occurring, non-pathogenic, motile, facultative anaerobes were selected for their ability to (1) degrade asphaltenes and paraffins and (2) produce and release surfactants and fatty acids. The selected bacteria have a prior history of surviving and thriving under similar reservoir conditions (pressure, temperature, and salinity).

The exact metabolic mechanisms for paraffin and asphaltene degradation is not entirely understood. However, the process likely relates to the presence of sulfur, nitrogen, iron, and/or other metallic cations present in the reservoir. The metallic cations may serve as electron acceptors under anaerobic conditions. In addition, the biochemical reactions likely occur by multiple pathways. Due to the aforementioned reasons, the biodegradation process cannot be explicitly described.

Although the exact pathway is unknown, bacterially produced surfactants and fatty acids are known to be an important component in the biodegradation of high molecular weight hydrocarbons. The surfactants and fatty acids assist paraffin and asphaltene degrading bacteria by increasing the bacteria's ability to invade and establish themselves within the reservoir ecosystem. Co-metabolism functions are also a possibility.

Bacteria for the Prudhoe Bay pilot were grown in three separate batches dependent upon their primary function: (1) paraffin degradation, (2) asphaltene degradation, and (3) surfactant/fatty acid production. The microorganisms were cultured in on-site portable fermenters to insure a highly active biological product with minimal shipping and handling complications. Fermentation times for population levels of 1×10^8 cells per milliliter were dependent on the specific culture and were reached in 48 to 72 hours.

For the expanded pilot program, microbial applications were initiated by either a full bore or CTU (coil tubing unit) squeeze treatment of the microorganisms followed by a crude or potassium chloride solution over flush volume sufficient to displace the bacteria 8 to 10 feet beyond the well bore. Initial treatment volumes were determined after considering such variables as the type and amount of paraffin and asphaltenes present in the produced crude, the type of completion and amount of sand perforated, and the anticipated flow rates. After inoculation, the wells were allowed to soak for 48 to 72 hours prior to returning to production. The initial treatments were augmented weekly with additional microbial treatments averaging 15 gallon/week. Previous experience from the initial pilot indicated a minimum 10 gallons per week augmentation treatment was required to sustain benefits. The augmentation treatments were performed by adding the bacterial product to the surface gas-lift supply. Table 4 gives the initial treatment volumes and supplemental weekly volumes performed on each well.

Well	Initial Treatment	Microbial Volume (gallons)	Shut-In Period (hours)	Weekly Treatment Volume (gallons)
A	Full Bore	220	48	15
B	Full Bore	290	72	15
C	Full Bore	330	72	15
D	CTU	275	72	15

Table 4: Microbial treatment program statistics by well.

Pilot Objectives

The primary objectives of the microbial treatment program were:

- (1) Positively establish the viability of microorganisms as an effective measure for the control of paraffin and asphaltenes.
- (2) Determine the feasibility of producing and applying biological treatments in an arctic environment.
- (3) Improve or stabilize production rates for severe paraffin/asphaltene producers.
- (4) Quantify the costs and benefits of microbial applications at Prudhoe Bay.

To determine the effectiveness of the microbial treatments, baseline data was obtained for crude oil physical and compositional characteristics. This information along with production performance data and operating costs would be compared on a pre and post microbial treatment basis. Compositional and physical data included:

- (1) Oil API Gravity ($^{\circ}$ API)
- (2) Asphaltene Concentration (weight %)
- (3) Paraffin Concentration (weight %)
- (4) Viscosity (cSt at 180 $^{\circ}$ F).
- (5) Sulfur Concentration (weight %)

Results

Four wells were treated as part of the six month pilot. The first well, B, was treated on 3/9/95. Wells A, D, and C followed on 3/20/95, 3/30/95, and 7/18/95 respectively. Six months after the initial treatment of well B, the pilot program was reviewed. Wells A, B, and D did not show sufficient benefits at the time of the pilot review to warrant continued treatments. Since well C exhibited some production benefits, the remaining supply of microbial product was exhausted on the producer. The final microbial augmentation treatment for well C was pumped on 12/27/95. The impacts of discontinued treatments was also monitored.

Of the four wells treated, two have sufficient test separator data to evaluate production impacts: A and C. Well test data

collected from the remaining two wells, B and D, is inconclusive due to complications with hydrate and paraffin formation. Wells B and D inability to maintain stable production rates also prohibited gathering meaningful pre and post-treatment fluid samples.

Figures 2-5 are plots of test separator results for wells A and C. The liquid rate of well C is noticeably impacted by the onset of microbial treatments. Prior to the microbial treatments, well C liquid rate averaged 2450 blpd. After treatment initiation, well C liquid rate increased to approximately 2890 blpd for an incremental 440 blpd or 18% increase. The increased liquid rate translates to an incremental 84 bopd at 81% WC. Unlike well C, no obvious production impacts were noted on well A.

In addition to well test information, crude oil physical and compositional property changes were measured. To insure oil samples adequately represented overall well characteristics, separate one gallon samples were taken over the course of two days and combined. Figures 6-10 represent the crude oil physical and compositional changes before, during, and after the microbial pilot. When available, the graphs include American Society for Testing and Materials (ASTM) testing reproducibility errors. In summary, the combined physical and compositional trends are consistent with the crude oil bioremediation process. As treatments were initiated, crude oil quality improved: (1) oil API gravity increased, (2) crude viscosity decreased, (3) combined asphaltene and paraffin concentration decreased, and (4) sulfur concentration decreased. The response is not unexpected. The increased paraffin concentration either (1) contains cleaved asphaltene constituents which now register as paraffin under lab analysis or (2) represents a decrease in the amount of paraffin deposition in the well bore. Overall, the combined concentration of the paraffin and asphaltenes decreased with treatment. To assist in verifying the effects of the microbes on the crude oil properties, weekly microbial treatments were discontinued after the trial period in order to monitor crude property changes. Crude oil properties were observed returning to pre-treatment values shortly after discontinuing the weekly augmentation treatments. Microbial counts indicated viable bacteria were still present in the produced crude for 3 months following suspension of the treatments, but in decreasing concentrations.

Total microbial costs for a six month program are included in Table 5. Table 6 includes individual project economic indicators for well C.

Well	6 Month Project Implementation Costs (\$)
A	\$49,025
B	\$38,540
C	\$30,578
D	\$57,958

Table 5: Total microbial treatment costs including associated well work. Well D treatment includes cost of a CTU.

Incremental Oil	
Average Incremental Oil Rate:	84 bopd
Project Cumulative Incremental Oil (180 Days):	15,120 bbls
Project Individual Well Cost/Cumulative Incremental Oil:	\$2.02/bbl

Table 6: Individual well project economic indicators for microbial treatment of well C.

For a treatment cost comparison, Table 7 lists conventional hot oil treatment (HOT) statistics compared to the microbial results. The HOT results are based on a limited search of wells in the adjacent patterns to the microbial pilot. Due to the wide range of HOT results, a conclusive cost comparison is inappropriate. The comparison of results for wells which showed favorable responses to their respective treatments is shown to negate the effects of treated wells which were unsuitable candidates.

	HOT	Microbes
Treated Wells:	8	4
Wells With Production Impacts:	3	1
Treatment Cost per Well:	\$2,166-\$5,388 (\$3,129 Average)	\$30,578-\$57,958 (\$42,777 Average)

Statistics on Wells with Favorable Responses:		
Average Liquid Production Increase:	+38%	+18%
Impact Duration:	9-40 Days (22 Day Average)	180 Days
Individual Well Cost/Incremental Oil:	\$0.83/bbl-\$23.95/bbl (\$4.01/bbl Average)	\$2.02/bbl

Table 7: Cost comparison of HOT versus microbial treatment. HOT statistics based on a limited search of wells adjacent to microbial pilot wells.

Conclusions

The following conclusions were determined from the results of the Prudhoe Bay expanded microbial pilot:

1. Application of microbial products can result in significant compositional changes in produced crude when applied at the reservoir level, including increased API gravity, reduced viscosity, reduced sulfur concentration, and reduction in the combined paraffin and asphaltene concentration.
2. Changes in crude oil characteristics due to microbial action can result in improved production rates and lower operating costs as compared to other conventional methods of paraffin and asphaltene control.
3. Microbial products are most suitable for wells with moderate to severe paraffin/asphaltene problems which are capable of sustained production rates prior to treatment. Wells with extreme paraffin/asphaltene problems which are incapable of sustained flow rates prior to treatment may not be suitable as microbial candidates.
4. Microbial treatment applications can be successfully cultured and applied in an arctic environment.
5. There were no significant benefits to performing the initial microbial squeezes with coil tubing as compared to simply bull heading the treatments.
6. Effects of microbial treatment, when applied successfully, should be evident within 30 days of initiating the treatments.

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References

1. Brown, F. G., "Microbes-The Practical and Environmental Safe Solution to Production Problems, Enhanced Production and Enhanced Recovery," SPE Paper 23955 (Mar. 1992)
2. Streeb, L. P., Brown F. G., "MEOR-Altman/Bluebell Field Project," SPE Paper 24334 (May, 1992)

3. Smalstig, W. H., "Microbial Pilot Project Results", AAI Internal Correspondence, (Dec. 30, 1993)

SI Metric Conversion Factors

°API	141.5/(131.5+°API)	=g/m ³
bbl	×1.589 873 E-01	=m ³
cp	×1.0 ⁻¹ E-03	=Pa·s
Feet	×3.048 ⁻¹ E-01	=m
°F	(°F-32)/5/9	=°C
gal	×3.785 412 E-03	=m ³
md	×9.869 233 E-04	=μm ²
psi	×6.894 757 E+00	=kPa

- Conversion Factor is exact

Well	Date	Oil, °API	Asphaltene (wt%)	Paraffin (wt%)	Pour Point, °F	μ @ 180 °F (cSt)	Pre/Post Microbial Treatment
A	07/21/87	23.7	8.7				Before
A	09/03/87		5.8				Before
A	03/28/91	23.1					Before
A	09/01/91	21.1					Before
A	07/23/94	25.07	7.7				Before
B	9/8/90	23.4					Before
B	8/10/93		2.5	20.2			Before
B	10/28/93		8.8				Before
B	4/17/95	29.7					After
C	6/15/95	25.6	8.58	8.7	-25	5.5	Before
C	8/3/95	26.8	5	10.8	-3	4.7	After
D	09/30/94	26.3	15.8				Before
D	1/9/95	11.9	0.87	17.6		327.9	Before
D	5/14/95	20.6	17.57	3.72		24.8	After

Table 8: Historical compositional and physical crude oil data for treated wells in microbial pilot.

Prudhoe Bay Type Log

GR	SPHI	Zones	Permeability (md)
		Zulu	50-300
		Victor	300-3000+
		Tango	300-700
		Upper Romeo	300-700
		Lower Romeo 1	200-400
		Lower Romeo 2	25-200

Figure 1: Prudhoe Bay type log.

Well A Production Test Data

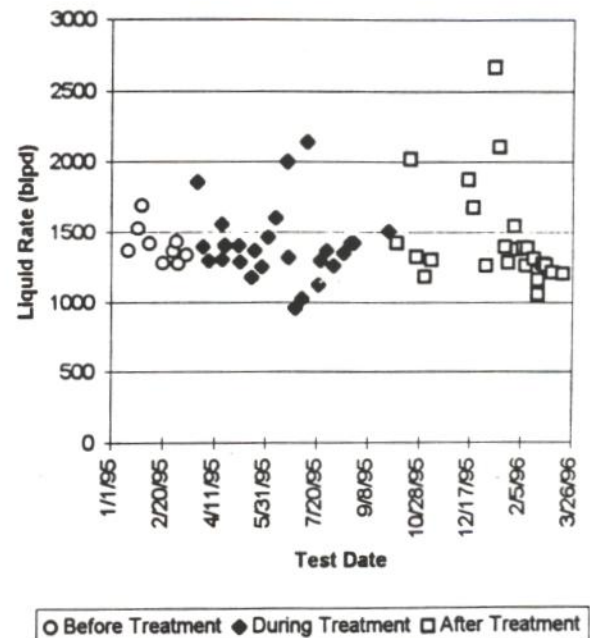


Figure 2: Well test liquid rate data from 1/1/95, for well A.

Well A Production Test Data

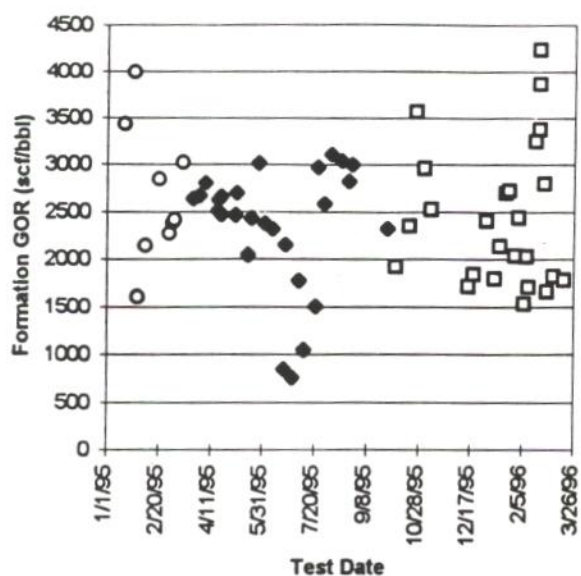


Figure 3: Produced formation gas to oil ratio (GOR) test separator data for well A.

Well C Production Test Data

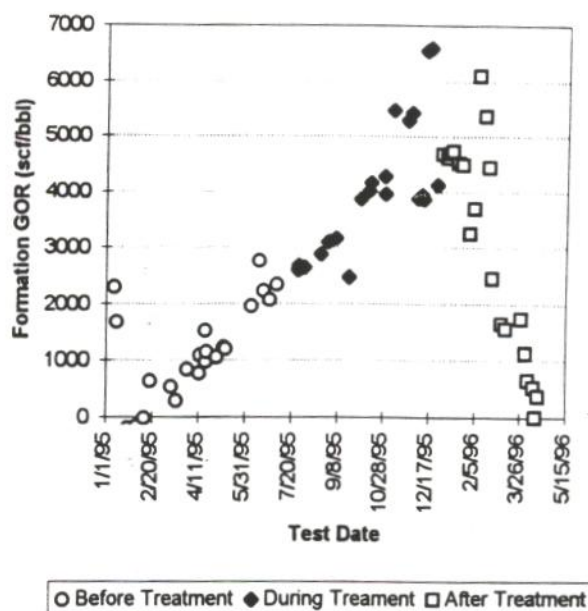


Figure 5: Produced formation gas to oil ratio (GOR) test separator data for well C.

Well C Production Test Data

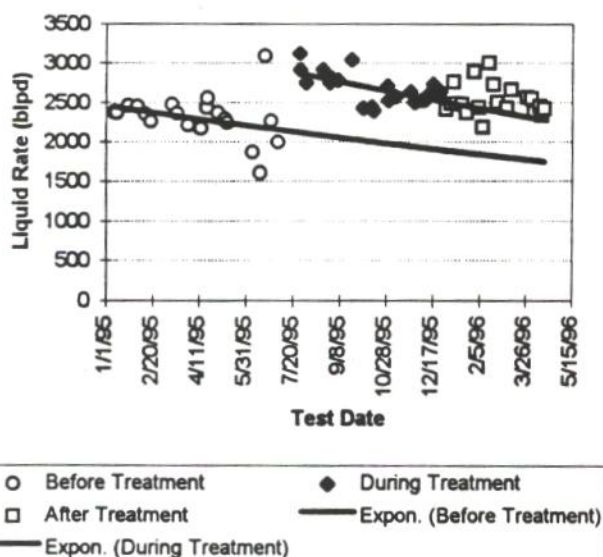


Figure 4: Test separator liquid rate data from 1/1/95, for well C. Pre and post-treatment exponential declines included.

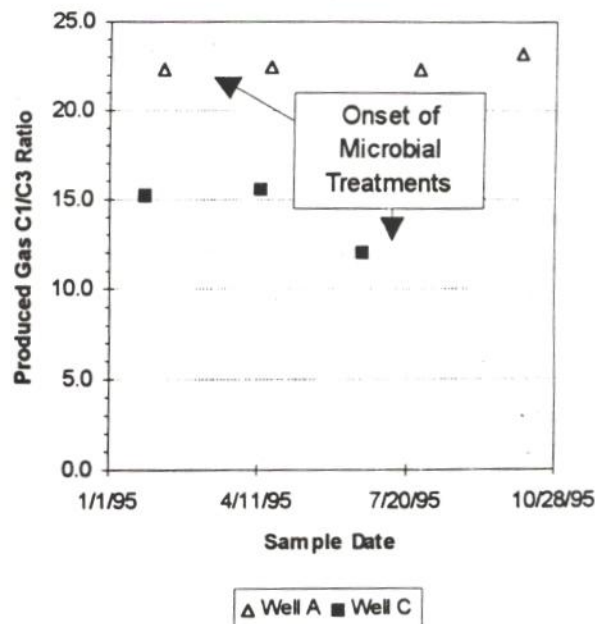


Figure 6: Produced gas compositional analysis results for wells A and C. Methane to pentane ratio (C1/C3) is an indicator of the relative amount of returned miscible injectant (MI). Baseline reservoir C1/C3 is approximately 21. A decrease in the C1/C3 value is an indicator of an increase in the amount of returned MI.

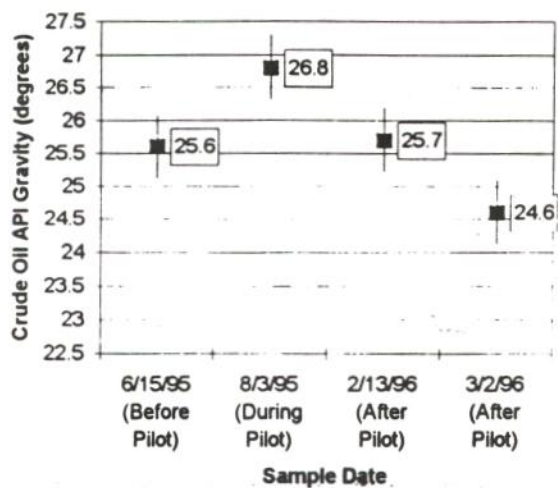


Figure 7: Well C crude oil API gravity measurements by ASTM D-287. Graph includes a 0.5 degree error bar according to ASTM testing standards.

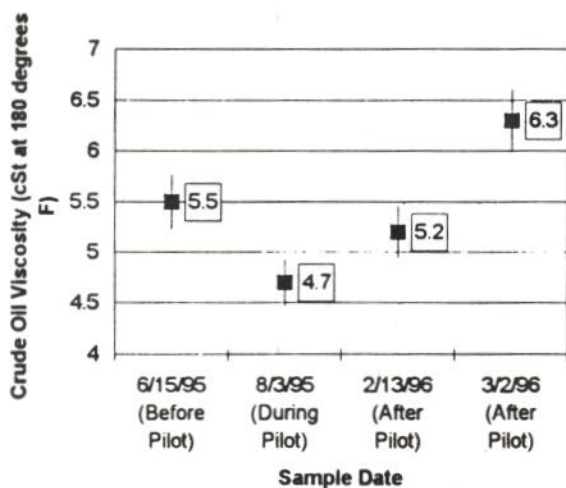


Figure 8: Well C crude oil viscosity measurements by ASTM method D-445. Graph includes 5% error established by ASTM testing procedures.

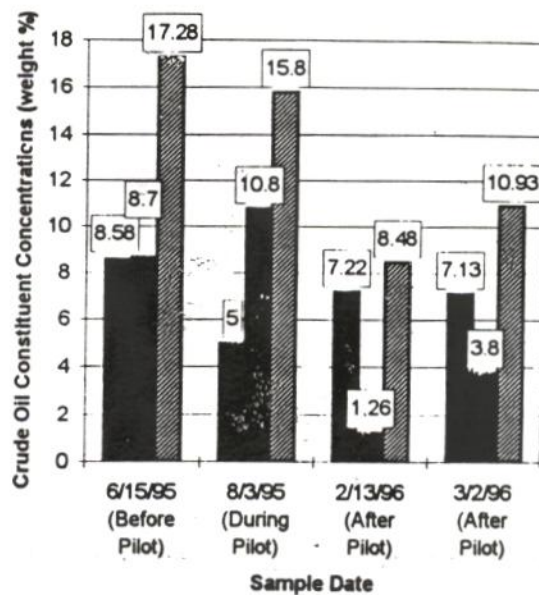


Figure 9: Asphaltene (ASTM D-3279) and paraffin (UOP-4664) concentration measurements for Well C.

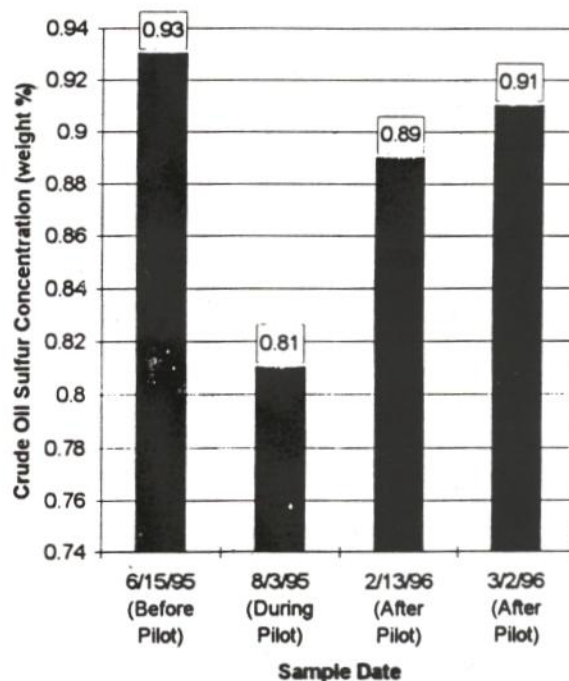


Figure 10: Sulfur concentration measurements for Well C by ASTM D-4294.