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MICROBIAL FLOODING INCREASES RECOVERY FACTOR OF DEPLETED PŁAWOWICE OIL FIELD – FROM LAB TO THE FIELD*****

1. INTRODUCTION

Development of bioproducts for application in crude oil production, transportation and storage began in the early in the early 1980's. This paper uses the term "bioproducts" to mean ready to use compositions of microbial species adapted to carry on specific metabolic processes under a variety of industrial conditions. Oil reservoir conditions are such that bioproducts used in hydrocarbon production technologies are most-likely produced in suspension in a 3% NaCl solution or higher.

A prerequisite for successfully implementing microbial oil recovery technology is selection of the proper bioproduct composition. It should be made up of synergistic microbial strains that can adapt to reservoir condition and exhibit optimum growth while producing the biochemicals and gases that improve the oil recovery factor (RF).

Practice has proven that the greatest benefits for the oil industry can be achieved using bioproducts for to:

- *microbial stimulation* of single wells to improve the flow of oil through the near well bore into the production tubing,
- *well bore clean-up* of single wells to remove paraffin residues in boreholes and surface installations, and mitigate near well bore damage,

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– *microbial enhanced waterflooding* of multi-well systems to increase overall recovery rates and extend the productive life of the treated injection/production system or oil field, and
– *bioremediation* – broadly defined as a microbial waste management technique used to remove or neutralize pollutants and hydrocabon contaminants from soil and water.

According to the most popular definition [11, 15, 16, 17], MEOR is a biological based technology, the purpose of which is to improve the recovery of oil entrapped in porous media while increasing economic profits. MEOR is considered to be a tertiary oil extraction technology allowing the partial recovery of the commonly residual two-thirds of oil, thus increasing the life of mature oil reservoirs. Tertiary production commences when waterflooding becomes uneconomical or when the rate falls below the economically limiting rate (Fig. 1).

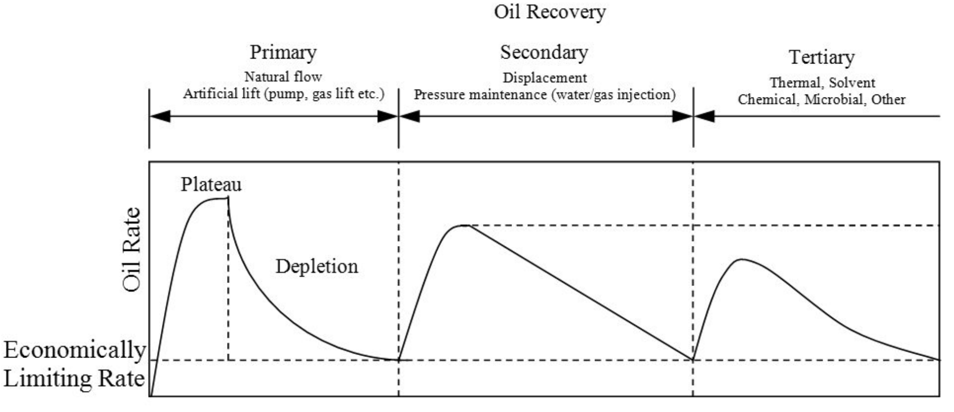

Fig. 1. Schematic of oil field production phases adapted from [9]

One of the most effective and widely understood MEOR technologies is microbial enhanced waterflooding. To implement this technology in the field, a standard waterflooding is modified by initially injecting suitable bacteria strains which can grow under the anaerobic reservoir conditions and colonize the reservoir bed. Standard waterflooding is continued after bioproduct injection, but nutrients such as beet molasses and mineral supplements containing phosphates are added to the injected water (brine) and periodically injected. (Fig. 2).

It is hard to assess the number of successful field projects that can be classified as being implemented with MEOR technology. Lazar [11] in 2007 estimated number to be few hundred. Most of them took place in the United States, Russia, Argentina [13], India, Malaysia and Romania. In the 1960s in Poland [9] a team led by Professor Karaskiewicz from Instytut Naftowy in Cracow (now Instytut Nafty i Gazu – Państwowy Instytut Badawczy) successfully completed number of treatments that, with some restrictions, can be qualified for the MEOR treatments.

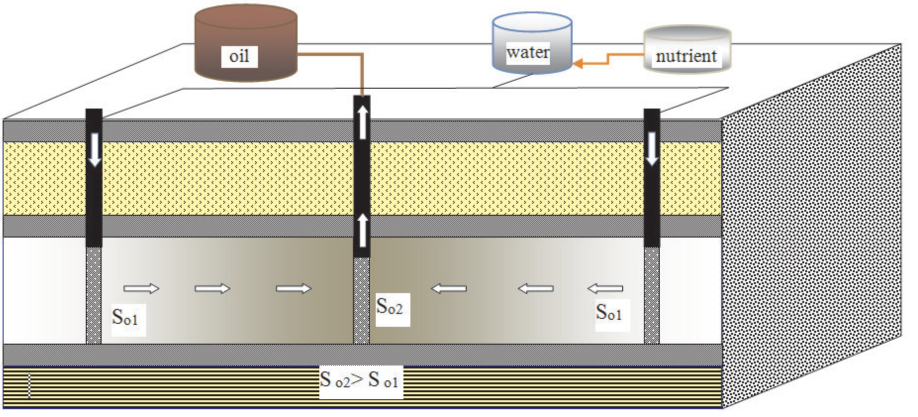

Fig. 2. Scheme of Microbial Enhanced Waterflooding treatment

Oil fields are selected for treatment with microbial technology based on a number of geochemical and geophysical factors of the reservoir in which they will reside. There are many factors that impact the physiology and growth characteristics of the bioproduct. The most crucial criteria are as follow:

- applicability temperature of microorganisms is between 10 to 85°C (optimum range is from 30 to 65°C);
- formation water salinity must be less than 15%; used in the procedures of 3% NaCl solution,
- pH of the environment must be greater than 3,
- H_2S content in the aqueous phase must be less than 10 000 ppm.

2. MECHANISM OF MEOR TREATMENTS

Mechanism of MEOR treatment that result in increased oil production is not fully understood [1, 2, 7, 11, 15, 16]. It is known that microorganisms produce a variety of compounds that are able to mobilize oil trapped in reservoirs and improve oil recovery such as surfactants, solvents, miscible gases, acids and biopolymers [1, 2]. However, there does not appear to be one single mechanism responsible for improved recovery performance, rather it is attributed to the multiple mechanisms operating synergistically.

Capillary pressure is the most basic rock-fluid characteristic of two-phase drainage flows and can be defined as in eq. (1):

$$P_{c_{ow}} = \frac{2\sigma_{ow}\cos\Theta_{ow}}{r} \tag{1}$$

where:

σ_{ow} – oil/water interfacial tension [mN/m],
Θ_{ow} – contact angle [°],
r – pore radius [μm].

Capillary pressure by itself does not cause flow – it is the pressure gradients within the phase that do this. However, capillary pressure can set up pressure gradients that will cause flow [10].

Products of anaerobic fermentation which occurs in reservoir during MEOR treatment may affect capillary pressure by:

- viscosity reduction caused by gases like CO_2 or H_2 and other miscible gases – changes in mobility ratio;
- wettability alteration – change of contact angle caused by surfactants and solvents;
- decreasing of interfacial tension caused by surfactants and solvents;
- permeability changes caused by acids or biofilm.

Wettability is a major factor controlling residual oil saturation, and thus, it is essential to characterize reservoir wettability. Reservoir rock wettability can be altered by contact with absorbable crude oil components as well as products of microbial metabolism, which can lead to heterogeneous forms of wettability (fractional or mixed wettability). A fractional-wet system is where a portion of the reservoir rock is strongly oil-wet, while the rest is strongly water-wet. Non uniform wettability can deflect the capillary pressure curve such that it no longer represents the true pore-size distribution and can have a dramatic effect on residual oil entrapment [10].

Oil recovery may be improved also by modifying the fluid flow through the reservoir by shifting fluid flow from the high permeability zones (preferential paths) to the moderate or low permeability zones thus increasing the sweep efficiency by forcing the injected water to pass through previously by-passed oil zones of the reservoir. The changes in flow pattern can be achieved by bio-clogging caused by an increase in biopolymers, biomass, microbial cells and precipitation of nutrient compounds in the pore space [3, 5, 11].

In addition, some of the fermentation processes are exothermic and may affect sweep efficiency especially in the case of shallow reservoirs.

All above described processes can occur synergistically, making MEOR extremely efficient technology. The great advantage of this technology is that once injected into the bed properly selected microorganisms are effective for a relatively long time, i.e. from six to eighteen months, and even longer.

3. REASONS FOR THE USE OF MICROBIALY ENHANCED OIL RECOVERY IN THE CARPATHIANS AND CARPATHIAN FORELAND

The most common basement oil trap in Carpathians and Carpathian Foreland is the combination structural-stratigraphic type with varying systems of sealing. Traps are related mainly to the sub-Miocene and less to the sub-Cretaceous unconformity. In Cenomanian sandstones occurs pinching-out stratigraphic traps [14].

Initially, many oil reservoirs had primary drive mechanism with the expansion (gas drive, gas cap) or water drive (connate water). It is assumed that average recovery factor after primary oil recovery is rather low and ranges from 10 to 25%. For a further increase in oil recovery, secondary recovery method must be employed which usually has a significant impact on the potential value of recovery of geological resources. Literature data show good results of secondary and tertiary oil recovery methods implemented in the Carpathians. Currently, production from most of the oil fields is carried out by pumping or applying inside-the-contour water flooding [5, 12].

One of the main problems, that must be resolved prior to suggestion of further exploitation of oil field in the Carpathians, is to assess Recovery Factor (RF) and thus assess remaining oil in place.

Estimation of this parameter can be made based on amount of produced oil from the beginning of the operation and theoretical recovery factor. It is assumed that the total oil production from the Carpathian oil fields has exceeded 12 million tonnes [12]. According to the literature, in the case of gravity regime, long-life production of oil field, and implemented secondary methods, the level of maximum recovery factor is about 0.4. Based on these values, it is easy to calculate that in the Carpathian deposits approx. 18 million tonnes of oil remain. Increasing the recovery factor by about 5% would give approx. 1.5 million tonnes of oil. Presented estimates were done on the averaged data from all Carpathians oil fields and do not take into consideration specifics and history of exploitation of various fields.

Results obtained on Carpathians oil fields Osobnica and Węglówka on which recovery factor after secondary recovery is on the level of 33 and 21%, respectively [12], suggest that in better technical condition of the stripper wells and implementation of tertiary oil recovery methods, a recovery of even 40% of documented recoverable reserves is possible.

One of the tertiary oil recovery methods which may increase recovery factor up to over 40%, without dramatic increase of production cost is microbial enhanced waterflooding.

4. COREFLOOD LABORATORY EVALUATION OF MICROBIAL SYSTEM (MS) EFFICIENCY AT PŁAWOWICE OIL FIELD SIMULATED CONDITIONS

The first step in the procedure of screening reservoirs for MEOR is checking reservoir parameters such as salinity, temperature, pH, H_2S content and performing laboratory tests using formation fluids.

Laboratory experiments performed in the Laboratory of Petroleum Engineering (INiG-PIB) focused on two areas; how much the selected microbes increase recovery factor and how they affect initial oil properties.

As mentioned above, microbial enhanced waterflooding is based on a single injection of microbial system into the bed, and then continuous waterflooding with addition of nutrient. In the case of Pławowice oil field, based on previous works [4, 5], selected microbial system was bioproduct produced by RAM Biochemicals Inc. which consist of three microbial strains: a facultative anaerobic surfactant strain, and anaerobic gas, acid and solvent strains. To facilitate implementation of this technology in Polish conditions in the laboratories of RAM Biochemicals Inc. preliminary selection of nutrient from the Polish Sugar factories was performed. The result showed the optimal nutrient is beet molasses produced by sugar factory from Ropczyce (southern Poland) in an amount up to 4% by weight of the injection water supplemented with lacking mineral nutrients required for microbial growth.

Because of lack of original formation rocks, cores were cut from the outcrop sandstone with absolute air permeability 2–1500 mD and porosity in a range 16–20%. The content of clay minerals was approximately 15% (mainly kaolinite and some mixed layered clay minerals i.e. illite and smectite). The plugs were cylinder – shaped with height 2.54 cm (1 inch) and length 4.5 cm. After determination of basic petrophysical parameters sandstone plugs were fully saturated by 5% NaCl. Then, irreducible water saturation was obtained by the oil flooding procedure. On plugs prepared in above described way water flooding treatment was performed, which let us to determine Waterflooding Recovery Factor (RF_{wf}). Then, prepared Microbial System (MS – bioproduct with nutrient) was injected into the plug in amount of about 0.5 of pore volume (PV) and plugs were incubated by 3 or 10 days. For selected samples additional injection of 1 PV of nutrient was performed (Tab. 2). After incubation time second waterflooding was performed and volume of additional recovered oil was measured. The difference between the two volumes of oil recovered represents the recovery efficiency (E_{mwf}) of the microbial system. Moreover, samples of oil were treated by microbial system and changes of viscosity and interfacial tension (IFT) were determined.

All flood tests were carried out in downhole simulated conditions on advanced lab stand TEMCO Inc. (now Core Lab, USA) intended for relative permeability measurements [6].

All saturation was carried out at the same rate equal 0.5 cm^3/min.

The complete procedure of the coreflood tests includes the following steps:

1. Measurement of absolute permeability k,
2. Vacuum saturation of core with brine (Sw = 100%) – evaluation of total Pore Volume (PV),
3. Saturation of core with oil (S_{wi}) – evaluation of total volume of oil in core V_{oi},
4. Saturation of core with brine (S_{or}) – evaluation of volume of recovered oil V_1,
5. Saturation of core with MS and incubation for 3 or 10 days,
6. Saturation of core with brine – evaluation of additional volume of recovered oil V_2.

Following formulas were used for computing:

– Waterflooding Recovery Factor (RF_{wf})

$$RF_{wf} = \frac{V_1}{Voi} 100\% \tag{2}$$

– Microbial Waterflooding Recovery Factor (RF_{mwf})

$$RF_{mwf} = \frac{V_1 + V_2}{Voi} 100\% \qquad (3)$$

– Efficiency of microbial waterflooding (E_{mwf})

$$E_{mwf} = RF_{mwf} - RF_{wf} \qquad (4)$$

Seven plugs were used in experiments. For six plugs complete procedure was implemented. One plug labeled “1-C” was treated as control what means these cores have not been saturated by microbial system. Results of performed tests are presented in Table 1 and 2.

Table 1

Effectiveness of waterflooding treatment at Pławowice oil field

Core	Air permeability [mD]	Perm for brine & S(or) [mD]	Core PV total [cm^3]	Amount of oil in core [cm^3]	Water flooding		
					Oil displaced [cm^3]	Oil remained [cm^3]	RF_{wf} [%]
1-C	267	4.1	4.36	3.0	1.0	2.0	**33.3**
2	295	1.82	4.30	2.8	1.1	1.7	**39.3**
3	424	5.64	4.15	2.6	1.1	1.5	**42.3**
4	344	5.4	4.17	2.6	1.2	1.4	**46.2**
5	335	4.3	4.21	2.2	1.3	0.9	**59.1**
14	81	0.73	6.54	3.8	0.9	2.9	**23.7**
15	97	0.85	6.52	4.3	0.9	3.4	**20.9**

Table 2

Results of laboratory evaluation of MEOR efficiency at Pławowice oil field

Core	RF_{wf} [%]	injected MS [PV]	Additional nutrient		Total time of incubation [days]	RF_{wfm} [%]	E_{mwf} [%]
			Amount of nutrient [PV]	Day of application			
1-C	33.3	X	X	X	3	33.3	**0.0**
2	39.3	0.5	1	2	3	55.4	**16.1**
3	42.3	0.5	1	3	3	53.8	**11.5**
4	46.2	0.5	X	X	10	50.0	**3.8**
5	59.1	0.5	1	7	10	61.4	**2.3**
14	23.7	0.5	X	X	10	27.6	**3.9**
15	20.9	0.5	1	7	10	24.4	**3.5**

In the case of simulated in laboratory treatment at Pławowice oil field waterflooding recovery factor RF_{wf} for examined plugs was in the range from 20.9% to 59.1%. This comes to a laboratory average value of RF equal to 38.6%, which is in the range of typical RF values for oil fields produced in the waterflooding regime EOR. Performed MEOR treatment after EOR depletion, gave an increase RF from 5 to 16%, which gives the analyzed 6 plugs an average value of ca. 7% beyond the EOR. Based on the obtained laboratory results and the available reservoir data, basic technological parameters of MEOR Pławowice program were determined.

5. PROGRAM OF MICROBIALY ENHANCED OIL RECOVERY AT PŁAWOWICE OIL FIELD

Pławowice oil field was discovered in 1963 (Fig. 3). Because of the very complicated structure of the field, two different drive mechanisms exist. Only the Cenomanian sandstones produce oil under the water-drive mechanism, with reservoir pressure exceeding the saturation pressure. The upper Oxfordian limestones and overlying Cenomanian conglomerates produce oil under the dissolved gas mechanism [14]. Maximum production of about 76 765 tonnes of oil was noticed in 1968, what gives approximately 210 tonnes of oil per day from 69 production wells. The maximum production rate from one well (Pl-3) was 21 tonnes/day. Currently, the highest production is observed in the well Pl-41, i.e. 38 600 tonnes, while the total production from Pławowice oil field exceed 602 000 tonnes of oil. In the years 1978–1986 waterflooding by two injectors was implemented. The observed influence of water on the production wells enabled distinguishing a zone of higher permeability (area of wells: Pl-52, Pl-53, Pl-159). These historical data had great impact on decision about choosing injector Pl-311 for MEOR treatment. Well Pl-311 is located on the anticline peak and the injected water flows downslope of the reservoir bed in the direction of well Pl-52 and Pl-159; these production wells are respectively 350 m and 410 m distant from the injector and 300 m apart from each other. Additionally, for the MEOR project two injectors Pl-311 and Pl-23 were chosen which affect the production of wells Pl-52, Pl-159 and Pl-41 and Pl-43, respectively. Basic reservoir and production data (2010) of selected production wells are given in Table 3.

In September 2011 prepared bioproduct was diluted and injected to well Pl-311 and Pl-23. Procedure of MEOR treatment was described in details in [5]. During monitoring program each month samples of reservoir fluids were collected in order to perform tests of viscosity and IFT as well as water analysis. Obtained data were needed to assess the project effectiveness and suggestion of technology modification. One month after bioproduct injection well Pl-23 was shut-off because of some technical problems. That is why further production data analysis was only for well Pl-52 and Pl-159.

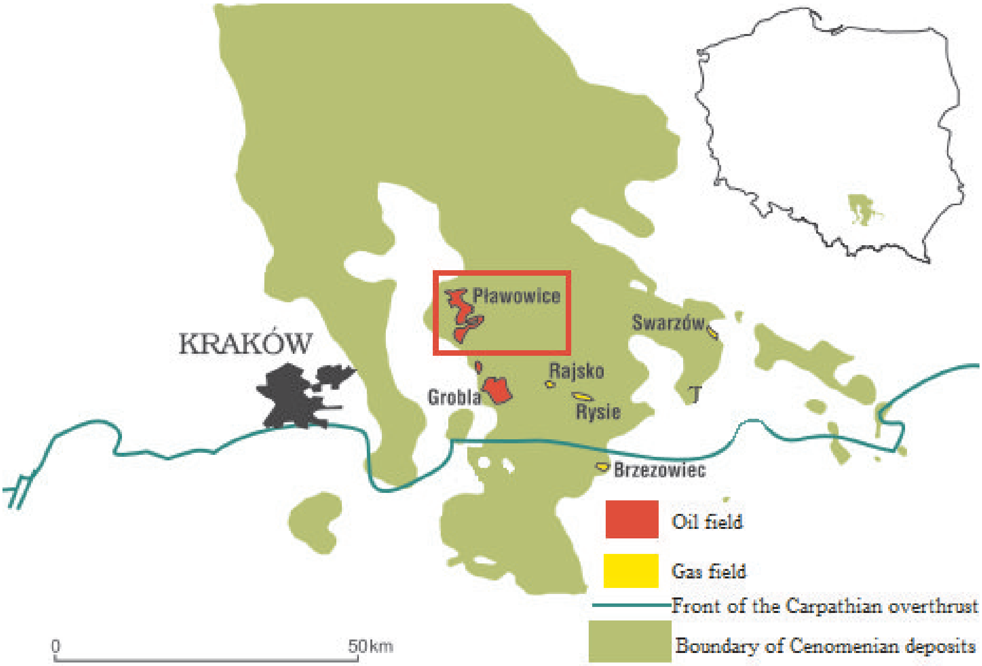

Fig. 3. Occurrence of gas and oil fields in Cenomanian deposits (adapted from [8])

Table 3

Selected production wells

	Injector	Producer	Producer	Producer
Well	Pl-311	Pl-41	Pl-52	Pl-159
Temperature [^{o}C]	24	23	24	24
Pressure [MPa]	X	0.13	0.1	0.6
Oil production [t/d]	X	4.4	2.3	1.8
Water injection/production [t/d]	3	0.4	0.05	0.2
Thickness of pay zone [m]	6.6	3.5	8.5	6

6. MEOR PROJECT EVALUATION

MEOR's long-term distinctive response is to increase net oil rate and simultaneously to reduce Water Cut. This typical duality in MEOR response is explained by the change in apparent oil and water mobility in the colonized portion of the reservoir – the bioreactor.

Changes in production are a key indicator of the MEOR project effectiveness. They are calculated based on production data in each month Q_m and average production in 9 months before the treatment Q_{av} using eq. (5):

$$\Delta Q = \left(\frac{Q_m - Q_{av}}{Q_{av}} \right) 100\% \tag{5}$$

After 6 month of microbial system injection in both producers significant increase of production was observed. As it is shown on the Figures 4 and 5 implementation of MEOR project dramatically changed the production of Pl-52 in which increase of over 110% was observed.

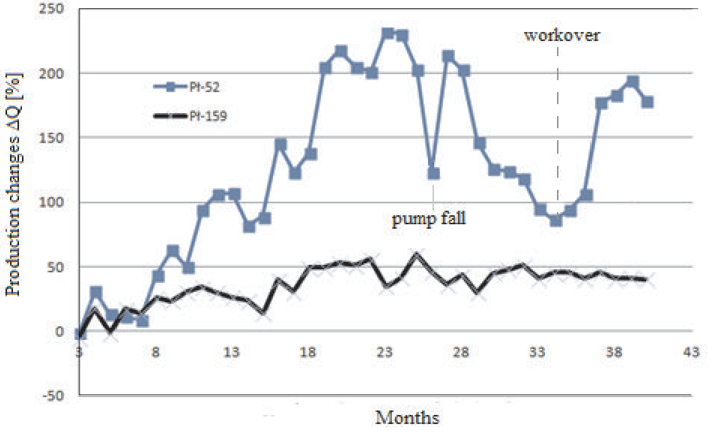

Fig. 4. Post-treatment Production changes of the well Pl-52 and Pl-159

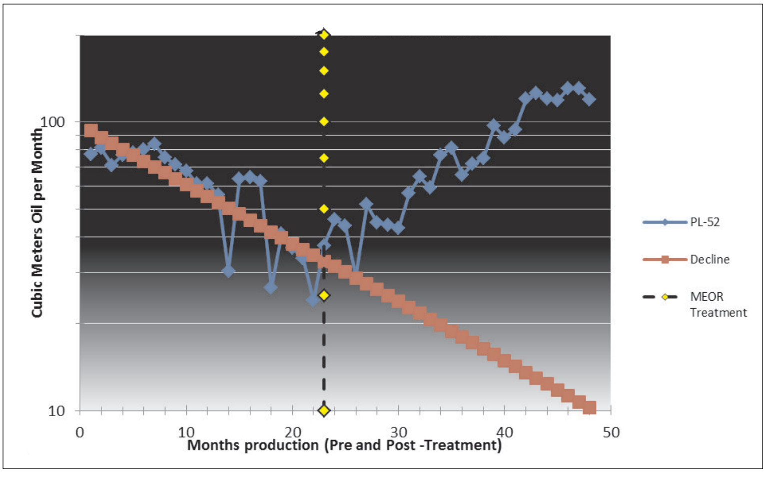

Fig. 5. Production changes in Pl-52 well showing 23 months of pre-treatment and post-treatment data

Figure 5 shows Pl-52 monthly production (blue line) and its decline trend line (red line). Pl-52 pre-treatment data shows a steep decline in production yet the well retains the ability to produce oil without a water cut. Post-treatment data shows a dramatic reversal of the decline curve and the ability to increase the pump rate (hours of pumping per month). The major laboratory and field findings show a decrease in viscosity after treatment (Tab. 4). The increased production can be linked directly mobility control allowing the ability to pump the well longer. It also shows that the production increase has been sustained over the course of the treatment.

Table 4

Pre and Post-treatment viscosity and density data

Well	Viscosity Pre-MEOR	Viscosity Post-MEOR	Density Pre-MEOR [°API]	Density Post-MEOR [°API]
Pl-52	14.74	9.52	32.5	36.0
Pl-159	14.96	9.79	32.5	35.9

Pl-159 pre-treatment data shows a negligible decline curve when plotted independently. Post-treatment data reflects the effects of lowered viscosity and interfacial tension caused by the microbial treatment. As with the Pl-52 well, there is the ability to pump Pl-159 longer in a sustainable fashion. Pl-159 shows a noticeable monthly increase in the volume of oil produced above the pre-treatment base line volume despite showing a slightly lower water cut.

7. CONCLUDING REMARKS

As a result of microbial enhanced waterflooding at the Pławowice oil field the first two years of the project produced ca. 2000 tons of oil that would otherwise not have been produced. Average production of the two wells involved in Phase I increased by 71%. These spectacular results were obtained with relatively low investment. Moreover, break-event-point was reached in the 8th month of the project. Based on these results, the authors have recommended the Plawowice project to be continued on Pl-311/Pl-52, Pl-159 and on additional injection/producer systems. Moreover, that microbial technology should be investigated for use on other oil fields in the Carpathians and Carpathian Foreland.

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