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(54) Title: METHOD OF ENHANCING OIL RECOVERY

(57) Abstract: The invention provides a method of enhancing oil recovery from a subterranean hydrocarbon reservoir, said method comprising injecting into said reservoir through a matrix injection section of a well a microorganism capable of digesting oil, and recovering oil from an oil receiving section of a production well, where said injection section is in said production well or is in an injection well and is above or adjacent said oil receiving section, and wherein microorganism injection is preceded by another oil extraction enhancing procedure.



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Method of enhancing oil recovery

This invention relates to a method of enhancing oil recovery from a subterranean hydrocarbon reservoir and to compositions for use in such methods.

Hydrocarbons, i.e. gas and oils, are a limited resource and thus it is important to maximize the amount of oil that is recovered from underground reservoirs.

For certain reservoirs, particularly heavy oil reservoirs in which the oil contains large quantities of long chain hydrocarbons, paraffins, waxes, aromatics (including polyaromatic hydrocarbons - PAH), terpenoids, asphaltenes, etc., oil sand or shale reservoirs, and bitumen reservoirs the techniques currently used result in the recovery of less than 10% wt. of the oil in the reservoir. To a large extent this is because the oil is of such a high viscosity, or otherwise flows so poorly, that only limited quantities will reach the production wells.

One approach that has been adopted to this problem is to inject superheated steam down injection wells above the production wells, e.g. in substantially horizontal sections of the bore holes where the injection bore hole is above the production bore hole. The temperature increase resulting from superheated steam injection serves to reduce the viscosity of the heavy oil which then, under the influence of gravity, flows more readily into the production bore hole. This procedure has been referred to as steam-assisted gravity drainage (SAG-D) or VAPEX.

A further approach to increasing hydrocarbon recovery is hot solvent extraction in which a heated organic solvent is injected into the matrix to reduce the viscosity of the hydrocarbon and improve its flow characteristics in the matrix. In this technique, injection may be into an injection bore hole (i.e. as with steam injection) or it may be into the production bore hole. Typically the hot solvent used is selected from naphtha, diesel, toluene, and other hydrocarbon fractions. The injection temperature will typically be in

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the range 20 to 400°C, especially 80 to 100°C.

Yet another extraction enhancement procedure is cold heavy oil production with sand (CHOPS) which involves sand influx into the production well. Another procedure is hydraulic fragmentation (fracking) of the matrix at the production well. Further examples of enhanced oil recovery techniques for heavy oil, oil sand or bitumen reservoirs include cyclic steam stimulation (CSS), and pulsed pressure flow enhancement. Down-hole generation of gases to increase down-hole pressure and hence oil flow into the production well may also involve direct contact steam generation and thermal oxidation processes (to generate CO₂ from combustion of hydrocarbons down-hole).

The techniques however are cumbersome, environmentally unfriendly and improvements and alternatives are desirable.

We have now realized that oil recovery may be enhanced if heavy oil-degrading microorganisms are introduced through an injection well into the formation above or adjacent a separate production well or into the formation at a production well, in conjunction with other oil recovery enhancement techniques such as steam injection, hot solvent extraction, CHOPS, fracking, CSS, etc., as described above.

Thus viewed from one aspect the invention provides a method of enhancing oil recovery from a subterranean hydrocarbon reservoir, especially a heavy oil reservoir, said method comprising injecting into said reservoir through a matrix injection section of a well a microorganism capable of digesting oil, and recovering oil from an oil receiving section of a production well, where said injection section is in said production well (e.g. at said oil receiving section) or is in an injection well and is above or adjacent said oil receiving section, and wherein microorganism injection is preceded by another oil extraction enhancing procedure (such as steam or hot solvent injection, CHOPS, hydraulic fragmentation, etc.), particularly preferably through the same injection section, e.g. 1 to 150 days beforehand

Microorganism injection is especially preferably effected through a plurality of injection wells for the (or each) production well, e.g. 5 to 20 such injection wells, for example using an array of "slim" injection wells each terminating (i.e. with a matrix entry site) near a matrix exit site of the production well, i.e. multi-tracking injection wells. This is particularly desirable for shallow reservoirs, e.g. at a depth of 200 to 600 m subsurface. This is shown schematically in the accompanying Figure.

By oil degrading or oil digesting it is meant that the microorganism (or microorganism mixture) is capable of chemically modifying oil to reduce the viscosity or wax, asphaltene or aromatics content thereof whereby to cause it to flow more freely in the matrix (i.e. the rock from which the reservoir is formed). Such modification will generally involve fragmentation of one or more components of the oil (e.g. fragmentation of alkanes into smaller alkanes), ring opening in aromatic compounds, or opening or cleavage of other large organic compounds, for example asphaltenes. Desirably, the microorganisms cleave or fragment the oil components so as to render the oil viscosity sufficiently low as to enhance oil recovery. Thus it is preferred that the microorganism used not simply be one that generates a surfactant or a gas (e.g. methane), and particularly preferably a microorganism cocktail is used which causes ring opening, especially in combination with a microorganism that causes hydrocarbon chain shortening. Other factors remaining constant, production flow is approximately inversely proportional to the down-hole (heavy) oil viscosity and so degradation using the technique of the invention may enhance liquid hydrocarbon flow by a factor of from ten to hundreds of percent by volume.

Many microorganisms (generally eubacteria or archae) are known to digest oil and such microorganisms may be used in the method of the present invention if they are capable of surviving at the temperatures and pressures experienced down-hole. Typical examples include *Bacillus* sp., *Thermus* sp., *Pseudomonas* sp., *Geobacillus* sp., *Arthrobacter* sp., *Sphingomonas* sp., *Mycobacterium* sp.,

Burholderia sp., *Acinebacter* sp., *Thermovirga* sp., *Archaeoglobus* sp., *Thermosiphon* sp., *Symbiobacterium* sp., *Methanosaeta* sp., *Epsilonproteobacterium* sp., *Syntrophus* sp., *Nocardioideis* sp., *Deferribacter* sp., *Chloraflexi* sp., etc.

Preferably however the inoculate, the microorganism composition injected in accordance with the present invention, will contain at least 2 and preferably at least 3 different microorganism species, in particular at least one capable of chain-shortening alkanes and at least one capable of ring opening aromatics. Examples of microorganisms capable of chain-shortening alkanes include *Bacillus* sp., *Geobacillus* sp., *Acinebacter* sp., *Methanosaeta* sp. and in particular *Acinebacter venetianus*, *Bacillus thermoleovorans*, *Bacillus aeolis* and *Geobacillus thermodenitrificans* while examples of microorganisms capable of degrading aromatics include *Nocardioideis* sp., *Geobacillus* sp., and *Syntrophus* sp., eg *Geobacillus subterraneus*. Use of *Thermus* sp. will result in decrease of aromatics, resins and asphaltenes and reduced viscosity, eg *Thermus* strains SP3, C2 and TH-2 (see Hao *et al.* J. Can. Petrol. Technol. 43:36-39 (2003), Can. J. Microbiol. 50:175-182(2004), and J. Petrol. Sci. Eng. 43:247-258(2004)). Use of *Pseudomonas* sp. will result in n-alkane and PAH degradation and reduced viscosity, eg *Pseudomonas aeruginosa*. Moreover, *Thermus brockii* is capable of degrading hexadecane and pyrenes (see Geitkenhauer *et al.*, Water Sci Technol 47: 123-130(2003)).

Rather than producing a microorganism inoculation composition by mixing (top-side or on site) individual microorganisms, it is possible and indeed preferable to use microorganism cocktails from or developed from naturally occurring microorganism communities, e.g. microorganism communities from subterranean hydrocarbon reservoirs, from oil shales, bitumen sources, or, especially from mud volcanoes. Likewise appropriate microorganisms may of course be produced by mutagenesis or by genetic engineering.

It is especially preferred that the inoculate contain microorganisms selected from the species *Bacillus thermoleovorans*, *Thermus brockii*, *Syntrophus aciditrophicus*, *Acinebacter venetianus*, *Deferribacter desulfuricans*, *Thermosiphon*

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geolei, *Thermosipho africanus*, *Symbiobacterium thermophilum*, *Thermovirga lienii*, *Sphingomonas stygia*, *Sphingomonas aromaticivorans*, *Sphingomonas subterranean*, *Sphingomonas yanoikuyae*, *Pseudomonas putida*, *Burholderia sp.*

and *Archaeoglobus fulgidus*. Particular deposited strains that can be used include *Bacillus thermoleovorans* AB034902 (Genbank), *Bacillus aeolis* AY603079 (Genbank), *Pseudomonas aeruginosa* AM087130 (Genbank), *Geobacillus thermodenitrificans* DQ243788 (Genbank), *Geobacillus subterraneus* DQ355385 (Genbank), *Sphingomonas stygia* DSMZ12445, *Sphingomonas sp* DSMZ 7526, *Sphingomonas sp* DSMZ 11094, *Sphingomonas aromaticivorans* DSMZ 12444, *Sphingomonas subterranean* DSMZ 12447, *Sphingomonas yanoikuyae* DSMZ 6900, *Pseudomonas putida* NCIMB 9815, *Pseudomonas putida* NCIMB 9816, *Pseudomonas putida* NCIMB 10015, *Methanosaeta sp.* AJ 133791, *Epsilonproteobacteria* AY 570641, *Syntrophus aciditrophicus* CP 000252, *Nocardioides sp.* D 87974, *Deferribacter desulfuricans* AB 086060, *Chlorflexi sp.* AB 074961, *Thermovirga lienii* DQ 071273, *Archaeoglobus fulgidus* DQ 131905, *Thermosipho geolei* AJ 272022, *Acinebacter venetianus* ATCC 31012 and *Symbiobacterium sp.* AB 052392. It is particularly preferred that it contain microorganisms of at least the species *Sphingomonas sp.*, *Pseudomonas sp.*, *Burholderia sp.*, *Thermovirga lienii*, *Archaeoglobus fulgidus*, *Acinebacter venetianus*, *Thermosipho geolii* and *Symbiobacterium sp.* Such mixtures are new and form a further aspect of the invention. Viewed from this aspect, the invention provides a microorganism mixture for hydrocarbon reservoir treatment, said mixture comprising microorganisms of at least two, preferably at least three, of the following species: *Sphingomonas sp.*, *Pseudomonas sp.*, *Burholderia sp.*, *Thermovirga lienii*, *Archaeoglobus fulgidus*, *Acinebacter venetianus*, *Thermosipho geolii* and *Symbiobacterium sp.* in particular a said mixture further comprising vitamins and minerals and preferably a mixture in liquid or dry powder form, and preferably alkane-free, eg isolated from any matrix or hydrocarbon in which it may occur naturally.

In particular, a combination of *Sphingomonas sp.*, *Pseudomonas sp.*, and *Burholderia sp.* may be used, eg *Sphingomonas stygia*, *Sphingomonas*

aromaticivorans, *Sphingomonas subterranean*, *Sphingomonas yanoikuyae*, *Pseudomonas putida*, and *Burholderia sp.*, especially *Sphingomonas stygia* DSMZ12445, *Sphingomonas sp* DSMZ 7526, *Sphingomonas sp* DSMZ 11094, *Sphingomonas aromaticivorans* DSMZ 12444, *Sphingomonas subterranean* DSMZ 12447, *Sphingomonas yanoikuyae* DSMZ 6900, *Pseudomonas putida* NCIMB 9815, *Pseudomonas putida* NCIMB 9816, *Pseudomonas putida* NCIMB 10015, and *Burholderia sp.*

For shallow oil fields it may be adequate to use in the inoculate microorganisms that grow at atmospheric pressure, however for deeper fields it is important that the microorganism be both thermophiles and piezophiles.

Selecting appropriate combinations of microorganisms for use in shallow fields is thus relatively simple. A candidate microorganism or microorganism cocktail may be incubated with a sample of heavy oil, preferably from the site to be treated, and if a reduction in viscosity is achieved the candidate may proceed. For deeper fields the incubation is preferably effected at the down hole temperatures and/or pressures of the site to be treated. In both cases, the ability to withstand temperatures of 60 to 120°C, especially 70 to 100°C is preferred as such microorganisms may readily be injected into sites where steam or hot solvent injection has been, is being or is to be effected : otherwise a significant delay between steam or hot solvent injection and microorganism injection may be required.

Where steam or hot solvent injection is to be used in the method of the invention, the timing of the microorganism injection should be such that the microorganisms are not injected into an environment in which the temperature is lethal. The delay time for microorganism injection may readily be calculated from the heat dissipation characteristic of the matrix.

Screening of a microorganism cocktail is preferably done repeatedly, with an aliquot of the culture at the end of one digestion period then being presented with a fresh heavy oil sample to digest. This is important as degradation may

require the contribution of one microorganism species after that of another and it may thus be necessary that, down hole, all of the necessary species continue to grow. Where, after several digestions, the microorganism population is stable, the candidate may be developed further.

Before down hole injection, the microorganism inoculate is preferably mixed with oil to prime its enzyme systems.

Down hole injection of the microorganism may if desired be preceded by, accompanied by or followed by down hole injection of nutrients for microorganism growth, e.g. minerals and amino acids, or oil digesting enzymes. The injection of further carbon sources, eg ones such as acetate which are water-soluble, is particularly preferred.

Down hole injection of the microorganism may if desired be preceded by fracturing of the matrix around the injection site, e.g. to provide a reservoir for microorganism growth.

Down hole injection of the microorganism into an injection well is preferably effected in conjunction with steam or superheated water or organic solvent injection down the same injection well, e.g. at an injection temperature of 100-400°C. This injection may precede microorganism injection (where the steam or solvent injection temperature is lethal to the microorganisms) or may occur simultaneously; however it is preferred that the enhanced oil recovery technique, steam or hot solvent injection, be effected before microorganism injection, e.g. a period of up to 1 year, for example 1 to 150 days, preferably 5 to 20 days, beforehand. Particularly desirably, the enhanced oil recovery technique (eg steam or hot solvent injection) and microorganism injection are effected repeatedly, in particular in specifically designed sequenced procedures.

Down hole injection of the microorganism into a production well is preferably effected in conjunction with the enhanced oil recovery technique, e.g.

CHOPS, hot organic solvent injection, hydraulic fragmentation, etc.; this may precede microorganism injection or be performed simultaneously or later. In the case of hot solvent injection, solvent injection is preferably effected beforehand with a sufficient time delay that the matrix temperature is tolerable to the microorganisms when they are injected, e.g. a delay of up to 1 year, for example 1 to 150 days, especially 5 to 20 days. Such treatments of a production well are preferably repeated.

Particularly preferably, microorganisms are injected into both injection and production wells, in each case preferably in conjunction with a further hydrocarbon extraction enhancing technique (i.e. SAG-D, CHOPS, etc).

If desired the microorganism inoculate may include microorganisms which generate gas and/or acid and hence degrade the matrix.

The method of the invention can serve to reduce the usage or aggressiveness of the other hydrocarbon extraction enhancing techniques, such as SAG-D and so reduce their environmental impact.

The invention is especially applicable to hydrocarbon reservoirs which yield heavy oils, e.g. from medium crude (31-22 API) to heavy crude (22-10 API) to extra heavy crude (<10 API) oils, and the microorganism treatment, particularly with thermophilic and/or piezophilic microorganisms, is preferably in conjunction with, e.g. simultaneously or sequentially, at least one of SAG-D, CHOPS, VAPEX, hot solvent extraction and hot water extraction.

The invention will now be illustrated by the following non-limiting Examples and the accompanying drawings, in which:

Figure 1 is a schematic vertical section through a shallow heavy oil reservoir; and Figure 2 is a chart of oil recovery and oil viscosity without and with treatment according to the invention.

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Referring to Figure 1 there is shown an offshore platform 1 having a producer well 2 extending into a shallow heavy oil reservoir 3. From platform 1 a series of slim injector wells 4 are fed by injection unit 5 which serves to inject steam and microorganism culture sequentially.

Example 1

Treatment of Zuata crude oil with microorganisms endogenous to Argentine bitumen

Materials:

Bitumen (from Argentina)

Treatment medium 1 (TMS1) content per litre: 5 g $\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$, 0.29 g $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$, 0.44 g $\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$, 0.15 g $\text{MnSO}_4 \cdot \text{H}_2\text{O}$, 0.01 g $\text{Na}_2\text{MoO}_4 \cdot 2\text{H}_2\text{O}$, 0.02 g $\text{CoCl}_2 \cdot 6\text{H}_2\text{O}$, 50 ml conc HCl.

Treatment medium 3 (TMS3) content per litre: 2021.2 mg $\text{Na}_2\text{SiO}_3 \cdot 9\text{H}_2\text{O}$, 445.5 mg NaF, 5651.7 mg $\text{K}_2\text{B}_4\text{O}_7 \cdot 4\text{H}_2\text{O}$, 47.9 mg NaIO_3 , 180.7 mg $\text{KAl}(\text{SO}_4)_2 \cdot 12\text{H}_2\text{O}$, $\text{SnCl}_2 \cdot 2\text{H}_2\text{O}$.

Treatment medium 4 (TMS4) content per litre: 346.8 mg $\text{NiCl}_2 \cdot 6\text{H}_2\text{O}$, 101.4 mg $\text{Na}_2\text{SeO}_3 \cdot 5\text{H}_2\text{O}$, 18 mg V_2O_5 , 14 mg $\text{K}_2\text{Cr}_2\text{O}_7$, 3.6 mg $\text{Na}_2\text{WO}_4 \cdot 2\text{H}_2\text{O}$.

Vitamin stock solution (VSS) content per litre: 2.00 g biotin, 2.00 g folic acid, 10.00 g pyridoxine-HCl, 5.00 g thiamine-HCl $\cdot 2\text{H}_2\text{O}$, 5.00 g riboflavin, 5.00 g nicotinic acid, 5.00 g D-Ca-pantothenate, 0.10 g vitamin B12, 5.00 g p-aminobenzoic acid, 5.00 g lipoic acid.

Mineral medium (MM) content per litre: 0.9 g NH_4NO_3 , 0.05 g $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, 0.2 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 3.06 g $\text{Na}_2\text{HPO}_4 \cdot 2\text{H}_2\text{O}$, 1.52 g KH_2PO_4 , 1 ml TMS1, 1 ml TMS3, 1 ml TMS4, 1 ml VSS. pH adjusted to pH 7.0.

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Process medium 1 (PM1): Zuata crude oil (from Venezuela) 0.4 % (w/vol) in MM

Process medium 2 (PM2): Zuata crude oil 1.6% (w/vol) in Light Gas Oil (LGO), 1 % (vol/vol) in MM

Inoculation:

Bitumen samples (0.5 g) were inoculated into shakeflasks (Bellco, 250 ml) containing 50 ml PM1 or PM2.

Cultivation:

The shake flasks were incubated at 50 °C on a rotary shaker at 200 rpm and 90 % humidity (Infors Multitron incubator) for 34 days.

Example 2Treatment of Zuata heavy oil with microorganisms endogenous to a mud volcano**Materials:**

Mud from mud volcano

Widdel Basal Salt Media B (WBSB) content per litre: 30.0 g NaCl, 0.15 g $\text{CaCl}_2 \cdot 2\text{H}_2\text{O}$, 3.0 g $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$, 0.9 g NH_4NO_3 , 0.5 g KCl, 0.18 g Na_2SO_4 , 3.06 g $\text{Na}_2\text{HPO}_4 \cdot 2\text{H}_2\text{O}$, 1.52 g KH_2PO_4 , 1 ml TMS1, 1 ml TMS3, 1 ml TMS4, 1 ml VSS. pH adjusted to 8.2.

Process medium 3 (PM3): Zuata crude oil dissolved 10% (w/vol) in heptamethyl nonane (HMN – an inert solute) added 5% (vol/vol) to WBSB

Inoculation:

Mud samples (0.5 ml) were inoculated into shakeflasks (Bellco, 250 ml) containing 50 ml PM3.

Cultivation:

The shake flasks were incubated at 50 °C on a rotary shaker at 200 rpm and 90 % humidity (Infors Multitron incubator) for 28 days.

Example 3**Treatment of Linerle crude oil with microorganism cocktail****Materials:**

Microorganism cocktail (MC): A mixture of the following strains:

Pseudomonas putida NCIMB 9815, NCIMB 9816 and NCIMB 10015 and *Burkholderia sp* isolates from bio-sludge from a refinery water treatment plant.

The microorganisms were cultivated in inoculum medium (IM) for up to 24 hours and harvested by centrifugation (10 min, 5 000 x g). The cell-pellets were washed twice with MM medium (20 ml) and the pellet resuspended in MM medium (500 µl). The microorganism cocktail (MC) was prepared by mixing the washed and resuspended microorganisms in equal concentrations.

Inoculum medium (IM) per litre: 20.0 g yeast extract, 1.0 g $\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$, 5 g NaCl, pH adjusted to 7.5.

Process medium 4 (PM4): 5 % (vol/vol) heat-treated Linerle crude oil (from the Norwegian continental shelf, heated to 60°C for 2 hours) was added to MM.

Process medium 4 with yeast extract (PM4-YE): 5 % (vol/vol) heat-treated Linerle crude oil (from the Norwegian continental shelf, heated to 60°C for 2 hours) was added to MM containing 0.1 g yeast extract.

Inoculation:

The MC was inoculation into shakeflasks (Bellco, 250 ml) containing 50 ml PM4 or 50 ml PM4-YE to a final $\text{OD}_{660} = 1.0$.

Cultivation:

The shake flasks were incubated at 30 °C on a rotary shaker at 200 rpm

(Infors Multitron incubator) for 9 days.

Example 4

Treatment of Zuata heavy oil in sand with microorganisms from sediment

Materials:

Microorganism inoculum (MI): A mixed inoculum of microorganisms isolated from sediment samples

Sand column: Zuata crude oil mixed in a 9:36 weight ratio with barskarp sand, packed into glass columns (Omnifit).

Inoculation:

MI (5 ml, approx 10^9 cells/ml) was added to the sand column after water flooding the column for 4 days.

Cultivation:

After inoculation, the sand columns were shut-in for 24 hours prior to circulation of MM was initiated. MM was circulated at a rate of 171 ml/hour.

The results of this treatment of heavy oil in reservoir-like conditions is shown in Figure 2 of the attached drawings. Figure 2 shows the oil recovery from sand packs as a percentage of standard total original in place (STOOIP - right hand ordinate and plot) and the viscosity in mPa.s of the treated oil at a shear rate of 100 s^{-1} and 55°C (left hand ordinate and bar chart). The left hand values are for Zuata heavy oil without treatment. The centre values are for Zuata heavy oil treated under the conditions specified in this Example. The right hand values are for Zuata heavy oil treated under the conditions specified in this Example, but with the addition of 5 g/L acetate (eg sodium acetate) to the MM.

Example 5

Viscosity effect on crude oils

The viscosity of treated and untreated heavy crude oil type 1 was determined at 30°C at a shear of up to 1000 s⁻¹. While untreated gave a viscosity value of 417 mPas, for the treated sample this was reduced to 130 mPas. In a further test using Zuata crude oil, treated and untreated, in a radial reservoir model, at 60°C and a shear rate of up to 700 s⁻¹, a significant reduction in viscosity was noted at all shear rates which became increasingly prominent at shear rates above 100 s⁻¹.

Claims:

1. A method of enhancing oil recovery from a subterranean hydrocarbon reservoir, said method comprising injecting into said reservoir through a matrix injection section of a well a microorganism capable of digesting oil, and recovering oil from an oil receiving section of a production well, where said injection section is in said production well or is in an injection well and is above or adjacent said oil receiving section, and wherein microorganism injection is preceded by another oil extraction enhancing procedure.
2. A method as claimed in claim 1 wherein microorganism injection is into an injection well.
3. A method as claimed in claim 2 wherein steam, superheated water or organic solvent is also injected through said injection well.
4. A method as claimed in any one of claims 1 to 3 wherein microorganism injection is into a production well.
5. A method as claimed in claim 4 wherein organic solvent is also injected through said production well.
6. A method as claimed in any one of claims 1 to 5 wherein as a said microorganism is used an alkane chain-shortening microorganism.
7. A method as claimed in any one of claims 1 to 6 wherein as a said microorganism is used an aromatic ring opening microorganism.
8. A method as claimed in any one of claims 1 to 7 comprising injecting said microorganism into said reservoir at a plurality of sites, each above or adjacent a said oil receiving section of a said production well.
9. A microorganism mixture for hydrocarbon reservoir treatment, said mixture comprising microorganisms of at least two, preferably at least three, of the following species: *Sphingomonas sp.*, *Pseudomonas sp.*, *Burholderia sp.*,

Thermovirga lienii, *Archaeoglobus fulgidus*, *Acinebacter venetianus*, *Thermosiphon geolii* and *Symbiobacterium sp.*

10. A mixture as claimed in claim 9 comprising microorganisms of the species *Sphingomonas sp.*, *Pseudomonas sp.*, and *Burholderia sp.*

11. A mixture as claimed in claim 10 comprising microorganisms of the species *Sphingomonas stygia*, *Sphingomonas aromaticivorans*, *Sphingomonas subterranean*, *Sphingomonas yanoikuyae*, *Pseudomonas putida*, and *Burholderia sp.*

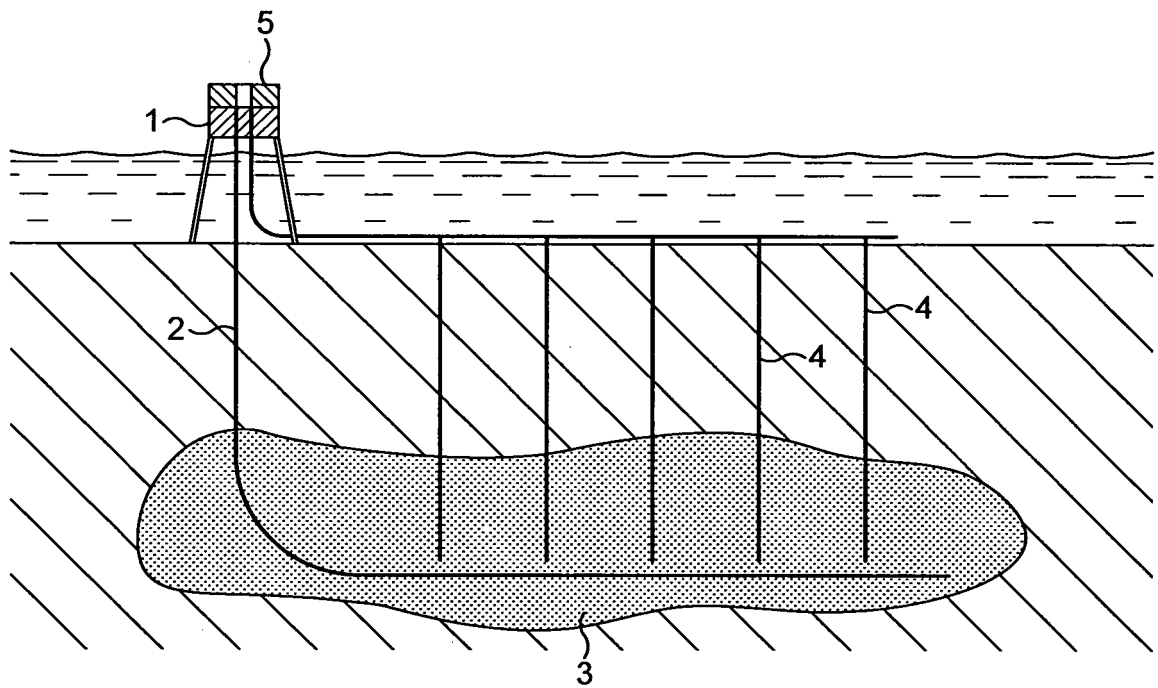


FIG. 1

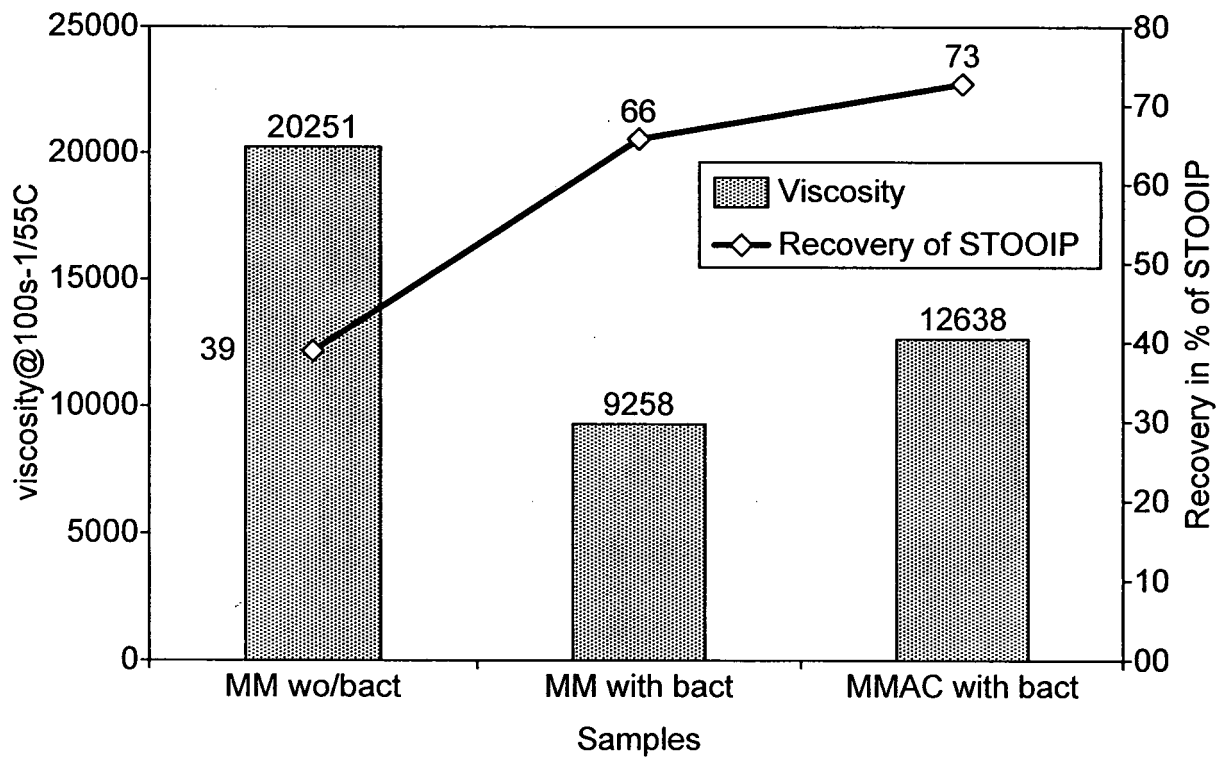


FIG. 2