Microbial Enhanced Oil Recovery: A Sober Look at an Infectious Idea

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The Producer’s Tale, Part 1

• Discovery, appraisal, development…

Life is good!
The Producer’s Tale, Part 2

- Primary recovery … doesn’t

Life is tough.
The Producer’s Tale, Part 3

- Secondary recovery battles physics
  - Poor sweep efficiency
The Producer’s Tale, Part 3

- Secondary recovery battles physics
  - Poor displacement efficiency
The Producer’s Tale (Chorus)

- Primary recovery … doesn’t
- Secondary recovery battles physics … and loses

Oil left in place
The Germ of an Idea

- Intelligent agent for oil recovery
- Featuring $DCF^*$

Self-directing!

Just add water!

Self-propagating!
The Germ

• Microbe produces recovery-enhancing chemicals

Nutrients → Products → Trapped oil
The Best Part

- The microbes consume residual oil!
  - Find their own carbon source in the reservoir!
  - Create recovery-enhancing chemicals right where needed!
  - **DCF** eliminates logistical hassle!
- The microbes **replicate**!
  - Process is self-sustaining!
The Producer’s Tale

New

EOR performance at waterflood cost

Life is good again!
The Hard Part

- process development, scale-up, field implementation....
Overview

• Scale-up, design issues for microbial enhanced oil recovery
• Derive performance constraints
• Review laboratory, field experience
What is MEOR?

- EOR, not well stimulation
- goal: increased displacement, volumetric efficiencies

![Diagram showing the comparison between the recovery process without stimulation and the enhanced recovery process with well stimulation at t₁. The diagram illustrates the incremental oil produced and the overall cumulative oil produced over time.]
EOR vs. Well Stimulation

• Stimulation treats producers
  – increase near-wellbore permeability
    • acidizing
    • hydraulic fracturing
  – increase near-wellbore oil mobility
    • thermal
    • chemical
    • microbial

• EOR process propagates from injector to producer
Microbial products*

- Acids
- Biomass
- Gases
- Solvents
- Surfactants
- Polymers

What is MEOR?

- MEOR is chemical EOR, but with chemicals generated in situ
What is MEOR?

- MEOR introduces reaction engineering into reservoir engineering

Injected nutrient: $N_0$
Required product: $C_{req}$
Stoichiometry: $N \rightarrow \nu_N C$
Kinetics: $dN/dt = -k_1 N$
<table>
<thead>
<tr>
<th>Design Feature</th>
<th>Options</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor type</td>
<td>Fixed, Growing, Mobile</td>
</tr>
<tr>
<td>Carbon source</td>
<td>In situ, Ex situ</td>
</tr>
<tr>
<td>Microbe provenance</td>
<td>Exogenous, Indigenous</td>
</tr>
</tbody>
</table>
MEOR Base Case Implementation

Inoculation

microbe, nutrient injection

Operation

water, nutrient injection

recovery enhancing chemicals

Shut-in

microbe colony

$r_m$
Reaction/Reservoir Engineering Constraints

- Residence time vs. reaction time
- Consumption of *in situ* carbon source
- Limiting reactant propagation
- *In situ* gas production
- Feasible reactor size
- Mobility control via *in situ* generation of viscosifying agents
**Reaction/Reservoir Engineering Constraints**

- **Product Concentration**
  - $C_{\text{req}}$
  - Time in Reactor: $\tau_{\text{rxn}}$

- **Residence time vs reaction time**

- **Injection well**
  - $Q$
  - microbes

- **Rate constant, 1/d**
  - $\tau_{\text{rxn}} = \tau_{\text{res}}$

- **Injection rate, bbl/d**

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$t_{\text{res}}$ is the residence time in the reservoir, and $t_{\text{rxn}}$ is the reaction time. The graph shows the relationship between the residence time and the injection rate, highlighting that for certain conditions, the reaction time equals the residence time.
Reaction/Reservoir Engineering Constraints

**Consumption of in situ carbon source**

- Reservoir volume
- Reactor volume

Graph showing:
- Injection well spacing vs. Slug size (product volume/reservoir volume)
- Lines for $C_{req} = 0.2\%$ and $C_{req} = 1\%$

Legend:
- Dotted line: $C_{req} = 0.2\%$
- Solid line: $C_{req} = 1\%$
Reaction/Reservoir Engineering Constraints

*Limiting reactant*

- Limiting reactant solubility, ppm
- Radius at which reactant is exhausted, ft

Graph showing the relationship between limiting reactant solubility (ppm) and the radius at which the reactant is exhausted (ft).
Reaction/Reservoir Engineering Constraints

**In situ gas production** (CO$_2$, CH$_4$)
- reactor volume limits CH$_4$ production

![Graph showing the relationship between methane slug size (PV) and injection well spacing (acres) at different pressures (P = 10 atm, P = 100 atm)]
Reaction/Reservoir Engineering Constraints

In situ gas production (CO₂, CH₄)
- generating CO₂ requires much O₂

![Graph showing oxygen concentration in water (g/m³) vs. water slug size/CO₂ slug size at different pressures (10 atm and 100 atm). The graph indicates that the oxygen concentration decreases with increasing water slug size and CO₂ slug size. Surface water is highlighted with a shaded box.]
Mobility Control for EOR

• Problem
  EOR processes subject to instabilities

• Solution
  mobility control in drive fluids
    • Polymer
    • Foam

• Lesson
  More is better (Lake, 1989)
Reaction/Reservoir Engineering Constraints

Mobility control via in situ generation of viscous agents

- effect of vertical heterogeneity

**Viscosity**

- Injection

**Pressure**

- Crossflow tendency

*crossflow reduces conversion, efficiency*
Reaction/Reservoir Engineering Constraints

Mobility control via in situ generation of viscous agents

- effect of perturbations

Viscosity generation is unstable to perturbations
Review of Laboratory Work

Information required:

- Reaction parameters
  - Rate constants
  - Form of rate expression
  - Stoichiometry (conversion, selectivity)
- Minimum effective concentrations

Such information is largely absent from the literature
Review of Laboratory Work

• Batch vs continuous reactor operation

• Typical recoveries 10%-20% ROIP
  – Low compared to chemical processes (50% ROIP)
  – High recoveries (30%-60%) may have involved other mechanisms

• Oil banks not observed

• Mechanisms very poorly understood
High MEOR recoveries in lab?

- Reported recoveries
  - 35% ROIP (after waterflood) light oil
  - 58% ROIP (after waterflood) heavy oil
- Residual established at 1-2 psi $\Delta P$
- Microbial flooding at 4-5 psi $\Delta P$
- Absolute P increased 60 psi in some expts.
High MEOR recoveries in lab?

- Reported recoveries 30-50% ROIP (after waterflood)
- Measured effluent interfacial tensions
  - 2-3 times lower than water-oil
  - Expect 25% ROIP from typical capillary desaturation curve
- Recovery strongly correlated with permeability reduction
Capillary Desaturation Curve  
(Lake, 1989)
Review of Simulator Development

• Small effort in modeling
  – mainly funded by DOE
  – SPE 28903
  – SPE 24202
  – SPE 22845

• Mechanisms poorly understood
  – Modeling/simulation premature
Review of Field Experience (1)

- Few EOR projects
- Many well stimulations

<table>
<thead>
<tr>
<th>Process</th>
<th>Measure of success</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEOR</td>
<td>% ROIP recovered</td>
</tr>
<tr>
<td>Stimulation</td>
<td>Increase in oil rate</td>
</tr>
</tbody>
</table>

ROIP = Remaining Oil In Place
Review of Field Experience (2)

• Three projects aimed at increasing displacement efficiency
  – Two watered-out, low oil rate Oklahoma fields
  – One high water cut, low oil rate Texas field
Review of Field Experience (2)

- Watered-out, low oil rate Oklahoma fields
  - Incremental recovery <1% ROIP in 2 years
  - Oil rates increased steadily four months before the trial
  - Residence time vs reaction time criterion not satisfied
  - Poor volumetric efficiency
    - Probable thief zone (rapid tracer breakthrough)
    - No polymer injection or biopolymer production
  - Microbe efficacy unknown (poor lab results as per above)
Review of Field Experience (3)

• Three projects aimed at increasing **volumetric** efficiency (SPE 75328, 59306, 35448, 27827)
  – Mixed results
    • Positive result (*SPERE*E Feb. 2002)
      – Uses native microbes
      – Extrapolates to ~5% ROIP ultimately recovered, comparable to polymer floods
    – Simpler mechanism
  – Issues
    • limiting reactant analysis
    • maintaining long-term injectivity

*Technical basis: growing biomass reduces permeability, redirects injected water*
Review of Field Experience (4)

• Well stimulation with microbes
  – Popular in some regions
  – Cheap
  – Mixed results
  – Inconclusive evidence for mechanism(s)
    • Some involve microbe/oil interaction
      – Viscosity reduction
    • MEOR analytical tools/engineering constraints applicable
      – Residence time
      – Limiting reactant
Microbial Well Stimulation

Inoculation

microbe, nutrient injection

Shut-in

microbe colony

Operation

Oil, water production

Viscosity reduction
Reaction/Production Engineering Constraints

- **Nutrient supply?**

- Residence time fixes reaction time
- Reaction time fixes viscosity reduction
- Viscosity reduction determines productivity increase
Conclusions (1)

- Key potential advantage of MEOR
  - ability to use in situ carbon source

*Just add water!*
Conclusions (2)

• Key disadvantages of MEOR
  – Likely microbial performance constraints
  – Poor lab, field performance relative to peers (other chemical EOR)
Conclusions (3)

• Preferred MEOR option
  – Profile modification via biomass
  – Simpler, esp. with indigenous microbes
  – Compared to waterflood
    • Small incremental cost
    • Marginal increase in difficulty
Conclusions (4)

- Reservoir/reaction engineering perspective needed
  - Missing in past MEOR research
  - Inadequate data for quantifying performance constraints
- Similar perspective needed for microbial well stimulation