Cartography of oil reserves and recovery factors of petroleum reservoirs - IOR/EOR methods to increase ultimate recovery

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Proved Oil Reserves (2009)

Total with oil sands : 1517 Gb
Oil recovery

Primary Recovery

Conventional oil recovery

Natural drainage

Pumping/Gas lift/horizontal drilling

From "Physical principles of oil production" by Muskat

Borregales 1977

Oil recovery (%) vs. oil viscosity in cp at reservoir conditions

Oil recovery (%)

Oil viscosity in cp at reservoir conditions
Oil recovery

Natural drainage

Primary Recovery
Drive
Water flood

Secondary recovery

Conventional oil recovery
Pumping/ Gas lift / horizontal drilling
Pressure maintenance
Water flood / Gas flood
Gas cycling

RF (sandstones)  25-45%

Worldwide average : 35 % but large variations
Example of the North Sea

Oil Resources and Oil Reserves in Fields in Production

54% Oil Left Behind

1% Increase equals approx. a gross value of 45 bill USD
Secondary and Tertiary recovery

- how to increase displacement efficiency
  oil that remains in the part of the reservoir already swept

- how to increase sweep efficiency
  oil that remains in the part of the reservoir not swept
Oil recovery

Natural drainage

Primary Recovery

Drive
Water flood

Secondary recovery

Conventional oil recovery

Pumping/ Gas lift / horizontal drilling

Pressure maintenance
Water flood / Gas flood Gas cycling

Tertiary recovery

Enhanced Oil Recovery (increased RF +10-20%)

Thermal
- Steam
- In situ combustion

Gas miscible/immiscible
- Hydrocarbon
- CO₂
- N₂

Chemical
- Polymer
- Surfactant
- Alkaline
- Foam

Other
- Microbial
# Mechanisms of action

<table>
<thead>
<tr>
<th>Action on sweep efficiency at the macroscopic scale</th>
<th>by increasing $\mu_w$</th>
<th>polymer flooding</th>
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<tr>
<td></td>
<td>by increasing $\mu_d$</td>
<td>foam drive / WAG</td>
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<td></td>
<td>by decreasing $\mu_o$</td>
<td>CO$_2$ drive</td>
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<td>by using a miscible</td>
<td>steam drive</td>
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<td>rock wettability</td>
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<tr>
<td>Action on displacement efficiency at the pore scale</td>
<td>by using a miscible</td>
<td>HC gas, CO$_2$, N$_2$</td>
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IOR / EOR

**EOR**

*Enhanced Oil Recovery*

EOR will involve processes in order to act on the reservoir recovery mechanisms
- Mobility control
- Reduction of Sor
- Increase of miscibility

**IOR**

*Improved Oil Recovery*

Based on technologies, IOR evolves versus time according to various standards across the world and among the companies
- Smart wells
- Reservoir management
- Reservoir characterization
- Down hole separation, ...
Optimized reservoir management and monitoring

- **Well productivity improvement** → **Acidification, stimulation, reduction of formation damage**
- **Better drainage architecture** → **Horizontal wells, Multilaterals, SAGD, VAPEX, THAI**
- **Reduction of uncertainties** → **Reservoir characterization, fractured reservoirs, 4D seisms**

**Diagrams:**
- Stacked multibranch well
- Dual opposing laterals
- Re-entry laterals from a vertical well
- Cluster well
- Multidrain or multilateral well
- 3D Well
EOR at work...

EOR consists in injecting specific fluids into a reservoir to help recovering some portion of remaining oil.

+1% Recovery factor = 2 to 3 years additional reserves!
Steam injection processes

- **HUFF AND PUFF**
- **STEAM DRIVE**
- **SAGD**
- **SAP**
Polymer flooding
(Macroscopic sweeping)

When polymer is added to the drive brine it reduces M and leads more to a piston like displacement and hence higher recovery efficiency.

Unfavorable mobility ratio $M$, results in an inefficiency of the water flood oil displacement mechanism.

Definition of mobility ratio

$$M = \left( \frac{k_{rw}}{\mu_w} \right) \left( \frac{k_{ro}}{\mu_o} \right)$$

krw = Water Relative Permeability, fraction
$\mu_w$ = Water viscosity, cp
kro = Oil Relative Permeability, fraction
$\mu_o$ = Oil viscosity, cp

RFmax: +10-15%


IFP Energies nouvelles
Surfactant flooding (Microscopic mobilization)

**Local scale**
Residual oil are immobilized as a result of capillary forces

\[ \Delta P = \frac{2\gamma}{r} \]

Illustration of capillary trapping in micromodels (developed at Rhodia LOF).

**Core scale**
To remobilize oil, capillary number \( Ca \), must be significantly increased

\[ Ca = \frac{\eta v}{\gamma} \]

This can be achieved by lowering \( \gamma \) with optimized surfactant formulations
ASP process

- Polymer
  - mobility ratio
- Surfactant
  - decrease interfacial tension
- Alkaline
  - decrease surfactant adsorption
  - ionize natural surfactants

**Diagram:**
- Water drive
- Oil bank
- Polymer
- Surfactant
- Alkali
- Oil
- Capillary trapping
Chemicals

Objective:
Design a formulation that will give optimal performance based on economical considerations

- Use of polymer
- Very favorable mobility ratio required
- Long chain & adapted chemistries
- Sourcing (raw materials) is critical
- Adapted synthesis process
- Robust surfactants & polymers are required
- Depends on:
  - Brine, rock (clays)
  - pH
  - Temperature
  - Additives
- Depends on:
  - Brine
  - Surfactant-polymer interactions
  - Surfactant-surfactant interaction
  - Temperature
  - Additives (cosolvents)

⇒ potential of green chemistry?
Screening criteria (heavy oils)

Primary cold production (reference)
- Water flooding or HC miscible
- Partial miscible CO2 flood
- Polymer flooding
- CHOPS
- VAPEX
- In situ combustion
- Cyclic Steam Stimulation
- Steam flood
- SAGD

Technologies
- CHOPS
- VAPEX
- In situ combustion
- Cyclic Steam Stimulation
-Steam flood
- SAGD

Regions
- North Sea
- Brazil
- Indonesia
- USA (Cal.)
- Venezuela
- USA (Alaska)
- Canada

μ/k (cp/mD)

EOR target in the world

Conventional Crudes
5 700 Gb

Heavy, extra-heavy and bitumen (API<20)
5 000 Gb

Non-recoverable today
3 800 Gb

Non-recoverable today
4 250 Gb

Recoverable with present technologies
700 Gb

Already produced
1 000 Gb

Already produced
50 Gb

Recovered with present technologies
900 Gb

Already produced
1 000 Gb
Worldwide EOR production in 2008

- Thermal injection
- Chemical injection
- CO₂ injection
- N₂ injection

Source: Oil & Gas Journal + IFP

Canada 18%
USA 28%
Mexico 22%
Venezuela 16%
India, Colombia, Trinidad, Brésil ~0.5%
Other countries ~0.5%
China 7%
Indonesia 8%

2.5% of the world oil production

~ 2.3 Mb/j
2008 EOR production
Breakdown by recovery method

Terms of Production

- 98% steam
- 1.5% combustion in situ
- <1% hot water
- Thermal 52%
- CO2 injection 12%
- Hydrocarbon gas injection 12%
- Chemical 2%
- Nitrogen injection 22%
- Others 0%

Source: IFP + Oil & Gas Journal
2008 EOR production
Breakdown by recovery method

Nb of actives projects

- Nitrogen injection (6)
- Chemical (23)
- Microbial (2)
- Thermal CO2 injection
- Hydrocarbon gas injection
- CO2 injection

About 350 active projects

- 133 steam
- 21 combustion in situ
- 3 hot water

122
157
38
2000-2008
EOR production evolution

2008/2006
-4.3%

Production Mb/d

Source: IFP + Oil & Gas Journal
2000-2008
EOR by number of projects

Active projects

314 308 302 348

2008/2006
+15%

Microbial
Nitrogen injection
Chemical
HC gas injection
CO2 injection
Thermal


IFP Energies nouvelles
EOR Costs & Recovery Rate

- Surfactantflood
- CO₂
- Polymerflood
- Waterflood

Costs in $/b vs. Recovery factor

Solvent aided process
Steam
Chemical EOR Alliance

World-class geosciences public-sector research

Global leader in specialty chemicals and formulation

A seamless team with complementary skills:
Senior reservoir engineers, chemical engineers, petrophysicists, geophysicists, simulation specialists, engineering specialists, ...

Independent E&P consulting and software editor (IFP subsidiary)

Polymer technologies for IOR and well performance (IFP subsidiary)
### Chemical EOR project milestones

<table>
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<th>Timeframe</th>
<th>Description</th>
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| 1-3 months      | **EOR Prefeasibility Study**  
- Data review for Development current status analysis  
- Selection of EOR methods  
- Estimation of additional recovery through phenomenological models  
- Economics in $/bbl  
- Recommendation for field development  |
| 6-12 months (II) | **Laboratory design**  
- Product design and selection  
- High throughput screening  
- Core flood validation  
- Lab-scale simulation  
- Impact on water management |
| 12-24 months    | **Pilot design**  
- Numerical simulation at pilot scale  
- Pilot economics  
- Pilot conceptual design (drilling, facilities, ...)  
- Water Management  
- Detailed engineering studies |
| 24-36 months    | **Pilot execution**  
- Chemicals supply  
- Field monitoring  
- Expertise and assistance to operations  
- Pilot results analysis |
| 5-10 years      | **Field-scale design**  
- Complementary lab studies  
- Numerical simulation at field scale  
- Field Development Plan  
- Engineering (EPCM)  
- Water Management  
- Large-scale chemical supply-chain management  |
|                 | **Field-scale deployment**  
- Chemicals supply  
- Field management and monitoring  
- Expertise and assistance to operations |
Conclusions

- EOR production is increasing but slowly
  - Despite a context of high oil price & increasing demand

- Today evolution technologies
  - **Steam** is decreasing for very viscous crude
    - Environmental impact of high water consumption
    - Price of gas, high CO₂ emissions for others
  - **CO₂** is highly increasing
    - Additional revenues for CCS
    - Answer to global warming concern
  - **Chemical** injection, mainly polymer flood
    - Allow to enhance waterflood, widely used technology
    - As a wide potential
    - Not no expensive technology