Oil Recovery Enhancement: Approaches, Methods, Project Design and Current Status, Application to Egyptian Oil Fields
Webster defines -- 'to enhance' is to increase, to make or become larger, to advance, to elevate.
Enhanced Oil Recovery (EOR) is...

- Oil recovery by the injection of materials not normally present in the reservoir
- Excludes conventional waterflooding
- Not necessarily "tertiary" recovery
**Approach No. 1**

- Increase contact between the Injection fluid and the remaining oil in the reservoir pore space.

- Lowering the Mobility ratio is the key! \((M = \lambda_w/\lambda_o)\)

- Viscosity of oil can be lowered by Hot water injection, Steam flooding, In-situ combustion and Solvents injection.

- Viscosity of water can be increased by Addition of viscosity builders such as Polymers.
• Kw can be decreased by addition of permeability modifying polymers to the injection water.

• Kco2 can be decreased by alternate injection of CO2 and water (WAG process).

• Ko can be increased by the addition of chemicals (such as Caustic Soda) to the injection water.
Approach No. 2

• Minimize or Eliminate Capillary Force.

• Lowering Interfacial Tension is the key!

• Oil-Water interfacial tension can be lowered by the addition of Surfactants to the injection water (Surfactant Flooding).

• Wettability can be altered by the addition of chemicals such as Caustic Soda (Caustic Flooding).
Recovery Mechanisms...

Primary Recovery

Secondary Recovery
  - Natural Flow
  - Artificial Lift
    - Pump
    - Gas Lift
    - Etc.

Tertiary Recovery
  - Waterflood
  - Pressure Maintenance
    - Water
    - Gas Reinjection

Enhanced Recovery
  - Thermal
  - Chemical
    - Solvent
    - Other

Conventional Recovery

Source: Adapted from the Oil & Gas Journal, Apr. 23, 1990
Development of a Recovery Method

Development of a recovery method for a specific reservoir is a lengthy process and involves:

- Laboratory research (1-2 years)
- Field screening (1-2 years)
- Field pilot (2-3 years)
- Field results analysis (1-2 years)
- Semi-commercial project (3-5 years)
- Commercial development
The important question is:

how much of this oil is recoverable and what techniques could be applied?
Current Thermal Recovery Methods

In Situ Combustion

Cyclic Steam Injection

Steam Injection
Steam Flooding

When steam is injected, a steam saturated zone forms around the injection well, and further beyond there is a zone containing condensed steam.
Cyclic Steam Stimulation

Is a single well process and involves:

- Injection of steam for several weeks (2 to 6 weeks) at the highest possible rates.

- The well is then shut-in for several days (3 to 6 days) to allow the steam to condense.

- Following the soaking phase, the well is put under production.
In Cold Lake, Alberta, it is over 25% or higher.

In Venezuela, recovery from this process as high as 40% have been noted.
**In Situ Combustion**

- This is a pattern flood process.
- A small portion of the oil in place is burned establishing heat to the rock and its fluids.
A burning front and combustion zone is propagated to the producing well by air injection into a well (forward combustion).
Current Chemical Recovery Methods
Polymer, Alkaline and Micellar

[Diagram of chemical recovery methods with labels for injection fluid, injection pump, production well, drive water, chemical 1, chemical 2, additional oil, and initial oil.]
SURFACTANT AND MICELLAR FLOODING

Significant reduction of capillary forces at the injected fluid / crude oil interface has given birth to many EOR processes. These aim at lowering the residual oil saturation and thereby improving displacement efficiency.
THE SURFACTANTS

A typical surfactant monomer is composed of a nonpolar portion, and a polar portion.
Surfactants
POLYMER FLOODING

• Polymer is a chemical that is composed of a number of individual molecules that are attached in some manner.

• These units are usually associated in a pattern that repeats itself throughout the length of each polymer repeating units and are called MONOMERS.

Example: Polyacrylamide (PAM)

\[ \text{CH}_2 - \text{CH} - \text{CH}_2 - \text{CH} - \text{CH}_2 - \text{CH} - \]
\[ \text{C} = \text{O} \quad \text{C} = \text{O} \quad \text{C} = \text{O} \]
\[ \text{NH}_2 \quad \text{NH}_2 \quad \text{NH}_2 \]
Mobility control must be designed by flooding in reservoir cores.

Total mobility = \( \frac{K_{rw}}{\mu_w} + \frac{K_{ro}}{\mu_o} \)
**Caustic and Emulsion Flooding**

The alkaline solution increase the capillary number value by reacting with the organic acids present in some crude oil to form emulsifying soaps, which reduces the interfacial tension by two or three orders of magnitude.

The alkaline agent changes the injection water pH and the rock wettability is reversed from oil-wet to water-wet.
Miscible oil displacement is the displacement of oil by fluids with which it mixes in all proportions without the presence of an interface, all mixtures remaining single phase.
Miscible Agents

- Propane, LPG mixtures, and low molecular-weight alcohols:
  - subjected to many limiting factors such as high costs, unfavorable mobility, and low volumetric sweep.
- Natural gas, flue gas, nitrogen at high pressure, and enriched hydrocarbon gas:
  - were found to achieve miscibility with reservoir oil.
- Surfactant slugs: technically efficient.
- Carbon dioxide: miscible with reservoir fluids.
**Miscibility is achieved by one of the two methods:**

- **First Contact Miscibility:** the injection fluid mixes with the crude oil in all proportions and all their mixtures remain single phase.

- **Multi-Contact Miscibility:** the injected fluid and the crude oil are not miscible on first contact but through components transfer from one to the other fluid, they reach miscibility in time through multiple contacts.
Miscible Oil Drive Processes

Processes

LPG Slug Process

Lean Gas Drive Process

Enriched Gas Drive Process

Miscible zone formed by gas becoming enriched with C_{2}-C_{6}

Miscible zone formed by oil becoming enriched with C_{2}-C_{6}
Carbon Dioxide Flooding

Factors that Make CO2 an EOR Agent

- **Reduction in oil viscosity:** improves the mobility ratio
- **Swelling of crude oil:** increases the recovery factor
- **Acid effect on carbonate and shaley rocks:** CO2 in solution with water forms carbonic acid which increases the permeability of the carbonate rock.
- **Miscibility effects:** CO2 may develop miscibility through multiple contacts.
Bio-Chemical Recovery Methods

- Cyclic well stimulation treatments.
- Microbial enhanced water flooding.
- Permeability modifications.
- Wellbore cleanup.
CURRENT STATUS AND PROJECT DESIGN
CURRENT STATUS

Active US EOR Projects and Production

![Bar chart showing Active US EOR Projects and Production](chart.png)
Some Active EOR Projects in the world

Venezuela  Turkey  Trinidad  Indonesia  Germany  Egypt  Brazil  Canada

Thermal  Gases  Chemical
World Status of the EOR projects during 2004 – 2014

Status of the EOR projects in 2014

Status of the EOR Projects in the World

Steam
- 135, 38.9%
- 7, 2.0%
- 4, 1.2%
- 2, 0.6%
- 1, 0.3%

Hot water
- 38, 11.0%
- 16, 4.6%

Combustion
- 2, 0.6%

CO2 Immiscible
- 13, 3.7%

CO2 Miscible
- 2, 0.6%

Hydrocarbon Miscible
- 135, 38.9%
- 2, 0.6%

Acid Gas Miscible
- 0.3%

Hydrocarbon Immiscible
- 38, 11.0%

Nitrogen Immiscible
- 1, 0.3%

Chemical (Polymer, Surfactant)
- 0.3%

MEOR
- 1, 0.3%

Thermal EOR Methods
- 143, 41.2%
- 174, 50.1%

Miscible EOR Methods
- 22, 6.3%

Immiscible EOR Methods
- 7, 2.0%

MEOR
- 1, 0.3%

**Project Design**

**Objective**

To establish a team of engineers in oil companies that they need to be both experienced in oil field EOR operations and looking for ways to improve the process under test.

To achieve the most feasible selection of EOR technique to be applied to the Egyptian candidate oil fields in an efficient and profitable way.
Methodology and Design

• Two stages are proposed for the EOR field project

Stage I  Project Studies

• The work will extend for two years, and will include the following phases:
Phase I

- Review of the successful EOR recovery projects world wide coupled with experimental results from previous and current research activities at different research institutions and organizations.

- A new analysis method is used to produce the rules of the expert system formulation.
Phase II

Field Data Collection

- **Field Geology**: Rock Type – Lithology – Heterogeneity - .... etc
- **Fluid properties**: oil and water viscosities – formation volume factors – saturation pressure – formation water composition and salinity – GOR ..... etc
Oil Viscosity - Centipoise at Reservoir Conditions

<table>
<thead>
<tr>
<th>EOR Method</th>
<th>0.1</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
<th>10000</th>
<th>100000</th>
<th>1000000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrocarbon-Miscible</td>
<td>Very Good</td>
<td>Good</td>
<td>More Difficult</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nitrogen and Flue Gas</td>
<td>Good</td>
<td>More Difficult</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂ Flooding</td>
<td>Very Good</td>
<td>Good</td>
<td>More Difficult</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surfactant/Polymer</td>
<td>Good</td>
<td>Fair</td>
<td>Very Difficult</td>
<td>Not Feasible</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Polymer</td>
<td>Good</td>
<td>Fair</td>
<td>Difficult</td>
<td>Not Feasible</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alkaline</td>
<td>Good</td>
<td>Fair</td>
<td>Very Difficult</td>
<td>Not Feasible</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fire Flood</td>
<td>May Not Be Possible</td>
<td>Good</td>
<td>Not Feasible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Steam Drive</td>
<td>(Can Be Waterflooded)</td>
<td>Good</td>
<td>Not Feasible</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Oil Viscosity - Centipoise at Reservoir Conditions

- Hydrocarbon-Miscible
- Nitrogen and Flue Gas
- CO₂ Flooding
- Surfactant/Polymer
- Polymer
- Alkaline
- Fire Flood
- Steam Drive

Dr. Helmy Sayyouh

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Phase III

- Establish the physical properties of the system.
- Carry out displacement recovery tests on representative cores.

Phase IV

- The data obtained in the course of the work (Field and Laboratory) will be analyzed.
- Simulation runs will be carried out.
- The necessary recommendations for pilot field application will be drawn.
Stage II Pilot Design and Operation

• Pilots play an important role in improving oil recovery and improving developed technology.

• They are expensive, but necessary.

• Pilots are in fact research projects run in the oil field.
The decision of performing stage II will depend upon the results and recommendations obtained from stage I and the proposed time will be determined accordingly.
Stage II includes the following activities:

- Injectors/producers pattern - type of injection - logging observations to monitor flood performance.... etc

- Pilot response – observations and results – lessons learned ..... etc

- Full field project: technical – economic
Management

• The work in this project is a team work from university and industry.

• The responsibilities will be divided based on the previous experience and background of each person.

• Stage II will be assigned after the completion of Stage I.
Oil Recovery Enhancement: Possible Application to Egyptian Oil Fields
Global oil demand and supply

Egyptian oil demand and supply

Current Status
- Production Rate: 717,000 b/d
- Consumption Rate: 813,000 b/d
- Proved reserves: 3.6 MMM bbl
- R/P: 13 Years

• Oil consumption is continuously increasing which motivated oil producing countries to optimize their production.

• Most of easy oil has been already extracted, leaving a non-negligible quantity of highly viscous trapped oil in the reservoirs.

• This requires the usage of what is commonly known by conventional and non-conventional enhanced oil recovery techniques.
A number of oil fields in Egypt are expected to undergo one or more of the EOR methods in the near future.

However, the implementation of any of the EOR methods involves high capital expenditure. These processes are a rather difficult and high risk operation.

Proper selection of the EOR method for any particular reservoir is necessary to achieve a successful and profitable project.

This needs research!!
EOR Research Projects (M.Sc. and PhD Theses) at Cairo University – Egypt
• In spite of the active research work in Egypt during the past decade, the petroleum industry has limited experience in actual field applications of EOR.

• Scarcity of previous field experience, coupled with the fact that only few experts know about all available EOR processes have prompted the current development, of a knowledge-based expert system that can facilitate the reservoir engineers task of selecting the most appropriate EOR method.
### Available Data Ranges for Egyptian Reservoirs in Western Desert

<table>
<thead>
<tr>
<th>Property</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>API gravity</td>
<td>36 - 43 Degree</td>
</tr>
<tr>
<td>Oil viscosity</td>
<td>0.43 – 3.7 Cp</td>
</tr>
<tr>
<td>Reservoir depth</td>
<td>1200-4220 m</td>
</tr>
<tr>
<td>Rock permeability</td>
<td>5 – 307 mD</td>
</tr>
<tr>
<td>Oil saturation</td>
<td>48 – 74 %</td>
</tr>
<tr>
<td>Reservoir temperature</td>
<td>163-223°F</td>
</tr>
<tr>
<td>Formation water salinity</td>
<td>80 – 98 MPPM</td>
</tr>
<tr>
<td>Net pay thickness</td>
<td>11-26 ft</td>
</tr>
<tr>
<td>Permeability variation coefficient</td>
<td>0.5 – 0.8</td>
</tr>
<tr>
<td>Formation type</td>
<td>SS - LS</td>
</tr>
<tr>
<td>Minimum miscibility pressure</td>
<td>2042-3770 psi</td>
</tr>
<tr>
<td>Initial pressure</td>
<td>2325-2800 psi</td>
</tr>
<tr>
<td>Parameter</td>
<td>Range</td>
</tr>
<tr>
<td>---------------------------------</td>
<td>-------------------</td>
</tr>
<tr>
<td>API gravity</td>
<td>16 - 22 Degree</td>
</tr>
<tr>
<td>Oil viscosity</td>
<td>13 - 30</td>
</tr>
<tr>
<td>Reservoir depth</td>
<td>2100-11250 ft</td>
</tr>
<tr>
<td>Rock permeability</td>
<td>27 - 5000 mD</td>
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<tr>
<td>Oil saturation</td>
<td>61 - 69 %</td>
</tr>
<tr>
<td>Reservoir temperature</td>
<td>124- 164°F</td>
</tr>
<tr>
<td>Formation water salinity</td>
<td>100 - 220 MPP</td>
</tr>
<tr>
<td>Net pay thickness</td>
<td>46-151 ft</td>
</tr>
<tr>
<td>Permeability variation coefficient</td>
<td>0.5 - 0.85</td>
</tr>
<tr>
<td>Formation type</td>
<td>SS - LS</td>
</tr>
<tr>
<td>Minimum miscibility pressure</td>
<td>1548-2053 psi</td>
</tr>
<tr>
<td>Initial pressure</td>
<td>1220-1849 psi</td>
</tr>
</tbody>
</table>
EOR method is specific for a specific reservoir!!

However, Egyptian oil reservoirs, technically, are good candidate for immiscible gas injection. Steam injection is feasible in some of the Gulf of Suez reservoirs. The chemical methods are feasible in most of the Western Desert reservoirs.
• The possibility of applying one of the unconventional EOR methods; namely, wave stimulation and MEOR, to the depleted Egyptian oil fields is to be investigated.

• Wave stimulation and MEOR technology has the potential for being a relatively low-cost procedure for enhancing oil recovery in depleted fields, or returning some shut-in wells to production.
• The problem faced by the reservoir engineer in our area is to identify all the EOR methods applicable to the candidate oil field and select the most appropriate method based on technical and economic criteria.

• This problem of selecting the most suitable EOR process created a crucial need for experts to help, sort, process, analyze and cross-refer the acquired reservoir data coupled with other sources of information to achieve the most feasible selection of EOR technique to be applied to the candidate fields in an efficient and profitable way.
SOME OF THE EGYPTIAN OIL FIELDS THAT USED IN OUR GRADUATE RESEARCH

- Abo-Sanan Field: GPC
- West Bakr Field: GPC
- Blaeim Oil Field: Petrobel
- El-Morgan Oil Field: GUPCO
- Ramadan Oil Field: GUPCO
- Hayat Field: Khalda Oil Company
- Ras-Budran Field: SUCO
- South Geisum Field: Geisum Oil Company
- Badr Oil Field: Badr El Din Oil Company