Enhanced Oil Recovery (EOR)- A Review Article

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TABLE OF CONTENTS

LIST OF FIGURES AND TABLES

REPORT

1. ABSTRACT

Enhanced Oil Recovery (EOR) is a set of techniques employed to extract oil from reservoirs after primary and secondary methods can no longer be applied, leaving behind two-thirds of the Original Oil in Place (OOIP). As a subset of the oil and gas industry in particular, and the chemical engineering domain as a whole, this sector holds immense potential for petroleum and chemical engineering students looking to work with oil and gas companies. This document provides a simple and concise introduction to EOR, the various methods with their merits and demerits and technically relevant data in the form of tables, graphs and comparisons. Tens of research papers, reports and web articles were sifted through to describe the processes and answer different relevant questions in the simplest possible way, and figures have also been provided for easy visualization. The appendix contains a table which demonstrates the physical effects of some EOR methods based on a study conducted by Schlumberger, and a case study which shows the arrest in declining oil output by application of EOR. This sector is projected to grow at a Compounded Annual Growth Rate (CAGR) of 6.5% between 2020 and 2025 due to the immense potential offered, high efficiency and increase in oil production (more than 500% in some cases).

2. INTRODUCTION

EOR facilitates the economical extraction of the OOIP left after employing primary and secondary methods, and can increase the oil recovered from the reservoir to about 60-70%. It is an important method as it maximises reserves recovered, extends life of oil fields and increases the recovery factor [1], thus helping the supply keep up with increasing demand for polymers, industrially relevant chemicals, and energy for power and transport in the backdrop of insignificant new reserve discoveries, and the limited capacity and high costs of renewable energy. Heterogenous and unconventional reservoirs, and those containing heavy crude are ideal candidates for application of EOR techniques [2 p.1]. Figs. 1. a. and b compare the typical production profile of an oilfield vs when secondary and tertiary methods are employed. The main objective of this document is to serve as a simple, yet wholesome introduction to EOR for undergraduate engineering students and high school students enrolled in the science stream, thereby encouraging them to appreciate the importance of crude oil even in this era of renewables, and work towards its efficient extraction while preserving the quality of the environment. This is because most manuscripts attempting the same provide in depth details which are tough to comprehend for the target audience of this document, and invariably, they are much lengthier, thereby failing to hold the reader's attention. The basic metrics to gauge an EOR process's performance have been discussed, after which the mechanism, advantages and disadvantages of various EOR methods have been provided in easy-to-understand language, thereby providing a good overview of the EOR industry. Data and graphics have been provided to support the theory where possible. Finally, the conclusion provides some inferences and an overview of the future of this industry, with innovative ideas to intrigue the reader and provide actionable thoughts, thereby achieving the objective.

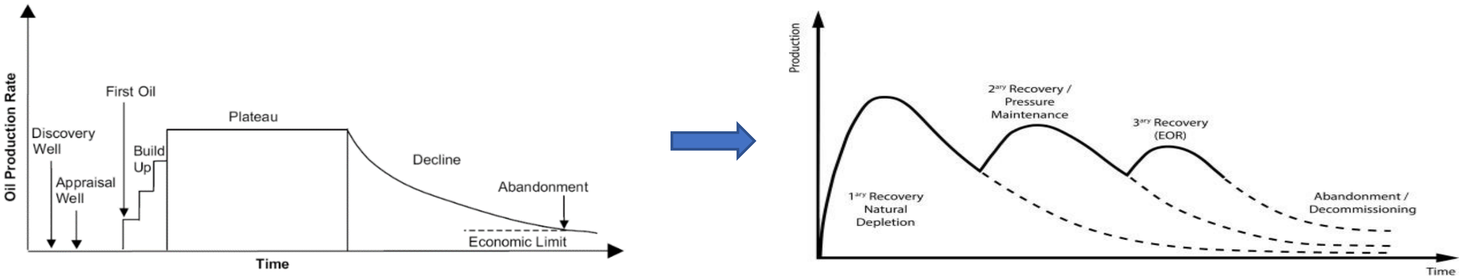


Fig. 1. a.: Typical Production Curve. Ref- M. Höök et al. The Evolution of Giant Oil Field Production Behavior [p.5]. *Natural Resources Research*, Mar 2009, 18 (1). [Online] Available from: https://www.researchgate.net/publication/225365392_The_Evolution_of_Giant_Oil_Field_Production_Behavior [Accessed 17 Feb 2021]. Fig. 1. b.: Curve for Production using 2° and 3° Methods as well. Ref- P. Druetta et al. Chemical enhanced oil recovery and the role of chemical product design [p.5]. *Applied Energy*, 2019, 252. [Online] Available from: https://www.sciencedirect.com/science/article/pii/S0306261919311547 [Accessed 17 Feb 2021].

3. PERFORMANCE METRICS

EOR projects aim to improve the oil displacement efficiency, and effects at both the pore and volumetric scales are important. Key performance indicators for EOR processes are:

Displacement Efficiency (E) = E_V*E_D, where E_V is the volumetric sweep efficiency and E_D is the pore scale efficiency.

Capillary Number (N_{Ca}) = viscous forces/capillary forces = $F_V/F_C = v\mu_D/\sigma_{oD}\cos\theta$, where v is the interstitial velocity, μ_D is the viscosity of the displacing fluid, σ_{oD} is the interfacial tension (IFT) between the displaced and displacing fluids, θ is the angle of contact.

Mobility Ratio (M) = mobility of displacing fluid/mobility of displaced fluid = $\lambda_D/\lambda_o = k_{rD}\mu_o/k_{ro}\mu_D$, where k_{rD} and k_{ro} are the relative permeabilities, μ_D and μ_o are the viscosities of the injected fluid and reservoir oil respectively.

Viscosity to Gravity Ratio ($R_{v/g}$) = viscous forces/gravity forces = $u\mu_oL/kg\Delta\rho h$, where u is the velocity of the injected fluid, μ_o is the oil viscosity, k is the permeability, g is the acceleration due to gravity, Δρ is the density difference between the injected fluid and reservoir oil, L is the horizontal distance in the reservoir, h is the height [3 p.2].

For efficient recovery, we desire high E and N_{Ca}, low $R_{v/g}$ and M<1.

4. COMMON EOR METHODS

Before employing EOR methods to a reservoir, it is essential to analyse whether the undertaking will be profitable and viable. This analysis is bound to be different for each project, given the wide variety of oil reserves currently being exploited by multiple oil and gas companies. The various physical characteristics of these reserves, their location, geology and contents, the requirements and cash reserves of companies operating them, prevailing oil prices, and many other factors are considered. As mentioned, these factors are variable for each project and hence mandate the development and use of different EOR methods for effective changes to oil mobility for facilitating enhanced production. For example, thermal methods are used for heavy oils, whereas chemical methods are applied in mature oilfields [4 p.35]. The commonly used EOR techniques fall into four major areas- thermal, chemical, gas injection, and microbial. Fig. 2 mentions the major methods in each category.

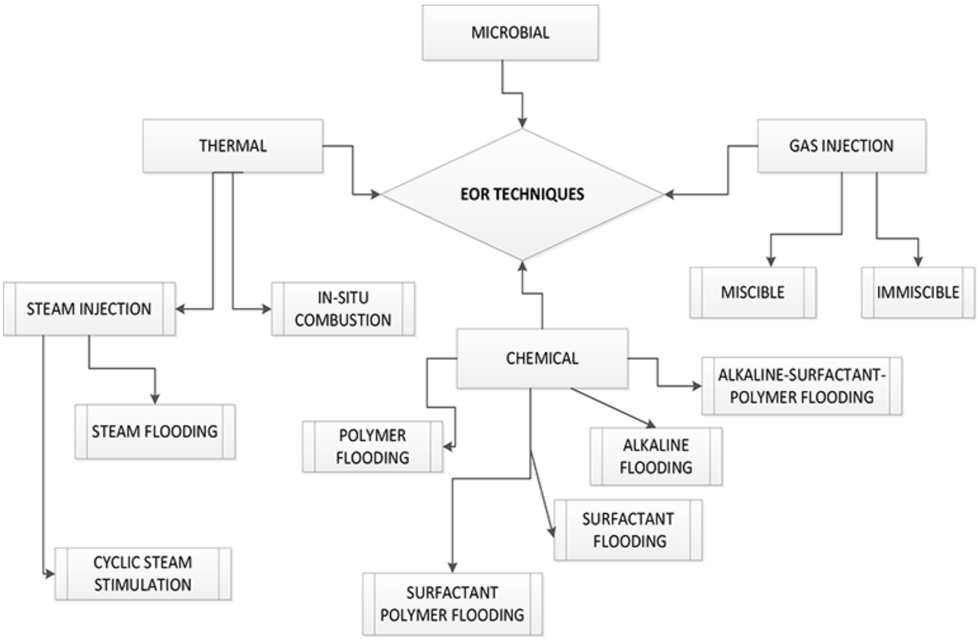


Fig. 2: Classification of EOR Techniques. Ref- L.N. Nwidee et al. EOR Processes, Opportunities and Technological Advancements [p.6]. In: L.R. Zerón (ed.), *Chemical Enhanced Oil Recovery (cEOR) a Practical Overview*. IntechOpen, 19 Oct 2016. [Online] Available from IntechOpen: https://www.intechopen.com/books/chemical-enhanced-oil-recovery-ceor-a-practical-overview/eor-processes-opportunities-and-technological-advancements [Accessed 20 Feb 2021].

4.1. Thermal EOR (TEOR)

TEOR techniques involve addition of heat energy to reservoirs. This causes a substantial increase in reservoir temperature and a corresponding enhancement in oil mobility due to changes in rock wettability and significant decrease in oil viscosity. These methods are usually employed to reserves with heavy and/or viscous crude (averaging a density of 920 kg/m^3 or 9.9°API [5 p.24]). Since about 70% of the world reserves contain heavy crude, TEOR has the potential to unlock 300 billion barrels of oil [4 p.6].

4.1.1. In-situ Combustion: A gas containing oxygen is injected into the reservoir and a special heater in the well ignites the oil, starting a fire. This causes cracking of the heavy hydrocarbons, vaporization of water and light hydrocarbons, and coke deposition. Along with the fire, combustion gases, steam and hot water move forward, displacing the oil towards the production wells by reducing viscosity [6].

<u>Advantages</u>- high recovery rates, cost effective, negligibly influenced by reservoir permeability.

<u>Disadvantages</u>- CO_2 emissions, gases like compressed air needed, high temperatures damage equipment, advancing combustion front is difficult to control.

4.1.2. Steam Flooding: Steam is constantly injected into the reservoir by means of dedicated injection wells. This heats the chamber near the injection well and as the chamber expands in the direction of the production well, the oil viscosity is reduced resulting in substantial displacement.

<u>Advantages</u>- most used EOR technique due to very high recovery, higher sweep efficiency when compared to Cyclic Steam Stimulation.

<u>Disadvantages</u>- expensive, significant heat loss, sand plugging at bottom hole in super heavy oil formations.

4.1.3. Cyclic Steam Stimulation (CSS): Steam is continuously injected through the production well for a pre-established period. The well is shut for several days to weeks to achieve desired viscosity reduction via heat transfer. The well is then opened for production and initial oil flow rates are high, but decline significantly as the reservoir temperature drops. At this point, another CSS cycle is applied and this process continues until oil production is profitable.

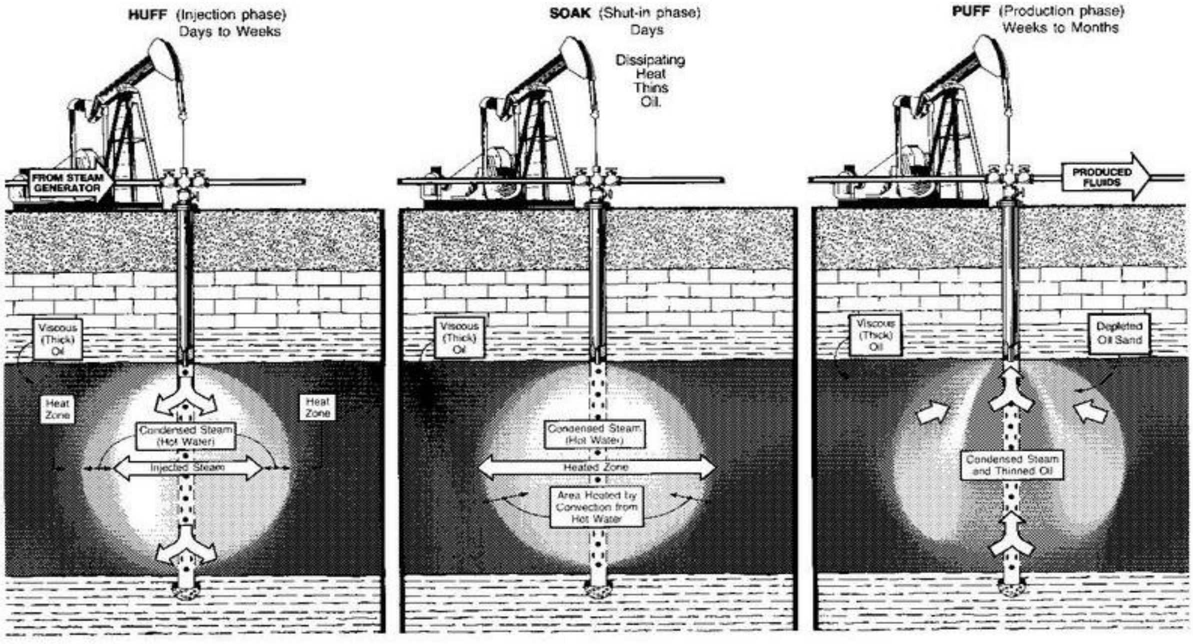


Fig. 3: CSS Stages. Ref- F. Ameli et al. Thermal Recovery Processes [p.8]. *In:* A. Bahadori (ed.), *Fundamentals of Enhanced Oil and Gas Recovery from Conventional and Unconventional Reservoirs*. Gulf Professional Publishing, 2018. [Online] Available from ResearchGate: https://www.researchgate.net/publication/329886519_Thermal_Recovery_Processes [Accessed 5 Mar 2021]

Advantages- reduced capital investment as no additional wells are required, substantial recovery in heavy oil reservoirs with thick pay zones (>15 m).

Disadvantages- complex, excessive heat loss, small radius of heat zone, uneconomical for thin pay zones (<6 m), early steam breakthrough [4 pp.9-11].

4.2 Chemical EOR (CEOR)

In CEOR, chemicals such as polymers, surfactants, alkalis, and their mixtures are injected to recover oil, and is best suited for mature reservoirs. These chemicals have different effects on oil production. The method to be used depends on reservoir characteristics and is backed by laboratory studies.

4.2.1. Polymer Flooding: Polymers such as Polyacrylamide, Xanthan gum, Hydrolysed polyacrylamide (most commonly used due to thermal and chemical stability event up to 99 ^oC), etc. are dissolved in water and injected into the reservoir, followed by long-term waterflooding to drive the oil in the direction of the production wells. The polymer increases the viscosity of the aqueous phase, reduces its effective permeability due to polymer retention, and thereby reduces the mobility ratio.

Advantages- effective in increasing viscosity and decreasing effective permeability of aqueous phase, cost effective.

Disadvantages- some polymers are susceptible to thermal, chemical, mechanical and bacterial degradation, pore plugging and injectivity are issues in low permeability reservoirs.

4.2.2. Surfactant Flooding: Surfactants (can be anionic, cationic, non-ionic or Zwitterionic) are soluble in water and organic solvents by virtue of them having both hydrophilic and hydrophobic regions. A dilute aqueous solution of surfactants is injected in the reservoir which migrates to the oil-water interface and reduces the IFT, thereby increasing their miscibility. A small surfactant concentration in the injected solution (0.1-5.0 wt%) can significantly reduce the IFT from 30 to 0.01 mN/m.

Advantages- effective IFT reduction, increased microscopic sweep efficiency.

Disadvantages- achievement of ultra-low IFT is complex, large amounts of surfactant needed for substantial recovery, addition of polymers may be needed if viscosity of surfactant formulation is less than that of oil.

4.2.3. Alkaline Flooding: Aqueous solution of an alkaline chemical such as NaOH (most commonly used), Na_2CO_3, Na_4O_4Si is injected into the reservoir. The alkaline solution and organic acids in the crude oil react to give natural surfactants in-situ, and thereby reduce the brine-oil IFT, form oil-water emulsions and alter the reservoir rock wettability.

Advantages- can be used for recovery of heavy oil in thin formations, low operational costs.

Disadvantages- alkali scale produced due to precipitate formation can harm the formation, low viscosity of alkaline solution (and hence high mobility ratio) causes unfavourable viscous fingering (few sections of reservoir bypassed resulting in inefficient sweeping action).

4.2.4. Surfactant-Polymer (SP) Flooding: Alternate slugs of surfactant and polymer are injected into the reservoir. Mobility control is achieved by injecting (in order) a surfactant slug, polymer slug, polymer buffer and chase water. Accurate SP formulations increase capillary number and reduce mobility ratio. IFT reduction, and increased viscosity and reduced effective permeability of the aqueous phase are achieved, which enhance mobility ratio and sweep efficiency.

Advantages- accurate SP formulations can achieve ultra-low oil-brine IFT.

Disadvantages- the injected chemicals and brine may be chemically incompatible.

4.2.5. Alkaline-Surfactant-Polymer (ASP) Flooding: ASP cocktails increase EOR efficiency by reducing IFT and improving mobility ratio. Alkali makes the reservoir more water-wet by decreasing surfactant adsorption on the rocks, surfactant reduces oil-brine IFT, while polymer enhances mobility ratio. The chemicals can be injected as separate slugs or as a single slug.

Advantages- cost effective, attractive due to synergistic effect of ASP mixture, low amount of chemicals used per unit volume of oil produced.

Disadvantages- scale formation, unstable emulsions, chemical separation [4 pp.12-18].

4.3 Gas Injection EOR (GEOR)

Gas is injected to displace oil towards production wells. Displacement efficiency (percentage of oil displaced by injected fluid) and sweep efficiency (measure of reservoir volume contacted by the injected fluid) are the factors which determine the process' success. CO_2 (most used), N_2 and hydrocarbons are the commonly used gases. CO_2 accounts for over 50% production by GEOR and in 2008, 101 CO_2-EOR projects yielded 2,50,000 barrels/day in the US.

4.3.1 Miscible Flooding: The injected gas completely mixes with the crude oil at or above the minimum miscibility pressure (MMP) at the reservoir temperature. Displacement efficiency is highly dependent on MMP. When CO_2 is injected, it mixes with oil through multiple interactions whereby light hydrocarbons vaporise into the CO_2 phase and this gas phase becomes progressively heavier and denser. It then condenses ahead of the displacement/miscible zone in the crude oil zone, thus reducing the oil viscosity and density. Due to miscibility between CO_2 and the residual oil, IFT becomes zero as there is no interface, residual oil saturation is very low, and the mixture is displaced as a single phase from the rock pores.

Advantages- increased overall displacement efficiency, very low residual oil saturation, near zero IFT, oil production increases significantly, more cost effective than TEOR.

Disadvantages- high gas compression costs, high operational costs, oil flow path may change due to change in density, failure in miscibility if pressure is less than MMP.

4.3.2. Immiscible Flooding: The gas is injected at a pressure below MMP, hence there is no miscibility and recovery is half that of miscible flooding. Here, oil swelling increases the macroscopic displacement efficiency and is mainly responsible for incremental recovery. The process is more favourable for light oil formations than for heavy oil ones.

<u>Advantages</u>- improves oil displacement efficiency, good potential for light oil formations.

<u>Disadvantages</u>- viscous fingering, poor sweep efficiency, poor recovery in heavy oil formations when compared to TEOR, early gas breakthrough [4 pp.19-22].

4.4 Microbial EOR (MEOR)

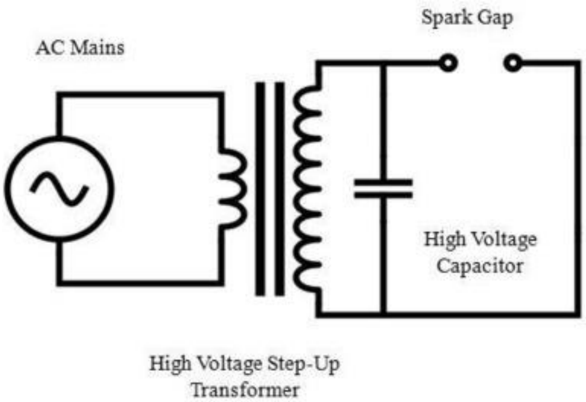
In in-situ mechanism, indigenous or exogenous bacteria can be activated or injected into the reservoir to interact with crude oil and produce biosurfactants, biopolymers, gases, acids, solvents, biomass and emulsifiers through metabolic reactions. This results in reduction of oil viscosity and IFT, and increase in oil mobility. The bacteria should be small, spherical and less than 20% of the size of pore throats in the formation. Cells of size 0.5 to 5.0 µm easily penetrate through the porous media. Clostridium and Bacillus are commonly used microbes [pp.26-27]. In ex-situ mechanism, biproducts generated by microbes via metabolic activities are selectively removed from the microbe surface and injected into the reservoir for achieving desired results. These processes, despite being around for quite a while and being advantageous haven't got much support due to lack of data, and complexity.

<u>Advantages</u>- economically efficient, environmentally friendly, low energy consumption.

<u>Disadvantages</u>- slow, aerobic microbial activity corrodes equipment, complex process, survival of microorganisms depends on reservoir conditions [7 pp.1-2].

5. NEW TECHNOLOGIES

5.1. Plasma Pulse Technology (PPT): A relatively newer method in which heat and acoustic waves generated by a highly energetic plasma arc remove clogged sediments and may create nano or micro scale fractures, thereby enhancing reservoir permeability. Even after the arc generation has stopped, the waves resonate deep into the reservoir and can break larger hydrocarbons into smaller ones, and reduce adhesion tension which increases oil mobility. The technology is directed at generating nonlinear, wide-band, periodic, directed and elastic oscillations between the fluid particles, preferably in the frequency range of 1 Hz to 20 kHz. The capital investment involved is less, and the process is environment friendly as no harmful chemicals are involved. PPT can be used for treating production, injection, mature, depleted, land, onshore, or offshore wells/boreholes/openings, and has been successfully applied to more than 200 wells, with some showing an over 500% improvement in production for 5-6 months.



Oil fields	Bbls/day (Before)	Bbls/day (After)	%increase
Lomovoe	119	728	511
Poludennoe	314	942	200
Sutorminskoe	157	1080	588
Tajlakovskoe	31	376	1100
Arlanskoe	31	138	340
Turchaninovskoe	125	546	335
Muravlenskovkoe	1727	4396	155

Fig. 4: Simplified Circuit of PPT Apparatus, Table 1: Results of PPT Application to Russian Oilfields. Ref- K. Patel et al. Plasma Pulse Technology: An uprising EOR technique [p.4,7]. *Petroleum Research.* 2018, 3 (2). [Online] Available from: https://www.sciencedirect.com/science/article/pii/S2096249518300012#bib16 [Accessed 22 Mar 2021].

Advantages- alleviates drawbacks of other EOR methods as no gas supply needed (GEOR), handling of toxic brine is not involved (CEOR), no flue gas emission (TEOR), and no separate injection wells needed.

Disadvantages- cannot push immobile oil, better suited for coarse grained consolidated sandstone reservoirs, not feasible when frequent clogging of pores and wellbores occurs [8 pp.1-8]

5.2. Water Alternating Gas (WAG): It is an advancement in the GEOR sector and improves recovery by combining the effects of water and gas flooding. Alternate slugs of water and gas are injected through the same well, and both displacement and volumetric sweep efficiencies are increased.

Advantages- reduced oil viscosity and residual oil saturation when compared to gas and water flooding, increased oil recovery factor, reservoir pressure is maintained [9 p.3].

Disadvantages- reduced injection rates, corrosion of equipment, gas may not be available, early breakthrough [10 p.22].

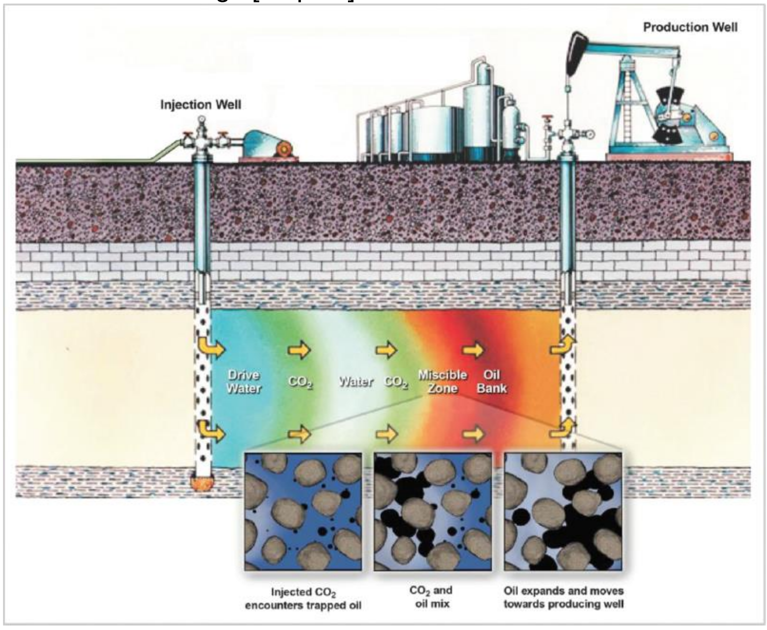


Fig. 5: WAG Injection. Ref- L.N. Nwidee et al. EOR Processes, Opportunities and Technological Advancements [p.20]. In: L.R. Zerón (ed.), *Chemical Enhanced Oil Recovery (cEOR) a Practical Overview*. IntechOpen, 19 Oct 2016. [Online] Available from IntechOpen: https://www.intechopen.com/books/chemical-enhanced-oil-recovery-ceor-a-practical-overview/eor-processes-opportunities-and-technological-advancements [Accessed 20 Feb 2021].

6. CONCLUSIONS AND FUTURE WORK

This document has summarised various EOR methods in the simplest possible language and hopes to serve as a good introduction to the booming sector. EOR helps exploit existing reserves to the greatest extent while being economically feasible. Clearly, it is the way to go for meeting demands for energy and chemicals in the wake of insignificant new discoveries. The data provided throughout this document, especially in the PPT section and appendix vindicate this claim. As discussed, each EOR technique has its own set of advantages and limitations. This prompts the use of a variety of combinations, which have proven to be more effective [11 p.2] and study of different combinations has immense potential to offer. When compared to other methods, TEOR requires larger amounts of energy and has a relatively low recovery factor [5 p.25] and also causes pollution due to emission of toxic flue gases. However, since it is the best technique for heavy oil formations and cannot be dispensed with, there is scope of innovation and use of renewable energy like solar for the heating purposes. The emerging field of nanotechnology offers great opportunities for exploratory studies on the effect of combinations of chemicals and nano particles on reservoir characteristics. Despite many challenges in the GEOR sector, oil companies can do their bit in cutting on carbon emissions by investing in carbon sequestration, storage and use by investing in the highly efficient CO_2-EOR, which could someday result in carbon-negative fuels being offered.

The global EOR market is expected to grow at a Compounded Annual Growth Rate (CAGR) of 6.5% from USD 43.3 billion in 2020 to USD 59.4 billion in 2025 [12]. This growth should be sustainable and hence development of clean EOR techniques is the need of the hour. Also, the application of EOR to offshore reserves is limited due to their lithology, high operational costs and environmental regulations. Efforts are on to make EOR practices more prevalent in offshore reserves, and chemical injection, hydrocarbon WAG injection and CO_2-EOR/sequestration have been identified as prospects [13 p.1]. PPT can also be used as only a 155-pound tool has to be lowered into the well [8 p.5]. On a personal note, PPT and WAG EOR methods appeal to me and have the potential to extract oil without harming the environment. I would hence definitely like to take up a research project pertaining to these areas.

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APPENDIX

1. COMPARISON OF SOME EOR TECHNIQUES

Table 1 depicts the effect of EOR techniques on the physical characteristics of the reservoir. Note that waterflooding is the base case and isn't considered an EOR technique.

EOR Method		Pressure Support	Sweep Improvement	IFT Reduction	Wettability Alteration	Viscosity Reduction	Oil Swelling	Hydrocarbon Single Phase	Compositional Change[1]	Incremental Recovery Factor
Waterflood	Waterflood									Base case[2]
	Engineered water									Low
Gasflood: immiscible	Hydrocarbon									Moderate
	CO_2									High
	Nitrogen or flue gas							3	3	Moderate
Gasflood: miscible	Hydrocarbon								4	High
	Hydrocarbon WAG								4	Very high
	CO_2									High
	CO_2 WAG									Highest
Thermal	Steam									High
	High-pressure air									High
Chemical	Polymer									Low
	Surfactant									Moderate
	ASP									High

IFT = interfacial tension
WAG = water-alternating-gas
ASP = alkali-surfactant-polymer

1. Change of composition of liquid hydrocarbon.
2. Waterflooding provides the base case for comparison of other methods.
3. Oil stripping occurs as miscibility develops.
4. Condensing and vaporizing exchange.

Table 1: Physical Effects of EOR Methods. Ref- R. Al-Mjeni et al. Has the Time Come for EOR? *Oilfield Review*, Winter 2010-11, 22 (4). [Online] Available from: https://www.slb.com/-/media/files/oilfield-review/eor [Accessed 20 Apr 2021].

7. CASE STUDY

The Magnus oilfield in the UK Continental Shelf is the most northerly producing field in the UK sector of the North Sea. It is operated by British Petroleum with 85% equity and originally contained 2.4 X 10^8 m^3 of oil (measured at surface conditions). The field was prepared by peripheral water flooding and production started in 1983, with plateau production rate of 24,000 m^3 at standard conditions per day (sm^3 day^{-1}) being maintained until 1995, when seawater broke through to wells at the crest of the reservoir. About 40% of the OOIP had been recovered, while the rest was believed to be trapped as residual oil on the pore scale and partly bypassed due to reservoir heterogeneity.

EOR was favourable despite residual oil saturation being just 25% due to large OOIP volumes. As the reservoir temperature was 115 ^oC, surfactant and polymer flooding ere ruled out, while CO_2 injection was ruled out due to lack of supply and costly equipment changes needed to sustain the associated corrosion. Miscible injection of lean hydrocarbon gas was deemed the best option due to the geology of Magnus, the light oil present there, and because reservoir pressure was sufficient to achieve miscibility. In2002, WAG injection was implemented and to prevent gravity segregation of the injected gas and water, injection rates were kept high. This method arrested the decline in output by 2005 and a secondary plateau was achieved. 3.2 X 10^9 sm^3 of gas had been injected by 2010, yielding 1.8 X 10^6 sm^3 of incremental oil overall, and contributed 40% of the production rate in 2010. The reservoir pressure was maintained above the MMP of 34.5 X 10^6 Pa [1 pp.11-14].

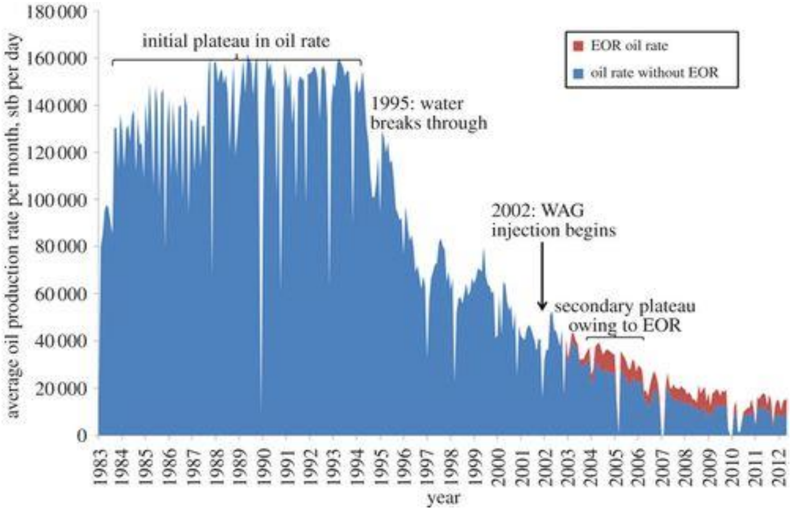

Fig. 1: Magnus Oilfield Production Profile. Ref- A. Muggeridge et al. Recovery rates, enhanced oil recovery and technological limits [p.13]. *Phil. Trans. R. Soc. A.*, 2014, 372. [Online] Available from: https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2012.0320 [Accessed: 22 Apr 2021].

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