

CO₂ Enhanced Oil Recovery in Unconventional Liquid Reservoirs

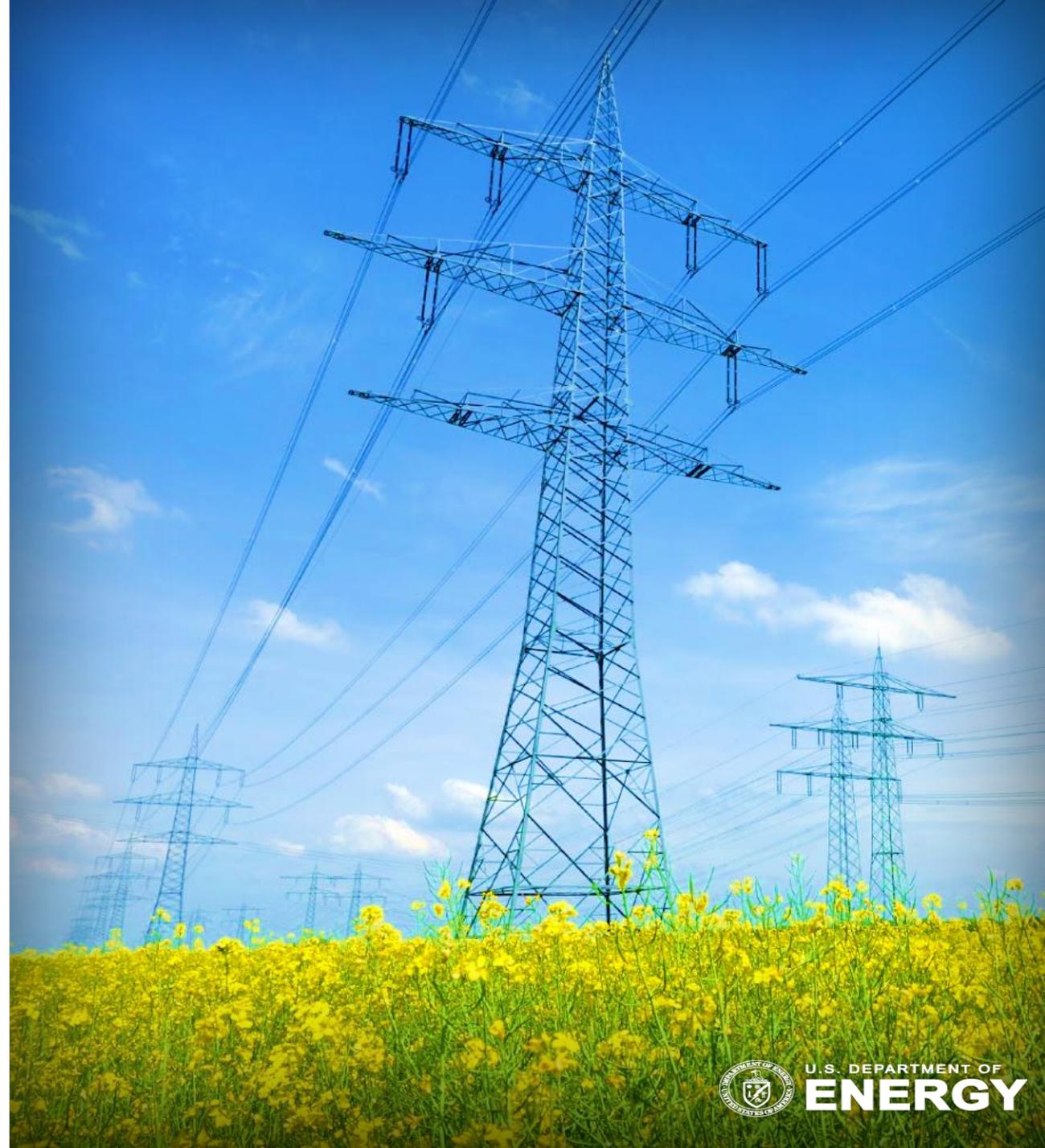
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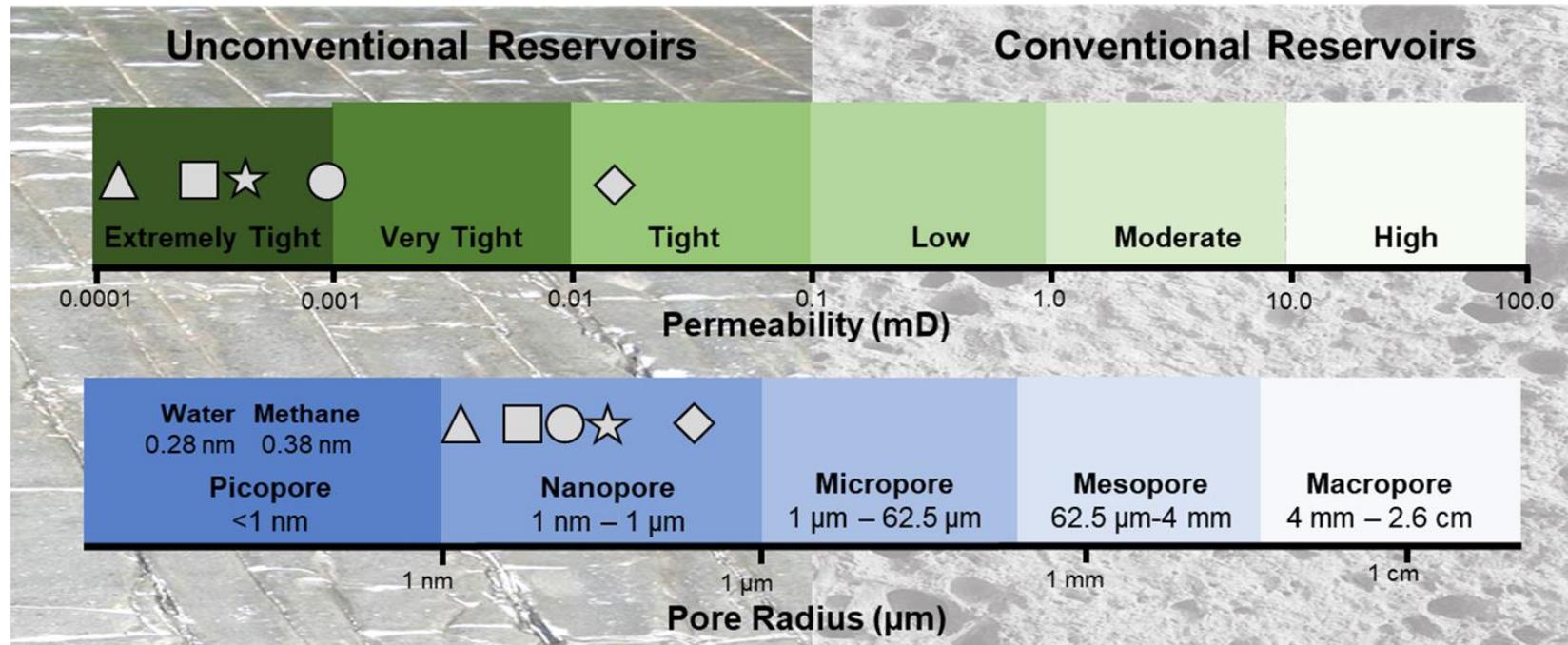
Objectives of NETL

- Increase domestic energy production (Improve U.S. energy security ,decrease dependence on foreign oil)
- Reduce environmental impact of fossil fuels



Despite Shale Revolution, much work to be done!

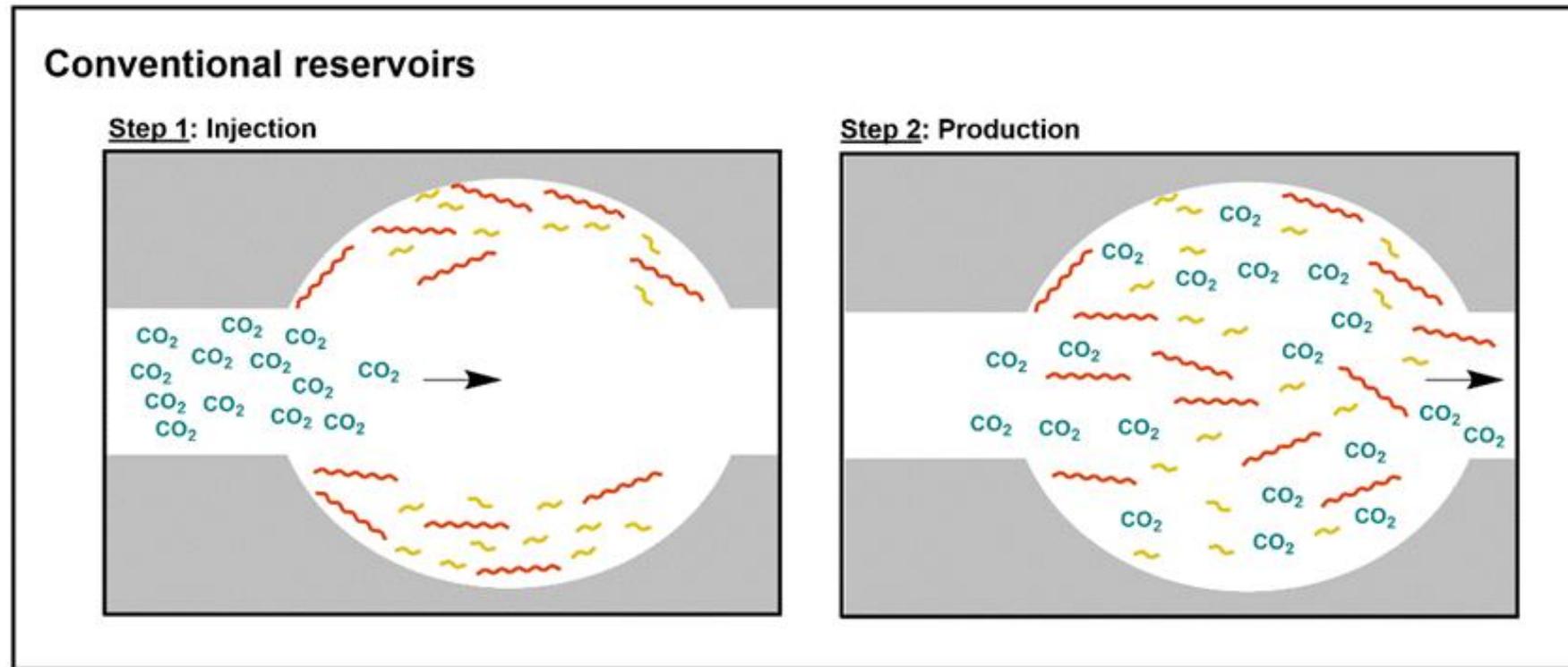
- EOR in unconventionals is **needed**: recovery after hydraulic fracturing + primary production = 4-6% (Bakken)
- Permeabilities are 1,000 to 10,000 times lower than in conventional reservoirs
- Low permeabilities are caused by low porosity, small pore sizes, oil-wetness



□ = Eagle Ford ☆ = Lower Bakken ◇ = Middle Bakken ○ = Barnett △ = Wolfcamp

Mechanism of CO₂ oil recovery in conventional reservoirs

- Conventional and unconventional mechanisms are very different due to the low permeability shale matrix
- CO₂ EOR in conventionals: CO₂ easily flows through pores
- Heavy and light hydrocarbons are both produced, no soak time needed

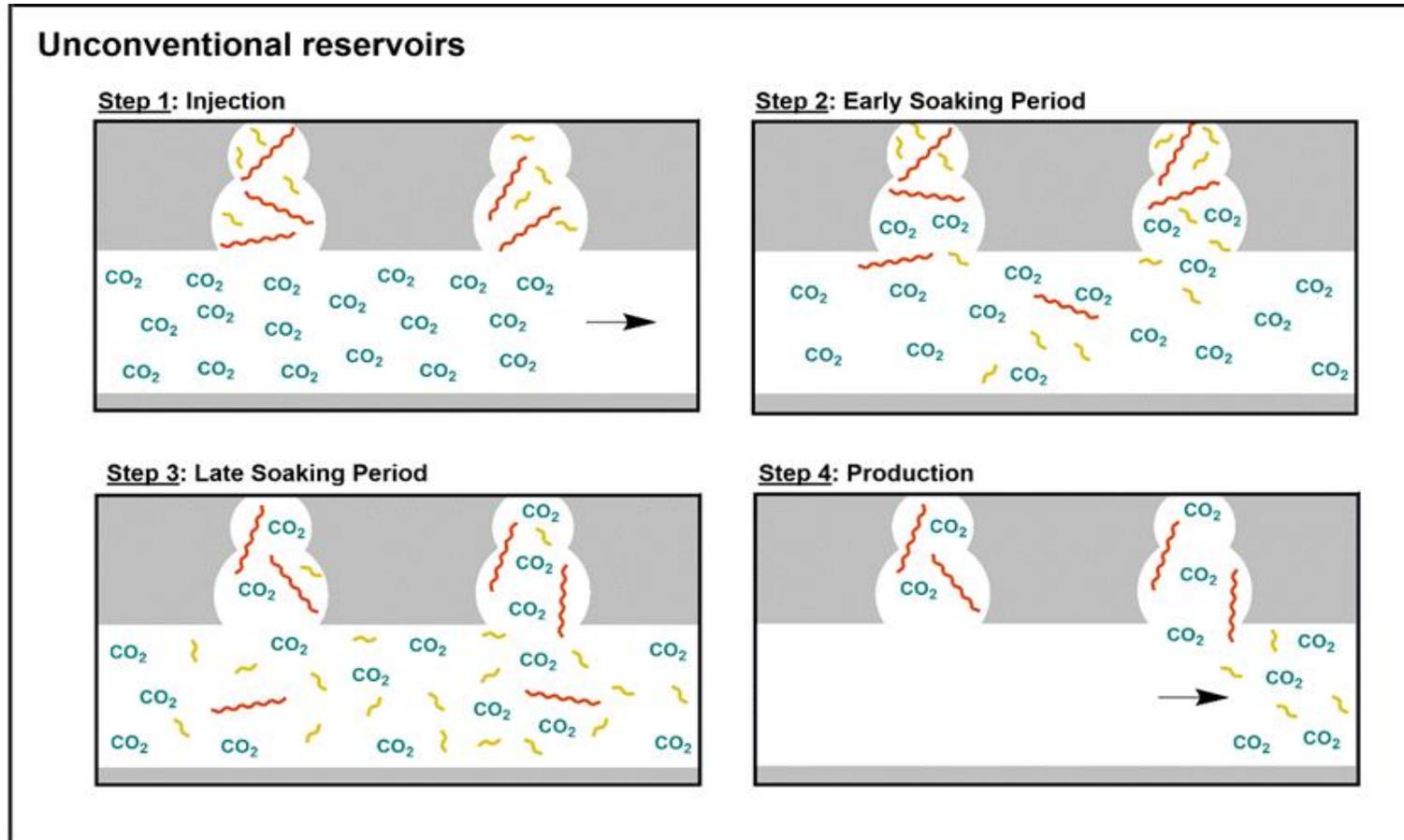


Mechanism of CO₂ Enhanced Oil Recovery in Fractured Shale Reservoirs

- Diffusion is a key mechanism: long soak times improve recovery, lighter hydrocarbons produced preferentially

CO₂ flows through fractures, driven by high injection pressures

Injection pressure equilibrates and CO₂ enters pores by diffusion

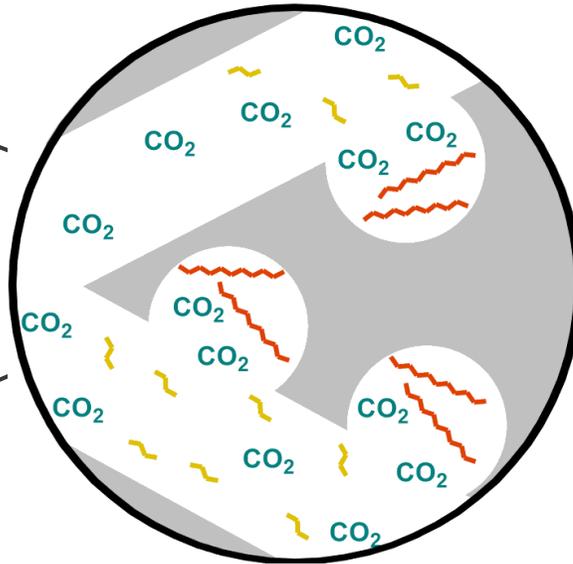


Some CO₂ enters pores, driven by high injection pressures

Oil and CO₂ in fractures move to production well

Implications of diffusion mechanism

Diffusion mechanism of CO₂ EOR in ULRs



Long soak times improve oil recovery

Huff n' Puff

soak

High exposed shale surface area improves recovery

Lighter hydrocarbons are produced preferentially

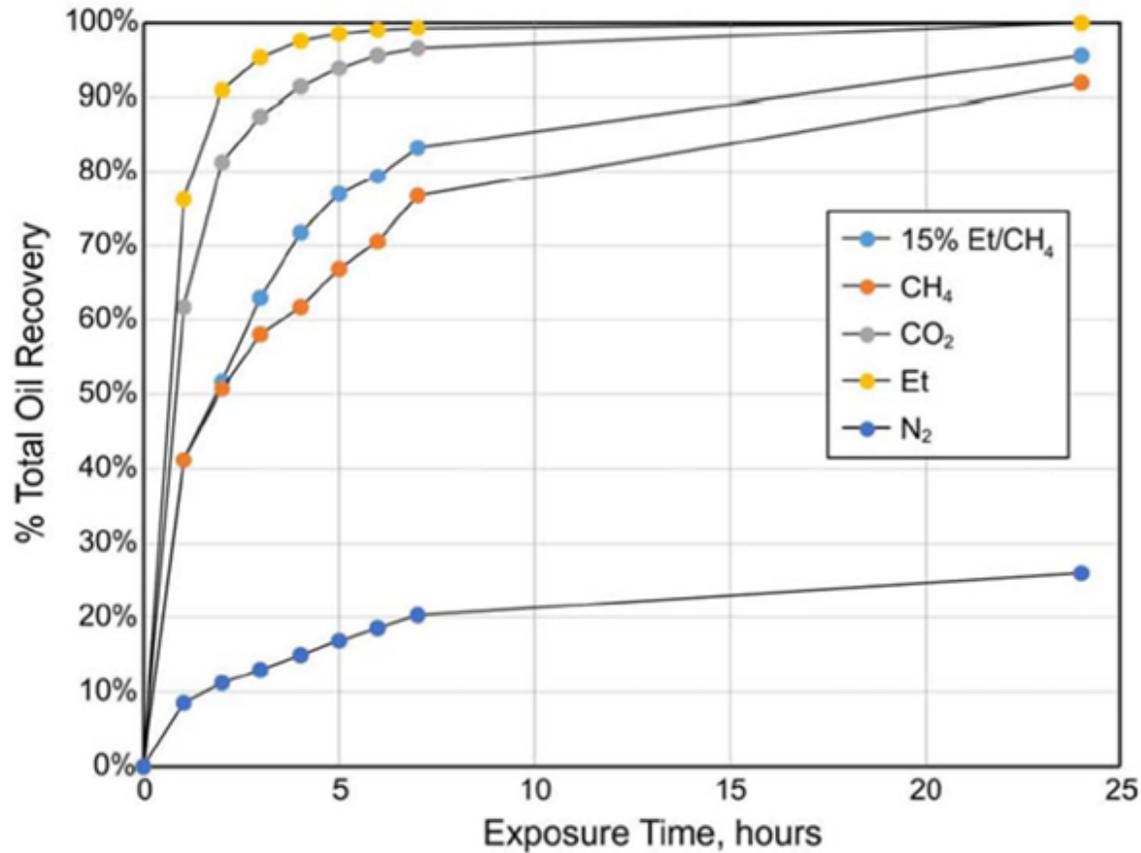
High injection pressures beyond MMP improve oil recovery

Fluids being considered for EOR in Fractured Shale Reservoirs

Attribute	CO ₂	Ethane	Methane	Nitrogen	Water
Kinetic diameter (nm) 78 , 79	0.33	0.44	0.38	0.36	0.27
Critical temperature, °C	31	32	-83	-147	374
Critical pressure, Mpa	7.4	4.9	4.6	3.4	22.1
Critical Density (g/cm ³) ^a	0.47	0.21	0.12	0.31	0.32
Viscosity (cP), 100 °C, 20.7 MPa ^a	0.039	0.038	0.018	0.025	0.29
MMP, Bakken oil (MPa), 110 °C 80	17.4	9.3	31.1	101.4	-
Swells oil?	Significant	Significant	Yes	No	No
Reduces oil viscosity?	Significant	Yes	Yes	No	No
Contaminant if present in produced oil/gas?	Yes	No	No	Yes	Yes
Forms acid in water?	Yes	No	No	No	No

Advantageous for oil recovery
 Moderate effect on oil recovery
 Disadvantageous for oil recovery

CO₂ and Nat. Gas are both viable gases for EOR in Shale



Rich natural gas (~15% C₂+) and CO₂ yield similar oil recovery in lab-scale huff 'n puff experiments

11 mm diameter rods from Middle Bakken, 110 °C, 5000 psi, Hawthorne *et. al.*, 2017

CO₂ and Nat. Gas are both viable gases for EOR in Shale

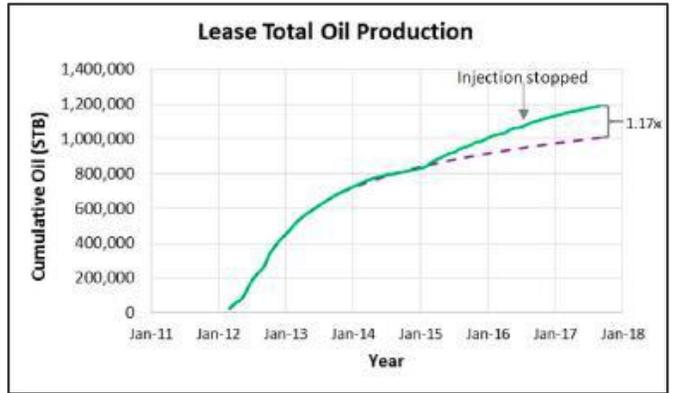


	Eagle Ford Formation	Bakken
Injectivity	Good	Good
EOR Results	Natural gas injection increased production*	Slight increase in production, regardless of fluid
Problems	Conformance control issues, early breakthrough, influence of nearby wells unknown	

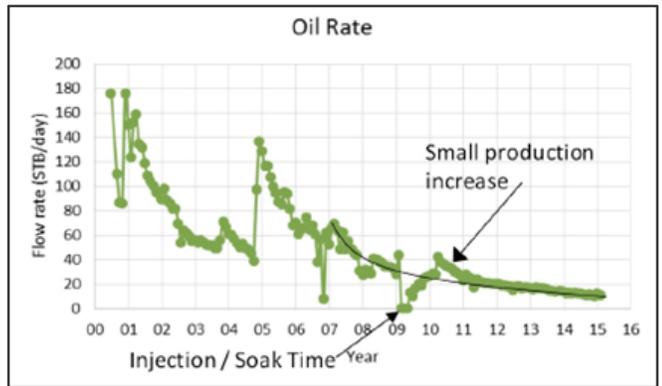
*No comparison to CO₂ reported.

Pilot tests do not clearly show which high-pressure gas is better for oil recovery.

Nat. Gas in Eagle Ford (Hoffman, 2018)

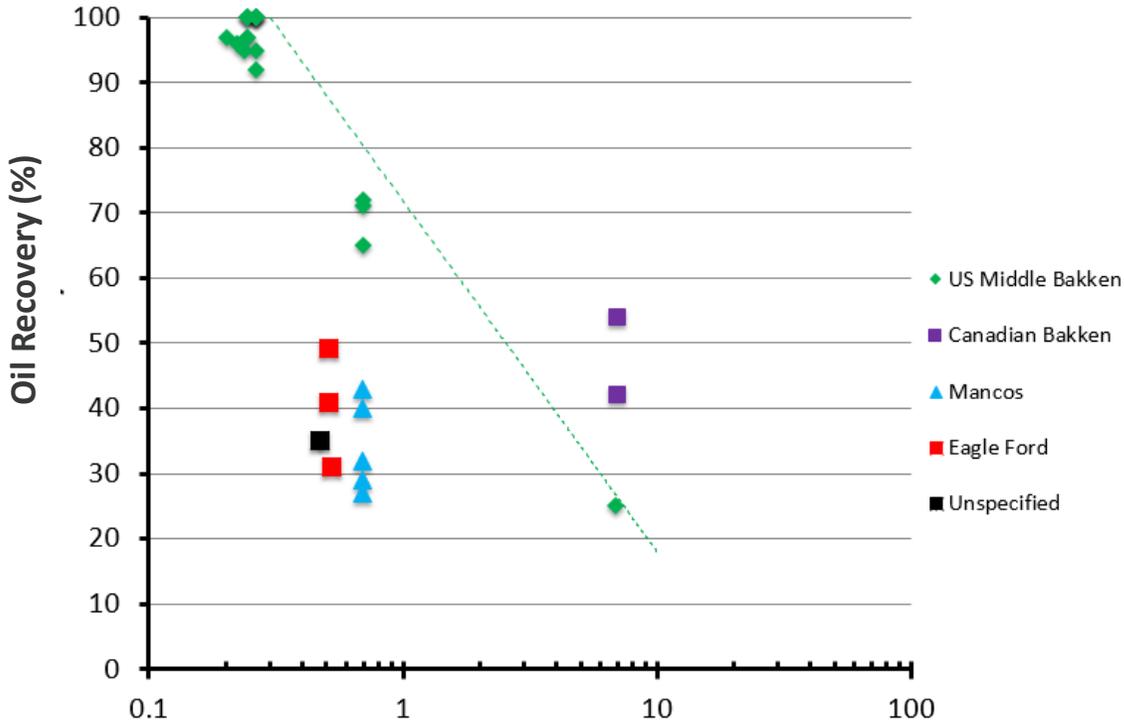


CO₂ in Bakken (Hoffman, 2016)



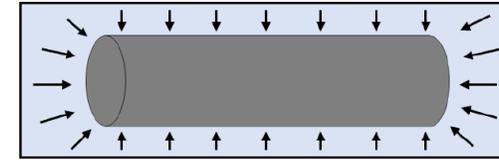
Lab tests are overly optimistic

24 hour CO₂ Huff 'n Puff Oil Recovery done at Near-Miscible (P~MMP) or Miscible Pressures (P>MMP)



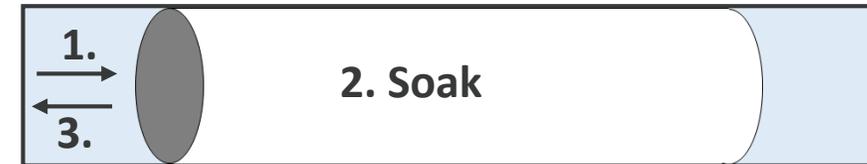
Core Volume / Surface Area Exposed to CO₂ (cm)

Surface area to volume ratio in laboratory is high, does not correspond to field



CO₂ is allowed to surround entire core

Confined Core Huff n' Puff



Confined cores to better model field conditions

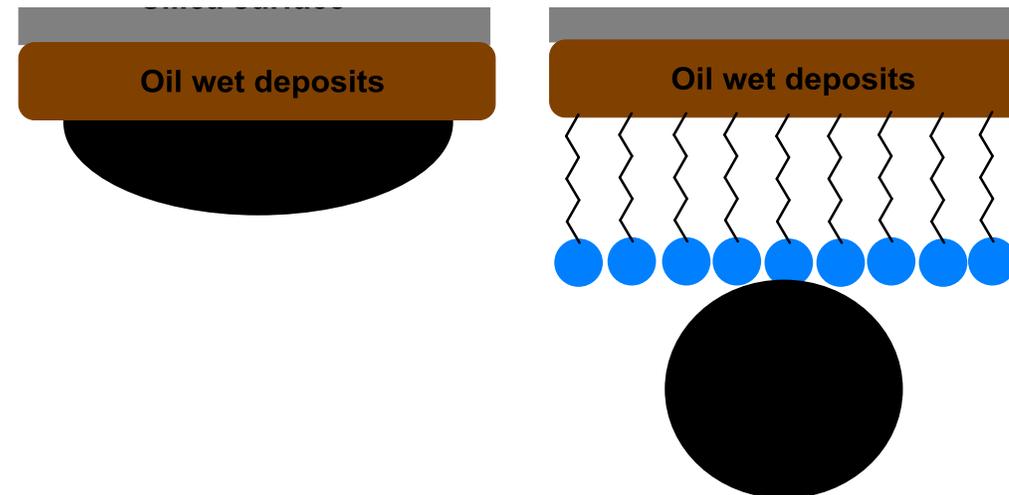
NETL Pittsburgh: CO₂

Morgantown: natural gas

At-depth cores from Eagleford

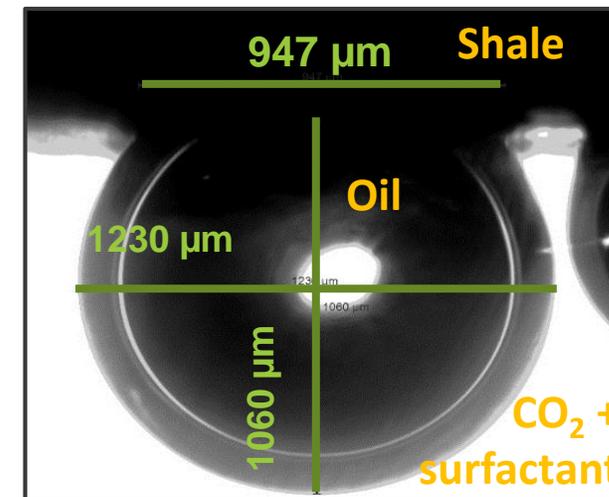
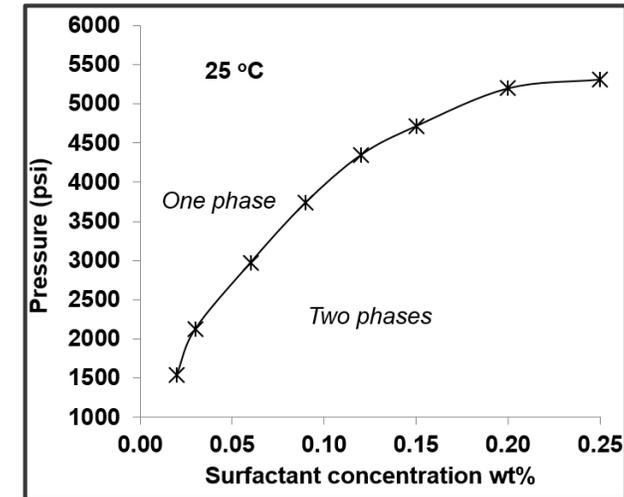
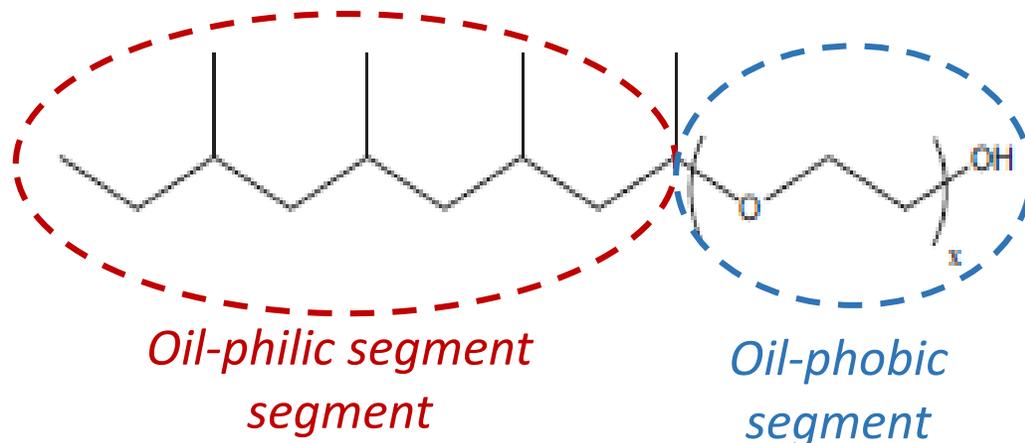
Combined strategy-surfactants for EOR in unconventionalals

- Surfactants are commonly used in waterflooding (conventionals) and fracturing fluid (Unconventionals)
- Surfactants improve hydrocarbon recovery by:
 - (1) Decreasing interfacial tension (IFT) between oil and water
 - (2) Changing surface from oil-wet to water-wet



CO₂-soluble surfactants for CO₂ EOR

- ✓ CO₂-soluble surfactants have already been studied for CO₂ foams
- ✓ Nonionic surfactants are inexpensive and commercially available
- ✓ Combine the advantages of low viscosity CO₂ with the IFT and wettability-altering capabilities of surfactants



Our experimental plans: CO₂ EOR using shale cores



- Pump, transfer vessel and soaking vessel are in place, setup completed
- Shake down with Berea in decane completed
- Experimental procedures: Huff n' Puff with confining pressure-setup in progress
- Oil analysis: Filtering the Eagle Ford oil, SARA analysis

Conclusions

- Natural Gas and CO₂ are both viable fluids for EOR in Unconventionals
- Use of CO₂ or natural gas largely depends on cost and availability
- Laboratory core floods for EOR in Unconventionals are more optimistic than field results
- We are using confined, “at-depth” cores for CO₂ EOR experiments
- Will combine the benefits of CO₂ with wettability-altering surfactants

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