

# *CCUS Conference*

*November 14 – 18, 2022*

*Sponsored By: The Research Council of Norway &*

*The Payne Institute for Public Policy Colorado School of Mines*

*“Whole Value Chain Carbon Capture, Utilization, and Storage (CCUS)”*

***CO<sub>2</sub> for EOR – Historical Perspectives, Current State of the  
Art Technology, and Technology Challenges***

***H. Kazemi, Professor***

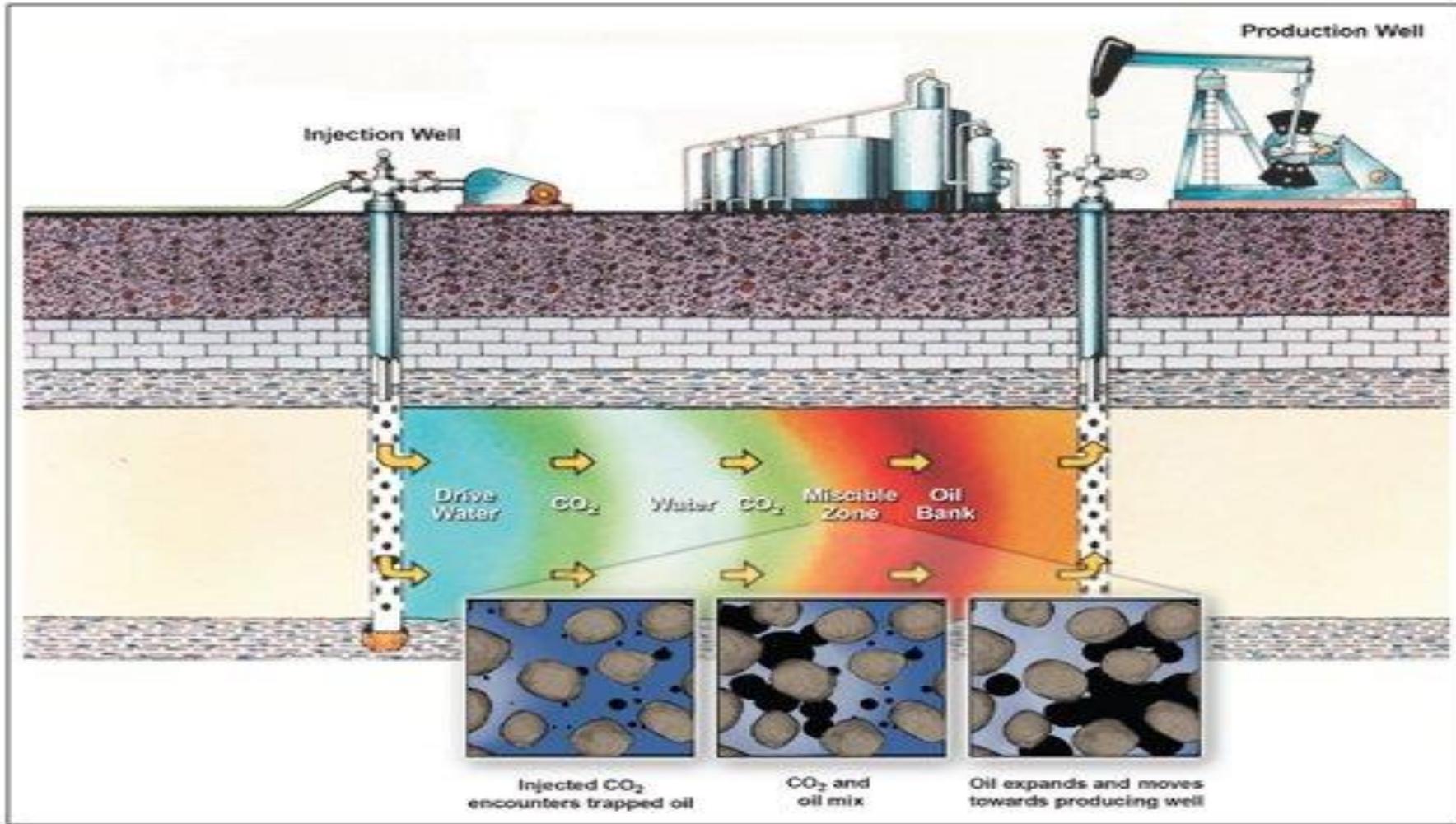
***CSM***

# *CO<sub>2</sub> Enhanced Oil Recovery (EOR)* *in Conventional Reservoirs*

- **Primary Production:** Oil is produced from many production wells. The production mechanism is primarily by reservoir fluid expansion. Approximately 10 to 15% of oil in place is produced this way.
- **Secondary Production:** Next injection wells are drilled to inject water to push additional amount of oil which amounts to, say, an additional 10 to 15%.
- **Tertiary Production:** The third phase is injecting **EOR** agents to mobilize additional oil to produce. The U.S. total EOR daily production is 7.3 %.
- Today, U.S. produces **2.7 %** of its daily oil production from **CO<sub>2</sub>**, **2.5 %** from **steam injection**, and another **2.0 %** from **hydrocarbon gas injection**. **CO<sub>2</sub> leads all EOR in the U.S.**

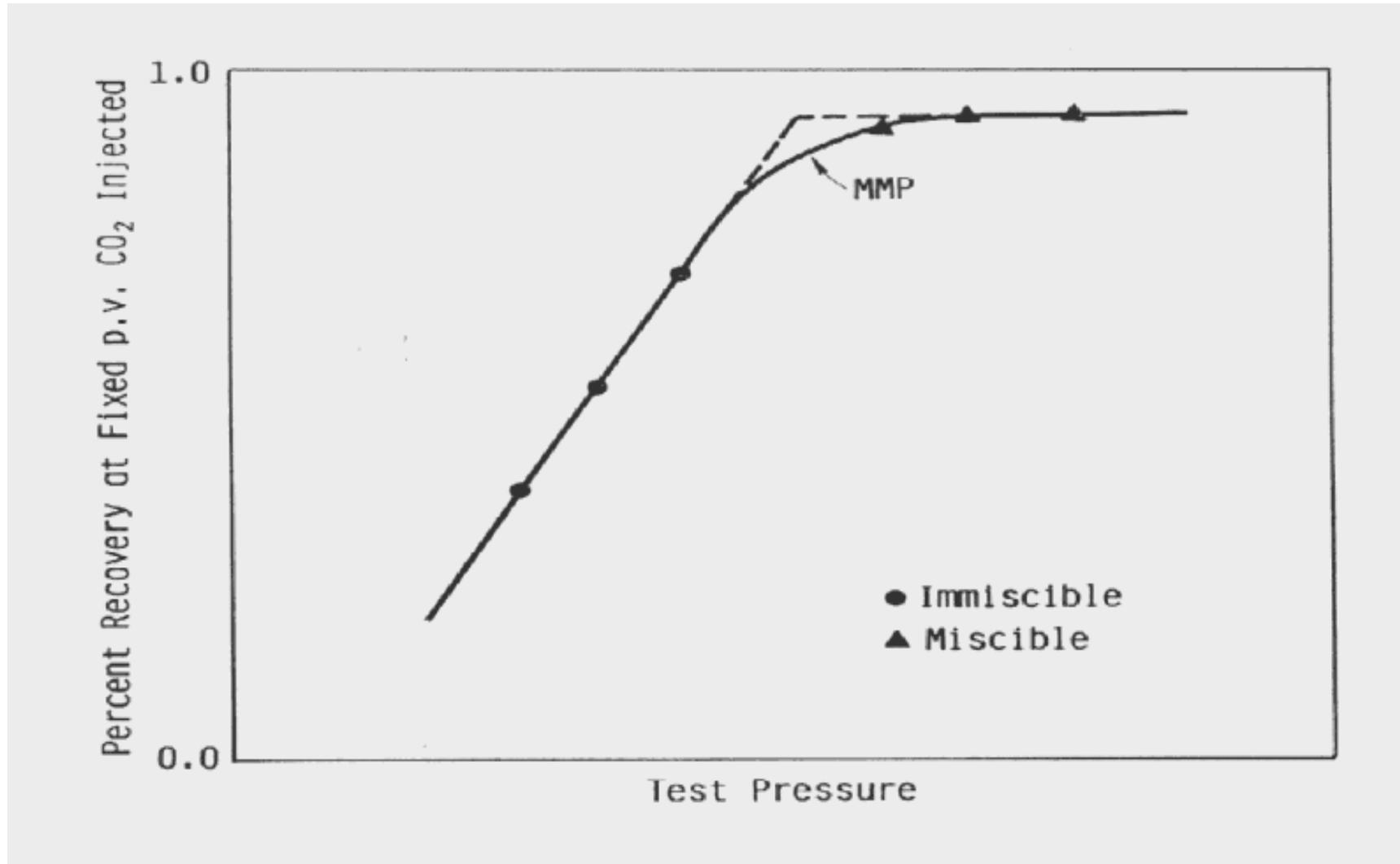
# *CO<sub>2</sub> Enhanced Oil Recovery*

*(Picture Source: U.S. DOE)*



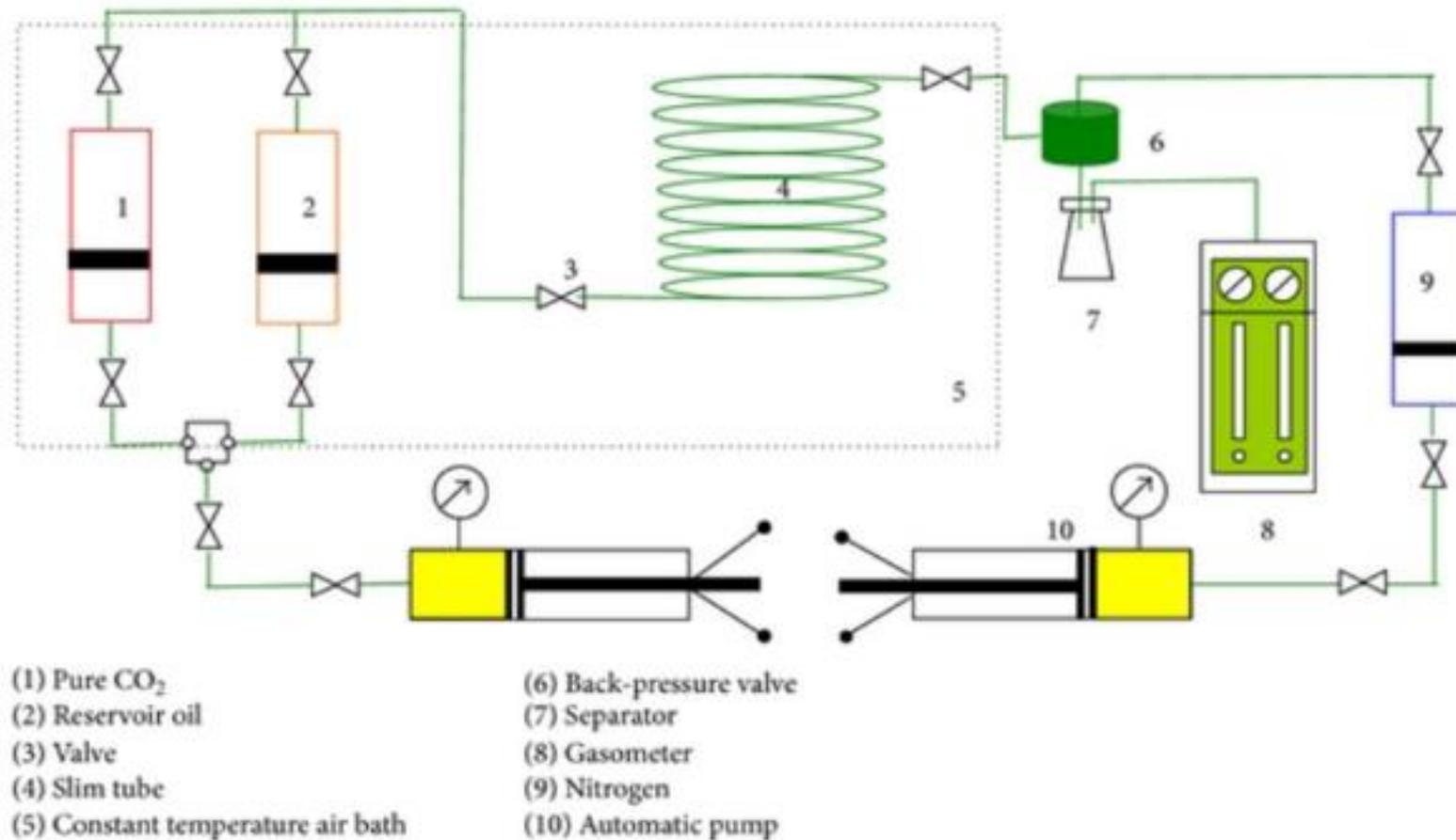
# Oil Recovery in Slim Tube & Minimum Miscibility Pressure (MMP)

(Source: G. Paul Willhite, University of Kansas)



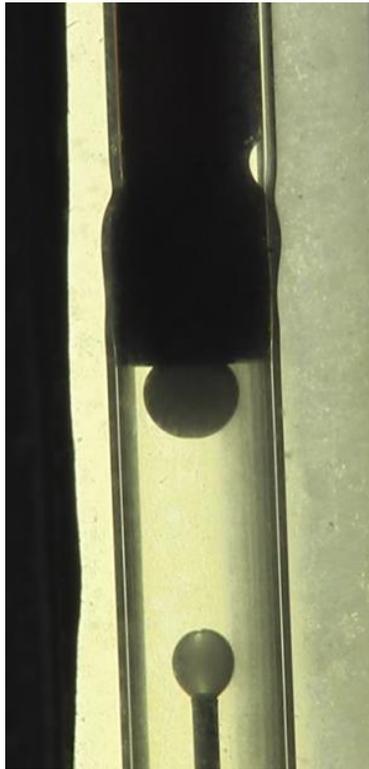
# *Slim Tube Schematic, Core Lab*

*(Source: Schlumberger)*



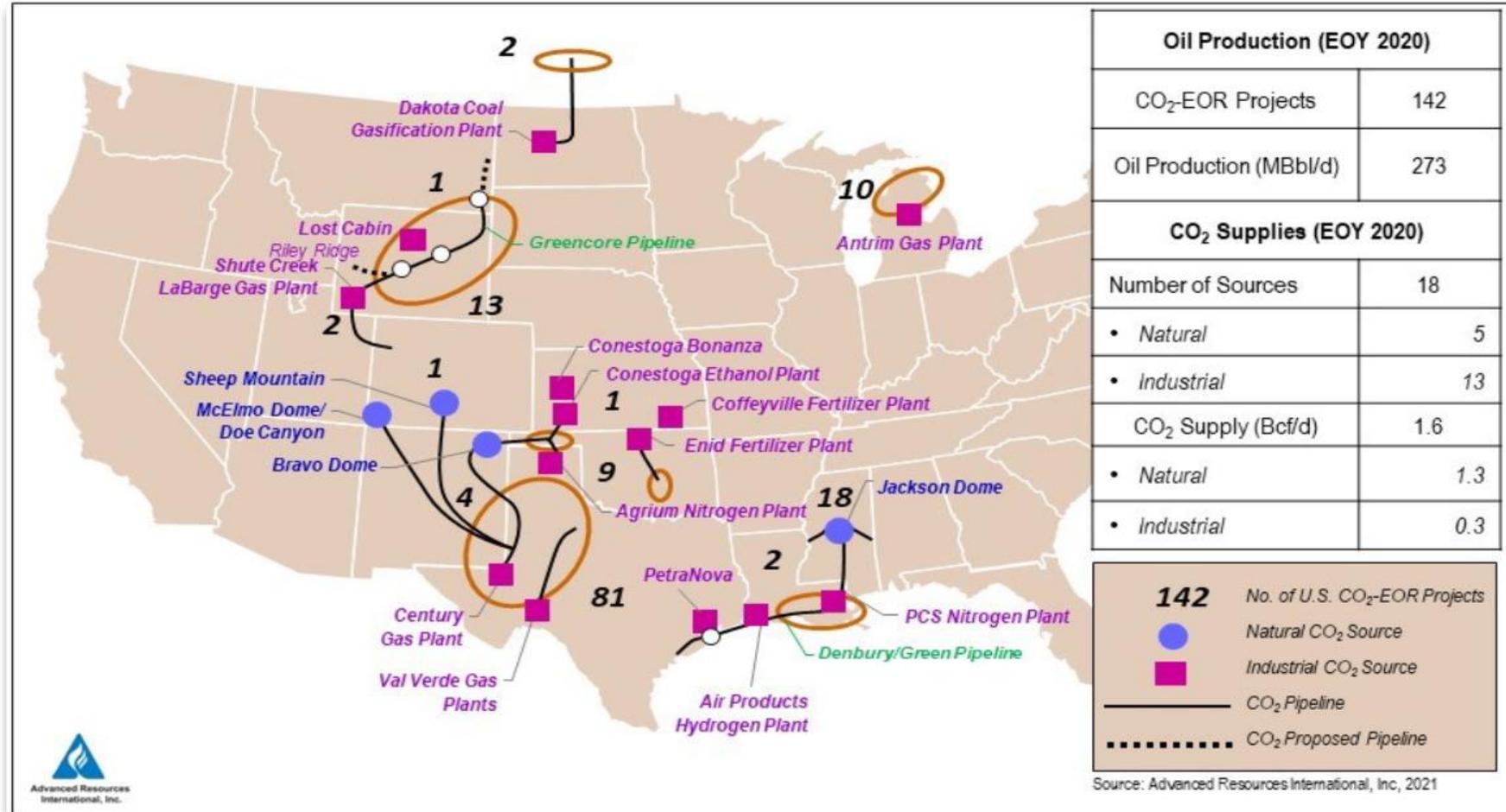
# *Oil Recovery in RBA & Minimum Miscibility Pressure (MMP)*

*(Source: Olawale Adekunle, M.S. Thesis, CSM)*



# CO<sub>2</sub> EOR Infrastructure in the United States

(Source: Advanced Resources International, Inc.)



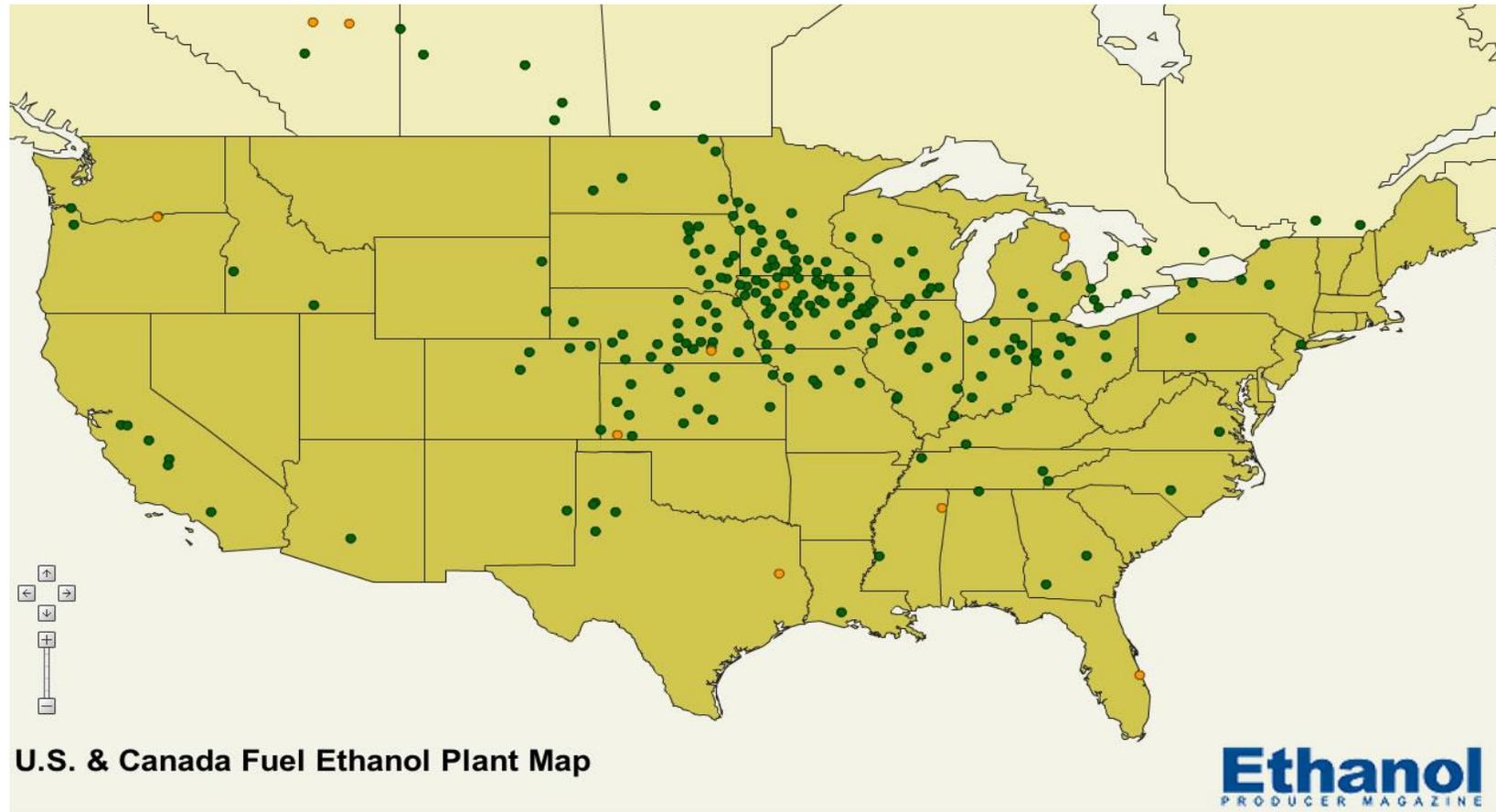
# ***Summary of CO<sub>2</sub> Field Projects in the U.S., 2020***

*(Source: Advanced Resources International)*

- ***Total projects 143, operators 23, and amount 273,000 STB/D, respectively***
- ***CO<sub>2</sub> supply sources 18:***  
***Natural 5 (0.3 BCF/D), Industrial 13 (1.6 BCF/D)***
- ***CO<sub>2</sub> EOR in Permian Basin*** consists of 80 ‘active’ projects (owned by 13 operators) declined from 204,000 STB/D in 2019 to 185 STB/D in 2020
- The ***45Q tax credit*** should increase the volume of industrial sources of CO<sub>2</sub> – specially utilization of CO<sub>2</sub> from ***ethanol plants*** across the U.S. (*map*)

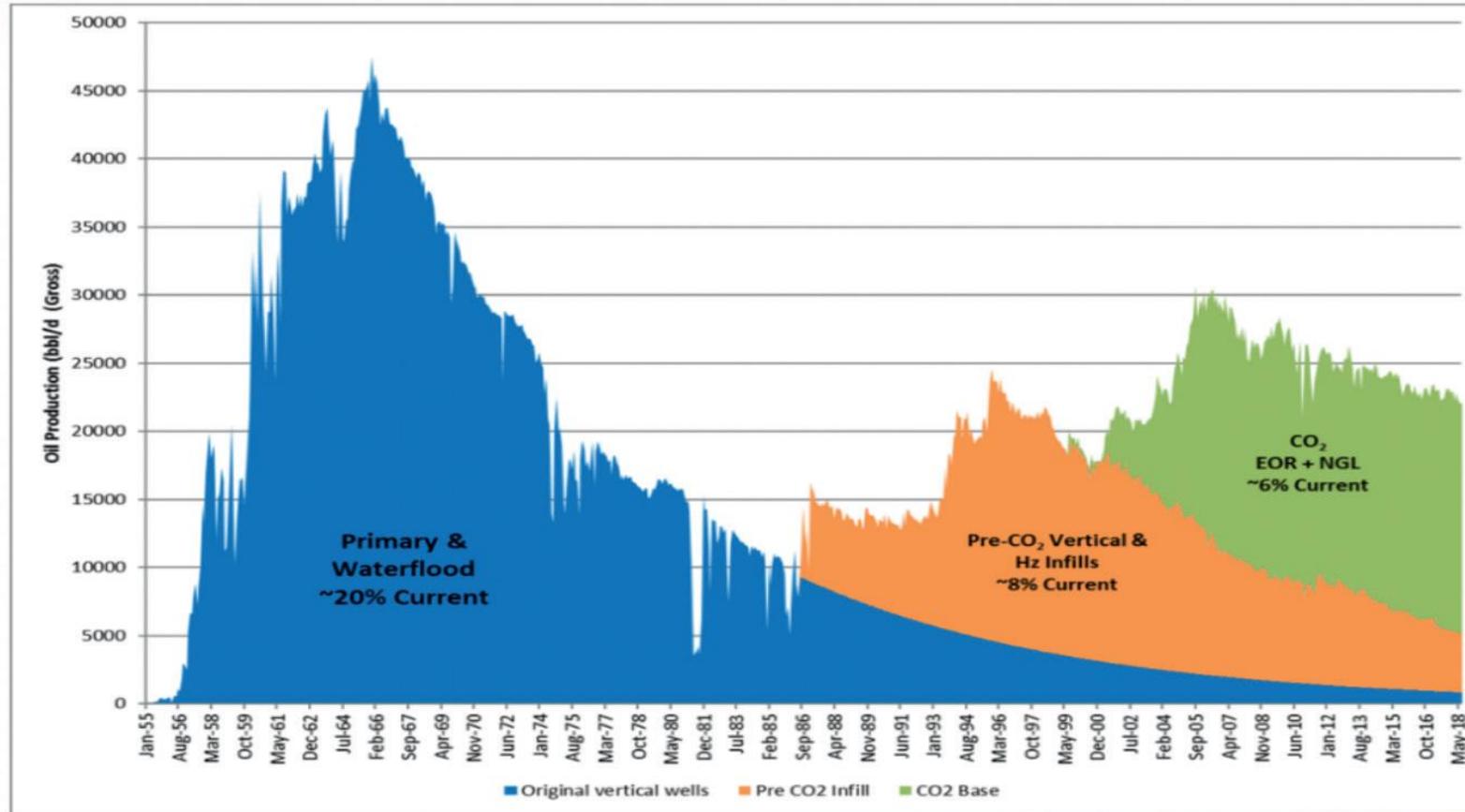
# Map of Ethanol Plants in the U.S. and Canada

There were 198 ethanol plants in the U.S. as of 2017, and in 2018, *60 billion liters of ethanol were produced at more than 220 ethanol production facilities in the United States and the estimated carbon dioxide (CO<sub>2</sub>) from fermentation was around 50 million metric tons* (From: Renewable Fuel Association)  
(Source: Institute for Energy Resourcefulness)



# Weyburn and Midale Fields

Since 2000, industrial-grade CO<sub>2</sub> has travelled 205 miles (330 km) by pipeline from the Great Plains Synfuels Plant in Beulah, North Dakota, to the Weyburn and Midale oil fields where the EOR operations will eventually produce an additional 200 million barrels of oil and permanently store 44 million tonnes of CO<sub>2</sub> (or, 836 BCF) deep underground in the oil-producing rocks. The net utilization ratio is 4,180 scf of CO<sub>2</sub>/barrel of EOR oil.



# *Great Plains Synfuels Plant*

- *The **Great Plains Synfuels Plant** is a model of how coal can be used to produce energy in an efficient and environmentally responsible manner. Each day the Synfuels Plant converts about 18,000 tons of lignite coal into an average 150 million cubic feet of **synthetic natural gas** for home heating and electricity generation. (Source: **Dakota Gasification Company**)*

# Great Plains Synfuels Plant

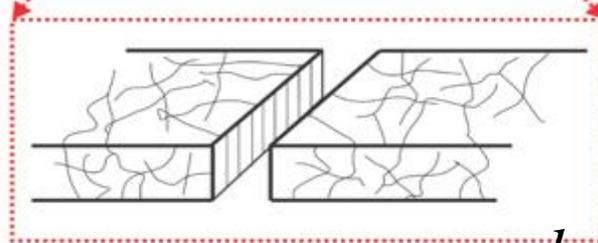
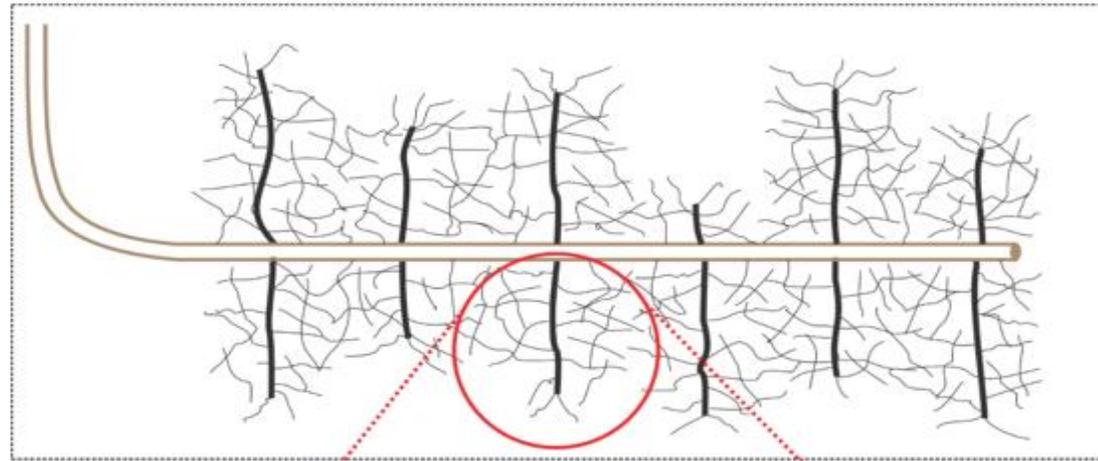
- *The **Great Plains Synfuels Plant in Beulah, North Dakota** has been in operation producing synthetic natural gas (SNG) from lignite coal for 25 years and remains the only coal-to-SNG facility in the United States. In addition to the production of SNG, the plant also produces high purity carbon dioxide (CO<sub>2</sub>), which is distributed through a pipeline to end users in Canada for enhanced oil recovery (EOR) operations. The plant also produces and sells anhydrous ammonia, as well as the following byproducts: ammonium sulfate, krypton, xenon, dephenolized cresylic acid, liquid nitrogen, phenol, and naphtha, most of the last of which is burned as fuel in plant boilers. (Source: U.S. National Energy Technology Laboratory)*

# *CO<sub>2</sub> Enhanced Oil Recovery (EOR) in Unconventional Reservoirs*

- **Primary Production:** *Oil is produced from many **hydraulic-fracture-stimulated** production wells. The production mechanism is primarily by reservoir fluid expansion. Approximately 4 to 8% of oil in place is produced this way.*
- **EOR Production:** *Only cyclic gas injection (huff-n-puff) process produces additional amounts of oil. **Hydrocarbon rich-gas** and **CO<sub>2</sub>** are the methods of choice.*
- *Unconventional reservoirs retain much of the injected **CO<sub>2</sub>**; thus, unconventional reservoirs are suitable both for **CO<sub>2</sub>-EOR (CCUS)** and **CO<sub>2</sub> storage (CCS)**.*

# Idealization of a Dual-Porosity Environment

(Source: Mehmet Torcuk et al., 2015, CSM)

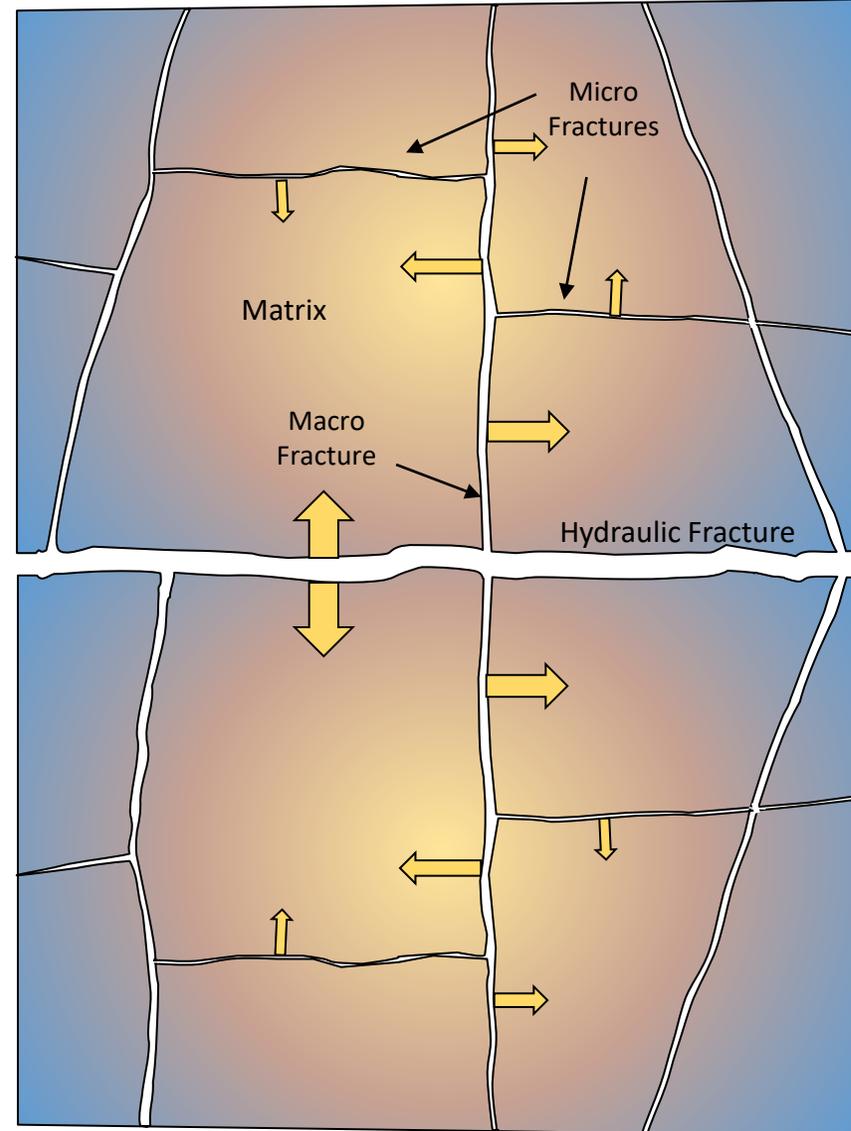


**Flow Hierarchy:**

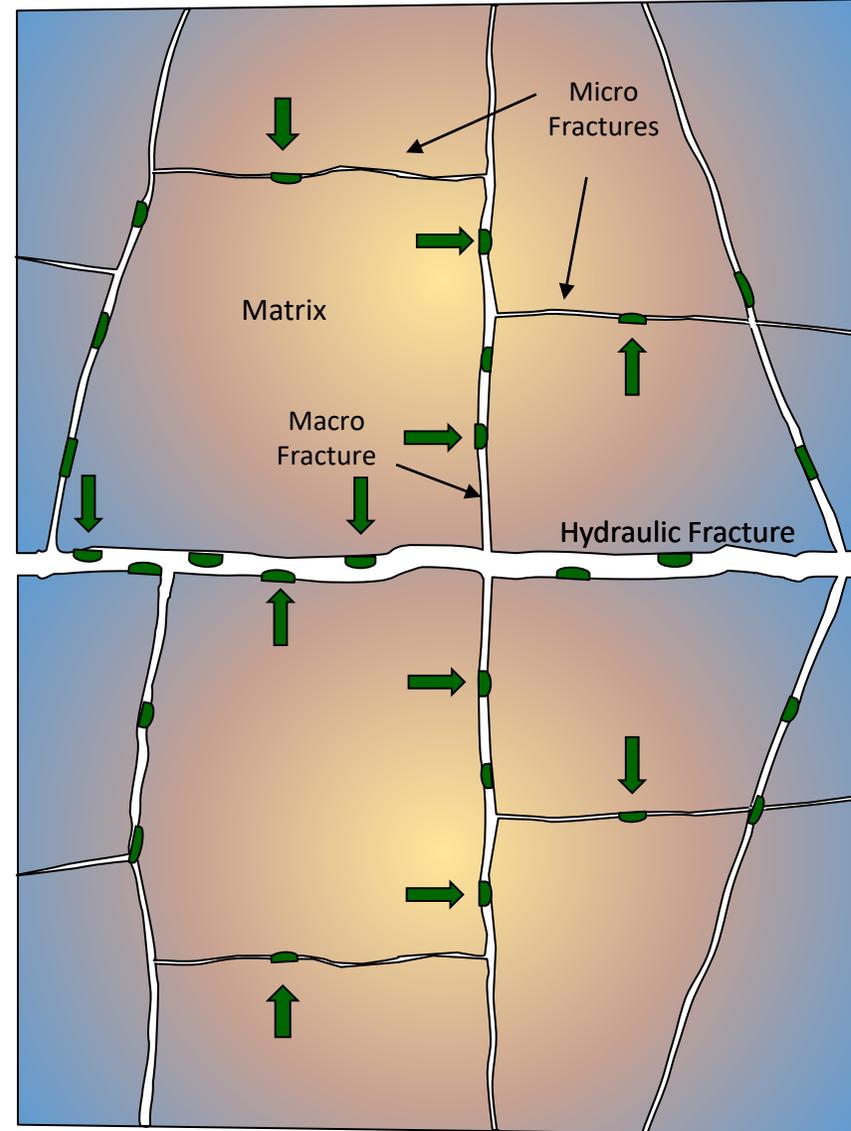
*Matrix*  $\xrightarrow{\text{FEEDS}}$  *Fracture*  $\xrightarrow{\text{FEEDS}}$  *Hydraulic Fracture*

$$k_{f,eff} = k_f \phi_f + k_m$$

***Cyclic gas injection  
'huff-n-puff' EOR  
process:  
CO<sub>2</sub> injection cycle***

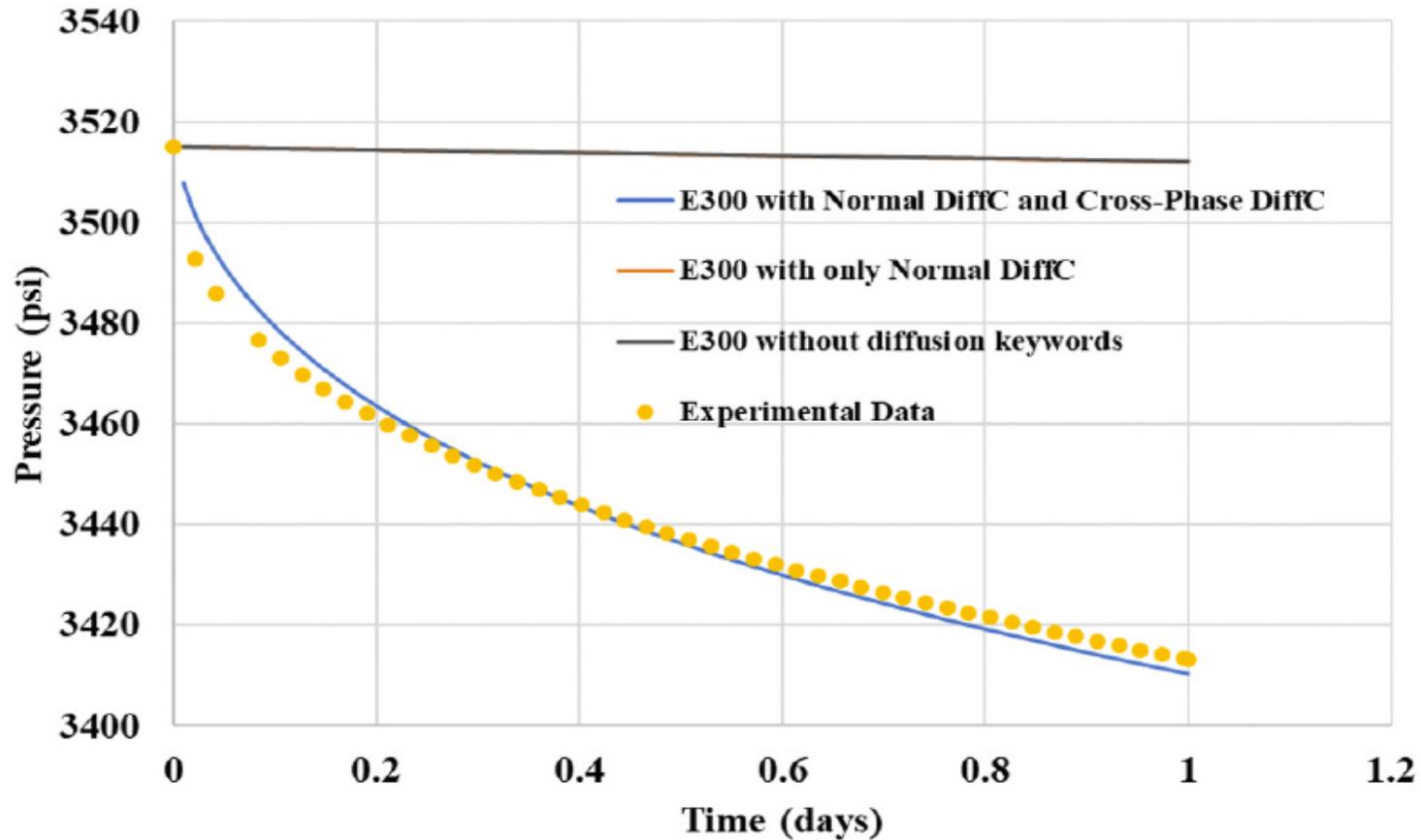


*Cyclic gas injection  
'huff-n-puff' EOR  
process:  
Oil production cycle*



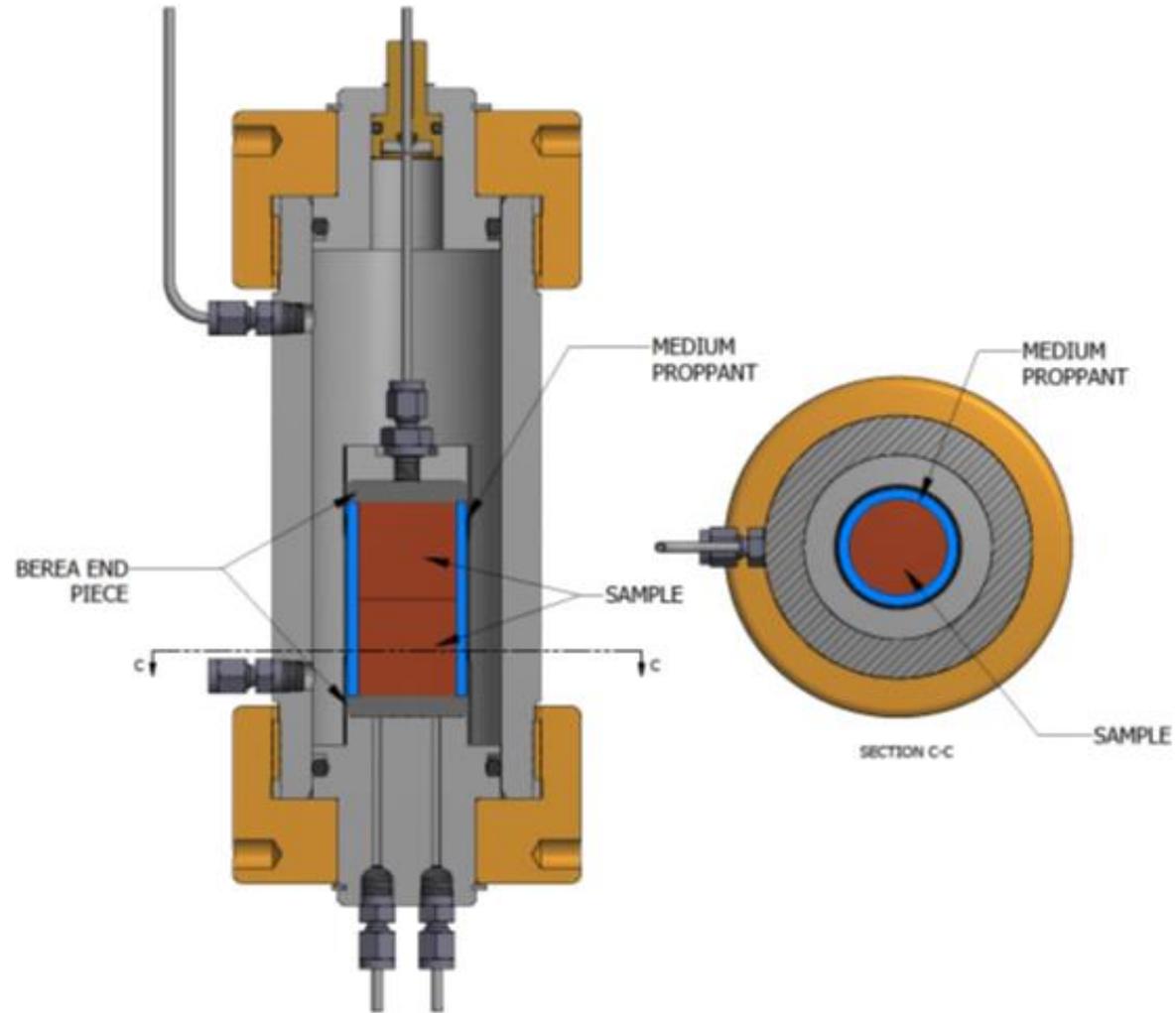
# Diffusion-driven EOR in Unconventional Shale Reservoirs

(Source: Fu et al., Journal of Petroleum Science and Engineering, 2021)



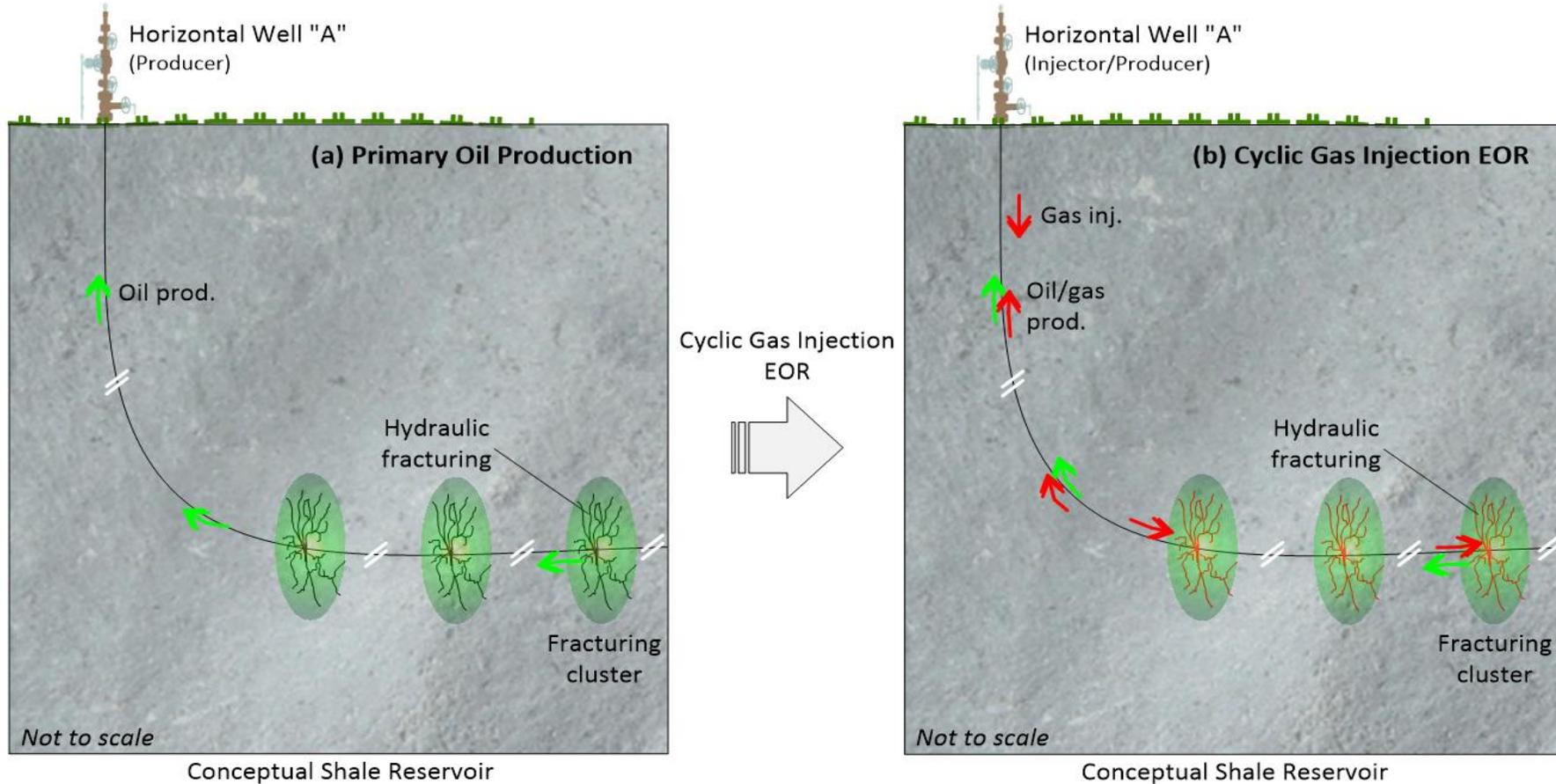
# Core Lab Huff-n-Puff EOR Apparatus

(Source: Liu et al., URTeC 2018)



# Idealization of CO<sub>2</sub> EOR via Huff-N-Puff Process

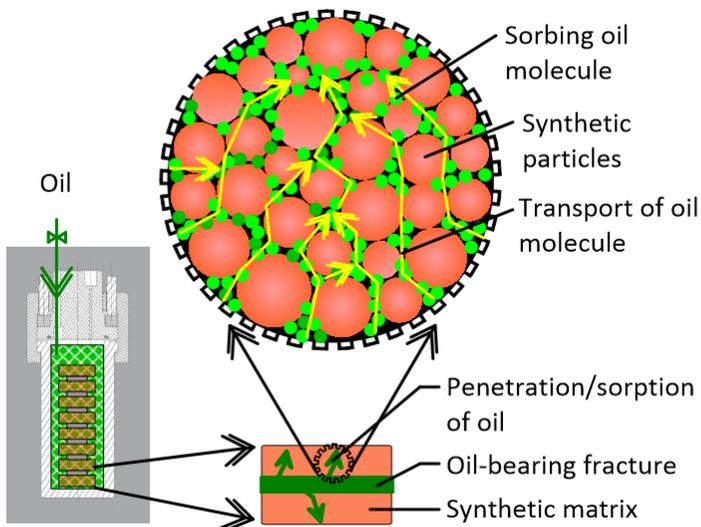
(Source: Asm Kamruzzaman, PhD Thesis, 2022, CSM)



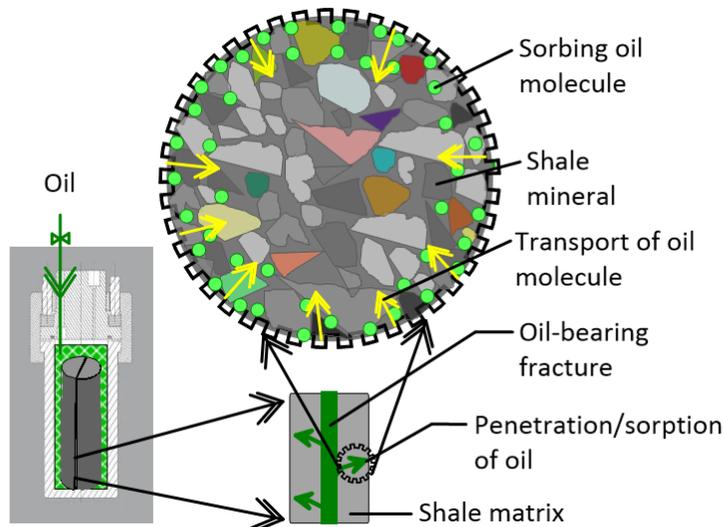
# Mechanism of Oil Pressurization by Gas Infusion

(Source: Asm Kamruzzaman, PhD Thesis, 2022, CSM)

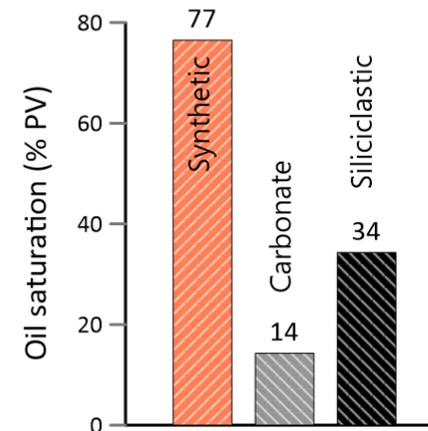
**Mechanism of oil infusion [synthetic core]**



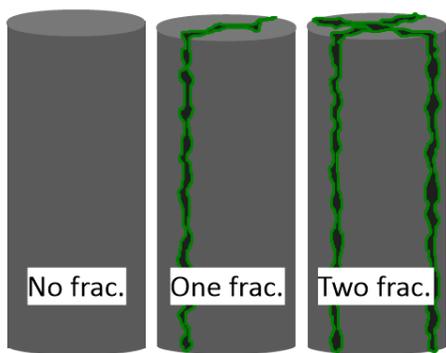
**Mechanism of oil infusion [shale core]**



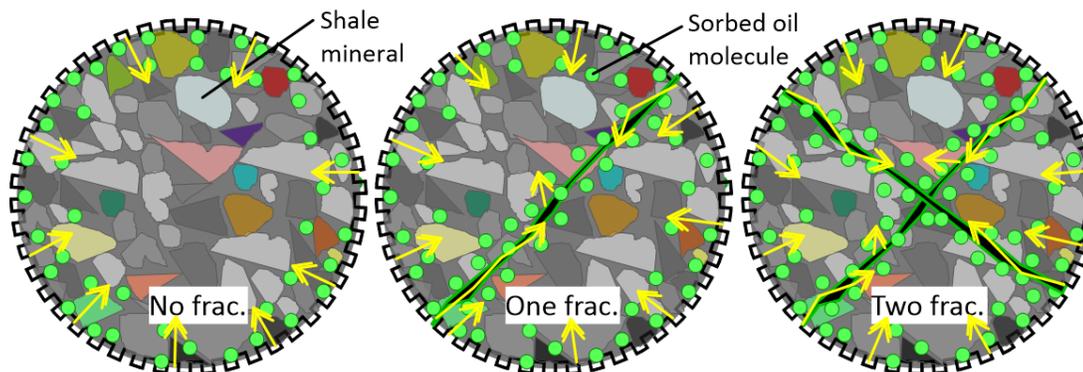
**Infused oil [synthetic vs. shale core]**



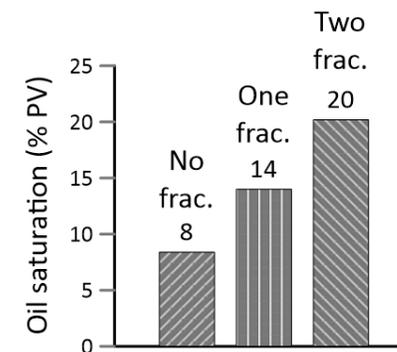
**Fracture geometry [carb. core]**



**Mechanism of oil infusion [carb. core]**



**Infused oil [carb. core]**

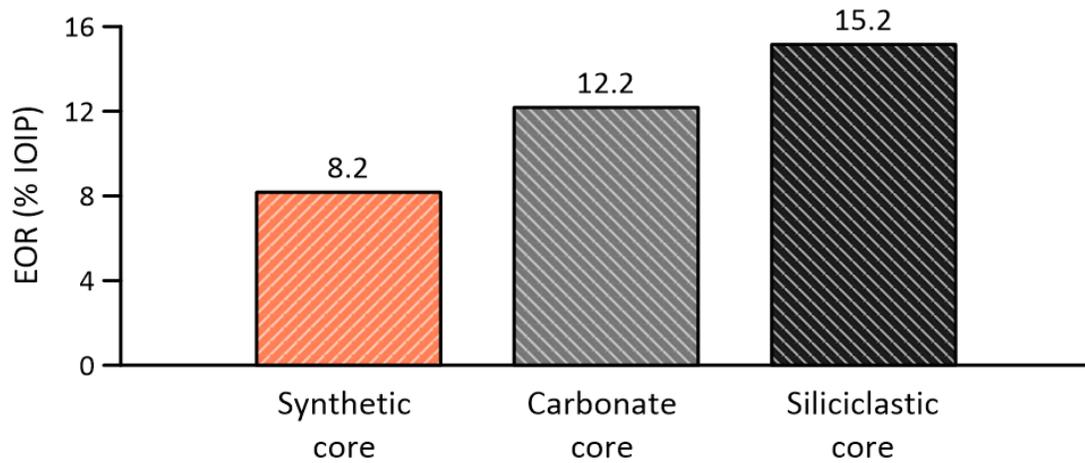


# Contribution of Fractures to Gas Injection Huff-N-Puff EOR

(Source: Asm Kamruzzaman, PhD Thesis, 2022, CSM)

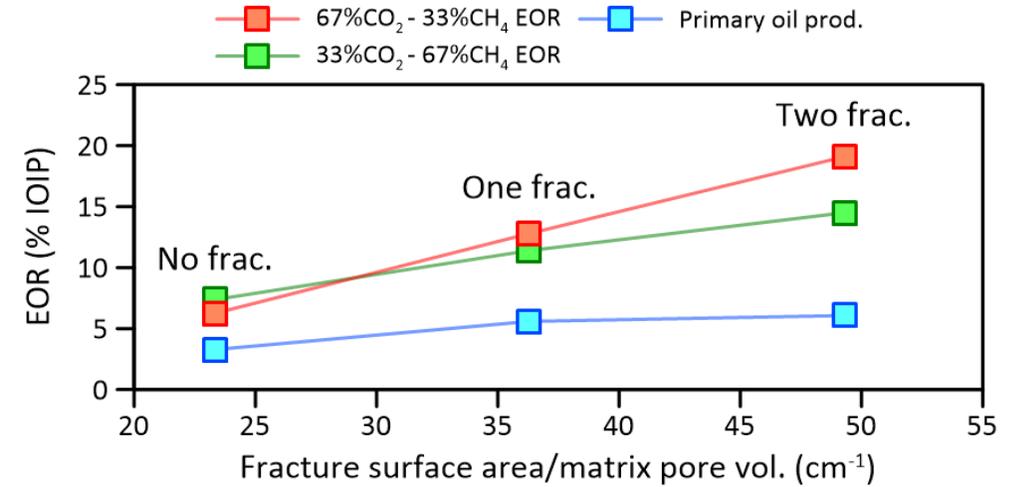
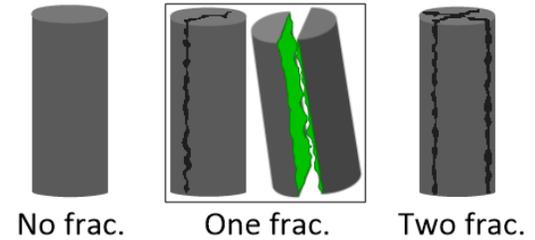
EOR comparisons:

Wolfcamp carbonate vs. siliciclastic vs. synthetic cores



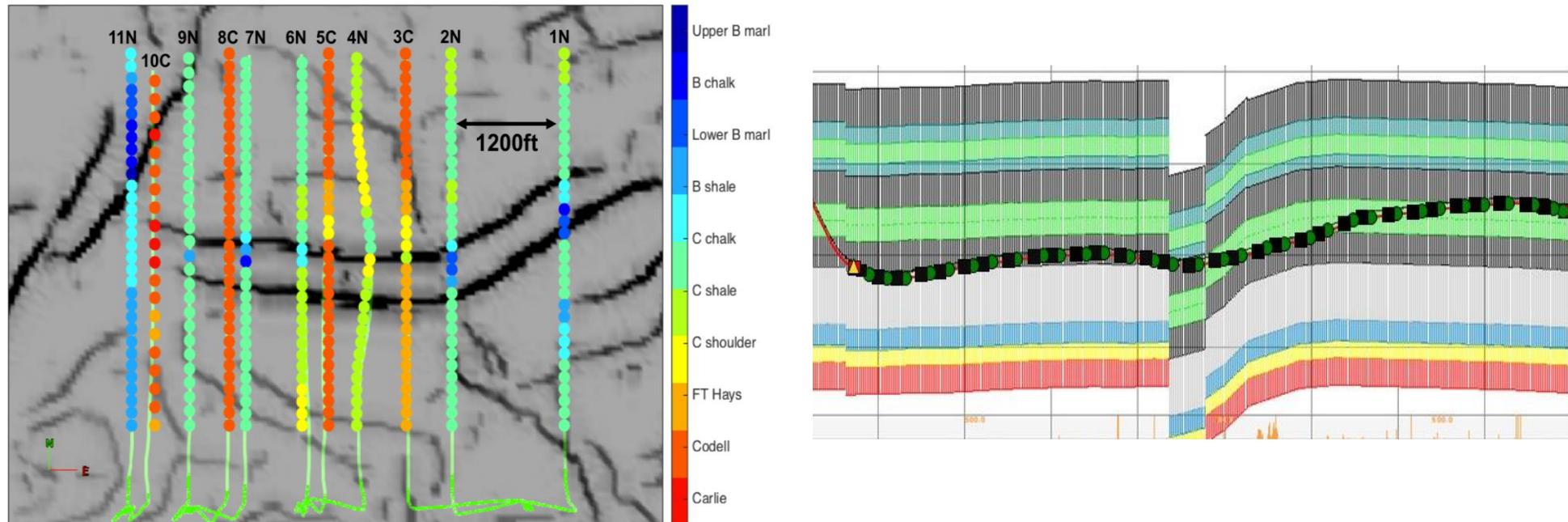
EOR comparisons:

Wolfcamp carbonate cores (frac. vs. unfrac.)



# 11 Wells in the 1-Square Mile Study Area and A Well Path

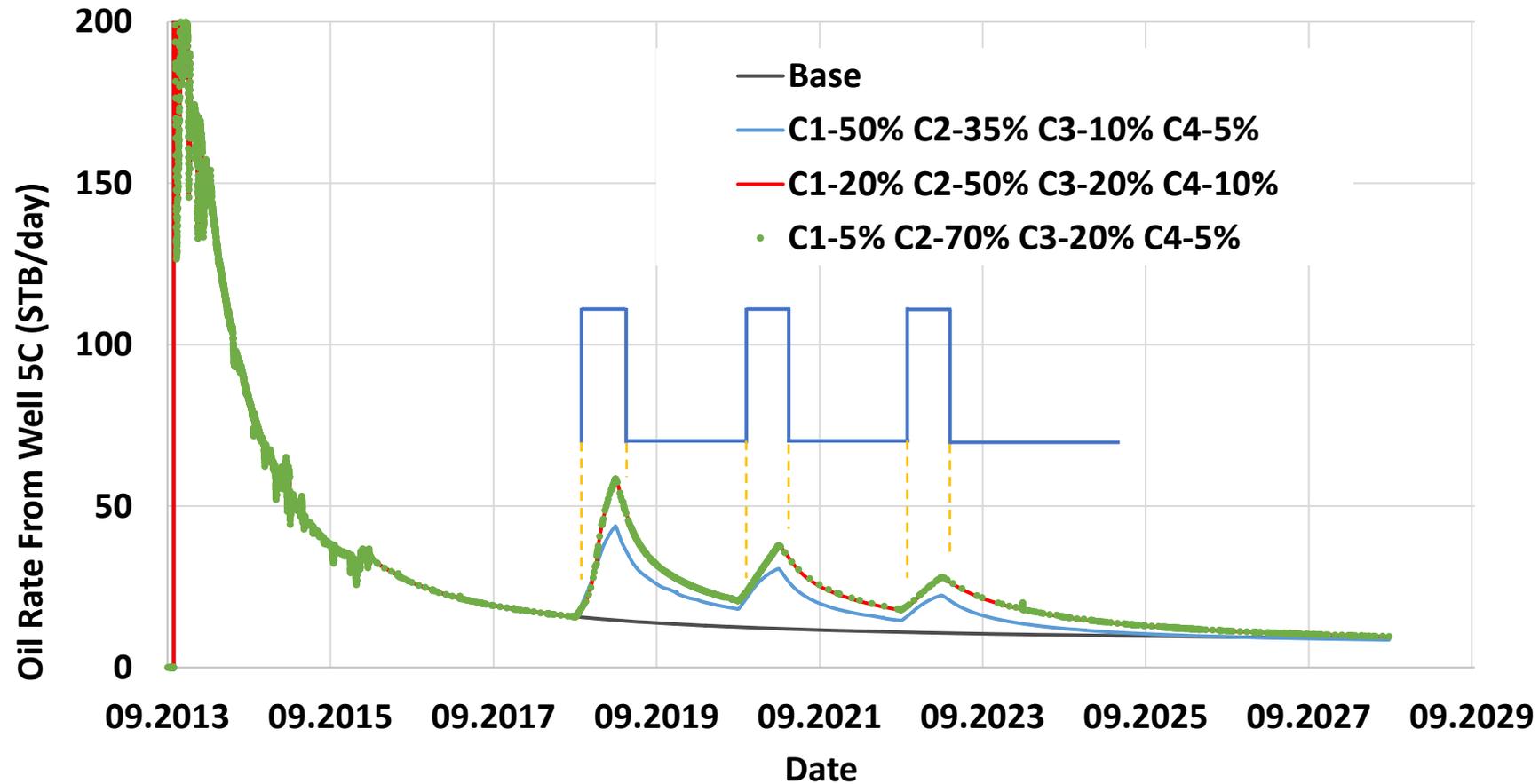
(Source: Yanrui Ning, PhD Thesis, 2018, CSM)



Pitcher, 2015

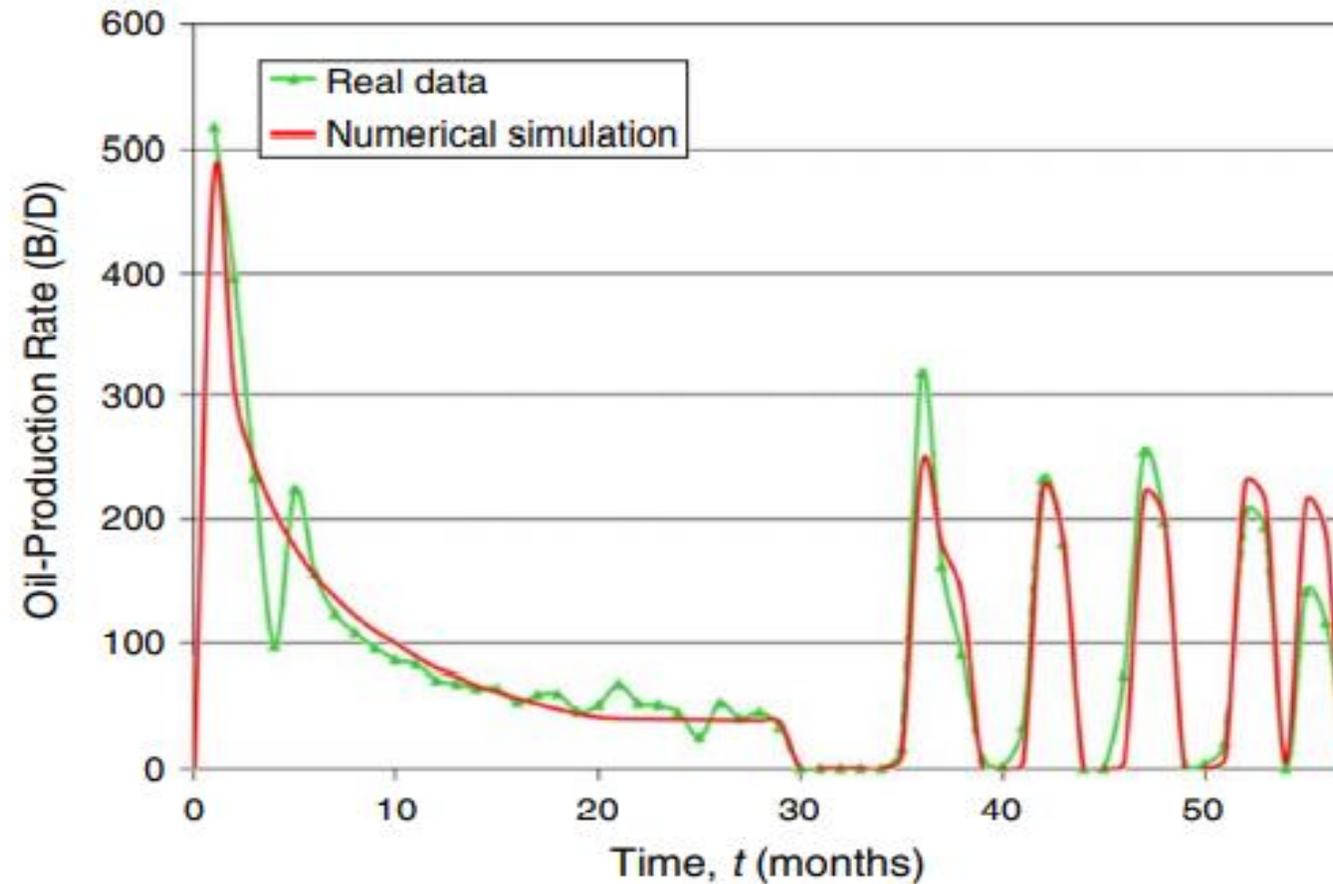
# Performance of Wishbone Well 5C, after Gas Injection in Well 6N at 1.0 MMscf/D

(Source: Yanrui Ning, CSM, 2018)



# Huff-n-Puff Gas Injection EOR in An Eagle Ford Pilot Test

(Source: Orozco et al.: SPE Res. Eval. & Eng., Feb. 2020)



# ***Energy Transition Dilemma***

- ***Global warming** resulting from emission of high quantities of **greenhouse gases (GHG)** has created great concern for the Earth. The main gases responsible for the greenhouse effect include **carbon dioxide, methane, nitrous oxide, and water vapor** (which all occur naturally), and **fluorinated gases** (which are synthetic). Greenhouse gases have different chemical properties and are removed from the atmosphere, over time, by different processes.*

# *Energy Transition ...*

- *Greenhouse gases are responsible for global warming because **they trap heat that would otherwise escape from the atmosphere.** Unlike oxygen and nitrogen, the GHG gases absorb radiation and hold onto the heat. Greenhouse gases keep Earth at a temperature that can harbor life—meaning that keeping temperature at around 58 °F rather than 0 °F!*

# ***Energy Transition ...***

*Two key indices defining how these gases differ from each other are:*

- (1) The gas ability to absorb energy (the radiative efficiency).*
- (2) How long the gas stays in the atmosphere — the lifetime **Global Warming Potential, GWP** (Tans et al. 2020). The GWP was developed to allow comparisons of the global warming impacts of different gases. Specifically, GWP is a measure of how much energy the emissions of one tonne of a gas will absorb over a given period, relative to the emissions of one tonne of carbon dioxide (CO<sub>2</sub>).*

***CO<sub>2</sub> has a GWP of 1 regardless of the time period used, because it is the gas being used as the reference. CO<sub>2</sub> remains in the climate system for a very long time (Tans et al., 2020).***

# *The Inevitable CCS*

*“The ‘road ahead’ is challenging but **Carbon Capture and Storage (CCS)** is increasingly well placed to make its significant and necessary contribution to achieving **net-zero emissions** around mid-century.”*

*(**Brad Page**, CEO, **Global CCS Institute**, Dec. 11, 2020, Report)*

# *Future of Energy*

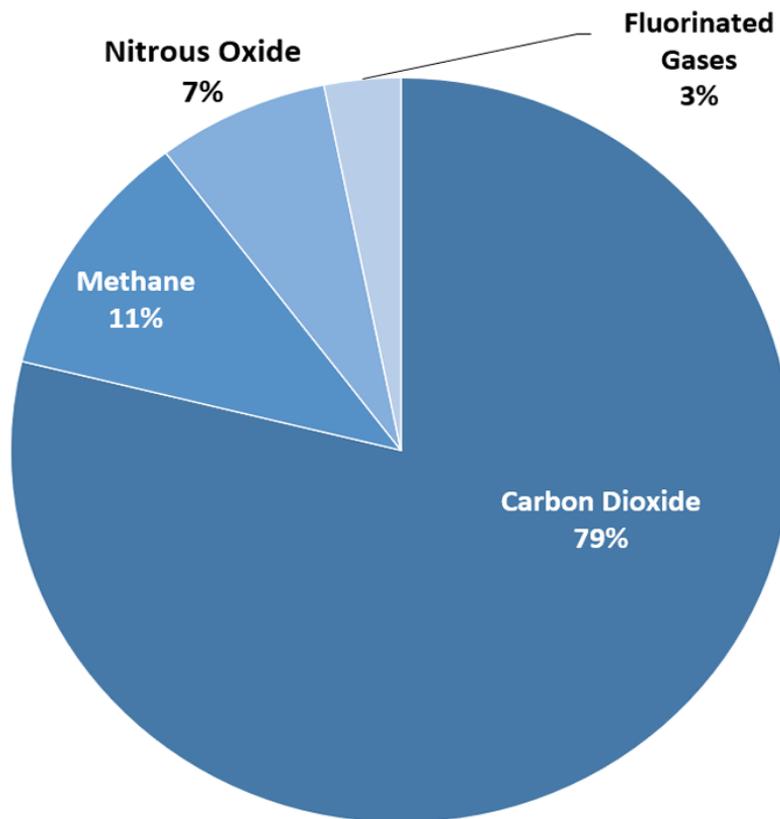
*World population is increasing at a rapid pace, and there is an increasing need for food, clean water, clean air, and energy. I believe hydrocarbons (oil and gas) will continue to be the leading fuel for the energy needs for several decades. What we really need is managing carbon emissions. Thus, I support both the Carbon Capture and Storage (CCS) and the Carbon Capture, Utilization, and Storage (CCUS) via CO<sub>2</sub>-EOR.*

# ***Energy Transition ...***

- ***Methane (CH<sub>4</sub>) is estimated to have a GWP of 28-36 over 100 years. When methane GWP is measured over a 20-year period, the GWP ratio grows to 84-86 times.***
- *CH<sub>4</sub> emitted today lasts about a decade on average, which is much less time than CO<sub>2</sub>. But CH<sub>4</sub> also absorbs much more energy than CO<sub>2</sub>. The net effect of the shorter lifetime and higher energy absorption is reflected in the GWP. The CH<sub>4</sub> GWP also accounts for some indirect effects, such as the fact that CH<sub>4</sub> is a precursor to ozone, and ozone is itself a greenhouse gas.*

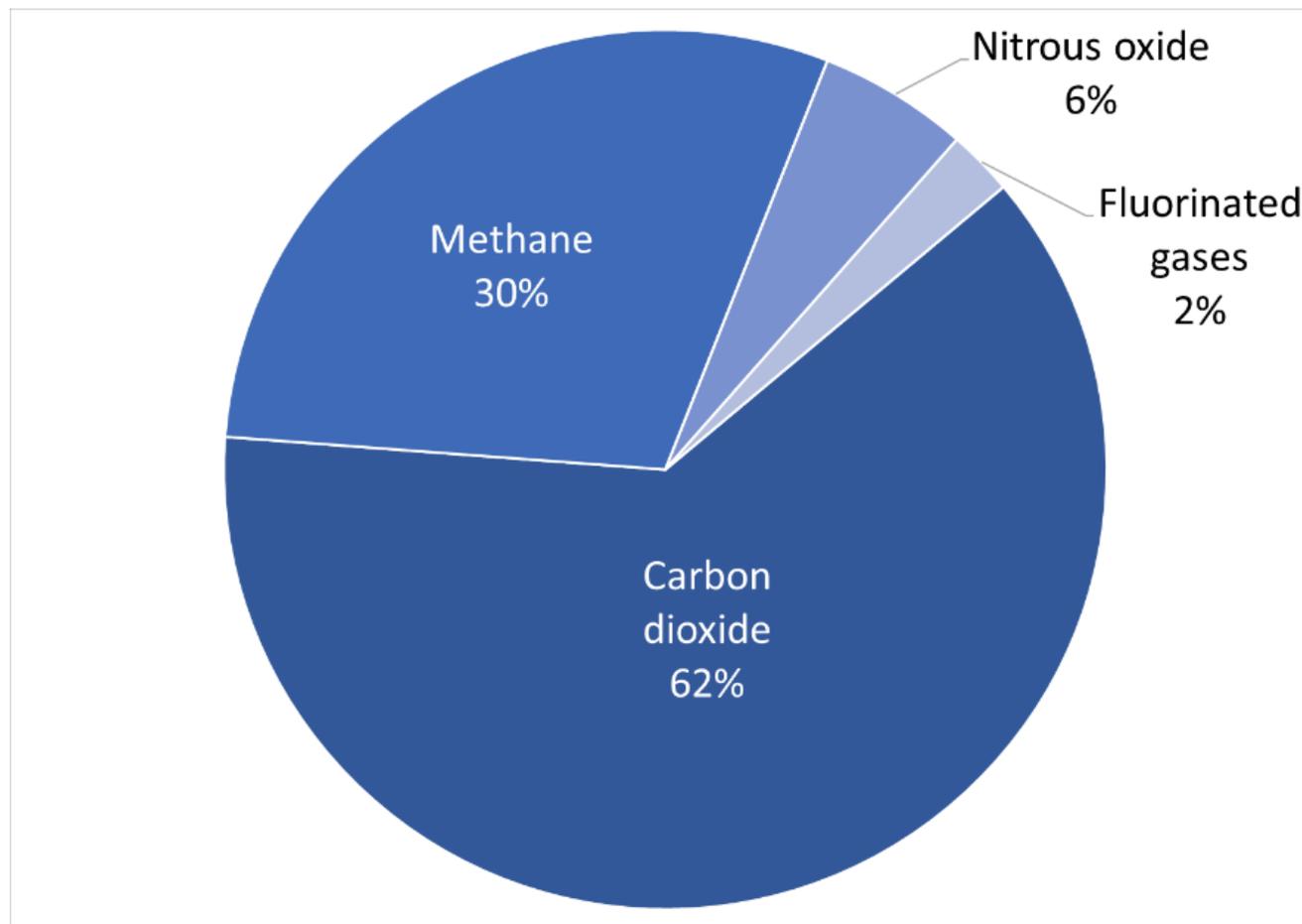
# *An overview of the greenhouse gas emissions (GHS) in the U.S. in 2020 in CO<sub>2</sub>e over a period of 100 years. (US EPA)*

## Overview of U.S. Greenhouse Gas Emissions in 2020



U.S. Environmental Protection Agency (2022). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020

*Replot of the U.S., 2020 greenhouse gas emissions (GHS) in CO<sub>2</sub>e over a period of 25 years. The only change from data reported by the U.S. EPA is replacing CO<sub>2</sub>e for methane from 25 to 86.*



# *Steam & Hydrocarbon Gas Injection EOR*

- ***U.S. oil from steam injection is 2.5 % of daily total oil production.***
  - *it is interesting to note that if one uses lease oil to generate steam, for every bbl of oil consumed it generates 13 bbl of cold-water equivalent which produces a little over 2 bbl of oil. Thus, the net steam EOR oil is 0.1 incremental barrel of oil. The oil consumed generates around 1000 pounds of CO<sub>2</sub>.*
- ***Hydrocarbon gas injection is 2.0 % of the daily total oil.***
  - *In conventional reservoirs, gas injection is a **gravity drainage** process.*
  - *In unconventional shale reservoirs, it is the **huff-n-puff** process.*

# ***U.S. Pipelines***

- ***U.S. has more than 2.6 million miles of pipelines safely delivering trillions cubic feet of natural gas and hundreds of billion ton-miles of liquid petroleum products each year. (Source: U.S. DOE, Pipelines and Hazardous Materials Safety Administration, 2018)***
- ***The primary mode of large-scale CO2 transport in the United States today is via pipeline, and in 2017, there were more than 5,000 miles of CO2 pipelines in operation. (Source: Energy Equipment & Infrastructure Alliance)***
- ***Approximately 90% of the CO2 pipeline infrastructure in the United States today is used for CO2 enhanced oil recovery (EOR) operations.***

# ***Recent CO<sub>2</sub> Pipeline Construction Metrics***

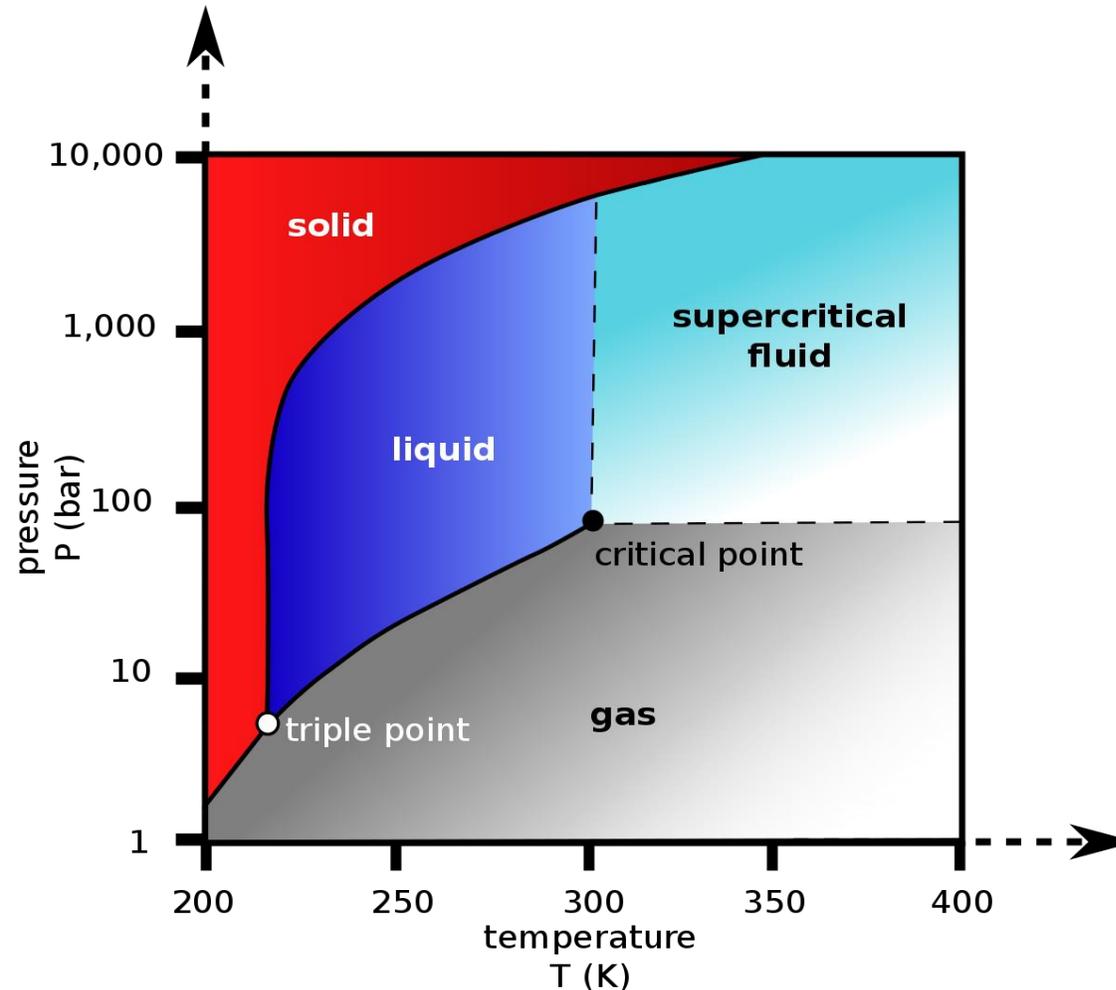
*(Source: Advanced Resources International, Inc.)*

*In the past 10 years, the construction of CO<sub>2</sub> pipeline infrastructure in the United States has been limited to establishing point-to-point pipelines that connect an identified source of CO<sub>2</sub> to the corresponding sink(s) where the CO<sub>2</sub> is used for either EOR or industry. The Greencore Pipeline is built across private ranchland as well as state and public lands in Wyoming and Montana and cost **\$69,000** per **'diameter-inch-mile'**. Contrast this with the Webster Pipeline built in a highly concentrated industrial and suburban area just south of Houston, Texas, that cost **\$199,000** per **'diameter inch-mile'**.*

***Commercial CO<sub>2</sub> pipelines typically operate at pressures between 1,200 and 2,200 psig, with some pipelines having a maximum operating pressure of 2,500 psig to 2,800 psig. At these pressures, CO<sub>2</sub> is in a **dense phase** - either as a **liquid** or a **supercritical fluid*****

# Pressure-Temperature Phase Diagram for CO<sub>2</sub>

( $P_c = 1070$  psia,  $T_c = 87.8^\circ$  F) (From: Wikipedia)



# ***CO<sub>2</sub> Emission from five Colorado Power Plants***

*Four Plants Use Coal and One Uses Natural Gas (Source: Professor Ali Tura, CSM)*

- ***Craig Power Plant:***

$$7.6 \text{ Mt/yr} = 396 \times 10^6 \text{ scf CO}_2/\text{D} \quad = 24,000 \text{ BOE/D}$$

- ***Haydon Power Plant:***

$$1.7 \text{ Mt/yr} = 88.5 \times 10^6 \text{ scf CO}_2/\text{D} \quad = 5,380 \text{ BOE/D}$$

- ***Comanche Power Plant:***

$$9.3 \text{ Mt/yr} = 486 \times 10^6 \text{ scf CO}_2/\text{D} \quad = 29,500 \text{ BOE/D}$$

- ***Pawnee Power Plant:***

$$3.6 \text{ Mt/yr} = 186 \times 10^6 \text{ scf CO}_2/\text{D} \quad = 11,300 \text{ BOE/D}$$

- ***Rawhide Energy Station:***

$$1.7 \text{ Mt/yr} = 88.5 \times 10^6 \text{ scf CO}_2/\text{D} \quad = 5,380 \text{ BOE/D}$$

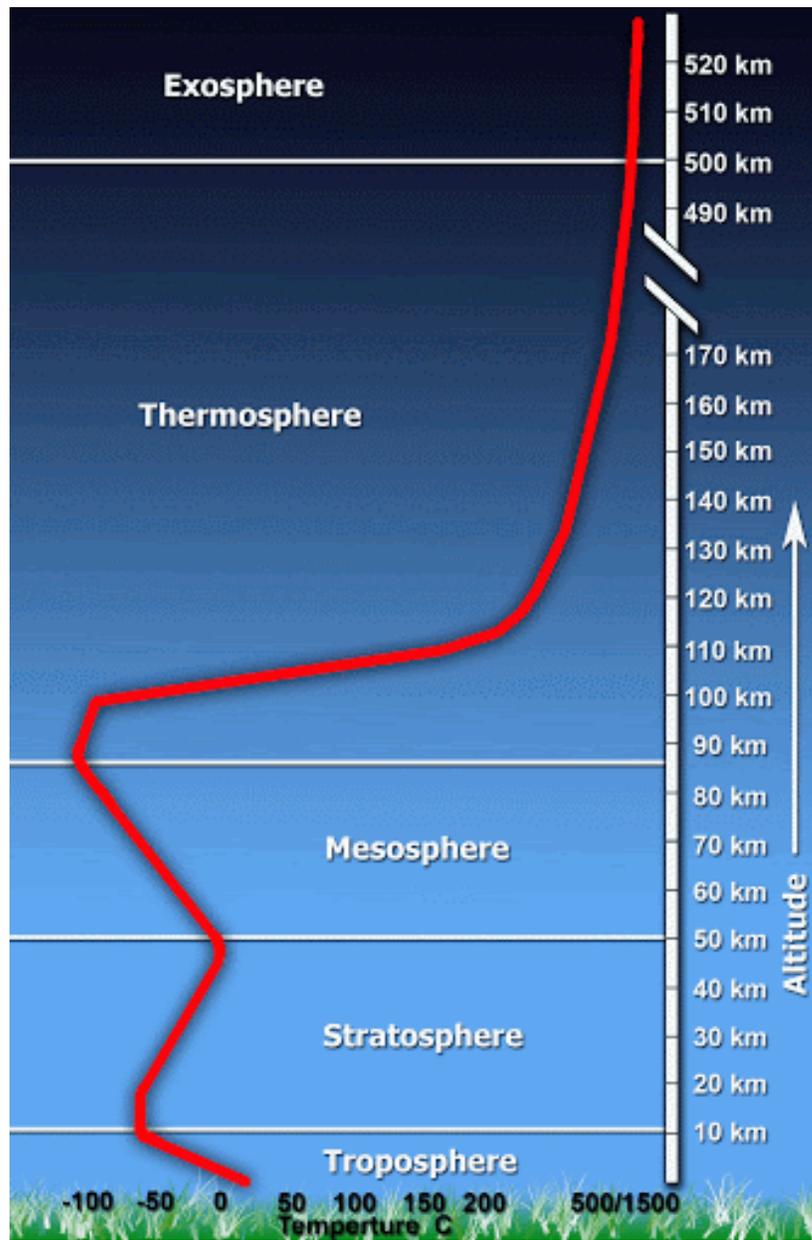
**Total:**  $1245 \times 10^6 \text{ scf CO}_2/\text{D} \quad = \underline{75,560 \text{ BOE/D}}$

# *US Renewable Energy Development*

*(Global Energy Prize News, October 30, 2020)*



***Thank you!***





***The Moon  
and Earth's  
Atmosphere  
(NASA)***