CO_2 EOR

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www.sequestration.org

Outline

- Basic Concepts
  - Historical terminology
  - CO_2 properties
- CO_2 EOR
  - Mechanisms: CO_2 and crude-oil mixture
  - Miscibility type
    - Immiscible
    - Miscible

Outline, contd.

- Oil Recovery and Displacement Efficiency
  - Microscopic (saturation) displacement
  - Macroscopic (volumetric) displacement
    - Areal
    - Vertical
    - Gravity
- Oil Recovery Estimates
- Summary

Historical Terminology: Chronologically-Based Terms

- Primary: first stage of production
- Secondary: second stage of production
- Tertiary: third stage of production

Historical Terminology: Process-Based Terms

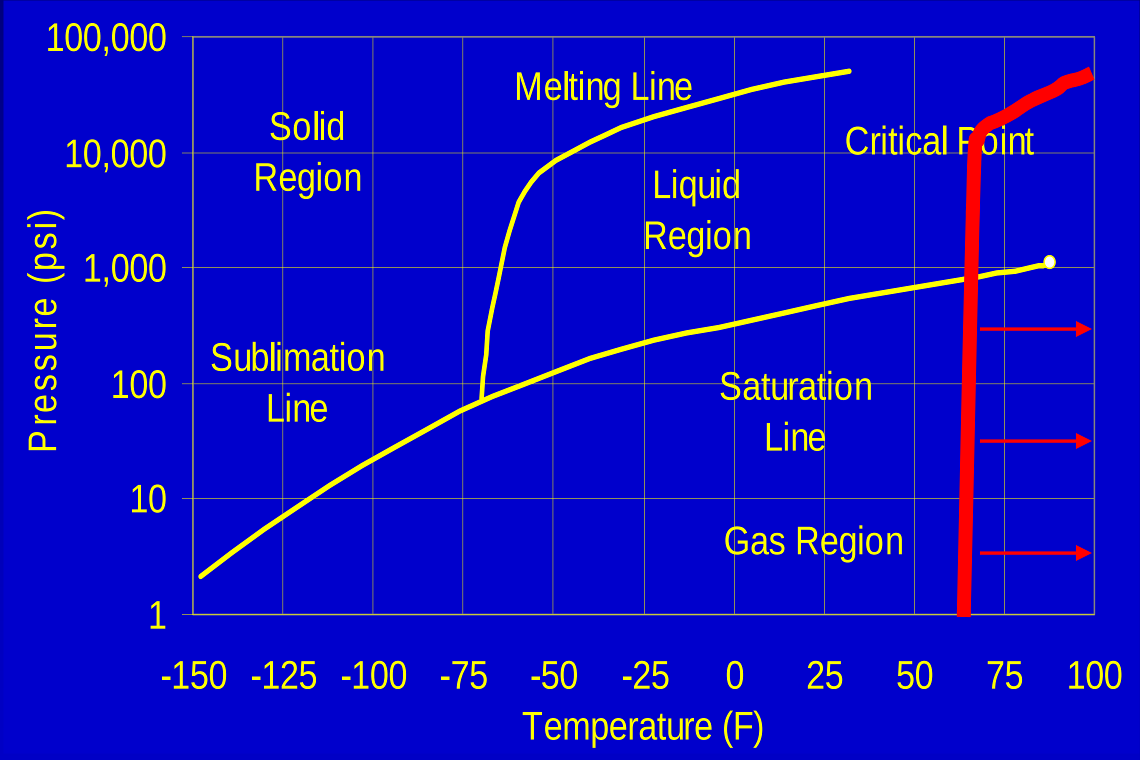
- Primary: naturally occurring reservoir energy
- Secondary: water or gas injection
  - pressure maintenance
  - immiscible displacement
    - 2-phase relative permeability
    - No fluid interaction, chemical reaction, or composition change
    - Relatively high interfacial tension

Historical Terminology: Process-Based Terms

- EOR: injection of miscible gas, liquid chemicals, and thermal energy
- IOR: includes all EOR and other engineering applications, e.g. infill drilling, multilateral completions, reservoir characterization, and 4-d seismic.

CO_2 Phase Behavior: Pressure-Temperature Diagram

- Liquid, gas, solid regions
- Supercritical CO_2
  - critical fluid
  - dense phase
  - liquid-like CO_2
- Oil Reservoirs
  - Gas or liquid
  - Supercritical p&T

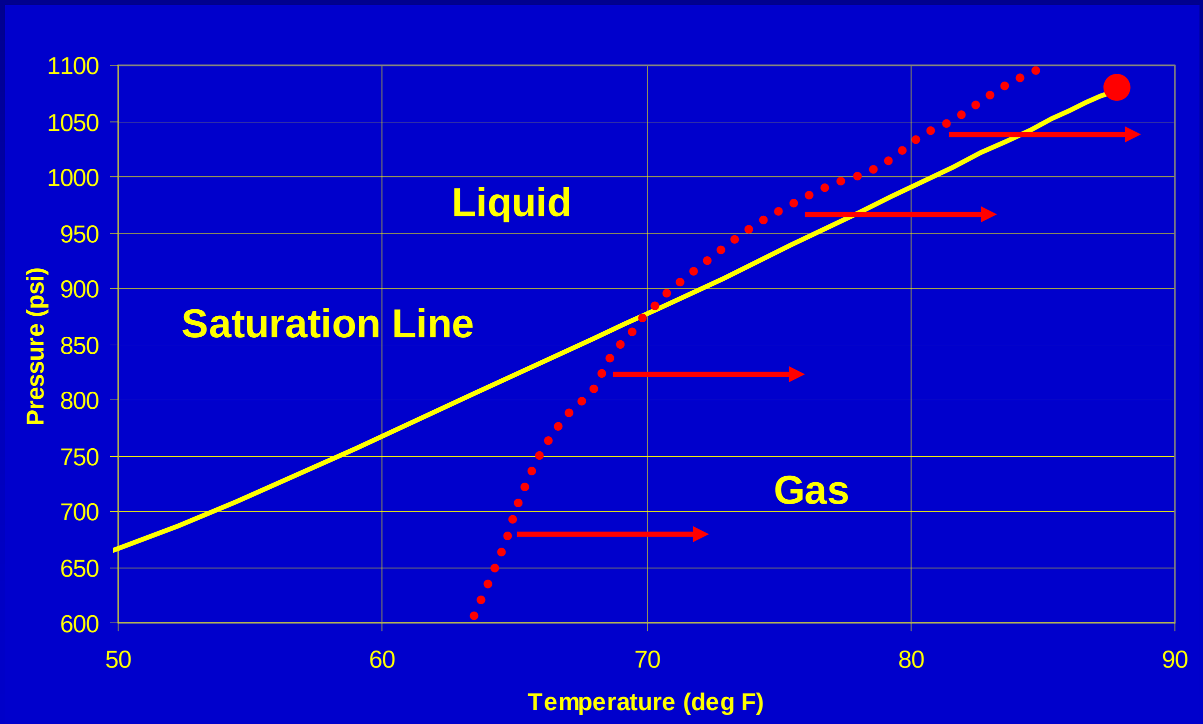


CO_2 Phase Behavior: Pressure Temperature Diagram

Fluid in the Reservoir?

Gas-like or Liquid-like

- Critical Temperature: 87.7 °F
- Critical pressure: 1073 psia



CO_2 EOR

- Miscibility type
  - Immiscible
  - Miscible
- Mechanisms: CO_2 and crude-oil mixture
  - Reduce oil viscosity
  - Swelling effect
  - Reduced surface tension
  - Pressure support
  - Reduce residual oil saturation

CO_2 EOR

- CO_2 is a solvent to crude oil
- CO_2 is used in core labs as a low temperature solvent to clean core of crude oil in preparation for routine core analyses
- In the field, geology, geology, geology… characterization, characterization, characterization

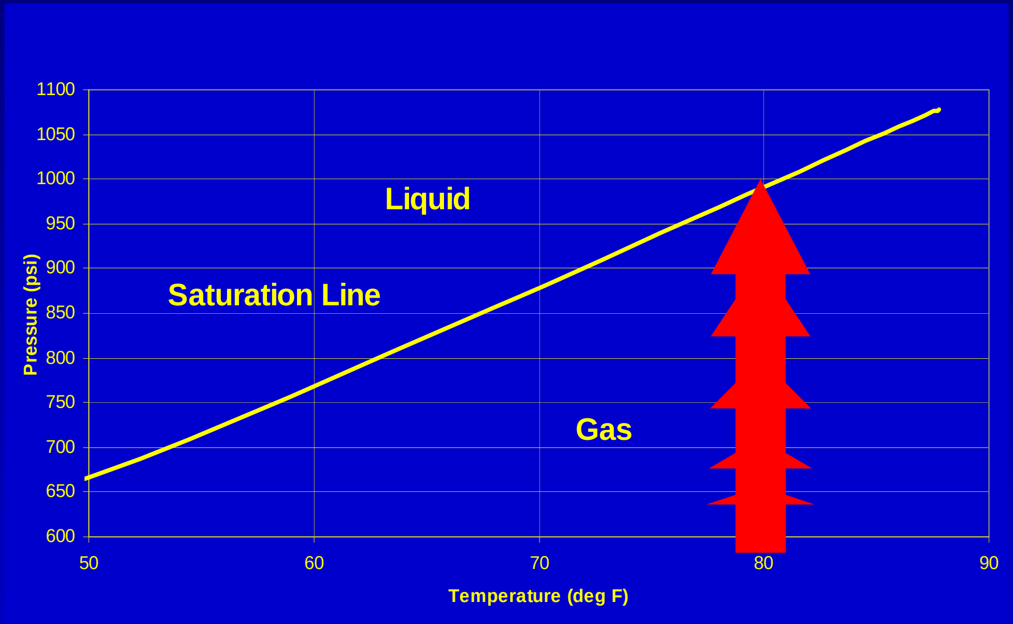
CO_2 must contact the oil

Miscibility Type

- Defined for specific crude oil at a specific reservoir pressure and temperature
- Immiscible
  - Two distinct fluids
  - Reduced mixing, similar to solution gas
- Miscible
  - One fluid
  - (Eventual) complete mixing, in all proportions
  - First contact and multicontact miscibility

Immiscible

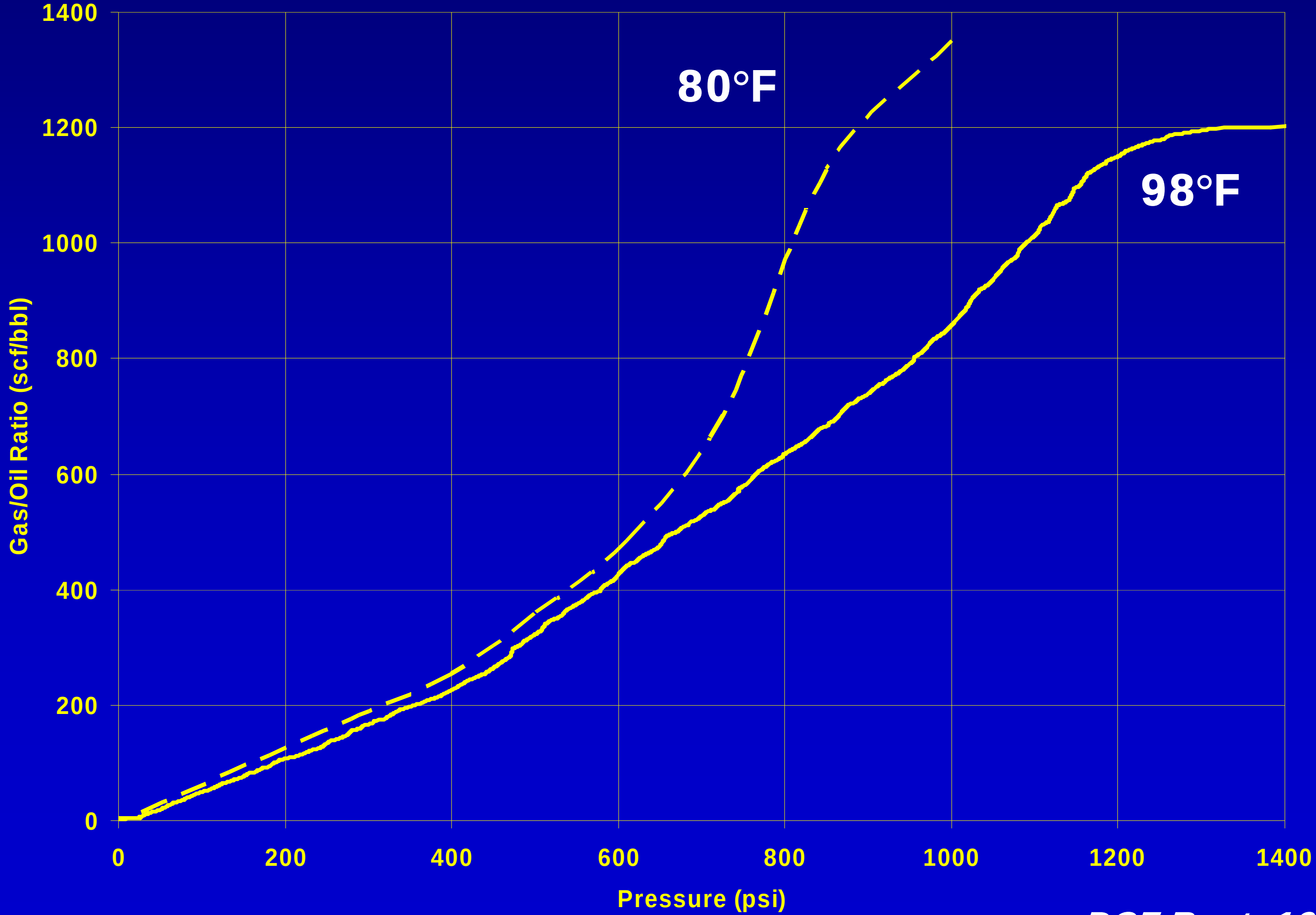
- Gas or gas-like CO_2:
  - Temperature **<** 88 °F
  - Pressure less than vapor pressure line of pure CO_2



Much less recent research for immiscible CO_2

CO_2 Solubility in Crude Oil

In situ CO_2 solubility w/oil higher for low temperature Illinois Basin Oil fields



Cypress (1750-1830 ft) Mattoon Field Coles Cty IL

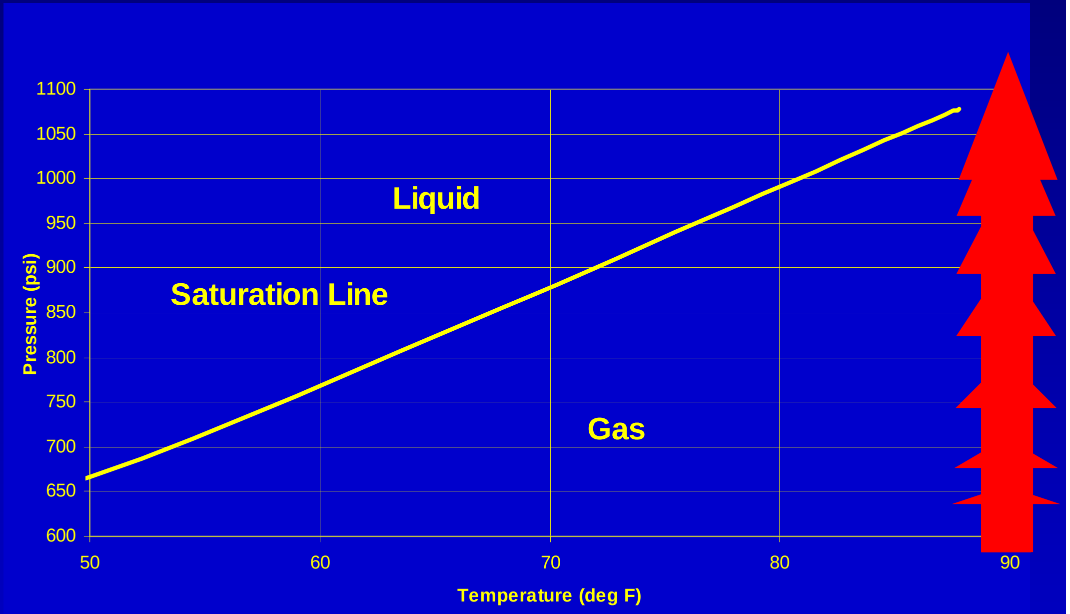
Aux Vases (3158-3176 ft) Dale Consolidated Franklin County

ISGS IP 140

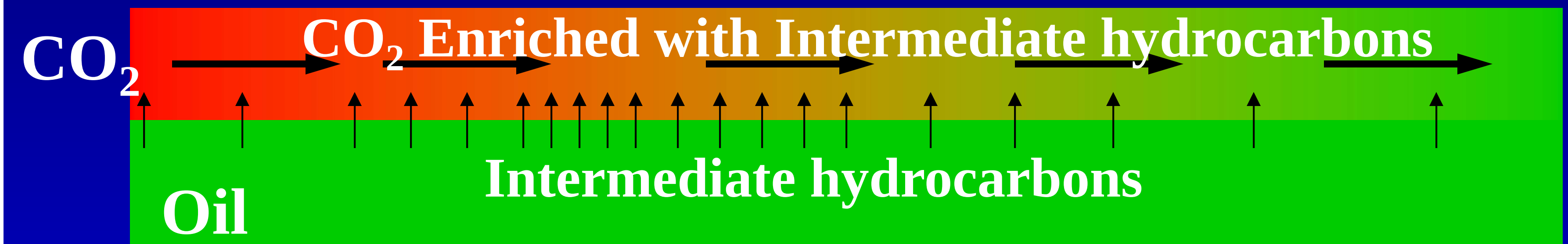
DOE Rept, 1995 DE-FC22-93BC 14955

Miscible

- Liquid CO_2:
  - Temperature < Tc:
  - Pressure > Vapor Pressure Pure CO_2
- Super critical CO_2:
  - Temperature **>**88 °F
  - Pressure > 1073 psia
  - **AND**, liquid-like density



Multicontact Miscibility



Low viscosity CO_2 moves through the crude oil vaporizing intermediate hydrocarbons. Eventually hydrocarbon enriched CO_2 becomes miscible with the crude oil.

Advantageous Mechanisms

- Miscible CO_2 liquid-like
  - Reduce oil viscosity
  - Swelling effect
  - Reduced surface tension
  - Pressure support
  - Reduce residual oil saturation
- Immiscible CO_2 gas-like (less of all above)
  - Pressure support
  - Solution (CO_2) Gas Drive

Disadvantageous Mechanisms

- CO_2 viscosity < Oil viscosity
  - CO_2 viscous fingers
- CO_2 density < Oil density
  - Gravity override
- Exacerbated by immiscible conditions

Oil Recovery and Displacement Efficiency

- Microscopic (saturation) displacement
- Macroscopic (volumetric) displacement
  - Areal
  - Vertical
  - Gravity

Oil Recovery

- Product of microscopic (E_D) and macroscopic (E_V) displacement efficiency

$$E = E_D E_V$$

Microscopic Displacement

- Capillary pressure
- Surface tension
- Initial saturations
- Fluids present

Microscopic Displacement

- X-axis

  Capillary Number, N_{ca}

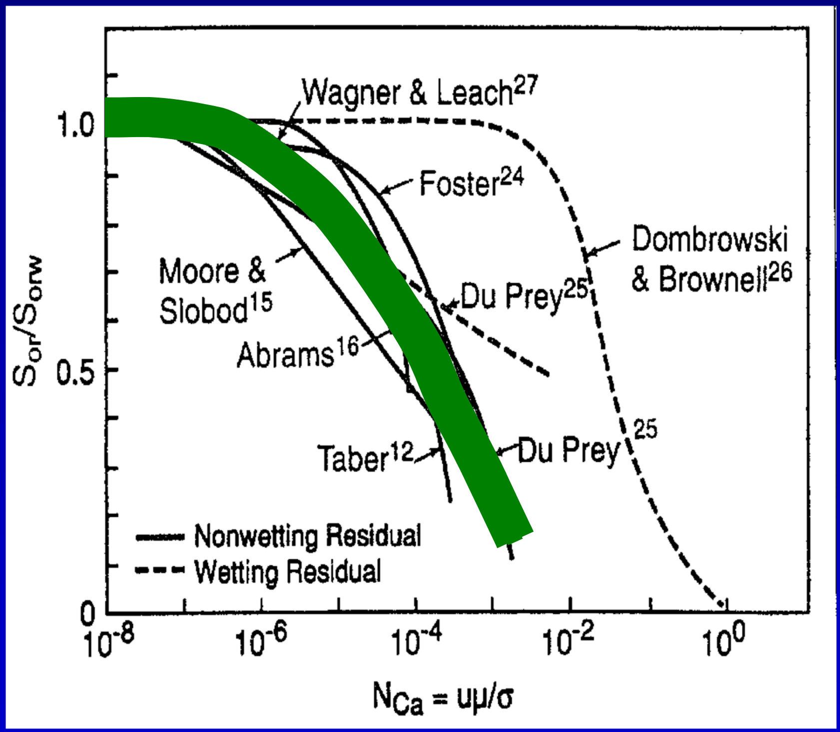
  $N_{ca} = v \mu / \sigma \cos \theta$

- Y-axis

  S_{or} / S_{orw}

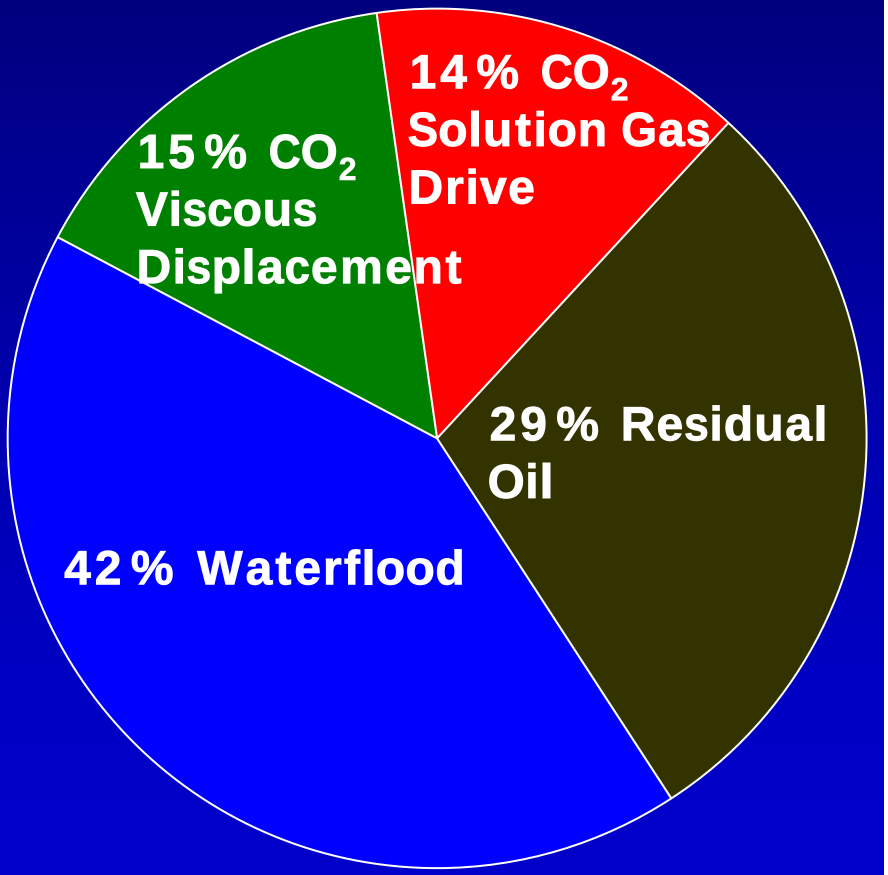
  Residual oil to “fluid”

  Residual oil to water



Liquid CO_2 Core Flood: Loudon Field, Fayette County, IL

- Loudon crude oil/Cypress ss core
- Oil recovery via waterflood: 42%
- Oil recovery via liquid CO_2: 29%
  - 15% Viscous Displacement
  - 14% Solution Gas (CO_2)
- Total oil recovery: 71%



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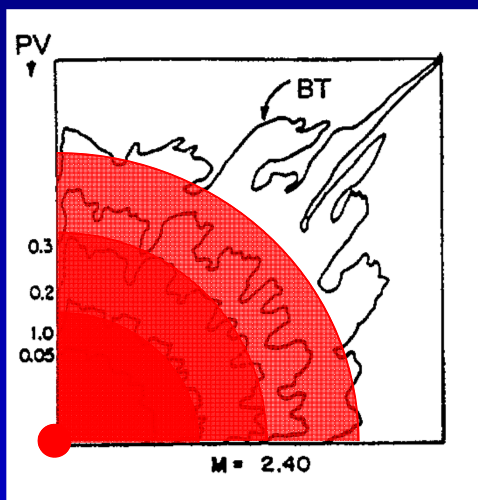
Macroscopic Displacement

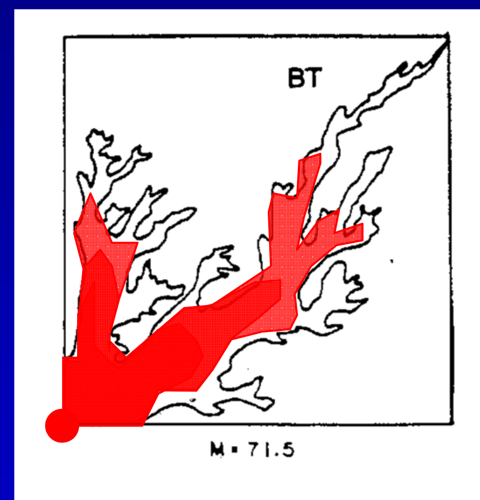
- Areal displacement efficiency (E_A)
- Vertical displacement efficiency (E_I)
- $E_V = E_A E_I$

- E_V
- Process dependent
- Geologic heterogeneity
- Injector/producer
  - Pattern
  - Spacing

Macroscopic Displacement: Areal



CO_2 Injector



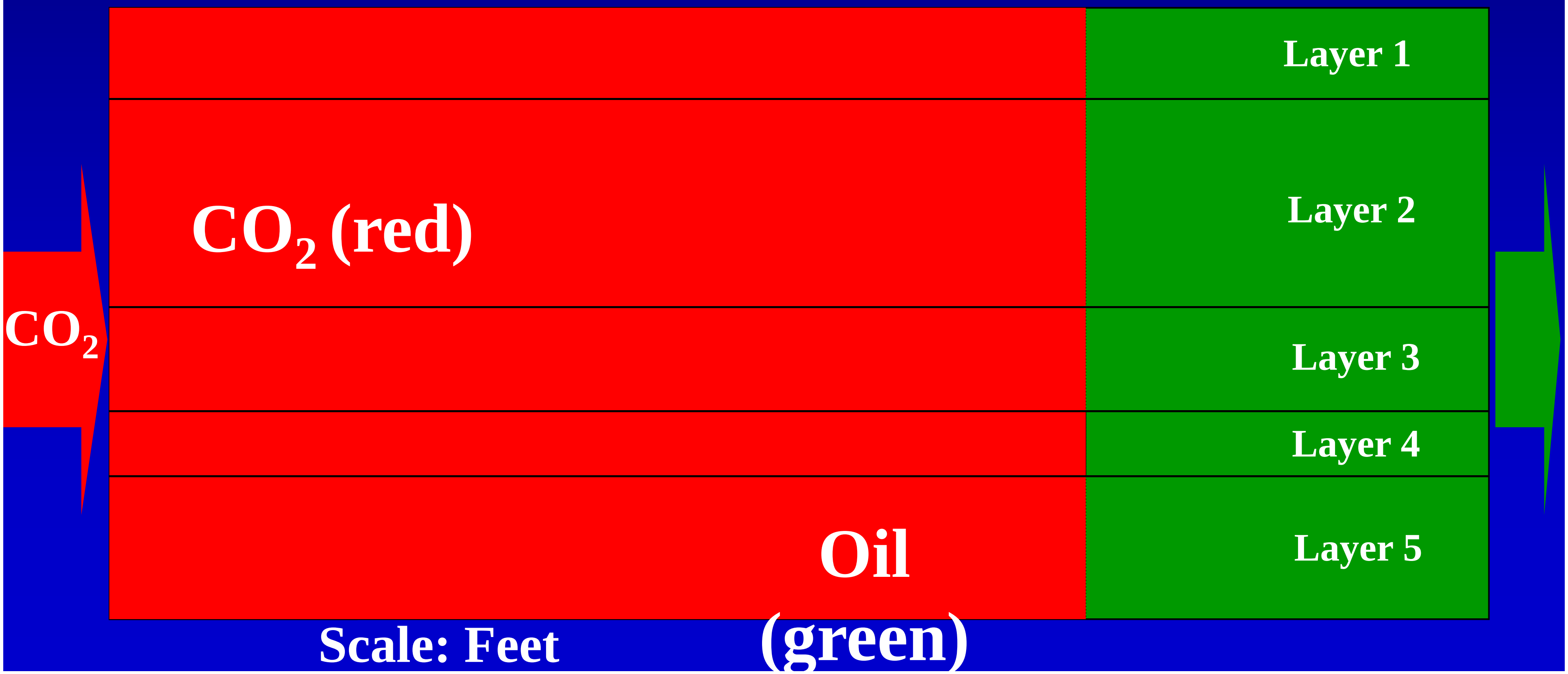
Scale: Acres

High Efficiency

Low Efficiency

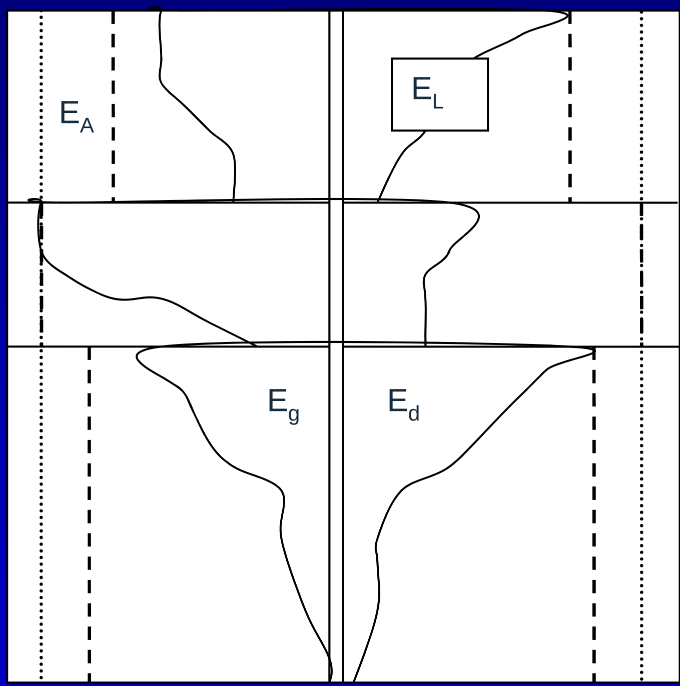
(Plan View)

Macroscopic Displacement: Vertical



Macroscopic Displacement: Gravity

- Within each layer, gravity can affect displacement efficiency
- Three layer example with gravity override and irregular shaped fronts



Oil Recovery Estimates

- West Texas Rules-of-Thumb (Misible)
  - 10% of OOIP
  - 25% of cumulative primary and waterflood production
- Example:
  - Oil reservoir with 100 MMstb OOIP and 30 MMstb production
  - OOIP r-o-t: 10 MMstb CO_2 EOR
  - Production r-o-t: 7.5 MMstb CO_2 EOR

Oil Recovery Estimates: Illinois Basin Example

- Illinois Basin Screening Example
  - 14.1 Bstb OOIP and 4.3 Bstb production
  - OOIP r-o-t: 1.4 Bstb CO_2 EOR
  - Production r-o-t: 1.1 Bstb CO_2 EOR
- Comparison to rigorous geologic and reservoir model-based Basin assessment
  - 0.86-1.3 Bstb CO_2 EOR
  - Lower estimate due to about half of the Basin assessed at immiscible conditions

Summary

- CO_2 is a solvent to crude oil
- Proven EOR in W. Texas (predominantly)
  - 10% OOIP; 25% production
- Reservoir pressure important to miscible/ immiscible condition: related to dense CO_2
- One of few options to generate revenue and store CO_2

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