CO2 Enhanced Oil Recovery Overview

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NETL

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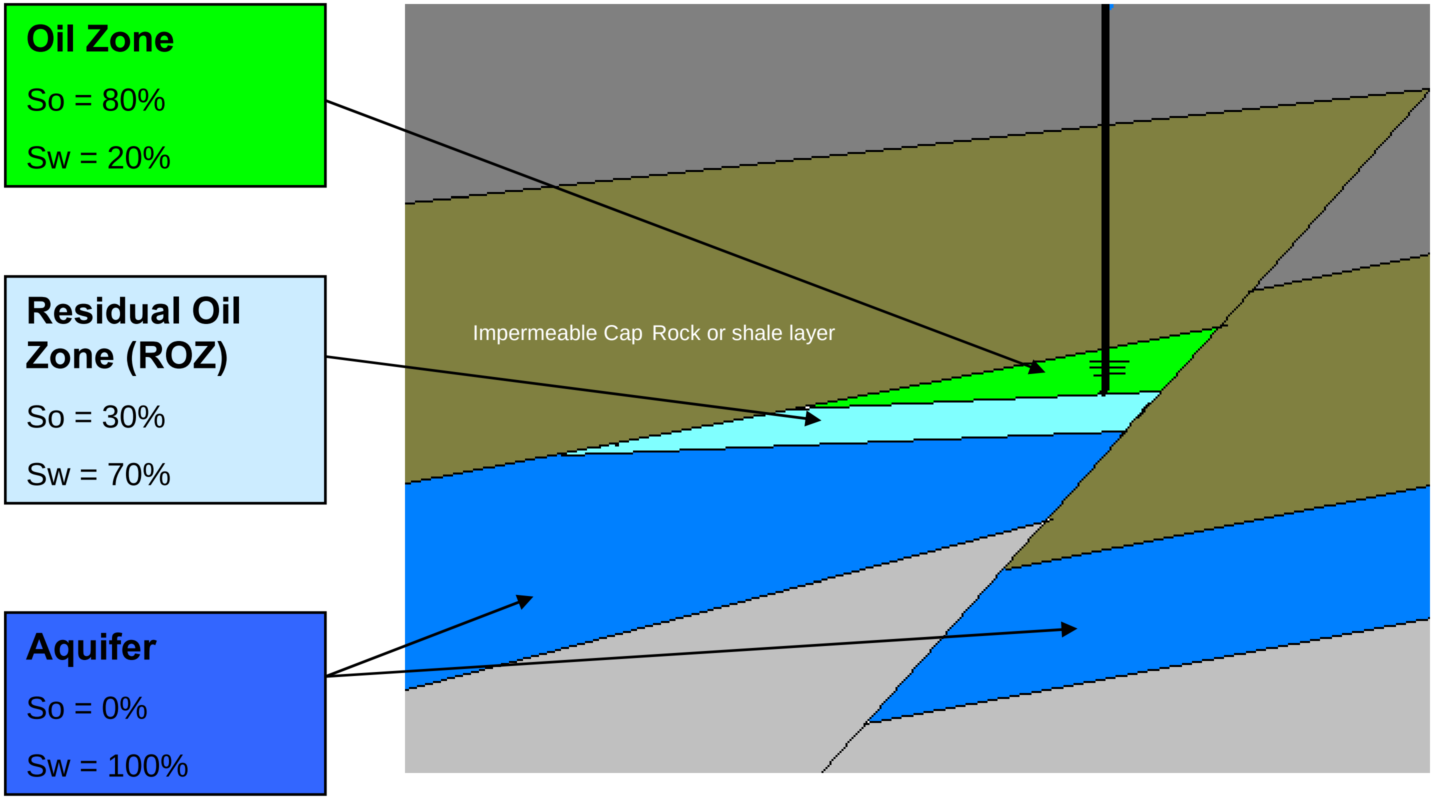
Overview

- Primary and Secondary Recovery Mechanisms
- Sweep Efficiency
- Tertiary Recovery Mechanisms
- Miscible flooding and CO2 Fluid Properties
- CO2 Flooding History
- Sources of CO2
- Typical CO2 Flood behavior
- CO2 Injection techniques
- Residual Oil Zone (ROZ)

Generic Oil Reservoir at discovery



Oil Zone

So = 80%

Sw = 20%

Residual Oil Zone (ROZ)

So = 30%

Sw = 70%

Aquifer

So = 0%

Sw = 100%

So = Oil Saturation

Sw = water saturation

Primary Production

- **Production using natural energy (pressure) of Reservoir**
- **Two major drive mechanisms potentially at work**
  - Water Drive
  - Solution Gas Drive
  - Combination Drive
- **Generally primary recovery ranges from 5% to 20% of Original Oil in Place**

Water Drive Mechanism

- “Strong” or large Aquifer relative to size of oil reservoir results in influx of water as oil is removed.
- This maintains pressure (energy) required to produced oil.
- Generally results in most efficient primary recovery.
- Wells generally produce at low Gas Oil Ratio (GOR) and good pressure until water reaches well resulting in well “watering out”.
- Optimization involves good well placement at top of structure and plugging lower water zones as necessary.
- Residual oil saturation is left behind in Swept zone (10-30%)

Solution Gas Drive Reservoirs

- Relatively weak or non-existent aquifer associated with reservoir
- Saturated or under saturated reservoir
- Mechanism of Production – reservoir energy is supplemented by gas coming out of solution and expanding as pressure reduced.
- Characteristics – rapid pressure drop until Bubble Point is reached. Pressure drop then slows but wells then begin producing high GOR, which makes wells uneconomic and results in high energy loss in reservoir.
- As energy is depleted, wells can be put on artificial lift (rod pumping, gas lift) to provide energy to lift fluid.

Secondary Production

- **Immiscible fluid injection in one or more wells to increase production above primary levels**
- **Water and/or Natural Gas are commonly used as injection fluids**
- **Production results both from "Pressure Maintenance" and displacement of produced fluid from pores.**
- **Generally results in additional 20% recovery over primary production alone. (Ultimate recovery for Primary + Secondary on order of 20-40% of Oil in Place[1].**

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[1] Stalkup F.L. Jr.: Miscible Displacement, Monograph Series, SPE, (1983) 2

Limitations on Recovery by Secondary Production

- Volumetric Sweep Efficiency of the Injection fluid. (What fraction of the reservoir is swept)

- Displacement Efficiency of the injection fluid in rock that is swept. (How much oil is residual)

- Ability of the producing wells to capture displaced fluid.

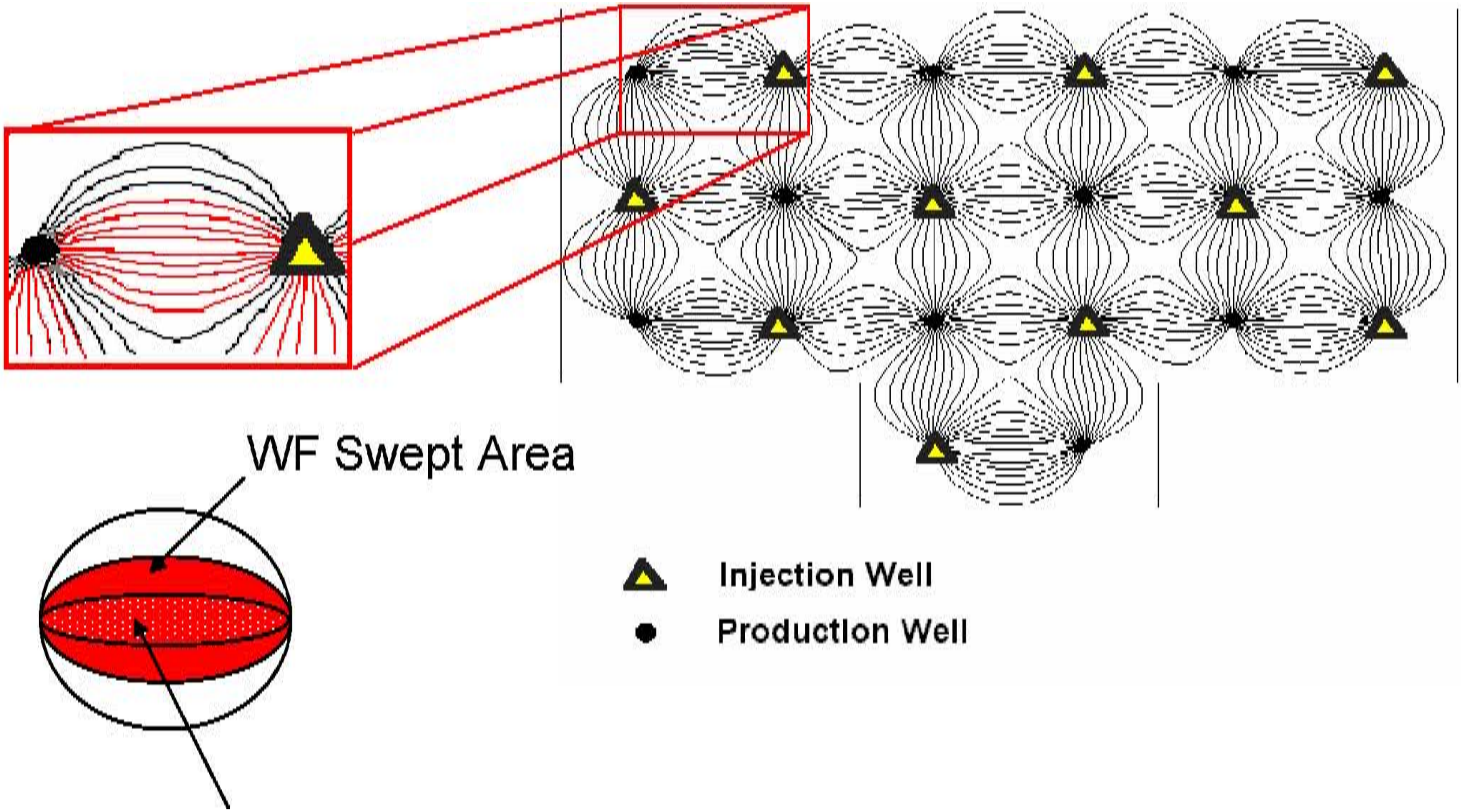
Factors effecting Volumetric Sweep

- Volumetric Sweep Efficiency (Ev)
- Areal Sweep Efficiency (Ea)
- Vertical Sweep Efficiency (Eh)

$$EV = Ea \times Eh$$

- Ea is function of Mobility Ratio and Pattern Configuration
- Eh is function of vertical reservoir heterogeneity and gravitational effects

Representation of Areal Sweep Efficiency



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Explanation of Mobility Ratio

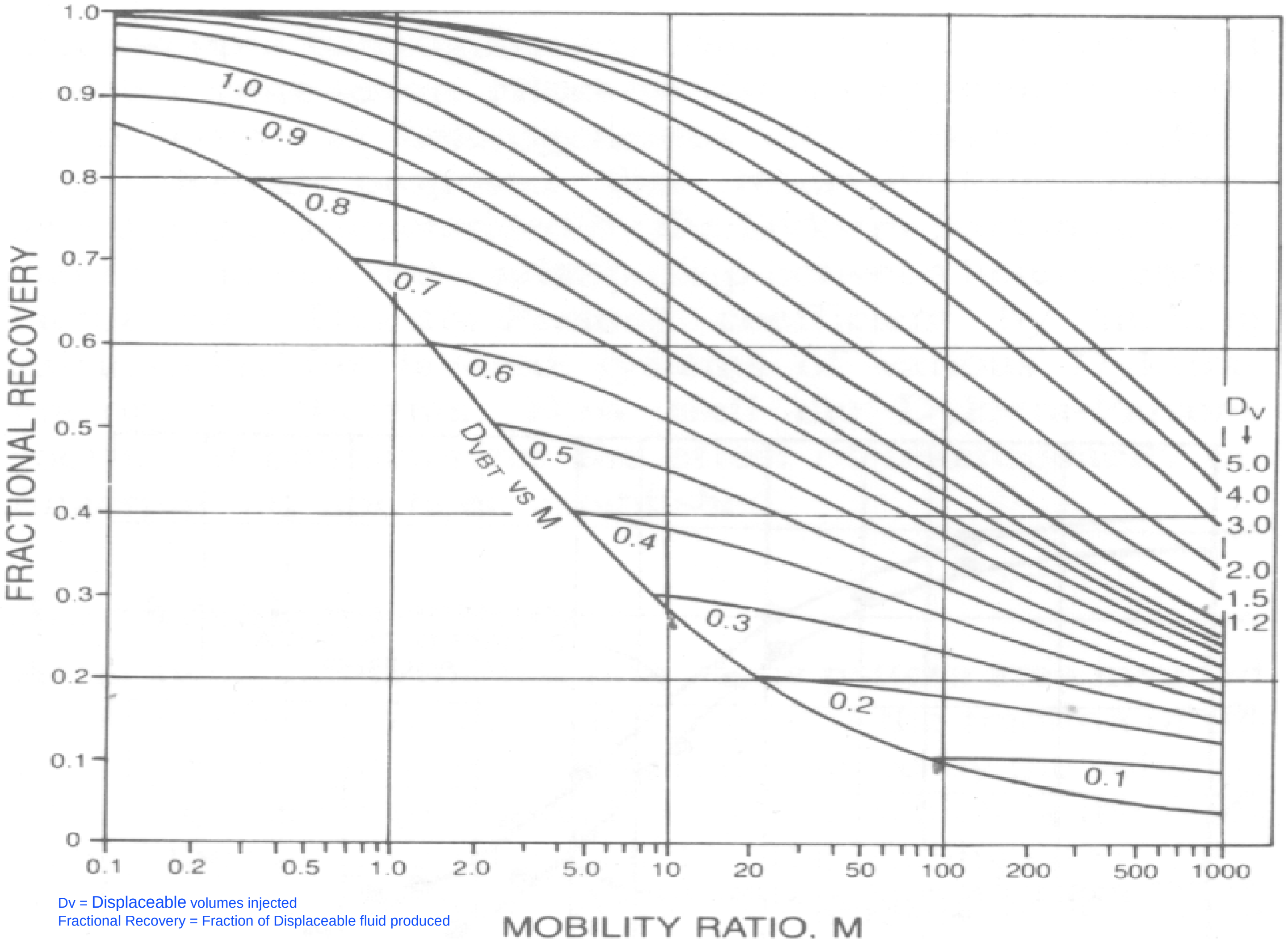
Fluid Mobility = K/μ = rel perm/viscosity

Mobility Ratio = $(\text{Mobility})_{\text{displacing}} / (\text{Mobility})_{\text{displaced}}$

Mobility Ratio (MR) = $K_w \times \mu_{oil} / K_{oil} \times \mu_{oil}$

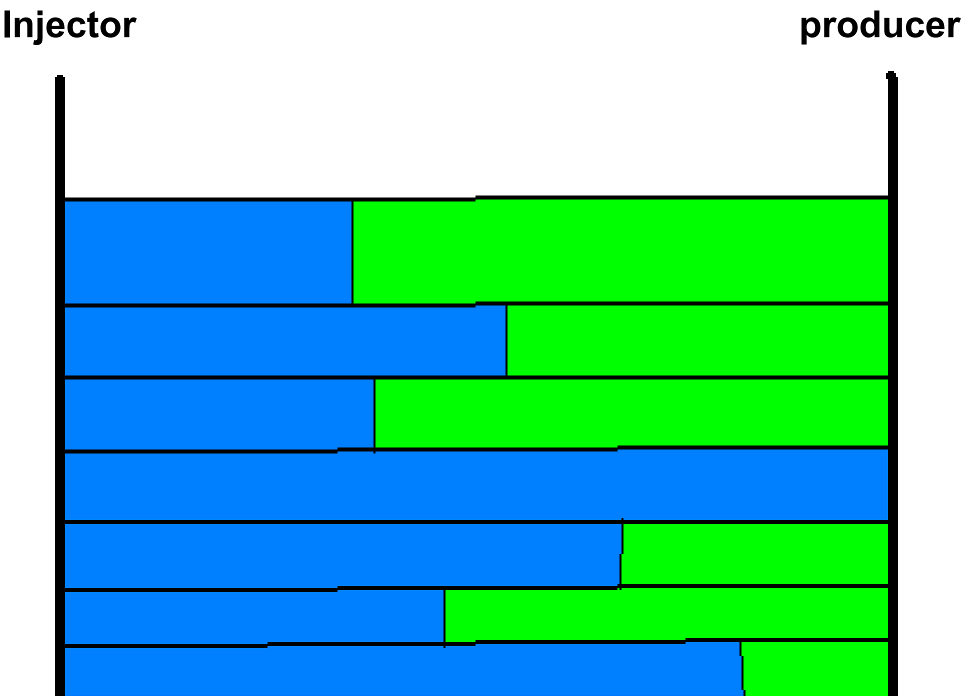
- Smaller MR is best for areal sweep efficiency
- Therefore want to minimize mobility of displacing fluid by maximizing its viscosity and minimizing its relative perm
- Want to maximize the mobility of oil by minimizing its viscosity and maximizing its relative perm

Fractional Recovery vs. Displaceable Volumes Injected



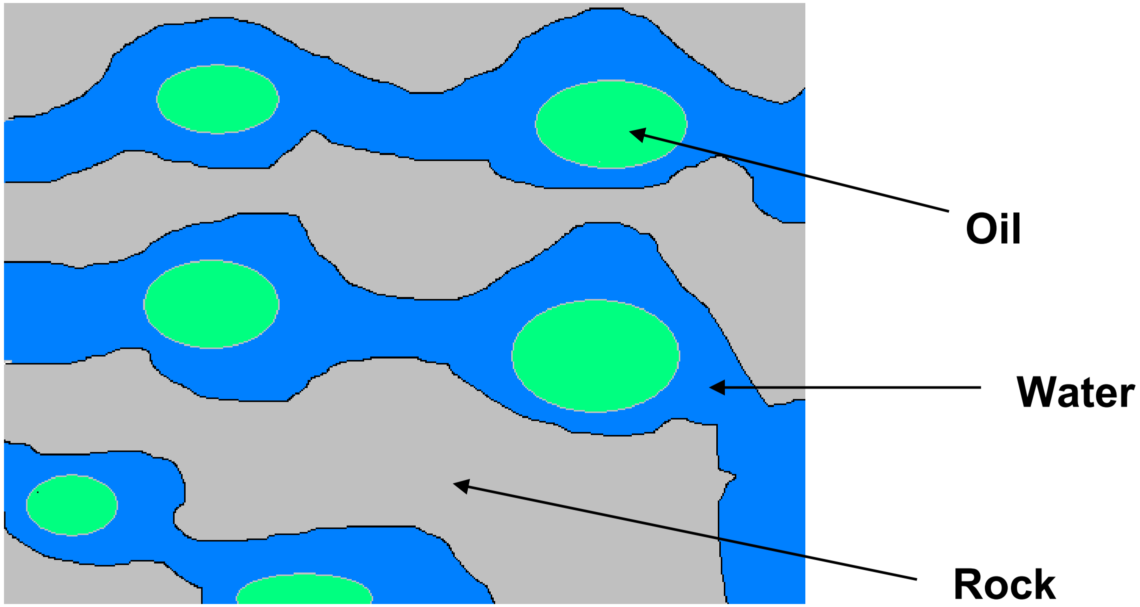
Dv = Displaceable volumes injected
Fractional Recovery = Fraction of Displaceable fluid produced

Representation of Vertical Sweep Efficiency



Once channel is established from injector to producer (breakthrough)
Injected fluid will preferentially follow this path resulting in poor sweep.

Factors effecting displacement efficiency of water wet rock



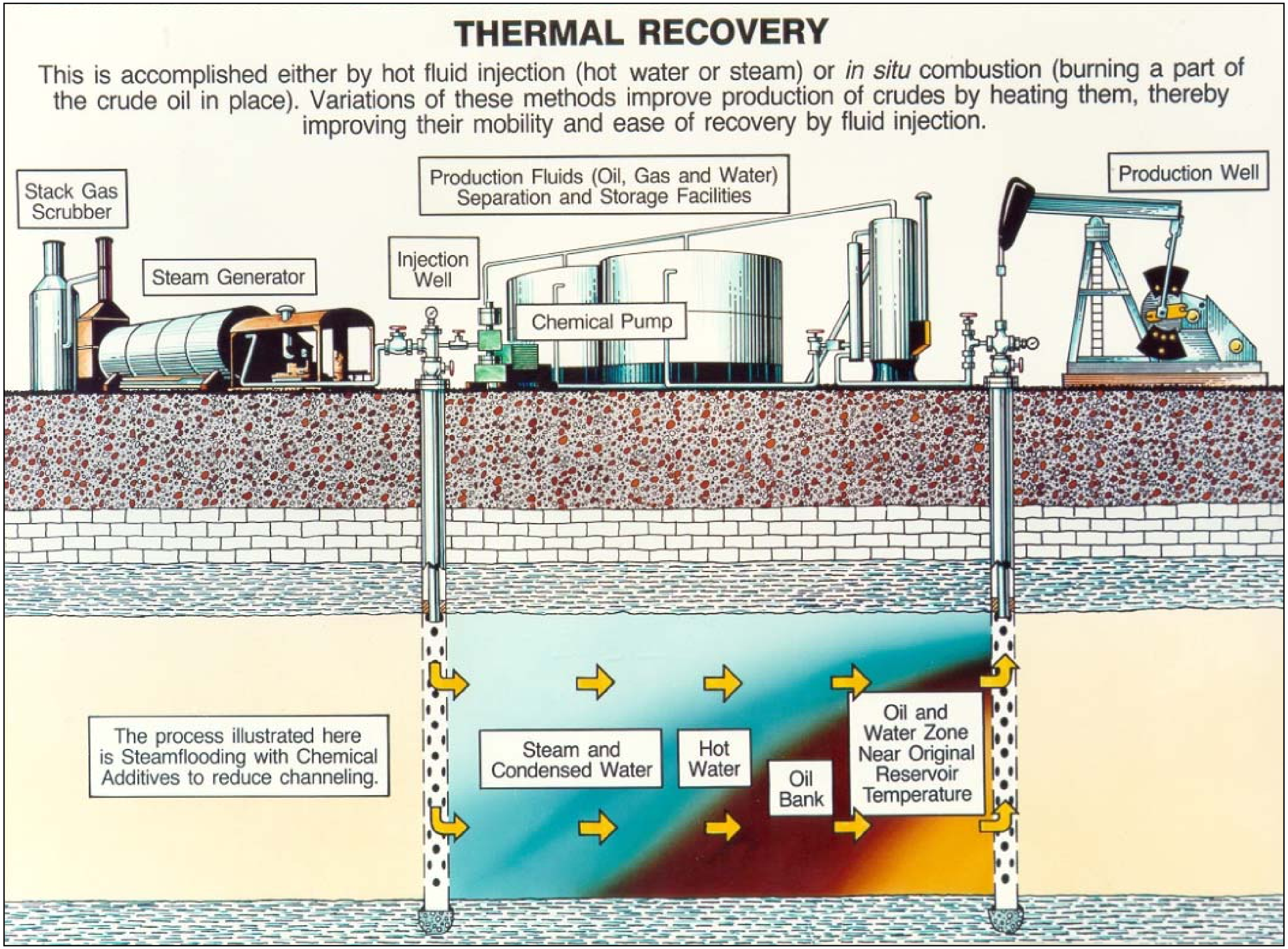
1.) Pore size and tortuosity of flow path

2.) Interfacial tension of oil/water interface

3.) Rock Properties (water wet or oil wet)

Advanced Secondary and Tertiary Recovery Techniques

- **Areal Sweep efficiency can be enhanced by Advanced Secondary techniques such as Polymer Augmented Waterflood and Infill Drilling**
- **Vertical Sweep can be enhanced by Advanced Secondary techniques such as profile modification by in-situ gellation of cross linked polymers.**
- **Displacement efficiency can be increased by reduction of interfacial tension using chemicals or by injection using a miscible fluid (no interface)**

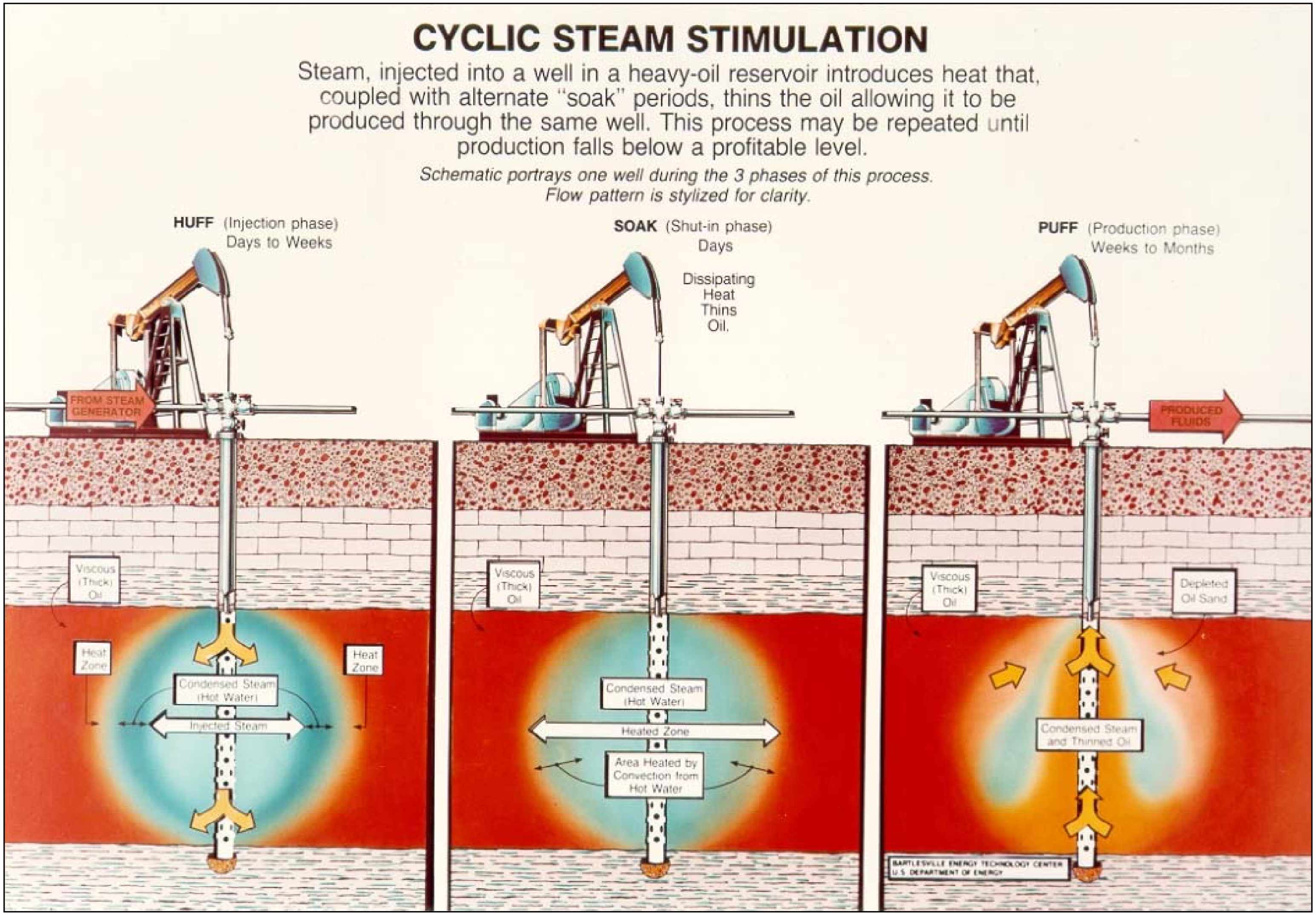


THERMAL RECOVERY

This is accomplished either by hot fluid injection (hot water or steam) or *in situ* combustion (burning a part of the crude oil in place). Variations of these methods improve production of crudes by heating them, thereby improving their mobility and ease of recovery by fluid injection.

The process illustrated here is Steamflooding with Chemical Additives to reduce channeling.

Source: U.S Dept. of Energy



CYCLIC STEAM STIMULATION

Steam, injected into a well in a heavy-oil reservoir introduces heat that, coupled with alternate "soak" periods, thins the oil allowing it to be produced through the same well. This process may be repeated until production falls below a profitable level.

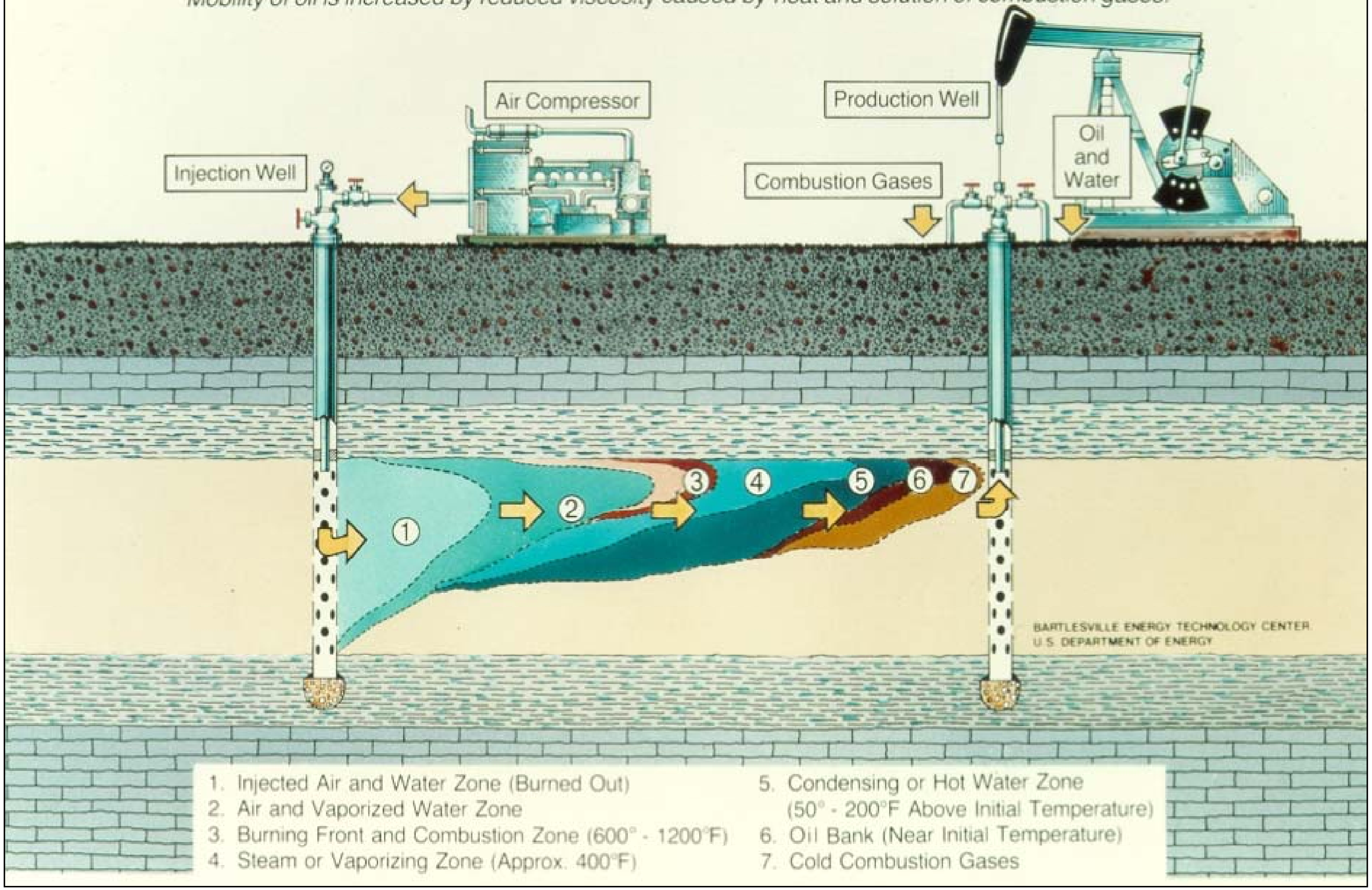
Schematic portrays one well during the 3 phases of this process. Flow pattern is stylized for clarity.

Source: U.S Dept. of Energy

IN-SITU COMBUSTION

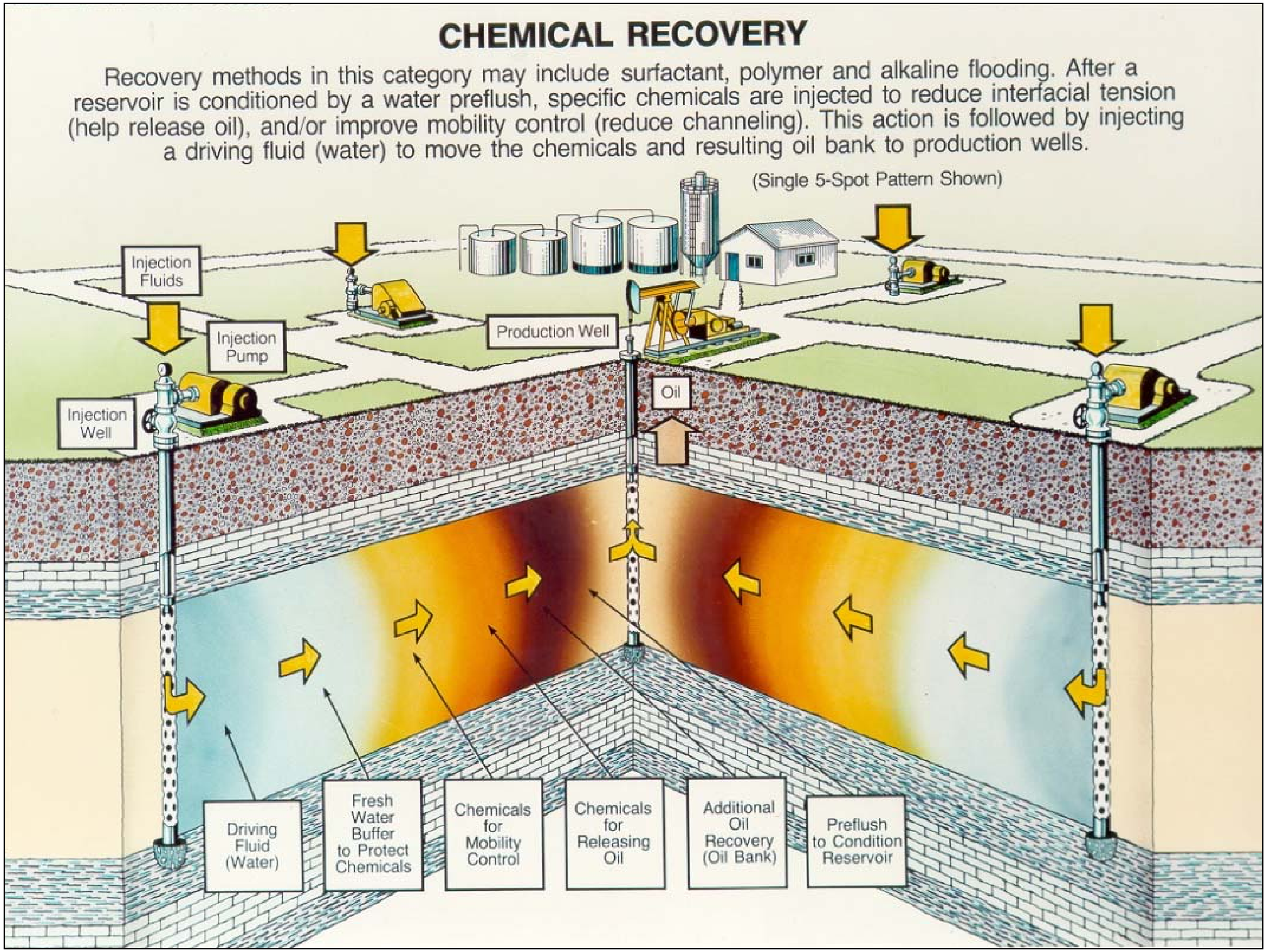
Heat is used to thin the oil and permit it to flow more easily toward production wells. In a fireflood, the formation is ignited, and by continued injection of air, a fire front is advanced through the reservoir.

Mobility of oil is increased by reduced viscosity caused by heat and solution of combustion gases.



1. Injected Air and Water Zone (Burned Out)
2. Air and Vaporized Water Zone
3. Burning Front and Combustion Zone (600° - 1200°F)
4. Steam or Vaporizing Zone (Approx. 400°F)
5. Condensing or Hot Water Zone (50° - 200°F Above Initial Temperature)
6. Oil Bank (Near Initial Temperature)
7. Cold Combustion Gases

Source: U.S Dept. of Energy



CHEMICAL RECOVERY

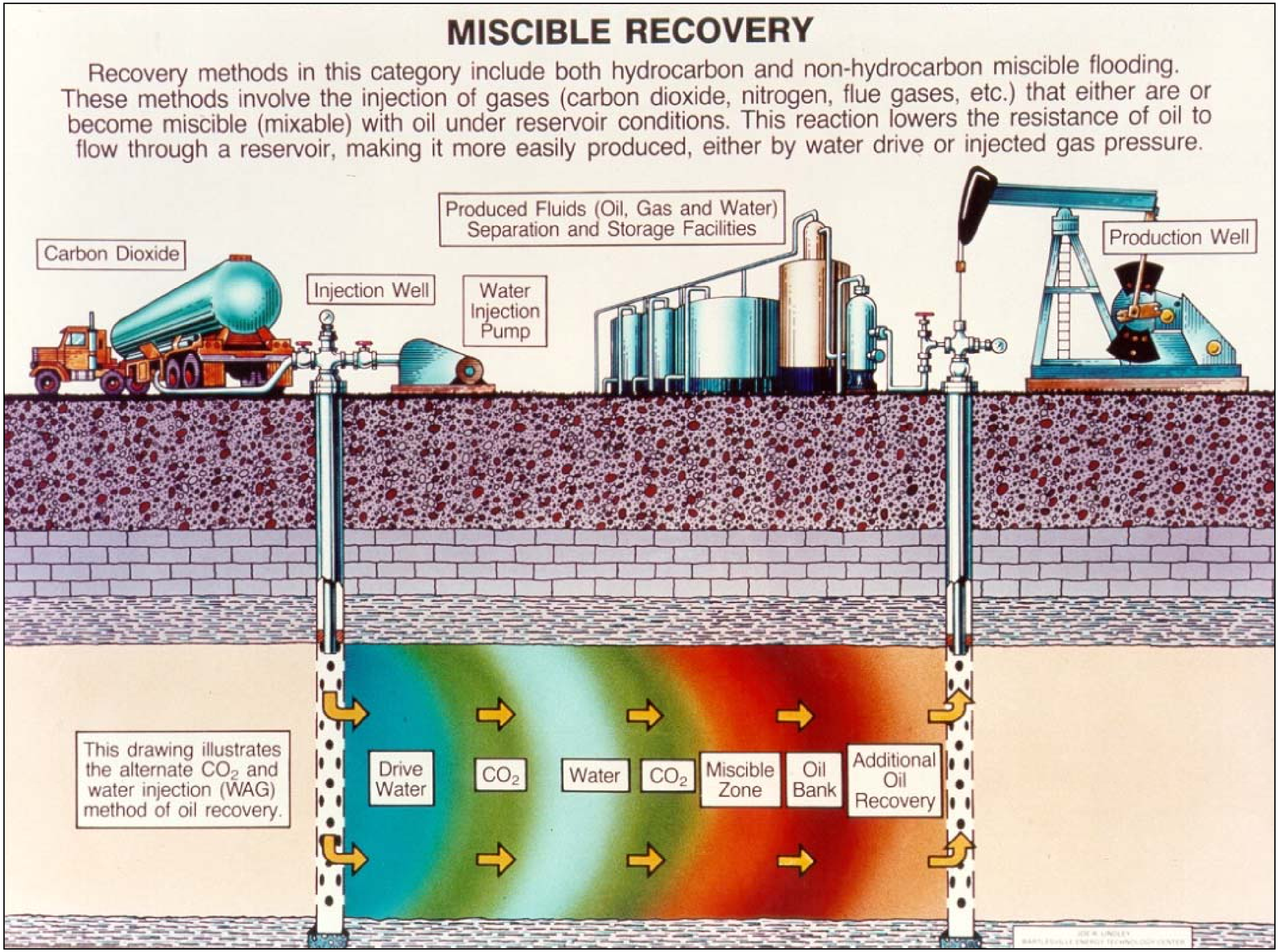
Recovery methods in this category may include surfactant, polymer and alkaline flooding. After a reservoir is conditioned by a water preflush, specific chemicals are injected to reduce interfacial tension (help release oil), and/or improve mobility control (reduce channeling). This action is followed by injecting a driving fluid (water) to move the chemicals and resulting oil bank to production wells.

(Single 5-Spot Pattern Shown)

Source: U.S Dept. of Energy

Applications of Chemical Flooding

- Surfactants designed to lower the interfacial tension between the oil and water or to change the wettability of the rock
- Water soluable polymers designed to increase water viscosity
- Surfactants to generate foams or emulsions
- Polymer gels for blocking or diverting flow
- Alkaline chemicals such as sodium carbonate to react with crude oil to generate soap and increase Ph.
- Many combinations of chemicals and methods



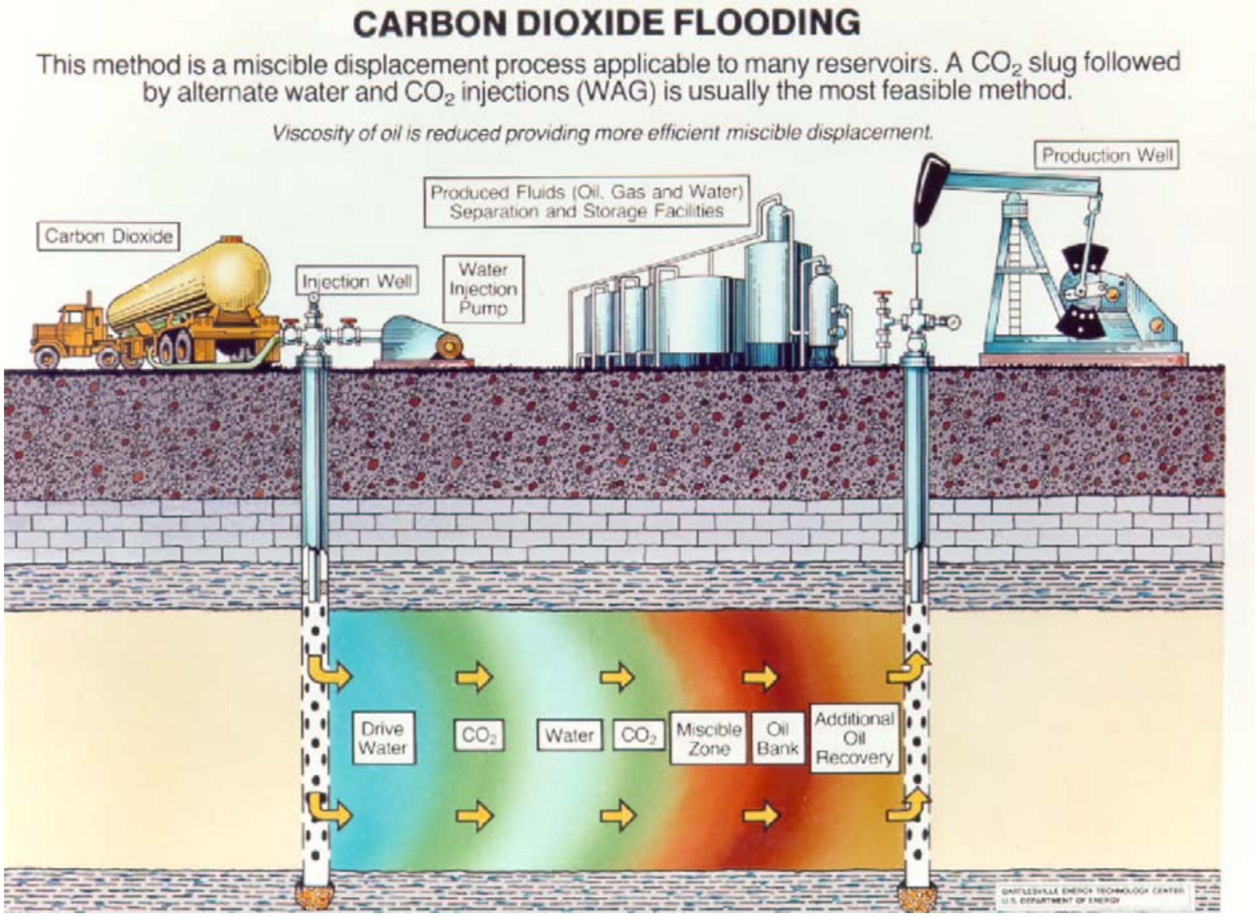
MISCIBLE RECOVERY

Recovery methods in this category include both hydrocarbon and non-hydrocarbon miscible flooding. These methods involve the injection of gases (carbon dioxide, nitrogen, flue gases, etc.) that either are or become miscible (mixable) with oil under reservoir conditions. This reaction lowers the resistance of oil to flow through a reservoir, making it more easily produced, either by water drive or injected gas pressure.

This drawing illustrates the alternate CO_2 and water injection (WAG) method of oil recovery.

Source: U.S Dept. of Energy

Process Diagram



CARBON DIOXIDE FLOODING

This method is a miscible displacement process applicable to many reservoirs. A CO_2 slug followed by alternate water and CO_2 injections (WAG) is usually the most feasible method.

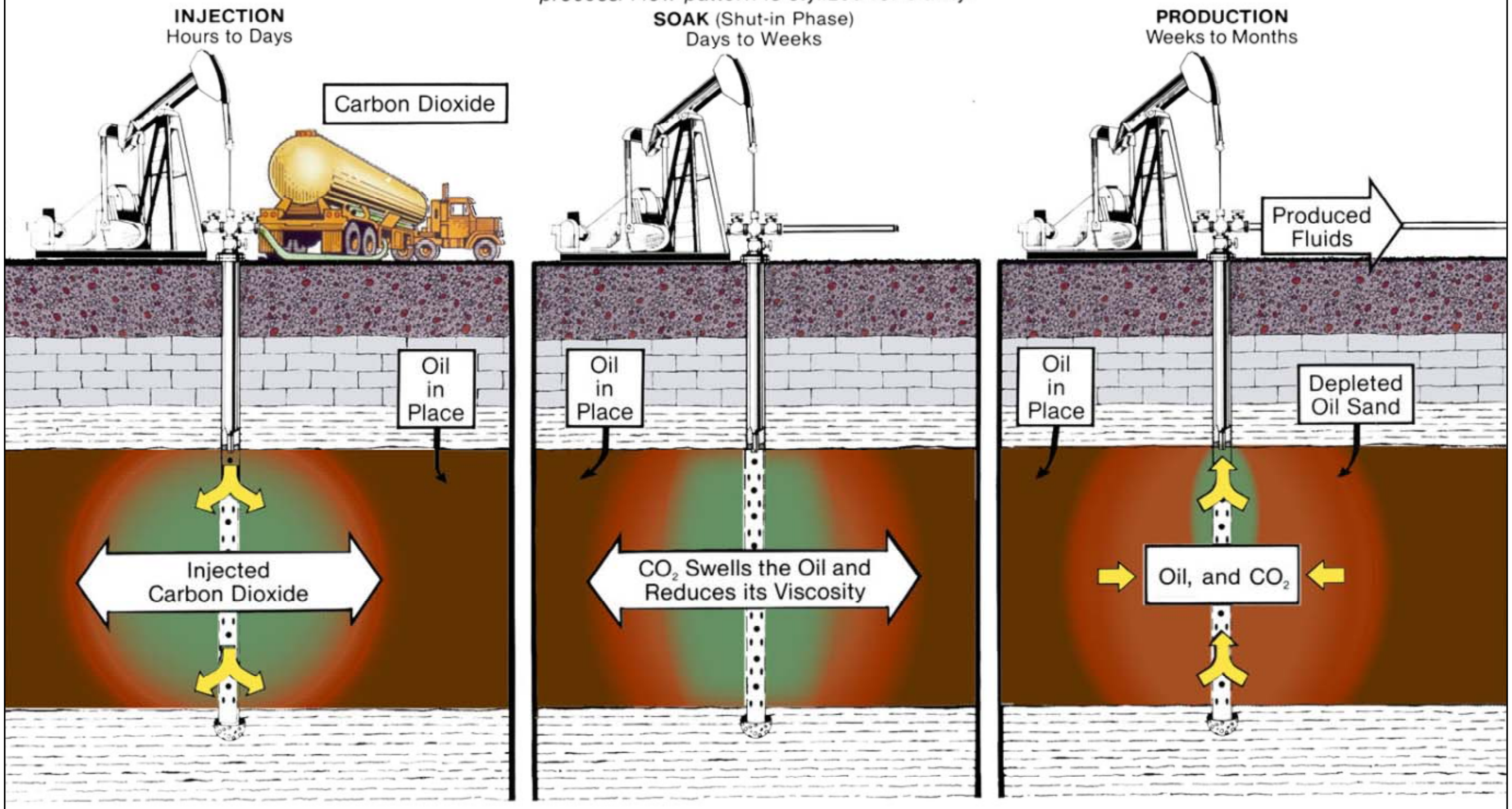
Viscosity of oil is reduced providing more efficient miscible displacement.

Source: U.S Dept. of Energy

CYCLIC CARBON DIOXIDE STIMULATION

Carbon dioxide is introduced into an oil reservoir during injection. The injection well is then shut in for a "soak period" during which the carbon dioxide swells the oil and reduces its viscosity. The well is then opened and the carbon dioxide provides a solution gas drive, allowing the oil and fluids resulting from the soak period to be produced. This process is repeated.

Schematic portrays one well during the 3 phases of this process. Flow pattern is stylized for clarity.

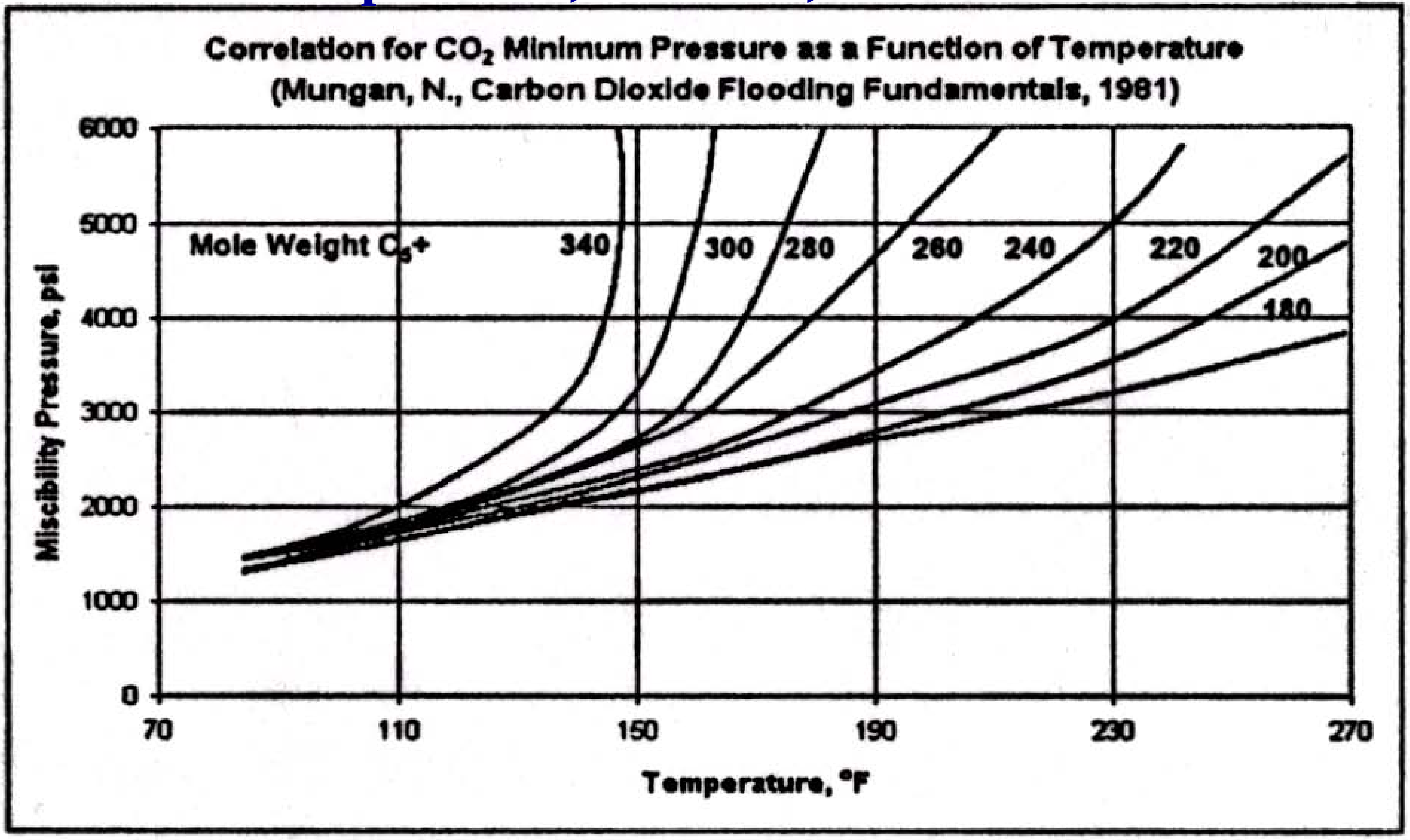


Source: U.S Dept. of Energy

What is Miscible Displacement

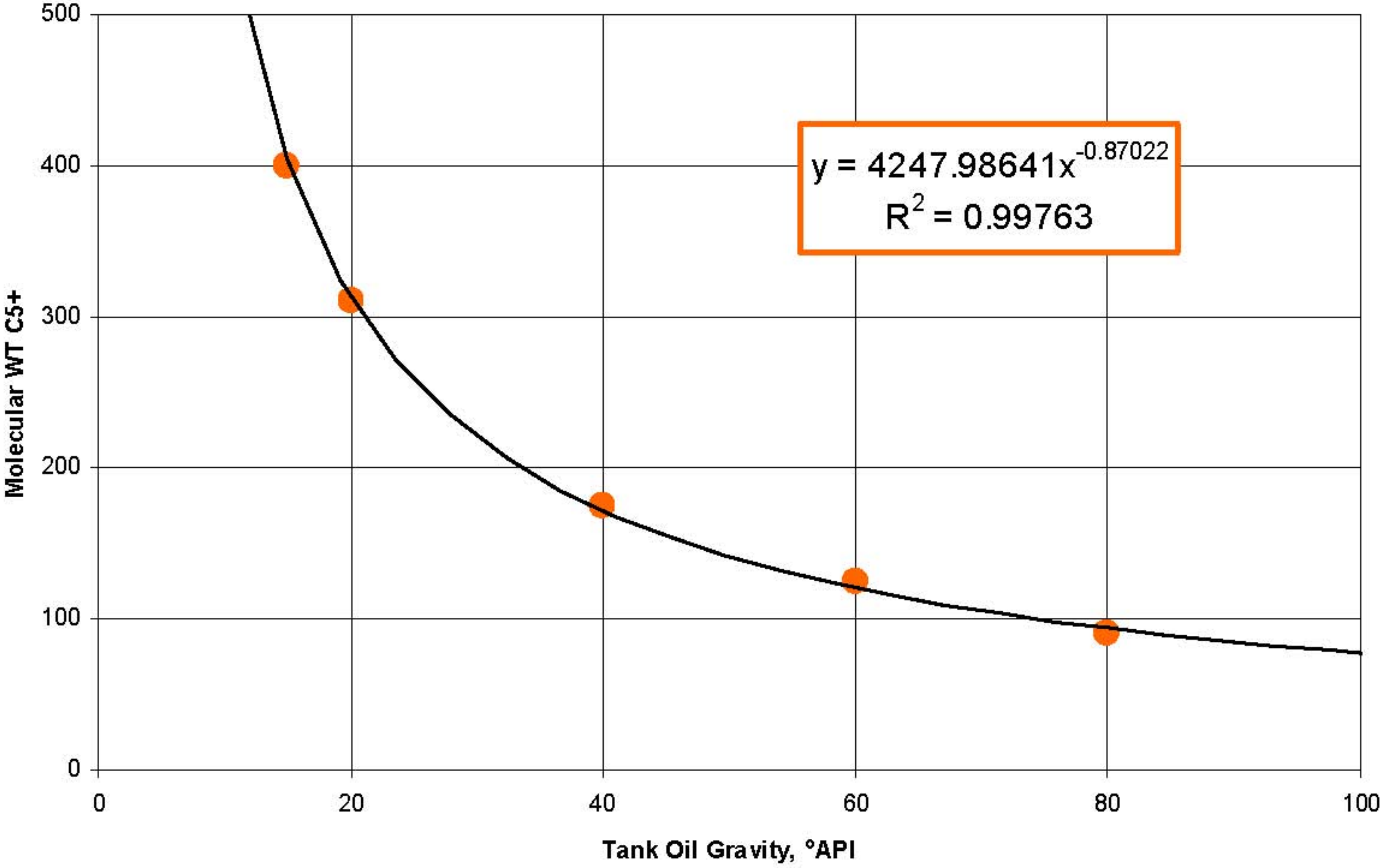
- Two fluids are miscible when they can be mixed together in all proportions and all mixtures remain single phase. (for example gasoline and kerosene)
- Immiscible fluids do not mix. (for example oil and water) there are always at least 2 phases separated by a sharp interface
- Displacement of a fluid by another fluid with which it is immiscible results in a residual saturation of the displaced fluid due to interfacial tension
- In theory, miscible displacement can result in 100% recovery of displaced fluid

Co2 Minimum Miscibility Pressure as function of Temperature, Pressure, and MW



Basin Oriented Stratogies for Co2 Enhanced Oil Recover California
Advanced Resources International, Inc.
http://www.adv-res.com/pdf/Basin%20Oriented%20Strategies%20-%20California.pdf

Effect of MW C5+ to Stock tank Oil Gravity



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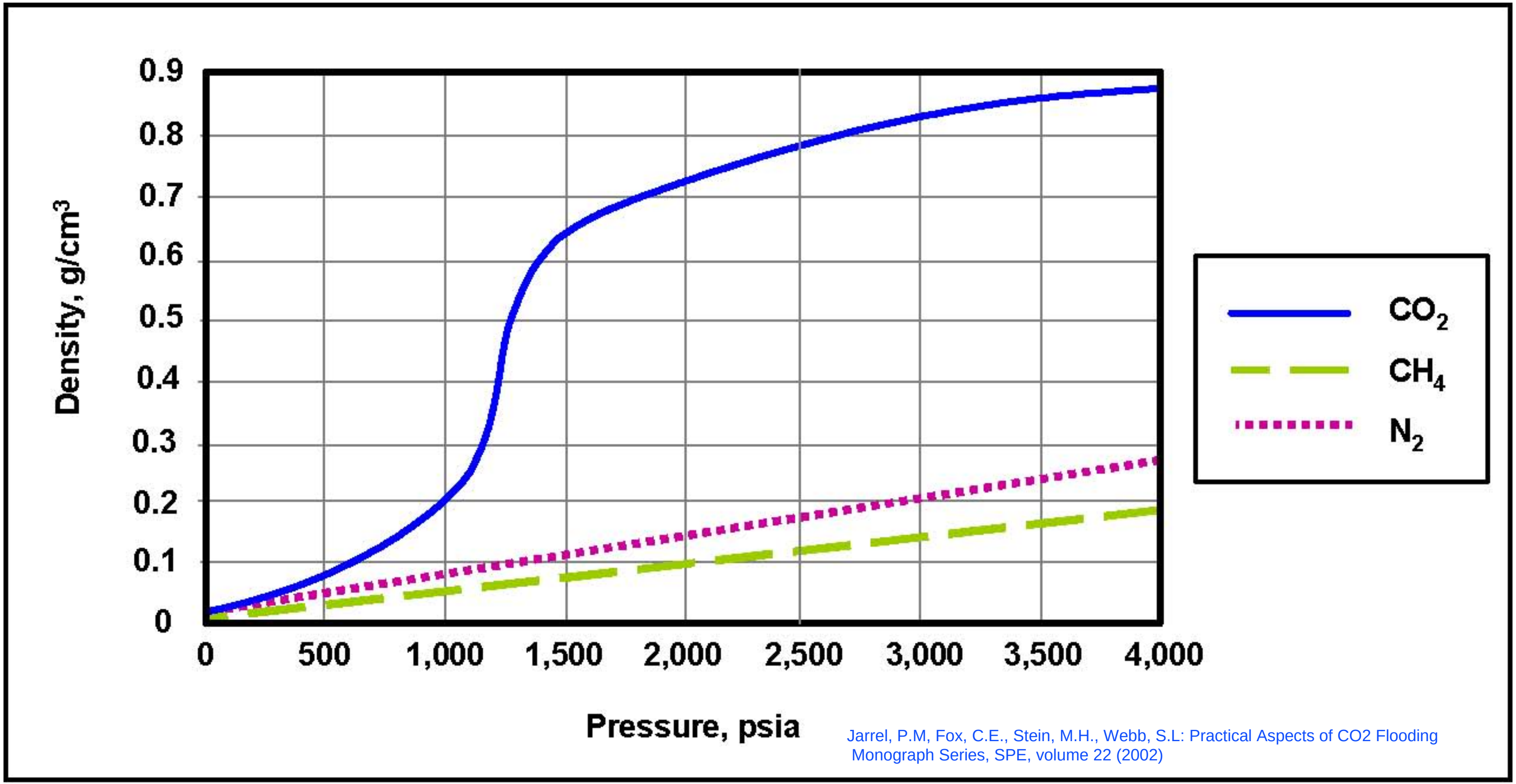
Why CO2?

- Miscible at lower pressures than Nitrogen or Methane
- Much cheaper and more plentiful than LPG/Enriched Hydrocarbon gas
- Density (In Dense Phase) closer to reservoir fluids (oil/water) – better mobility ratio
- Has proven to be technically viable in miscible and immiscible reservoir conditions
- Reduces residual oil saturation in swept volume very effectively, but has sweep problems due to gas like viscosity

CO2 Immiscible flooding Characteristics

- **Poor recovery relative to miscible flooding**
- **Still can be effective in certain applications**
- **Works through two mechanisms**
  - Oil Swelling
    - Oil volume increase (up to 50%)
    - Incremental oil below MMP
    - Oil from dead end pores
  - Viscosity reduction
    - Reduces mobility ratio
    - Improves oil relative perm
    - Improves sweep efficiency

Density behavior of CO2 @ 105 degrees F



Jarrel, P.M, Fox, C.E., Stein, M.H., Webb, S.L: Practical Aspects of CO2 Flooding Monograph Series, SPE, volume 22 (2002)

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Figure 6A. Carbon Dioxide, CH4 and N2 densities at 105F. At high pressures, CO2 has a density close to that of a liquid and much greater than that of either methane or nitrogen. Densities were calculated with an equation of state (EOS).

Viscosity behavior of CO2 @ 105 degrees F

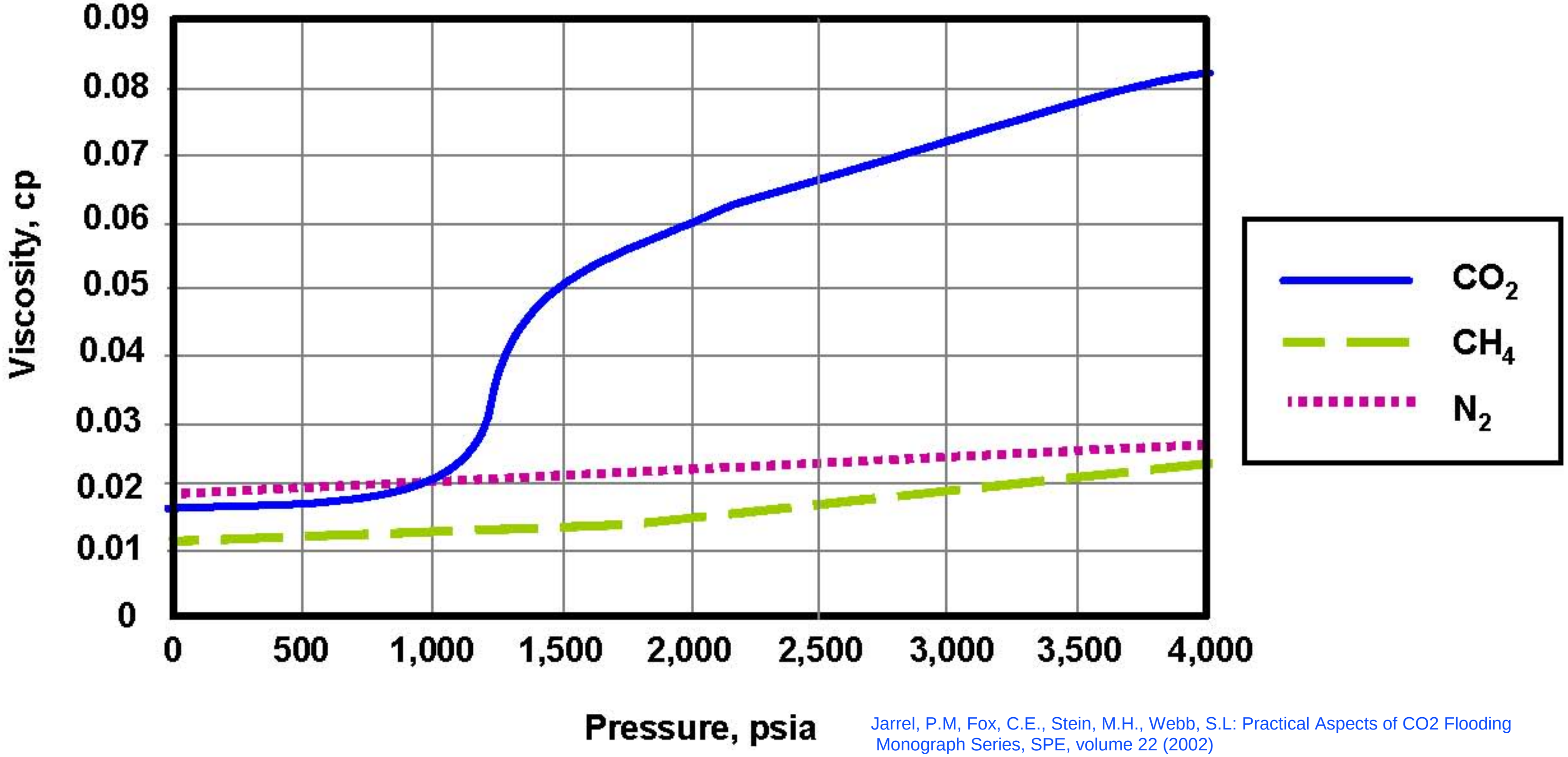

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Figure 6B. Carbon Dioxide, CH4 and N2 viscosities at 1050F. At high pressures, the viscosity of CO2 is also greater then that of methane or nitrogen, although it remains low in comparison to that of liquids. Viscosities were calculated with an EOS.

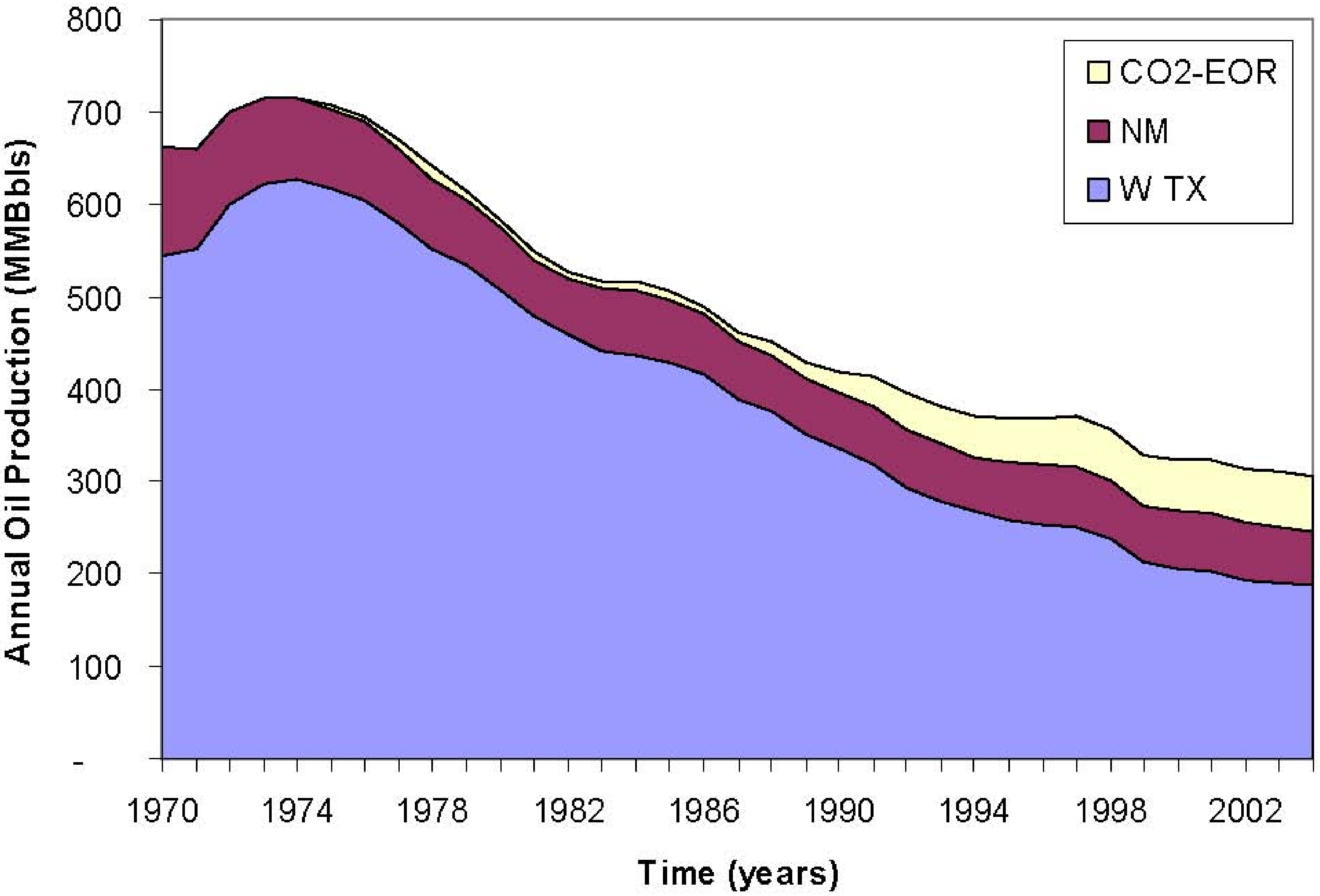
History of CO_2 EOR Development

- **1950s** Early research showed CO_2 to be promising oil recovery agent
- **1960s** Laboratory research on miscible flooding, NGLs and CO_2; large CO_2 sources sought
- **1970s** CO_2 sources defined; pipelines built from native fields; 20 pilot floods initiated; research on miscibility pressure and phase behavior
- **1980s** Full scale projects started in early 80s, WAG most common; late 80s price collapse stalled expansion
- **1990s** Low cost CO_2 floods started; showed better mobility control needed; currently 68 CO_2 floods in progress; pipelines nearing capacity

History of CO_2 EOR Development
(Continued)

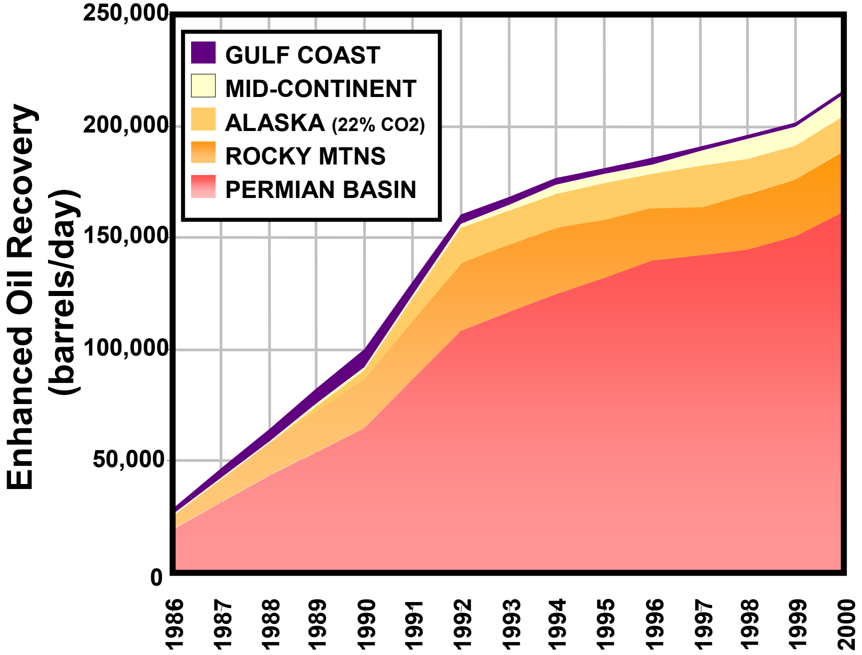
- In 2006, 82 active CO_2 projects produced an average of 263,000 barrels of oil per day. About 211,000 of this value is EOR
- 53 projects are in Permian Basin, the 5 largest accounting for 1/3 worldwide CO_2 enhanced production
- Fields generally operated by majors and large independents (Oxy, ConocoPhillips, Texaco, Amerada, Anadarko, Pioneer, Kinder-Morgan)
- Generally low permeability, 2 - 3 millidarcies
- Expect to recover an additional 7 - 8 % original oil in place

Permian Basin Oil Production

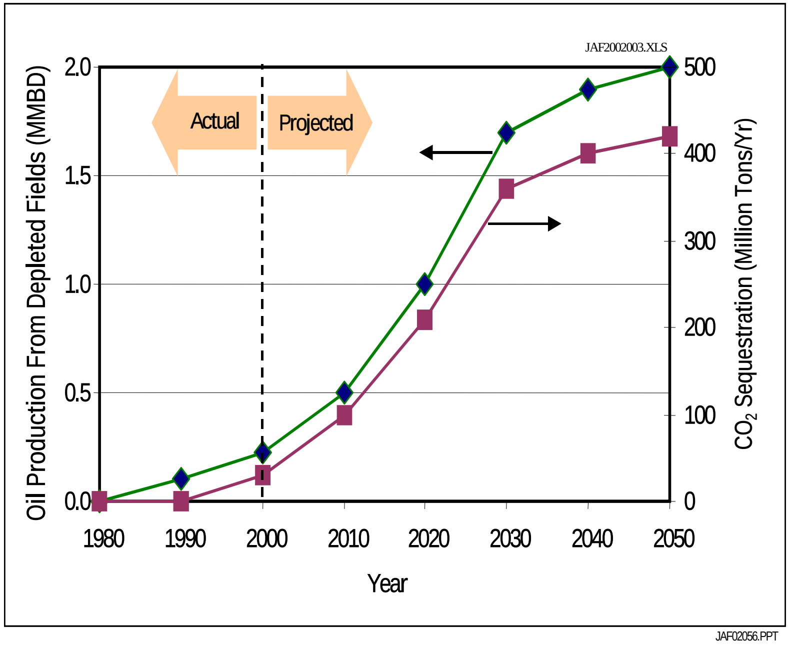


History of CO_2 EOR Development
(Continued)

Historical Production for CO_2 EOR

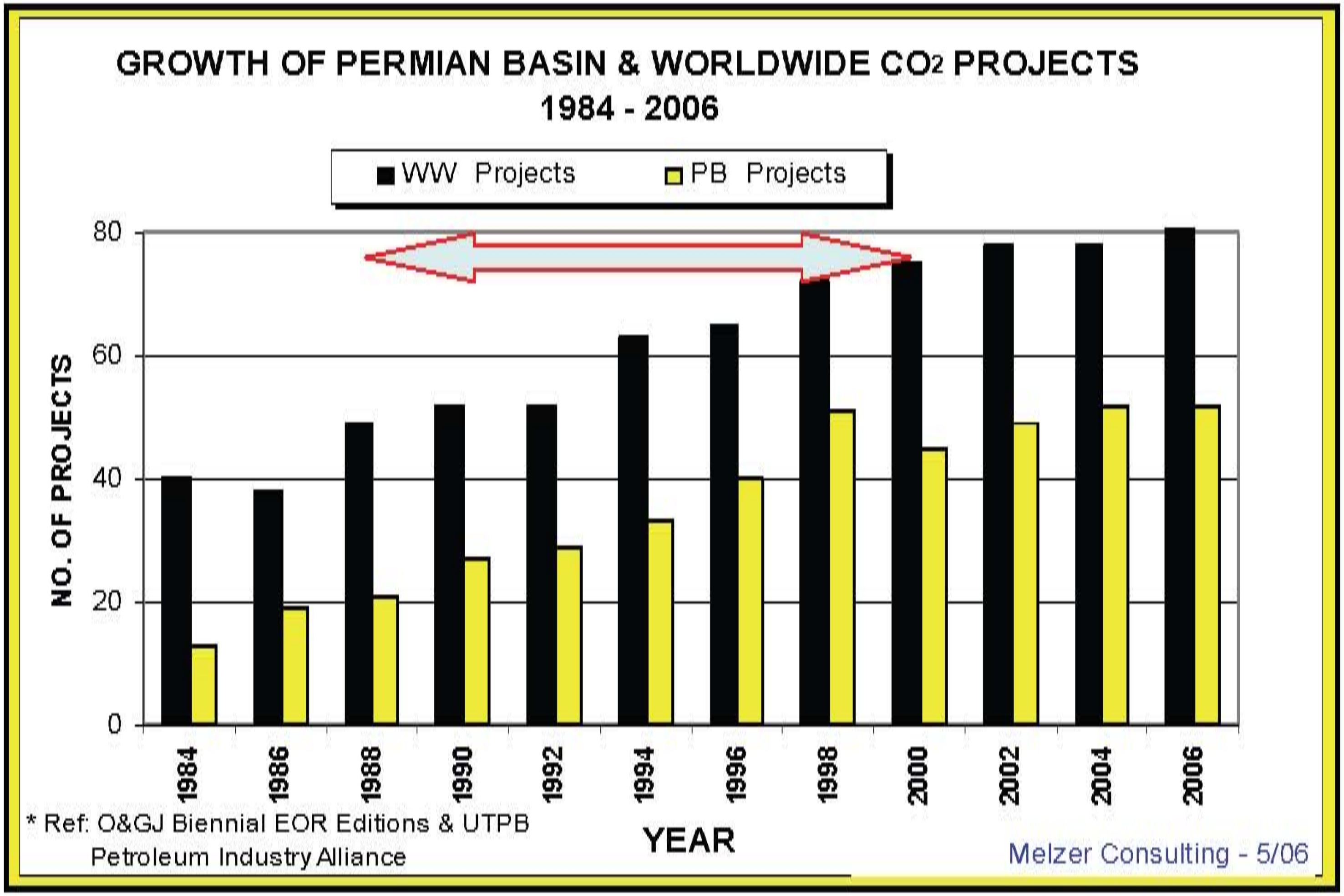


Future Potential from CO_2 Sequestration in Depleted Oil Fields



Source: Advanced Resources International

Growth of CO2 Projects Worldwide



The 'Nuts and Bolts' of CO2 Enhanced Oil Recovery
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Natural Underground CO2 Sources

- Mc Elmo Dome (CO), Sheep Mtn. (CO), and Bravo Dome (NM) service Permian Basin
- Reserves of 20+ TCF
- Producing around 1.4 Bcf/day at ($.7 - $.80/Mcf)
- Expansion of 100 MMcf/d announced for next year through Cortez pipeline

- Jackson Dome (MS)
- Reserves around 5-6 TCF
- Production Capacity 400-500 MMcf/d (Denbury Resources)

- St. Johns helium/Co2 field (AZ) Ridgeway Petroleum
- Reserves estimated at 5 TCF
- Plans to supply CO2 to Permian Basin eventually

Current Anthropogenic CO2 Sources

- **Natural Gas Separation Plants**
  - Shute Creek (La Barge, WY)
  - Val Verde (TX)
  - Mi Vida (TX)
- **Ammonia (fertilizer) Plants**
  - Borger (TX)
  - Enid (OK)
- **Coal Gasification Plant**
  - Dakota Gasification Corp. (ND)
- **Ethylene / Polyethylene Plant**
  - Alberta, Canada

North America CO2 Source Deliveries for EOR (4th quarter 2007)

Source	**MMcfpd**	**Tons/Day**
Underground(4)	1,700	97,143
Natural Gas Plant(3)	260	14,857
Coal Synfuels(1)	155	8,857
Ammonia(2)	42	2,400
Ethylene(1)	3	171
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	2,160	123,429

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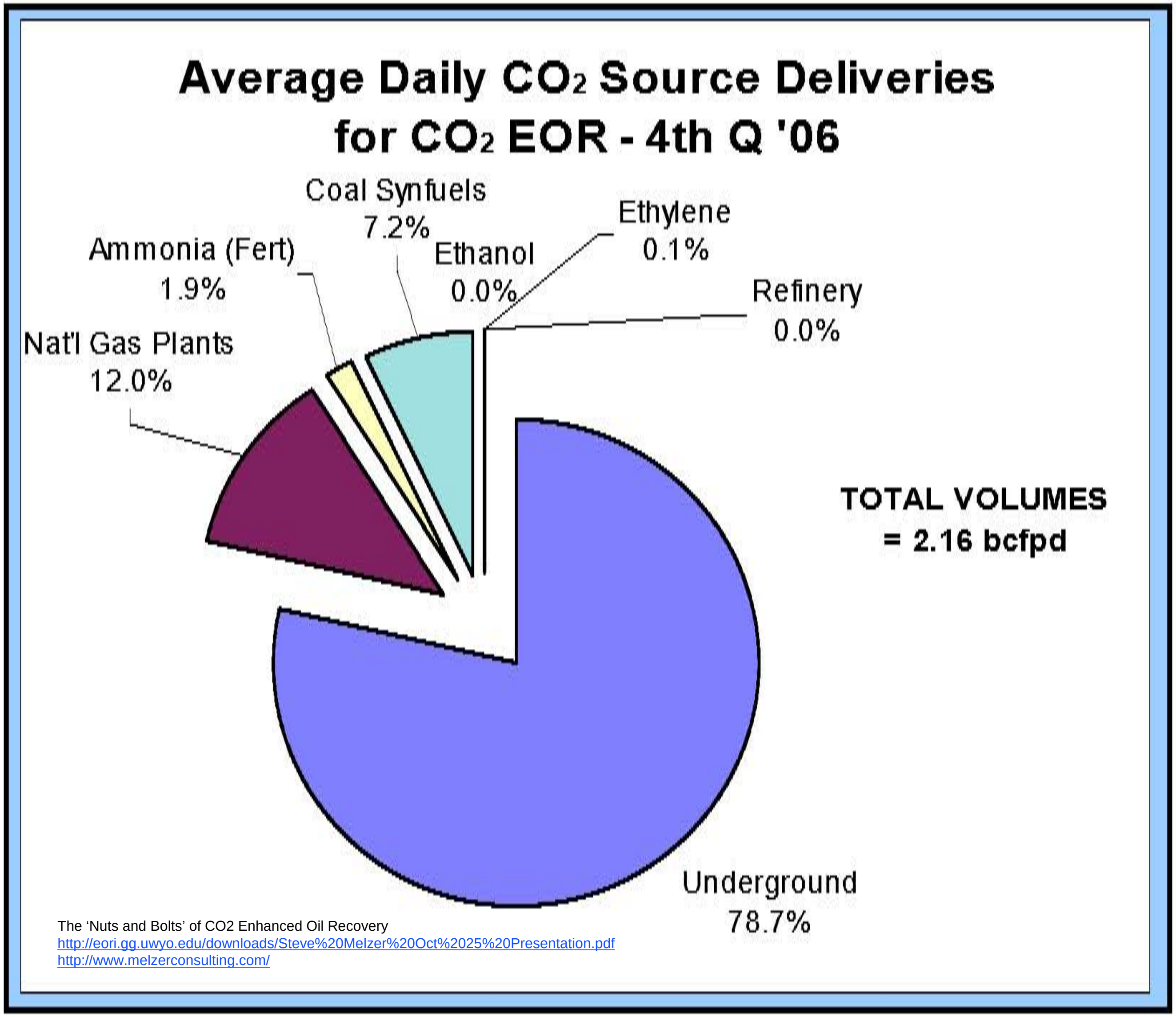
CO2 Relative Source Volumes



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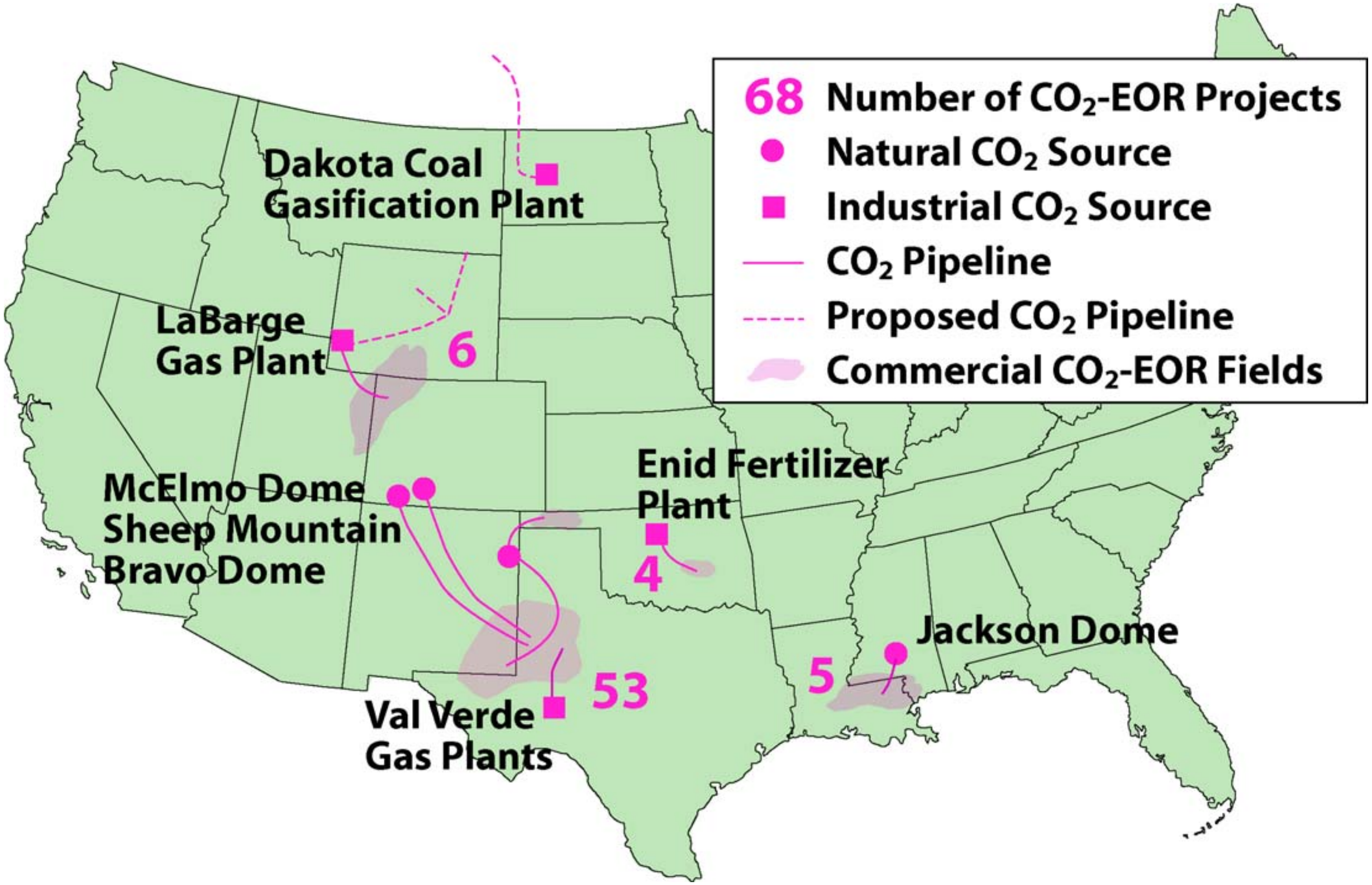
Commercial CO_2 Projects and Sources in the USA



West Texas CO_2 Market

- **Company**- **Kinder Morgan**
- **CO_2 Source** – **Natural and Anthropogenic sources**
- **History** – **major pipelines built in 1980's**
- **Volume\capacity** – McElmo Dome 650-1,000 MMcf/day– **Approximately 7.3 TCF or 380 MM tones used**
- **# reservoirs** – **app. 70**
  - Carbonate and sandstone
- **Additional usage-** **none**
- **CO_2 price** – **a function of oil price**
- **Scale-** **1,500 miles of major pipelines**

CO2 Source: Supplying an Obtaining Necessary CO2 for EOR and Sequestration
Mark Holtz, Praxair Inc.

Gulf Coast CO_2 Market

- **Company**- Denbury
- **CO_2 Source** – Natural
- **History** -1999 Denbury purchased Jackson dome and pipeline,1996 Airgas purchased from Shell
- **Volume\capacity** – 450-700 MMcf/day, currently 265 MMCF/D
- **# of reservoirs** – 7
  - Sandstone lithology
- **Additional usage** - chemical industry
- **CO_2 price** – on contract basis
- **20”, 183 mi high pressure pipeline**

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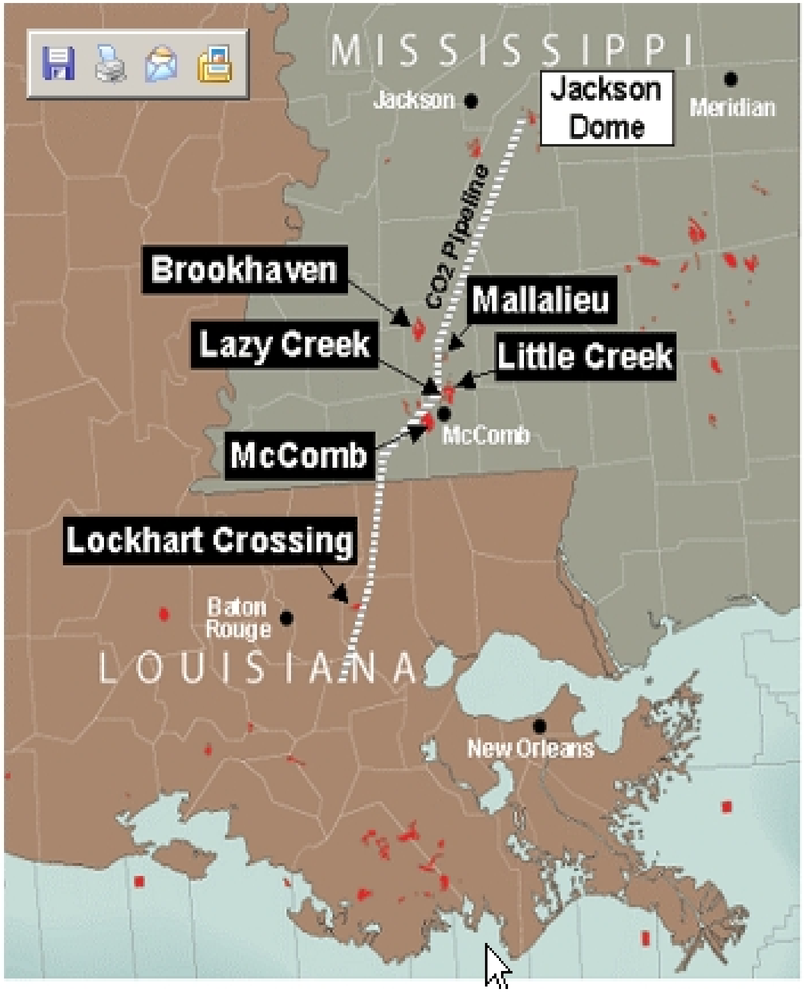
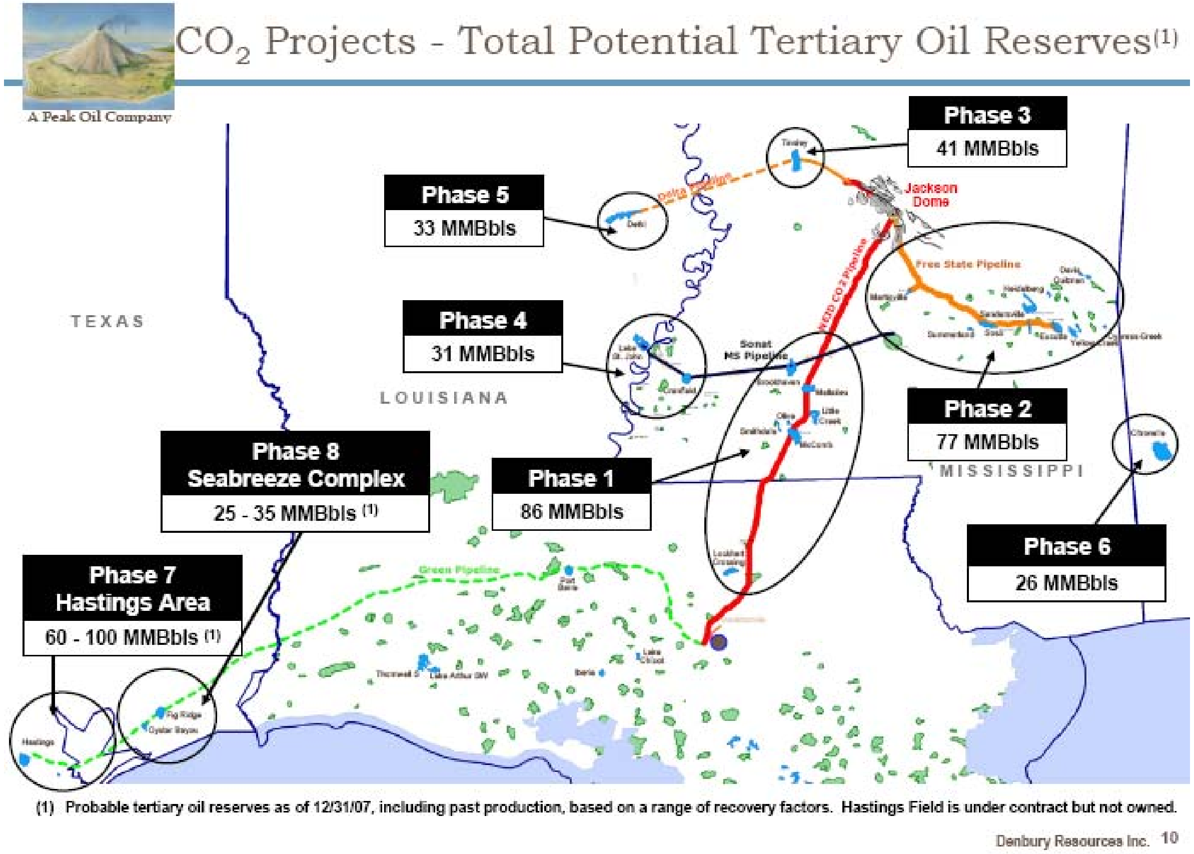


8 Phase Denbury Expansion



CO$_2$ Projects - Total Potential Tertiary Oil Reserves(1)

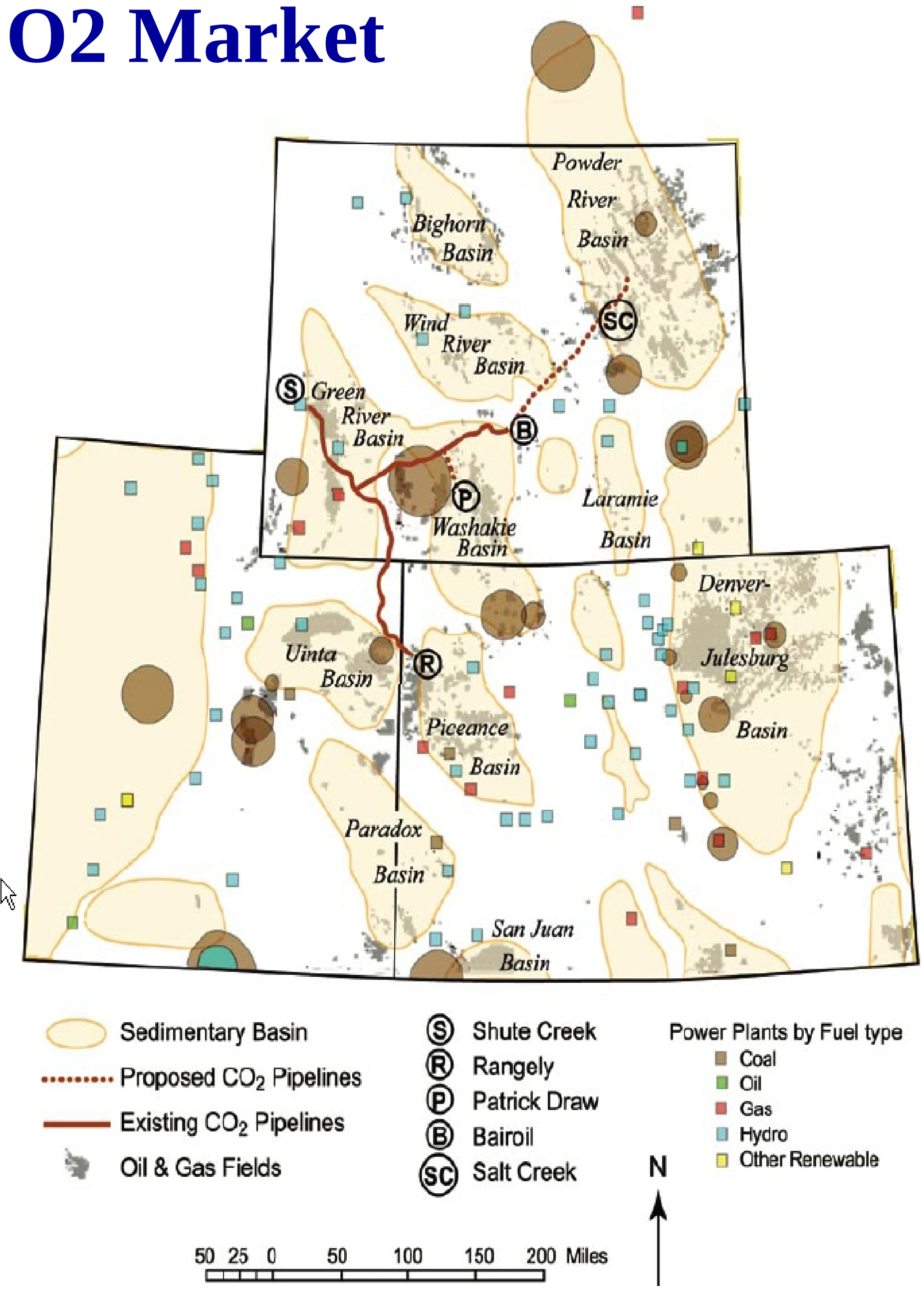
A Peak Oil Company

(1) Probable tertiary oil reserves as of 12/31/07, including past production, based on a range of recovery factors. Hastings Field is under contract but not owned.

Denbury Resources Inc. 10

Rocky Mountain CO2 Market

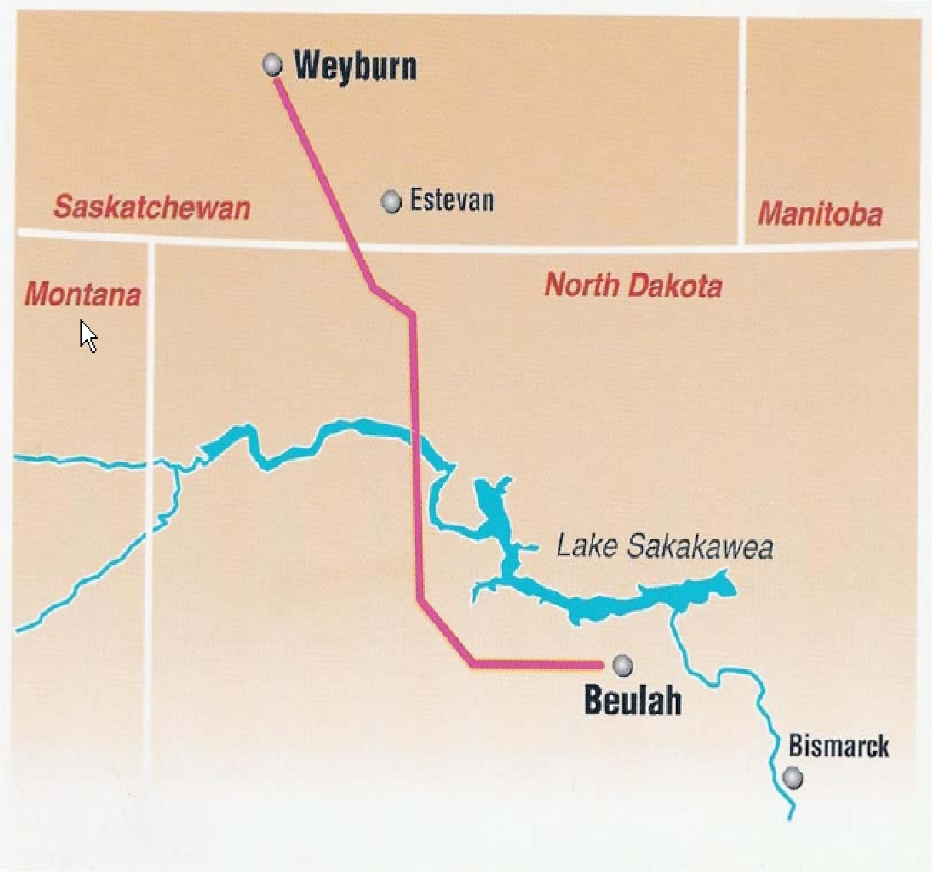
- **Company** **–Exxon, Anadarko, Chevron**
- **Source** **– Shute Creek gas processing plant, La Barge gas field**
- **History** **– start-up 10/1986**
- **Volume\capacity** – 89 MM tons/yr, 250-600 MMcf/day
- **# reservoirs** **– 5**
  - Sandstone lithology
- **Additions usage** **– frac jobs**
- **CO_2 price** **–**



CO2 Source: Supplying an Obtaining Necessary CO2 for EOR and Sequestration
Mark Holtz, Praxair Inc.

Northern Plains

- **Company- Encana**
- **Source –** coal gasification plant
- **History – Start-up 10/2000**
- **Volume –** Takes ~5,000 tonnes/day CO_2
- **# reservoirs – 1-2**
  - Carbonate lithology
- **Additional usage - none**
- **CO_2 price - Cost approximately $19/ton**
- **Expected reserves 130 MMSTB or approximately and additional 9% of OOIP**



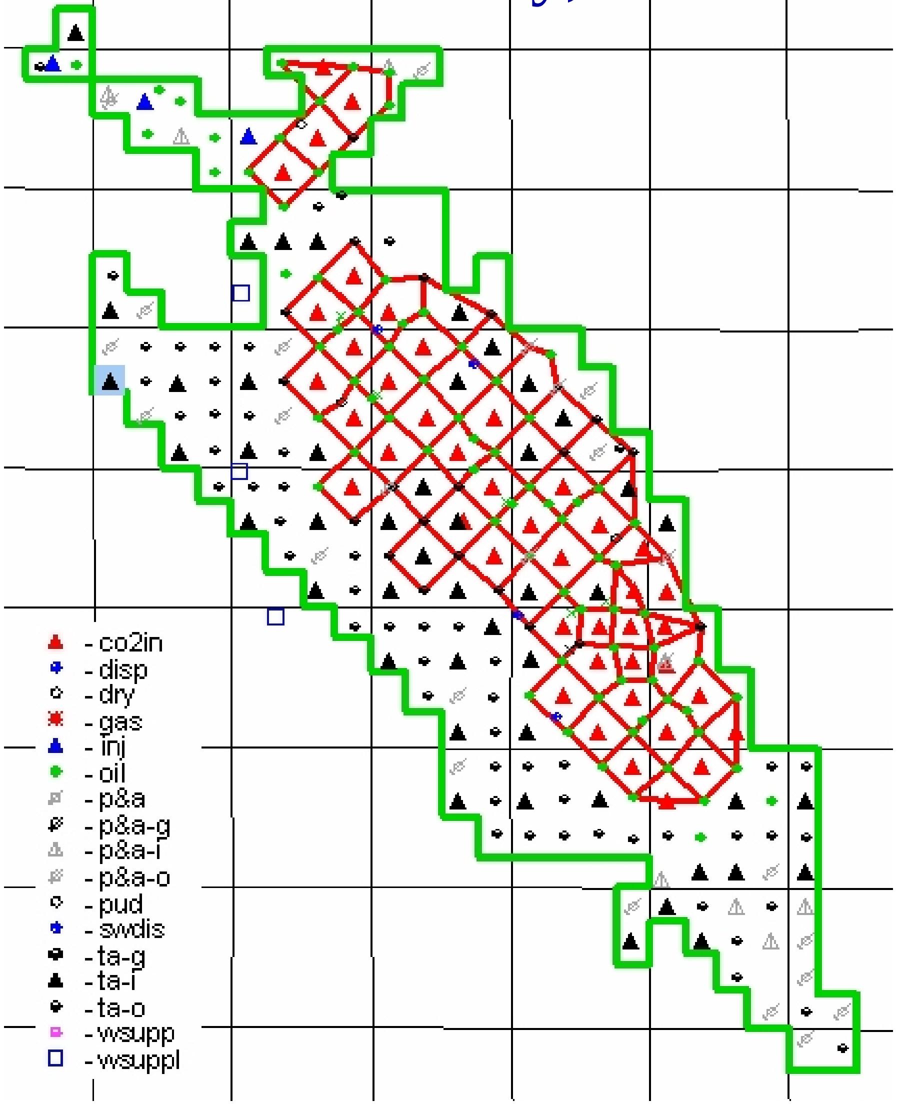
CO2 Source: Supplying an Obtaining Necessary CO2 for EOR and Sequestration
Mark Holtz, Praxair Inc.

Typical Large Scale CO_2 Flood

- **Eighty percent of full field floods are located in the Permian Basin dolomites**
- **Typical Unit – Oxy Slaughter Unit San Andres flood, Hockley County, Texas**
  - Begun in 1984
  - Approximately half way through producing life
  - 5700 acres, previously waterflooded
  - 191 producing wells, 161 injection wells
  - Currently producing 6,206 barrels of oil daily, 5,000 attributed to tertiary CO_2 flood

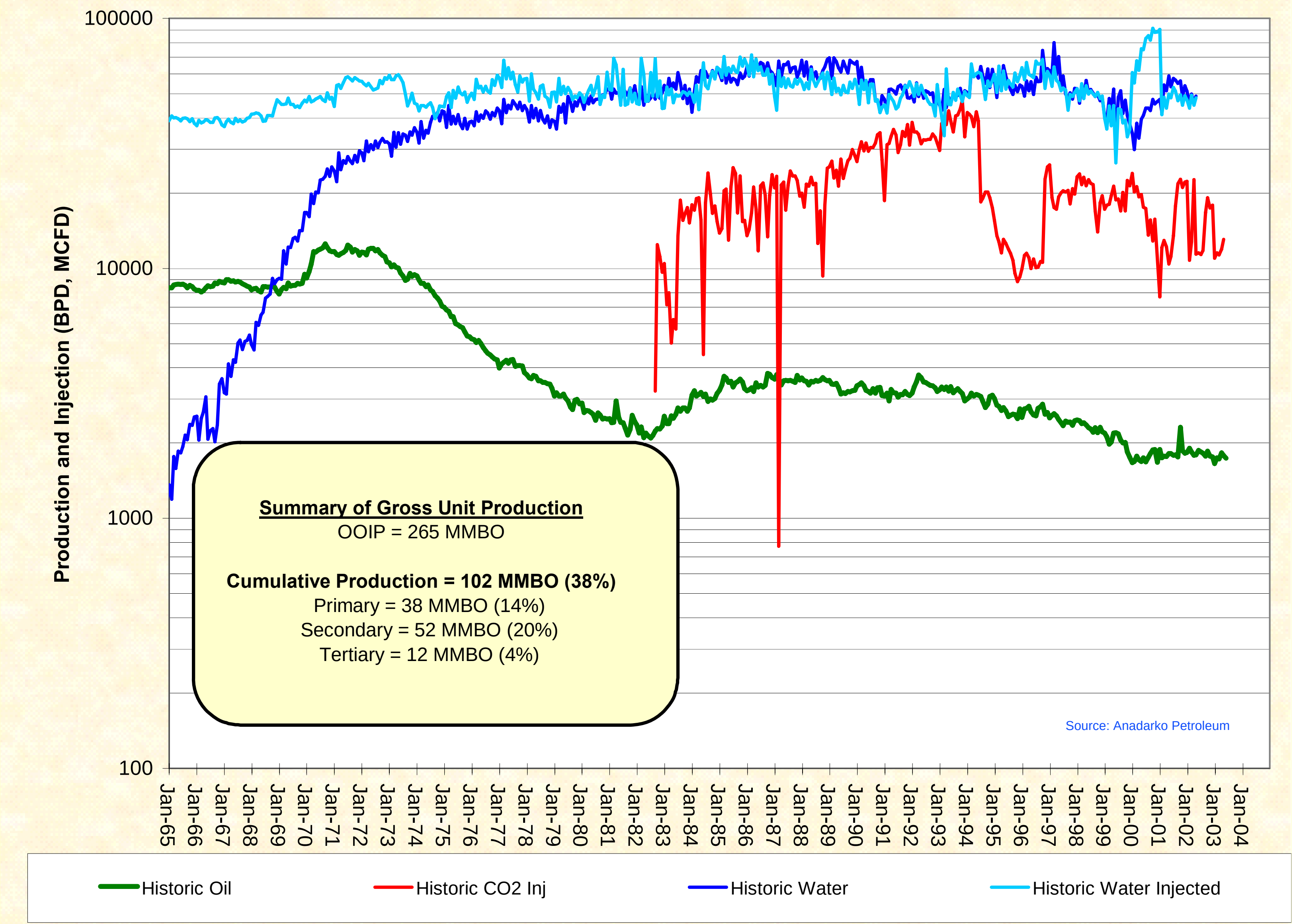
Anadarko NE Purdy Springer Unit

Garvin County, OK



Source: Anadarko Petroleum

NE Purdy Springer Unit Garvin County, OK



Summary of Gross Unit Production

OOIP = 265 MMBO

Cumulative Production = 102 MMBO (38%)

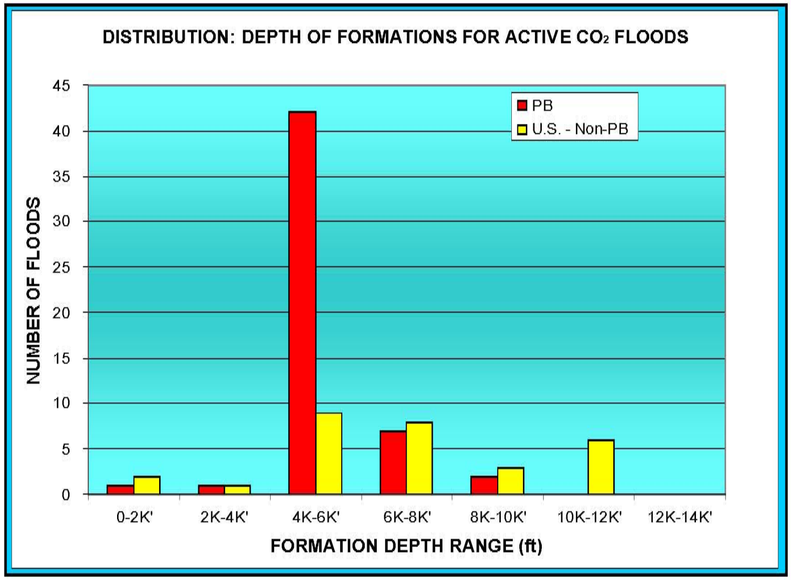
Primary = 38 MMBO (14%)

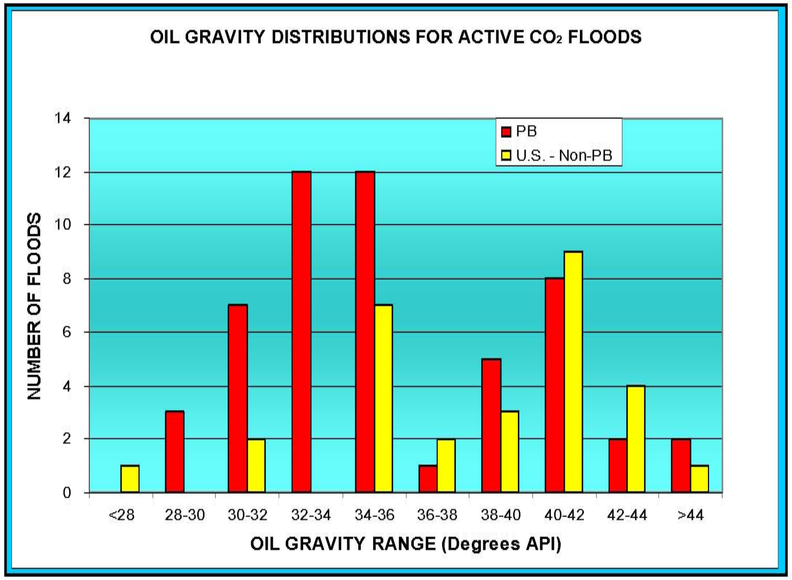
Secondary = 52 MMBO (20%)

Tertiary = 12 MMBO (4%)

Source: Anadarko Petroleum

Depth and Gravity Distribution of CO2 Projects





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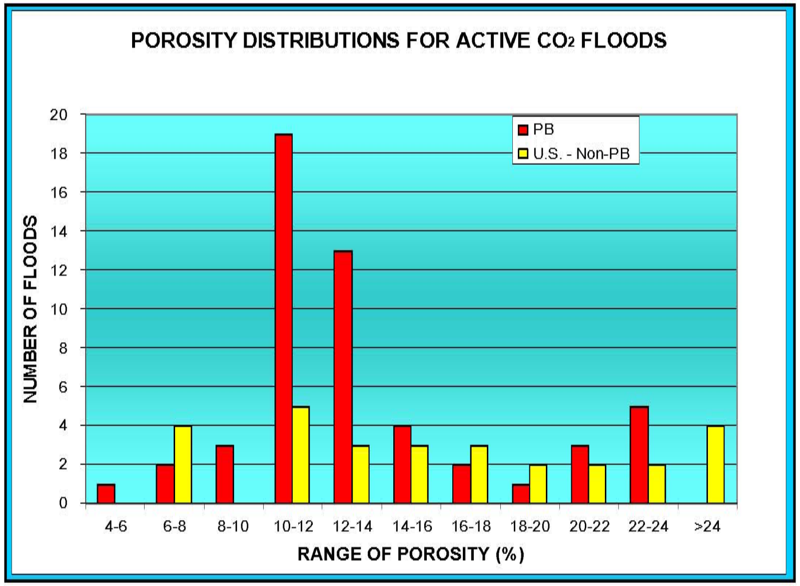
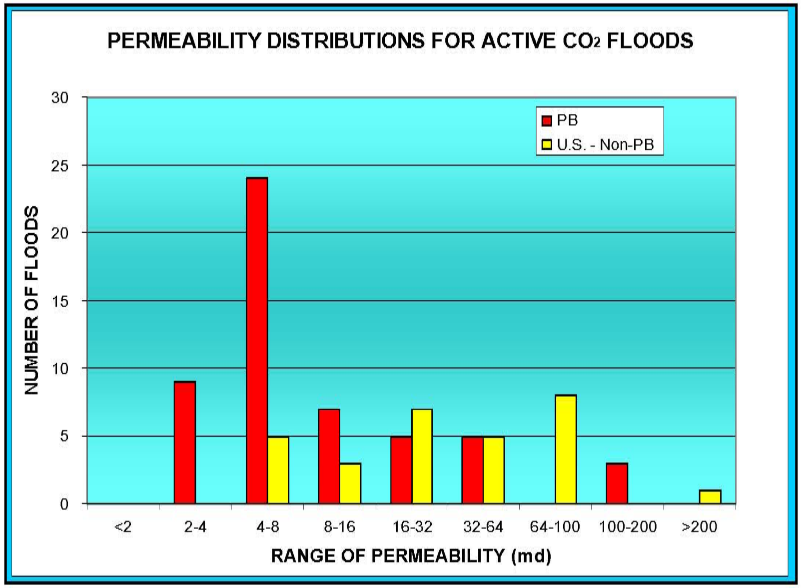
Porosity and Permeability Distribution of CO2 Projects


POROSITY DISTRIBUTIONS FOR ACTIVE CO_2 FLOODS


PERMEABILITY DISTRIBUTIONS FOR ACTIVE CO_2 FLOODS

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Concept of CO2 Utilization

- **A measure of the efficiency of a flood (Amount of CO2 needed to produce a barrel of oil)**

- **Is specified as NET or GROSS**
  - Net Utilization (new or purchased CO2)
  - Gross Utilization (Total purchased + recycle CO2)

- **Can be specified as instantaneous or cumulative**

CO2 Net Utilization Factors

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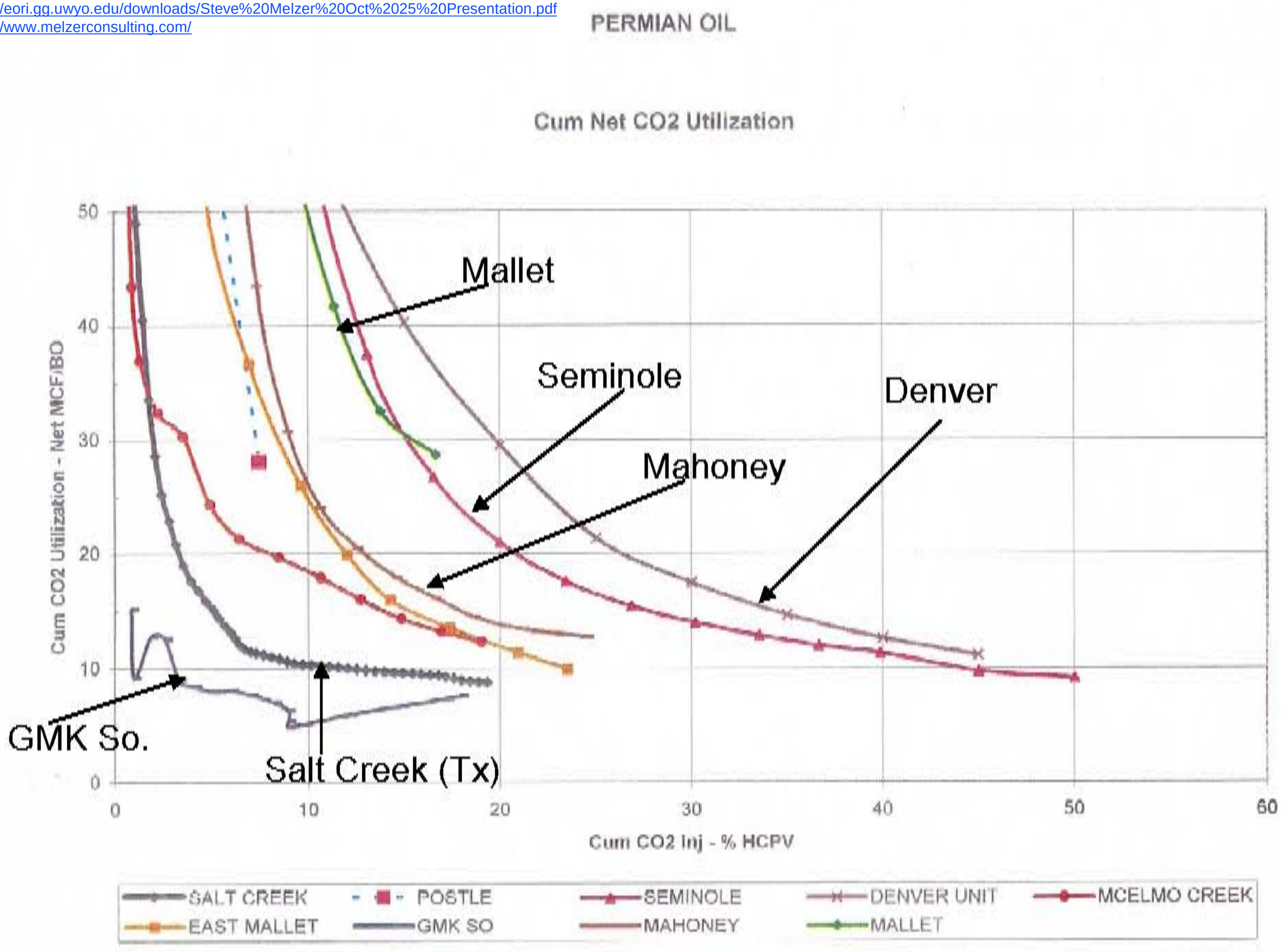
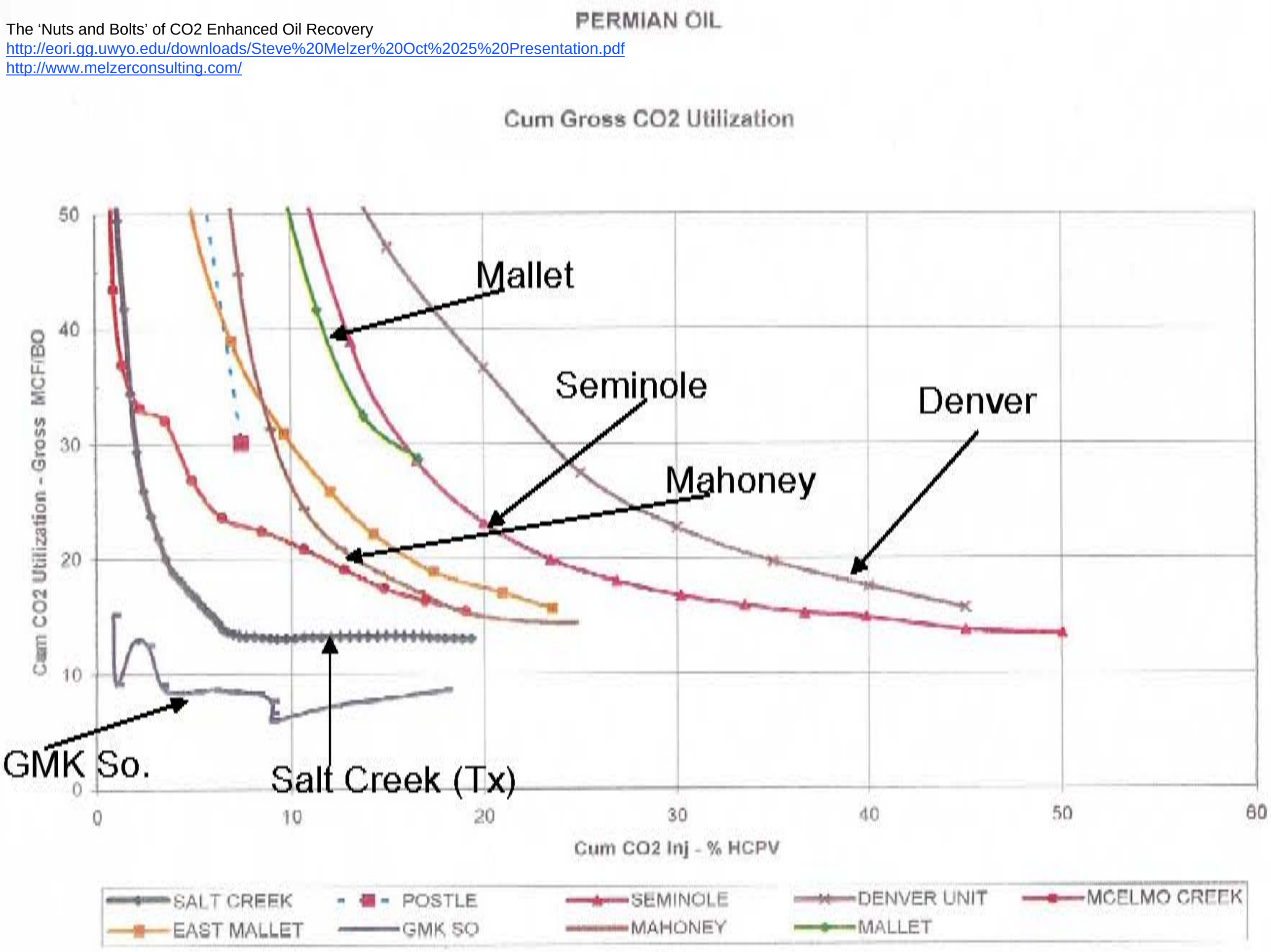


CO2 Cumulative Gross Utilization Factors



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CO2 Injection Methods

- **Continuous CO2 Injection – (currently practiced by Denbury Resources in MS)**
  - Continuously inject 100% CO2
  - Works better in more homogenous formations
- **WAG (Water Alternating Gas)**
- **Tapered WAG – (most common approach in Permian Basin)**
  - Start with continuous CO2 injection
  - Gradually increase WAG ratio as time goes on to optimize production of oil and CO2

WAG (Water Alternating Gas Injection)

- **Ratio varies from 1:2 to 3:1 but are usually on the order of 1:1**
- **Slug size usually on the order of 1% to 2% of pore volume**

- **Advantages:**
  - Control sweep efficiency by maintaining a more uniform flood front
  - Control CO2 recycle volumes
  - Facilitate management of produced gas and liquid ratios under both flowing and artificial lift status
  - Maximize profitablility

- **Drawbacks:**
  - Additional labor required
  - Water is ultimately detrimental to recovery mechanism
    - Decrease displacement efficiency
    - Water trapping of mobilized oil and CO2
  - Most WAG decisions involve balance between maximizing oil recovery and controlling Operating Costs associated with gas production

Methods for Improved Conformance when WAG not effective

- Surfactant Foams – worked in Lab but not found to be effective in field tests so far
- Gel Polymers – good for sealing thief zones in cemented wellbores
- Cement Squeezes
- Sand Plugbacks – used to stop fluid entry into lowest payzone and below the pay
- These techniques do not work well when there is crossflow between adjacent rock layers

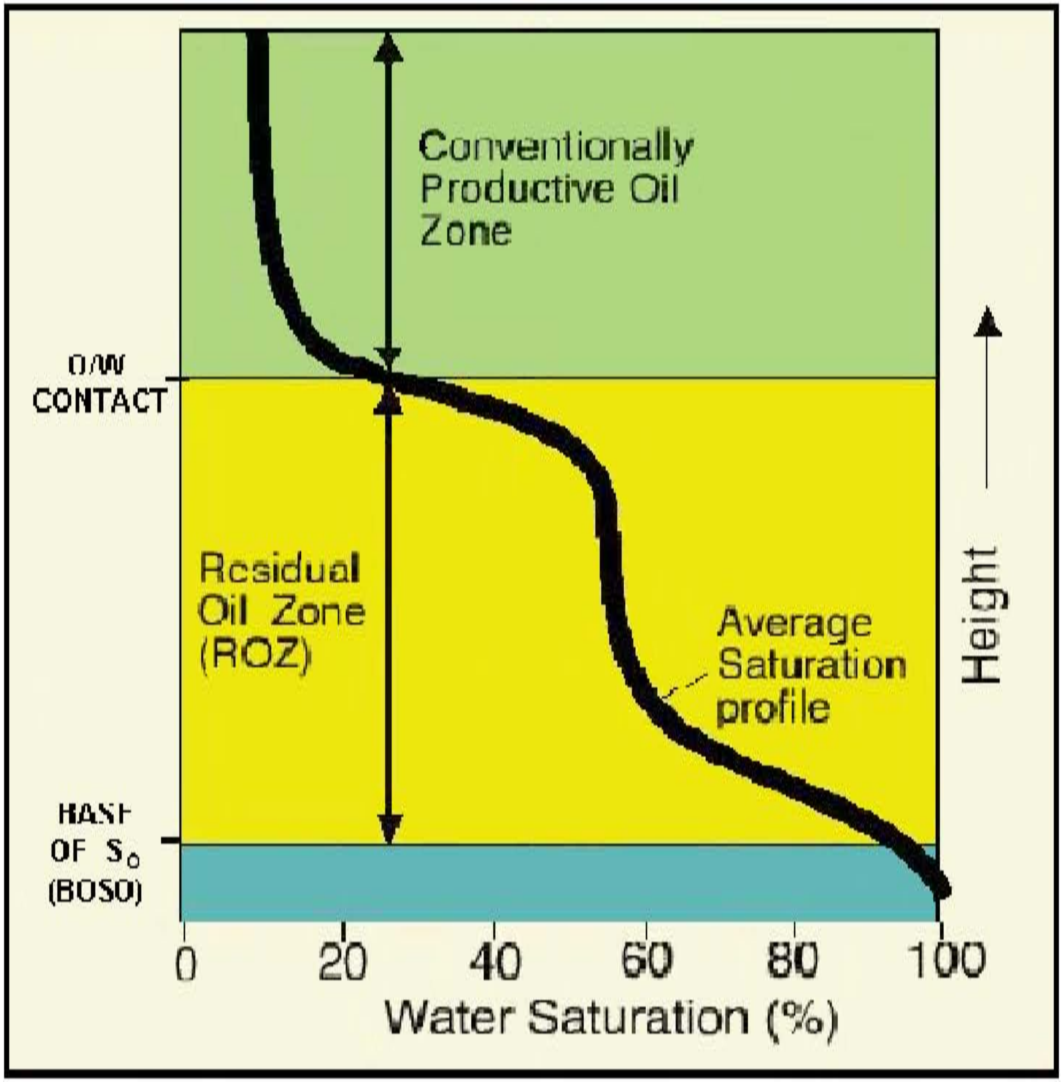
Gravity Stable Displacement

- Can work in steeply dipping reservoirs
- Can eliminate need for WAG to control conformance
- High recovery efficiency (60-70% OOIP)
- Injection rate is critical, must be maintained below critical gas velocity.
- Too high and oil is bypassed
- Problem is that in many cases, critical gas velocity is associated with an uneconomic level of oil production

Residual Oil Zones (ROZ)

- DEFINITION – Partially oil saturated intervals that produce non-commercial volumes of oil under primary or secondary production.
- Generally not completed or even drilled
- Analogous to waterflood swept intervals (basically residual oil saturation)
- Can be target for CO2 EOR when Sow > 20%
- Some ROZ’s may be of substantial thickness offering important targets for CO2 EOR
- Evidence for ROZ’s has been shown in Permian, Big Horn, Williston, and Powder River basins
- Modeling has shown that technically recoverable oil from ROZ is potentially greater than that of the main pay zone in certain areas

Water Saturation Profile showing ROZ



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Type 1 ROZ Formation – Regional Tilt

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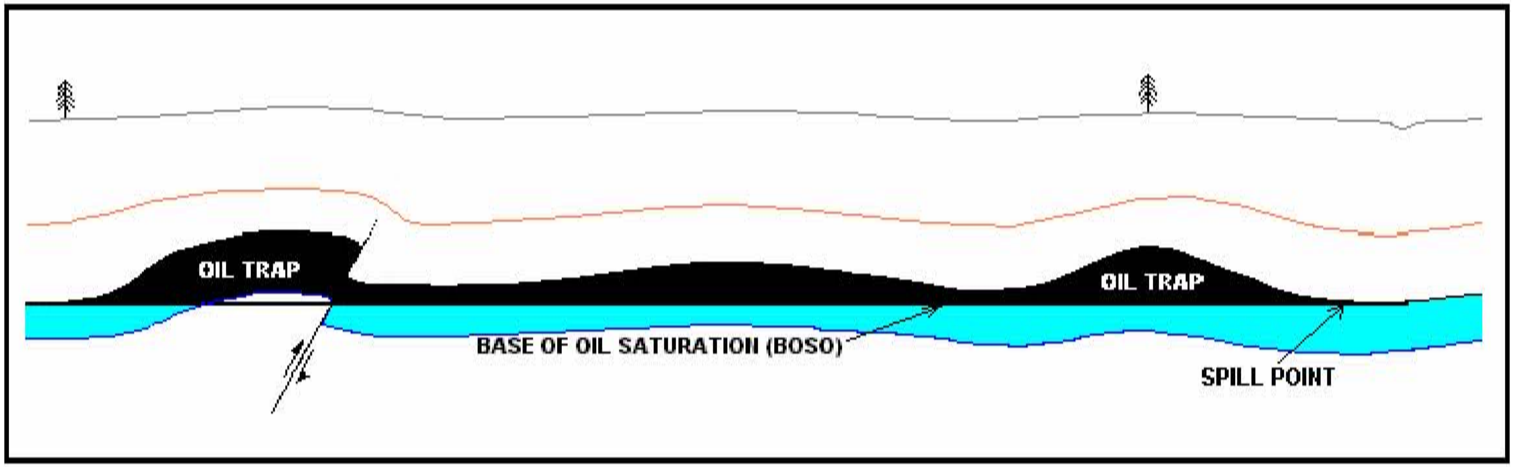
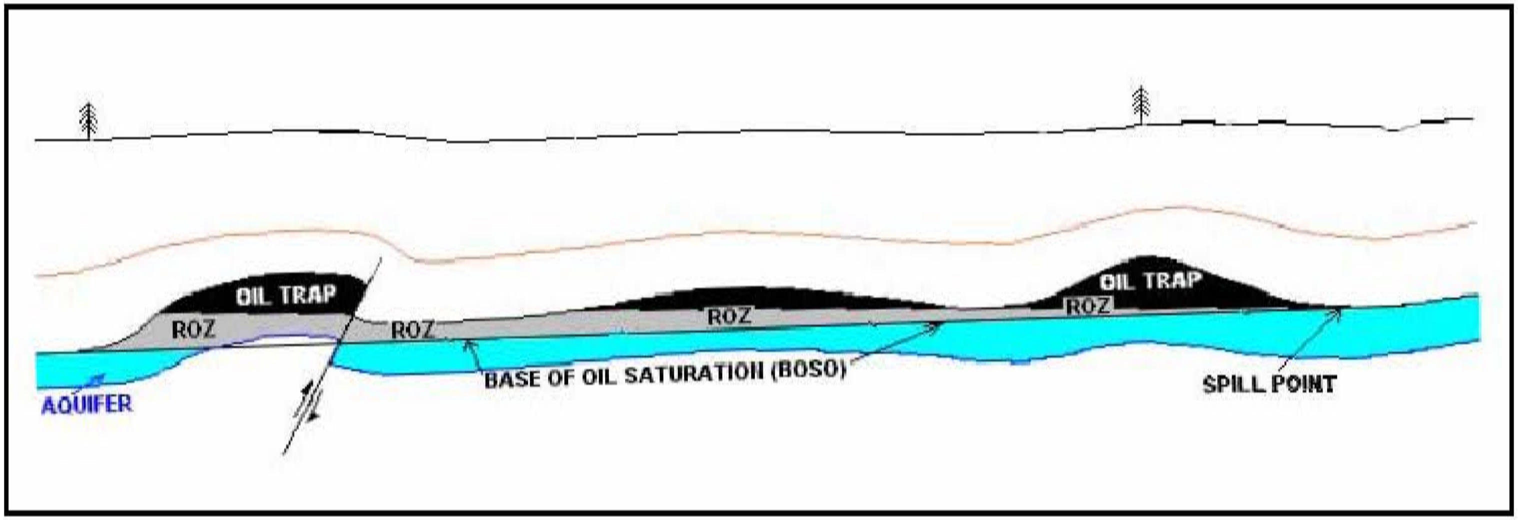
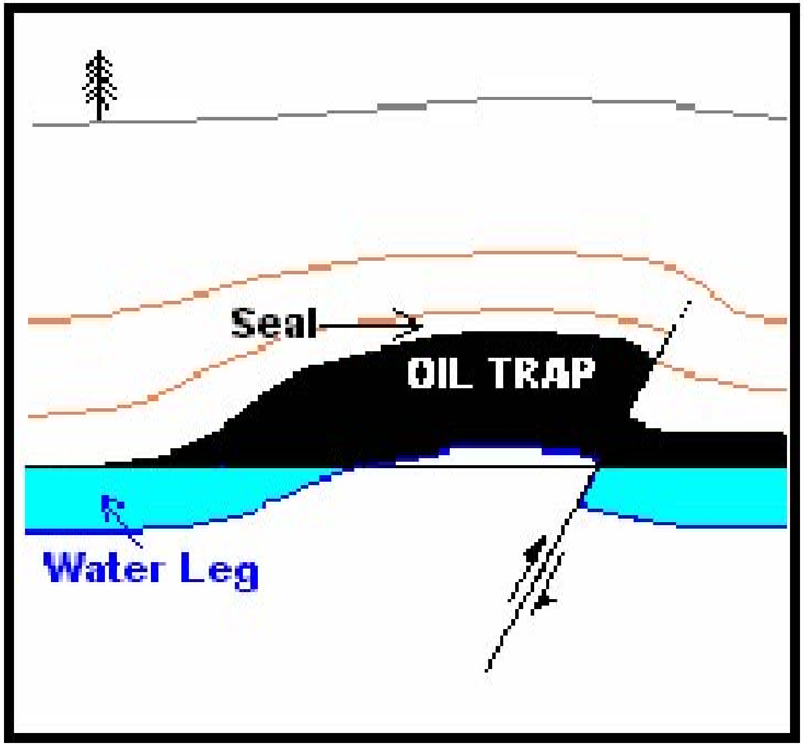
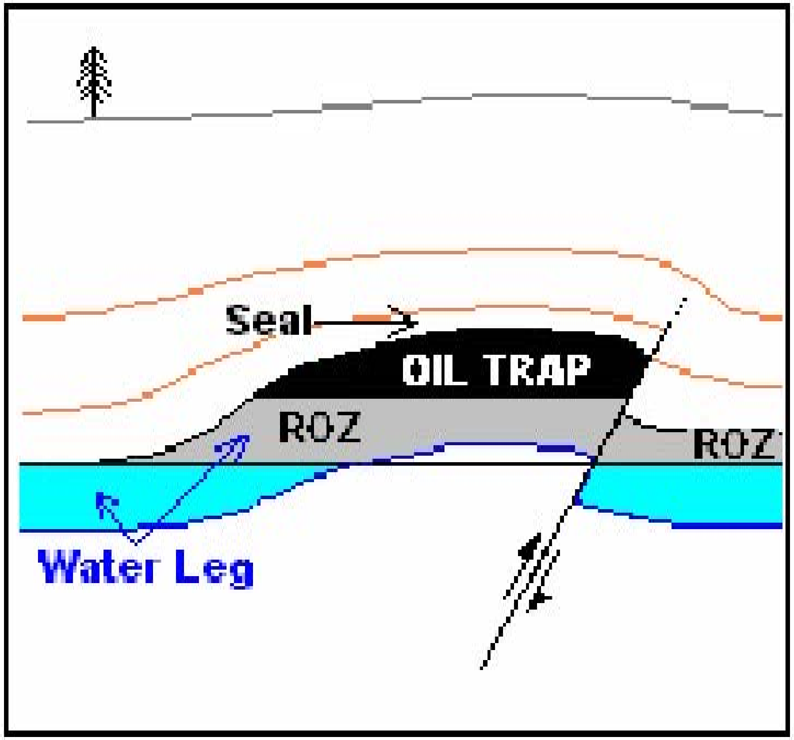




Type 2 ROZ Formation – Ruptured and Repaired Seal





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Type 3 ROZ Formation – Change in Hydrodynamic Conditions

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