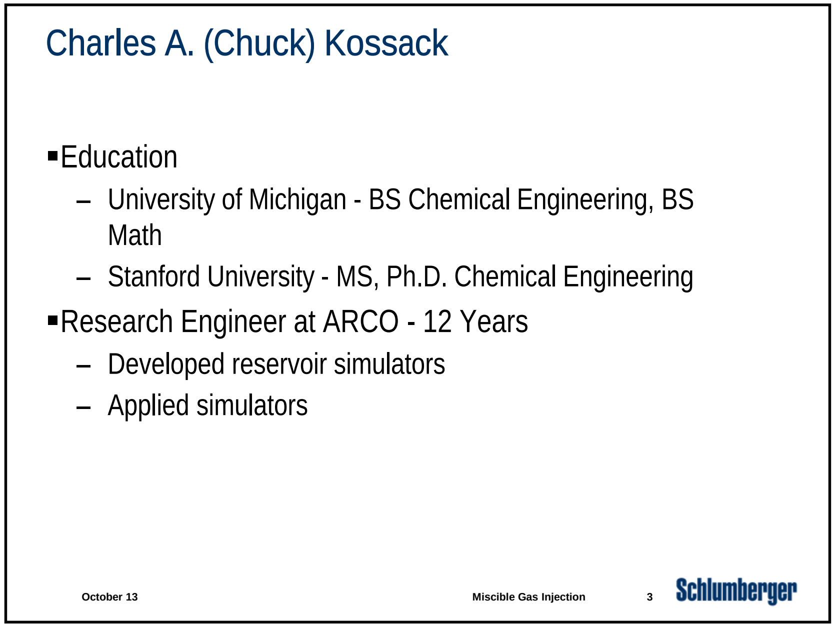
EOR Processes – Miscible Gas Injection

Miscible CO_2 and/or H-C Solvent Injection: Lecture

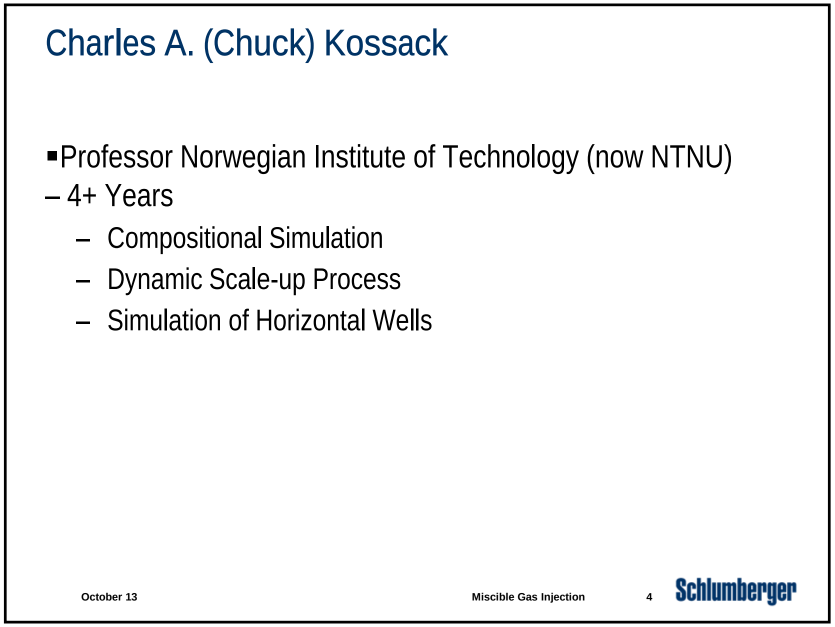
- Chuck Kossack, Ph.D.
- Schlumberger / SIS Training and Development
- Las Vegas, Nevada, USA

Charles A. (Chuck) Kossack



Charles A. (Chuck) Kossack

- Education
  - University of Michigan - BS Chemical Engineering, BS Math
  - Stanford University - MS, Ph.D. Chemical Engineering
- Research Engineer at ARCO - 12 Years
  - Developed reservoir simulators
  - Applied simulators



Charles A. (Chuck) Kossack

- Professor Norwegian Institute of Technology (now NTNU)

– 4+ Years
  - Compositional Simulation
  - Dynamic Scale-up Process
  - Simulation of Horizontal Wells

Charles A. (Chuck) Kossack

- Independent Consultant – 5+ Years
  - Norsk Hydro - Oslo, Norway
  - AGIP - Milan, Italy
  - BEB - Hanover, Germany
- Schlumberger - 17+ Years
  - GeoQuest: ECLIPSE Support
  - Consulting with GeoQuest Reservoir Technologies-Holditch-Reservoir Technologies - Now SIS Training and Development, Houston (live in Las Vegas)

Charles A. (Chuck) Kossack

Charles A. (Chuck) Kossack

- Courses Taught
- Applied Reservoir Simulation
- Equation Of State and PVT Analysis
- Compositional Simulation, Theory and Applications
- Simulation of Naturally Fractured Reservoirs
- Computer Aided History Matching Using MEPO

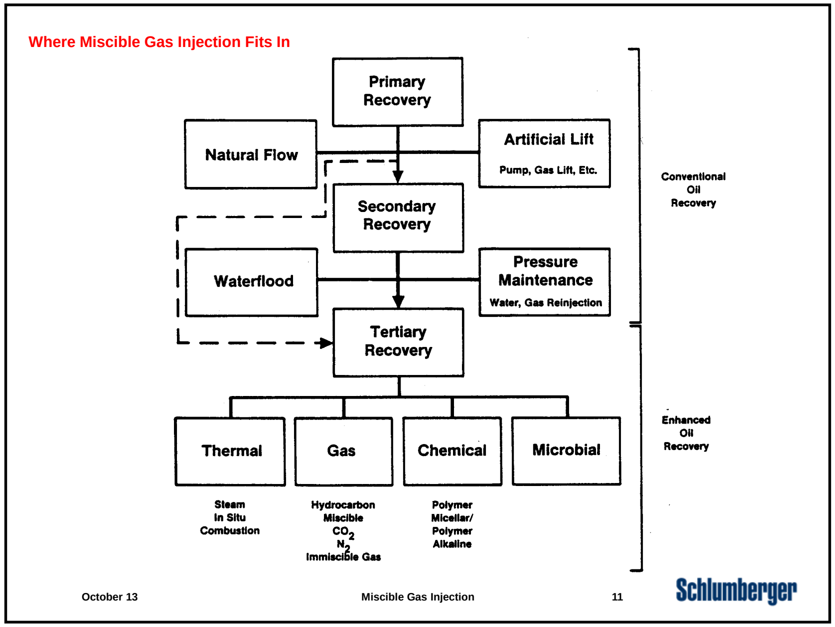
Charles A. (Chuck) Kossack

- Courses Taught
- Thermal Reservoir Simulation Using ECLIPSE
- Simulation of In-situ Combustion and Chemical Reactions Using ECLIPSE
- Simulation of Enhanced Oil Recovery Processes

Agenda

- Overview of EOR Processes
- Overview of Miscible/Immiscible Gas Injection
- Nitrogen / Flue Gas Injection
- Understand Vaporizing and Condensing Drive Mechanisms
- Understand Vaporizing/Condensing Mechanism
- CO_2 Properties
- CO_2 Injection into Oil Fields

Overview of EOR Processes



Where Miscible Gas Injection Fits In

Primary Recovery

Natural Flow

Artificial Lift
Pump, Gas Lift, Etc.

Secondary Recovery

Waterflood

Pressure Maintenance
Water, Gas Reinjection

Tertiary Recovery

Thermal
Steam
In Situ
Combustion

Gas
Hydrocarbon
Miscible
CO_2
N_2
Immiscible Gas

Chemical
Polymer
Micellar/
Polymer
Alkaline

Microbial

Conventional Oil Recovery

Enhanced Oil Recovery

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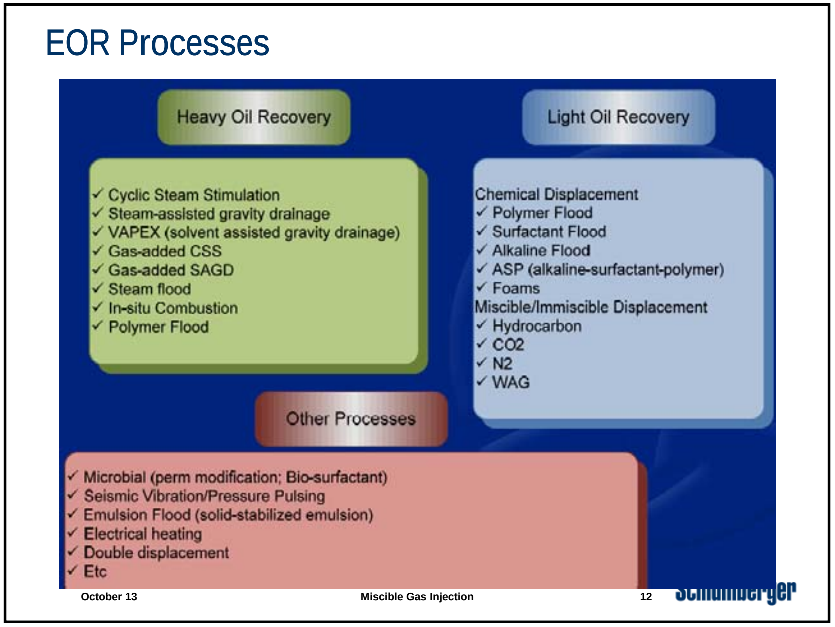


EOR Processes

Heavy Oil Recovery

- ✓ Cyclic Steam Stimulation
- ✓ Steam-assisted gravity drainage
- ✓ VAPEX (solvent assisted gravity drainage)
- ✓ Gas-added CSS
- ✓ Gas-added SAGD
- ✓ Steam flood
- ✓ In-situ Combustion
- ✓ Polymer Flood

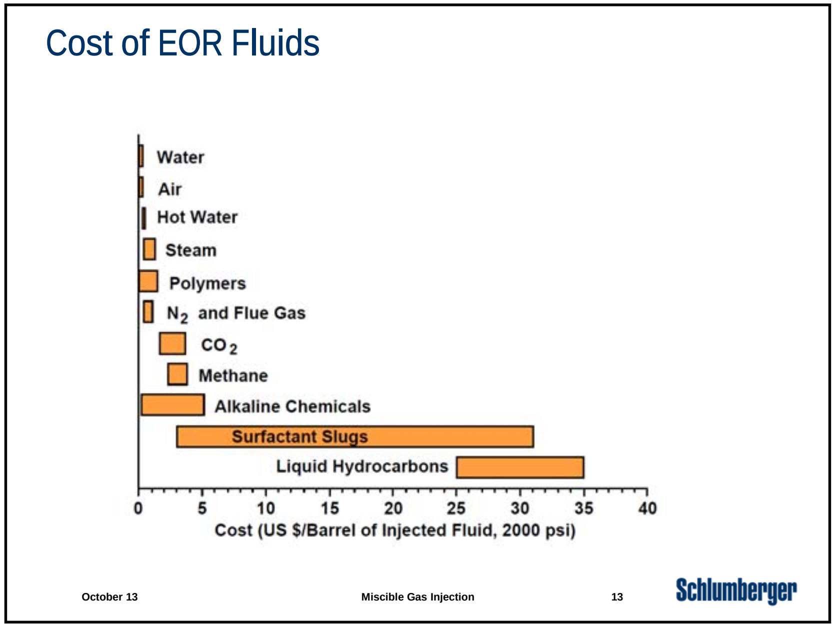
Light Oil Recovery

Chemical Displacement
- ✓ Polymer Flood
- ✓ Surfactant Flood
- ✓ Alkaline Flood
- ✓ ASP (alkaline-surfactant-polymer)
- ✓ Foams

Miscible/Immiscible Displacement
- ✓ Hydrocarbon
- ✓ CO2
- ✓ N2
- ✓ WAG

Other Processes

- ✓ Microbial (perm modification; Bio-surfactant)
- ✓ Seismic Vibration/Pressure Pulsing
- ✓ Emulsion Flood (solid-stabilized emulsion)
- ✓ Electrical heating
- ✓ Double displacement
- ✓ Etc



Cost of EOR Fluids

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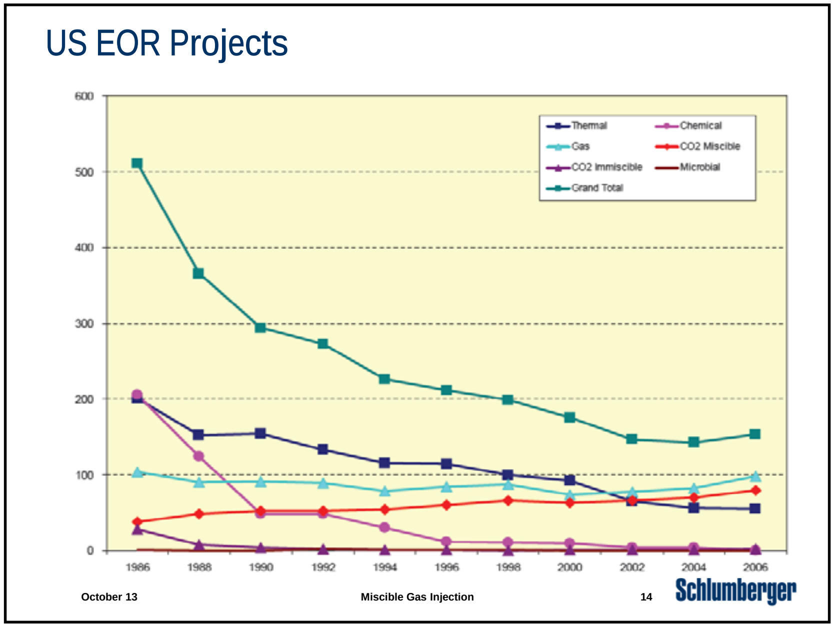

US EOR Projects

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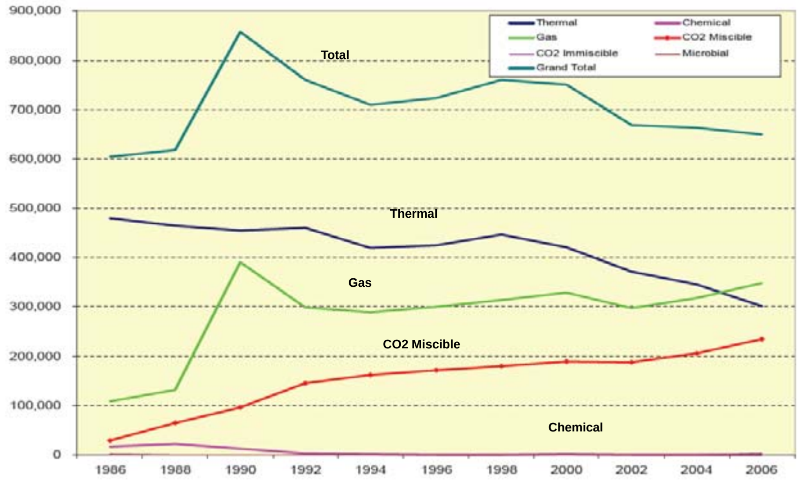
US EOR Production (STB)



Overview of Miscible/Immiscible Gas Injection

Choices of Injection Gas

- CO_2 (most of this lecture will concentrate on CO_2)
- N_2
- Methane – dry separator gas
- Methane + intermediate MW components (C_2, C_3, C_4…)
- Flue gas – $N_2 + CO_2 + CO$
- H_2S

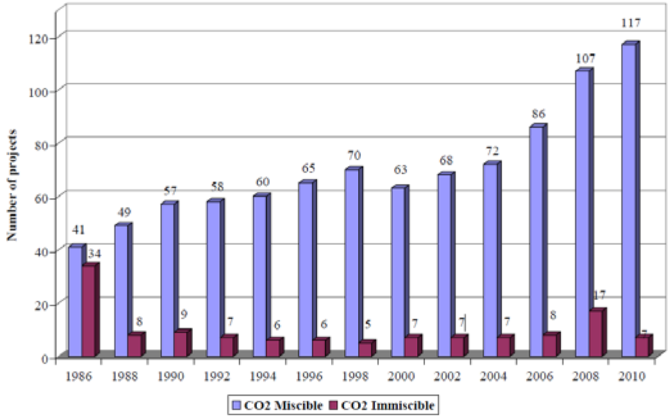
CO2 EOR: Where?

Latest CO2 Capture and EOR Projects

Project Name	Start Date	Location
Brindisi	2010	Italy
Husnes	2011	Norway
Plant Barry	2011	USA
Port Arthur	2012	USA
WA Parish	2013	USA
TCEP	2014	USA
Trailblazer	2014	USA
Kemper County	2014	USA
HECA	2014	USA
Bow City	2014	Canada
Longannet	2014	UK
Leucadia	2014	USA
Williston	2014	USA
Maasvlkte	2015	Netherlands
Boundary Dam	2015	Canada
NZEC	2015	China
Swan Hills	2015	Canada
Magnum	2015	Netherlands
Masdar CCS Project	Delayed	UAE

http://sequestration.mit.edu/tools/projects/index.html

CO2 EOR: How many projects?



Source: EOR Survey, OGJ, Apr 19, 2010

From: “CO_2-EOR Mobility and Conformance Control: 40 Years of Research and Pilot Tests” Dennis Denney, JPT January 2013

- USA CO_2 projects – 110 fields – 60% in Permian Basin in West Texas.
- Injecting 3.1 Bscf/day of CO_2 into sandstone and carbonate formations.
- Recovers 280,000 bbl of oil per day.
- Approximately 74.4% of EOR CO_2 comes from gas-treatment and –processing facilities from production of CO_2 rich natural gas.

From: “CO_2-EOR Mobility and Conformance Control: 40 Years of Research and Pilot Tests” Dennis Denney, JPT January 2013

- Approximately 19.4% of EOR CO_2 comes from natural gas plants.
- Approximately 4.8% of EOR CO_2 comes from coal-synfuel plants.
- Miscible-CO_2 floods typically recovers 10-20% of the OOIP (after primary and water flooding).
- Typical CO_2 injection volumes are 80% of the hydrocarbon pore volume (HCPV).

Read this paper or SPE 154122 for a good over view of CO_2 flooding

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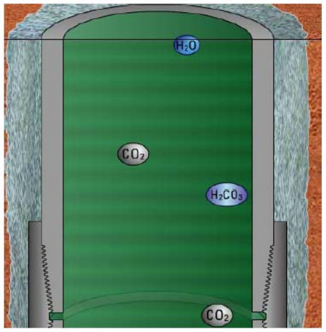
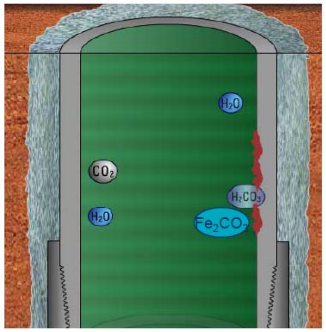
CO2 EOR: Why NOT do it?
Chemical Corrosion in Tubing



Carbon dioxide dissolved in water produces carbonic Acid



Carbonic acid reacts with steel to form a brittle siderite scale

Miscible Gas Flooding Limitations

- Minimum depth is set by the pressure needed to maintain the generated miscibility.
- The required pressure ranges from about 1,200 psi for the LPG process to 3,000-5,000 psi for the High Pressure Gas Drive, depending on the oil.
- A steeply dipping formation is very desirable -permits gravity stabilization of the displacement that normally has an unfavorable mobility ratio.

Miscible Gas Flooding Challenges

- Viscous fingering results in poor vertical and horizontal sweep efficiency.
- Large quantities of expensive products are required.
- Solvent may be trapped and not recovered.

Nitrogen / Flue Gas Injection

Nitrogen / Flue Gas Flooding Limitations

- Miscibility can only be achieved with light oils at high pressures; therefore, deep reservoirs are needed.
- A steeply dipping reservoir is desired to permit gravity stabilization of the displacement, which has a very unfavorable mobility ratio.

Nitrogen / Flue Gas Flooding Challenges

- Viscous fingering results in poor vertical and horizontal sweep efficiency.
- Flue gas injection can cause corrosion.
- Non hydrocarbon gases must be separated from saleable gas

Understand Vaporizing and Condensing Drive Mechanisms

Compositional Processes

First Contact Miscible

- LPG slugs - designed to achieve first - contact miscibility with oil at leading edge of slug and with driving gas at trailing edge

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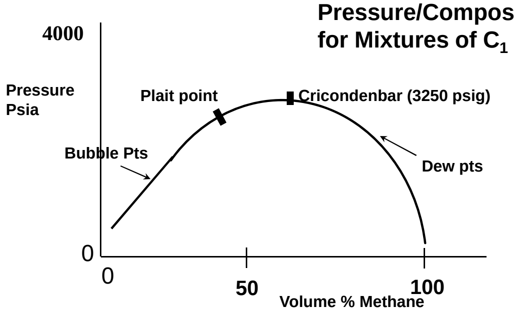
Compositional Processes

Example Oil: **C_1 - 31%**
nC_4 - 55%
C_{10} - 14%

Injection gas: C_1



Pressure/Composition Diagram for Mixtures of C_1 with $C_1/nC_4/C_{10}$ Oil.

Compositional Processes

Rule: For 1st Contact Miscible - Pressure of Displacement must be above Cricondenbar

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Condensing - Gas Drive Process

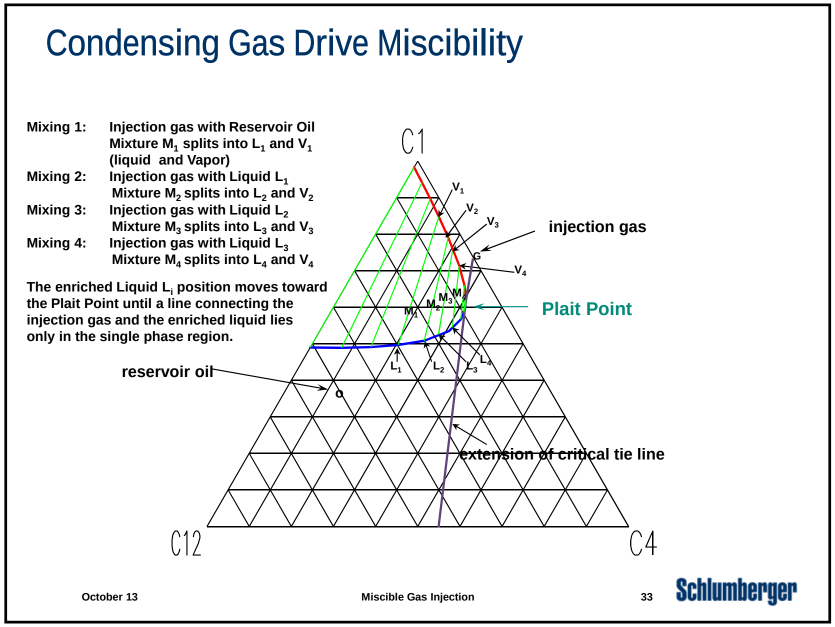
Injection gas is enriched with intermediate components such as:

C_2, C_3, C_4 etc

Mechanism:

Phase transfer of intermediate MW hydrocarbons from the injected gas into the oil. Some of the gas "*condenses*" into the oil.

The reservoir oil becomes so enriched with these materials that miscibility results between the injection gas and the enriched oil.



Condensing Gas Drive Miscibility

Mixing 1: Injection gas with Reservoir Oil
Mixture M_1 splits into L_1 and V_1
(liquid and Vapor)

Mixing 2: Injection gas with Liquid L_1
Mixture M_2 splits into L_2 and V_2

Mixing 3: Injection gas with Liquid L_2
Mixture M_3 splits into L_3 and V_3

Mixing 4: Injection gas with Liquid L_3
Mixture M_4 splits into L_4 and V_4

The enriched Liquid L_i position moves toward the Plait Point until a line connecting the injection gas and the enriched liquid lies only in the single phase region.

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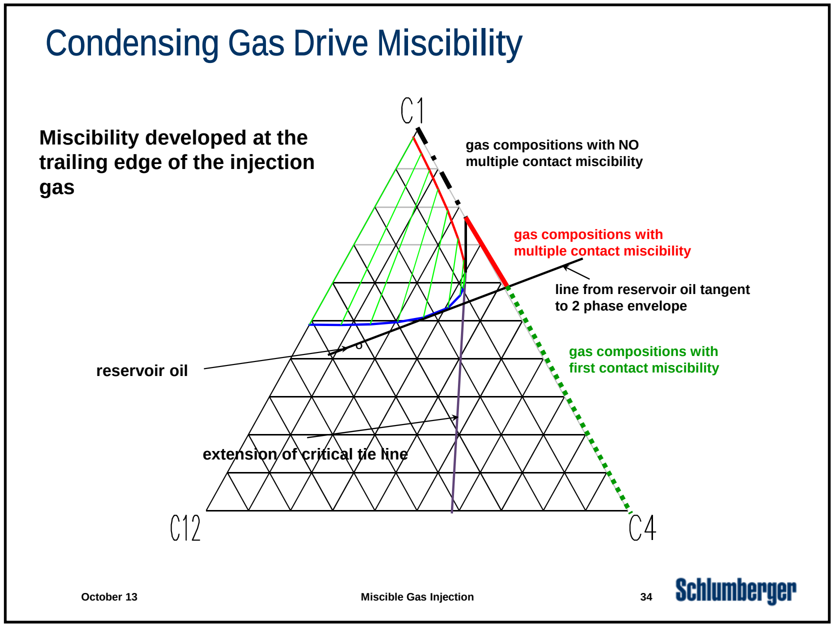

Condensing Gas Drive Miscibility

Miscibility developed at the trailing edge of the injection gas

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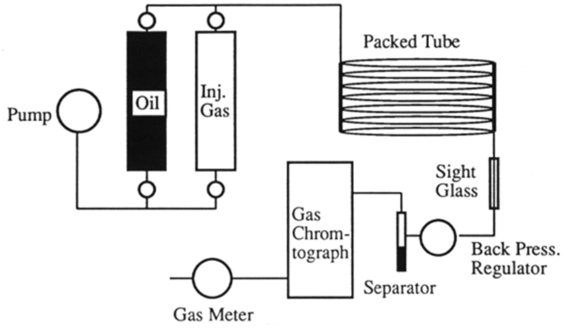
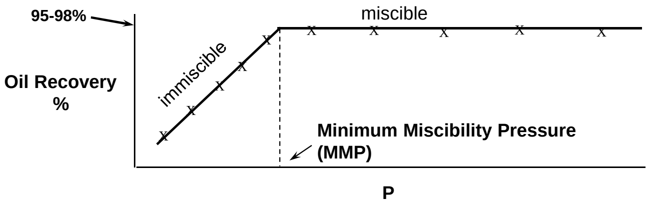
Slim Tube Apparatus



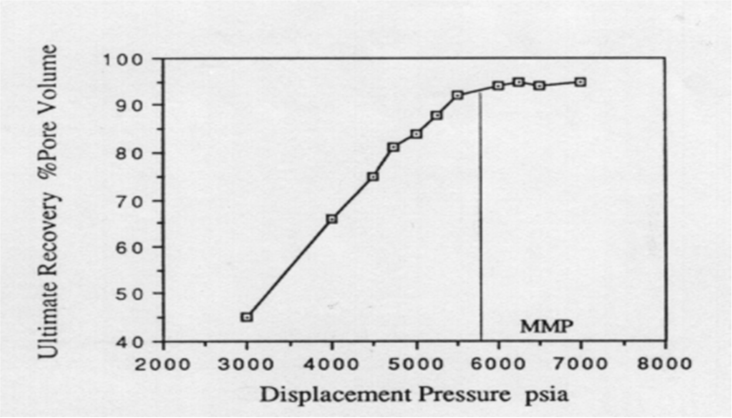
Condensing - Gas Drive Process

As P increases the two phase region becomes smaller. At some point gas A is to the right of the limiting tie line and MCM develops.



Results from slim tube displacements at various pressures

Slim Tube Recovery of a North Sea Oil at 100º C



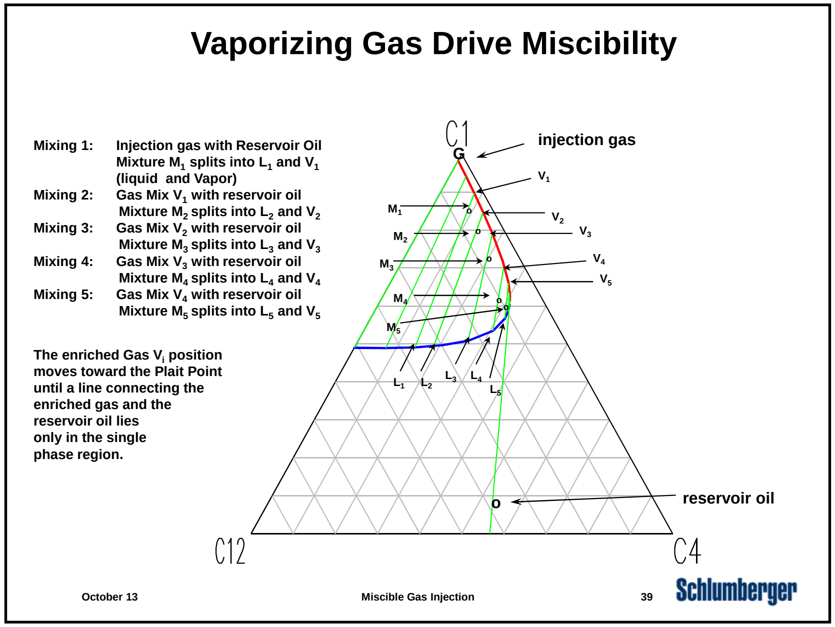
Vaporizing Gas Drive Process

Injection Gas - Lean Gas, C_1, CO_2, N_2

For vaporizing gas drive - multiple contact miscibility

Mechanism: Intermediate hydrocarbon components in the oil *vaporize* to enrich the gas.

As the leading edge of the gas slug becomes sufficiently enriched, it becomes miscible with the reservoir oil.



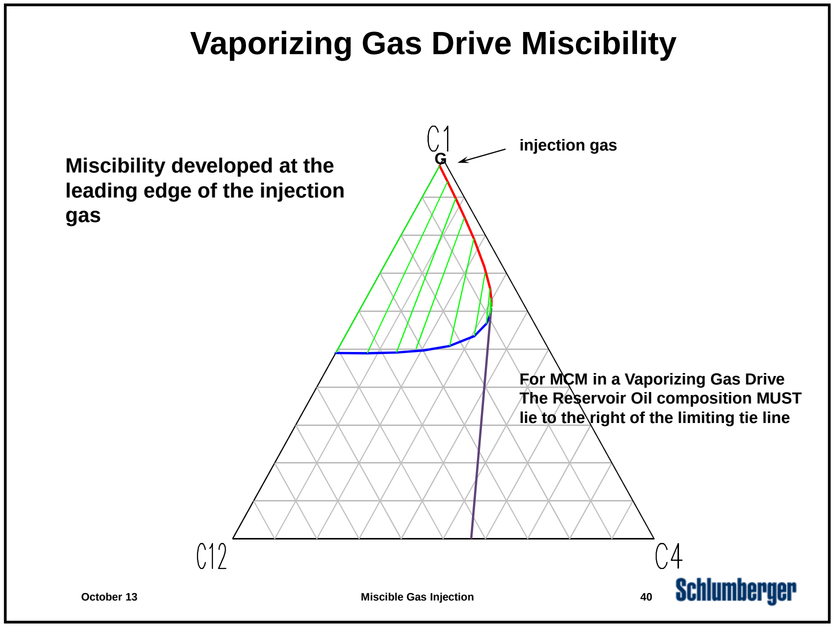
Vaporizing Gas Drive Miscibility

Mixing 1: Injection gas with Reservoir Oil
Mixture M_1 splits into L_1 and V_1
(liquid and Vapor)
Mixing 2: Gas Mix V_1 with reservoir oil
Mixture M_2 splits into L_2 and V_2
Mixing 3: Gas Mix V_2 with reservoir oil
Mixture M_3 splits into L_3 and V_3
Mixing 4: Gas Mix V_3 with reservoir oil
Mixture M_4 splits into L_4 and V_4
Mixing 5: Gas Mix V_4 with reservoir oil
Mixture M_5 splits into L_5 and V_5

The enriched Gas V_i position moves toward the Plait Point until a line connecting the enriched gas and the reservoir oil lies only in the single phase region.

injection gas

reservoir oil



Vaporizing Gas Drive Miscibility

Miscibility developed at the leading edge of the injection gas

injection gas

For MCM in a Vaporizing Gas Drive
The Reservoir Oil composition MUST
lie to the right of the limiting tie line

Understand Vaporizing/Condensing Drive Mechanism

ECLIPSE Compositional Simulation of Condensing/Vaporizing Gas Drive

- From Aaron Zick's and Fred Stalkup's SPE Papers
  - SPE15493
  - SPE16715
  - SPE18060

Reservoir Fluid A

12 component characterization:

component	mole fraction
CO2	0.0699
C1	0.4146
C2	0.054
C3	0.036
C4	0.0245
C5	0.0173
C6+	0.0411
C7+	0.0781
C11+	0.0716
C15+	0.0635
C20+	0.0586
C30+	0.0708

Condensing/Vaporizing Gas Drive

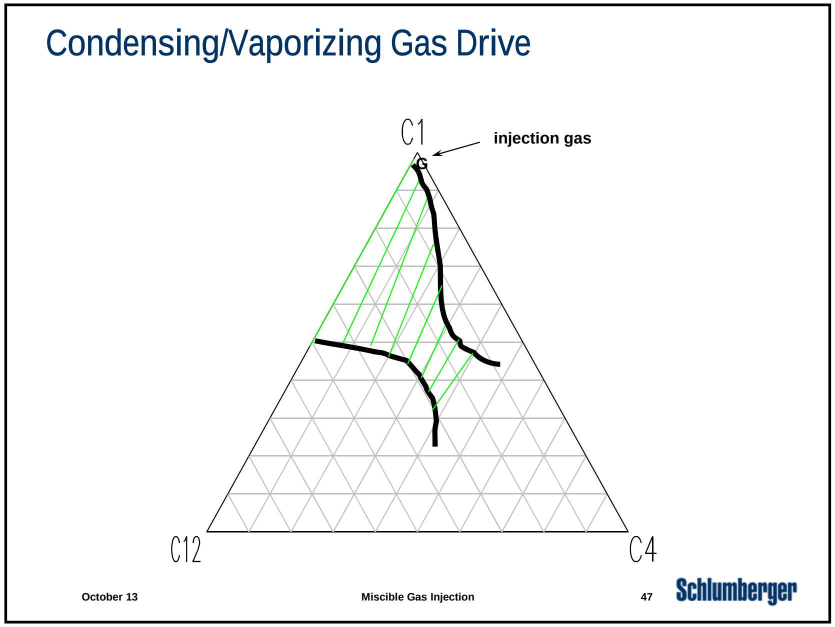
- Vaporizing gas drive not strictly valid for real reservoir fluids
- Injection gas does not generally contain middle heavy fractions which are present in the oil
- More realistic process is called Condensing/Vaporizing Gas Drive since contains some of both processes

Condensing/Vaporizing Gas Drive

- Injection gas enriches the oil in the light intermediate range
- Also, it strips the heavier intermediate fractions
- Thus, reservoir in contact with fresh gas initially becomes lighter, but as it contacts more fresh gas it continues to lose the middle intermediates, it tends to get heavier

Condensing/Vaporizing Gas Drive

- This heavier oil becomes LESS miscible with the injection gas
- The bubble point and the dew point curves on the pseudo ternary diagram initially converge and then diverge



Condensing/Vaporizing Gas Drive

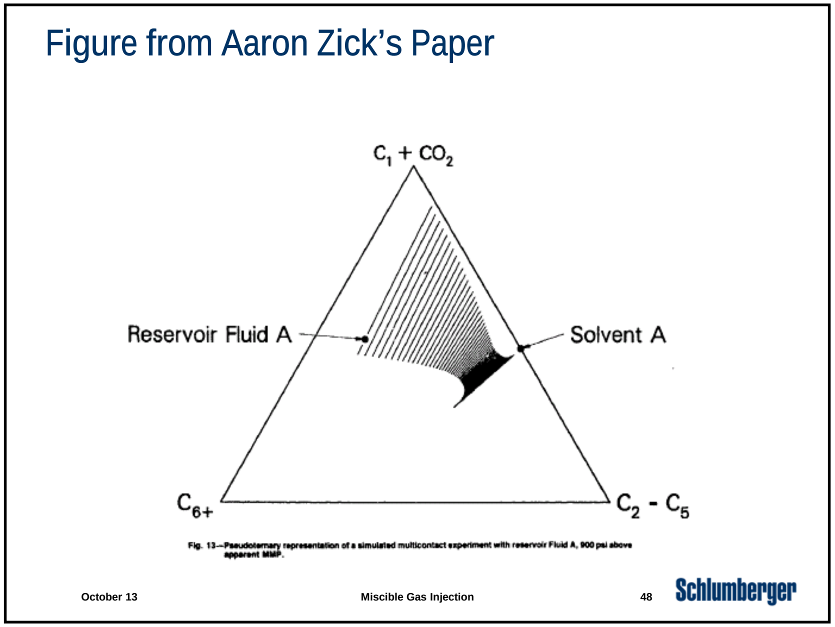


Figure from Aaron Zick's Paper

Fig. 13—Pseudoternary representation of a simulated multicontact experiment with reservoir Fluid A, 900 psi above apparent MMP.

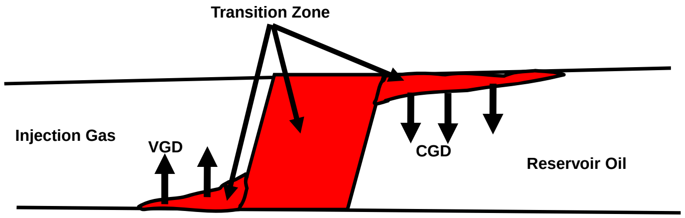
Condensing/Vaporizing Gas Drive

- Fresh gas that moves through will be rich in light intermediates (oil already saturated with these) and intermediate heavies – so richer than original gas
- When this gas contacts fresh oil original the acquired heavier intermediates will condense

Condensing/Vaporizing Gas Drive

- In Real situation miscibility (or near miscibility) achieved within a transition zone
- Front of transition zone = Condensing Gas Drive (CGD)
- Tail of transition zone = Vaporizing Gas Drive (VGD)

Condensing/Vaporizing Gas Drive

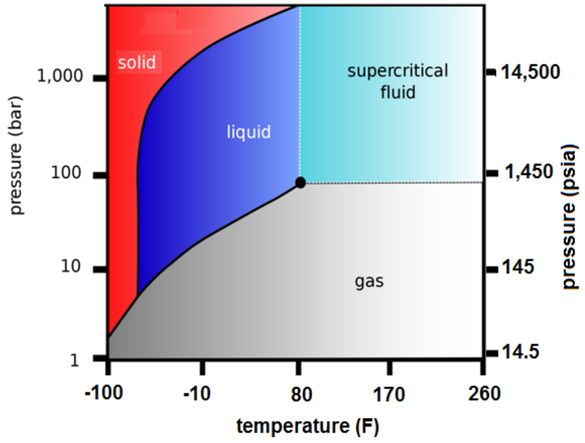


CO_2 Properties

CO_2

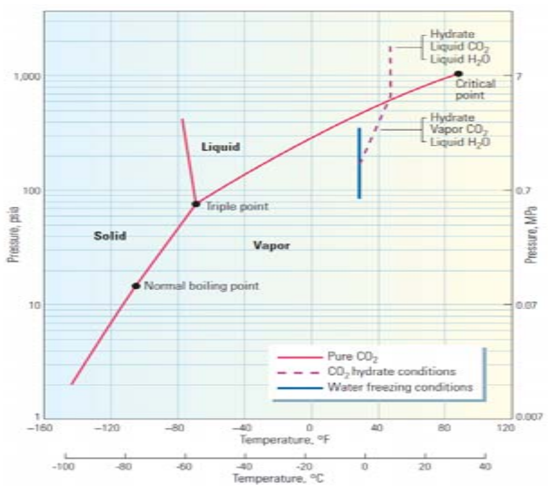
- Stable non toxic compound
- Found in gaseous state at standard conditions
- For petroleum applications
  - A gas or liquid like supercritical fluid

Pure CO_2 Phase Behavior

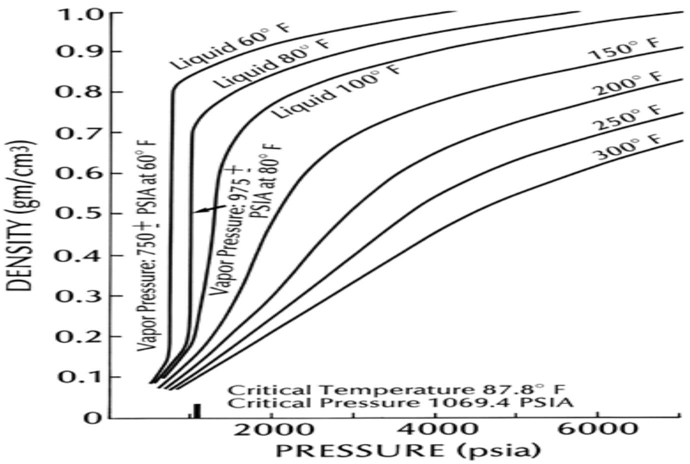


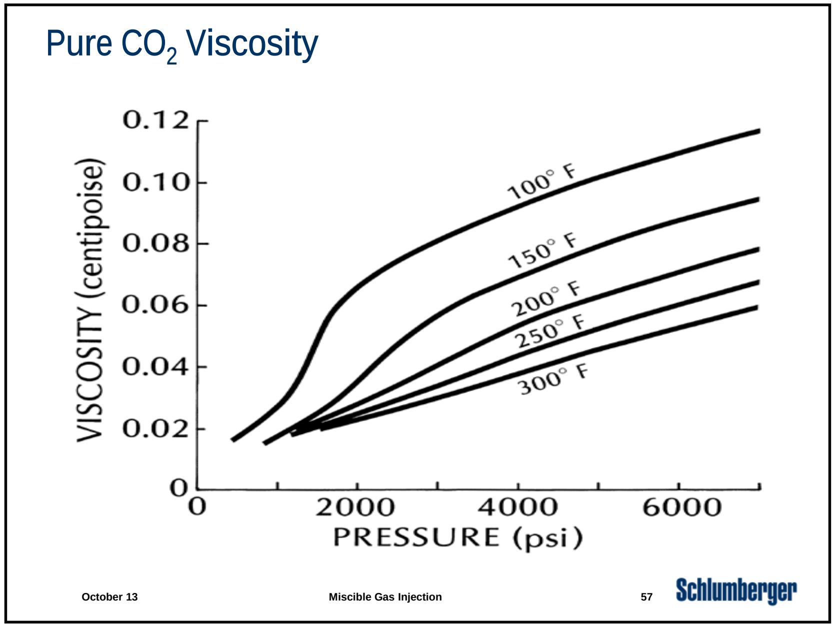
Tc = 31°C (88 F)
Pc = 75 bar (1085 psi)

Pure CO_2 Phase Behavior

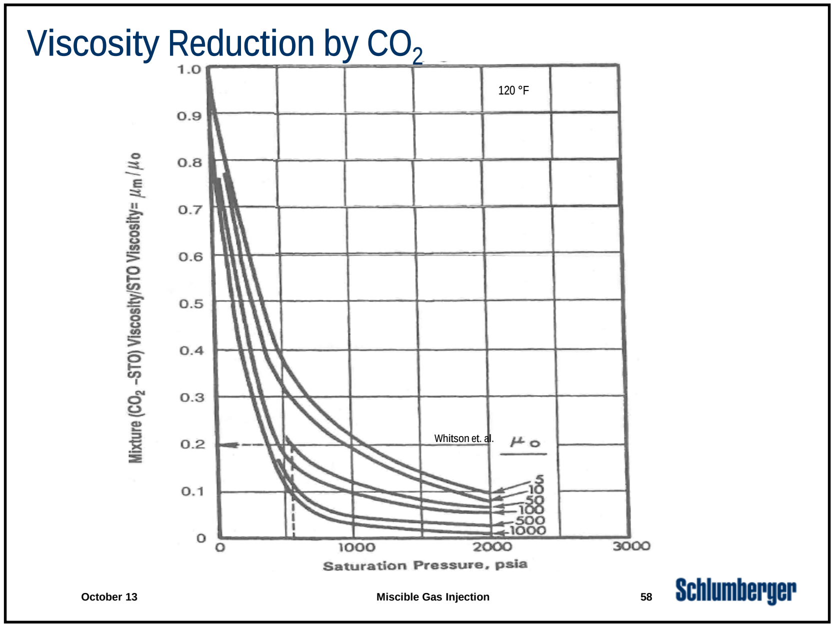


Pure CO_2 Density





Pure CO_2 Viscosity



Viscosity Reduction by CO_2

Comments on Contaminated CO_2

- Pure CO_2 often not available
- Contamination with CH_4 increases miscibility pressure
- Contamination with H_2S lowers miscibility pressure, but…
  - Many problems due to corrosion and health hazards

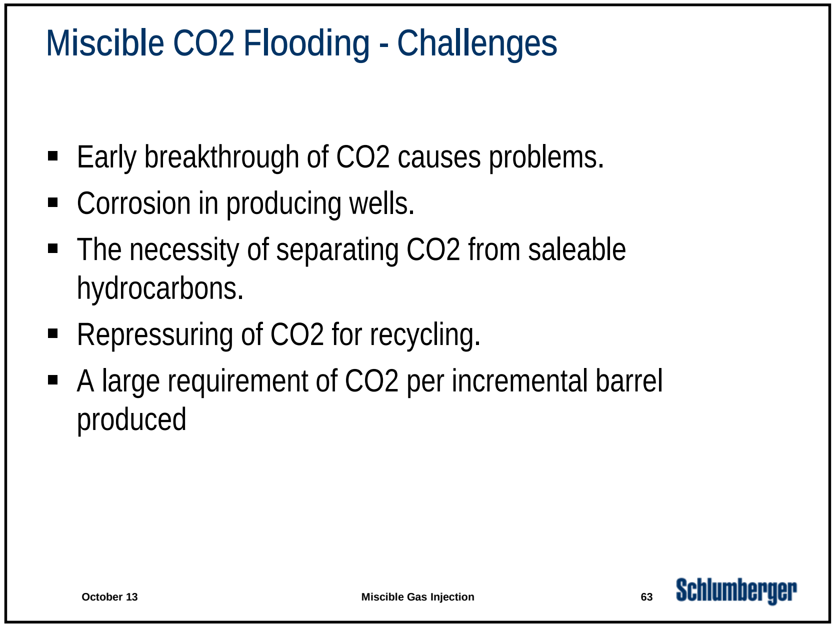
CO_2 Injection into Oil Fields

Brief History of CO_2 EOR

- 1960's - First successful field test (Mead Strawn, TX)
- 1970's - First full-scale floods (SACROC, North Cross)
- 1980's - Development of natural CO_2 sources in Colorado and New Mexico
  - Number of new projects (some outside Permian Basin & U.S.)
  - Significant effort on laboratory and pilot studies
- 1990's - Implementation of new projects with heavy

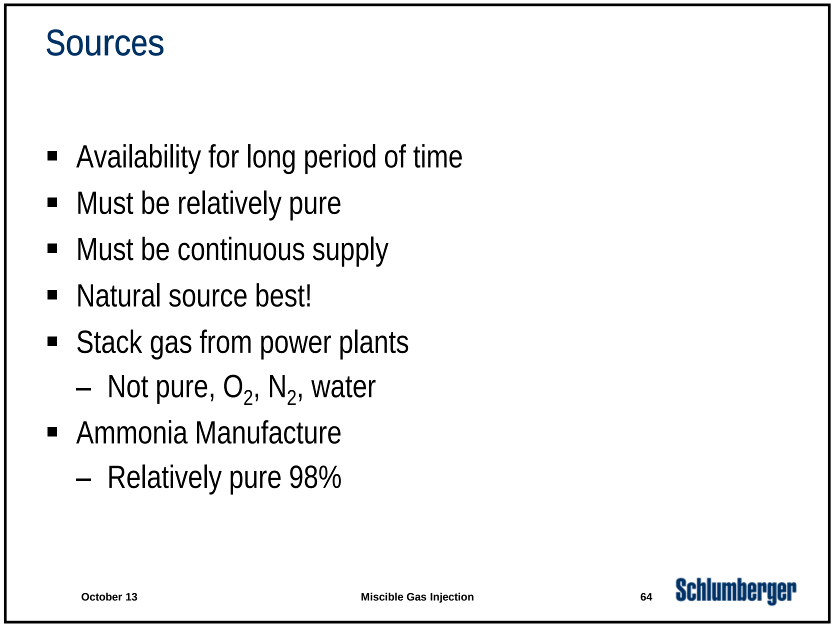
Miscible CO2 Flooding - Limitations

- Very low viscosity of CO2 results in poor mobility control.
- Availability of CO2 –Source?
- Surface Facilities



Miscible CO2 Flooding - Challenges

- Early breakthrough of CO2 causes problems.
- Corrosion in producing wells.
- The necessity of separating CO2 from saleable hydrocarbons.
- Repressuring of CO2 for recycling.
- A large requirement of CO2 per incremental barrel produced



Sources

- Availability for long period of time
- Must be relatively pure
- Must be continuous supply
- Natural source best!
- Stack gas from power plants
  - Not pure, O_2, N_2, water
- Ammonia Manufacture
  - Relatively pure 98%

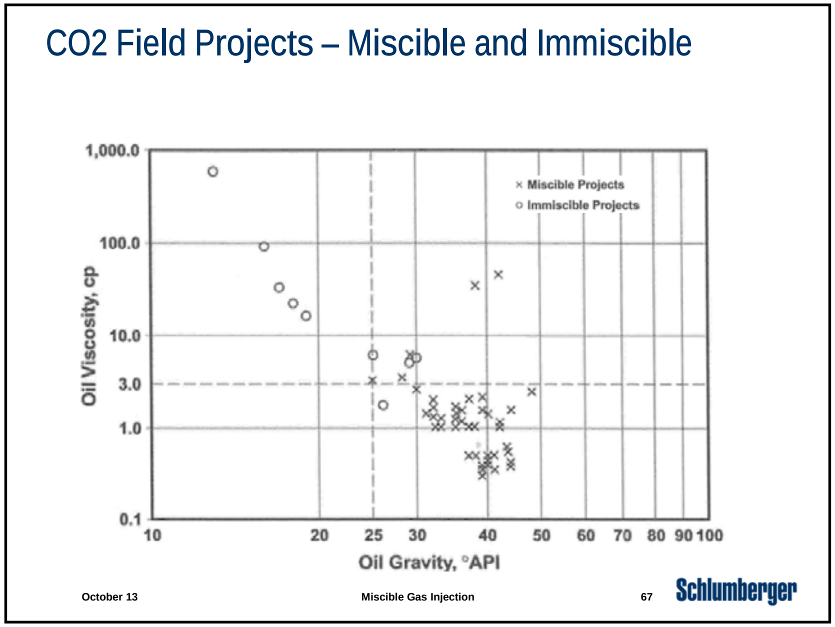
Conditions for CO_2 Flooding

- Stock tank oil gravity: 15º to 45º API
- Reservoir temperature: 80 – 300 ºF
- Reservoir Pressure: 1,000 - > 4,000 psia

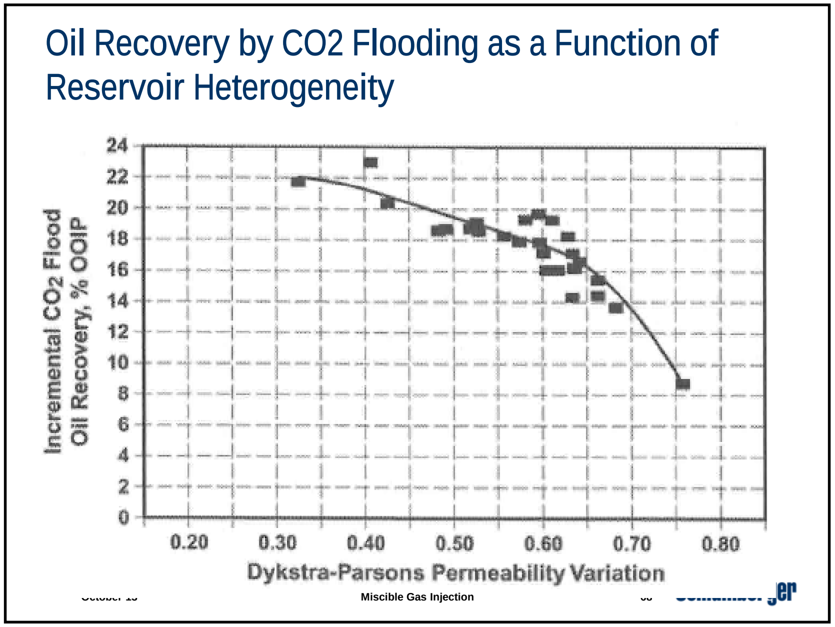
- Sandstone & Carbonate reservoirs
- Thickness <10’ to 100s’

Screening Reservoirs for CO_2 Miscible EOR

- Oil Properties
  - API Gravity: > 25, Ideal 36
  - Viscosity : < 10 cp, Ideal < 1.5 cp
  - Composition: High percentage of C_5 and C_{12}
- Reservoir Properties
  - Depth: >2500 ft
  - Pressure: > 1500 psi (P_{res}>MMP ; $P_{inj} < P_{frac}$)
  - Temperature: Low enough for miscibility
  - Gas Cap: Small to none.
  - Heterogeneity: Low
  - Oil Saturation: >20%, Ideal >55%
  - Permeability: > 1 mD
  - Formation Type: Carbonate or sandstone
- Site
  - Large volumes of CO_2 are available



CO2 Field Projects – Miscible and Immiscible

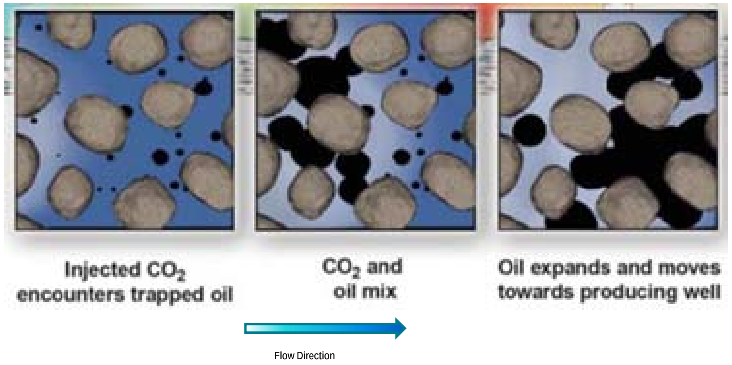


Oil Recovery by CO2 Flooding as a Function of Reservoir Heterogeneity

Recovery Mechanisms for CO_2 Flooding

- Swelling of crude oil
- Reduction of crude oil viscosity
- Vaporization of intermediate and heavy hydrocarbons ($C_5 – C_{30}$)
- Multi-contact miscibility
- Interfacial tension lowering (miscibility)
- Internal solution gas drive.

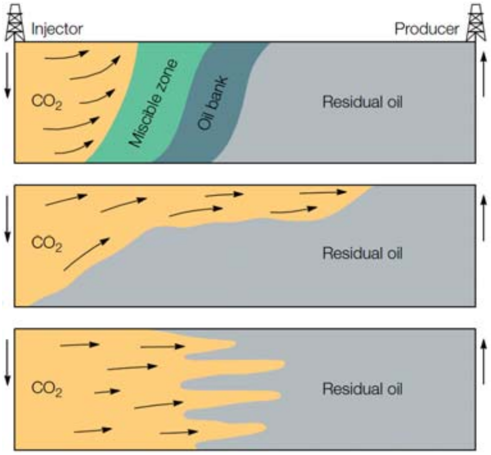
Mechanisms for CO_2



Problems with Gas Injection into Oil Reservoirs

- Density differences
- Viscosity differences

Reduced Sweep Due to Density and Viscosity Contrast



Ideal Case

Density Contrast

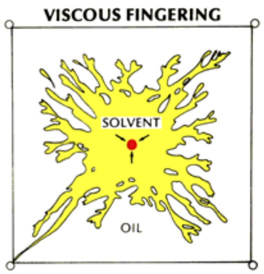
Viscosity Contrast

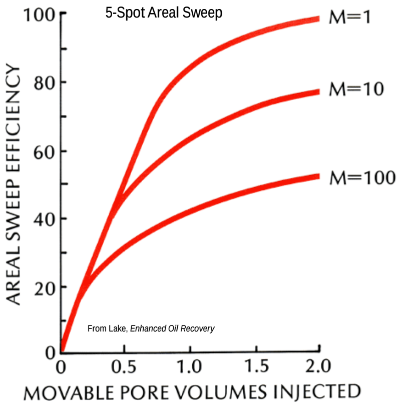
Reduced Sweep due to Viscosity Contrast

The Mobility Ratio

$$M \equiv \frac{\text{Mobility of Displacing Fluid}}{\text{Mobility of Displaced Fluid}}$$

$$Mobility = \frac{\text{Relative Permeabilty}}{\text{Viscosity}}$$





From Lake, *Enhanced Oil Recovery*

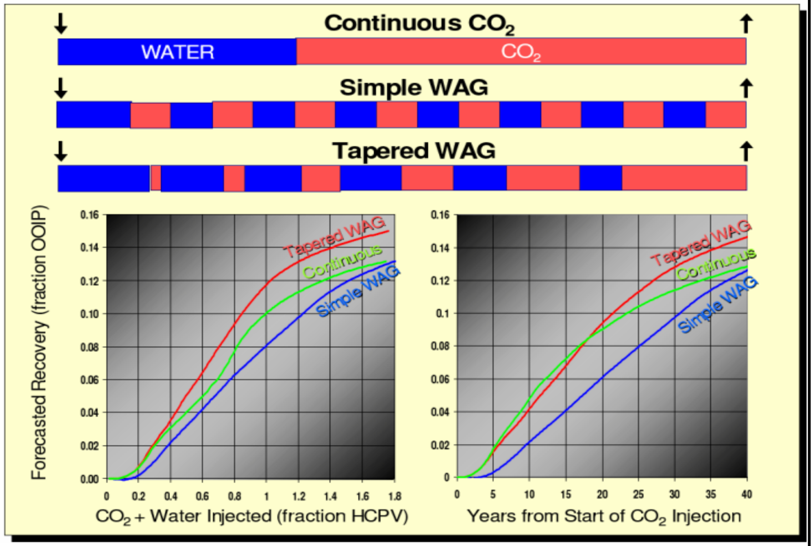
Displacement Mechanisms

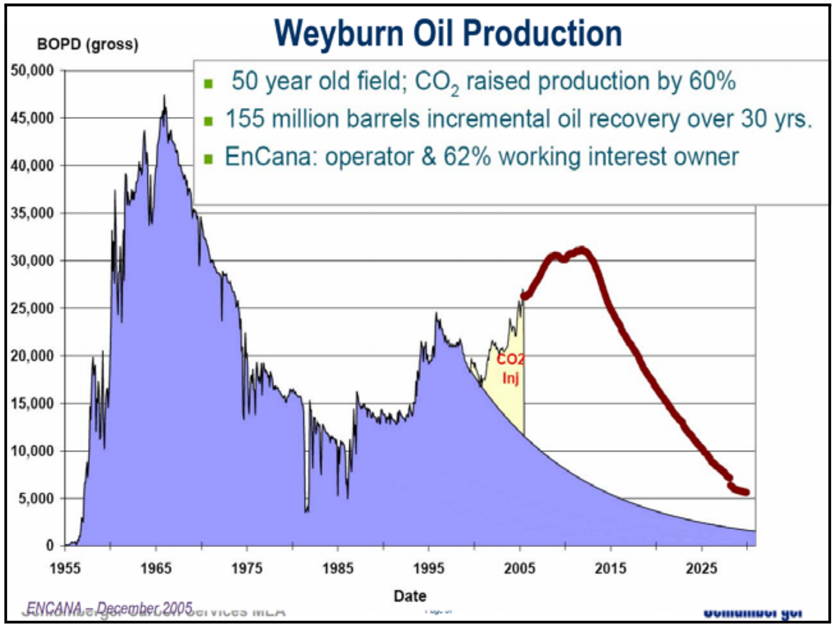
1. Continuous injection of CO_2
2. Injection of slug of CO_2 followed by water
3. Injection of alternate slugs of CO_2
4. Simultaneous injection of CO_2 and water

Comments on Displacement Mechanisms

- Limited field experience to demonstrate the best method…
- Simulation results of oil recovery by CO_2 flooding of oil left behind after water flooding (sandstone)
  - Simultaneous CO_2 Water - proved best
  - Tapered WAG - second best
  - Straight CO_2 and slug followed by water - Good
  - Simple WAG - OK

Water Alternation Gas (CO_2)

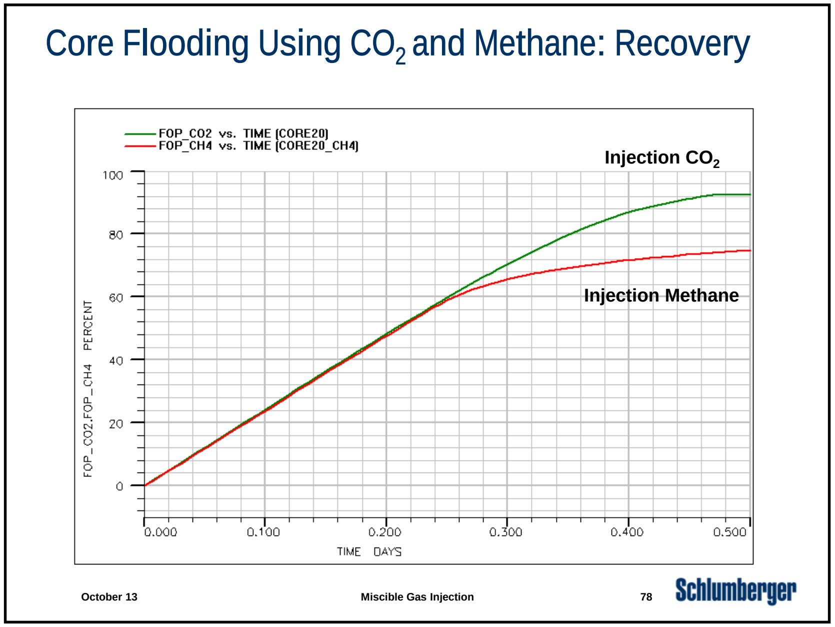




Weyburn Oil Production

- 50 year old field; CO_2 raised production by 60%
- 155 million barrels incremental oil recovery over 30 yrs.
- EnCana: operator & 62% working interest owner

ENCANA – December 2005



Core Flooding Using CO_2 and Methane: Recovery

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Steeply Dipping Reservoirs

- Continuous CO_2 will be a gravity stable process
- Expanding gas cap pushes oil down
- Gravity stabilizes displacement
- Increased sweep of CO_2
- Good even without miscibility

Possible Difficulties

- Asphaltene deposition
- CO_2 solubility in water
- 3-phase behavior at low temperatures
  - Vapor-Liquid-Liquid

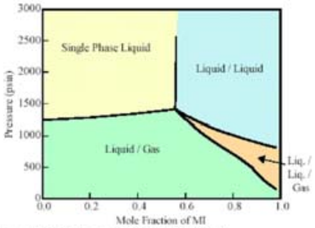

Fig. 1—Phase diagram for Schrader Bluff fluids.

Immiscible CO_2 Displacement

- Low pressure reservoirs
- Reservoirs with oil less than 30 API
- Gravity stable displacement

- Viscosity reduction of dead stock tank oils
- CO_2 solubility in crude increases with decreasing temperature

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EOR Processes – Miscible Gas Injection

End of Lecture