“The Energy Gap – How CO$_2$ Tertiary Recovery will mark its place in the 21$^{st}$ Century”

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Tertiary CO$_2$ Flooding
“CO$_2$ Flood History since 1972”

Since 1972 over 120+ CO$_2$ Tertiary Projects have been implemented in the United States.
Today, over 237,000 BOPD of Tertiary Oil is produced with CO$_2$ Injection with over 3,100 miles of CO$_2$ pipeline.

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Permian Basin Statistics

Permian Basin – Central Basin Platform

- Has produced oil for over 80 years
- Is the 3rd largest petroleum producing area in the U.S. after the Gulf of Mexico and Alaska
- 29 billion barrels produced from the Permian Basin
- 1.2 billion barrels of tertiary oil have been recovered due to CO₂ Injection
CO₂ Well Operations

10,000 Production Wells
8,000 CO₂ Injection Wells

Note: Since 1972, the oil and gas industry has:

Excellent Safety Record.

Note: Corrosion is not an issue - Casing, Tubulars, Field Piping, etc. are 95+% Carbon Steel
Approximately 75% of the CO₂ today is supplied by Natural CO₂ Source Fields
1. Permian Basin - McElmo Dome, Sheep Mountain, Bravo Dome
2. Mississippi – Jackson Dome
3. Wyoming – LaBarge
Conventional CO₂ Pipeline Operations

Pipeline Transport is “Best Overall”

Note: Since 1972, the oil and gas industry has:

1. Produced and injected more than 10.8 TCF of CO₂ from 7 sources. 1.2 TCF of which came from sources otherwise would have been vented.

2. Constructed over 3,100 miles (4,960 kilometers) of CO₂ mainline pipeline systems.

3. In 2010, Producing at Maximum Capacity of over 3.1 BCF/day.
Conventional CO₂ Pipeline Operations

Pipeline Transport is “Best Overall”

Note: Since 1972, the oil and gas industry has:

**Excellent Safety Record.**

The CO₂ is dehydrated (water removed), pumped, and transported as a super-critical fluid. Very little corrosion problems have been reported to date.
Conventional CO$_2$ Operations

Oil Production Facilities and Gas Separation Facilities

Note: Corrosion is not an issue Vessels, piping, etc. is 95+% Carbon Steel

Merchant Consulting - Midland CO$_2$ Conf - Dec 2012
What are they doing?

CO₂ Tertiary Flood Management

Pattern Review In Progress: Control Central

1. Evaluating Individual Well Performance
2. Evaluating Individual Pattern Performance
3. Making WAG Adjustments based on Pattern Performance
Tertiary CO$_2$ Flooding

“The Energy Gap”
21$^{st}$ Century
In the 21st Century, CO₂ Sequestration will provide CO₂ from IGCC Natural Gas and Coal Fired Power Plants, Refineries, and other large scale Anthropogenic CO₂ Sources to fill the Energy Gap that exists between “Peak Oil” and the future “Hydrogen Energy Economy”.
Peak World Oil Rate Timing is a function of how fast the top 14 Super Giant Oil Fields in the World decline and how much new Refining Capacity can be added to replace Oil Consumption.
Gap Fillers

1. Primary Oil Recovery
2. Secondary Oil Recovery
3. Tertiary CO$_2$ - Conventional Tertiary Oil Recovery
4. Tertiary CO$_2$ - Residual Oil Zone (ROZ)
5. Tertiary CO$_2$ – Heavy Oil (14+ API)
6. Offshore – Shallow and Deep Water
7. Natural Gas (Conventional Reservoirs)
8. Liquefied Natural Gas (LNG)
9. Shale Oil (Bakken, Others)
10. Shale Gas (Marcellus, Barnett, Eagle Ford)
11. Coal to Gas, Coal to Liquids
12. Steam, Thermal, and MEOR (Bacteria)
Hydrogen Economy – “Clean Air Environment”

1. Wind Power
2. Solar Power
3. Nuclear (Fission)
4. Nuclear (Fusion)
5. Hydrogen Power (Hydrogen Cars and Hydrogen Fuel Cells)
6. Tertiary CO₂ – EOR and CO₂ Sequestration
7. Mass Transportation (Automobiles poor means to move people)
8. Clean Coal Gasification (Pre-Post Combustion, Oxy-fuel)
9. Clean Natural Gas – (Conventional and Un-Conventional)
10. Biomass – Balance with Mother Nature
11. Nano Tech
12. Algae (Clean Fuels)
CO₂ Flood Basics – What makes CO₂ work?
Oil Field Basics

Oil Field Life Cycle – (All Fields Worldwide)

Recovery Mechanisms
Primary Oil Recovery
Secondary Recovery
Tertiary Oil Recovery
Primary and Secondary Oil Recovery

Historical Unit Oil Production Performance

(World Perception - Two Stages of Oil Recovery)
Primary, Secondary, and Tertiary Oil Recovery

Primary, Secondary, and Tertiary Prediction

CO₂ Tertiary Flooding

(Three Stages of Oil Recovery)

Field Example

CO₂ Startup
Jan 2005

Primary Prediction
Secondary Prediction
Tertiary Prediction

Field Discovery
Primary Recovery
Secondary Recovery
Tertiary Recovery

BOPD

Time, years

BOPD (WF)
BOPD (Tertiary)
BOPD (History)
BOPD (Primary)
BOPD (Primary)

(Three Stages of Oil Recovery)
Primary, Secondary, and Tertiary Oil Recovery (Main Pay + ROZ)

Primary, Secondary, and Tertiary Prediction  ROZ CO₂ Flooding

(Four Stages of Oil Recovery - ROZ)
Permian Basin (Residual Oil Zone - ROZ)

ROZ - Oil Saturation Profile

Note:
- Reservoir originally contained full column of oil
- Oil migrated elsewhere in basin
- A Residual Oil Saturation remained afterwards

Note: ROZ Pay Zones do not exist in all Basins
CO$_2$ Flooding Techniques
Tertiary CO₂ Flooding

Eight CO₂ Recovery Methods used for Tertiary Oil Recovery in the United States

1. Conventional WAG Recovery (90%+)
2. Residual Oil Zone (ROZ) (Seminole)
3. Gravity Drainage (Yates Field)
4. Double Displacement (Yates Field)
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What is Conventional WAG Management?

Conventional WAG Injection Techniques

Water (% HCPV Inj.)  CO₂ (% HCPV Inj.)
DIFFERENT OPERATORS
DIFFERENT PHILOSOPHIES (Reservoir Driven)

- Continuous CO₂ - Continuously inject CO₂ (No water)

- Constant WAG - example - 1:1 WAG with (1.0 % CO₂, 1.0% H₂O)
  Note: No change in WAG Ratio with time

- Simultaneous WAG – Hourly WAG Changes

- Tapered WAG - Combination of both continuous and WAG
  example - Continuous injection for 20% HCPV
  WAG (1.0 % CO₂, 0.10 % H₂O) for 5% HCPV
  WAG (1.0 % CO₂, 0.50 % H₂O) for 10% HCPV
  WAG (1.0 % CO₂, 1.00 % H₂O) for 20% HCPV
  WAG (1.0 % CO₂, 2.00 % H₂O) for 30% HCPV
  Chase Water Injection

“Wetting the WAG”

Note: Total Slug Size = 85% HCPV Inj. Of CO₂
Tertiary CO₂ Flooding

“The Previous Millennium”

20th Century

“Life to 80% HCPV Injected”
**Tapered WAG Injection**

**Advantages**
1. Controls Mobility (Reduces Gas Processing)
2. Improves Operations (less gas cycling)
3. Extends flood life beyond 50% HCPV Inj.
4. Can control the flood to Plant and Pipeline Capacities
5. Can accelerate or retard Flood Response

**Disadvantages**
1. None to date

**1980’s**

**LEVEL LOAD**

**BOPD (20,30,50,70,90 - %HCPV (Inj))**

**BFPD (Total) (20,30,50,70,90 - %HCPV (Inj))**
CO₂ Flooding in the United States
40 Years of CO₂ Flood History

### 1980’s – 1990’s

<table>
<thead>
<tr>
<th>Field</th>
<th>State</th>
<th>Reservoir</th>
<th>Lithology</th>
<th>SAIPF</th>
<th>Injected</th>
<th>% OOIP</th>
<th>Recov.</th>
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**7% to 12% OOIP Rec**
**30% to 40% HCPV Inj**

### 2000’s

**18% OOIP Rec**
**80% HCPV Inj**

### 2010’s

**20% to 26% OOIP Rec**
**140% to 190% HCPV Inj**

*Note: Not all fields will achieve this*
Tertiary CO$_2$ Flooding

“The New Millennium”

21$^{st}$ Century

“Life beyond 80% HCPV Injected”
Economic Case Comparisons – Continuous 30, Constant WAG 50, Tapered 70)

Gross – CO₂ Utilization

Net – CO₂ Utilization

CO₂ Storage - % HCPV

CO₂ Utilization and CO₂ Retention

CO₂ Gross Utilization is a measure of the Efficiency of the CO₂ Process (Amount of Total CO₂ Injected per Bbl Tertiary Recovered)

CO₂ Net Utilization is a measure of the Efficiency of the CO₂ Process (Amount of Purchased CO₂ Injected per Bbl Tertiary Recovered)
Example - WAG BENEFITS
(Control CO$_2$ Process)

Slaughter Estate Unit in Slaughter Field

SPE Paper 26624 – “Reservoir Management in Tertiary CO$_2$ Floods”

Merchant Consulting - Midland CO$_2$ Conf - Dec 2012
Example - WAG BENEFITS  
(Control CO₂ Process)

Slaughter Estate Unit in Slaughter Field 

Slaughter Estate Unit CO₂ Tertiary Study

- Oil Production 1984 - 1994
- Gas Production 1984 - 1994
- Gas Injection 1984 - 1994
- Water Injection 1984 - 1994

1989 WAG Adjustment

SPE Paper No. 26624
Example - WAG BENEFITS

(Control CO$_2$ Process)

Level Load Gas Production
WAG Change - 1989

Effect of Constant WAG Injection Operations

Effect of Over-WAG Ops.
Tertiary CO₂ Flooding

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Tertiary CO₂ Flooding

Permian Basin (Seminole Field)

The Seminole field recovers Tertiary Oil from the San Andres Formation about 5,500 ft. deep which also includes a large Residual Oil Zone (ROZ). The Field is developed on 9-spot pattern spacing.
Permian Basin (Residual Oil Zone - ROZ)

ROZ - Oil Saturation Profile

Oil Saturation
0%                  100%

Note: ROZ Pay Zones do not exist in all Basins

Note:
Reservoir originally contained full column of oil
Oil migrated elsewhere in basin
A Residual Oil Saturation remained afterwards
Seminole San Andres Unit

Total Unit Performance

Historical Production and Injection - Rate Predictions
(Primary, Secondary, Tertiary Recovery Mechanisms)

Field Discovery - 1936

Primary Peak Oil Production - 25,000 BOPD

Primary Recovery

Today

BOPD

BOPD (WF)

BOPD (PRIMARY)

BWPD

BOPD (PREDICTION)

MCFD (PRIMARY PRED)

BWPD (PRIMARY PRED)
Seminole San Andres Unit

Secondary Recovery

Seminole San Andres Unit

Total Unit Performance

Historical Production and Injection - Rate Predictions
(Primary, Secondary, Tertiary Recovery Mechanisms)

Field Discovery - 1936

Secondary Peak Oil Production - 75,000 BOPD

Water Injection

Today
Seminole San Andres Unit

Tertiary Recovery
(Main Pay Only)

Historical Production and Injection - Rate Predictions
(Primary, Secondary, Tertiary Recovery Mechanisms)

Field Discovery - 1936
Secondary Peak Oil Production - 75,000
Tertiary Peak (MP) Peak Oil Production - 43,000 BOPD

Today

CO₂ Injection

1935
1983 (MP)
2000
2012
2040

Time, years

BOPD

BWPD, MSCFD

100,000 BOPD

250,000 BWPD, MCFD
Seminole San Andres Unit

Tertiary Recovery
(ROZ Addition)

Historical Production and Injection - Rate Predictions
(Primary, Secondary, Tertiary Recovery Mechanisms)

Field Discovery - 1936
Secondary Peak Oil Production - 75,000

Tertiary Peak (MP) Peak Oil Production - 43,000 BOPD

CO₂ Injection 1983 (MP) 1996 (ROZ) 2012 2040

Today

Time, years

BOPD

100,000 BOPD

200,000 BOPD

300,000 BOPD

400,000 BOPD

500,000 BOPD

600,000 BOPD

700,000 BOPD

800,000 BOPD

900,000 BOPD

100,000 BWPD

200,000 BWPD

300,000 BWPD

400,000 BWPD

500,000 BWPD

600,000 BWPD

700,000 BWPD

800,000 BWPD

900,000 BWPD

100,000 MCFD

200,000 MCFD

300,000 MCFD

400,000 MCFD

500,000 MCFD

600,000 MCFD

700,000 MCFD

800,000 MCFD

900,000 MCFD

100,000 BWPD, MCFD
Tertiary CO₂ Flooding

“Size of the Prize - Permian Basin ROZ”

ARI estimates 30 BBOIP are sitting in ROZ zones in the Permian Basin alone.

- Large opportunity for EOR
- Big impact on West Texas Oil Industry
- Huge Potential Energy Resource for America

Active ROZ Projects
- Seminole - Hess
- Wasson - Oxy
- Hanford - Fasken
- Vacuum – Chevron
- Means – Exxon
- East Seminole – Tabula Rasa
- Goldsmith – Legado

Ref: ARI ROZ Report

Advanced Resources International (ARI) Estimates – 30 Billion Barrel OOIP Target in ROZ
Tertiary CO\textsubscript{2} Flooding
“Residual Oil Zone Target”
Big Horn Basin
Tertiary CO₂ Flooding

“Wyoming - Big Horn Basin”

1. Main Pay  500 to 800 Million barrels over 40 years
2. ROZ      800 to 1,200 million barrels over the next 40 years
3. Existing Wells  Implementation will utilize a majority of the estimated 2,000 existing wells drilled
4. Facilities  New Facilities will be required for implementation
5. Sequestration EORI estimates between 12 and 19 TCF can be sequestered in petroleum reservoirs

Ref: Enhanced Oil Recovery Institute
Tertiary CO₂ Flooding

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**CO₂ Sequestration, Gas Storage and Gravity Drainage Projects**

**Low Dip Reservoir**  
(Conformance can be detrimental)  
Gas Cycling is a big problem

**Moderately Low or High Dip Res.**  
(Can run Miscible or Immiscible)  
Conduct a gravity Stabilized CO₂ flood with chase gas

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**Displacement Process**

**Replacement Process**

**CO₂ Conformance Problems**

**Chase Gas Inj.**  
CO₂, Flue gas, Nitrogen, Air

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San Andres Map – Yates Field
Yates Reservoir History

Discovery: 1926
Discovered in 1926
550’ of Oil Column at Structure Top

1926 - 1976
Produced By Individual Operators
Unitized in 1976 to Prevent Aquifer Influx

1976 - 1992
Gas Re-injected, Water Re-injected
Oil Column Thinned

1992 - 2000
Double Displacement
Reservoir Dewatering
Contact Lowering

2000 - 2012
Contact Stabilization (30 ft oil column)
Gas Cap Injection
Aquifer “Maintenance” By Offsite Disposal
Yates Unit Historical Performance

Yates Total Unit Performance
Production and Injection

Oil Production (Peak)
130 MBOPD (approx.)

Primary Production History
Secondary and Tertiary Production History

BOPD, MSCFD

Time, years

Field Production and Injection

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Yates Unit Historical Performance

Yates Total Unit Performance
Gas Injection Only

- Gas Inj Startup - July 1976
- Tertiary Production History
- CO2 Gas Injection
- Comb Gas Injection
- CO2 Injection Startup - Nov. 1985

Time, years

BOPD, MSCFD

CO2 Flue Gas
CO2
Nitrogen/CO2
CO2

Field Gas Injection Breakout

Merchant Consulting - Midland CO\textsubscript{2} Conf - Dec 2012
Yates Unit Historical Performance

Historical N₂ and CO₂ Injection

Kinder Morgan returned CO₂ injection to Yates field in 2003 in addition to a horizontal drilling program.
Yates Unit Historical Performance

Yates Total Unit Performance
Oil Production (Current)

Historical Oil Rate

Kinder Morgan returned CO2 injection to Yates field in 2003 in addition to horizontal drilling program

10,000 BOPD Increase

Field Production (Current)
Tertiary CO$_2$ Flooding

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Gas Cycling Example – Denbury

Little Creek Field and West Mallalieu Field
Gas Cycling Example – Denbury

Little Creek Field and West Mallalieu Field

Denbury: 2006 CO₂ Conf
Tertiary CO₂ Flooding

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Heavy Oil Example – 14+ API Gravity

Wilmington Field – Los Angeles (3 CO₂ Pilots)

Wilmington CO₂ Pilot Results

1. Pilots were Demonstration Projects (Not Oil in the Tank Pilots)
2. Wilmington Oil – 10 fold decrease in Viscosity (300 cp to 30 cp)
3. Wilmington Oil – 1.15 fold increase in Oil Swelling
4. Wilmington Oil – Immiscible with 85% CO₂ and 15% N₂
5. Wilmington Oil Response – Single Well Response 30 BOPD to 300 BOPD
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Williston Basin – Bakken Formation – Shale Oil Target

To improve Primary Oil Recovery, operators have resorted from single to bilateral Horizontal Well Completions with massive sand fracture technology to improve Primary Oil Recovery.
Williston Basin – Bakken Formation

To make this technology work, large investments involving many horizontal wells on steep decline are required to keep a reasonable continuous rate profile. This results in a many well, many year continuous drilling program.
Williston Basin – Bakken Formation

Results of this effort are shown below

The 10 year Bakken development plan shown above contains 10 one year phases. **Ninety wells per phase per year** are required for the first four phases with **45 wells per phase per year** for the last six phases. This results in a total of 635 wells to be drilled over a 10 year period with a single well cost of around 3 million dollars. For other areas of the Bakken drilling costs can exceed 12 million dollars per well.

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Simulation Comparison study results are shown above. Primary recovery was limited to 5 years (3.64% OOIP) with CO$_2$ Injection over 95 years. Continuous Injection outperformed water injection and other cyclic Huff-n-Puff injection schemes.
Williston Basin – Bakken Formation

Reservoir Model Study – CO₂ Tertiary Prediction

The simulation results show that CO₂ flooding presents a technically promising method for recovering Bakken oil, but over a very long injection period (95 years of injection). Also, note the long time to breakthrough (several months to many years).

Water flood Recovery

CO₂ Recovery

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Tertiary CO₂ Flooding

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**Ninth CO₂ Recovery Method used for EOR and CO₂ Sequestration**

*Note: Remove both Tertiary Oil and Water*
Merchant Thanks to Steering Committee!

1995 Reservoir Management in Tertiary CO₂ Floods – SPE 26624

1999 Screening CO₂ Candidate Reservoirs Fundamentals of Pattern Analysis

2000 Setting up the Pieces – What Constitutes a Simulation?

2004 Pattern Performance as a Diagnostic Tool for Reservoir Surveillance

2004 Monitoring the CO₂ Flood - Problem Identification and Solutions

2009 Comparisons of Conventional CO₂ WAG Injection Techniques used in the Permian Basin

2010 Life beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV in CO₂ Tertiary Floods – SPE 139516

2012 The Energy Gap - “How CO₂ Tertiary Recovery will mark its place in the 21st Century”
Thanks,

Now its your turn?

David H. Merchant

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WEB: www.CO2StorageSolutions.com
Key Words: Merchant Consulting, CO2 Storage Solutions, CO2 Seminars on Wheels

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