CMTC-440075 “SPE-139516 “Life beyond 80 – A Look at Conventional WAG Recovery beyond 80% HCPV Injection in CO2 Tertiary Floods”

CMTC-440223 “The Energy Gap – How CO2 Tertiary Oil Recovery will mark its place in the 21st Century”

David H. Merchant

WEB Site: www.CO2StorageSolutions.com
Email: merchantconsulting@comcast.net

Presented to Midland CO2 Conference

December 9, 2015
Midland, Texas
Permian Basin

Welcome to the Permian Basin?

300 miles (480 km) North South
250 miles (400 km) East West
Carbon Management Technical Conference
November 2015
Sugarland, Texas

CMTC-440075  “SPE-139516 “Life beyond 80 – A Look at Conventional WAG Recovery beyond 80% HCPV Injection in CO2 Tertiary Floods”

CMTC-440223  “The Energy Gap – How CO$_2$ Tertiary Oil Recovery will mark its place in the 21st Century”

Thanks: CMTC Management Team
George Koperna  (ARI)

Greatly Appreciated, Thank you
CMTC-440075-MS

SPE-139516 “Life beyond 80 – A Look at Conventional WAG Recovery beyond 80% HCPV Injection in CO2 Tertiary Floods”
David Merchant, Merchant Consulting

Note: This paper, along with my other SPE and CMTC Publications can be downloaded from my WEB sites listed above.
What is CO$_2$ Tertiary Oil Recovery?
Since 1972 over 130+ CO$_2$ Tertiary Projects have been implemented in the United States. Today, CO$_2$ projects in the United States produce over 350,000 BOPD with CO$_2$ transported over 4,500 miles of CO$_2$ pipeline.
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
- 13 billion barrels have been produced from the Central Basin Platform carbonates (45% of Permian total)
  - San Andres > 4 billion barrels
  - Clear Fork > 2 billion barrels
Permian Basin

“First Commercial CO$_2$ Flood - 1972”

“Latest Success Story”

Sacroc Unit in Kelly Snyder Field
EXISTING MARKETS

Year - 2000

CURRENT CO2 SOURCES and PIPELINES

Wyoming

Great Plains Coal Plant

LaBarge

McElmo Dome

Sheep Mountain

Bravo Dome

Jackson Dome

Permian Basin

Louisiana/Mississippi

Sacroc Unit

Kelly Snyder Field

EXISTING MARKETS

Year - 2000

Wyoming

Great Plains Coal Plant

LaBarge

McElmo Dome

Sheep Mountain

Bravo Dome

Jackson Dome

Permian Basin

Louisiana/Mississippi

Sacroc Unit

Kelly Snyder Field
The Kelly Snyder Field (Sacrooc Unit) recovers Tertiary Oil from the Canyon Reef Limestone Formation about 6,700 ft. deep.
Sacroc Unit – Production History

Historical Production and Injection

- Field Discovery: November 1948
- Peak Oil Rate: 209,000 BOPD
- Current Oil Rate: 9,071 BOPD
- Peak Water Inj.: 126,000 BWIPD

- Water Injection: September 1954
- CO2 Injection: January 1972

Year 2000
Sacroc Unit
Pennzoil Operatorship
1992 - 1999
Sacroc Unit

Pennzoil Operatorship
1992 - 1999
**Sacroc Unit** – Pennzoil Ownership

Center-line Project

1996 CO$_2$ Pattern Development Plan
300 Acre Pilot

Pennzoil Team
1. Ghasem Bayat
2. Tony Benvegnu
3. Claud Pickard
4. Jack Horkowitz
5. Tom Wingate
6. Don Hartman
Sacroc Unit – Pennzoil Ownership

Historical Production – Oil Production and CO₂ Injection

SACROC UNIT
KELLY SNYDER FIELD

BOPD, MCFD, MCFIPD

Time, years

Pennzoil
3 years

Merchant Consulting - Midland CO₂ Conf - Dec 2015
Sacroc Unit – Pennzoil Ownership

Historical Production by Project Area

SACROC UNIT
KELLY SNYDER FIELD
Oil Rate - Historical (1990 - 2000)

Center-line Project
Up – 3000 BOPD
Sacroc Unit

Devon Operatorship
1999 – 2000

Kinder Morgan Ownership
2000 - Today
Sacroc Unit

Current CO₂ and Water Injection

Historical Water and CO₂ Injection

Kinder Morgan Company purchased Shell CO₂ Company in April 2000

CO₂ Injection Increase

120 MMSCFD

800 MMSCFD
Sacroc Unit

Current Oil Production

In 2015, the field continues to produce over 30,000 BOPD

Kinder Morgan Company purchased Shell CO2 Company in April 2000

Tertiary Oil Response

8,500 BOPD

33,000 BOPD
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>Uplift</th>
<th>SWPV</th>
<th>Rec, PVT</th>
<th>Gross Net Wells</th>
<th>% OOIP Retained</th>
<th>% HCPV injected</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dessau</td>
<td>Texas</td>
<td>Delaware</td>
<td>30</td>
<td>14</td>
<td>2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>East Texas</td>
<td>Texas</td>
<td>San Andres</td>
<td>30</td>
<td>17</td>
<td>5.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ford Sandstone</td>
<td>Texas</td>
<td>Delaware</td>
<td>30</td>
<td>17</td>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>Texas</td>
<td>San Andres</td>
<td>30</td>
<td>17</td>
<td>9.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**2000’s**

Tapered WAG Injection

**2010’s**

Tapered WAG Injection – to 190% HCPV Inj

7% to 12% OOIP Rec
30% to 40% HCPV Inj

18% OOIP Rec
80% HCPV Inj

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

Note: Not all fields will achieve this
General Material Balance Equation (Mass Balance)

The General Material Balance Equation can be written for any material that enters or leaves any process system. This is no different for projects where CO₂ or Water is injected.

Since there is no chemical reaction, the generation and consumption terms will become zero. Since CO₂ flooding is a displacement process, the amount of Tertiary Oil that can be recovered and CO₂ stored will depend on the simplified equation:

Accumulation = Input - Output

Five Parameters determine the amount of tertiary oil that can be recovered. These are:
1. Reservoir Volume
2. Reservoir Operating Pressure and Fracture Pressure
3. Reservoir Temperature (Non Entity – Little Influence)
4. Reservoir Phase Trapping
5. Reservoir Conformance
You can’t fool Mother Nature……

The amount of CO$_2$ TRAPPED, STORED, OR SEQUESTERED is dependent on the Composition of the Residual Oil Saturation and Phase Trapping of the Non-Wetting Phase, which in this case is CO$_2$.
CO$_2$ Miscible Process
Compositionally Driven

Oil Bank Transition Zone

Multiple Contact Miscible Process
(time and compositionally dependent)

Miscible Zone formed by CO$_2$
becoming enriched with C$_2$ – C$_{30}$
CO$_2$ Trapping of the Non-wetting Phase and Relative Permeability

**Water Wet - Sandstones**

- **Summary of Water Wet Option**
  - Curves Used by Model
  - Model Curves
    - $k_{rw}$, $k_{rwh}$, $k_{rhw}$, $k_{rg}$, $k_{rgh}$, $k_{rog}$
  - Relative Permeability Tests
    - Water-oil, oil-water
    - Gas-oil, gas-water
- Wetting phase-water
  - Intermediate wetting phase-oil
  - Non-wetting phase-gas

**Intermediate Wet - Both**

- **Summary of Water Repellent Option**
  - Curves Used by Model
  - Model Curves
    - $k_{rg}$, $k_{rgh}$, $k_{rog}$
  - Relative Permeability Tests
    - Water-oil, oil-water
    - Gas-oil, gas-water
- Wetting phase-oil
  - Intermediate wetting phase-gas
  - Non-wetting phase-water

**Oil Wet - Dolomites, Limestone**

- **Summary of Oil Wet Option**
  - Curves Used by Model
  - Model Curves
    - $k_{rwo}$, $k_{rwh}$, $k_{rwoh}$, $k_{rog}$, $k_{rgh}$, $k_{rog}$
  - Relative Permeability Tests
    - Water-oil, oil-water
    - Gas-oil, gas-water
- Wetting phase-oil
  - Intermediate wetting phase-water
  - Non-wetting phase-gas

**Note:** Tertiary Oil Recovery and CO$_2$ trapping is governed by Relative Permeability Hysteresis of the non-wetting phase.
Reservoir Operating Pressure

Note: All CO₂ Floods should be operated at or just below Formation Fracture Pressure (Amoco Philosophy during the 1980’s and 1990’s.)
Minimum Miscibility Pressure

Note: CO₂ Floods are most efficient is operated above Minimum Miscibility Pressure. But, can be operated below MMP, but at a lesser efficiency rating.
Ten CO₂ Recovery Methods
Tertiary CO₂ Flooding

**Ten 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)
5. Gas Cycling (Denbury, Mississippi).
6. Huff-and-Puff (100+ Projects)
7. Heavy Oil - Calif. (14+ API Gravity)
8. Shale Oil (Bakken) (Under Investigation)
9. Horizontal Well Pattern Development
10. CO₂ Gas Drive w/ Nitro Boost
Conventional WAG w/ ROZ

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Conventional WAG Injection Techniques

CO₂
Key To Tertiary Oil

Water (% HCPV Inj.)

CO₂ (% HCPV Inj.)
Permian Basin – History of “WAG”

1950’s – 150 small scale Miscible and Immiscible Projects

1958 – Lab Experiments Caudle and Dyes introduced water to decrease solvent mobility

1972 – Sacroc Field (Constant WAG) First Commercial Large Scale Project

1980’s – Early Projects (Constant WAG)

1986 – Reservoir Model (Amoco - Merchant)

1989 – Amoco Implemented Tapered WAG in Slaughter and Wasson Fields

1990’s – Tapered WAG adopted most operators
CO\textsubscript{2} Flooding in the United States
40+ Years of CO\textsubscript{2} Flood History

1980’s – 1990’s

2000’s

2010’s

7% to 12% OOIP Rec
30% to 40% HCPV Inj

18% OOIP Rec
80% HCPV Inj

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

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

“The Previous Millennium”

20$^{th}$ Century

“Life below 80% HCPV Injected”
Example - WAG BENEFITS
(Control CO₂ Process)

Oxy-Permian - Slaughter Estate Unit in Slaughter Field

SPE Paper No. 26624
Example - WAG BENEFITS
(Control CO₂ Process)

Oxy-Permian - Slaughter Estate Unit in Slaughter Field Production and Injection (1984 – 1994)
Example - WAG BENEFITS

(Control CO₂ Process)

Level Load Gas Production WAG Change - 1989

Effect of Constant WAG Injection Operations

Effect of Over-WAG Ops.

Oil Prod

Gas Prod

1984 1994
Tertiary CO₂ Flooding

“The New Millennium”

21ˢᵗ Century

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

**Gross - CO₂ Utilization**

\[
\text{Gross Utilization} = \frac{\text{Cum CO₂ Injection (Total)}}{\text{Cum Oil (Total) - Cum Oil (Waterflood)}} \times 100
\]

**Net - CO₂ Utilization**

\[
\text{Net Utilization} = \frac{\text{Cum CO₂ Injection (Purchase)}}{\text{Cum Oil (Total) - Cum Oil (Waterflood)}} \times 100
\]

**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)
Field Example
Seminole Field
Oil Field Basics

Oil Field History – (All Fields Worldwide)

Recovery Mechanisms
Primary Oil Recovery
Secondary Recovery
Tertiary Oil Recovery
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)

SSAU MPZ & ROZ CrossSection and Zonal Attributes

<table>
<thead>
<tr>
<th></th>
<th>Gross Thickness</th>
<th>Net Thickness</th>
<th>Porosity</th>
<th>Permeability Range</th>
<th>OOIP</th>
<th>Initial Oil Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main Pay Zone (MPZ):</td>
<td>160'</td>
<td>126'</td>
<td>12%</td>
<td>0.8-120 md</td>
<td>1 billion stbo</td>
<td>0.84</td>
</tr>
<tr>
<td>Residual Oil Zone (ROZ):</td>
<td>246'</td>
<td>197'</td>
<td>12.6%</td>
<td>0.5-270 md</td>
<td>960 million stbo</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Total Gross= 406 ft  Total Net= 333 ft
Permian Basin (Residual Oil Zone - ROZ)

**ROZ - Oil Saturation Profile**

Note: ROZ Pay Zones do not exist in all Basins

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

Primary Recovery

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

- **Field Discovery - 1936**
  - Primary Peak Oil Production - 25,000 BOPD

- **Today**

**Note:** Little Water Production occurred during Primary Recovery

**Note:** Reservoir Pressure depleted during this time frame
Note: Water Injection is introduced into the Reservoir in 1971
Note: Mass Balance – Water had to be found to initiate Waterflood operations
Seminole San Andres Unit
Secondary Recovery - Waterflood

Field Discovery - 1936
Secondary Peak Oil Production - 75,000 BOPD
Water Injection
Today

Note: Good Secondary Oil Response after Water Injection
Note: Gas Production collapsed after Water Injection (Pressure-up)
Note: Water Production occurred shortly after Water Injection
Seminole San Andres Unit

**Tertiary Recovery**
(Main Pay Only)

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

Field Discovery - 1936

- 100,000 BOPD
- 200,000 BWPD, MCFD

Secondary Peak Oil Production - 75,000

CO₂ Injection - 1983 (MP)

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

- (Level Load)

Today

- 2012

Note: The Reservoir produced a strong Tertiary Oil Response

Note: Total Gas Production increased with rapid breakthrough

Note: Water Injection and Production were decreasing prior to 1996

prior to ROZ start-up in 1996

Note: Total Gas Rate is “Level Loaded” to Plant Inlet Rate

Merchant Consulting - Midland CO₂ Conf - Dec 2015
Note: Total Gas Injection has been constant since CO₂ Injection in 1983
Note: Water Injection was decreasing from 1983 to 1996 (Prior to ROZ)
Seminole San Andres Unit

Tertiary Recovery (Main Pay Only)

Historical Oil (Primary + Secondary + Tertiary) Recovery - % OOIP

Expected Ultimate Oil Recovery - 68.7%

Tertiary Oil Recovery - 26.0%

Waterflood Oil Recovery - 29.9%

Primary Recovery - 12.8%

Total Incremental Tertiary Oil Recovery to Date - 18.9%

Note: The Reservoir is expected to Recover 26% of its OOIP with CO₂ Injection
**Seminole San Andres Unit**

**Tertiary Recovery**
(ROZ Addition)

**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

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

**CO₂ Injection**

1935
1983 (MP)
1996 (ROZ)
2012
2040

**BOPD**

100,000
200,000
300,000
400,000
500,000

**BWPD, MCFD**

250,000

**Note:** The ROZ produced a strong Tertiary Oil Response
**Note:** Total Gas Production has been “Level Loaded” to Plant Inlet Rate
**Note:** ROZ Water Production will be strong initially, but should decrease with time, level out, and then increase as WAG Ratio is increased

Merchant Consulting - Midland CO₂ Conf - Dec 2015
**Seminole San Andres Unit**

**Historical and Prediction - Water and CO₂ Injection**

**Note:** Total Gas Injection has been constant since CO₂ Injection in 1988

**Note:** Water Injection was decreasing from 1983 to 1996 (Prior to ROZ)

**Note:** ROZ Increase in Water Injection in 1996 and decrease in 2000
Gravity Drainage / Double Displacement

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10. CO₂ Gas Drive w/ Nitro Boost
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

CO₂ Conformance Problems

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

Displacement Process

Replacement Process
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

Primary Production History

Secondary and Tertiary Production History

Oil Production (Peak)
130 MBOPD (approx.)

Field Production and Injection
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

Field Gas Injection Breakout

BOPD, MSCFD

Yates Unit Historical Performance

Gas Injection Only

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

Field Gas Injection Breakout

BOPD, MSCFD
Yates Unit Historical Performance

Yates Total Unit Performance
Nitrogen and CO2 Injection (Current)

Historical N\textsubscript{2} and CO\textsubscript{2} Injection

Kinder Morgan returned CO\textsubscript{2} injection to Yates field in 2003 in addition to a horizontal drilling program.
Yates Unit Historical Performance

In 2015, the field continues to produce between 20,000 BOPD and 30,000 BOPD

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

10,000 BOPD Increase
Gas Cycling – Denbury Resources

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Gas Cycling Example – Denbury

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

Little Creek Field and West Mallalieau Field
Huff-n-Puff (Single Well Injection)

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Small Field and Huff-n-Puff Example

Pioneer Energy Portable Enhanced Recovery Technology (PERT) System

- CO₂ output: 500 Mcf/day
- CO₂ product purity: 94%
- CO₂ out pressure: 10 bar
- Gross electrical output: 1500 kWh
- Net electrical output: 1200 kWh
- Power generation CO₂ emissions: Less than 10% those of natural gas
- Natural gas feed requirement: 550 Mcf/day
- Oxygen production: Included
- CO₂ separation system: Included
- Configuration: Fully mobile, trailer mounted systems

The trailer mounted, truck mobile Portable Enhanced Recovery Technology (PERT) System
Heavy Oil (14+ API Gravity)

**Ten CO₂ Recovery Methods used for Tertiary Oil Recovery in the United States**

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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
Shale Oil – Bakken, Wolfcamp

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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.
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 programs.
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.
Simulation Comparison study results are shown above. Primary recovery was limited to 5 years (3.64% OOIP). With CO₂ Injection over 95 years, Continuous Injection of CO₂ out-performed 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).
Horizontal Well Development

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Horizontal Drilling CO₂ Projects

Canada - Weyburn Field

Utah - Aneth Field

Montana – Cedar Creek Anticline

North Sea – Denmark – Dan Field

Current CO₂ Floods

Future CO₂ Floods
**CO₂ Gas Drive w/ Nitro Boost**

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

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California
Kern County Oil Fields

Kern County

Kern County Oil Fields - California

San Joaquin Basin

CO2 Evaluation
Merchant Consulting

Field Location ID
Lost Hills NW
Antelope Hills
North and South Belridge
North and South Coles Levee
Elk Hills
Paloma
Buena Vista
Cuyama
Yowellumne
Russell Ranch
Midway-Sunset
Cymric
Mckittrick
Greeley
Jaemin
Mount Poso
Kern Front
Round Mountain
Kern River
Fruitvale
Edison
Mountain View
Tejon North Tejon Hills

Kern County California
Rio Bravo Field - Phased-in Pattern Development

Conventional WAG Case – Producer and Injector Pattern Development
Rio Bravo Field - Phased-in Pattern Development

Gravity Drainage Case - Injectors

Gravity Drainage Development Plan
Injector Count: 5 Wells
Producer Count: 19 Wells
Phase One

Phase 1
Phase 2
Phase 3
Phase 4
Phase 5
Phase 6
Phase 7
Phase 8
Rio Bravo Field - Phased-in Pattern Development

Gravity Drainage Case - Producers
Oxy Fuel Concept

Input: Hc-Gas

Output: CO₂, Electricity, Water, N₂
Rio Bravo Unit Field - Phased-in Pattern Development

Gravity Drainage Case – CO\textsubscript{2} Injection w/ Nitro Boost
Rio Bravo Field - Phased-in Pattern Development

Gravity Drainage Case – with addition of Nitro Boost

Gravity Drainage Development Plan
CO2 Injector Count: 5 Wells
N2 Injector Count: 5 Wells
Producer Count: 113 Wells

Nitro Boost Addition

N2 Injection Wells (up-dip)

Additional CO2 Injection Wells (down-dip)
Eleventh 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)
5. Gas Cycling (Denbury, Mississippi).
6. Huff-and-Puff (100+ Projects)
7. Heavy Oil - Calif. (14+ API Gravity)
8. Shale Oil (Bakken) (Under Investigation)
9. Horizontal Well Pattern Development
10. CO₂ Gas Drive w/ Nitro Boost

Note: Recover both Tertiary Oil and Water

Eleventh CO₂ Recovery Method used for CO₂ Sequestration
The Energy Gap – How CO\textsubscript{2} Tertiary Oil Recovery will mark its place in the 21st Century
David Merchant, Merchant Consulting

Note: This paper, along with my other SPE and CMTC Publications can be downloaded from my WEB sites listed above.
In the 21st Century, CO$_2$ Sequestration will provide CO$_2$ from IGCC Natural Gas and Coal Fired Power Plants, Refineries, and other large scale Anthropogenic CO$_2$ Sources to fill the Energy Gap that exists between “Peak Oil” and the future “Hydrogen Energy Economy”.
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)

Gap Fillers

1. Primary Oil Recovery
2. Secondary Oil Recovery
3. Tertiary CO₂ - Conventional Tertiary Oil Recovery
4. Tertiary CO₂ - Residual Oil Zone (ROZ)
5. Tertiary CO₂ – 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)
In 2005, Peak World Oil Rate Timing was a function of how fast the top 14 Super Giant Oil Fields in the World declined and how much New Refining Capacity can be added to replace Oil Consumption.

World Oil Prediction at 100 Percent Current Reserves

- BP WORLD OIL PRODUCTION
- BP WORLD OIL CONSUMPTION
- CONSUMPTION PREDICTION
- HYDROGEN ECONOMY
- Merchant Oil Prediction 1
- Merchant Oil Prediction 2
- Merchant Oil Prediction 3

World Consumption (Assume Constant)

2005

Gap Fillers

Hydrogen Economy

1973 Oil Embargo

World Oil Production and Consumption


Time, years

MBOPD (Million Bbls per day)

Ultimate Oil Rec. = 1,108 Billion Barrels (100% Rec.)

Merchant Consulting - Dec 2005
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 (Wolfcamp, Eagle Ford, Bakken, Others)
10. Shale Gas (Marcellus, Barnett, Eagle Ford)
11. Coal to Gas, Coal to Liquids
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Hydrogen Economy – “Clean Air Environment”

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10. Biomass – Balance with Mother Nature
11. Nano Tech
12. Algae (Clean Fuels)
# BP 2015 Statistical Review

**Oil: Total proved reserves**

<table>
<thead>
<tr>
<th>Country</th>
<th>at end 1994 (thousand million barrels)</th>
<th>at end 2004 (thousand million barrels)</th>
<th>Inc/Dec over 1994</th>
<th>at end 2004 (thousand million barrels)</th>
<th>Inc/Dec over 2004</th>
<th>Share of total</th>
<th>R/P ratio</th>
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<tbody>
<tr>
<td><strong>Total World</strong></td>
<td>1118.0</td>
<td>1366.2</td>
<td></td>
<td>1700.1</td>
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<td>Venezuela</td>
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<td>79.7</td>
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<td>100.0</td>
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<td>264.3</td>
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<td>48.1</td>
<td>179.6</td>
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<td>10.2%</td>
<td>100.0</td>
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<td>157.8</td>
<td>18.9%</td>
<td>9.3%</td>
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<td>Iraq</td>
<td>100.0</td>
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<td>150.0</td>
<td>30.4%</td>
<td>8.8%</td>
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<td>115.1</td>
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<td>0.0%</td>
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<td>United States</td>
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<td>48.5</td>
<td>65.4%</td>
<td>2.9%</td>
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<td>Libya</td>
<td>22.8</td>
<td>39.1</td>
<td>71.6%</td>
<td>48.4</td>
<td>23.6%</td>
<td>2.8%</td>
<td>100.0</td>
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<tr>
<td>Nigeria</td>
<td>21.0</td>
<td>35.9</td>
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<td>2.2%</td>
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<td>233.3%</td>
<td>1.8%</td>
<td>48.3</td>
</tr>
<tr>
<td>Qatar</td>
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<td>26.9</td>
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<td>25.7</td>
<td>-4.3%</td>
<td>1.5%</td>
<td>35.5</td>
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<tr>
<td>China</td>
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<td>-4.5%</td>
<td>18.5</td>
<td>19.0%</td>
<td>1.1%</td>
<td>11.9</td>
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<tr>
<td>Brazil</td>
<td>5.4</td>
<td>11.2</td>
<td>109.2%</td>
<td>16.2</td>
<td>43.7%</td>
<td>1.0%</td>
<td>18.9</td>
</tr>
<tr>
<td>Angola</td>
<td>3.0</td>
<td>9.0</td>
<td>204.8%</td>
<td>12.7</td>
<td>40.2%</td>
<td>0.7%</td>
<td>20.3</td>
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<td>Algeria</td>
<td>10.0</td>
<td>11.8</td>
<td>18.2%</td>
<td>12.2</td>
<td>3.4%</td>
<td>0.7%</td>
<td>21.9</td>
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<td>Mexico</td>
<td>49.8</td>
<td>14.8</td>
<td>-70.3%</td>
<td>11.1</td>
<td>-25.2%</td>
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<td>10.9</td>
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<td>5.1</td>
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<td>58.1%</td>
<td>0.5%</td>
<td>39.4</td>
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<td>Azerbaijan</td>
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<td>7.0</td>
<td>505.0%</td>
<td>7.0</td>
<td>0.0%</td>
<td>0.4%</td>
<td>22.6</td>
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<td>Norway</td>
<td>9.7</td>
<td>9.7</td>
<td>0.2%</td>
<td>6.5</td>
<td>-32.7%</td>
<td>0.4%</td>
<td>9.5</td>
</tr>
<tr>
<td>India</td>
<td>5.8</td>
<td>5.6</td>
<td>-4.2%</td>
<td>5.7</td>
<td>3.2%</td>
<td>0.3%</td>
<td>17.6</td>
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<tr>
<td>Oman</td>
<td>5.1</td>
<td>5.6</td>
<td>9.3%</td>
<td>5.2</td>
<td>-7.6%</td>
<td>0.3%</td>
<td>15.0</td>
</tr>
<tr>
<td>Australia</td>
<td>3.8</td>
<td>3.9</td>
<td>1.9%</td>
<td>4.0</td>
<td>2.4%</td>
<td>0.2%</td>
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</tr>
<tr>
<td>Malaysia</td>
<td>5.2</td>
<td>5.2</td>
<td>-0.8%</td>
<td>3.8</td>
<td>-27.3%</td>
<td>0.2%</td>
<td>15.4</td>
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<tr>
<td>Indonesia</td>
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<td>-13.7%</td>
<td>3.7</td>
<td>-14.1%</td>
<td>0.2%</td>
<td>11.9</td>
</tr>
<tr>
<td>Colombia</td>
<td>3.1</td>
<td>1.5</td>
<td>-52.9%</td>
<td>2.4</td>
<td>65.5%</td>
<td>0.1%</td>
<td>6.8</td>
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<tr>
<td>Argentina</td>
<td>2.3</td>
<td>2.5</td>
<td>10.0%</td>
<td>2.3</td>
<td>-6.1%</td>
<td>0.1%</td>
<td>10.1</td>
</tr>
<tr>
<td>Other Europe &amp; Eurasia</td>
<td>2.3</td>
<td>2.2</td>
<td>-1.5%</td>
<td>2.0</td>
<td>-11.7%</td>
<td>0.1%</td>
<td>14.0</td>
</tr>
<tr>
<td>Other S. &amp; Cent. America</td>
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<td>1.5</td>
<td>53.3%</td>
<td>0.5</td>
<td>-64.3%</td>
<td>*</td>
<td>9.6</td>
</tr>
</tbody>
</table>
Merchant Thanks to Steering Committee!

1995 First CO₂ Conference: Talk on: Montage approach to Reservoir Management in Tertiary CO₂ Floods – SPE 26624

Newspaper Article celebrates CO₂ Injection start-up into the Elmar field along with the CO₂ Conference scheduled for December 4-5, 1995

Pictured:
Tom McKnight (Union Royalty)
David Merchant (Amoco)
Ron Brockmeyer (Amoco)
Russell Martin (Enron Gas Pipeline)
Merchant Thanks to Steering Committee!

1995 Montage approach to 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”

2013 Short Course: Surveillance and Monitoring of CO₂ Injection Projects – “Pattern Balancing and Mass Balance”


2015 CMTC440075 Life beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV in CO₂ Tertiary Floods – SPE 139516
Thanks,

Now its your turn?

David H. Merchant

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

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