Life beyond 80 - A look at Conventional WAG Recovery beyond 80% HCPV Injection in CO$_2$ Tertiary Floods

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Life beyond 80 – Conventional WAG CO\textsubscript{2} Oil Recovery

Setting Up the Pieces - Talk Objective

**Last Year’s Talk:**
Comparisons of Conventional CO\textsubscript{2} WAG Injection Techniques used in the Permian Basin (2009 CO\textsubscript{2} Conference)

**This Year’s Talk:**
1. Life up to 80 – A look at Conventional WAG Recovery Techniques as seen Today in CO\textsubscript{2} Tertiary Projects
2. Life beyond 80 – A look at Conventional WAG Recovery Techniques beyond 80% HCPV in CO\textsubscript{2} Tertiary Projects
   SPE 139516 – Presented in New Orleans Nov. 2010
3. Tertiary Oil Recovery Conformance Issues (Steve Melzer’s Request)
Tertiary CO$_2$ Flooding

“The Previous Millennium”

CO$_2$ Flood History since 1972

“Life up to 80% HCPV Injected”
Today, 82 active CO₂ projects operate in the United States producing over 237,000 BOPD with over 2000 miles of CO₂ pipeline.
Tertiary CO$_2$ Flooding
Permian Basin (10 Producing Formations)

In 2009, the Permian Basin produced Tertiary Oil from 10 Producing Formations from 7,998 Producing wells and 5,325 CO$_2$ Injection Wells.
Tertiary CO$_2$ Flooding

“The New Millennium”

21$^{\text{st}}$ Century

“Life beyond 80% HCPV Injected”
In the 21st Century, CO₂ Sequestration will open-up New Oil Markets in basins that contain EOR potential, but lacked the CO₂ to make projects profitable.
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”.
Tertiary CO$_2$ Flooding

“CO$_2$ Tertiary Recovery Methods”
Tertiary CO$_2$ Flooding

**Five Basic CO$_2$ Recovery Methods used for Enhanced Oil Recovery Projects in the United States**

1. Conventional WAG Recovery (90%+)
2. Gravity Drainage (Yates field)
3. Double Displacement (Yates field)
4. Gas Cycling (Denbury, Mississippi)
5. Huff-and-Puff (100+ projects)
Tertiary CO$_2$ Flooding

Five Basic CO$_2$ Recovery Methods used for Enhanced Oil Recovery Projects in the United States

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SPE Paper 139516 covers only Conventional WAG Techniques
Tertiary CO$_2$ Flooding

What makes CO$_2$ WAG Recovery Work?
What is Conventional WAG Management?

Conventional WAG Injection Techniques

- Water (% HCPV Inj.)
- CO₂ (% HCPV Inj.)
What is Conventional WAG Management?

- The Water Alternating Gas (WAG) process is a cyclic method of injecting alternating cycles of CO$_2$ followed by water and repeating this process over a number of cycles.
- The WAG process provides mobility control in the fast zones which extends CO$_2$ project life and oil recovery.

Why CO$_2$ WAG Optimization?

- One element vital to the technical success of any CO$_2$ flood is the Optimum Utilization of CO$_2$ Injectant.
- WAG Optimization is widely recognized as a viable technique in controlling the Miscible Process.
Conventional WAG Recovery

West Texas Ramp Sequence Reservoirs -
(Poor Sweep can be detrimental)
Gas Cycling is a big problem

1. Tertiary Recovery – 10% to 20% OOIP
2. Total Slug Size – + 80% HCPV
3. WAG Necessary to Control Sweep
4. Recoverable Oil primarily in Fast Zones
5. Usually Run Miscible
6. Well Development: Pattern
Definitions
WAG Process

Pattern Parameters

- Original Oil-in-Place  - Amount of Oil in Place (Standard conditions)
- HCPV  - Amount of Oil in Place (Reservoir conditions)
- Total Slug Size  - Total Amount of CO₂ Inj. (20-100+ % HCPV)
- Half Cycle CO₂ Slug Size  - HCPV of CO₂ Inj in one cycle (0.25 - 30.00 %)
- Water Cycle CO₂ Slug Size  - HCPV of H₂O Inj in one cycle (0.25 - 10.00 %)
- WAG Ratio  - Ratio of Half cycle Water to Half cycle CO₂
- GWR Ratio  - Ratio of Half cycle CO₂ to Half cycle H₂O
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
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
Reservoir Simulation

Reservoir Model Comparison

1. Base Waterflood Injection
2. Continuous CO₂ Injection
3. Constant WAG Ratio CO₂ Injection
4. Tapered WAG Ratio CO₂ Injection
Slaughter Estate Unit - Example
Reservoir Simulation

Reservoir Model Study - San Andres 5 Spot

Single 5 Spot Pattern (10X10X6 Grid)

References:

1986
Amoco
GWR and Slug Size Optimization of the WAG Process
Report and Figures, Prepared by: David H. Merchant,
Amoco Production, West Division,
Production Dept, Date: January, 1988,
File: JWA-539.41-111

2004
BP
CO₂ Capture Project - An Integrated, Collaborative Technology Development
Project for Next Generation CO₂ Separation, Capture and Geologic
Sequestration
Subcontract C010: EOR/CO₂ Storage Optimization and Economics - 2004
Program
Supplemental Report - Evaluation of Enhanced Oil Recovery (EOR)
“Conventional CO₂ WAG Injection Methods”

Table No. 1
Average Model Properties

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Waterflood History

BOPD, MCFD(hc), BWPD

BWIPD, BWPD

GOR, Water-Cut

Oil Recovery - % OOIP
Reservoir Simulation

Tertiary CO₂ Predictions

CO₂ Injection Case Comparison
(20%, 30%, 50%, 70%, and 90% - HCPV CO₂ Injected)

- Continuous CO₂ Injection
- Constant WAG Ratio CO₂ Injection
- Tapered WAG Ratio CO₂ Injection
Continuous Injection

- Advantages
  1. Quick Oil Response

- Disadvantages
  1. Controlling Gas Breakthrough as flood matures
  2. Optimum Slug Size may be 30 % HCPV Inj.
Constant WAG Injection

- **Advantages**
  1. Controls Mobility (Reduces Gas Processing)
  2. Improves Operations (less gas cycling)

- **Disadvantages**
  1. Controlling Gas Breakthrough as flood matures
  2. Optimum Slug Size may be 50 % HCPV Inj.
  3. Loss of Injectivity (water) can be as high as 70%
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

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

LEVEL LOAD

BFPD (Total) (20,30,50,70,90 - %HCPV (Inj))
Reservoir Simulation

Tertiary CO\textsubscript{2} Predictions

(Economic Case Comparison) – 30\%, 50\%, 70\% HCPV Injected)

• Continuous CO\textsubscript{2} Injection
• Constant WAG Ratio CO\textsubscript{2} Injection
• Tapered WAG Ratio CO\textsubscript{2} Injection
Tertiary CO$_2$ Predictions

Reservoir Model Injection Case Comparison
Tertiary Oil Recovery vs. HCPV(Inj)
No Economic Limit

Reservoir Model Injection Case Comparison
Tertiary Oil Recovery vs. CO$_2$ HCPV(Inj)
With Economic Limit

Oil Recovery Comparison:
Continuous – Same
Constant WAG – Same
Tapered WAG – Same

Optimum Slug Size:
Continuous – 30% HCPV Inj.
Constant WAG – 50% HCPV Inj.
Tapered WAG – 70% HCPV Inj.
CO$_2$ Recovery Methods

Conventional WAG Model

WAG Injection Program Comparison

Tapered WAG - 70% HCPV

2to1 Constant WAG - 50% HCPV

Continuous Inj - 30% HCPV

Total CO$_2$ Slug Size - Percent of HCPV Injected
Economic Case Comparisons – Continuous 30, Constant WAG 50, Tapered 70

Gas Injection Rate

Graph showing CO₂ injection rates for Continuous, 2t01, Tapered.

Gas Production Rate

Graph showing CO₂ production rates for Continuous, 2t01, Tapered.

CO₂ Storage - % HCPV

Graph showing CO₂ storage percentages for Continuous, 2t01, Tapered.

Tapered WAG Ratio Injection

- Advantages
  1. Controls Mobility (Reduces Gas Processing)
  2. Improves Operations (Less Gas Cycling)
  3. Extends Flood life beyond 50% HCPV Inj.
  4. CO₂ Storage increases to (30% to 40% HCPV)
Economic Case Comparisons – Continuous 30, Constant WAG 50, Tapered 70)

**Gross – CO₂ Utilization**

**Net – CO₂ Utilization**

**CO₂ Retention**

**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)
- **CO₂ Retention** is an Engineering term used to measure the total amount of CO₂ Retained in the reservoir to the total amount of CO₂ injected
Tertiary CO₂ Predictions

CO₂ Injection – Life beyond 80% HCPV CO₂ Injected

(Tapered WAG Case Comparison)

- 20% Continuous CO₂ Injection
- 30% Tapered WAG Ratio CO₂ Injection
- 50% Tapered WAG Ratio CO₂ Injection
- 70% Tapered WAG Ratio CO₂ Injection
- 90% Tapered WAG Ratio CO₂ Injection
- 110% Tapered WAG Ratio CO₂ Injection
- 130% Tapered WAG Ratio CO₂ Injection
- 150% Tapered WAG Ratio CO₂ Injection
- 170% Tapered WAG Ratio CO₂ Injection
- 190% Tapered WAG Ratio CO₂ Injection
Tapered WAG Injection – to 190% HCPV Inj

- Oil Production Rate Comparison
- CO2 Production Rate Comparison
- Total Fluid Rate Comparison
- BOPD (20, 30, 50, 70, 90, 110, 130, 150, 170, 190)
- MCFD (20, 30, 50, 70, 90, 110, 130, 150, 170, 190)
- BFPD (20, 30, 50, 70, 90, 110, 130, 150, 170, 190)
- Oil Recovery (20, 30, 50, 70, 90, 110, 130, 150, 170, 190)

- Level Load
- 26% OOIP Recovery
- 190% HCPV Injected
Conventional WAG Recovery
“Not All Reservoirs will recover 26% OOIP”

Factors that control Tertiary Oil Recovery
The ability to achieve High Tertiary Recovery in New CO₂ floods depends on the following factors:

1. Large Original Oil-in-Place
2. Rock Type: Dolomite and Sandstone better than Limestone, Un-fractured Formations better than Fractured Formations
3. Good Pattern Development – Fields with many patterns achieve the highest tertiary recovery
4. Historical Primary and Secondary Waterflood Performance (Prim + Secondary Rec should be above 40% OOIP)
5. Primary + Secondary + Tertiary Recovery less than 70% OOIP (CO₂ will never remove all the oil)
6. CO₂ miscible with the oil (100% efficiency is best but can be operated below MMP)
7. Good Reservoir Conformance between injectors and producers
8. Good Porosity, Good Permeability, and Good k/phi distribution
9. Good Residual Oil Saturation Target (Approx. Range: Dolomites – 30%, Cherts – 25%, Sandstones – 20%)
10. Good Economics: High Oil Price, Low CO₂ Purchase Price, Low Recycle Plant and Field Capital Investments
11. CO₂ Source that is reliable and of high quality (Pipeline in close proximity)
12. Conventional WAG should be able to Sequester or STORE 30% to 40% HCPV (CO₂ Purchase Volume)
Life beyond 80% HCPV - Report Contains 7 Tables of EOR Recovery and Utilization Projections w/ 100 SPE/DOE References

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<tr>
<th>Formation, Field, Lease</th>
<th>EOR Rec, Utilization</th>
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### Table 3. - Clearfork Formation – Limestone (Tight - Low Permeability)

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### Table 4. - Devonian Formation – Tri politic Chert

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### Table 5. - Canyon Reef Formation – Karsted Limestone (High Permeability)

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## Life beyond 80% HCPV - Report Contains 7 Tables of EOR Recovery and Utilization Projections w/ 100 SPE/DOE References

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## Bibliography

- 71,72
- 73,74,75
- 78
- 79
- 80

## Table 7 - Tensleep, Mesaverde Almond, Weber, Sprayberry (Fractured Sandstone)

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<tr>
<th>State</th>
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<th>Gross CO₂ Utilization (MSCF/STB)</th>
<th>Net CO₂ Utilization (MSCF/STB)</th>
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## Table 8 - Heavy Oil

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<td>Ranger</td>
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<td>F81, F83, F85</td>
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## Bibliography

- 82 thru 96
- 67 thru 92
- 53,94
- 25 thru 99
- 59, 100
Tertiary CO$_2$ Flooding

“Conformance Issues in CO$_2$ Flooding ”
“Montage Approach – SPE 26624”
Integrated Log Montage w/ Conformance

Volumetric Sweep Efficiency = \( E_{\text{area sweep effic}} \times E_{\text{vertical sweep effic}} \)

Most Conformance Issues occur at the Wellbore
Example: Out-of-Zone Inj.
WAG Objective
Design for the Reservoir

WAG Ratio and Half Cycle Slug Size can be Modified

- Reservoir Heterogeneity Variations

1. A more Heterogeneous Reservoir will usually require cutting the CO₂ half cycle to a smaller volume to reduce production well gas cycling (Short-Cycling the WAG).
Reservoir Simulation

Reservoir Model Study - San Andres 5 Spot

Single 5 Spot Pattern (10X10X6 Grid)

Injection Profiles

X-Cross Section - Oil Saturation
Reservoir Simulation

Injection Profiles – Cycles 1 through 15

Injection Well Profile Comparison

- Early Time Results (Cycles 1 through 15)
  1. Can be difficult to interpret
  2. During Waterflood, Zone 5 had the greatest percent fluid throughput prior to CO₂ injection
  3. During CO₂ Injection, Zone 5 throughput decreases as the tertiary oil bank develops
Reservoir Simulation

Injection Profiles – Cycles 1 through 15 Comparison

CO₂ Half Cycle

Cycle No. 1

Layer 5

Cycle No. 15

H₂O Half Cycle

Cycle No. 1

Cycle No. 15
Reservoir Simulation

Injection Profiles – 20% HCPV to 70% HCPV
Reservoir Simulation

Injection Profiles – Continuous, 2to1, Tapered WAG

INJECTION WELL PROFILE STUDY

PLOT OF PERCENT TOTAL INJECTION

30% HCPV Inj

CO₂ Half Cycle

H₂O Half Cycle

CONT INJ

Layer 5

2TO1 INJ

TAPERED INJ
Reservoir Simulation

Injection Profiles – Continuous, 2to1, Tapered WAG

50% HCPV Inj

Layer 5

CO₂ Half Cycle

H₂O Half Cycle

CONT INJ

2TO1 INJ

TAPERED INJ
Reservoir Simulation

Injection Profiles – Continuous, 2to1, Tapered WAG

INJECTION WELL PROFILE STUDY

70% HCPV Inj

Layer 5

CONT INJ

2TO1 INJ

TAPERED INJ

CO₂ Half Cycle

H₂O Half Cycle
Reservoir Simulation

Saturation Profiles – 20% HCPV to 70% HCPV

Note: Saturations similar with HCPV Injection
Reservoir Simulation

Saturation Profiles – 20% HCPV to 70% HCPV

Note: Saturations similar with HCPV Injection
Reservoir Simulation

Saturation Profiles – Cont, 2to1, Tapered WAG

INJECTION WELL PROFILE STUDY

30% HCPV Inj

TERTIARY SATURATION HISTORY

OIL SATURATION

- ABOVE 0.600
- 0.550 – 0.600
- 0.500 – 0.550
- 0.450 – 0.500
- 0.400 – 0.450
- 0.350 – 0.400
- 0.300 – 0.350
- 0.250 – 0.300
- 0.200 – 0.250
- 0.150 – 0.200
- 0.100 – 0.150
- BELOW 0.100

Oil Saturation

TIME = 9517

CONT INJECTION

TIME = 9850

2TO1 INJ

TIME = 9908

TAPERED INJ
Reservoir Simulation

Saturation Profiles – Cont, 2to1, Tapered WAG

INJECTION WELL PROFILE STUDY

50% HCPV Inj

Oil Saturation

TIME = 10315

CONT INJECTION

TIME = 10897

2TO1 INJ

TIME = 12009

TAPERED INJ

TERTIARY SATURATION HISTORY

OIL SATURATION

ABOVE 0.600
0.550 – 0.600
0.500 – 0.550
0.450 – 0.500
0.400 – 0.450
0.350 – 0.400
0.300 – 0.350
0.250 – 0.300
0.200 – 0.250
0.150 – 0.200
0.100 – 0.150
BETWEEN 0.100
Reservoir Simulation

Saturation Profiles – Cont, 2to1, Tapered WAG

70% HCPV Inj

Cont. Injection

Tertiary Saturation History

Oil Saturation

Time = 10865

Time = 11706

Time = 14894

Cont. Injection

2to1 Inj

Tapered Inj

Property of Merchant Consulting – Dec 2010
Thanks,

Now its your turn?

David H. Merchant

Merchant Consulting
Email: MerchantConsulting@comcast.net

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

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