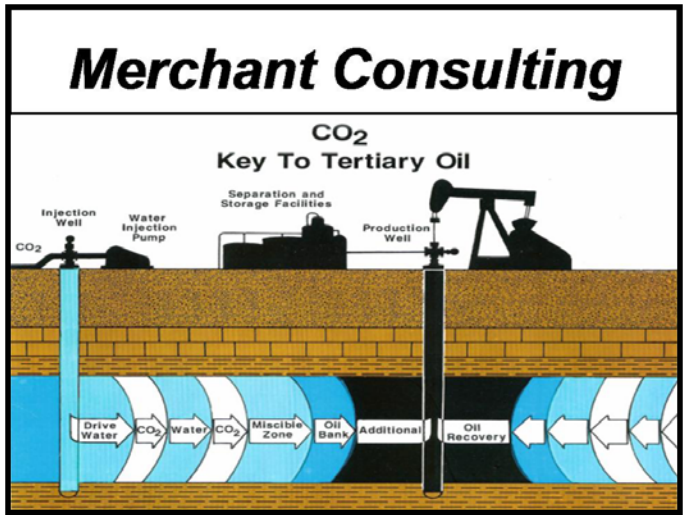
Life beyond 80 - A look at Conventional WAG Recovery beyond 80% HCPV Injection in CO_2 Tertiary Floods

David H. Merchant



CO_2 Storage Solutions

WEB Site: www.CO2StorageSolutions.com

Merchant Consulting

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Presented at the 16th Annual CO_2 Flooding Conference
December 9-10, 2010

Midland, Texas

Life beyond 80 – Conventional WAG CO_2 Oil Recovery

Setting Up the Pieces -Talk Objective

Last Year's Talk:

Comparisons of Conventional CO_2 WAG Injection Techniques used in the Permian Basin (2009 CO_2 Conference)

This Year's Talk:

1. Life up to 80 – A look at Conventional WAG Recovery Techniques as seen Today in CO_2 Tertiary Projects
2. Life beyond 80 – A look at Conventional WAG Recovery Techniques beyond 80% HCPV in CO_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

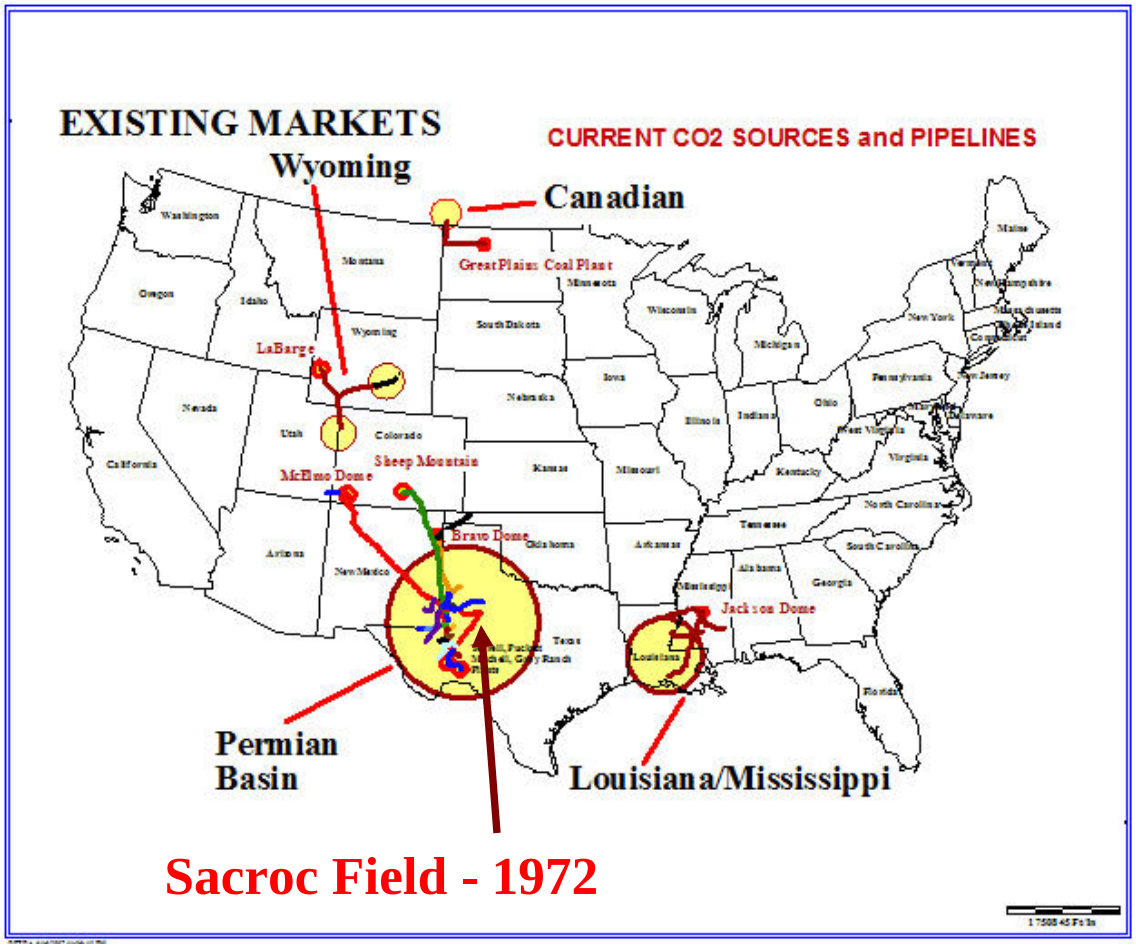
"The Previous Millennium"

CO_2 Flood History since 1972

"Life <u>up to</u> 80% HCPV Injected"

Tertiary CO_2 Flooding

"CO_2 Flood History since 1972"

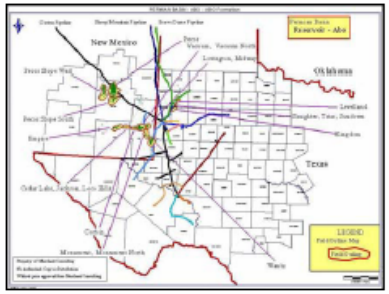


Today, 82 active CO_2 projects operate in the United States producing over 237,000 BOPD with over 2000 miles of CO_2 pipeline.

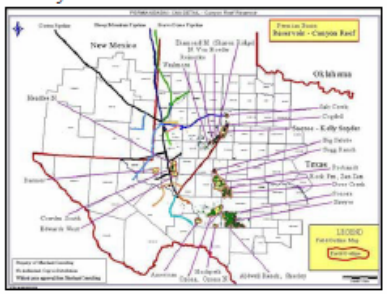
Tertiary CO_2 Flooding

Permian Basin (10 Producing Formations)

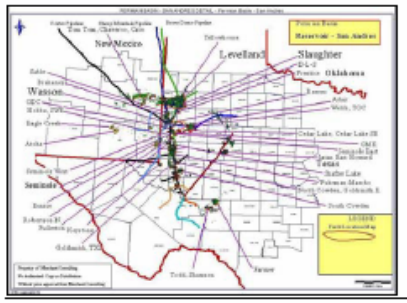
Abo Formation



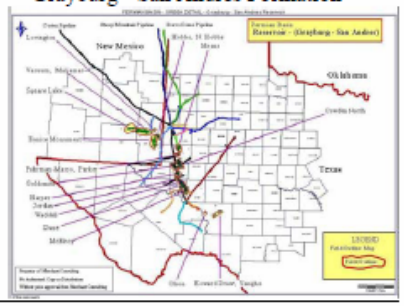
Canyon Reef Formation



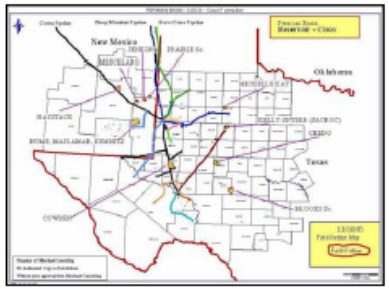
San Andres Formation



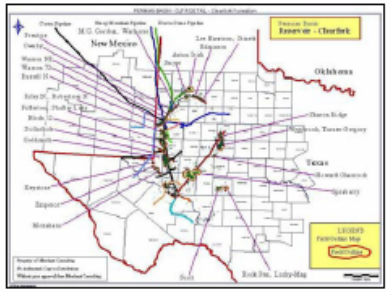
Grayburg - San Andres Formation



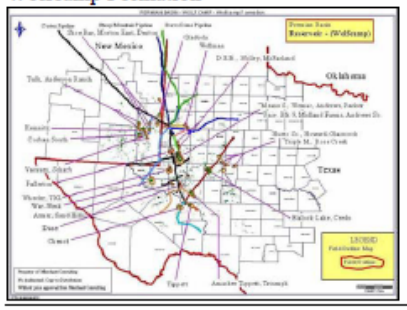
Cisco Formation



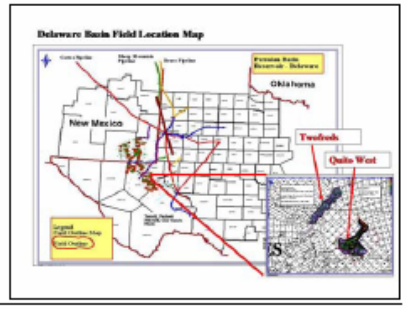
Clearfork Formation



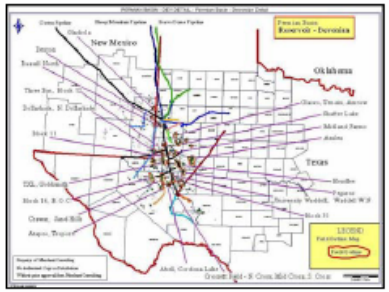
Wolfcamp Formation



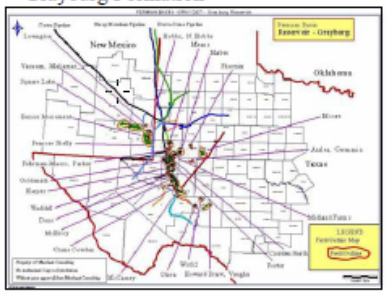
Delaware Basin Sandstone Formation



Devonian Formation



Grayburg Formation



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

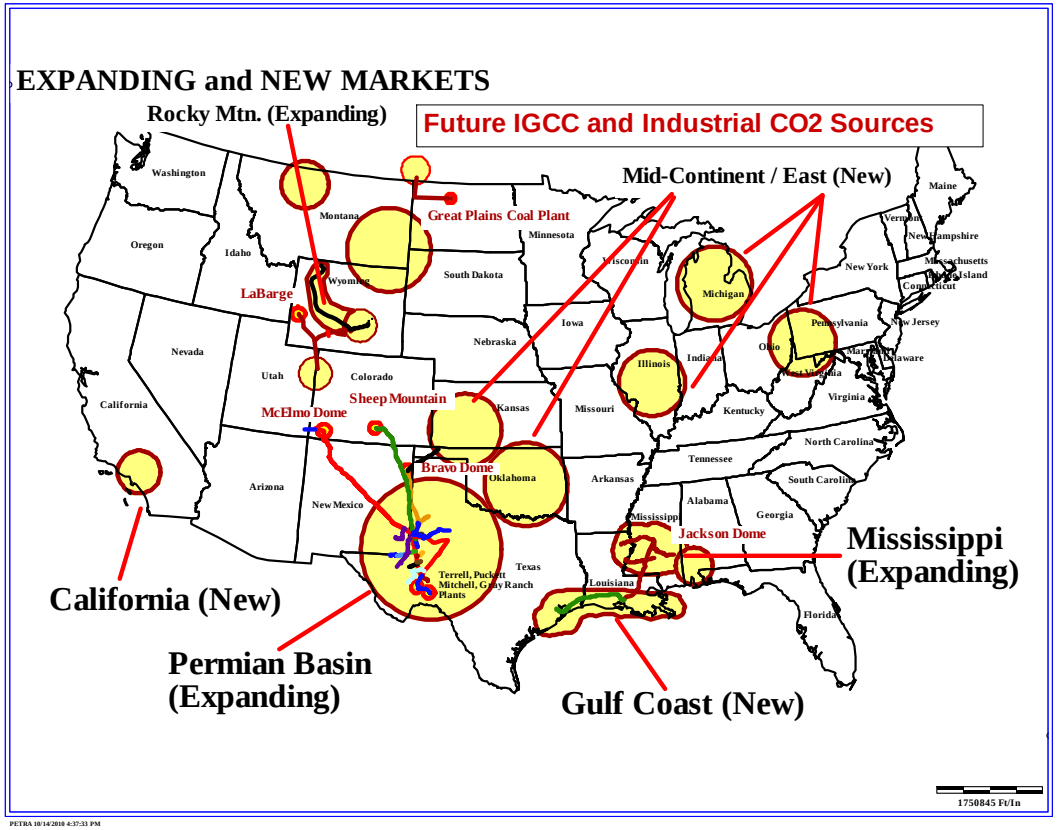
"The New Millennium"

21st Century

"Life beyond 80% HCPV Injected"

Tertiary CO_2 Flooding

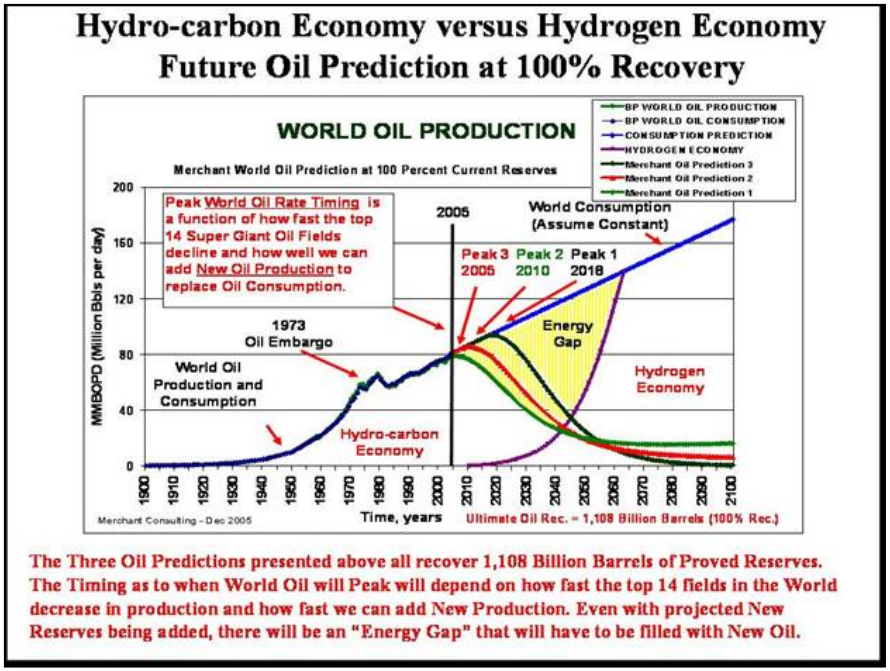
"New Millennium"



In the 21st Century, CO_2 Sequestration will open-up <u>New Oil Markets</u> in basins that contain EOR potential, but lacked the CO_2 to make projects profitable.

Tertiary CO_2 Flooding

"CO_2 Sequestration Future"



The Three Oil Predictions presented above all recover 1,108 Billion Barrels of Proved Reserves. The Timing as to when World Oil will Peak will depend on how fast the top 14 fields in the World decrease in production and how fast we can add New Production. Even with projected New Reserves being added, there will be an "Energy Gap" that will have to be filled with New Oil.

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 <u>Energy Gap</u> that exists between "Peak Oil" and the future "Hydrogen Energy Economy".

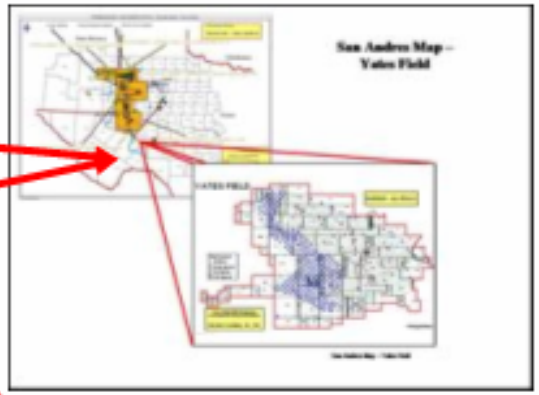
Tertiary CO_2 Flooding

"CO_2 Tertiary Recovery Methods"

Tertiary CO_2 Flooding

<u>Five</u> 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

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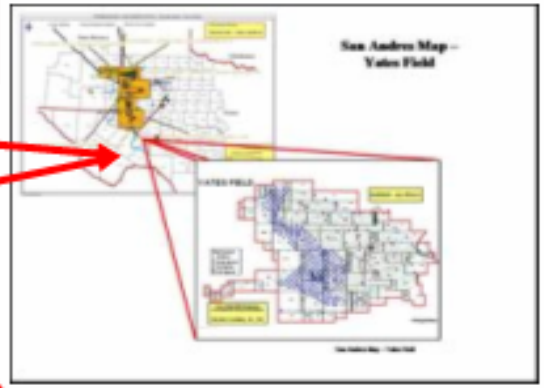


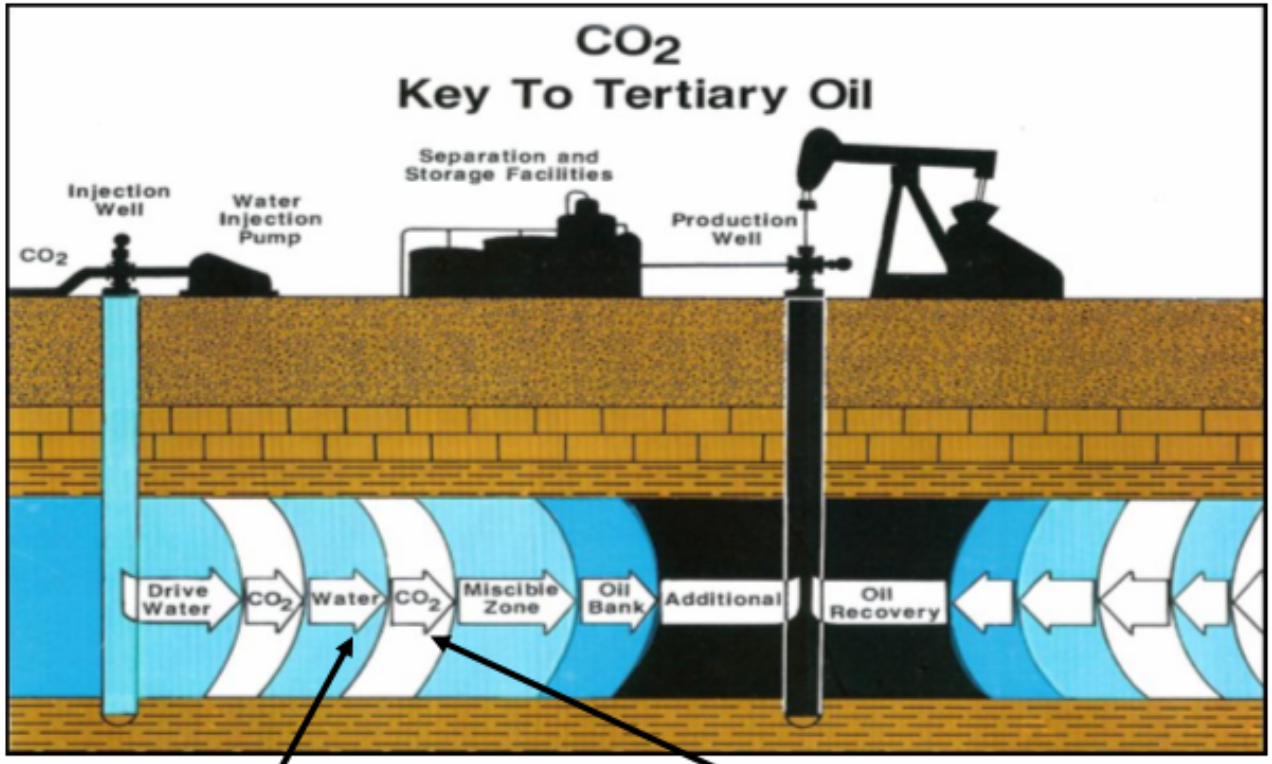
SPE Paper 139516 covers only Conventional WAG Techniques

Tertiary CO_2 Flooding

What makes CO_2 WAG Recovery Work?

What is Conventional WAG Management?

Conventional WAG Injection Techniques



Water (% HCPV Inj.) CO_2 (% 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?

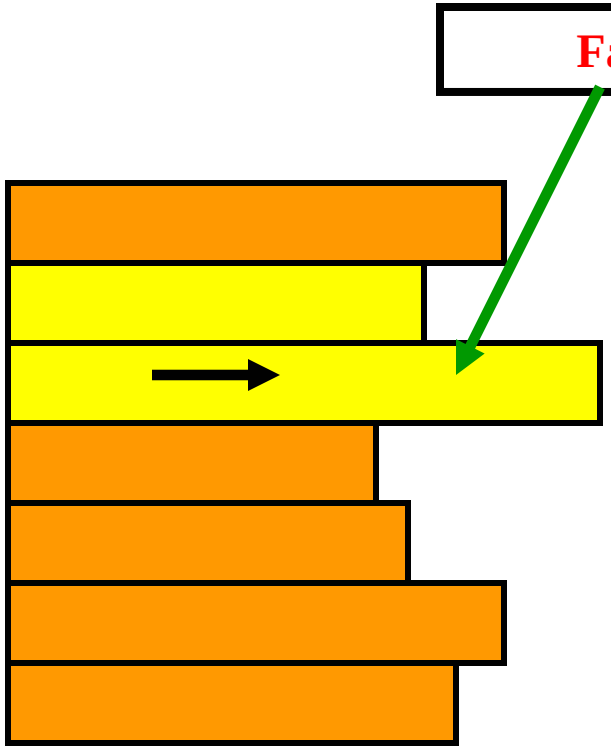
- One element vital to the technical success of any CO_2 flood is the Optimum Utilization of CO_2 Injectant.
- WAG Optimization is widely recognized as a viable technique in controlling the Miscible Process.

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

Slaughter Estate Unit

5 – Spot and Chickenwire Well Patterns

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 CO_2 Inj. (20-100+ % HCPV)
- Half Cycle CO_2 Slug Size - HCPV of CO_2 Inj in one cycle (0.25 - 30.00 %)
- Water Cycle CO_2 Slug Size - HCPV of H_2O Inj in one cycle (0.25 - 10.00 %)
- WAG Ratio - Ratio of Half cycle Water to Half cycle CO_2
- GWR Ratio - Ratio of Half cycle CO_2 to Half cycle H_2O

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 CO_2 - Continuously inject CO_2 (No water)
- Constant WAG - example - 1:1 WAG with (1.0 % CO_2 , 1.0% H_20)
  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 % CO_2 , 0.10 % H_2O) for 5% HCPV
  WAG (1.0 % CO_2 , 0.50 % H_2O) for 10% HCPV
  WAG (1.0 % CO_2 , 1.00 % H_2O) for 20% HCPV
  WAG (1.0 % CO_2 , 2.00 % H_2O) for 30% HCPV
  Chase Water Injection

"Wetting the WAG"

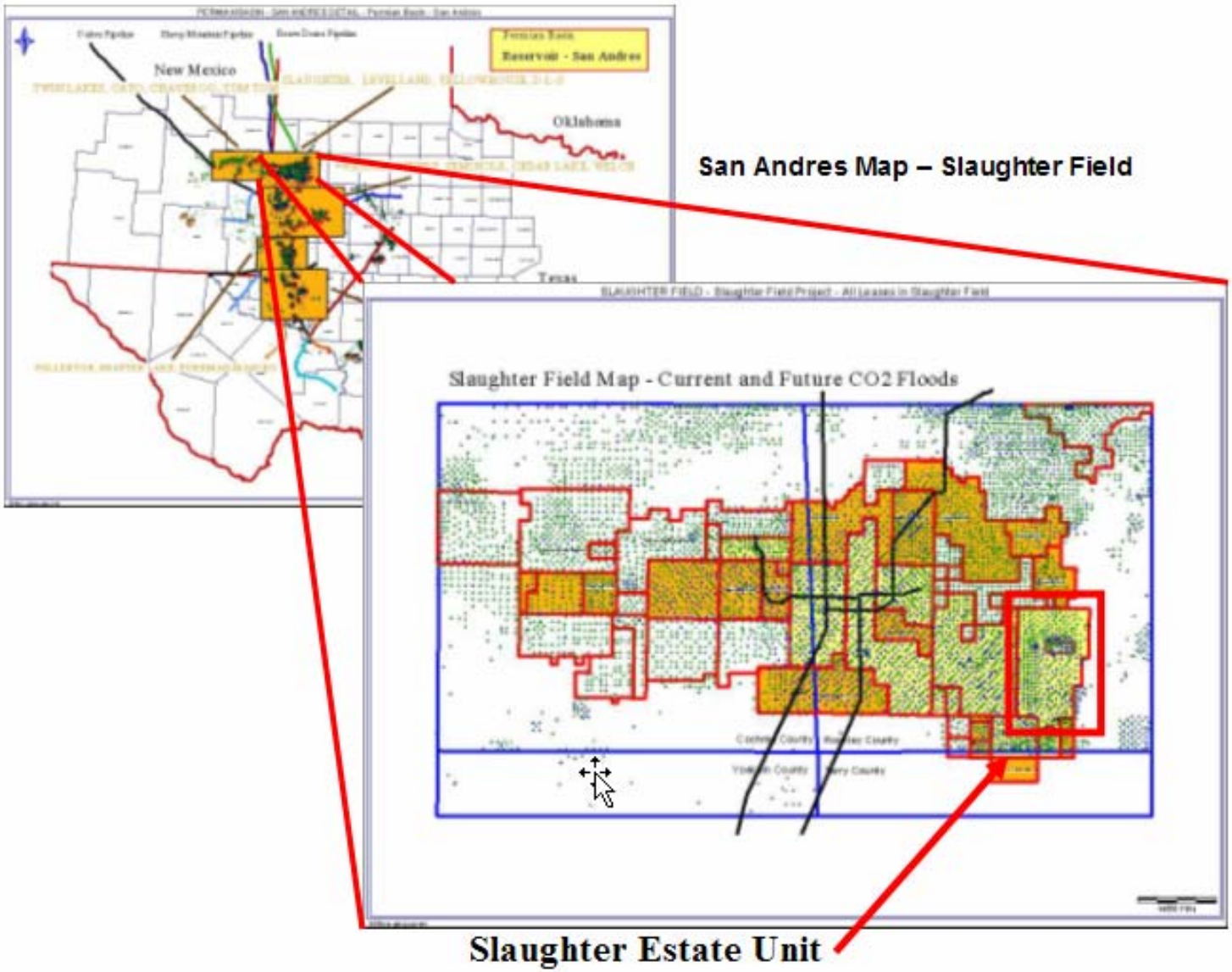
Note: Total Slug Size = 85% HCPV Inj. Of CO_2

Reservoir Simulation

Reservoir Model Comparison

1. **Base Waterflood Injection**
2. **Continuous CO_2 Injection**
3. **Constant WAG Ratio CO_2 Injection**
4. **Tapered WAG Ratio CO_2 Injection**

Slaughter Estate Unit - Example



Reservoir Simulation

Reservoir Model Study - San Andres 5 Spot

Single 5 Spot Pattern (10X10X6 Grid)

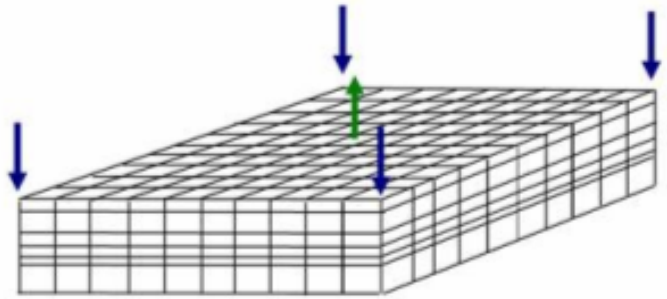


Table No. 1
Average Model Properties

Depth, Feet	5000
Reservoir Temperature, deg F	105
Net Pay, feet	104
Average Porosity, percent	11.4
Average Permeability, md	6.4
Oil FVF @ Original Bubble Point, RB/STB	1.228
Oil Reservoir Pressure @ 1300 feet subsea, psi	1710
Bubble Point Pressure @ 1300 feet subsea, psi	1710
Pattern Segment Model Acreage	25
No. of Model Layers	6

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

CO_2 Capture Project - An Integrated, Collaborative Technology Development Project for Next Generation CO_2 Separation, Capture and Geologic Sequestration

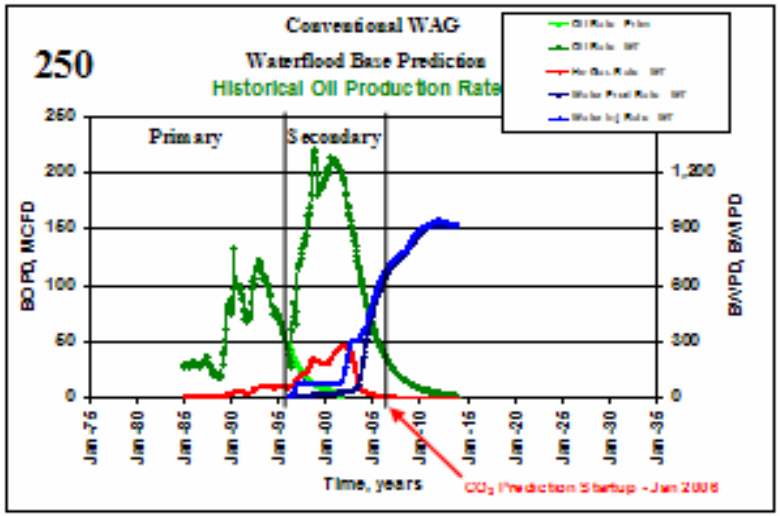
Subcontract C010: EOR/CO2 Storage Optimization and Economics – 2004 Program

Supplemental Report - Evaluation of Enhanced Oil Recovery (EOR) "Conventional CO_2 WAG Injection Methods".

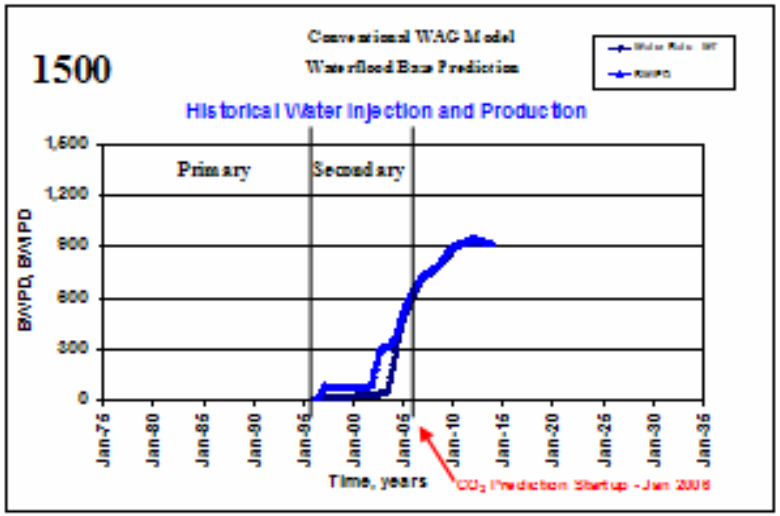
Table No. 2
Average Layer Grid Properties in the Model

Model Layer	Thickness ft	Porosity-Thickness ft	Permeability-Thickness md-ft	k-h/phi-h
1	16.8	1.46	21.8	15
2	24.0	2.95	129.6	44
3	12.6	1.68	127.3	76
4	13.7	2.15	160.3	75
5	9.9	1.08	166.3	154
6	27.1	2.57	56.9	22
Total	104.1	11.89	662.2	56

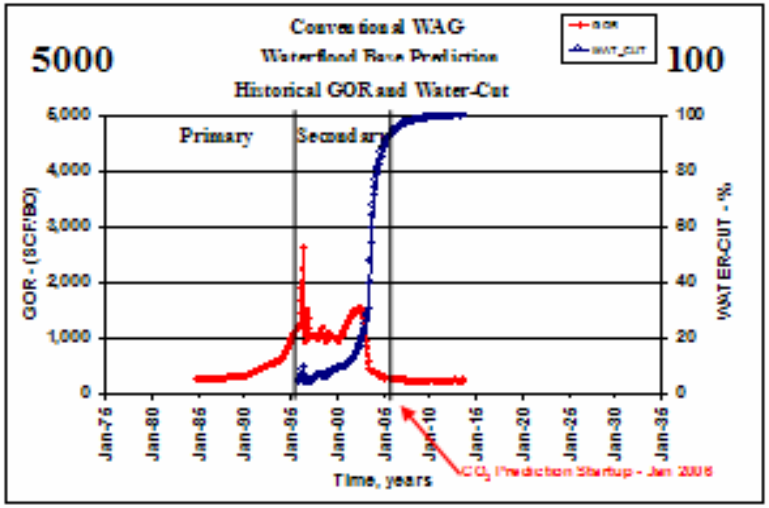
Waterflood History



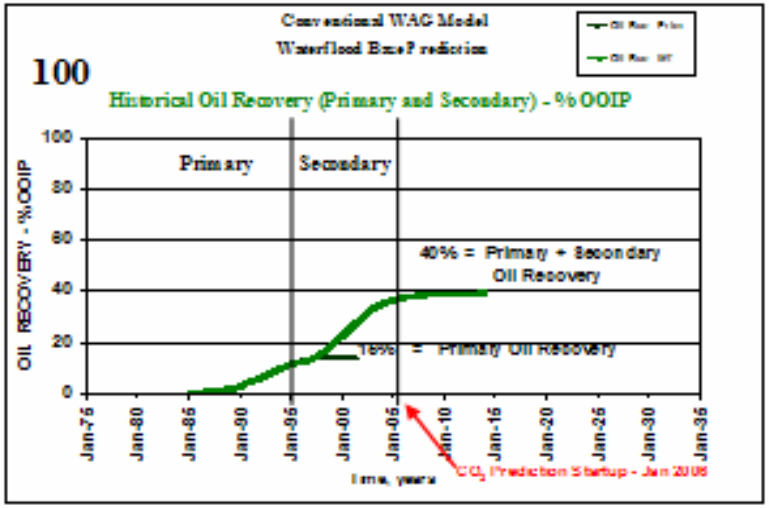
BOPD, MCFD(hc), BWPD



BWIPD, BWPD



GOR, Water-Cut



Oil Recovery - % OOIP

Reservoir Simulation

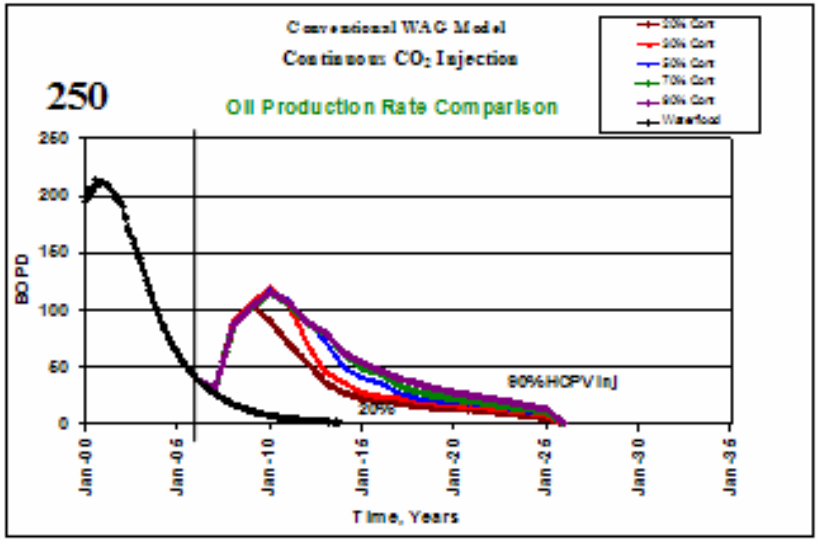
Tertiary CO_2 Predictions

CO_2 Injection Case Comparison

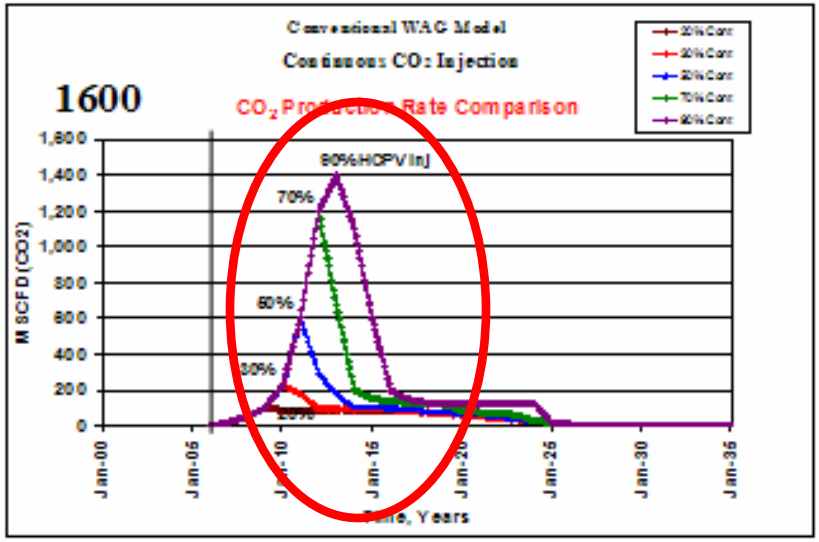
(20%, 30%, 50%, 70%, and 90% - HCPV CO_2 Injected)

- **Continuous CO_2 Injection**
- **Constant WAG Ratio CO_2 Injection**
- **Tapered WAG Ratio CO_2 Injection**

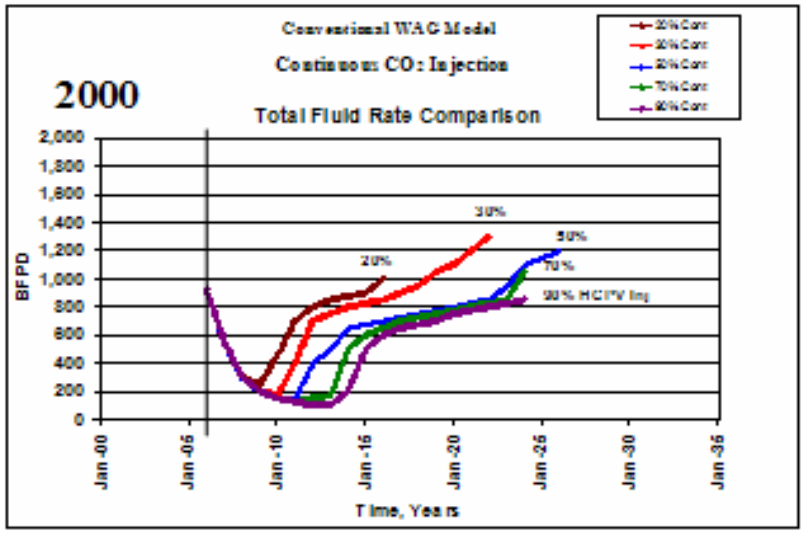
Continuous Injection



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



MCFD (CO2) (20,30,50,70,90 - %HCPV (Inj)

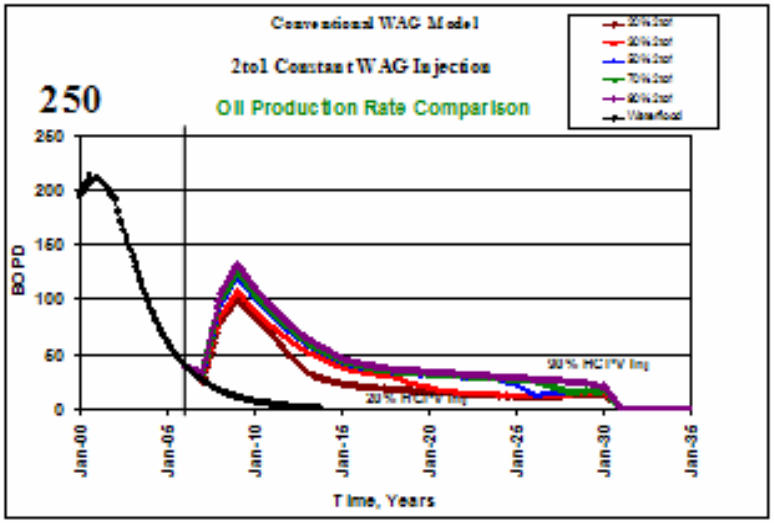


BFPD (Total) (20,30,50,70,90 - %HCPV (Inj)

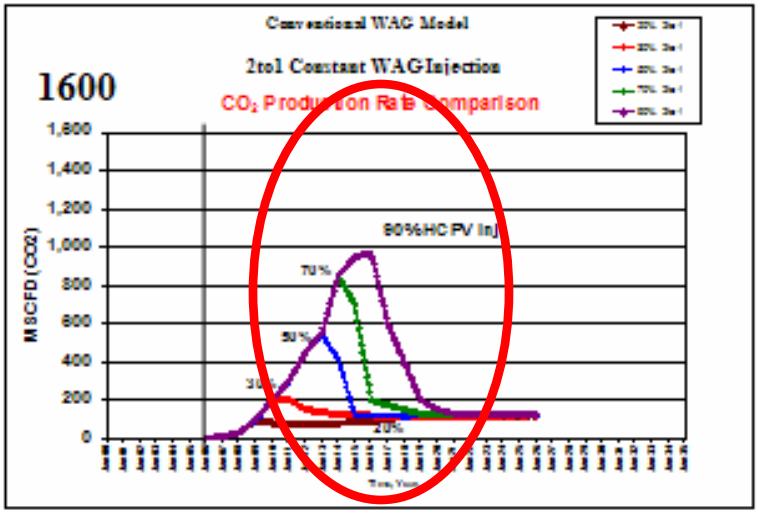
Continuous Injection

- Advantages
  1. Quick Oil Response
- Disadvantages
  1. Controlling Gas Breakthrough as flood matures
  2. Optimum Slug Size may be 30 % HCPV Inj.

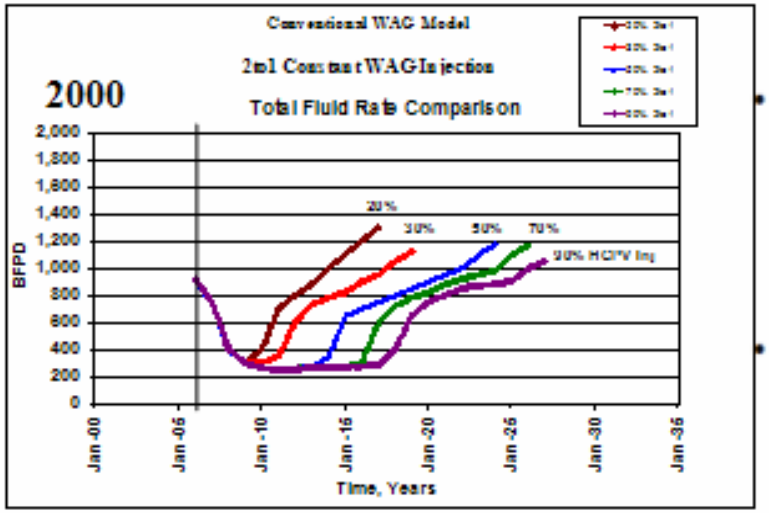
Constant WAG Injection



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



MCFD(CO2) (20,30,50,70,90 - %HCPV (Inj)

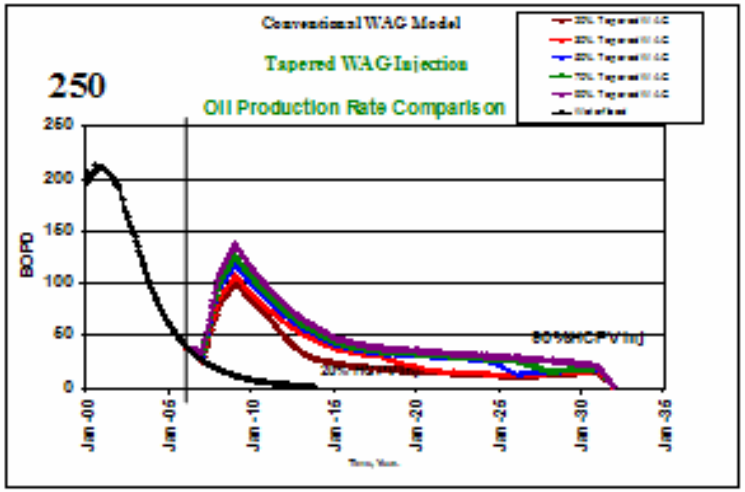


BFPD (Total) (20,30,50,70,90 - %HCPV (Inj)

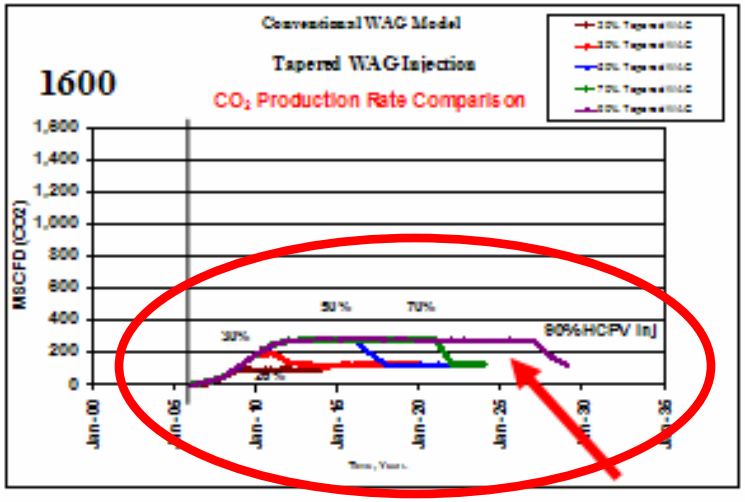
Constant WAG Ratio Injection

- 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%

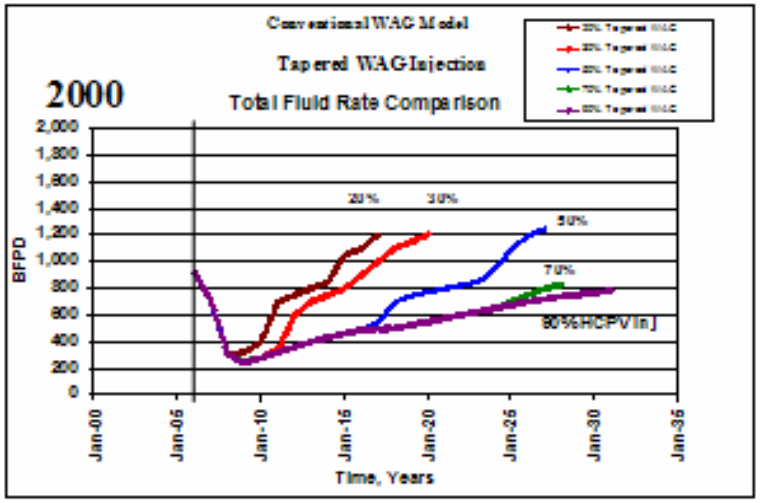
Tapered WAG Injection



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



LEVEL LOAD



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

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. Can control the flood to Plant and Pipeline Capacities
  5. Can accelerate or retard Flood Response
- Disadvantages
  1. None to date

Reservoir Simulation

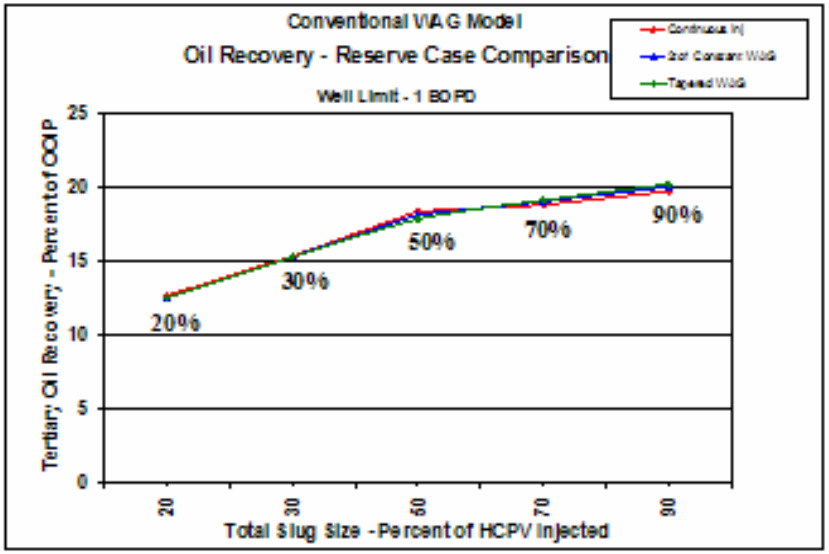
Tertiary CO_2 Predictions

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

- **Continuous CO_2 Injection**
- **Constant WAG Ratio CO_2 Injection**
- **Tapered WAG Ratio CO_2 Injection**

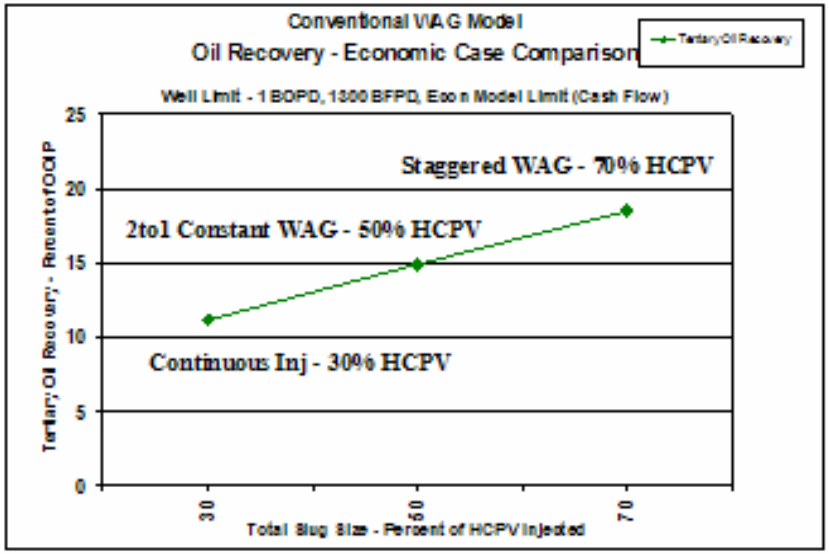
Tertiary CO_2 Predictions

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



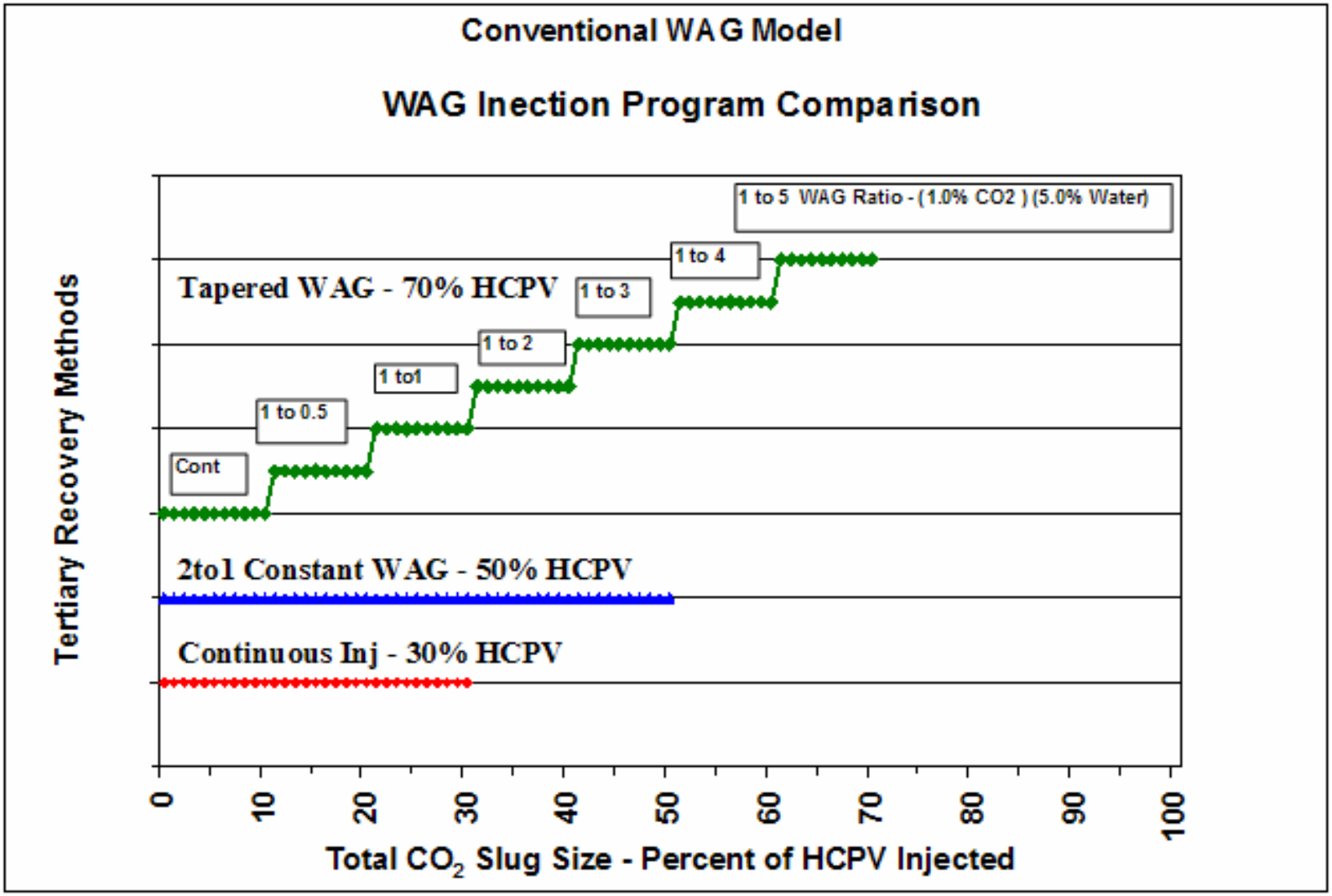
Oil Recovery Comparison:
Continuous – Same
Constant WAG – Same
Tapered WAG – Same

Reservoir Model
Injection Case Comparison
Tertiary Oil Recovery vs. CO_2 HCPV(Inj)
With Economic Limit



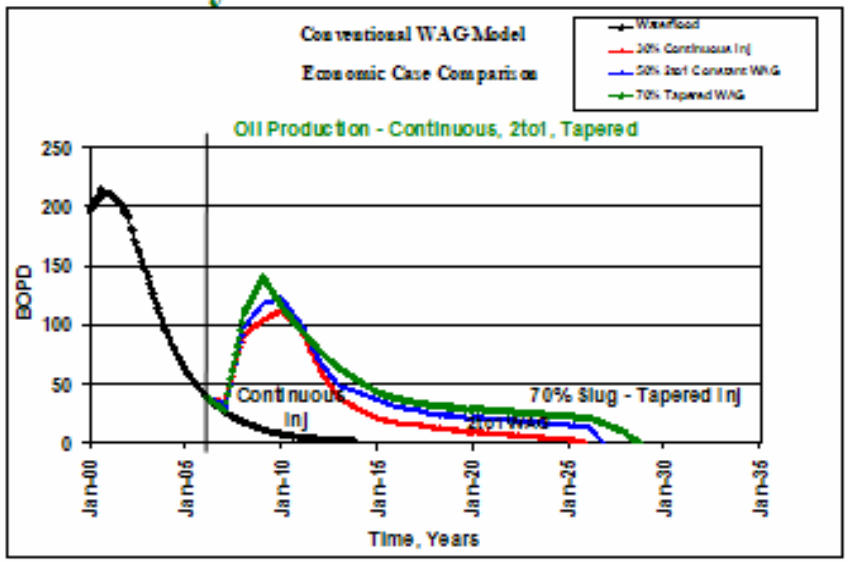
Optimum Slug Size:
Continuous – 30% HCPV Inj.
Constant WAG – 50% HCPV Inj.
Tapered WAG – 70% HCPV Inj.

CO_2 Recovery Methods

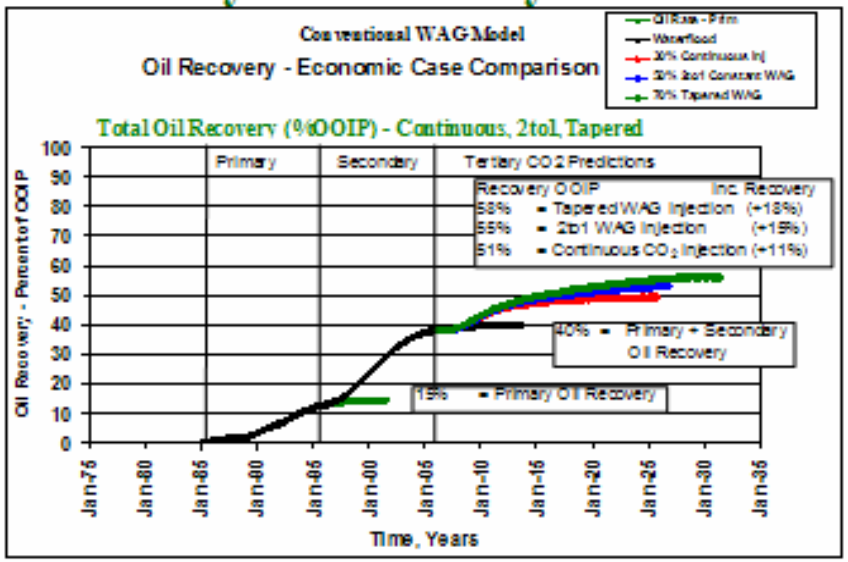


Economic Case Comparisons – Continuous 30, Constant WAG 50, Tapered 70)

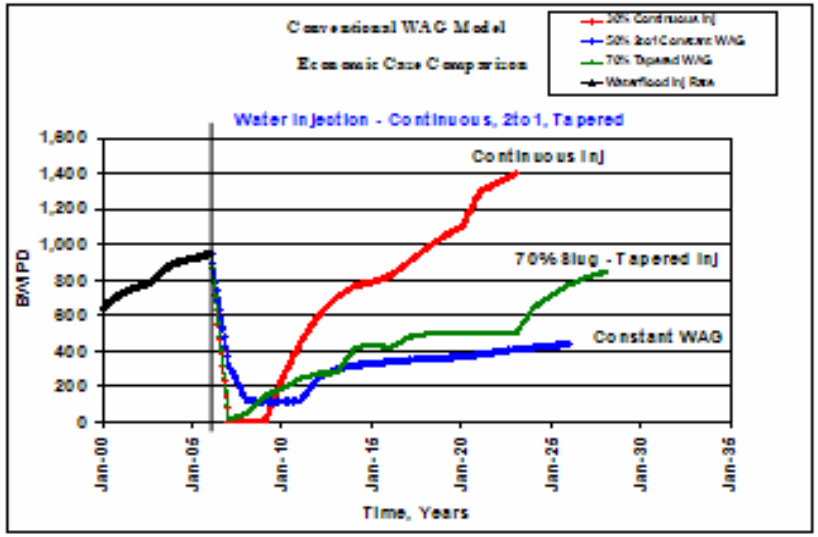
Tertiary Oil Rate



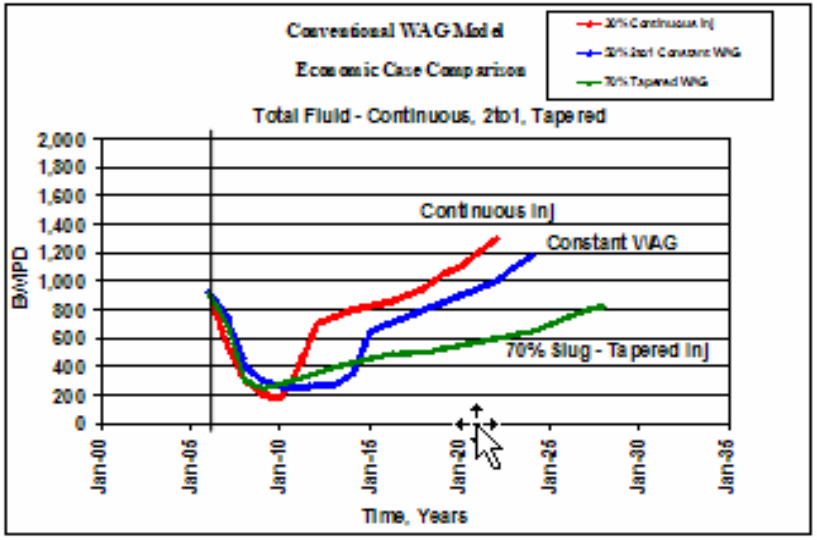
Tertiary Oil Recovery



Water Injection Rate

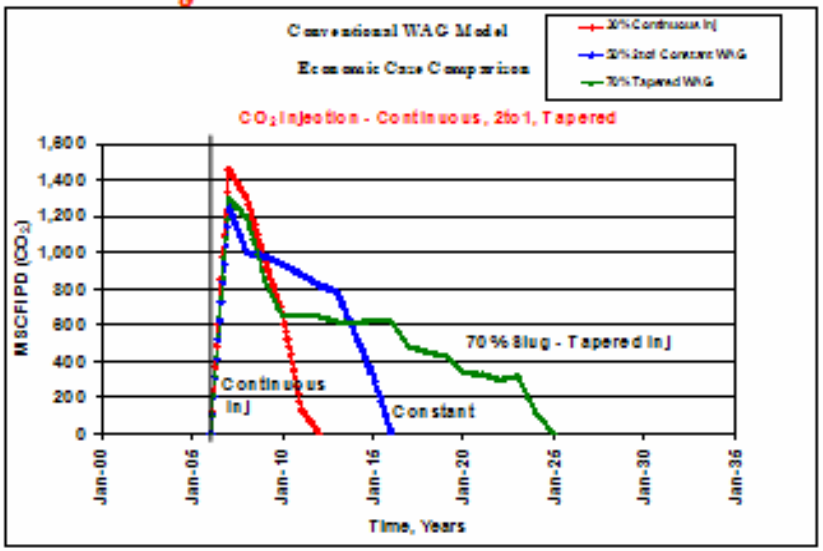


Total Fluid Production Rate

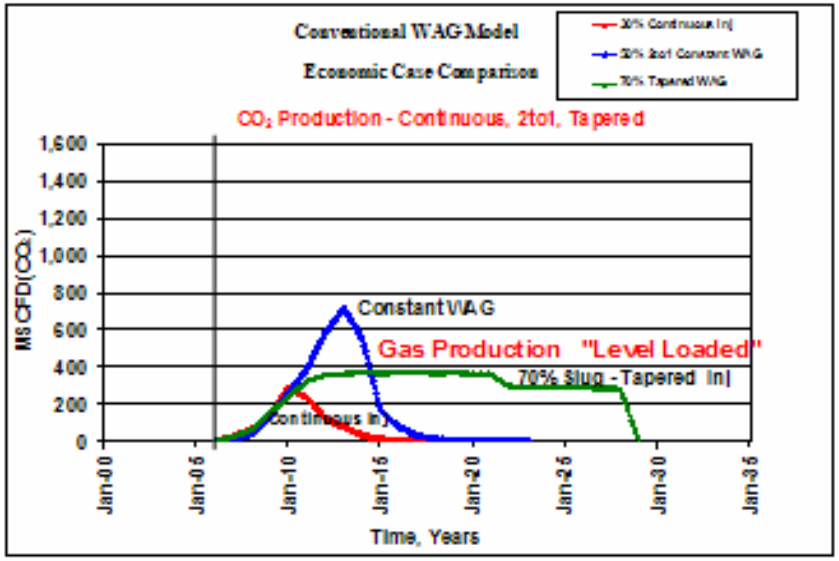


Economic Case Comparisons – Continuous 30, Constant WAG 50, Tapered 70)

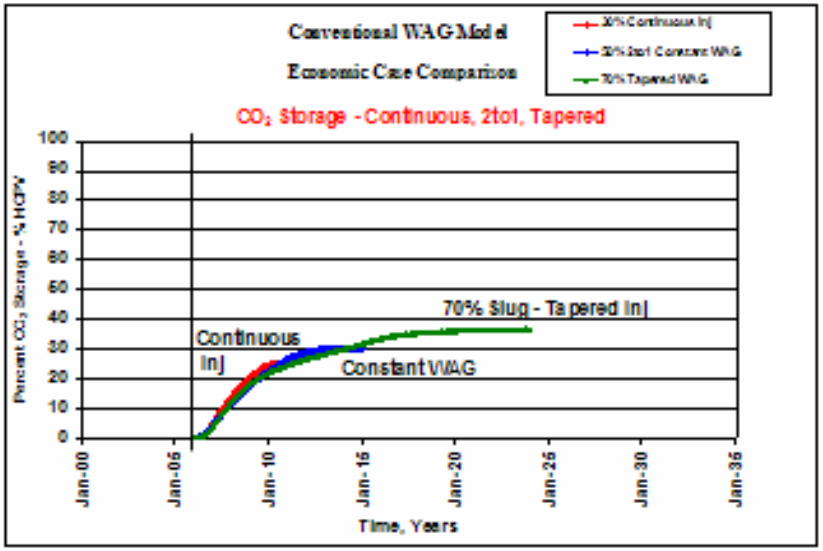
Gas Injection Rate



Gas Production Rate



CO_2 Storage - % HCPV



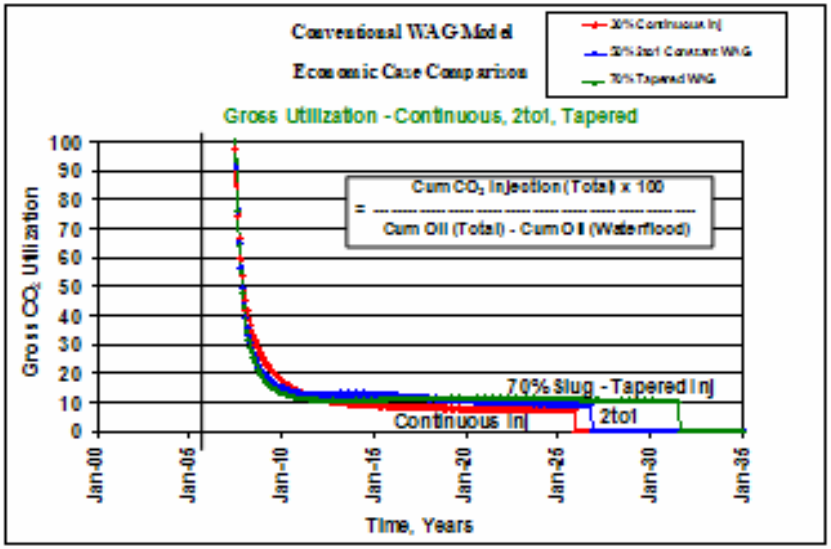
Tapered WAG Ratio Injection

- Advantages

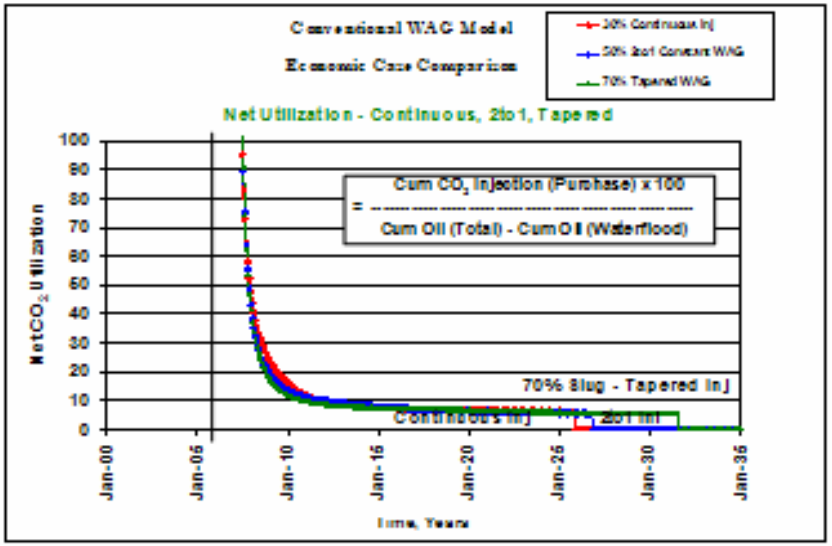
1. Controls Mobility (Reduces Gas Processing)
2. Improves Operations (Less Gas Cycling)
3. Extends Flood life beyond 50% HCPV Inj.
4. CO_2 Storage increases to (30% to 40% HCPV)

Economic Case Comparisons – Continuous 30, Constant WAG 50, Tapered 70)

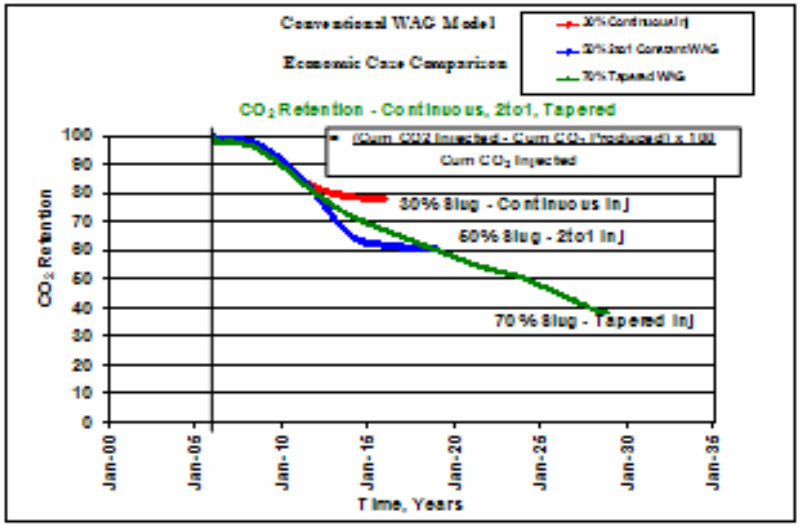
Gross – CO_2 Utilization



Net – CO_2 Utilization



CO_2 Retention



CO_2 Utilization and CO_2 Retention

- **CO_2 Gross Utilization** is a measure of the **Efficiency** of the CO_2 Process (Amount of Total CO_2 Injected per Bbl Tertiary Recovered)
- **CO_2 Net Utilization** is a measure of the **Efficiency** of the CO_2 Process (Amount of Purchased CO_2 Injected per Bbl Tertiary Recovered)
- **CO_2 Retention** is an Engineering term used to measure the total amount of CO_2 Retained in the reservoir to the total amount of CO_2 injected

Reservoir Simulation

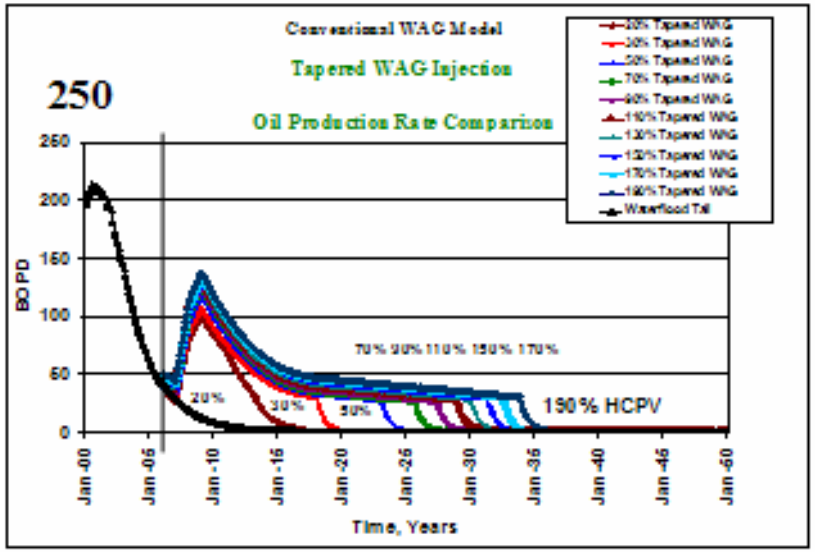
Tertiary CO_2 Predictions

CO_2 Injection – Life beyond 80% HCPV CO_2 Injected

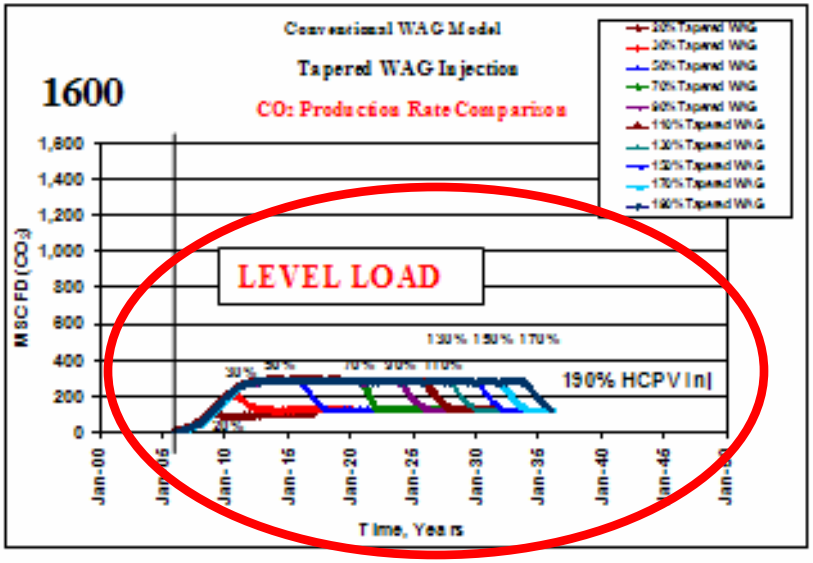
(Tapered WAG Case Comparison)

- 20% Continuous CO_2 Injection
- 30% Tapered WAG Ratio CO_2 Injection
- 50% Tapered WAG Ratio CO_2 Injection
- 70% Tapered WAG Ratio CO_2 Injection
- 90% Tapered WAG Ratio CO_2 Injection
- 110% Tapered WAG Ratio CO_2 Injection
- 130% Tapered WAG Ratio CO_2 Injection
- 150% Tapered WAG Ratio CO_2 Injection
- 170% Tapered WAG Ratio CO_2 Injection
- 190% Tapered WAG Ratio CO_2 Injection

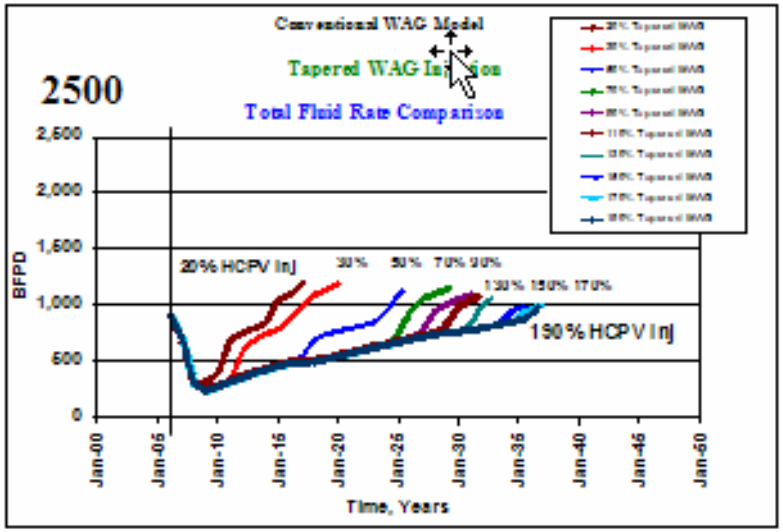
Tapered WAG Injection – to 190% HCPV Inj



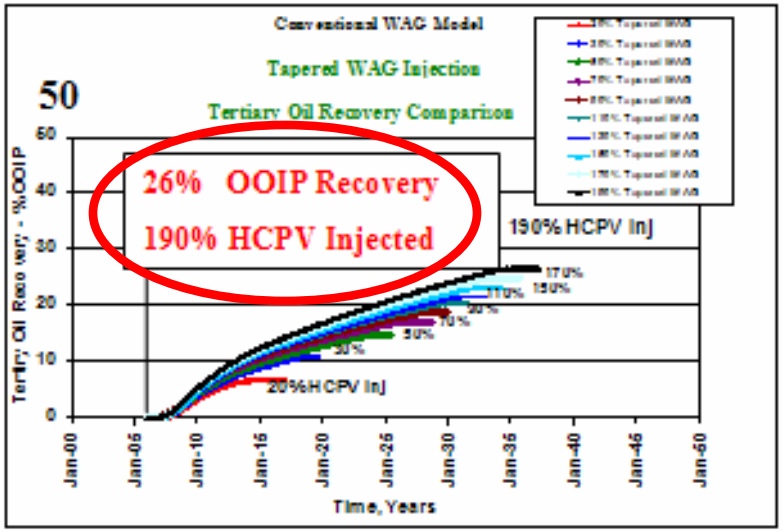
BOPD (20,30,50,70,90,110,130,150,170,190)



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)

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 CO_2 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 (CO_2 will never remove all the oil)
6. CO_2 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 CO_2 Purchase Price, Low Recycle Plant and Field Capital Investments
11. CO_2 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 (CO_2 Purchase Volume)

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

Formation, Field, Lease **EOR Rec, Utilization** **Life beyond 80+ Bibliography**

Table 2. - San Andres and Grayburg Formation – Dolomite

				Current Economic			Life beyond 80% HCPV Inj			
State	Formation	Field	Lease	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Tertiary Recovery (%OOIP)	Gross CO2 Utilization (MSCF/STB)	Net CO2 Utilization (MSCF/STB)	Bibliography References
Texas	San Andres	Wasson	Denver Unit	15 to 20	10 to 15	5 to 10	20 to 25	5 to 10	1 to 5	7,8,9,10
Texas	San Andres	Wasson	Denver Unit-ROZ	10 to 15	15 to 20	5 to 10	15 to 20	10 to 15	5 to 10	11,18
Texas	San Andres	Wasson	Wasson ODC Unit	15 to 20	10 to 15	5 to 10	20 to 25	5 to 10	1 to 5	12
Texas	San Andres	Wasson	Cornell Unit	15 to 20	10 to 15	5 to 10	20 to 25	5 to 10	1 to 5	13
Texas	San Andres	Wasson	Bennett Ranch Unit	15 to 20	10 to 15	5 to 10	20 to 25	5 to 10	1 to 5	14,15
Texas	San Andres	Wasson	Willard Unit	15 to 20	10 to 15	5 to 10	20 to 25	5 to 10	1 to 5	16
Texas	San Andres	Seminole	Seminole Unit-Main Pay	20 to 25	10 to 15	5 to 10	25 to 30	5 to 10	1 to 5	17
Texas	San Andres	Seminole	Seminole Unit-ROZ	10 to 15	15 to 20	5 to 10	15 to 20	10 to 15	5 to 10	11,18
Texas	San Andres	Slaughter	Slaughter Estate Unit	15 to 20	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	19 thru 24
Texas	San Andres	Slaughter	Frazier Unit	15 to 20	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	
Texas	San Andres	Slaughter	Central Mallet Unit	15 to 20	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	25
Texas	San Andres	Slaughter	Slaughter Sundown	15 to 20	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	26, 27,28
Texas	San Andres	Slaughter	Mobil Mallet Unit	15 to 20	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	29
Texas	San Andres	Slaughter	H T Boyd Unit	15 to 20	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	
Texas	San Andres	Slaughter	Igoe Smith	15 to 20	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	
Texas	San Andres	Slaughter	Alex Slaughter Estate	15 to 20	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	
Texas	San Andres	Levelland	Levelland	5 to 10	15 to 20	5 to 10	10 to 15	15 to 20	5 to 10	30,31,32
Texas	San Andres	Means (San Andres)	Means (San Andres)	10 to 15	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	33,34
Texas	San Andres	Goldsmith	Goldsmith	10 to 15	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	35,36
Texas	San Andres	Hanford	Hanford	10 to 15	15 to 20	5 to 10	20 to 25	10 to 15	5 to 10	37
New Mexico	Grayburg San Andres	Vacuum	East Vacuum	10 to 15	15 to 20	5 to 10	15 to 20	10 to 15	5 to 10	38,39
New Mexico	Grayburg San Andres	Vacuum	Central Vacuum	10 to 15	15 to 20	5 to 10	15 to 20	10 to 15	5 to 10	40
New Mexico	Grayburg San Andres	Maljamar	Maljamar Unit	10 to 15	15 to 20	5 to 10	15 to 20	10 to 15	5 to 10	41,42
New Mexico	Grayburg San Andres	North Hobbs	North Hobbs	10 to 15	15 to 20	5 to 10	15 to 20	10 to 15	5 to 10	
Texas	San Andres	East Penwell (SA) Unit	East Penwell (SA) Unit	5 to 10	15 to 20	5 to 10	10 to 15	15 to 20	5 to 10	
Texas	Grayburg	Mabee	Mabee	10 to 15	15 to 20	5 to 10	15 to 20	10 to 15	5 to 10	43
Texas	San Andres	GMK South	GMK South	5 to 10	15 to 20	5 to 10	10 to 15	15 to 20	5 to 10	44
Texas	San Andres	Adair San Andres Unit	Adair San Andres Unit	5 to 10	15 to 20	5 to 10	10 to 15	15 to 20	5 to 10	
Texas	San Andres	Cedar Lake	Cedar Lake	5 to 10	15 to 20	5 to 10	5 to 10	15 to 20	5 to 10	
Texas	San Andres	Welch	West Welch	5 to 10	15 to 20	5 to 10	10 to 15	10 to 15	5 to 10	45
Texas	San Andres	Welch	South Welch	5 to 10	15 to 20	5 to 10	10 to 15	10 to 15	5 to 10	46
Texas	Grayburg San Andres	Cowden	North Cowden Demo.	5 to 10	15 to 20	5 to 10	5 to 10	15 to 20	5 to 10	
Texas	San Andres	Cowden	South Cowden	5 to 10	15 to 20	5 to 10	5 to 10	15 to 20	5 to 10	47, 48

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

Formation, Field, Lease **EOR Rec, Utilization** **Life beyond 80+ Bibliography**

Table 3. - Clearfork Formation – Limestone (Tight - Low Permeability)

				Current Economic			Life beyond 80% HCPV Inj			
State	Formation	Field	Lease	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Bibliography References
Texas	Clearfork	Anton Irish	Anton Irish	5 to 10	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	49
Texas	Clearfork	Wasson (South)	Wasson (South)	1 to 5	10 to 15	5 to 10	1 to 5	10 to 15	5 to 10	50

Table 4. - Devonian Formation – Tripolitic Chert

				Current Economic			Life beyond 80% HCPV Inj			
State	Formation	Field	Lease	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Bibliography References
Texas	Devonian	Dollarhide	Dollarhide Devonian Unit	10 to 15	5 to 10	1 to 5	15 to 20	5 to 10	1 to 5	51 thru 54
New Mexico	Devonian	Dollarhide	West Dollarhide Unit	10 to 15	5 to 10	1 to 5	15 to 20	5 to 10	1 to 5	
Texas	Devonian	Dollarhide	North Dollarhide Unit	5 to 10	5 to 10	1 to 5	10 to 15	5 to 10	1 to 5	55
Texas	Devonian	North Cross	N. Cross-Devonian Unit	35 to 40	5 to 10	1 to 5	40 to 45	5 to 10	1 to 5	56-57

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

				Current Economic			Life beyond 80% HCPV Inj			
State	Formation	Field	Lease	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Bibliography References
Texas	Canyon Reef	Kelly Snyder (Sacroc)	Sacroc Unit	10 to 15	10 to 15	5 to 10	15 to 20	10 to 15	5 to 10	58 thru 65
Texas	Canyon Reef	Salt Creek	Salt Creek	10 to 15	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	66,67
Texas	Canyon Reef	Sharon Ridge	Sharon Ridge	5 to 10	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	68
Texas	Canyon Reef	Cogdell	Cogdell	5 to 10	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	69

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

Formation, Field, Lease **EOR Rec, Utilization** **Life beyond 80+ Bibliography**

Table 6. - Strawn, Morrow, Delaware, Springer, Marmaton, and Yates (Fluivial Deltaic, Point Bar, Turbidite)

				Current Economic			Life beyond 80% HCPV Inj			
State	Formation	Field	Lease	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Bibliography References
Texas	Strawn	Katz	Katz	10 to 15	10 to 15	5 to 10	15 to 20	10 to 15	5 to 10	70
Oklahoma	Morrow	Postle	Postle	10 to 15	10 to 15	5 to 10	15 to 20	10 to 15	1 to 5	71,72
Oklahoma	Morrow	Camrick	Camrick	10 to 15	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	
Texas	Delaware Ramsey	Twofreds	Twofreds	10 to 15	10 to 15	5 to 10	15 to 20	10 to 15	5 to 10	73,74,75
Texas	Delaware Ramsey	Ford Geraldine	Ford Geraldine	10 to 15	10 to 15	5 to 10	15 to 20	10 to 15	5 to 10	76,77
Texas	Delaware Ramsey	El Mar	El Mar	10 to 15	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	
Texas	Delaware Ramsey	East Ford	East Ford	10 to 15	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	
Texas	Springer	Northeast Purdy	Northeast Purdy	10 to 15	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	78
Texas	Marmaton	Hansford Marmaton	Hansford Marmaton	10 to 15	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	79
Texas	Yates	North Ward Estes	North Ward Estes	5 to 10	10 to 15	1 to 5	10 to 15	10 to 15	1 to 5	80
California	Stevens MMB	Elk Hills	Elk Hills MMB	10 to 20	10 to 15	5 to 10	20 to 30	10 to 15	5 to 10	81

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

				Current Economic			Life beyond 80% HCPV Inj			
State	Formation	Field	Lease	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Bibliography References
Wyoming	Tensleep	Wertz	Wertz	5 to 10	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	82
Wyoming	Tensleep	Lost Soldier	Lost Soldier	5 to 10	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	83 thru 86
Wyoming	Mesaverde Almond	Patrick Draw Monell	Patrick Draw Monell	5 to 10	10 to 15	5 to 10	10 to 15	10 to 15	5 to 10	
Colorado	Weber SS	Rangely	Rangely Weber Unit	5 to 10	5 to 10	1 to 5	10 to 15	5 to 10	1 to 5	87 thru 92
Texas	Sprayberry	Sprayberry	Sprayberry	0 to 2	10 to 15	5 to 10	0 to 2	10 to 15	5 to 10	93,94

Table 8. - Heavy Oil

				Current Economic			Life beyond 80% HCPV Inj			
State	Formation	Field	Lease	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Tertiary Recovery (%OOIP)	Gross CO_2 Utilization (MSCF/STB)	Net CO_2 Utilization (MSCF/STB)	Bibliography References
California	Ranger	Wilmington (Onshore)	FB1, FB3, FB5	10 to 15	15 to 20	5 to 10	10 to 15	15 to 20	5 to 10	95 thru 98
Arkansas	Ozan (Meaken Sand)	Lick Creek	Lick Creek Unit	10 to 15	15 to 20	5 to 10	10 to 15	15 to 20	5 to 10	99, 100

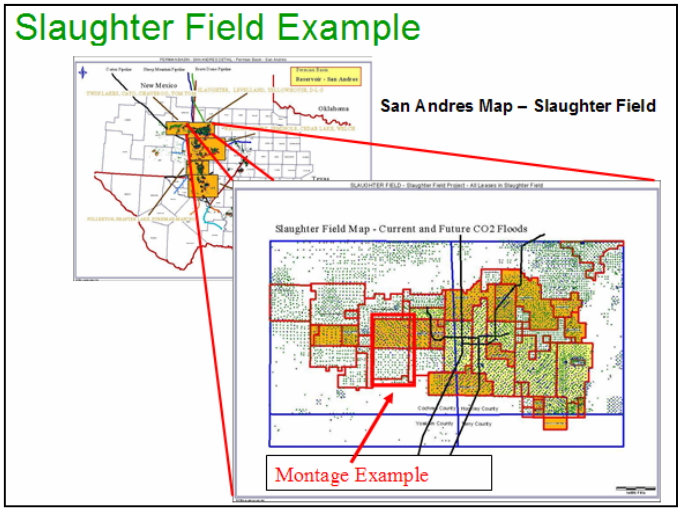
Tertiary CO_2 Flooding

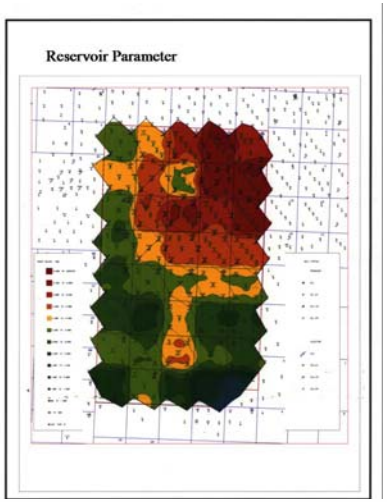
"Conformance Issues in CO_2 Flooding "

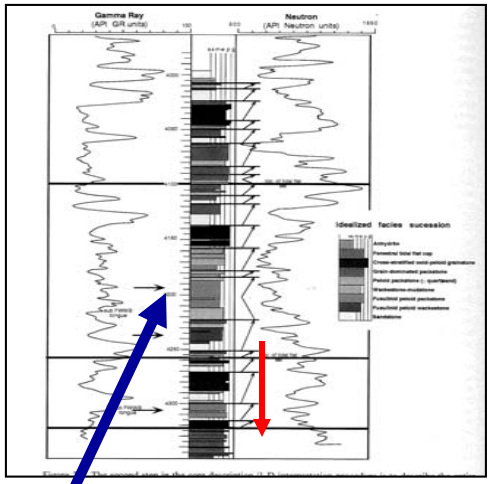
"Montage Approach – SPE 26624"

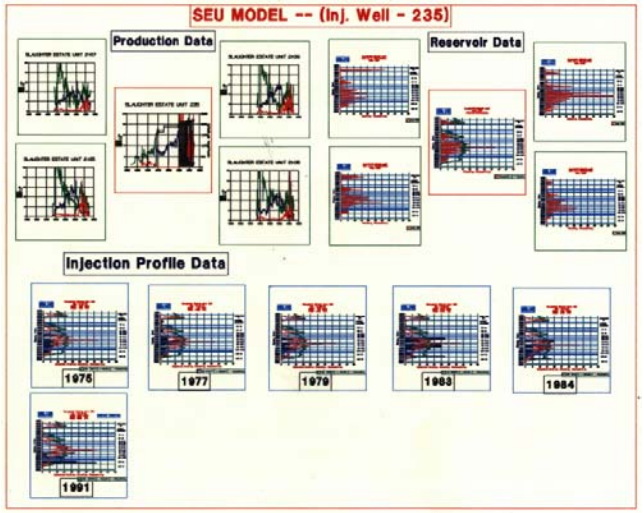
Integrated Log Montage w/ Conformance

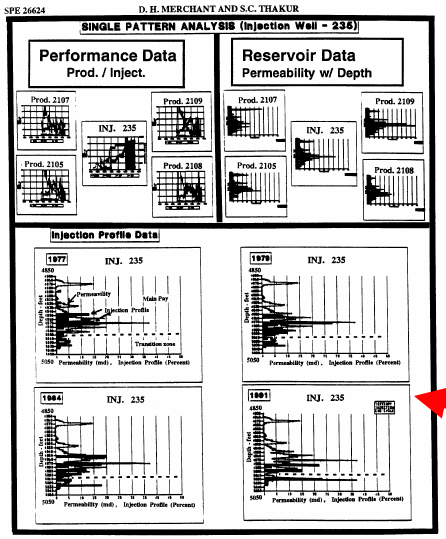
Volumetric Sweep Efficiency = $E_{area\ sweep\ effic}$ X $E_{vertical\ sweep\ effic}$











Most Conformance Issues occur at the Wellbore

Example: Out-of-Zone Inj.

Injection Profile History

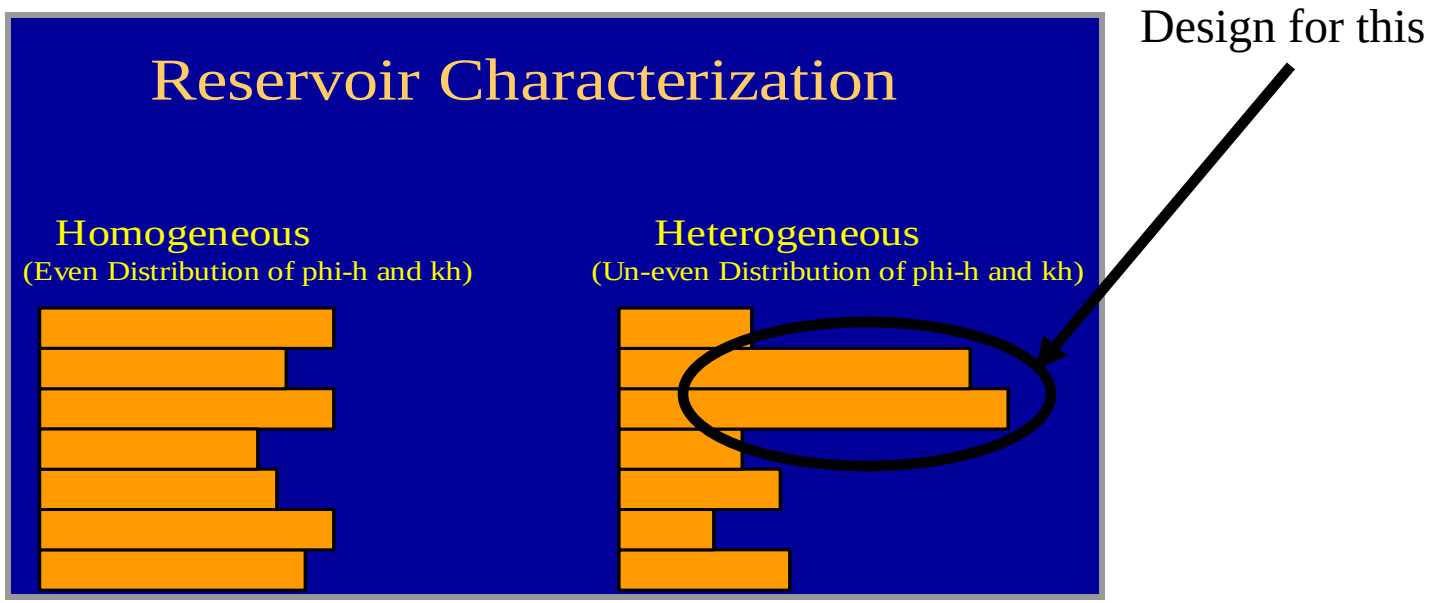
Property of Merchant Consulting- Dec 2010

WAG Objective
Design for the Reservoir

WAG Ratio and Half Cycle Slug Size can be Modified

- Reservoir Heterogeneity Variations

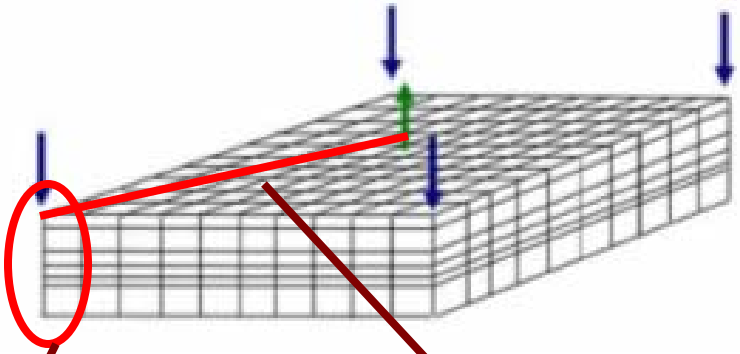
1. A more Heterogeneous Reservoir will usually require cutting the CO_2 half cycle to a smaller volume to reduce production well gas cycling (Short-Cycling the WAG).



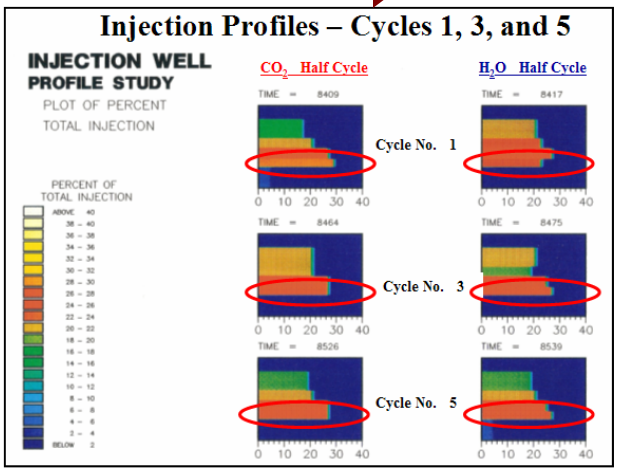
Reservoir Simulation

Reservoir Model Study - San Andres 5 Spot

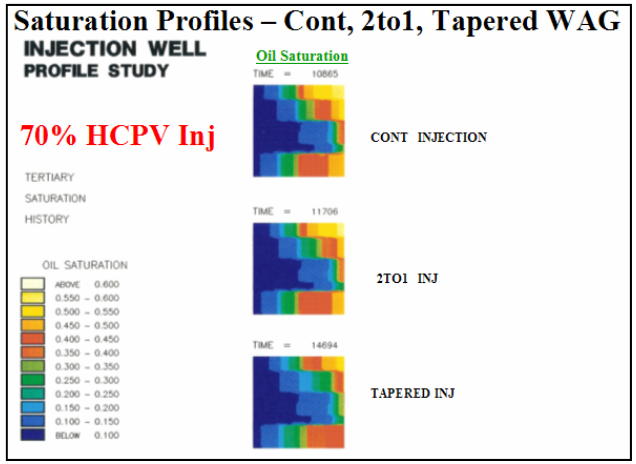
Single 5 Spot Pattern (10X10X6 Grid)



Injection Profiles

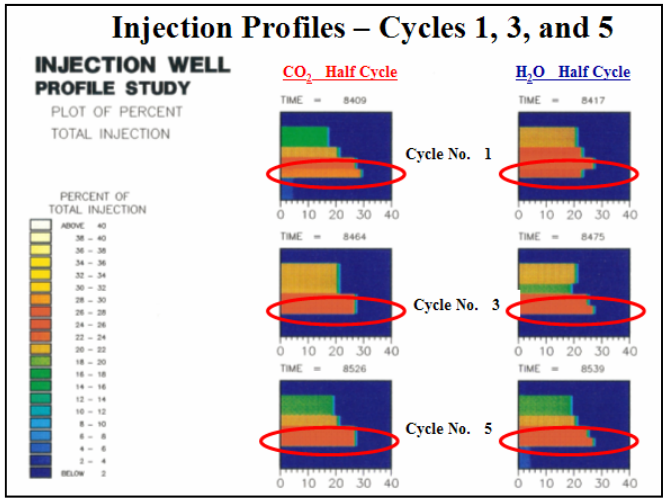


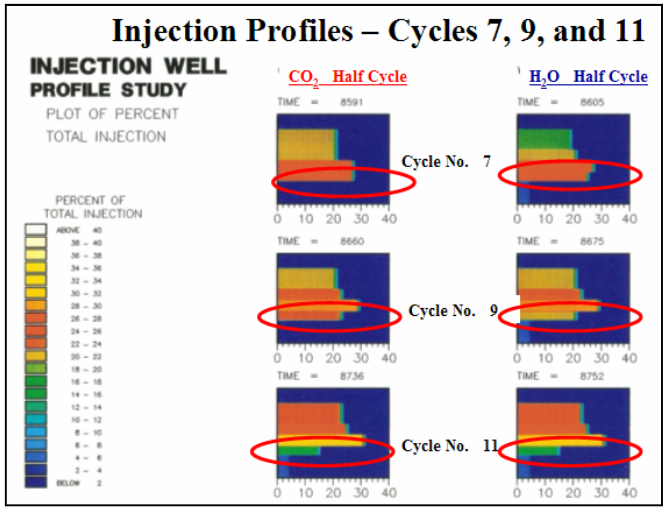
X-Cross Section - Oil Saturation

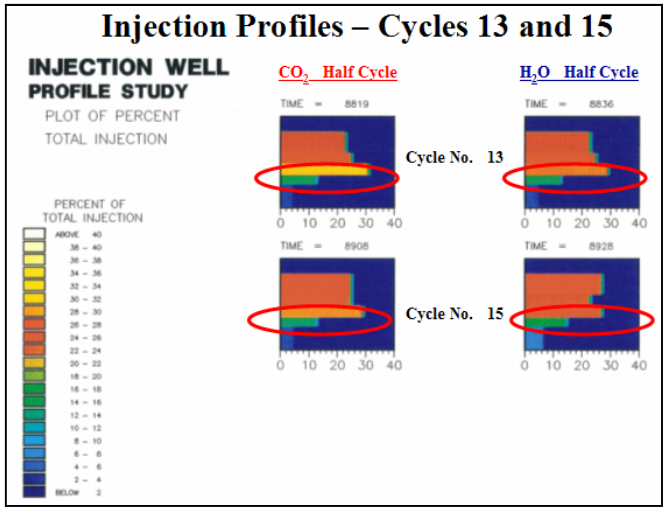


Reservoir Simulation

Injection Profiles – Cycles 1 through 15







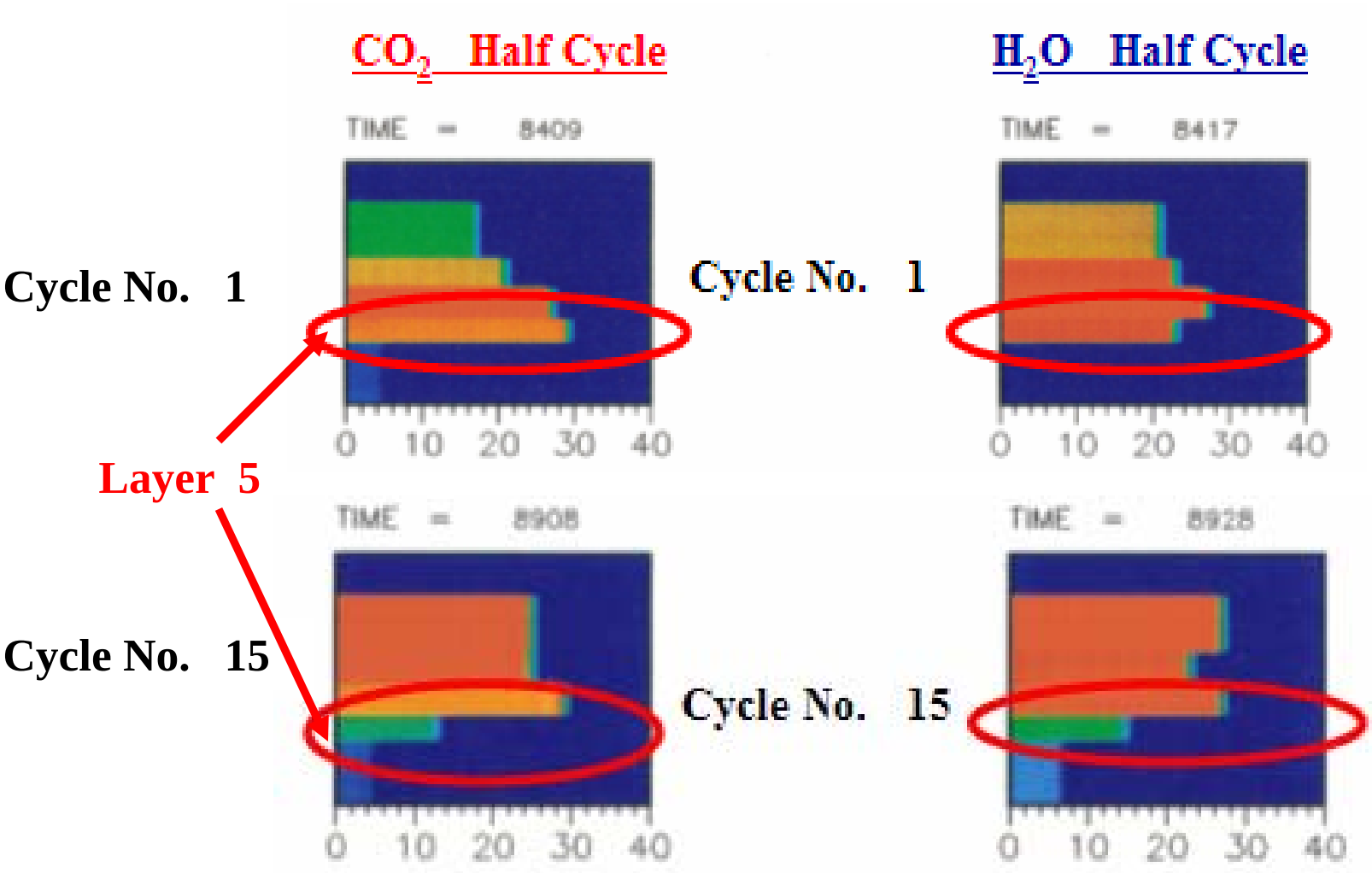
Injection Well Profile Comparison

- 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 CO_2 injection
3. During CO_2 Injection, Zone 5 throughput decreases as the tertiary oil bank develops

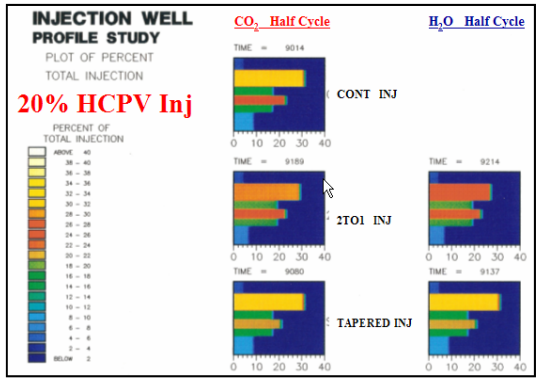
Reservoir Simulation

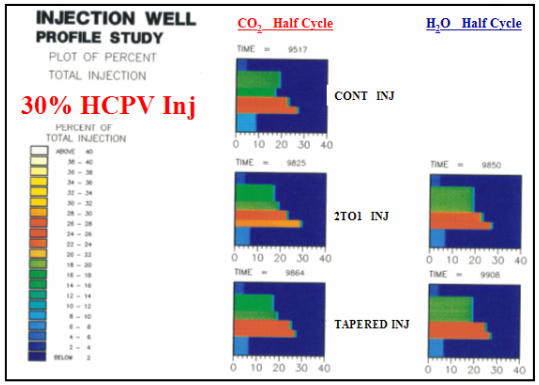
Injection Profiles – Cycles 1 through 15 Comparison

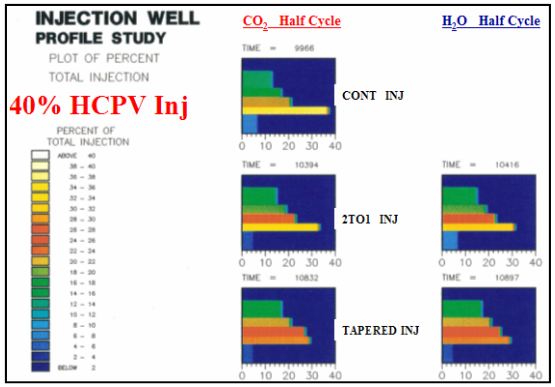


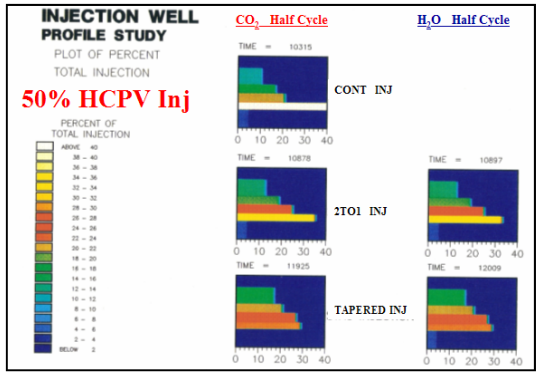
Reservoir Simulation

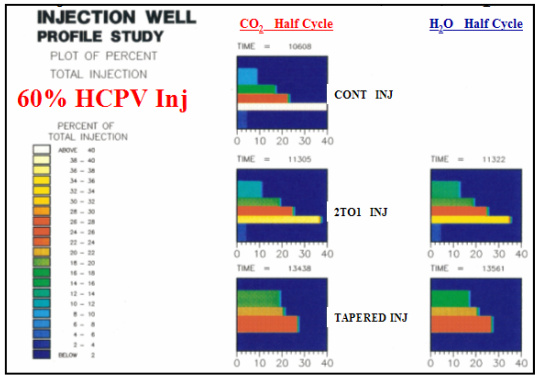
Injection Profiles – 20% HCPV to 70% HCPV

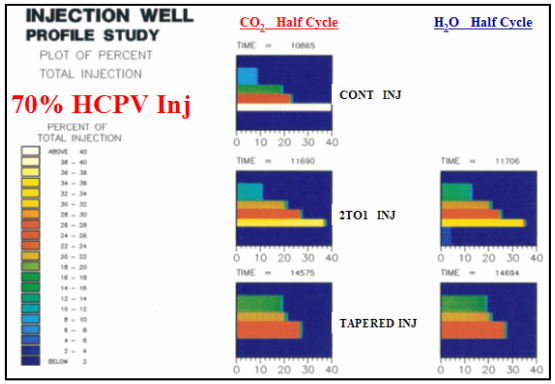












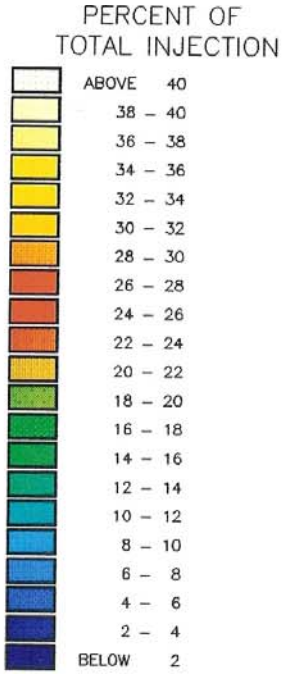
Reservoir Simulation

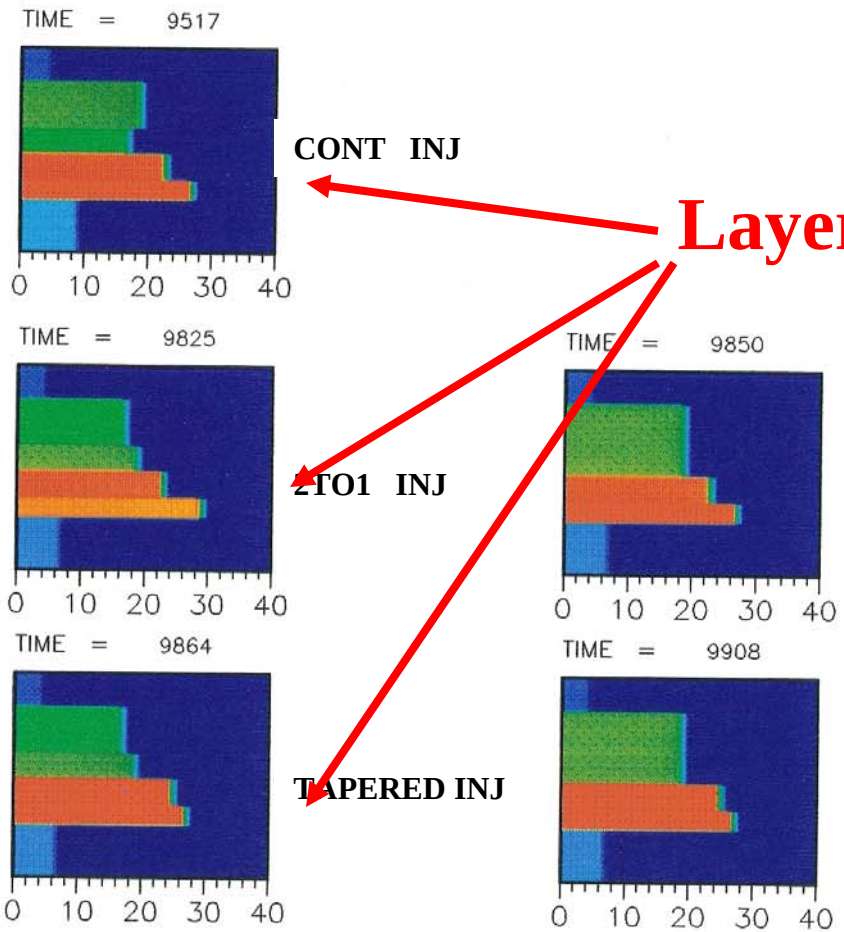
Injection Profiles – Continuous, 2to1, Tapered WAG

INJECTION WELL PROFILE STUDY

PLOT OF PERCENT TOTAL INJECTION

30% HCPV Inj





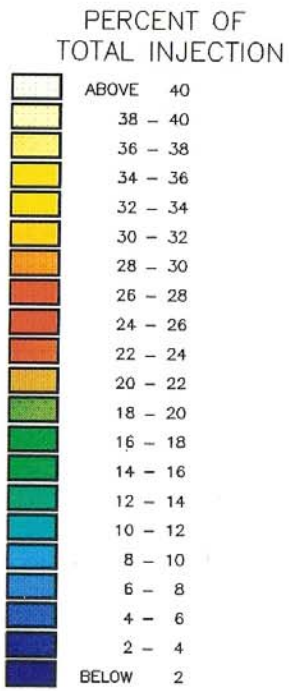
Reservoir Simulation

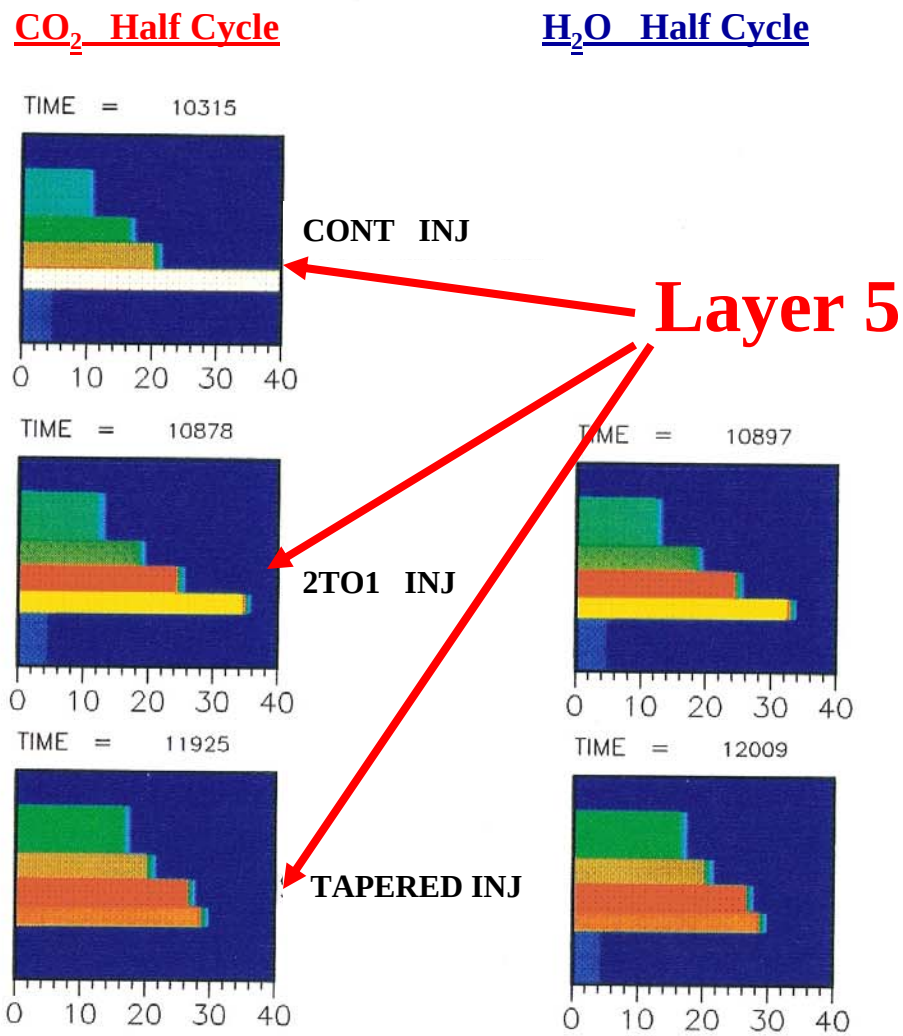
Injection Profiles – Continuous, 2to1, Tapered WAG

INJECTION WELL PROFILE STUDY

PLOT OF PERCENT TOTAL INJECTION

50% HCPV Inj





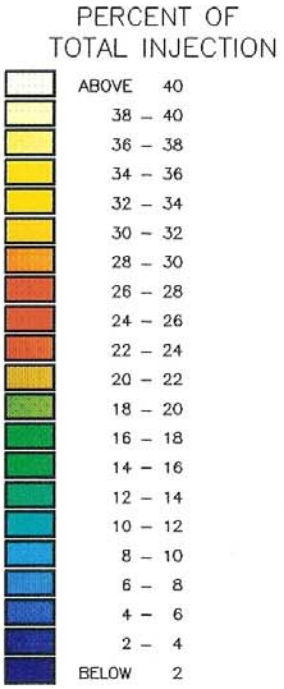
Reservoir Simulation

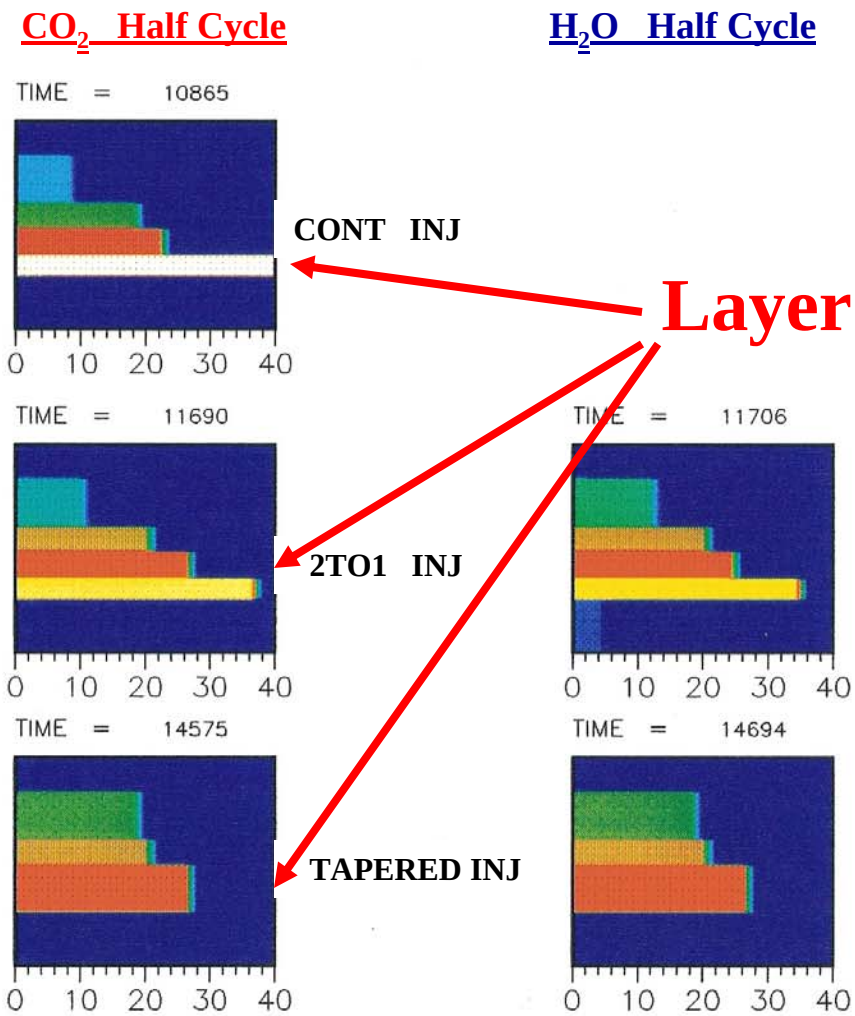
Injection Profiles – Continuous, 2to1, Tapered WAG

INJECTION WELL
PROFILE STUDY

PLOT OF PERCENT
TOTAL INJECTION

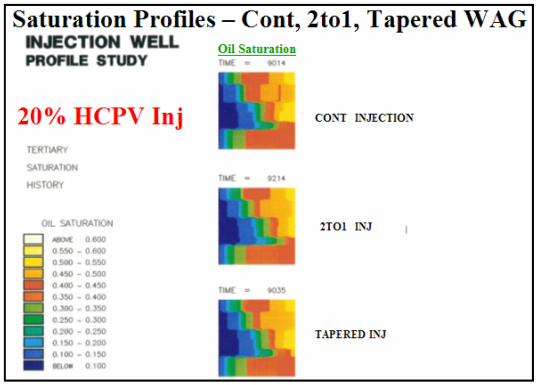
70% HCPV Inj

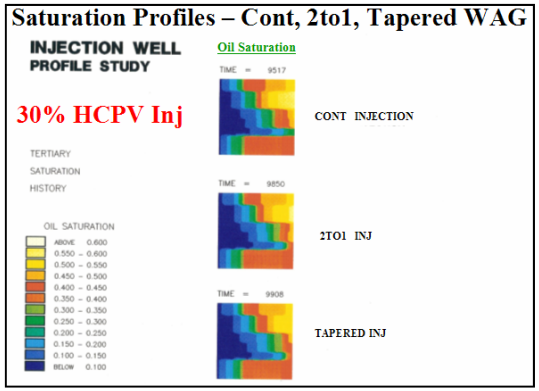


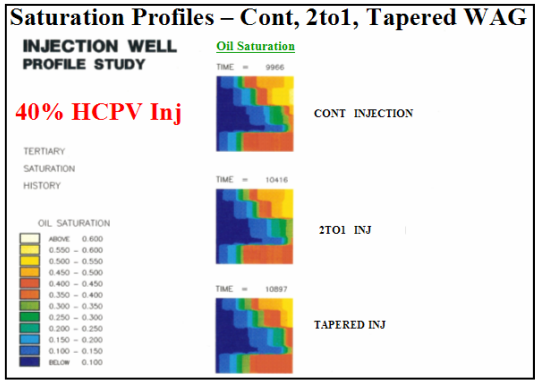


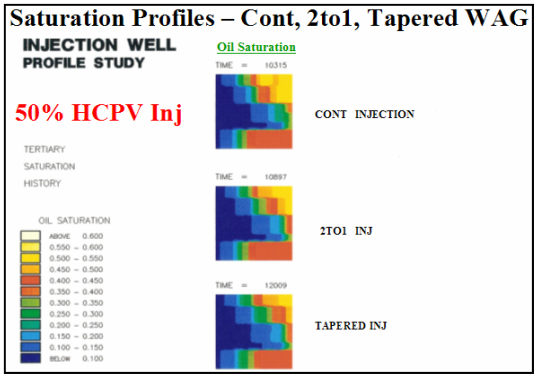
Reservoir Simulation

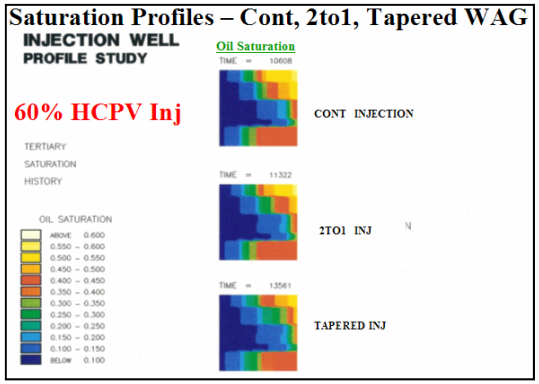
Saturation Profiles – 20% HCPV to 70% HCPV

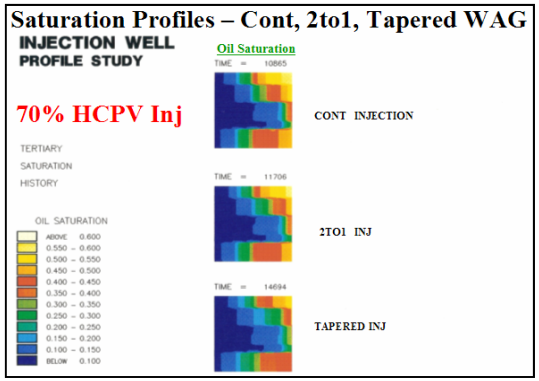








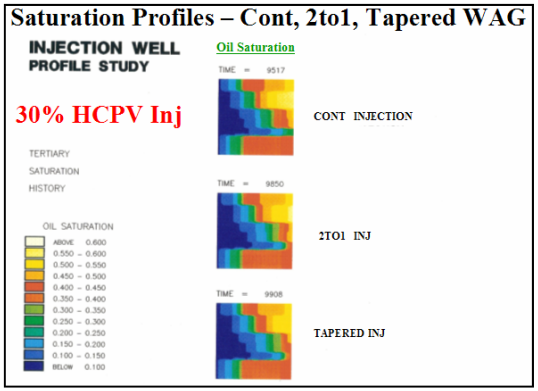


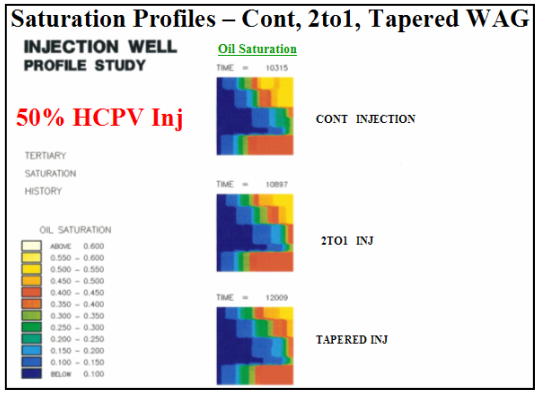


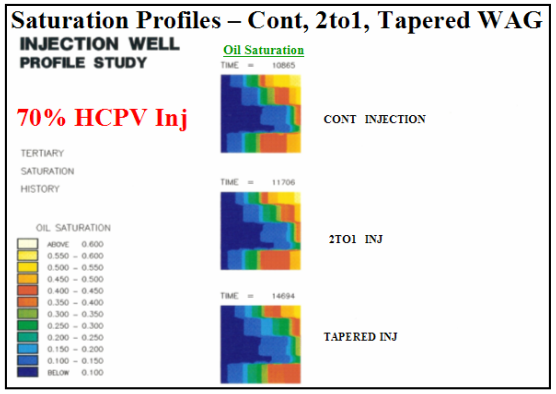
Note: Saturations similar with HCPV Injection

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

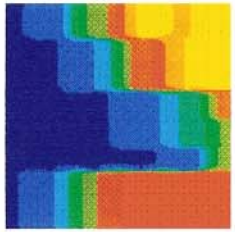
TERTIARY
SATURATION
HISTORY

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

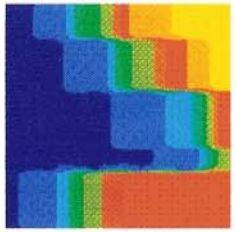
Oil Saturation

TIME = 10315



CONT INJECTION

TIME = 10897



2TO1 INJ

TIME = 12009

TAPERED INJ

Reservoir Simulation

Saturation Profiles – Cont, 2to1, Tapered WAG

INJECTION WELL
PROFILE STUDY

70% HCPV Inj

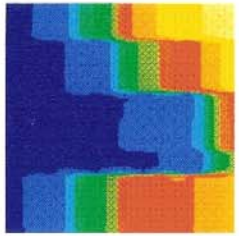
TERTIARY
SATURATION
HISTORY

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 = 10865



CONT INJECTION

TIME = 11706

2TO1 INJ

TIME = 14694

TAPERED INJ

Thanks,

Now its your turn?

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CO_2 Storage Solutions

WEB: www.CO2StorageSolutions.com

Key Words: Merchant Consulting, CO2 Storage Solutions, CO2 Seminars on Wheels

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