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

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## Abstract

During the past 38 years, $CO_2$ flood technology for Enhanced Oil Recovery projects evolved from a partially understood process filled with uncertainties to a process based on proven technology and experience. Many questions involved with $CO_2$ flooding have been thoroughly analyzed and answered. This knowledge is currently being used by a limited number of companies that actually know how to design, implement, and manage a $CO_2$ flood for long term profit. Unfortunately, this knowledge has not been disseminated to operating companies interested in EOR flooding or to $CO_2$ Sequestration Communities interested in storing $CO_2$ in EOR projects.

The primary objective of this report is to target "Conventional WAG Techniques" which have been used in over 90% of all the Enhanced Oil Recovery projects implemented in the Permian Basin in Texas, Colorado, Oklahoma, and Wyoming. Over the years, oil companies have reported a wide range of values of Tertiary Oil Recovery, $CO_2$ Utilization, and $CO_2$ Retention, resulting in a wide range of variation and uncertainty. Many of the numbers reported to date are tied to a specific HCPV $CO_2$ Injected based on some Economic Cut-off. This typically has been in the range of 30% to 80% HCPV Injected. The question becomes "What is life after 80% HCPV?" And "What effect does life after 80% HCPV have on Tertiary Oil Recovery, $CO_2$ Utilization and $CO_2$ Retention in different producing formations?" Results of this study show Tertiary Oil Recovery can be as high as 26% OOIP when slug sizes exceed 190% HCPV injected.

## Carbon Sequestration Options: Five Recovery Methods for Enhanced Oil Recovery (EOR)

Most Enhanced Oil Recovery Projects use one of the following five operating methods: Conventional WAG Recovery, Gravity-stabilized Recovery, Double Displacement, Gas-cycling or Huff-and-Puff. The primary difference between methods depends on the reservoir geology and well pattern configuration. In Conventional $CO_2$ floods, typical of West Texas, the formations are basically flat (Ramp Sequence), low perm, the fields are developed on pattern spacing (e.g. 5-spot patterns, 9-spot patterns, or Chickenwire patterns), and Conventional WAG Operating schemes are used to control mobility and $CO_2$ flood response. In conventional WAG operations, the objective is to minimize the amount of $CO_2$ purchased ($CO_2$ stored in Sequestration projects), which is typically in the range of range of 30%-40% of the total HCPV $CO_2$ injected. In un-conventional Gravity-Stabilized and Double Displacement case histories, Flue Gas, $CO_2$, Lean Gas or $N_2$ is usually injected in the top of the structure and oil is produced from the bottom. More $CO_2$ can be sequestered than conventional WAG operations. As much as 80% of the total pore volume can be displaced with $CO_2$. However, the reservoir must meet certain fluid-dynamic criteria and have structure to make the gravity-stabilized process work. In Gas-cycling projects, typical of projects operated by Denbury in Mississippi, $CO_2$ is cycled through the formation. As much as 6 pore-volumes of $CO_2$ are injected to recover 18% OOIP. In Huff-and-Puff operations, the $CO_2$ is injected into and produced from the same well. The objective is to mobilize tertiary oil in the near vicinity of the well-bore, and then produce the $CO_2$ and tertiary oil back. Then repeat the process (typically with 3 cycles). The process technically works. The economic success or failure depends on many factors. The amount of $CO_2$ sequestered is minimal when compared to the other recovery methods.

## Conventional WAG Recovery

Conventional WAG Operating Methods in the Permian Basin fall into one of four categories:

1. Continuous $CO_2$ Injection
2. Constant WAG Injection
3. Tapered WAG Injection
4. Simultaneous $CO_2$ Injection (Limited use)

### What is WAG Management?

All Conventional WAG Injection Projects have one thing in common. $CO_2$ is injected into the reservoir and the produced recycle $CO_2$ must be re-injected back into the reservoir to maximize oil recovery. This was first demonstrated by Caudle and Dyes in 1958 when water was added to $CO_2$ to decrease solvent mobility [Turek, 1]. As $CO_2$ technology was transferred from the lab to the field, most all of the Major Oil Companies in the 1970's and early 1980's adopted the use of Constant Water-Alternating-Gas (WAG) Injection based on the theory that alternate gas water injection is necessary to maintain mobility control and maximize oil recovery. During the late 1980's, Tapered WAG Operations were adopted to improve the overall recovery process [Merchant, 2,3,4,5, and 6]. WAG Injection can be best demonstrated as shown in Figure 1a and 1b. $CO_2$ and Water are injected into the reservoir in alternating $CO_2$ and water slug sizes. For Constant WAG operating schemes, the half cycle slug size is typically fixed for example at 1.0% HCPV $CO_2$ for the Gas Cycle and 1.0% $H_2O$ for water. For Tapered Wag projects, WAG Ratios change with time. Typically for most $CO_2$ operations today, "Wetting the WAG" or increasing water half cycle volume with time improves conformance by slowing the gas in the fast zones. The water half cycle can be increased or decreased to help operational switch times in the field to improve overall conformance problems or adjusted to "Level Load" gas production to a Plant inlet rate improving overall project economics while maximizing oil recovery.

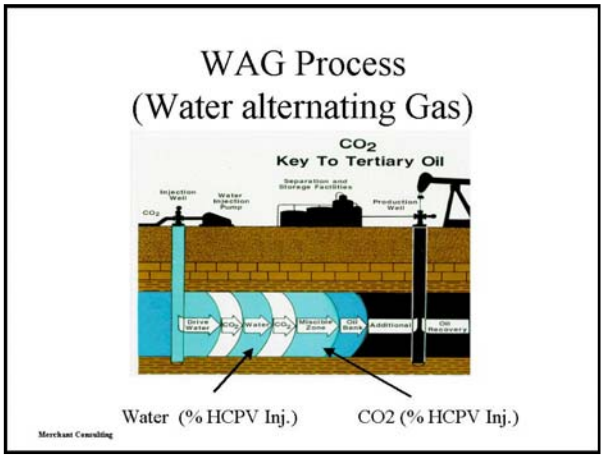



**Figure 1a. Conventional WAG Process**

**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% $H_2O$)
  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% $CO_2$, 1.50% $H_2O$) | for 30% HCPV |
| | Chase Water Injection | |

Note: Total $CO_2$ Slug Size = 85% HCPV Injection of $CO_2$

**Figure 1b. Conventional WAG Process**

### Reservoir Modelling

Through the 1980's and 1990's, Amoco, Shell, Arco, Mobil, and Texaco committed significant manpower to evaluate the feasibility of full field scale $CO_2$ flooding in the Permian Basin. Before the initiation of field scale floods, many pilots were drilled and much reservoir simulation was conducted to understand the $CO_2$ flooding process. Today, there are over 82 active $CO_2$ projects in the United States producing over 237,000 BOPD and $CO_2$ flooding is expanding to many parts of the world. Reservoir simulation has been an integral part of reservoir management in understanding the $CO_2$ flood tertiary recovery process. Reservoir Modelling was used in the development of Tapered WAG [2,3,4,5, and 6]. Simulation today is used in the initial design of slug sizes and gas-water ratios (GWR), and allows Reservoir Engineers to explore different operating scenarios that best match field performance.

The development of Reservoir Simulators over the years has permitted a greater reliability in simulating the miscible process over a wide range of injection gas-water ratios. Confidently estimating the response of the reservoir to $CO_2$ injection generally involves history matching Primary and Secondary performance. The model developed for this study has properties that are typical of West Texas San Andres Dolomite reservoirs. These models incorporate the latest state-of-the-art understanding of the physics and mathematics pertaining to reservoir characteristics, recovery mechanisms, and operating conditions. In 1986, the model used to develop tapered WAG was simulated with Amoco's GCOMP simulator in Blackoil mode with a miscible option (3 hydrocarbon component model). This model implies the solvent mixes with the reservoir oil in all proportions with no phase separation. Today, Compositional Simulation is being used to simulate the miscible process.

### Model Development

For this analysis, it was important to determine if the predictions generated by the simulator reasonably agreed with actual field performance. The model used in this study incorporates historical production and injection waterflood performance from the Slaughter Estate Unit in Slaughter field and scaled to a single five-spot pattern [2,3,4,5, and 6]. In addition, lessons learned from full-field $CO_2$ flooding experience provided additional insight of both reservoir heterogeneity and understanding of the complex $CO_2$ flood process. The Model represents an inverted 5-spot (10X10X6 Grid) Well Configuration with Injector in the middle and one-quarter Producers located on the corners. The model contains six layers with phi-h and k-h varying areally. The model contains both a Primary Recovery Period as well as a Secondary Recovery Period of water injection. Reservoir Parameters are shown on the next page in Table 1.

## Table 1 – Model Grid Properties (General)

| Average Model Properties | |
|---|---|
| Model Type: | Average Pattern (5-spot) |
| Pattern Segment Model Size - acres | 25 |
| 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 |
| $CO_2$ Miscibility Pressure, psi | 1200 |
| Number of Model Layers | 6 |

**Average Model Properties**

| Model Layer | Net-Thickness ft | Porosity-Thickness ft | Permeability-Thickness md-ft | k/phi k-h / phi-h |
|---|---|---|---|---|
| 1 | 17 | 1.5 | 21.8 | 15 |
| 2 | 24 | 3.0 | 129.6 | 44 |
| 3 | 13 | 1.7 | 127.3 | 76 |
| 4 | 14 | 2.2 | 160.3 | 75 |
| 5 | 10 | 1.1 | 166.3 | 154 |
| 6 | 27 | 2.6 | 56.9 | 22 |
| Total | 104 | 11.9 | 662.2 | 56 |

## Model – Primary and Secondary Recovery

Primary and Secondary Production and Injection History for the 25-acre model are shown on Figures 2a, 2b, 3a, and 3b. For the 25 acre model, Primary Oil Rate peaked around 125 BOPD and Secondary Oil Rate peaked around 215 BOPD.

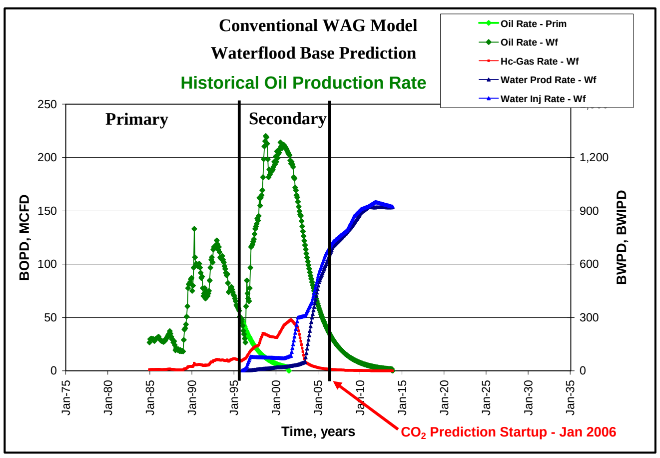



**Figure 2a. – Historical Production Performance**

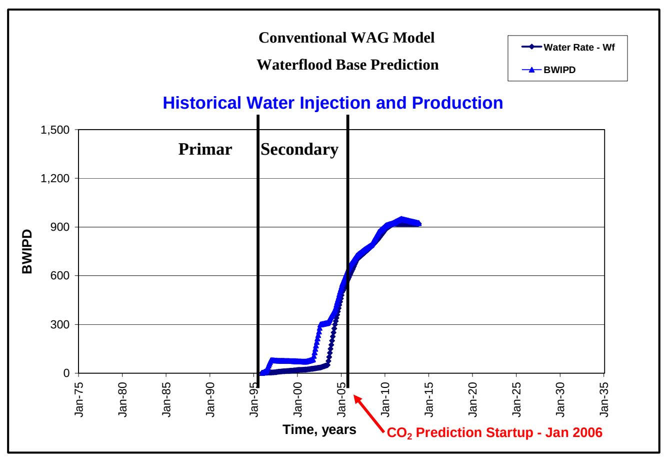



**Figure 2b. – Historical Injection Performance**

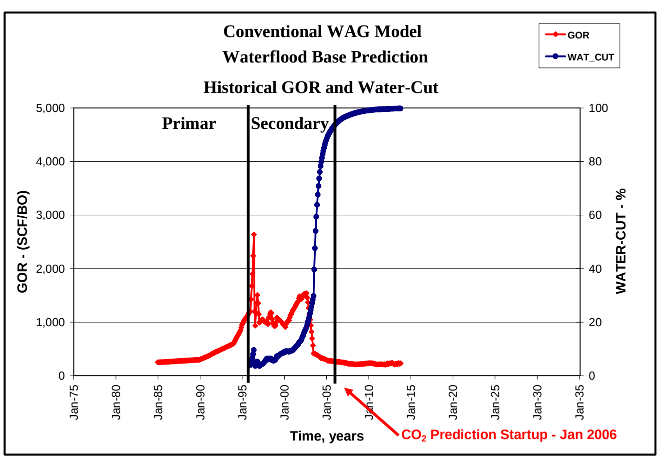



**Figure 3a. – Historical GOR, Water-Cut**

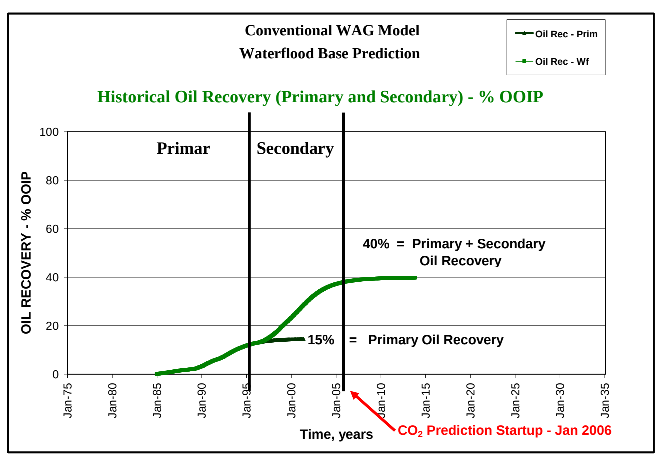


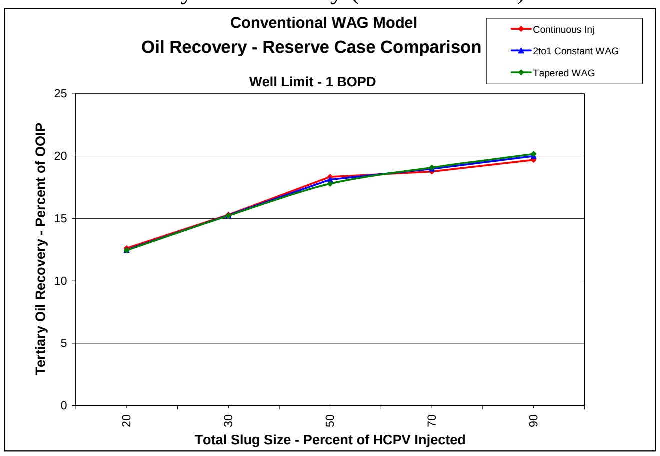

**Figure 3b. – Historical Oil Recovery Performance**

When conducting Tertiary $CO_2$ predictions, Historical Primary plus Secondary Waterflood Performance is a key parameter to achieving high Tertiary Oil Recovery. The Primary and Secondary waterflood oil recovery performance shown above is considered "Good" waterflood response when Primary plus Secondary Recovery exceed 40% OOIP. When waterflood performance is less than 40%, Tertiary Performance Predictions should be scaled-down to match historical performance.

## Optimization Case Comparisons - Case Studies (20% HCPV to 80% HCPV Injected)

Future Predictions under any type of Recovery Mechanism are a very important aspect of any type of Economic Analysis. For Optimization, the factors which influence $CO_2$ Flood Economics are: (1) Oil and Hc-gas Price, (2) $CO_2$ Plant and Pipeline Capital Investment Costs, (3) $CO_2$ Purchase Costs (including Pipeline Tariffs), (4) $CO_2$ Plant Processing Costs, (5) Field Operating Costs (Workover and Lift), and (6) Overhead.

Tertiary Oil Recovery (No Economics)




Tertiary Oil Recovery (With Economics)

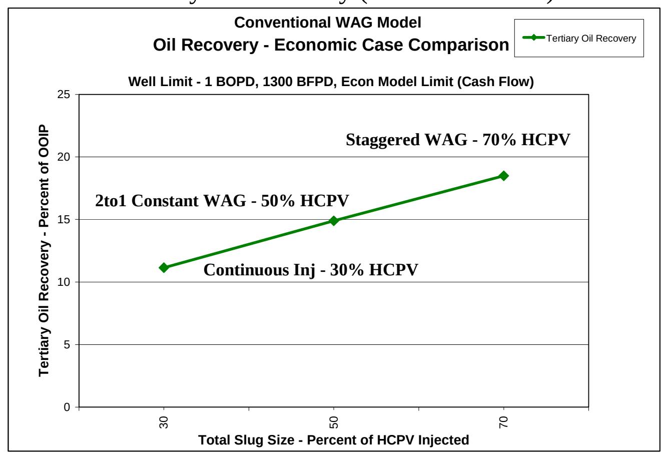
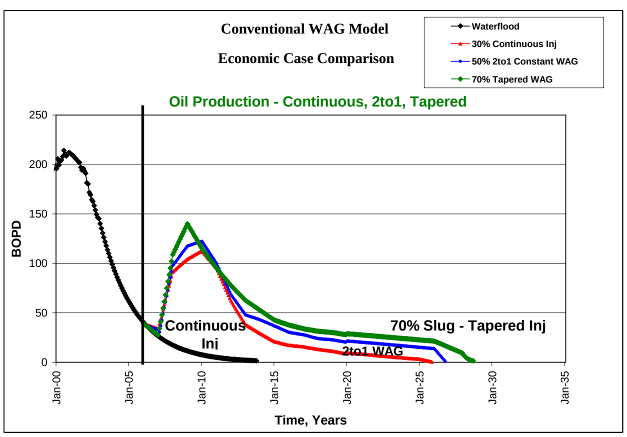



**Figure 4a. – Oil Recovery (without Economics)** **Figure 4b. – Oil Recovery (with Economics)**

Tertiary Oil Recovery under $CO_2$ Injection is a function of the total amount of $CO_2$ Injected. As shown in Figure 4a, comparing total $CO_2$ HCPV injection between cases assuming a 1.0 BOPD cutoff (No Economics), Reservoir Recovery for the three operating methods are statistically the same. When economics are applied to each of the cases, Figure 4b, the amount of Tertiary Oil Recovered and Present Value Economics are different between cases. Based on Economics, a 30% HCPV $CO_2$ Slug is Economically Optimum for Continuous $CO_2$ Injection, a 50% HCPV $CO_2$ Slug is Economically Optimum for Constant WAG Injection, and a 70% HCPV $CO_2$ Slug is Economically Optimum for Tapered WAG Injection.

### Economic Comparison - Tertiary Oil Rate and Oil Recovery



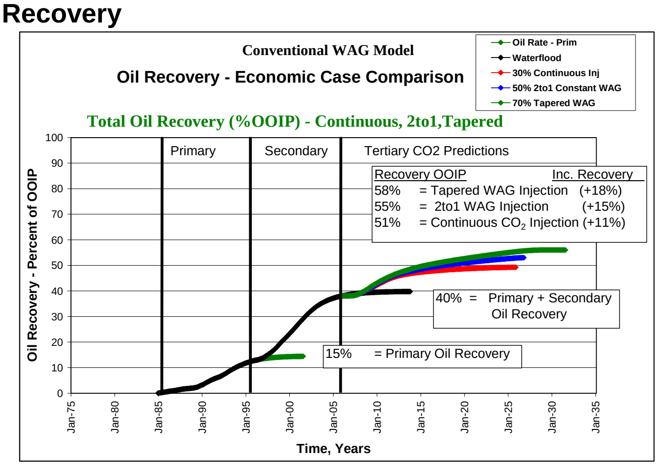




**Figure 5a. – Tertiary Oil Rate** **Figure 5b. – Tertiary Oil Recovery**

Oil Production Rate and Tertiary Oil Recovery comparing the three Economic cases are shown above on Figures 5a and 5b. The total amount of $CO_2$ injected determines the amount of Tertiary Oil Recovered. The greater the amount of $CO_2$ injected, the greater the Tertiary Oil Recovery. The objective in a $CO_2$ flood is to accelerate the $CO_2$ Injection as quickly as possible, without fracturing the reservoir. Continuous Injection accomplishes this goal. Constant WAG Injection has the ability to control reservoir sweep, extending $CO_2$ flood life. Tapered WAG Injection combines the best of both. In addition to accelerating the front end Economics, it also recovers the most tertiary reserves.

### Economic Comparison – $CO_2$ Injection and Production

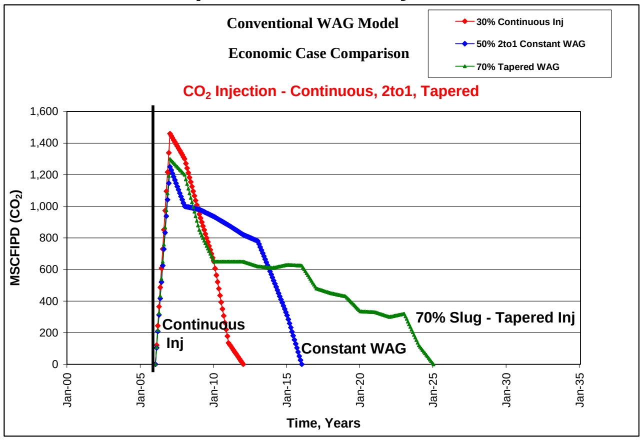



**Figure 6a. – Tertiary $CO_2$ Injection Rate**

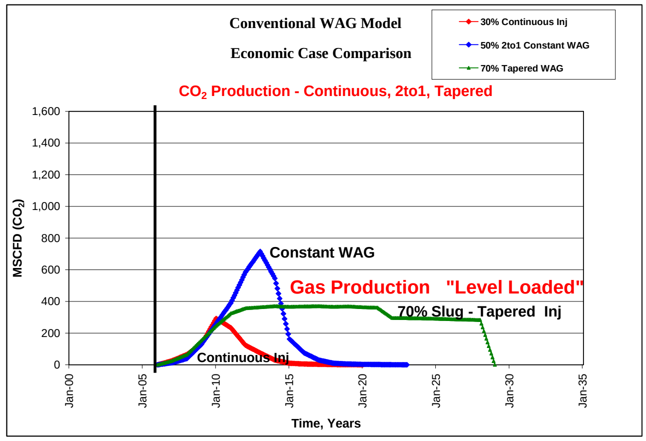



**Figure 6b. – $CO_2$ Production Rate**

$CO_2$ Production and its associated Plant Investment is a major component in Economic analysis. A taperd WAG operating scenario extends tertiary oil recovery beyond Continuous and Constant WAG operations by controlling $CO_2$ production by "Level-loading Inlet Plant Rate $CO_2$ Production" to a plant inlet rate to control costs.

### Economic Comparison – $CO_2$ Purchase Rate and $CO_2$ Storage ($CO_2$ Sequestration)

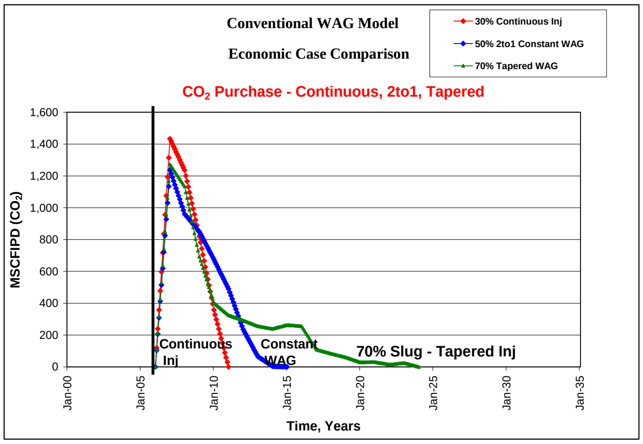



**Figure 7a. – Tertiary $CO_2$ Purchase Rate and**

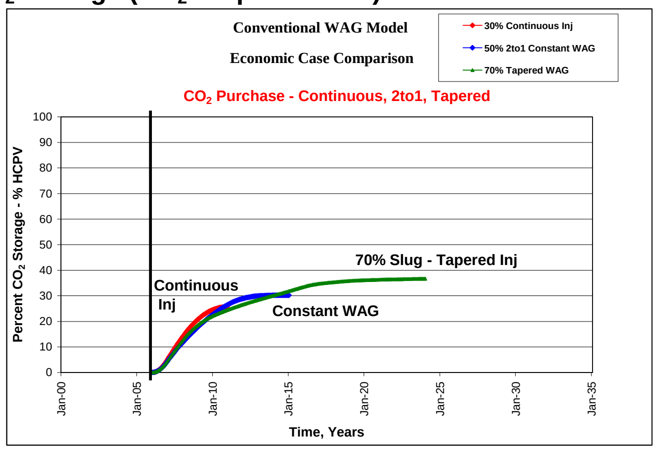



**Figure 7b. $CO_2$ Storage Rate**

The Total $CO_2$ Slug Size consists of two parts. The $CO_2$ Purchase portion always occurs at the start of the project. The Recycle Portion, which is the $CO_2$ recovered through production, is processed through a plant and injected back into the reservoir. The volume purchased and the purchase times for injection are dependent on the total $CO_2$ slug injected. In Tapered WAG designs, $CO_2$ is purchased throughout the life of the $CO_2$ flood. As shown above, the amount of $CO_2$ purchased declines as the tertiary flood matures.

### $CO_2$ Sequestration

The amount of $CO_2$ Purchased in EOR operations is also the amount of $CO_2$ Sequestered in $CO_2$ Sequestration projects. As shown above in Figure 7b, this amount is typically in the range of 30% to 40% of the total HCPV injected. Separate from $CO_2$ Retention, which is the amount of $CO_2$ retained as a percent of total amount of $CO_2$ injected, the amount of $CO_2$ stored in the reservoir or sequestered is always 100% of the $CO_2$ purchased volume.

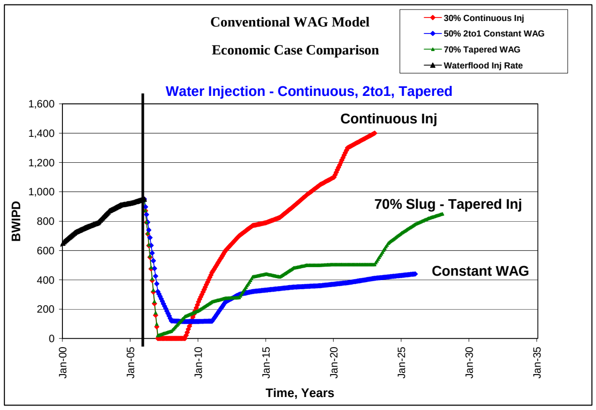



Figure 8a. – Tertiary Water Injection Rate

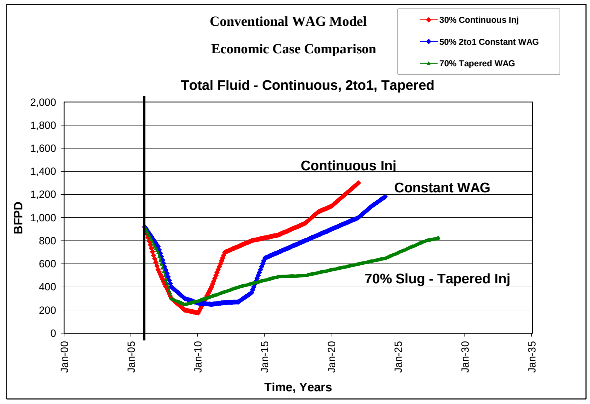



Figure 8b. – Total Fluid Production Rate

The key to Optimization is the ability to control $CO_2$ processing costs. This is accomplished by injecting water as a mobility control agent. For this study, increasing half cycle water volumes occurred every 10% HCPV Inj $CO_2$. This resulted in a nearly flat $CO_2$ production response to "Level Load" $CO_2$ Gas Production Rate to a "Plant Inlet Rate".

### Economic Comparison – Gross $CO_2$ Utilization and Net $CO_2$ Utilization)

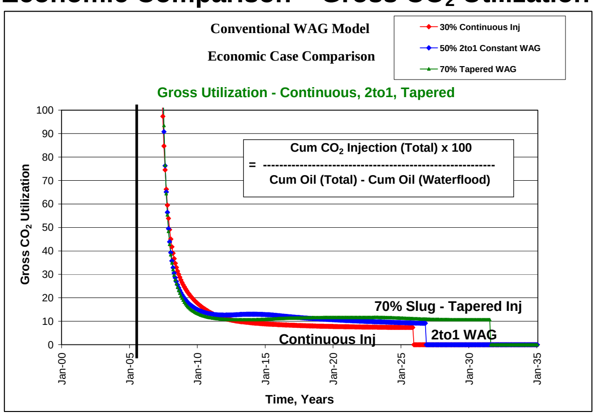



Figure 9a. – $CO_2$ Gross Utilization

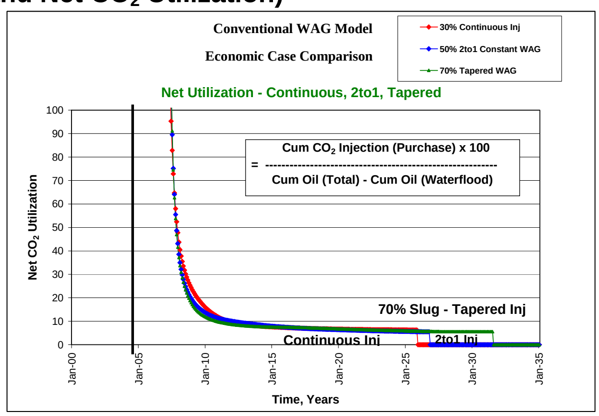



Figure 9b. – $CO_2$ Net Utilization

$CO_2$ Utilization is an efficiency measure of how much $CO_2$ is used to recovery a barrel of Tertiary Oil. Gross Utilization is defined as the Cumulative Total amount of $CO_2$ Injected per total amount of Tertiary Oil Produced, typically 10 to 20 MSCF/BO. Net $CO_2$ Utilization is defined as the Cumulative Purchased amount of $CO_2$ per total amount of Tertiary Oil Produced, typcically in the range of 5-10 MSCF/BO.

### Economic Comparison – $CO_2$ Retention

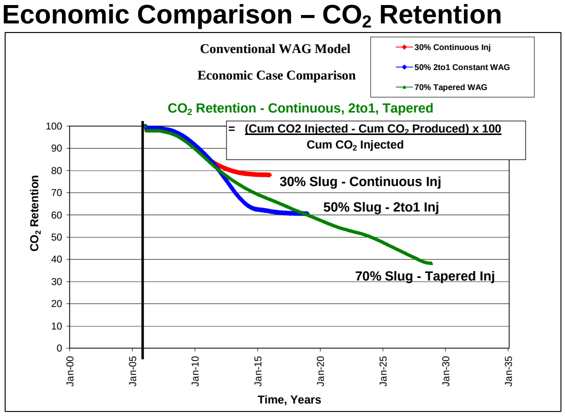



Figure 10a. – $CO_2$ Retention

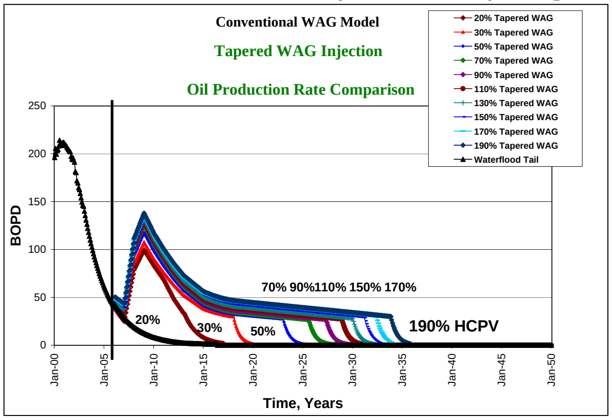
$CO_2$ Retention is an Engineering term used to relate the total amount of $CO_2$ retained in the reservoir to the total amount of $CO_2$ injected. It repreents the percent of Cumulative $CO_2$ Injected minus Cumulative $CO_2$ Produced divided by the amount of Cumulative $CO_2$ Injected. As the $CO_2$ flood matures, the retention will decrease from 100% to some minimum value.

## Life beyond 80% HCPV- Tapered WAG Injection (20% HCPV to 190% HCPV Injected)

The question becomes "What is life after 80% HCPV?" And "What effect does life after 80% HCPV have on $CO_2$ Utilization and $CO_2$ Retention in different producing formations?" The answer to those questions is shown below.

### Life beyond 80% HCPV - Tertiary Oil Rate and Oil Recovery

Oil Production Rate and Tertiary Oil Recovery comparing the extended $CO_2$ Slug size fom 20% HCPV to 190% HCPV



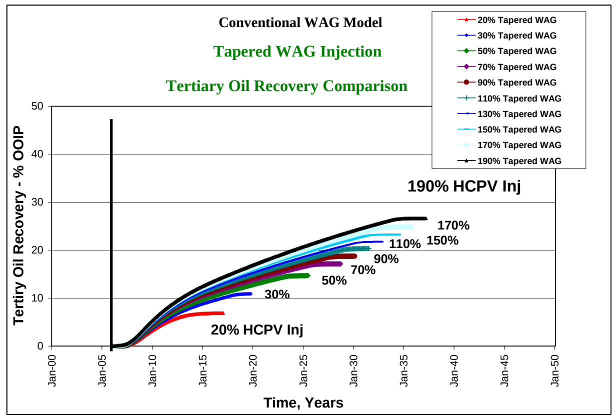
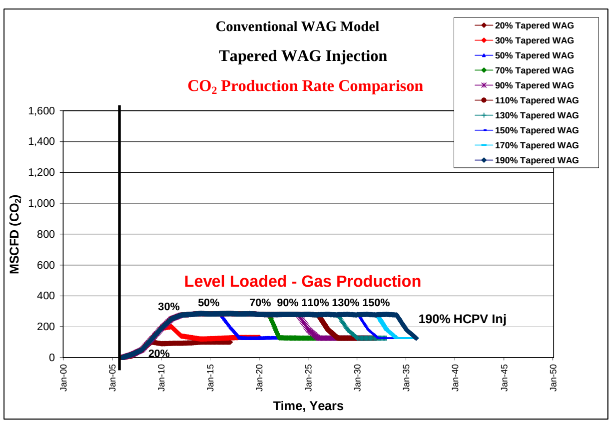




**Figure 11a – Tertiary Oil Rate (Tapered WAG)** **Figure 11b. – Tertiary Oil Recovery (Tapered WAG)**

$CO_2$ Production (Level Loaded) and Total Fluid Rate comparing $CO_2$ Slug size fom 20% HCPV to 190% HCPV



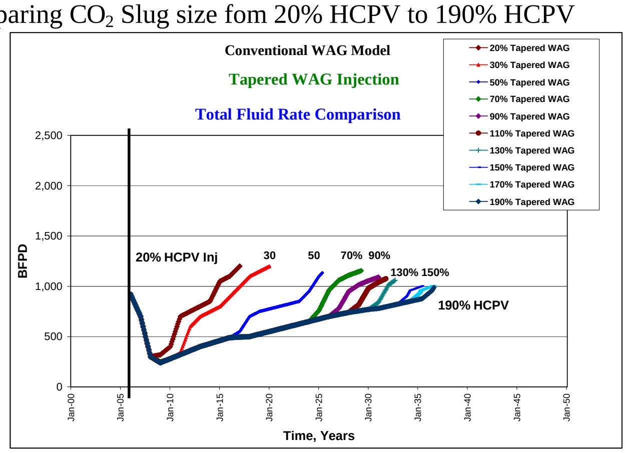




**Figure 12a – Tertiary $CO_2$ Rate (Tapered WAG)** **Figure 12b – Total Fluid Rate (Tapered WAG)**

As shown above, extending Total CO2 slug size beyond 80% HCPV extends Teritary Oil Recovery. A 190% HCPV slug size improves Tertiary Oil Recovery to 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- (Tertiary Oil Recovery, $CO_2$ Gross and Net Utilization)

Since 1972, over 100 Commercial $CO_2$ floods have been operated in the United States, with 72 of these projects still active today. During this time, Engineers have reported a wide range of Tertiary Oil Recovery, Gross Utilization and Net Utilization values at varying stages of maturity. The question becomes "What would Operators report on these $CO_2$ floods today?" And "What would Oil Recovery, Gross Utilization and Net Utilization look like under Extended $CO_2$ Slug volumes?" The answer to those questions depends on Reservoir Type. Data from these $CO_2$ projects from various SPE and DOE reports are listed below by formation type:

**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 |

**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 |

**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 |

# Conclusion

With more than thirty-eight years of successful enhanced oil recovery (EOR) projects in the Permian Basin (Texas), Mississippi, Wyoming, Colorado, California, Oklahoma, and several countries worldwide, carbon dioxide $CO_2$ flooding is a proven method for extending field life. $CO_2$ acts as a solvent to overcome forces that trap oil in tiny rock pores, helping sweep immobile oil left after primary or secondary recovery operations. Generally, $CO_2$ is not miscible at first contact with reservoir oils, but miscibility can be developed in reservoirs above or near the Minimum Miscibility Pressure (MMP). $CO_2$ can attain miscibility through a multiple-contact process that vaporizes or extracts both intermediate and higher molecular weight hydrocarbons from the reservoir oil. The $CO_2$ phase picks up many intermediate hydrocarbon components from the oil, swells the oil, and reduces oil viscosity, making it mobile to move through the rock.

Advances in technology and reservoir understanding have made detailed evaluation of potential EOR candidates obtainable within months, not years. In addition, improved reservoir management and innovative investment plans have significantly reduced risks and increased rewards. Many of the original questions about $CO_2$ flooding involved the displacement efficiency of the process, how $CO_2$ would interact with the oil, and how much oil could be recovered. Many of these questions have been answered with better reservoir management tools. Not all fields are good candidates for $CO_2$ Tertiary Recovery. A reservoir must contain certain characteristics for a $CO_2$ flood to be successful. In the past, it was thought the oil must be found at depths sufficient to allow for high pressures, so that $CO_2$ and oil develop total miscibility. This is not necessary correct. Most $CO_2$ floods operate at reservoir pressures that are above their minimum miscibility pressure. But today, it is not uncommon to find $CO_2$ projects that operate below or near the minimum miscibility pressure. The $CO_2$ still produces tertiary oil. The process is not as efficient as that operated above the minimum miscibility pressure. Most historical $CO_2$ floods have targeted reservoirs that have a gravity of 25 API units or greater, but low API Gravity reservoirs are also targets. For example: Wilmington field in California produces 14 API Gravity crude from the Ranger formation. Three pilots were conducted in Fault Blocks I, III, and V. Eventhough economic performance was reported poor, mostly due to an inadequate $CO_2$ source and low oil price enviornment, a good number of wells increased oil rate from 30 BOPD to over 300 BOPD after $CO_2$ was injected. $CO_2$ has the ability to affect the full $C_2$ through $C_{30+}$ compositional range. Whereas, Nitrogen, and in some cases flue gas injection, will only extract the lighter components ($C_2$ through $C_6$). In addition, a high percentage of intermediate hydrocarbons in the oil composition can be beneficial in making the overall recovery process more efficient. If these occur naturally in the oil, then the oil will probably contain a low value of Minimum Miscibility Pressure (MMP). If the oil has a high MMP, then additions such as propane, butane, condensate, or other types of hydrocarbons can be added to the $CO_2$ injection stream to lower the minimum miscibility pressure and improve overall oil recovery.

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