CMTC-502866-MS

Enhanced Oil Recovery – The History of CO_2 Conventional WAG Injection techniques developed from Lab in the 1950's to 2017

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Abstract

During the past 45 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. The purpose of this report is to help disseminate this knowledge to operating companies interested in EOR flooding or to CO_2 Sequestration Communities interested in storing CO_2 in EOR projects.

In 2015, Merchant Consulting published CMTC-440075-MS "Life beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV Injection in CO_2 Tertiary Floods". The primary objective of the report was to target all 10 CO_2 Recovery Methods used today including "Conventional WAG Techniques" which have been used in over 90% of all the Enhanced Oil Recovery projects implemented to date. These include projects in the Permian Basin in Texas, Colorado, Oklahoma, and Wyoming. The paper presents answers to the question "What is life after 80% HCPV Injected?" 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.

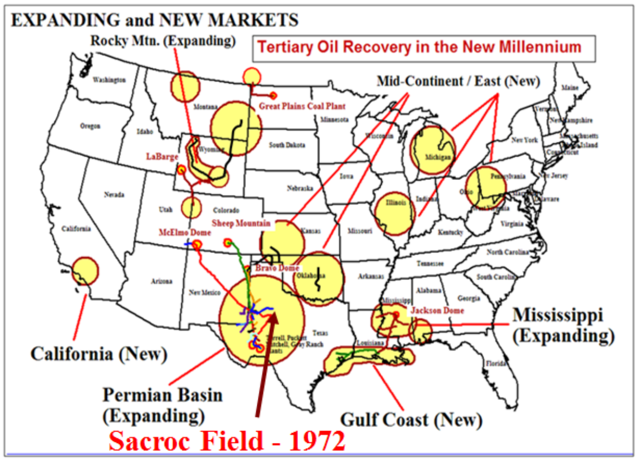
Conventional WAG History in CO_2 Tertiary Oil Projects:

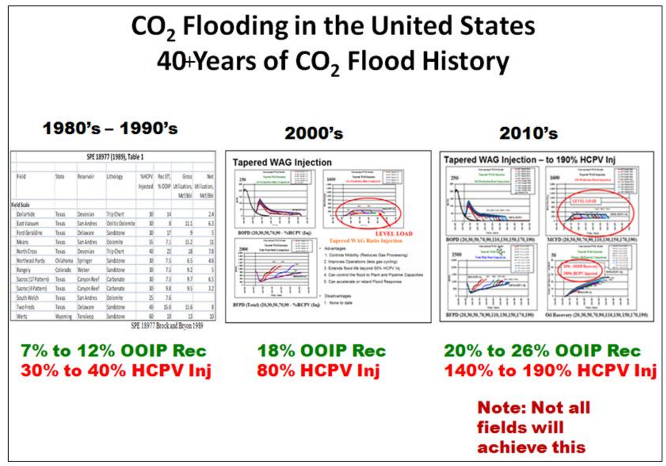
To achieve CO_2 Injection beyond 80% HCPV Injection requires proper CO_2 WAG Management. The purpose of this report is to provide both the EOR and CO_2 Sequestration Communities an understanding of the "History of Conventional WAG" and how it has changed from first introduced in the Lab in the 1950's, to how it was implemented and developed in the 1980's by the Major Oil Companies in the Permian Basin, and how Conventional WAG is being managed today in the field.

Introduction – CO_2 Flooding

CO_2 Flood History

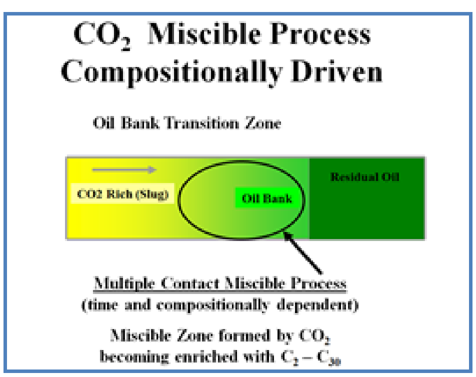
The Permian Basin has had over 85+ years of oil production history and produced over 30 billion barrels of oil and represents the 3rd largest petroleum producing area in the United States after the Gulf of Mexico and Alaska. In 1972, CO_2 injection was first introduced commercially in the Sacroc Field. Today, over 1.3 billion barrels have been produced with CO_2 and accounts for over 350,000 BOPD from over 17,000 production wells and 14,000 CO_2 injection wells, through 4,500 miles of pipeline.

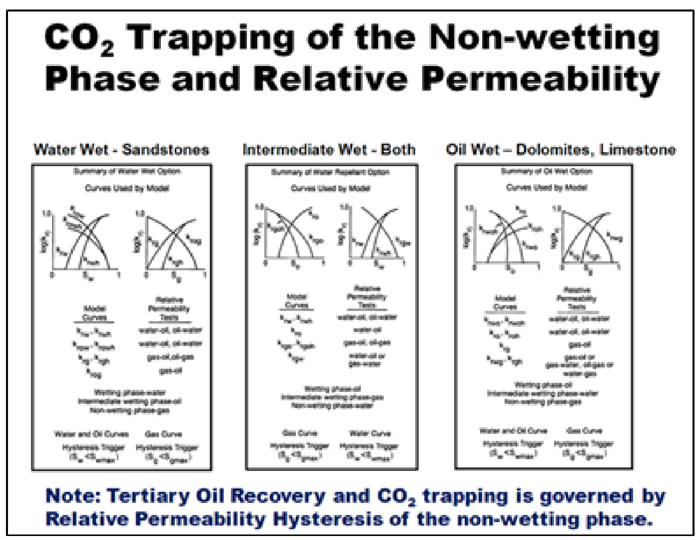




What makes CO_2 Tertiary Oil Recovery Work?

The reason why CO_2 works is simple. The CO_2 acts as a solvent when injected into the reservoir and swells the Residual Oil (oil left after water flood) and reduces its viscosity. This causes the Residual Oil to swell and become mobile and be produced.



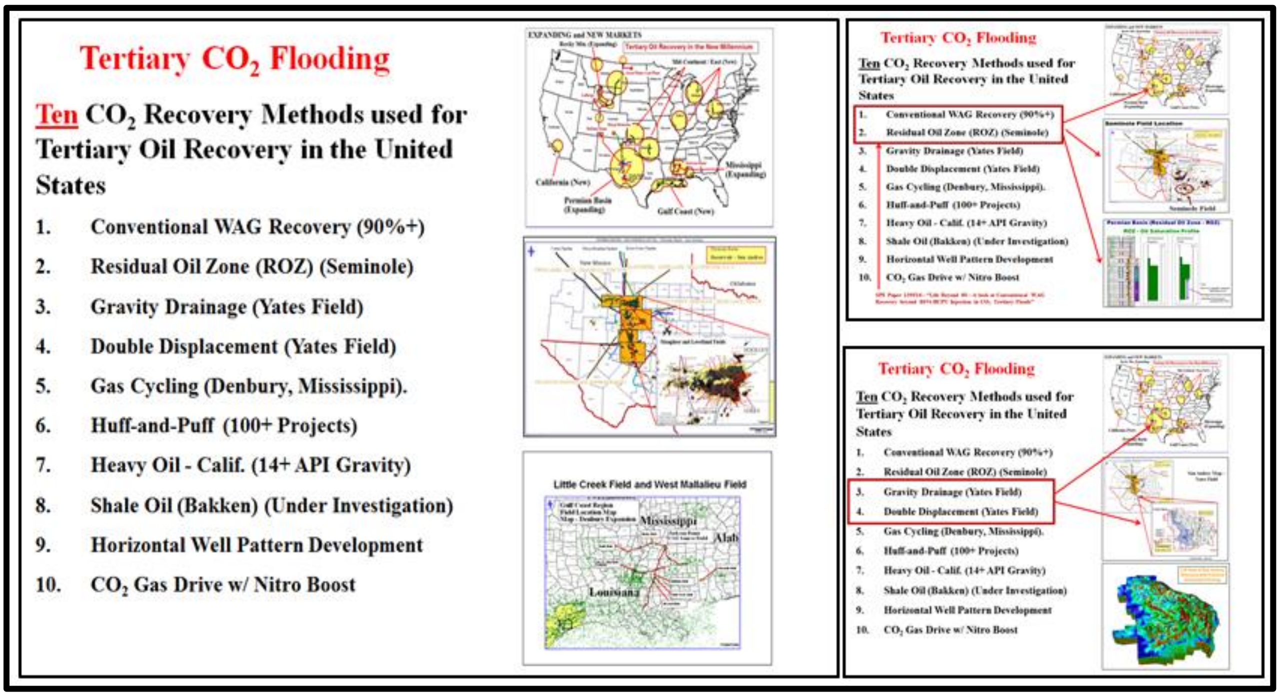


The amount of Tertiary Oil Recovered and the amount of CO_2 Trapped or Sequestered is dependent on the rock type. In addition to mobilizing residual oil saturation, a portion of the CO_2 becomes trapped. In the Petrophysical world, this is known as Relative Permeability Hysteresis or Trapping of the Non-wetting Phase. In this case CO_2 is the non-wetting phase. As demonstrated above, this phenomenon occurs in Water Wet Rocks (Sandstones), Intermediate Wet Rocks (Sandstones or Carbonates), and in Oil Wet Rocks (Dolomites and Limestone formations).

CO_2 Tertiary Recovery Methods

Introduction

CO_2 Tertiary Recovery Processes to date encompass "**Ten**" Recovery Methods. Four of these methods are used in the Permian Basin. Conventional WAG Techniques have been used in over 90+% of the CO_2 floods around the World. The Seminole field example presented in this report is an example of a field operated under Conventional WAG that targets both the Main Pay and ROZ zones.



Additional information can be found: SPE Paper 139516 or CMTC-502866-MS ("Life Beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV Injection in CO_2 Tertiary Floods")

Carbon Sequestration Options: Ten Recovery Methods for EOR

Most Enhanced Oil Recovery Projects use one of the following **ten** operating methods: Conventional WAG Recovery, ROZ Recovery, Gravity-stabilized Recovery, Double Displacement, Gas-cycling Huff-and-Puff, Heavy Oil-California, Shale Oil (Bakken, Wolfcamp), Horizontal Well Pattern Development, and CO_2 Gas Drive w/ Nitro Boost. 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%-50% 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. 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. In California the Wilmington field had three CO_2 pilots in 14 API Gravity Crude. Recovery was comparable with West Texas Operations. Shale Oil with CO_2 is still under investigation. Horizontal Well CO_2 floods are operational in Aneth field in Utah and Weyburn field in Canada. The Gravity Drainage case with added Nitro-Boost was developed for rate acceleration cases where nitrogen follows CO_2 Injection.

CO_2 Storage - Mis-conceptions about EOR

Over the years, there have been many mis-conceptions and half truths developed about EOR and its ability to store CO_2.

The **first mis-conception** about CO_2 flooding deals with ranges of Tertiary Oil Recovery reported over the years. In the 1990's, most all of the major oil companies reported tertiary oil recovery in the range of 10%-12% OOIP with a 30%-40% HCPV CO_2 slug size. By 2000, this number grew to 18% OOIP recovery with an 80% slug size. Today, expected recoveries in certain fields are expected to exceed 26% OOIP with 190% HCPV CO_2 injected. However, NOT all fields will achieve this level of oil recovery. Each CO_2 project must be judged on its own merits.

The **second mis-conception** about CO_2 flooding deals with the amount of CO_2 Storage in EOR operations. Normal EOR operations have always stored or trapped CO_2 in the reservoir. Tertiary recovery is a displacement process. For the EOR process to work, CO_2 must be cycled through the reservoir, similar to water flood operations. The CO_2 acts as a solvent to swell the remaining oil left after water flood and decreases the oil's viscosity; thus, allowing the tertiary oil to flow. Three phase relative permeability dictates the amount of CO_2 trapped in the formation due to phase trapping. From existing CO_2 flood evaluations, this equates to the amount of CO_2 purchased and represents approximately 30%-40% of the Hydrocarbon-Pore-Volume. With extended WAG with CO_2 volumes exceeding 125% HCPV, the storage capacity could increase to 50%-60% HCPV, but involves large volumes of CO_2 through-put with little incremental gain in oil recovery.

The **third mis-conception** deals with throughput Injection Rate and Injection Pressure (Water Injection or CO_2 Injection). All reservoirs have a Maximum Through-put Rate that can be injected into the reservoir. The maximum amounts of CO_2 that can be stored in a reservoir are based on a number of factors. These include: The total number of production and injection wells available, pattern configuration, current reservoir pressure, fracture pressure, injection flow capacity (permeability-thickness (kh) of each injection well), and relative permeability. Most water flood operations operate at or near fracture pressure. The same is true for CO_2 floods. The objective is to provide maximum CO_2 throughput rate across the reservoir at a level that maintains good seal integrity.

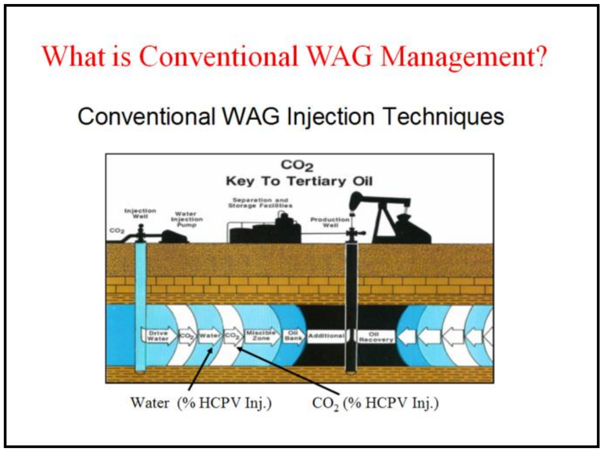
The **fourth mis-conception** about CO_2 flooding deals with the Total CO_2 Storage Capacity of a reservoir. To date, all CO_2 floods operate with the intent to minimize the amount of CO_2 purchased. Under these conditions, CO_2 is purchased up-front and cycled through the reservoir until the revenue from the oil and hc-gas production doesn't have the ability to support the cost to recover the oil (abandonment). This date has been very elusive to determine. Of all the CO_2 projects operated to date, most are still operating today. A limited few projects have been shut-in due to a low oil price environment, but could be returned back to production if given the right economic conditions.

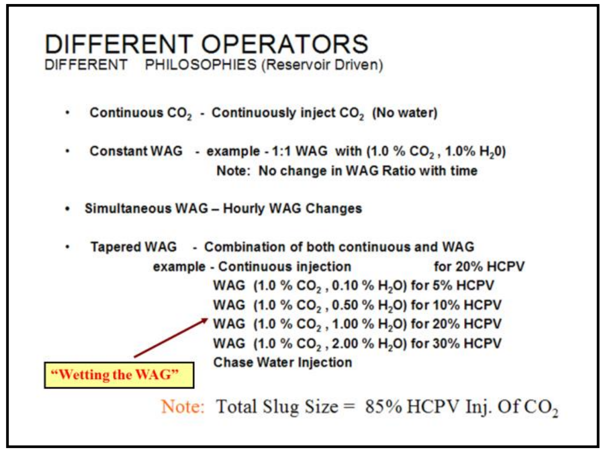
The **fifth mis-conception** about CO_2 flooding deals with CO_2 Storage Timing. Is it at the beginning? Does it occur during EOR CO_2 operations? Or, is it at the end of EOR operations? For those advocating a switch from EOR to CO_2 Storage two-thirds though or near the end of the EOR project should think through the physics. You can't fool Mother Natue. The amount of CO_2 **TRAPPED**, **STORED**, OR **SEQUESTERED** is dependent on the Composition of the Residual Oil Saturation and Phase Trapping of the Non-Wetting Phase, which occurs throughout the life of CO_2 injection, with 75% of CO_2 storage occurring during the first one-third of the project's life. After this initial period, most of the CO_2 that is injected is re-cycle CO_2 from the CO_2 recovery plant. CO_2 purchases near the end of the life of an EOR project are minimal.

The **last mis-conception** deals with achieving Total CO_2 Storage Potential of the reservoir. Currently there are ten methods used by the industry to recover oil with CO_2. All target the remaining tertiary oil. None target the **water**. The Eleventh Recovery Method which targets CO_2 storage removes both the **CO_2** and **Water** from the reservoir. In a World where there is an infinite amount of CO_2 available for storage, the remaining water in the reservoir becomes a commodity target along with the oil. Under this scenario, the objective will be to displace as much of the remaining oil plus water from the reservoir and replace it with CO_2. Since seal integrity will always be maintained below formation parting fracture pressure, the additional storage capacity provided by removing both the oil and water would far exceed EOR storage operations alone.

Conventional WAG Techniques

Conventional WAG Techniques have been used in over 90% of the CO_2 Floods implemented today. They are designed to work well in reservoirs that are developed on pattern spacing. These include: Five-spot, Nine-spot, and Chickenwire pattern development. The objective is to "Level Load" produced gas production to a CO_2 Recovery Plant inlet gas rate, which extends field life and recovers more tertiary oil.





Today, most operators have adopted the Tapered WAG approach to optimize WAG management.

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 or Hybrid WAG Injection
4. Simultaneous CO_2 Injection (Limited use)

What is WAG Management?

Through the 1980's and 1990's, Amoco, Shell, Arco, Exxon, 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. The results are presented below.

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, 1,102]. 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 1990's, Tapered and Hybrid WAG Operations were adopted to improve the overall recovery process [2,3,4,5, 6,104,105]. During the WAG process, CO_2 and Water are injected into the reservoir in alternating CO_2 and water slug sizes time periods. 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. "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 to improve overall conformance or adjusted to "Level Load" gas production to a Plant inlet rate.

Conventional WAG History

Lab Experiments in the 1950's and 1960's

Conventional **W**ater-**A**lternating-**G**as (**WAG**) was originally discovered in the 1950's when Caudle and Dyes introduced water in Lab experiments to decrease gas mobility. During the 1960's over 150 small scale Miscible and Immiscible projects were implement across the United States by labs and oil companies interested in developing Enhanced Oil Recovery for additional recovery of oil beyond Waterflood operations.

Permian and Rocky Mountain Basins History of "WAG"

1950's and 1960's

1950's – 150 Small Scale Miscible and Immiscible Projects
1958 - Lab Experiments Caudle and Dyes introduced water to decrease solvent mobility

1970's

1972 – Sacroc Unit (Kelly Snyder field) First Commercial Large Scale Project
1972-1979 North Cross, Two Freds, Maljamar, others

1980's Large Scale Permian Basin and Rocky Mountain Expansions

Slaughter field three projects plus Wasson ODC Unit – Amoco's Tapered WAG
Wasson field Denver Unit – Shell's Continuous Injection area plus DUWAG
Wasson field Willard Unit - Arco's Area Wide WAG went to Individual Patterns
Seminole field – Amerada Hess's Constant WAG scheme
Rangely field – Chevron's Wide Area WAG scheme
Bairoil (Lost Soldier and Wertz field) – Amoco's Tapered WAG

1990's, 2000's, and 2010's

Most new CO_2 flood projects adopt the "Tapered WAG" approach to WAG Management

SPE 18977 (1989), Table 1

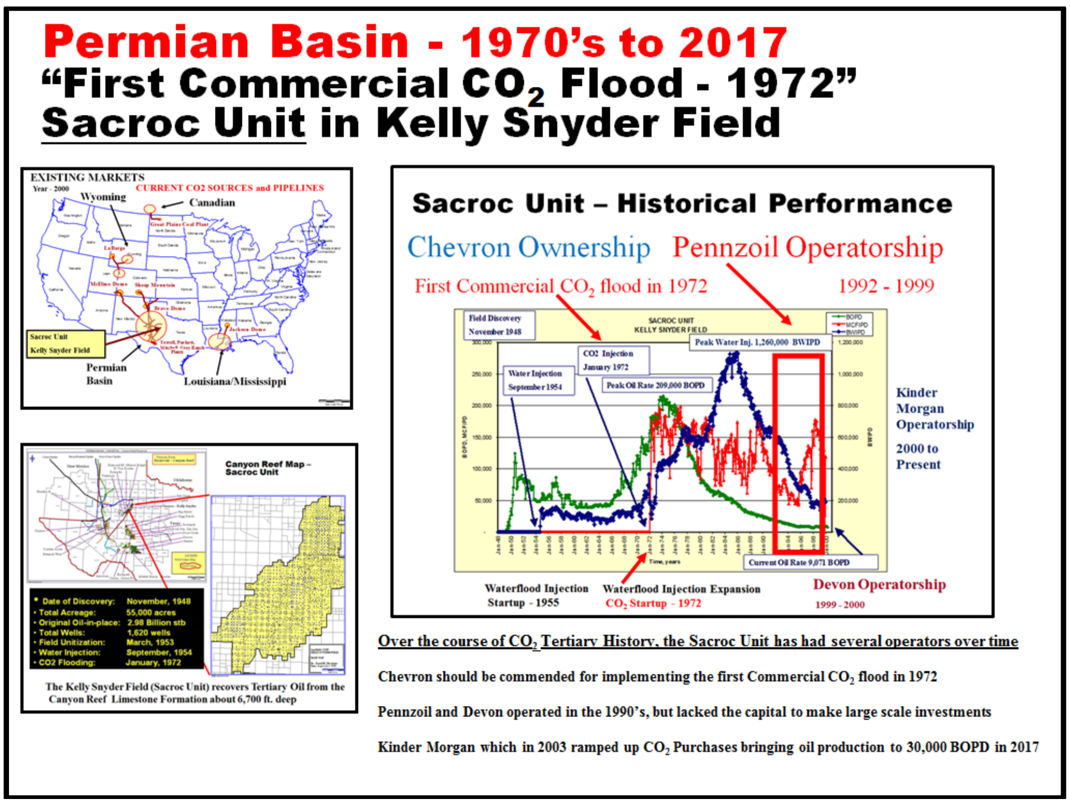
Field	State	Reservoir	Lithology	%HCPV Injected	Rec Eff, % OOIP	Gross Utilization, Mcf/Bbl	Net Utilization, Mcf/Bbl
Field Scale							
Dollarhide	Texas	Devonian	Trip Chert	30	14		2.4
East Vacuum	Texas	San Andres	Oolitic Dolomite	30	8	11.1	6.3
Ford Geraldine	Texas	Delaware	Sandstone	30	17	9	5
Means	Texas	San Andres	Dolomite	55	7.1	15.2	11
North Cross	Texas	Devonian	Trip Chert	40	22	18	7.8
Northeast Purdy	Oklahoma	Springer	Sandstone	30	7.5	6.5	4.6
Rangely	Colorado	Weber	Sandstone	30	7.5	9.2	5
Sacroc (17 Pattern)	Texas	Canyon Reef	Carbonate	30	7.5	9.7	6.5
Sacroc (4 Pattern)	Texas	Canyon Reef	Carbonate	30	9.8	9.5	3.2
South Welch	Texas	San Andres	Dolomite	25	7.6		
Two Freds	Texas	Delaware	Sandstone	40	15.6	15.6	8
Wertz	Wyoming	Tensleep	Sandstone	60	10	13	10

SPE 18977 Brock and Bryon 1989

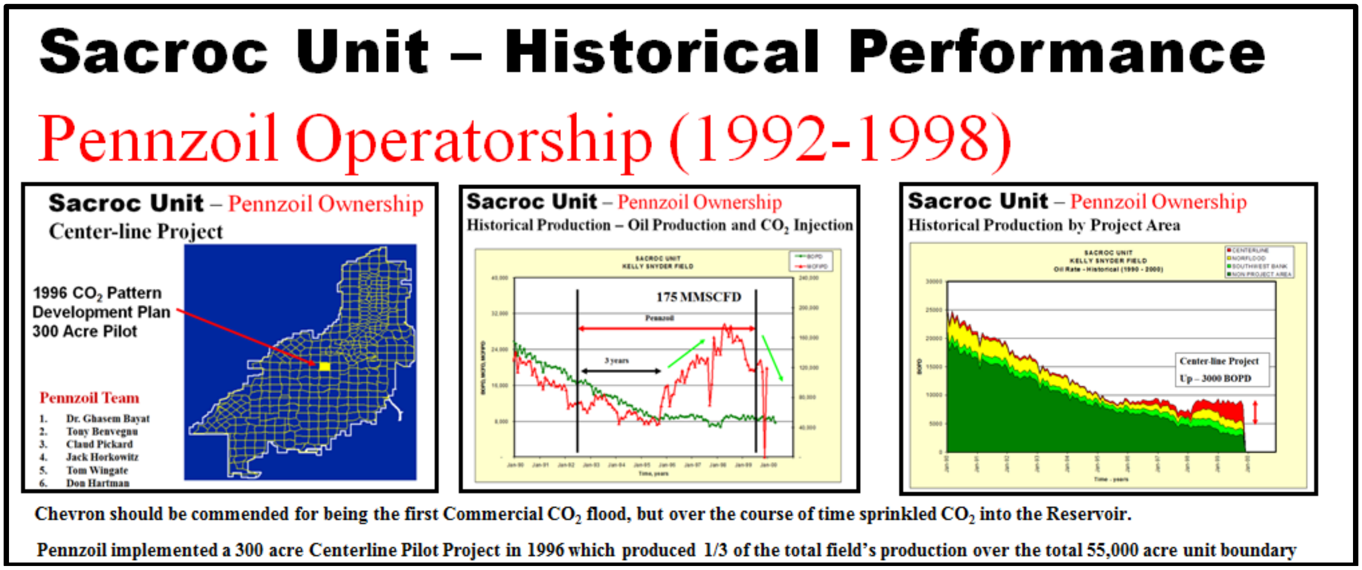
CO_2 Flooding in 1970's

First Commercial Scale CO_2 Flooding in 1970's

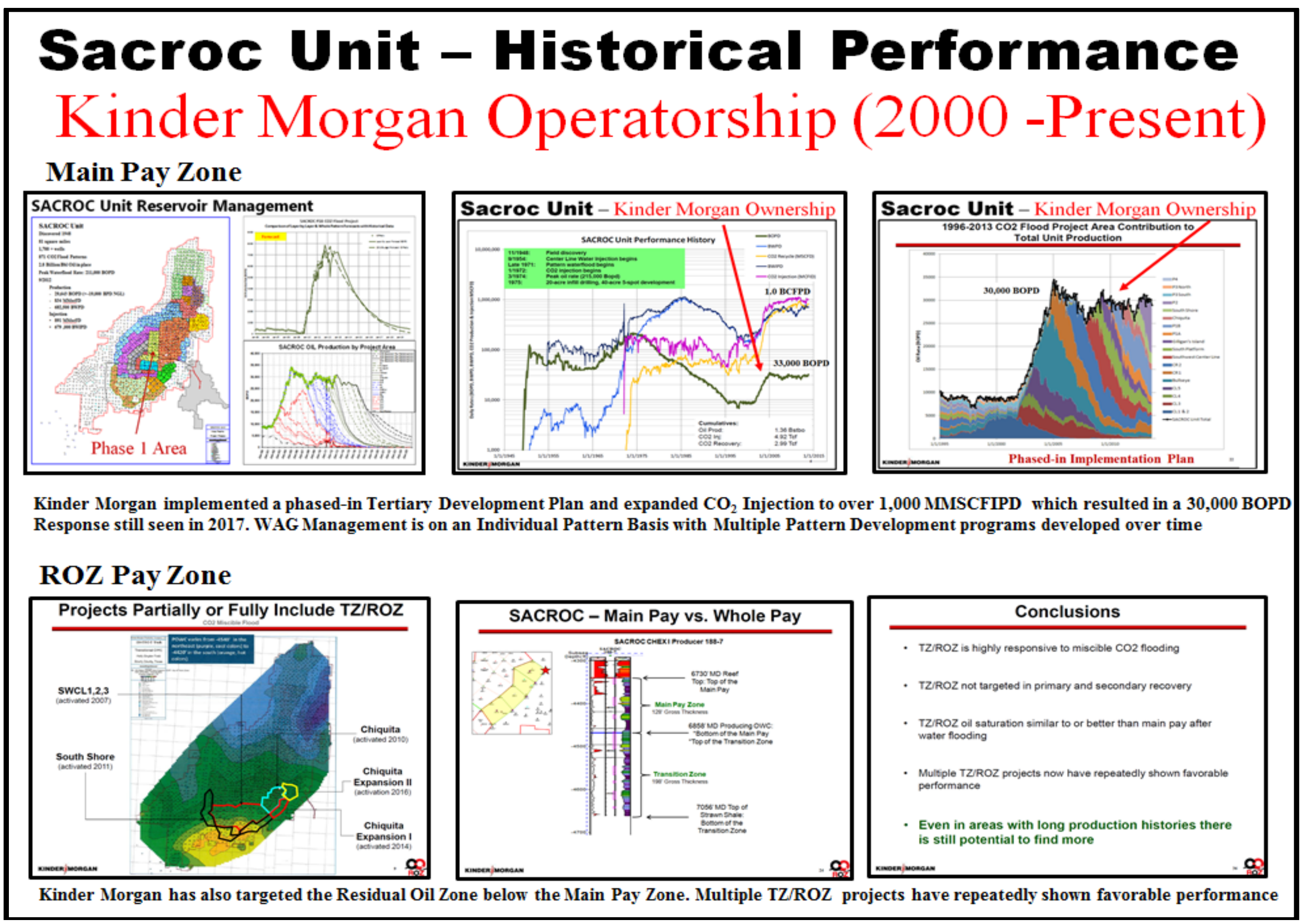
Chevron, who operated the Sacroc Unit in the Permian Basin, was the first field to inject CO_2 as a commercial project in1972. Chevron injected CO_2 over the total unit with less than 15% in any one pattern and sold the property in 1992 to Pennzoil. Pennzoil ramped up CO_2 Injection and implemented a 300 acre pilot in the middle of the field of which 1/3 of the total field's production out of 55,000 acres was being produced from the pilot area. In 1998, Pennzoil sold the field to Devon and Devon then sold the field to Kinder Morgan in 2000. Kinder Morgan then ramped-up CO_2 injection to over 900 MMSCFIPD. The result was a Tertiary oil response growth from 9,600 BOPD to over 30,000 BOPD.



Chevron should be commended for implementing the first Commercial CO_2 flood in the United States, but only sprinkled CO_2 over the total reservoir limit.



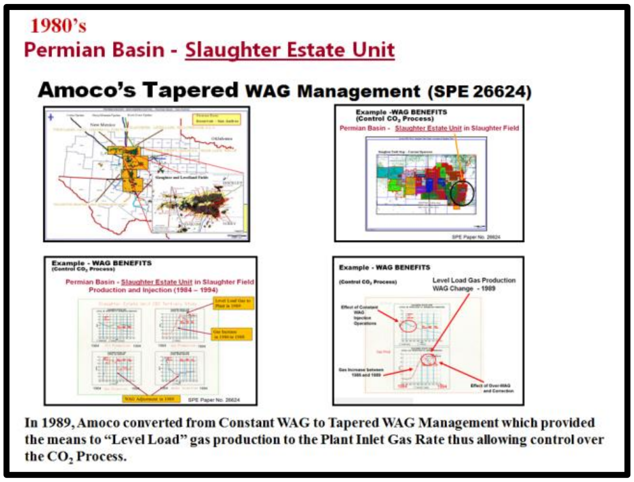
Pennzoil in 1996 implemented a 300 acre Centerline Pilot Project which produced one third of the fields 9,600 BOPD production. (Ref: 106) In 1998, Pennzoil sold the field to Devon who later sold the field to Kinder Morgan in 2000.

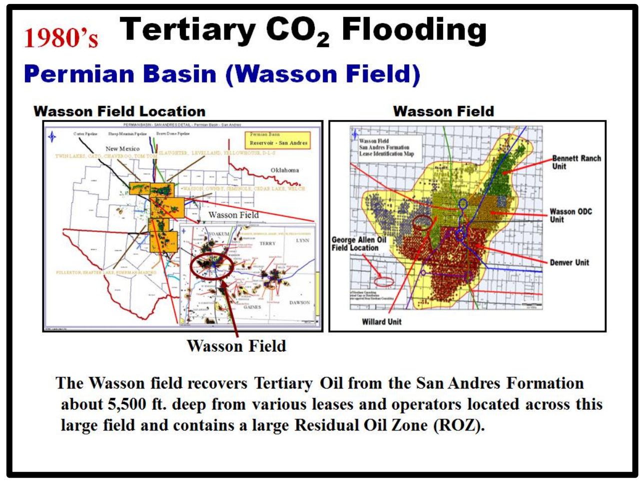


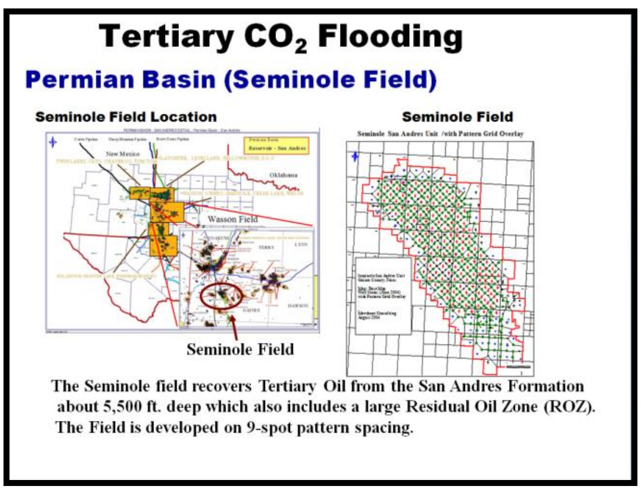
In 2000, Kinder Morgan implemented a multi-phase Tertiary Development Plan that increased CO_2 Injection to over 800 MMSCFIPD, which resulted in a 30,000 BOPD Response still seen in 2017.

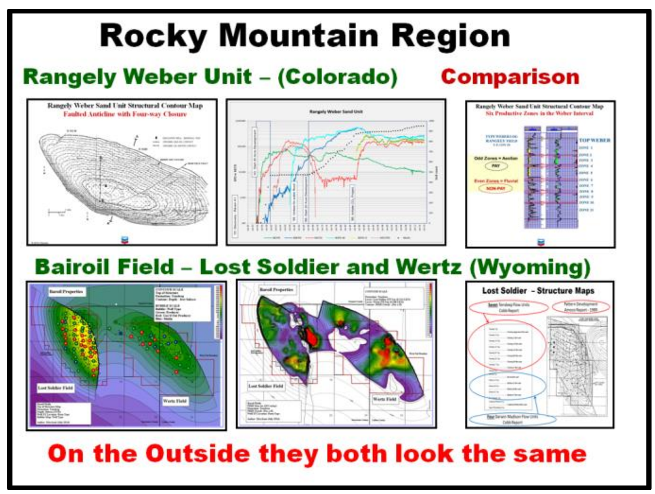
CO_2 Flooding in 1980's

In the 1980's, major oil companies including Shell, Amoco, Texaco, Arco, Phillips, Oxy, and Exxon implemented CO_2 projects in many of the large fields located across the Permian Basin, Rockies, and Gulf Coast Regions. As reported by the major oil companies, expected tertiary recovery was typically in the 8% to 12% OOIP range. Optimum slug size for most projects was projected to be in the 30% to 40% HCPV CO_2 injection range.









In the 1980's, Major Oil Companies also implemented different types of CO_2 Recovery Methods to both experiment and determine which process works best. Each will be discussed below.

Permian and Rocky Mountain Basins History of "WAG"

1980's Large Scale Permian Basin and Rocky Mountain Expansions

Slaughter field three projects plus Wasson ODC Unit – Amoco's Tapered WAG
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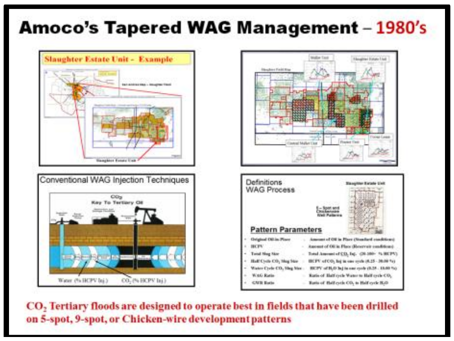
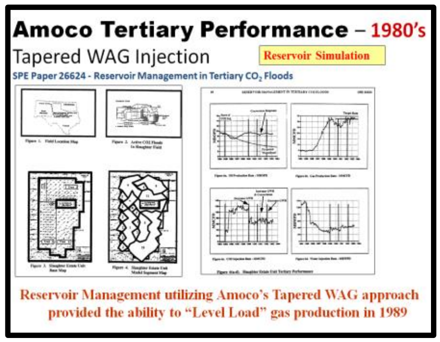
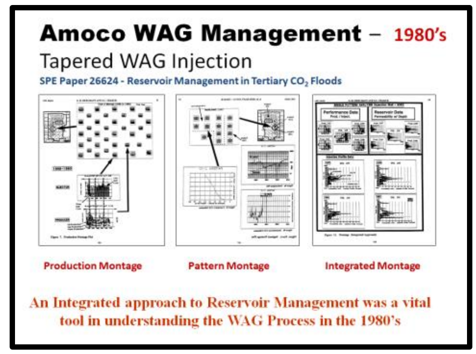
CO_2 Flooding in 1980's (Amoco – Tapered WAG)

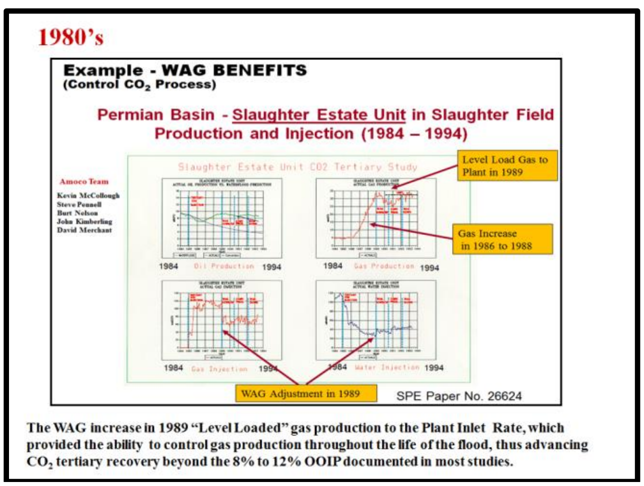
Amoco initiated CO_2 injection into four floods in the mid 1980's. These included: Slaughter Estate Unit, Central Mallet Unit, and Frazier Unit in Slaughter field plus Wasson ODC in Wasson field. All initially were operated under a constant WAG. During this time frame, extensive modelling was conducted to determine a method that could optimize the WAG process and extend oil recovery. (Ref: 107) The result was "Tapered WAG" which provided the means to "Level Load" total gas production from the field to a maximum "Plant Inlet Gas Rate". In 1989, Amoco implemented this new technology into all four projects, achieving total success.

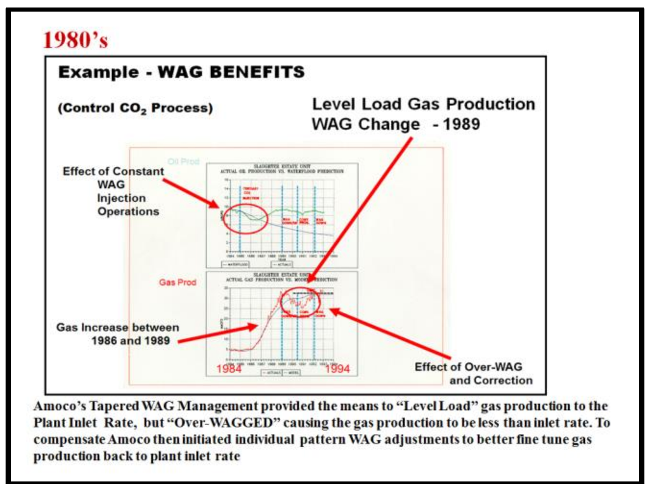
As this technology improved, advancements in CO_2 flood design have been implemented into more improved reservoir management practices. In the 1990's, Constant WAG was being replaced with Tapered WAG operations and tertiary oil recovery increased to 18% of a field's Original Oil-in-Place. Today, most fields implemented during the 1980's have surpassed the 40% HCPV injection, advancing to or passing earlier HCPV CO_2 predictions.

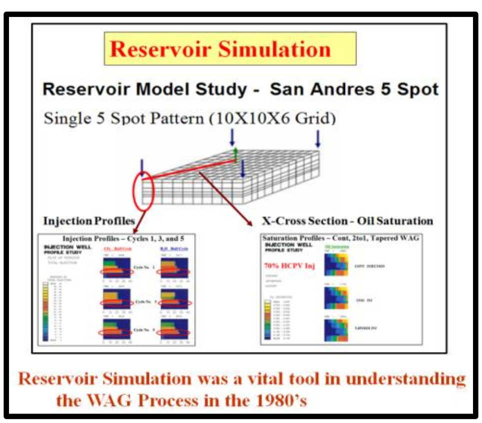


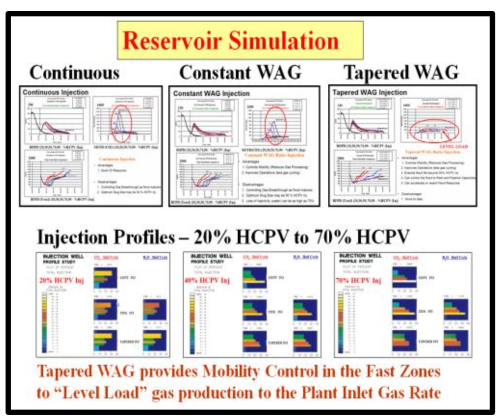










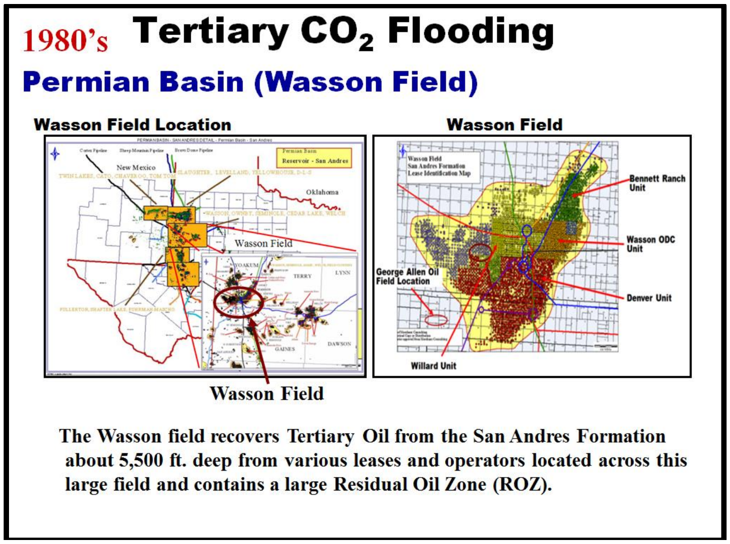


Slaughter Field
Bibliography References: 19 thru 29

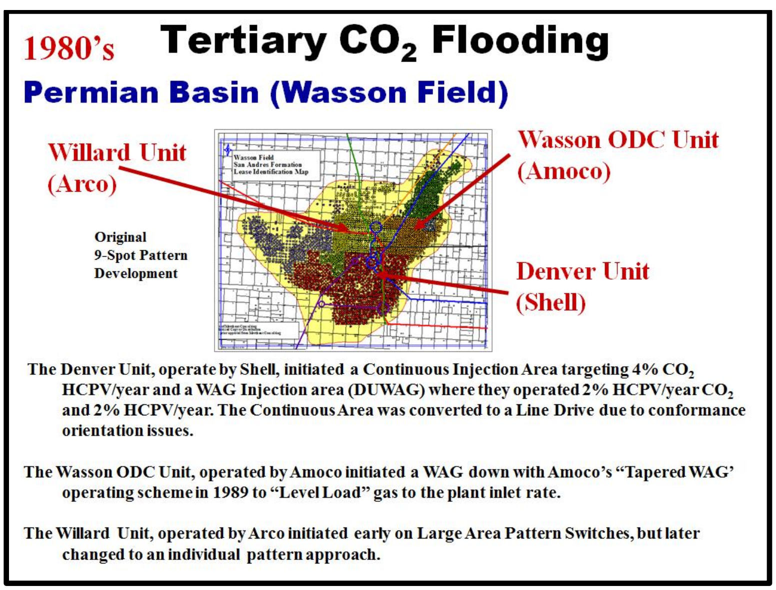
"Tapered WAG Management" can provide Reservoir Engineers with a "Reservoir Management Tool" that can properly manage WAG, but only through proper "Reservoir Management Practices"

CO_2 Flooding in 1980's Wasson Field (Shell, Arco, and Amoco)

Shell, in the Denver Unit of Wasson field took a different approach to understanding CO_2 management. It first divided the Denver Unit up into three project areas. The main area was a Continuous Injection project where they targeted 4% HCPV/per year, the second project area was a Constant WAG injection area (DUWAG Area) where they tartegeted 2% HCPV/per year CO_2 and 2% HCPV/per year Water. The final injection area in the western part of the unit was poorer quality reservoir and reminents of a gas cap. As technology improved, advancements in CO_2 flood design were implemented into reservoir management practices by Shell through the 1990's. The nine-spot inverted line drive configuration was changed to more of a direct line drive after conformance issues were identified in the field based on performance and pattern adjustments could better control conformance issues.



Arco, in the Willard Unit first implemented an area wide switching program based on making large area switches. The reservoir responed with some injectors taking 4% HCPV where others may have had 1% HCPV injected. Due to pattern imbalance issues, Arco then switched to an individual pattern WAG management program.



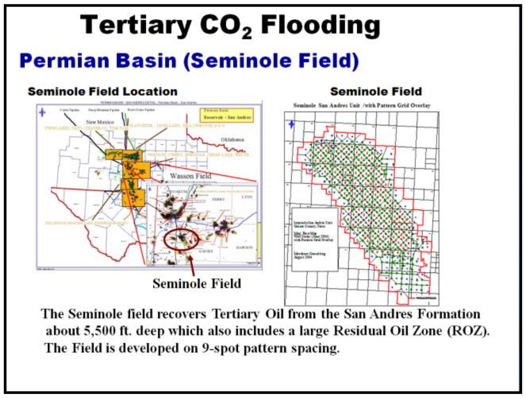
Wasson Field
Bibliography References:
7,8,9,10,11,18,12,13,14,15,16

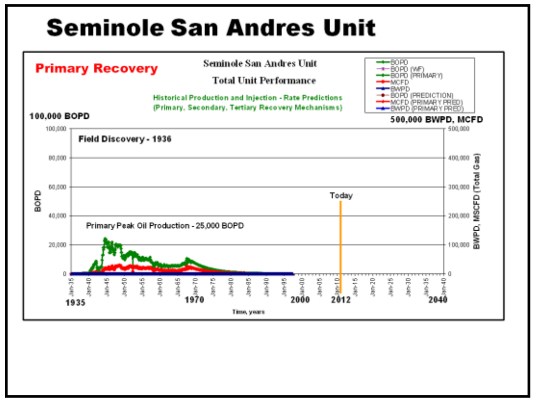
Amoco, in 1989, at the same they implemented Tapered WAG in Slaughter field, implemented a Tapered WAG at Wasson ODC Unit to "Level Load" gas production to its Ryan Holmes Plant Gas Rate Limit. As a result, the benefit of modifying to a Tapered WAG extended Tertiary Oil Recovery way beyond all of Amoco's original model predictions.

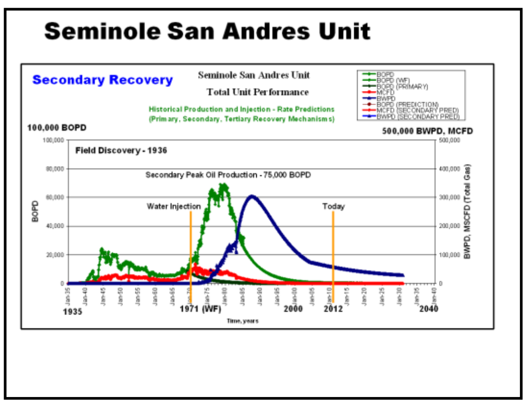
CO_2 Flooding in 1980's (Amerada Hess – Seminole San Andres Unit – Constant WAG)

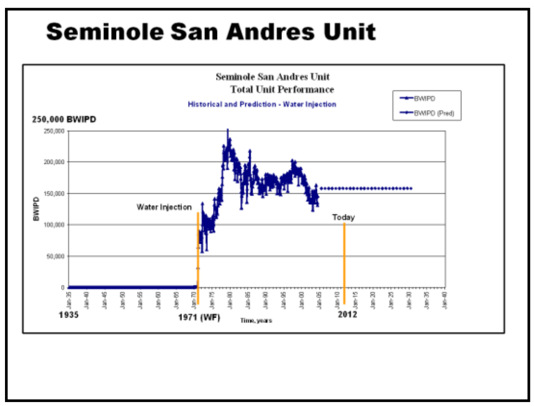
The best example of CO_2 Tertiary Recovery is the Seminole San Andres Unit in the Permian Basin. The field has undergone Primary, Secondary Waterflood, CO_2 Tertiary operations in the Main Pay, and in 1996 initiated CO_2 Tertiary operations in the Residual Oil Zone (ROZ).

The Seminole field was discovered in 1936 with **water injection operations** initiated in 1971. Under Primary Recovery the field would have only recovered 12.8% of its Original Oil-in-Place (OOIP). With Secondary Water flood operations, the field would have recovered 42.7% of its Original Oil-in-Place.

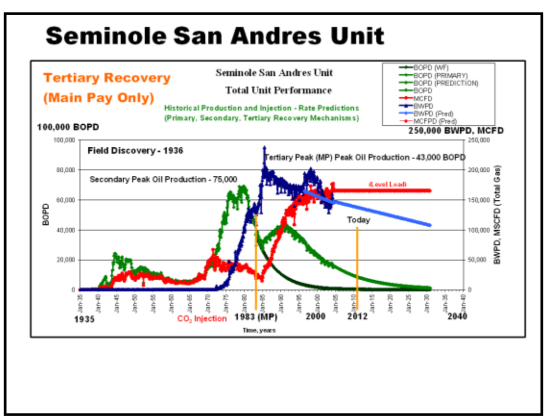


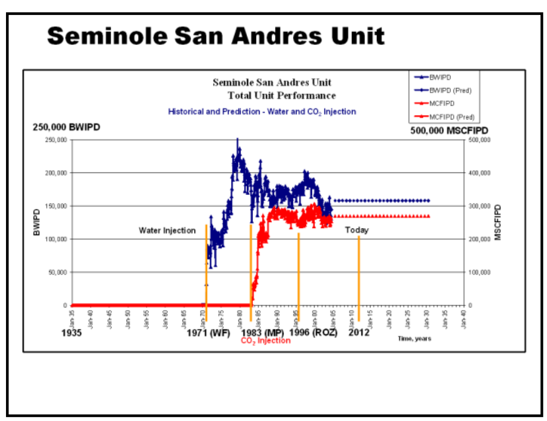






Tertiary CO_2 Injection operations into the Main Pay Zone was initiated in 1983. Under CO_2 Injection the field's Main Pay Section is expected to recover an additional 24% of its Original Oil-in-Place (OOIP).

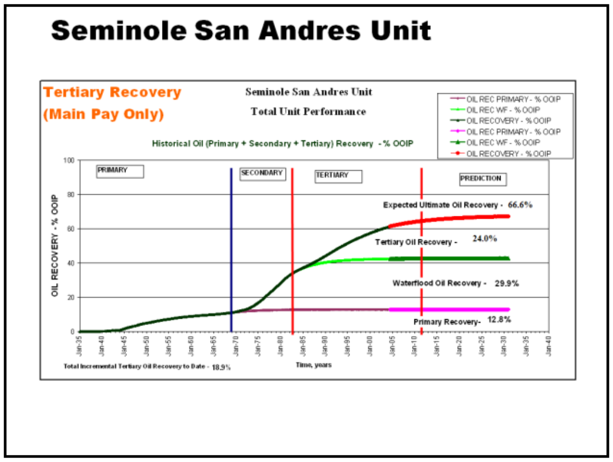


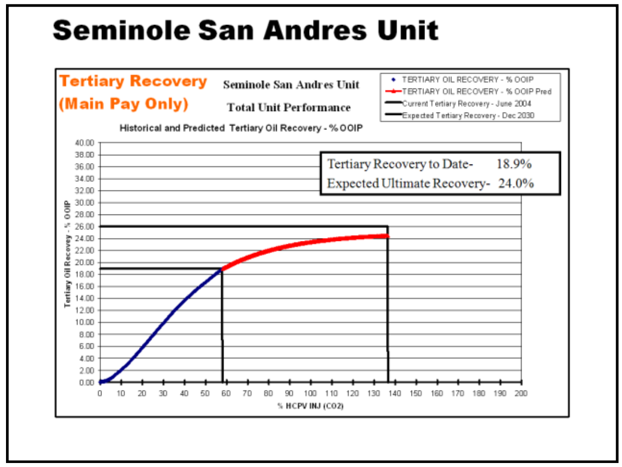


Seminole Unit
Bibliography References: 58 thru 65

Seminole San Andres Unit – (Main Pay Oil Zone Example)

Primary, Secondary, and CO_2 Tertiary Main Pay Oil Recovery as a percent of Original Oil-in-Place (OOIP) are shown below. Under Primary Operations, the field would have recovered 12.8% of its OOIP before abandoning operations. Water flood operations would have increased oil recovery to 42.7% OOIP (Primary plus Secondary). Tertiary operations with CO_2 in the Main Pay zone would have increased oil production by 24% OOIP. Total Primary+Secondary+Tertiary (MP) = 66.6% OOIP.



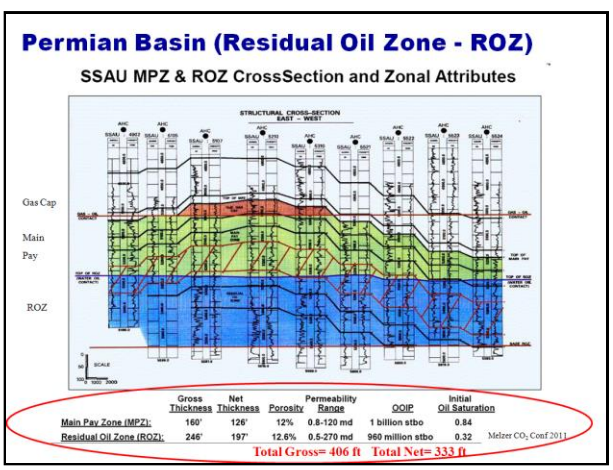


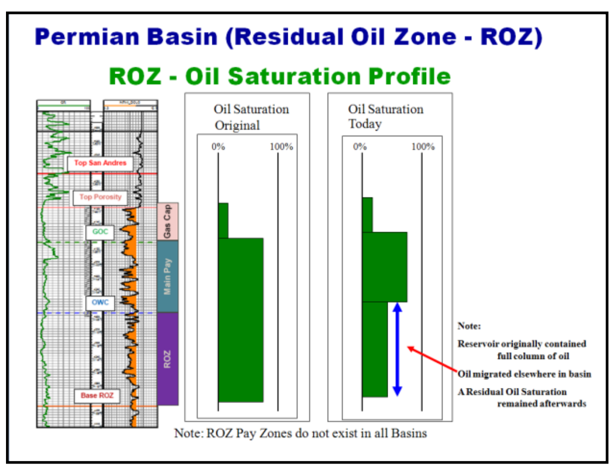
Seminole San Andres Unit – (Main Pay – Amerada Hess WAG Management)

The Main Pay Zone was developed on Inverted a Nine-spot Pattern development. In 1983, the field initiated CO_2 injection into a phased-in pattern development across the field. By 1987, 95% of the CO_2 flood had been completed south to the town of Seminole. Amerada Hess's WAG Management was based on a 2:1 WAG Ratio with 3.0% HCPV CO_2 Half cycles and 6.0% HCPV Water Half Cycle. The field has maintained or increased the water to better control gas breakthrough over time.

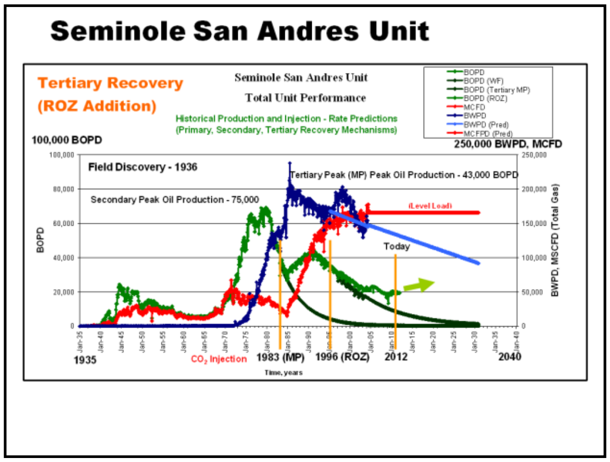
Seminole San Andres Unit – (Residual Oil Zone (ROZ) Example)

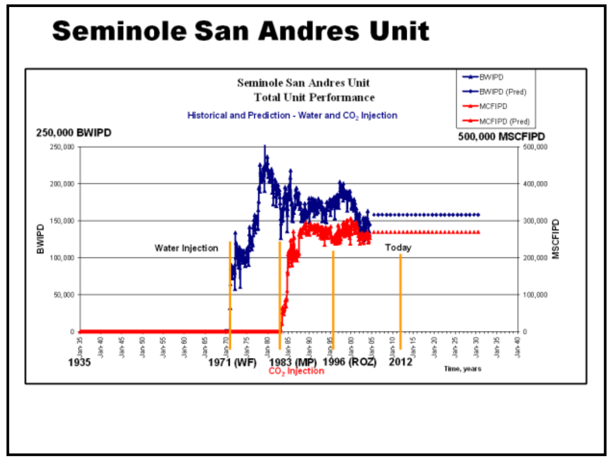
A Residual Oil Zone (ROZ) is created when oil within the original oil column migrates away from the field over geologic time creating a ROZ interval. In addition to the Main Pay Zone, the Seminole field contains a very large Residual Oil Zone (ROZ). The size of the ROZ is about the same size at the residual oil remaining in the Main Pay. CO_2 Injection commenced in 1996 into the ROZ. Injection into the ROZ will extend field life beyond the 2050's.





Seminole Unit
Bibliography References: 58 thru 65

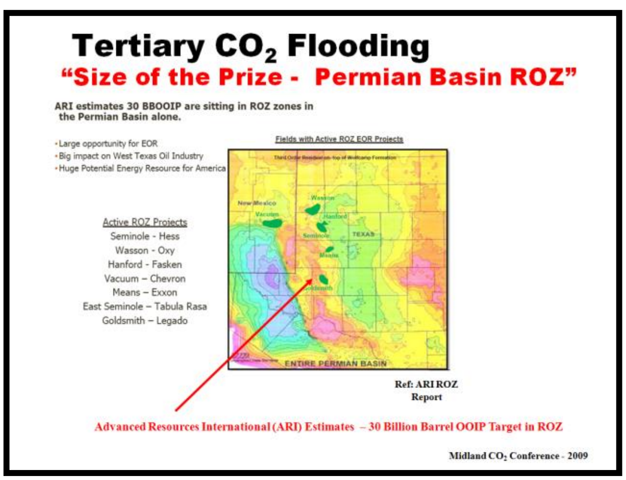


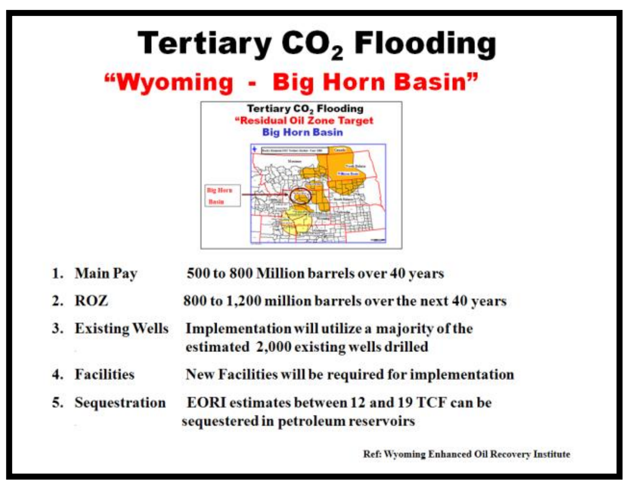


The Residual Oil Zone is responding well to CO_2 Injection. Since the ROZ reserves have never been tied to any Basin Study Estimates, these reserves are "NEW" bookable reserves. Future Performance is based on ROZ reservoir characterization unique to the Seminole field. Tertiary Performance is expected to be similar to that of the Main Pay or better, which depends on the quality of the ROZ pay section.

Residual Oil Zone (ROZ) Enhanced Oil Recovery Potential

Compared to other types of oil recovery mechanisms, CO_2 is the best method designed to recover tertiary oil from Residual Oil (ROZ) Zones. Residual Oil Zones have been identified across the World. The Permian basin is the first region to identify it, characterize it, and now exploit it. Advanced Resources International has estimated the ROZ in the Permian Basin could contain as much as 30 Billion barrels of recoverable tertiary oil from the ROZ. The Wyoming Enhanced Oil Recovery Institute has estimated the state of Wyoming may contain as much as 800 to 1,200 million barrels of ROZ potential in the Big Horn Basin of Wyoming, not counting potential in other basins in the region.

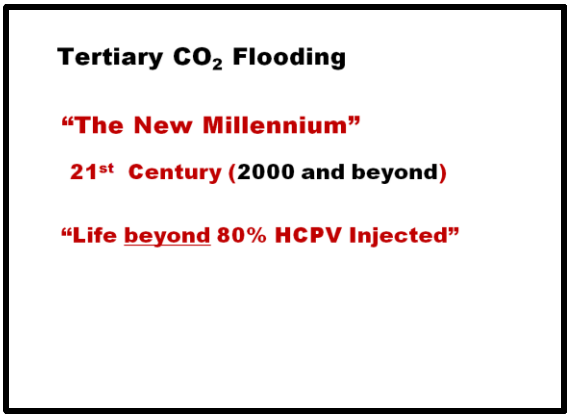


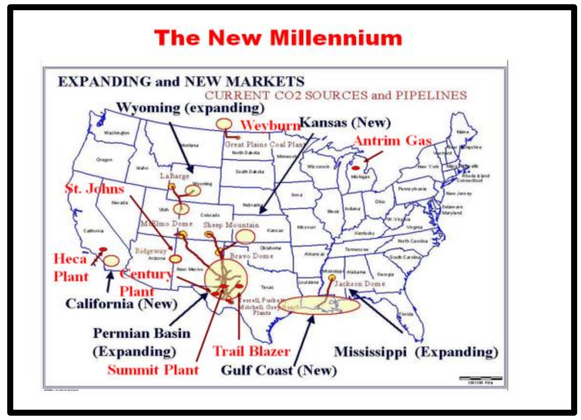


Anthropogenic CO_2 through CO_2 sequestration could expand this target to areas of the World that contain ROZ zones, but lacked the CO_2 to make the projects economically attractive.

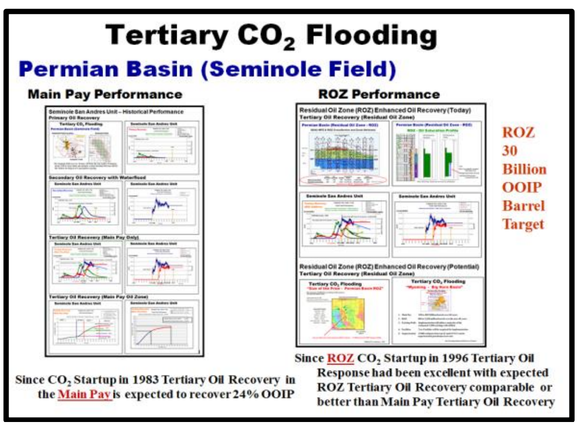
CO_2 Flooding in the 2000's (New Millennium)

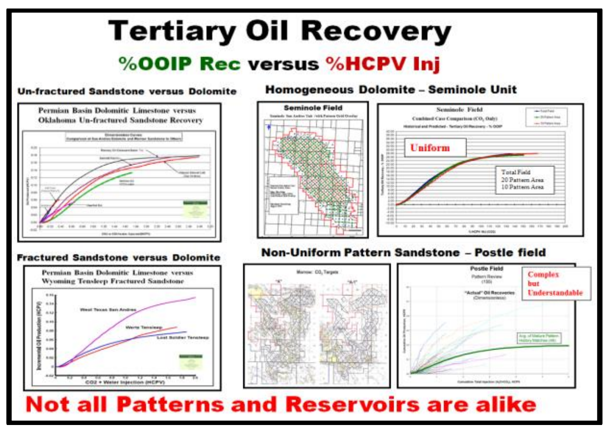
In the 21st Century, the benefit of controlling the CO_2 WAG process has extended oil recovery to new levels. As previously shown, the Seminole Main Pay CO_2 flood in the Permian Basin is expected to recover 24% of its Original Oil-in-Place with a 140% HCPV injection of CO_2, not counting the additional recovery from the ROZ.

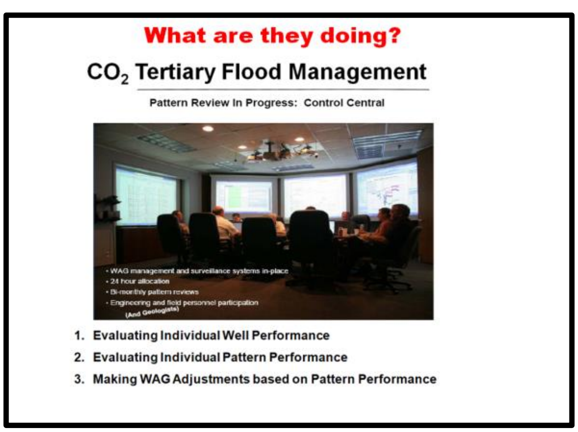


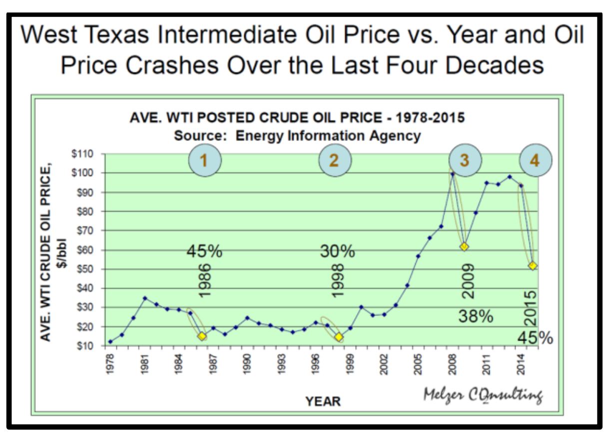


However, not all CO_2 floods are alike; Tertiary Oil Recovery from sandstone reservoirs are different from recovery from carbonate reefs just as un-fractured reservoirs are different from fractured reservoirs.









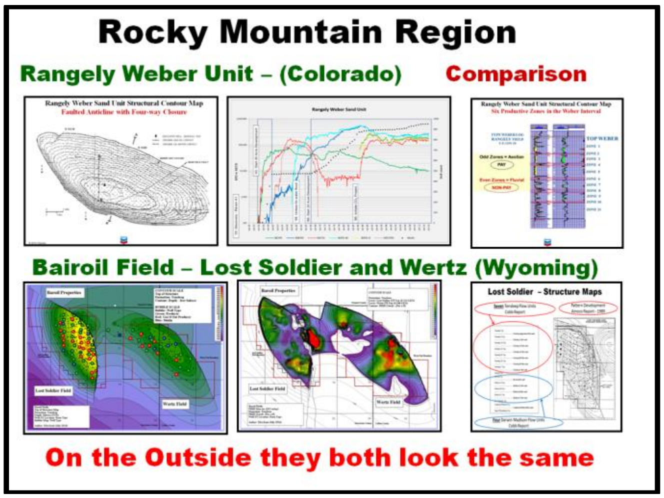
Ref. 108

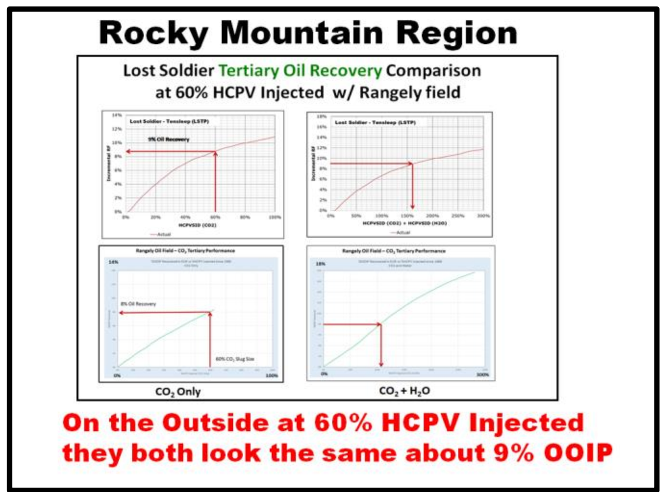
Tertiary Oil Recovery with CO_2 has also weathered **Four** Oil Price Adjustment Periods with the last one in 2015 dropping 45% just like the one back in 1986 that also dropped oil price by 45%. Today, over 90% of the CO_2 Floods that were put on in the 1980's are still producing today. This could only be accomplished through **good Reservoir Management Practices** including the **"Pattern Review Process"** where WAG adjustments are made.

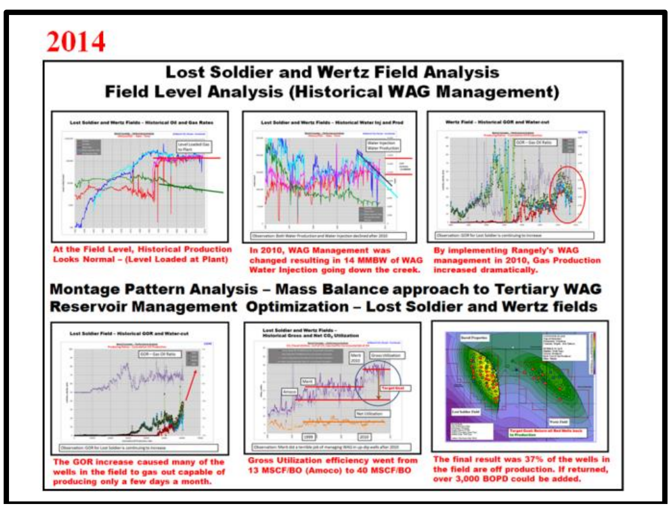
CO_2 Flooding in the Rocky Mountains (WAG Management Decisions (The Good, the Bad, and the Ugly)
Different Operators in the 1980's developed different WAG philosophies depending on the reservoir pattern configuration, formation dip, reservoir pressure, miscibility pressure, etc. As technology improved, advancements in CO_2 flood design were implemented into reservoir management practices to improve overall performance. However, companies should be aware that **NOT** all reservoirs are alike even though they were formed in the same geologic time period with similar producing characteristics.

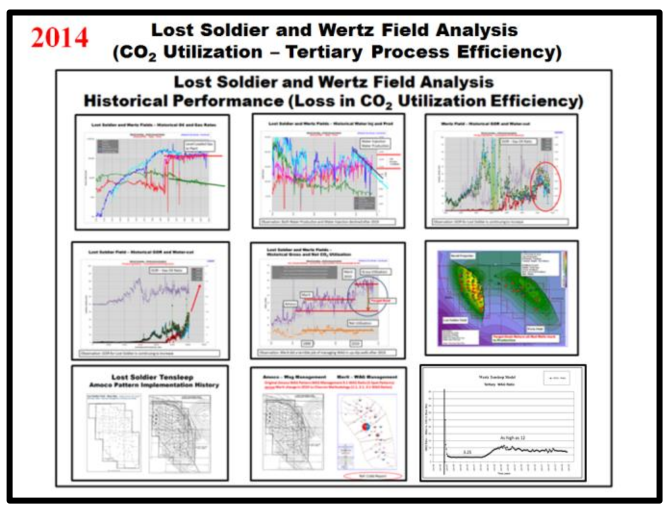
The example shown below illustrates the fact that not all reservoirs are alike. The Rangely Weber Unit in Wyoming produces from the Weber Sand which is similar in geologic age to Bairoil's Tensleep Reservoir producing section. In addition, CO_2 Tertiary WAG performance at 60% CO_2 HCPV Injected recovers about 9% OOIP in both fields.

NOT ALL FORMATIONS ARE THE SAME









In 2010, Merit Company, who operated the field, modified Amoco's five-spot pattern 9:1 WAG scheme to Rangely's 1:1, 2:1, and 3:1 WAG scheme by dividing the unit up into thirds. From 2010 to 2014, 14 million barrels of water went down the creek that was supposed to be used for WAG Management. The overall effect gassed out 37% of the wells in the Lost Soldier field that deteriated Amoco's Gross CO_2 Utilization WAG efficiency rating of 13 MSCF/BO to over 40 MSCF/BO under Merit's operatorship.

Fortunately BAD WAG Practices can be fixed…..

Life beyond 80% HCPV- (Tertiary Oil Recovery, CO_2 Gross and Net Utilization)

Since 1972, over 130+ Commercial CO_2 floods have been operated in the United States with the majority 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)

State	Formation	Field	Lease	Current Economic: Tertiary Recovery (%OOIP)	Current Economic: Gross CO_2 Utilization (MSCF/STB)	Current Economic: Net CO_2 Utilization (MSCF/STB)	Life beyond 80% HCPV Inj: Tertiary Recovery (%OOIP)	Life beyond 80% HCPV Inj: Gross CO_2 Utilization (MSCF/STB)	Life beyond 80% HCPV Inj: 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)

State	Formation	Field	Lease	Current Economic: Tertiary Recovery (%OOIP)	Current Economic: Gross CO_2 Utilization (MSCF/STB)	Current Economic: Net CO_2 Utilization (MSCF/STB)	Life beyond 80% HCPV Inj: Tertiary Recovery (%OOIP)	Life beyond 80% HCPV Inj: Gross CO_2 Utilization (MSCF/STB)	Life beyond 80% HCPV Inj: 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)

State	Formation	Field	Lease	Current Economic: Tertiary Recovery (%OOIP)	Current Economic: Gross CO_2 Utilization (MSCF/STB)	Current Economic: Net CO_2 Utilization (MSCF/STB)	Life beyond 80% HCPV Inj: Tertiary Recovery (%OOIP)	Life beyond 80% HCPV Inj: Gross CO_2 Utilization (MSCF/STB)	Life beyond 80% HCPV Inj: 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

State	Formation	Field	Lease	Current Economic: Tertiary Recovery (%OOIP)	Current Economic: Gross CO_2 Utilization (MSCF/STB)	Current Economic: Net CO_2 Utilization (MSCF/STB)	Life beyond 80% HCPV Inj: Tertiary Recovery (%OOIP)	Life beyond 80% HCPV Inj: Gross CO_2 Utilization (MSCF/STB)	Life beyond 80% HCPV Inj: 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 forty-five 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 a14 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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106. Pennzoil’s Sacroc Development Team (1994-1998): Dr. Ghasem Bayat, Tony Benvegnu, Claud Pickard, Jack Horkowitz, Tom Wingate, Don Hartman; Team was Responsible for Sacroc’s Centerline Project plus two other pilot programs that was responsible for 1/3 of Sacroc’s total 9,600 BOPD Production through this time period.
107. Amoco’s Permian Basin Original Model Development Group: Jack Aulick(Manager), Reservoir Modellers: Kevin McCollough, Steve Pennell, Burt Nelson, Gary Pariani, Dennis Edens, John Kimberling, and David Merchant, Operations: Perry Jarrell; Team was responsible for developing Amoco’s Tapered WAG Operating scheme.
108. Steve Melzer, Midland 2016 CO_2 Conference, “Plot of Historical Oil Price Crash Periods from the 1970’s through 2016”, Date: December 2016.

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