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

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This paper was prepared for presentation at the Carbon Management Technology Conference held in Sugarland, Texas, USA, 17–19 November 2015.

Abstract

During the past 43 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 2010, Merchant Consulting published SPE 139516 "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 "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. 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.

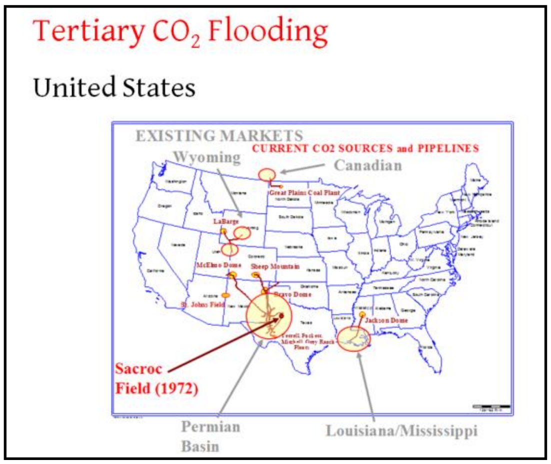
Carbon Sequestration Options for EOR:

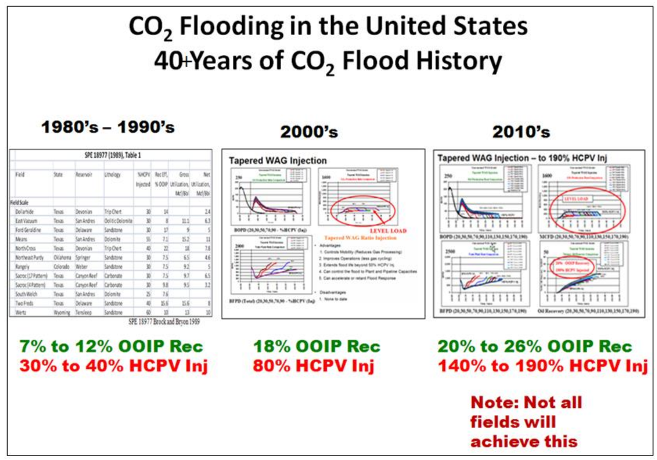
The purpose of this report is to provide the CO_2 Sequestration Community an update to the original SPE 139516 paper presented in 2010 at the SPE International Conference on CO_2 Capture, Storage, and Utilization held in New Orleans, Louisiana. The original paper covered only 5 of the 10 methods currently used today to recover tertiary oil with the injection of CO_2. This report will provide insight to all 10 methods used today in EOR operations.

Introduction – CO_2 Flooding

CO_2 Flood History

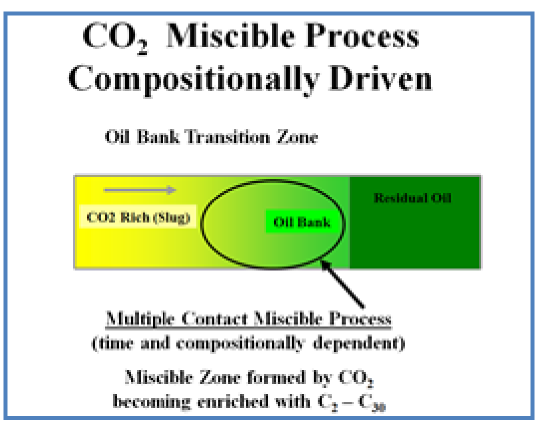
The Permian Basin has had over 85+ years of oil production history and produced over 29 billion barrels of oil and represents the 3rd largest petroleum producing area in the United States after the Gulf of Mexico and Alaska. Today, it produces 20% of the U.S. oil production excluding Alaska. In 1972, CO_2 injection was introduced, first in the Sacroc Field. Today, over 1.1 billion barrels have been produced with CO_2 and accounts for over 237,000 BOPD or 15% of all Permian Basin oil production from over 15,000 production wells and 12,000 CO_2 injection wells.

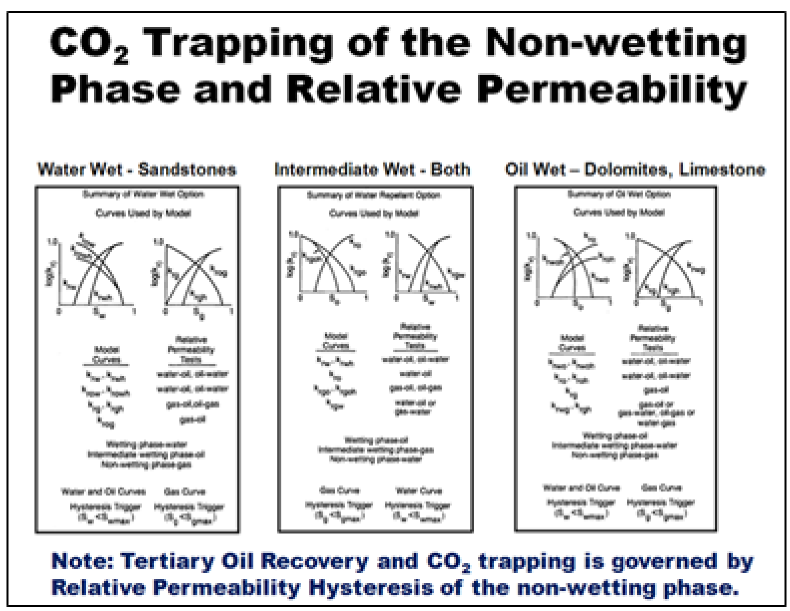




What makes CO_2 Tertiary Oil Recovery Work?

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.



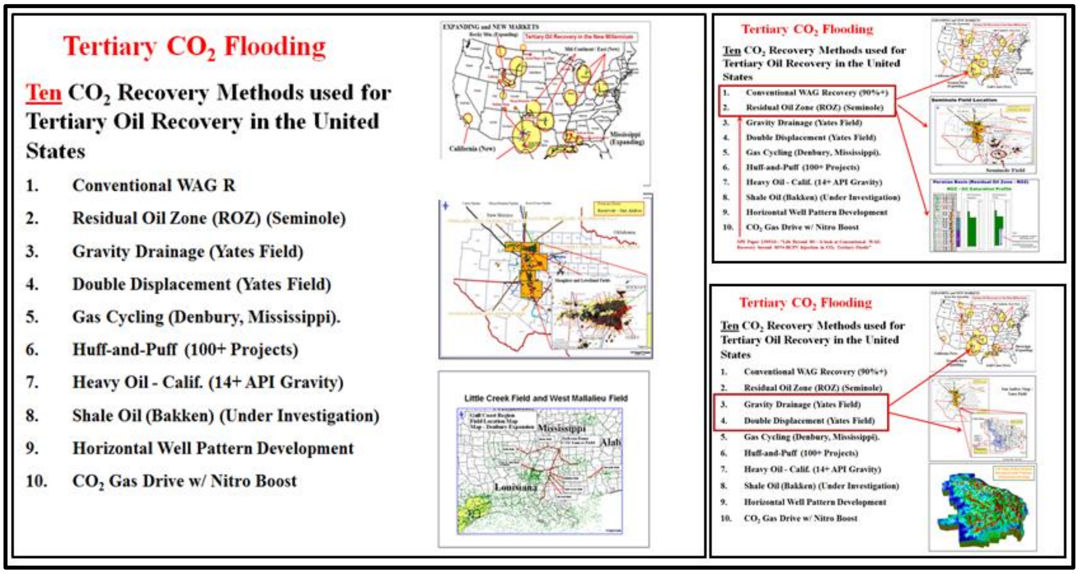


The amount of Tertiary Oil Recovered and the amount of CO_2 Trapped or Sequestered is dependent on the rock type. In addition to mobilizing residual oil saturation, a portion of the CO_2 becomes trapped. In the Petrophysical world, this is known as Relative Permeability Hysteresis or Trapping of the 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

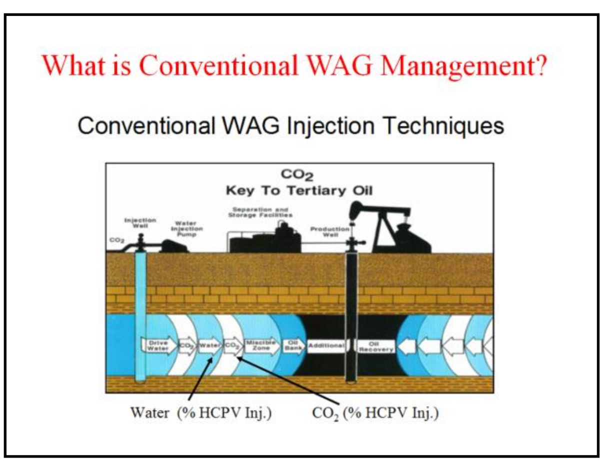
CO_2 Tertiary Recovery Processes to date encompass "**Ten**" Recovery Methods. Four of these methods are used in the Permian Basin. Conventional WAG Techniques have been used in over 90+% of the CO_2 floods around the World. The Seminole field example presented in this report is an example of a field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

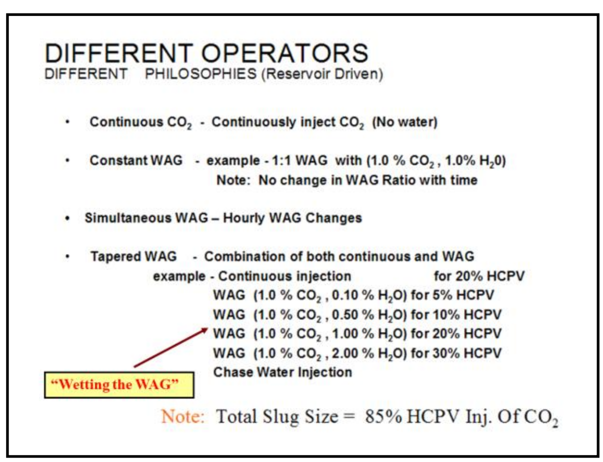


Additional information can be found: SPE Paper 139516 – "Life Beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV Injection in CO_2 Tertiary Floods"

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_2Recovery Plant inlet gas rate, which extends field life and recovers more tertiary oil.

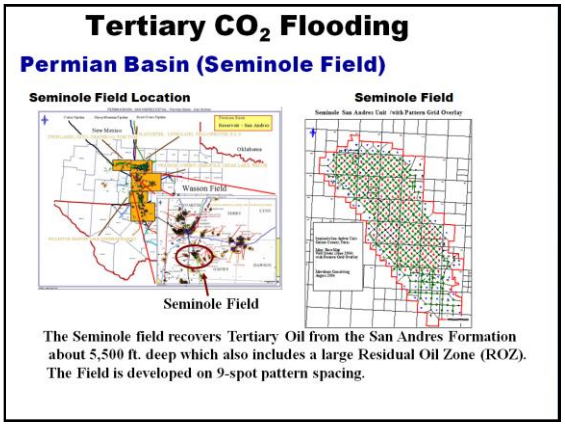


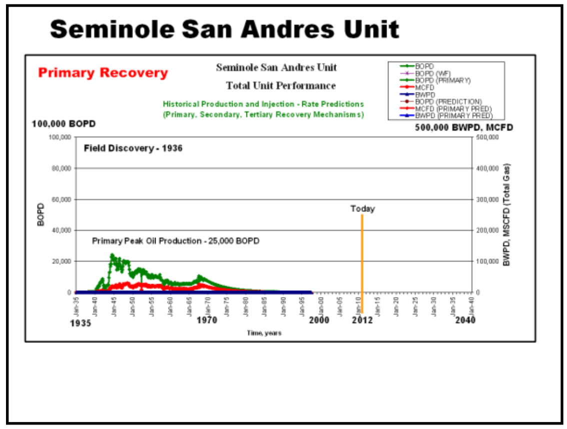


Today, most operators have adopted the Tapered WAG approach to optimize WAG management.

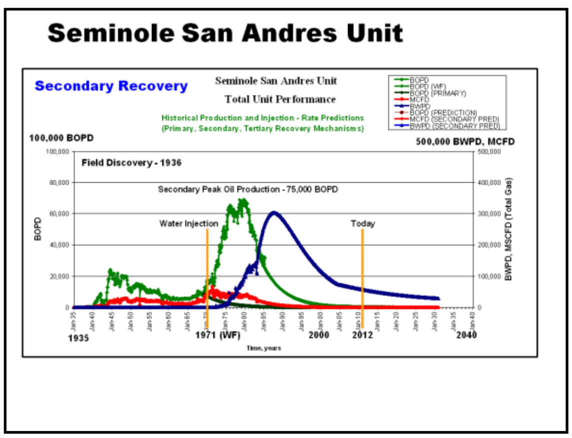
Conventional WAG Management – Seminole San Andres Unit

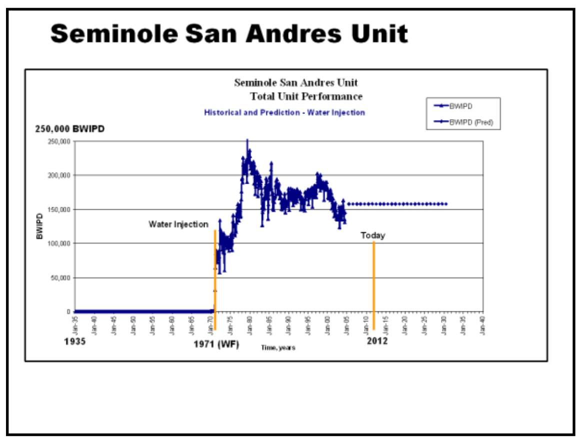
The best example of CO_2 Tertiary Recovery is the Seminole San Andres Unit in the Permian Basin. The field has undergone Primary, Secondary, CO_2 Tertiary operations in the Main Pay, and CO_2 Tertiary operations in the Residual Oil Zone (ROZ).



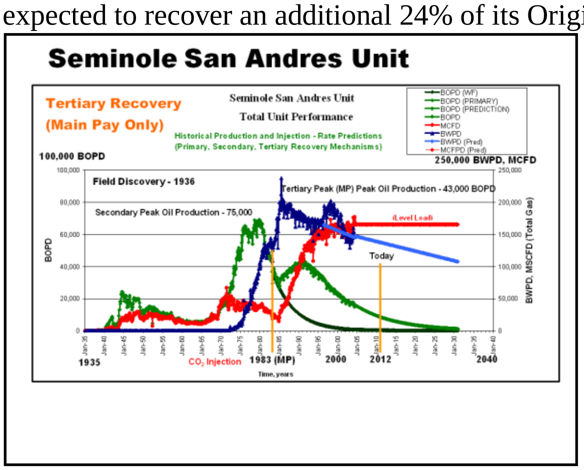


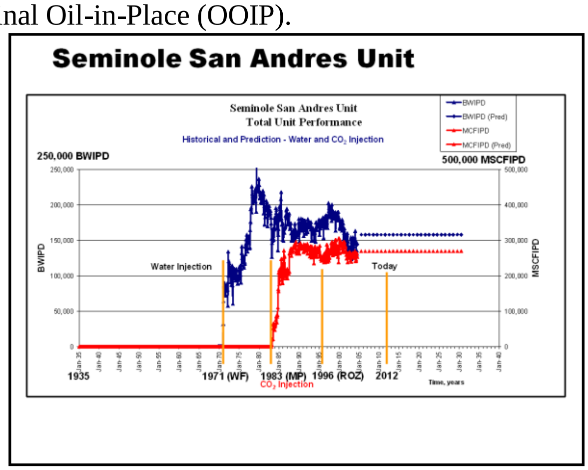
The Seminole field was discovered in 1936 with water injection operations initiated in 1971. Under Primary Recovery the field would have only recovered 12.8% of its Original Oil-in-Place (OOIP). With Secondary Water flood operations, the field would have recovered 42.7% of its Original Oil-in-Place.





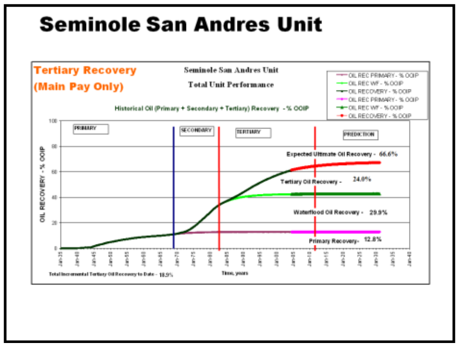
Tertiary CO_2 Injection operations into the Main Pay Zone was initiated in 1983. Under CO_2 Injection the field is expected to recover an additional 24% of its Original Oil-in-Place (OOIP).

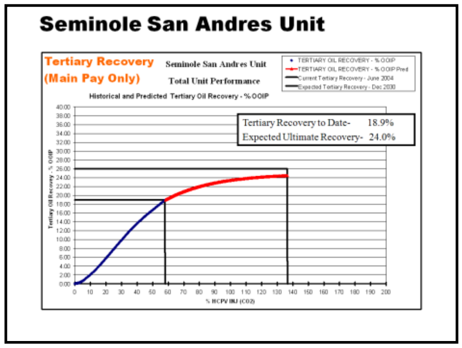




Seminole San Andres Unit – (Main Pay Oil Zone Example)

Primary, Secondary, and CO_2 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 should increase oil production to 24% OOIP. Total Primary+Secondary+Tertiary (MP) = 66.6% OOIP.

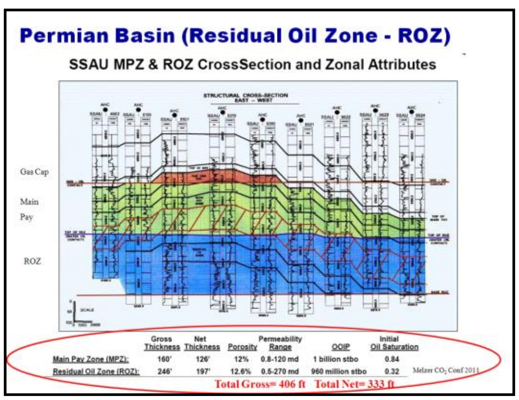


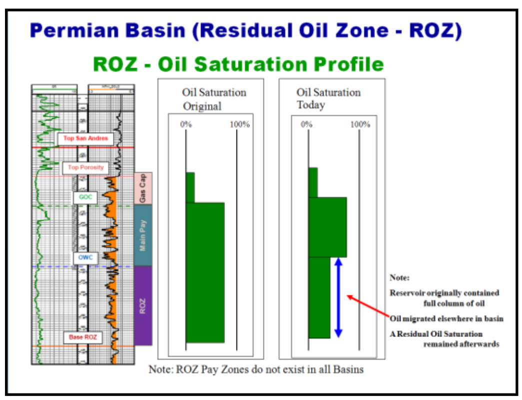


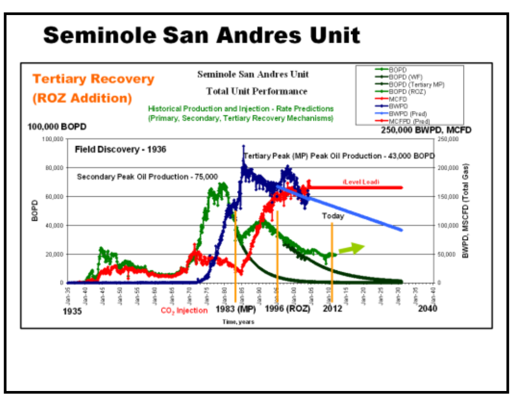
Seminole San Andres Unit – (Residual Oil Zone (ROZ) Example)

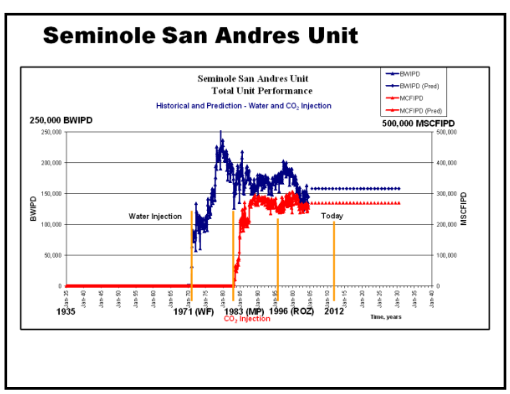
A Residual Oil Zone (ROZ) is created when oil within the original oil column migrates away from an oil field over geologic time creating a ROZ interval. In addition to the Main Pay Zone, the Seminole field contains a very large Residual Oil Zone (ROZ). The size of the ROZ is about the same size at the 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.

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. Tertiary Performance is expected to be similar to that of the Main Pay, but depends on the quality of the ROZ pay section.









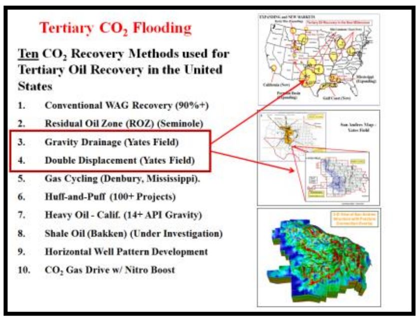
Gravity Drainage and Double Displacement Techniques

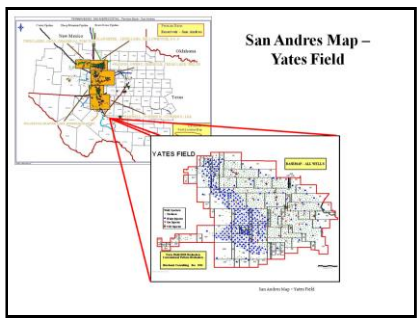
Gravity Drainage and Double Displacement

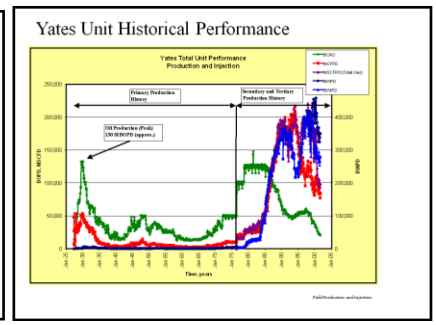
Gravity Drainage and Double Displacement CO_2 Flood Techniques work in reservoirs that have structure. The Hc-gas, Flue Gas, Nitrogen, or CO_2 is usually injected at the top of the reservoir and oil is produced at the bottom. The Yates field in the Permian Basin is an example where CO_2 has used both Gravity Drainage and Double Displacement Recovery Mechanisms to recover tertiary oil in this heavily fractured and karsted reservoir.

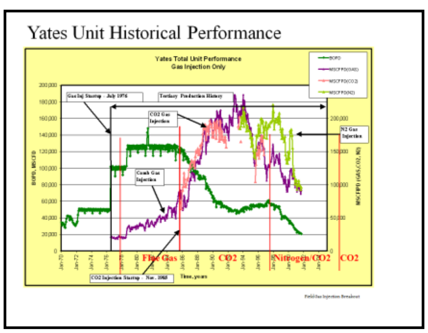
Yates Field (Gravity Drainage and Double Displacement Example)

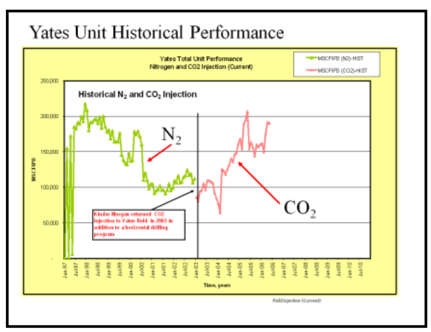
The Yates field has undergone a long history of Gravity Drainage, Double Displacement, and Contact Stabilization operations to recover oil. This included the injection of Flue Gas between 1976 and 1986, 100% CO_2 from 1986 to 1994, Nitrogen Injection from 1994 to 2003, and from 2003 a continuation back to CO_2 injection.

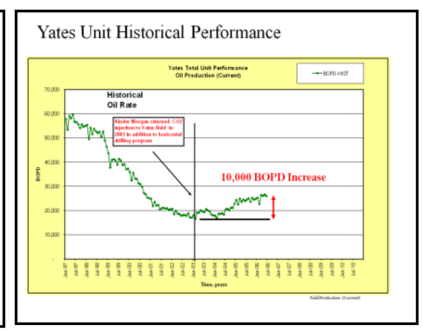












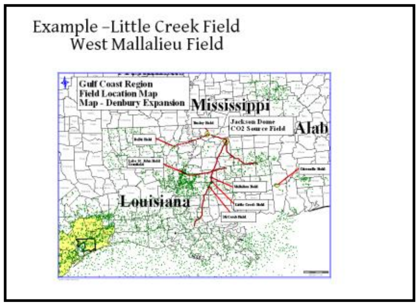
The Yates field is a highly fractured San Andres Dolomite formation. Gravity Drainage in a fractured system involves movement of the CO_2 from the fracture to the matrix displacing oil from the matrix back into the fracture system. This “Counter-flow” movement provides the driving force behind recovery in fractured formations. The degree of oil recovery depends on the permeability and relative permeability of the matrix and the miscible interaction between the injected gas and the residual oil saturation. Since CO_2 is more miscible to residual oil than N_2, the CO_2 has the capability of recovering more oil than with nitrogen injection.

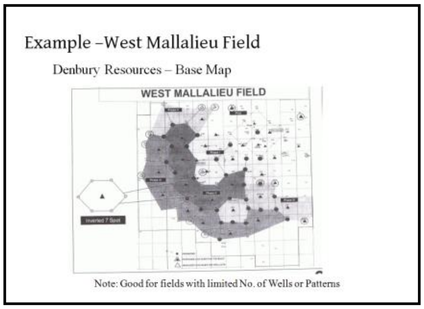
This was proven in 2003 when Kinder Morgan acquired the Yates field from Marathon Oil Company and replaced the nitrogen (1994+) that was being injected back to 100% CO_2 injection (1986-1993). The results are shown above. The field experienced a 10,000 BOPD increase in oil rate and continues to be strong today.

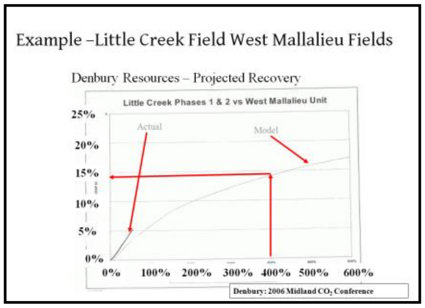
The primary force behind “Gravity Drainage” is Gravity. Today, the field still produces over 20,000 BOPD. The CO_2 provides “Mobilization” of the remaining tertiary oil in the gas cap. Horizontal producing wells have been drilled in the 30 foot oil column at the bottom to ”Capture” the remaining oil as it drains from the gas cap.

Gas Cycling CO_2 Project Techniques

Gas Cycling CO_2 projects are a common flooding technique used in Mississippi and Louisiana CO_2 flood projects by Denbury Resources. The objective is to inject continuous CO_2 through the reservoir and recycle CO_2 with many pore volumes of injection. The 17% OOIP tertiary recovery predicted by Denbury will be achieved with 5 pore volumes of re-cycled CO_2.



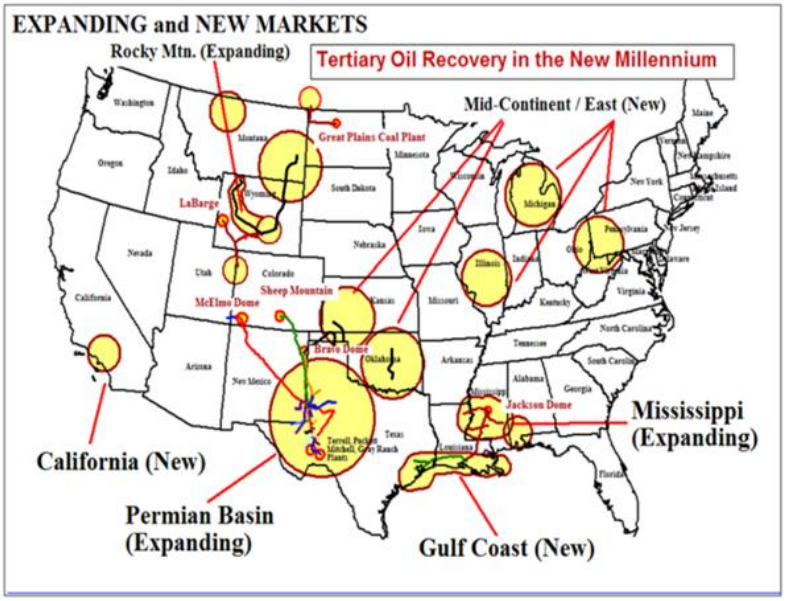




This technology works well in sandstone reservoirs that have a high injection flow capacity. Under this type of operating philosophy, pumping units and submersibles are removed from the production wells which are allowed to flow on their own due to the lifting capacity of the CO_2. In this case, these savings offset the additional costs to compress and re-cycle CO_2 through the reservoir.

Huff-n-Puff CO_2 Single Well Techniques

There have been over 100+ Single Well CO_2 Injection projects implemented since 1972 in most regions of the United States. Most of these projects were implemented as pilot projects to understanding reservoir parameters such as injection well injectivity and tertiary oil recovery response. There have been reported commercial projects.

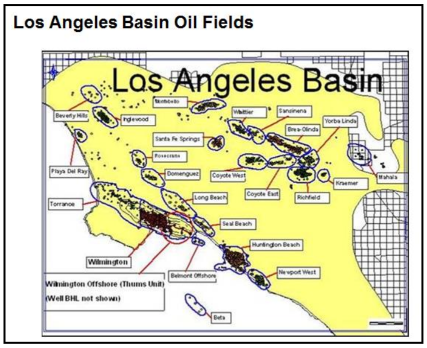


The technique involves injecting CO_2 into individual wells, allow a certain soak time for the CO_2 to work, and then back-producing the well to recover additional tertiary oil. The objective is strictly for EOR purposes and little CO_2 is stored.

Heavy Oil (14+ API Gravity) CO_2 Projects

Heavy Oil (14+ API) CO_2 Projects

In California during the 1980's, three CO_2 Pilots were conducted to test the feasibility of recovering tertiary oil from the Wilmington field in Los Angeles, California. The pilots proved tertiary oil could be recovered with some wells increasing rate from 30 BOPD to over 300 BOPD without severe CO_2 breakthrough. With a severe oil price drop in 1986, all of these projects were abandoned. However, the pilots did prove the CO_2 recovery process works well in moderately heavy oils.



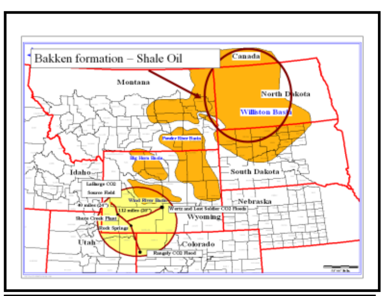
Wilmington CO_2 Pilot Results

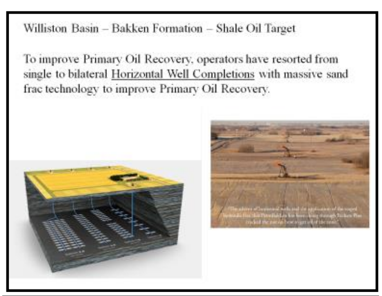
1. Pilots were Demonstration Projects (Not Oil in the Tank Pilots)
2. Wilmington Oil – 10 fold decrease in Viscosity (300 cp to 30 cp)
3. Wilmington Oil – 1.15 fold increase in Oil Swelling
4. Wilmington Oil – Immiscible with 85% CO_2 and 15% N_2
5. Wilmington Oil Response – Single Well Response 30 BOPD to 300 BOPD

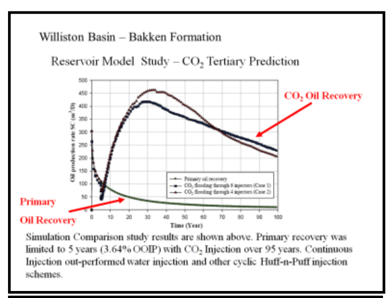
Shale Oil (Bakken) CO_2 Injection Techniques

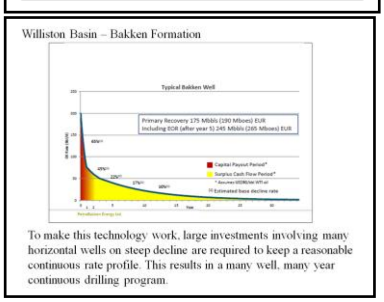
Shale Oil (Bakken) CO_2 Projects

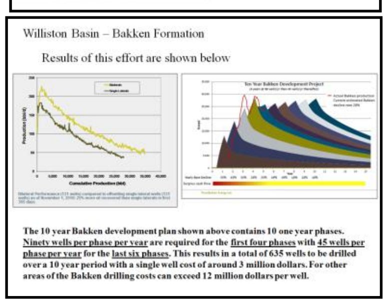
Shale Oil reservoirs, such as the Bakken in the Williston basin are extremely tight. Horizontal wells with extensive fracking are the only way to recover oil. Single well recoveries under primary recovery are typically in the range of 4% to 6% OOIP. Oil response rate is high initially but severely falls off. Development plans include in certain cases hundreds of wells in order to maintain oil rate. Several CO_2 injectivity tests have been conducted in the Bakken formation in Canada, with little documented results.

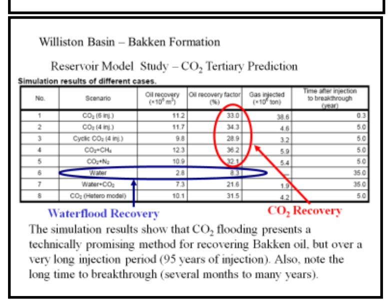












No.	Scenario	Oil recovery ($\times 10^4$ m^3)	Oil recovery factor (%)	Gas injected ($\times 10^4$ ton)	Time after injection to breakthrough (year)
1	CO_2 (6 inj.)	11.2	33.0	38.6	0.3
2	CO_2 (4 inj.)	11.7	34.3	4.6	5.0
3	Cyclic CO_2 (4 inj.)	9.8	28.9	3.2	5.0
4	CO_2+CH_4	12.3	36.2	5.9	5.0
5	CO_2+N_2	10.9	32.1	5.4	5.0
6	Water	2.8	8.3	—	35.0
7	Water+CO_2	7.3	21.6	1.9	35.0
8	CO_2 (Hetero model)	10.1	31.5	4.2	5.0

Reservoir model studies show high CO_2 recoveries can be achieved in excess of 30% OOIP compared to today's expected 4% to 6% per well oil recovery demonstrated under Primary Recovery. However, this high oil recovery can only be achieved with over 100 years of CO_2 injection. First tertiary response may not occur until after 10 years of CO_2 injection. At this time, the technology may not be here today, but the Tertiary Target is certainly large enough that it will supply both the 21[st] and 22[nd] Centuries with oil and other hydro-carbon products, once these technology are developed.

CO_2 Injection with Nitro Boost Techniques

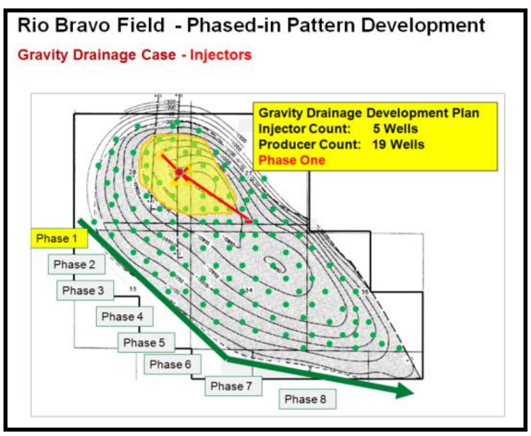
Gravity Drainage and Nitro Boost

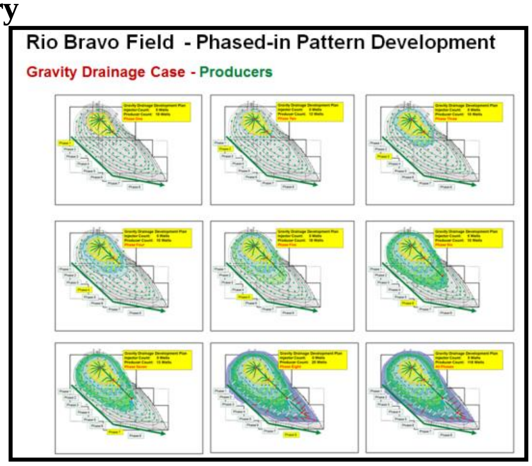
Gravity Drainage and Double Displacement CO_2 Flood Techniques work in reservoirs that have structure. The Hc-gas, Flue Gas, N_2, or CO_2 is usually injected at the top of the reservoir and oil is produced at the bottom. In Oxy-fuel Power Plant operations, which also require a separate Air Separation Plant to extract O_2 from the air, recovers both a clean stream of CO_2, along with a clean stream of Nitrogen. The Question has always been: "Does the six molecules of Nitrogen generated with the one molecule of CO_2 have any use except to be vented to the atmosphere?"

The Rio Bravo field in California is a field that has under-gone multiple types of recovery mechanisms over the years. In the 1940's, Conventional Gravity Drainage Double Displacement techniques were implemented in the field where Hc-gas was injected at the top in a limited number of wells. Production occurred as the front advanced down-dip towards the original oil water contact. The reservoir was then back flooded with water and then pressure depleted. Current performance has shown this type of recovery method left a large tertiary oil target with many millions of barrels of tertiary oil remaining.

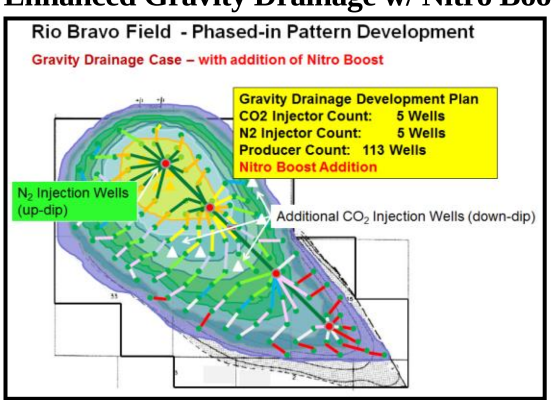
With the Nitro-boost concept, an additional recovery stage is introduced into the reservoir. This last stage of recovery uses CO_2 to mobilize the remaining oil and Nitrogen to accelerate the process. The CO_2 is first introduced at the crest to build a bank. Once built, N_2 is injected at the crest to create a secondary gas cap and displace CO_2 down-dip through a pattern development. The re-cycled CO_2 is recovered to be injected down-dip again at the front of the developing oil bank. The objective is to recover more tertiary oil through better Reservoir Management Practices through improved accelerate response and better CO_2 Utilization Managment.

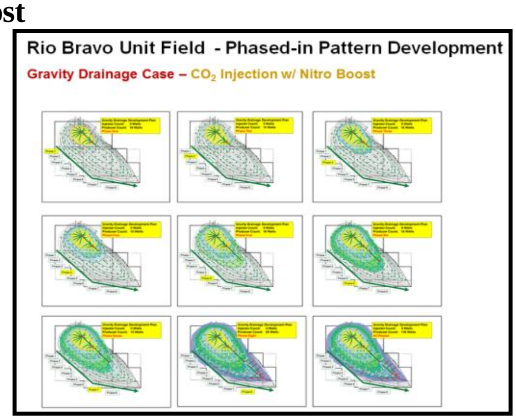
Conventional Gravity Drainage Recovery





Enhanced Gravity Drainage w/ Nitro Boost



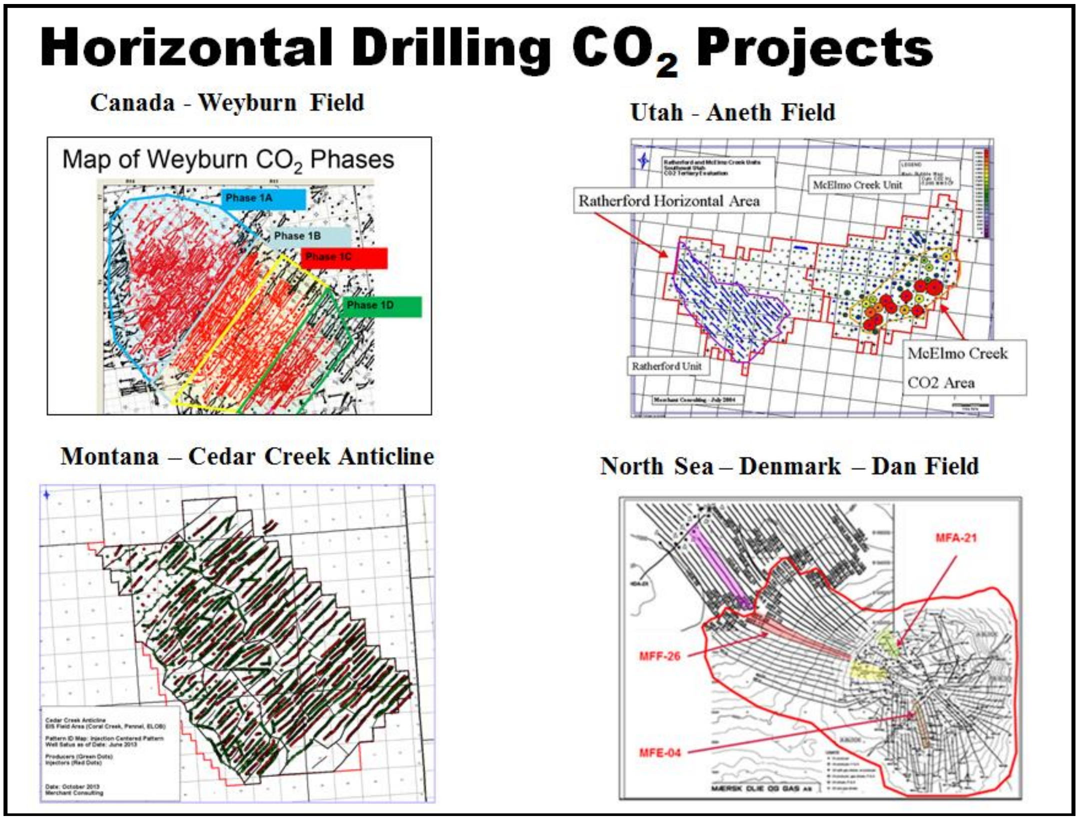


Patent Pending

Horizontal Drilling w/CO_2 WAG Techniques

Gravity Drainage and Nitro Boost

Horizontal Drilling in CO_2 Flood projects are not new to the oil Industry. They have been successfully operated for many years in Canada at the Weyburn project and at the Aneth CO_2 flood in Utah. Future CO_2 flood projects using Horizontal Well Technology exist at Cedar Creek Anticline in Montana and the Dan field, located in the North Sea, Offshore Denmark.



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