Abstract
During the past 43 years, CO₂ 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 CO₂ 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 CO₂ 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 CO₂ Sequestration Communities interested in storing CO₂ in EOR projects.

In 2010, Merchant Consulting published SPE 139516 “Life beyond 80 – A look at Conventional WAG Recovery beyond 80% HCPV Injection in CO₂ 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, CO₂ Utilization and CO₂ 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 CO₂ Sequestration Community an update to the original SPE 139516 paper presented in 2010 at the SPE International Conference on CO₂ 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 CO₂. This report will provide insight to all 10 methods used today in EOR operations.
Introduction – CO₂ Flooding

CO₂ 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, CO₂ injection was introduced, first in the Sacroc Field. Today, over 1.1 billion barrels have been produced with CO₂ and accounts for over 237,000 BOPD or 15% of all Permian Basin oil production from over 15,000 production wells and 12,000 CO₂ injection wells.

What makes CO₂ Tertiary Oil Recovery Work?
The reason why CO₂ works is simple. The CO₂ 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 CO₂ Trapped or Sequestered is dependent on the rock type. In addition to mobilizing residual oil saturation, a portion of the CO₂ becomes trapped. In the Petrophysical world, this is known as Relative Permeability Hysteresis or Trapping of the Non-wetting Phase. In this case CO₂ 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).
**CO₂ Tertiary Recovery Methods**

**Introduction**

CO₂ 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 CO₂ 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 CO₂ Tertiary Floods”

**Conventional WAG Techniques**

Conventional WAG Techniques have been used in over 90% of the CO₂ 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 CO₂ 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 Management – Seminole San Andres Unit

The best example of CO₂ Tertiary Recovery is the Seminole San Andres Unit in the Permian Basin. The field has undergone Primary, Secondary, CO₂ Tertiary operations in the Main Pay, and CO₂ 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 CO₂ Injection operations into the Main Pay Zone was initiated in 1983. Under CO₂ 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 CO₂ 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 CO₂ 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. CO₂ 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 CO₂ 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 CO₂ Flood Techniques work in reservoirs that have structure. The Hc-gas, Flue Gas, Nitrogen, or CO₂ 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 CO₂ 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% CO₂ from 1986 to 1994, Nitrogen Injection from 1994 to 2003, and from 2003 a continuation back to CO₂ injection.

The Yates field is a highly fractured San Andres Dolomite formation. Gravity Drainage in a fractured system involves movement of the CO₂ 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 CO₂ is more miscible to residual oil than N₂, the CO₂ 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% CO₂ 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 CO₂ 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 CO₂ Project Techniques

Gas Cycling CO₂ projects are a common flooding technique used in Mississippi and Louisiana CO₂ flood projects by Denbury Resources. The objective is to inject continuous CO₂ through the reservoir and recycle CO₂ with many pore volumes of injection. The 17% OOIP tertiary recovery predicted by Denbury will be achieved with 5 pore volumes of re-cycled CO₂.

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 CO₂. In this case, these savings offset the additional costs to compress and re-cycle CO₂ through the reservoir.

Huff-n-Puff CO₂ Single Well Techniques

There have been over 100+ Single Well CO₂ 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 CO₂ into individual wells, allow a certain soak time for the CO₂ to work, and then back-producing the well to recover additional tertiary oil. The objective is strictly for EOR purposes and little CO₂ is stored.
Heavy Oil (14+ API Gravity) CO₂ Projects

Heavy Oil (14+ API) CO₂ Projects
In California during the 1980’s, three CO₂ 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 CO₂ breakthrough. With a severe oil price drop in 1986, all of these projects were abandoned. However, the pilots did prove the CO₂ recovery process works well in moderately heavy oils.

![Los Angeles Basin Oil Fields](image)

**Wilmington CO₂ 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% CO₂ and 15% N₂
5. Wilmington Oil Response – Single Well Response 30 BOPD to 300 BOPD

Shale Oil (Bakken) CO₂ Injection Techniques

Shale Oil (Bakken) CO₂ 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 CO₂ injectivity tests have been conducted in the Bakken formation in Canada, with little documented results.

![Shale Oil (Bakken) CO₂ Projects](image)

Reservoir model studies show high CO₂ 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 CO₂ injection. First tertiary response may not occur until after 10 years of CO₂ 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 21st and 22nd Centuries with oil and other hydro-carbon products, once these technology are developed.
CO₂ Injection with Nitro Boost Techniques

Gravity Drainage and Nitro Boost
Gravity Drainage and Double Displacement CO₂ Flood Techniques work in reservoirs that have structure. The Hc-gas, Flue Gas, N₂, or CO₂ 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 O₂ from the air, recovers both a clean stream of CO₂, along with a clean stream of Nitrogen. The Question has always been: “Does the six molecules of Nitrogen generated with the one molecule of CO₂ 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 CO₂ to mobilize the remaining oil and Nitrogen to accelerate the process. The CO₂ is first introduced at the crest to build a bank. Once built, N₂ is injected at the crest to create a secondary gas cap and displace CO₂ down-dip through a pattern development. The re-cycled CO₂ 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 CO₂ Utilization Management.

Conventional Gravity Drainage Recovery

Enhanced Gravity Drainage w/ Nitro Boost

Patent Pending
Horizontal Drilling w/CO₂ WAG Techniques

Gravity Drainage and Nitro Boost
Horizontal Drilling in CO₂ 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 CO₂ flood in Utah. Future CO₂ 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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