Enhanced Recovery of Shale Oil: Eagle Ford Shale and Other Shale Basins

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Unconventional Reservoir Cyclic Injection Projects

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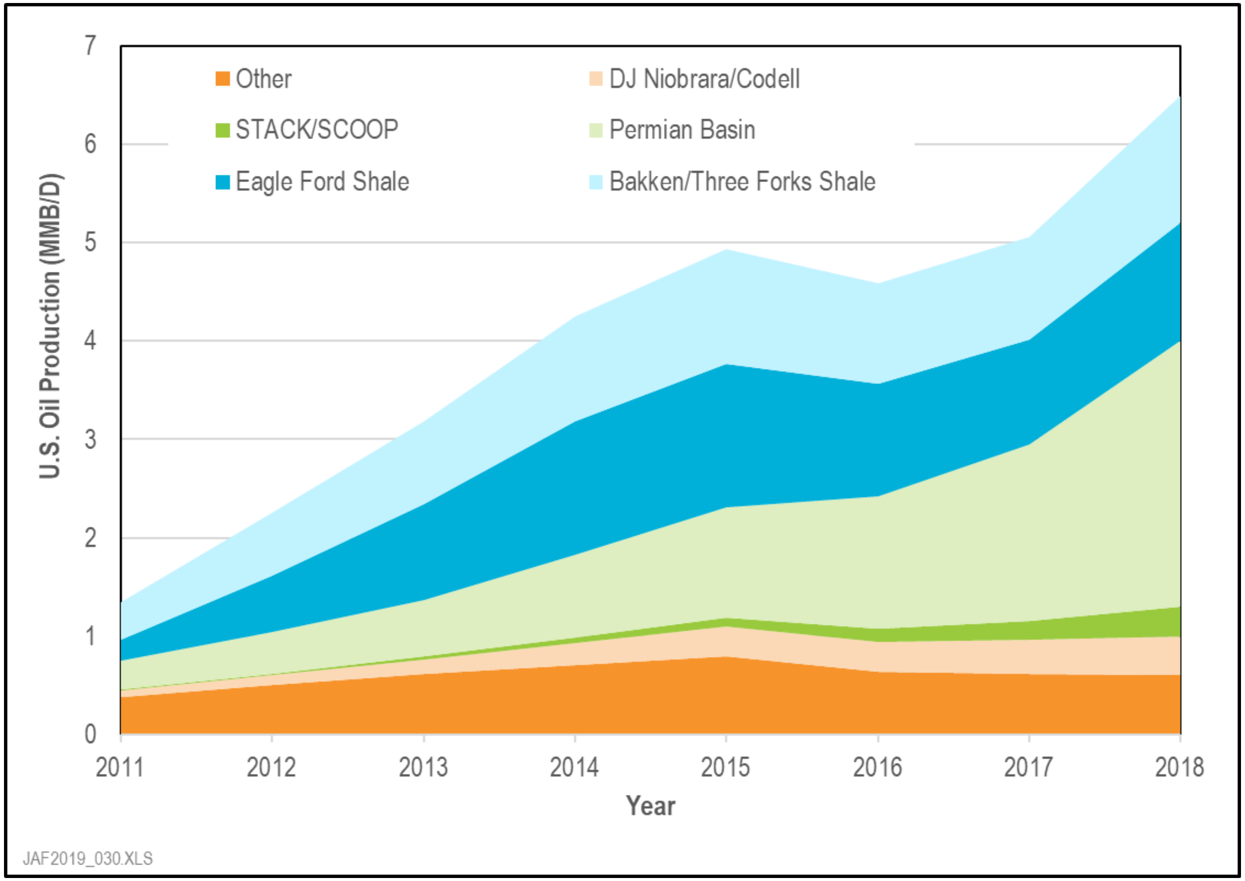
U.S. Tight/Shale Oil Production (2011-2018)



Source: Advanced Resources International's Tight Oil Database, 2018; Drilling Info, 2018.

The pursuit of the Bakken Shale with long Hz wells launched the modern tight/shale oil era.

Tight/shale oil production reached the 1 MMB/D threshold in 2011 and has grown to 6.5 MMB/D in 2018.

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Changes in Eagle Ford Shale Well Performance

Shale oil well performance has been improving, as "best well completion practices" become widely used.

Tight Oil Play Areas	Well Performance (EUR, MB)			Average Lateral Length (ft)		
	2016	2018	% Change	2016	2018	% Change
Eagle Ford Shale Oil Dominant Areas	340	370	+9%	6,300	7,000	+11%
Karnes Trough	430	420	(2%)	4,800	5,300	+10%

Source: Advanced Resources International's Tight Oil Database 2018; DrillingInfo, 2018.

- However, once shale oil "sweet spot" areas become increasingly developed, well performance can begin to decline, as illustrated by the mature Karnes Trough area of the Eagle Ford Shale.
- As such, new technologies are needed to maintain progress in shale oil recovery and its economic viability.

Shale Oil Recovery Efficiencies: Primary (Pressure Depletion) Recovery

Large volumes of Original Oil In-Place (OOIP) exist in domestic shale oil basins. However, oil recovery efficiency in shale oil basins, using primary (pressure depletion) recovery methods, is low – ranging from 5 to 9 percent of OOIP -- in selected areas of three shale oil formations evaluated by Advanced Resources.

As such, a large remaining shale oil in-place target exists for enhanced recovery.

Shale Formation	Total OOIP (Billion Barrels)	Pattern Area (Acres)	OOIP (MB)	Estimated Ultimate Recovery (MB)	Recovery Efficiency (%OOIP)
Eagle Ford	140	112	4,620	372	8.1
Bakken	91	313	5,240	466	8.8
Wolfcamp (Bench B)	268	180	7,630	434	5.3

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Publicly Available Information on Field Trials of Enhanced Recovery from Shale Oil Formations

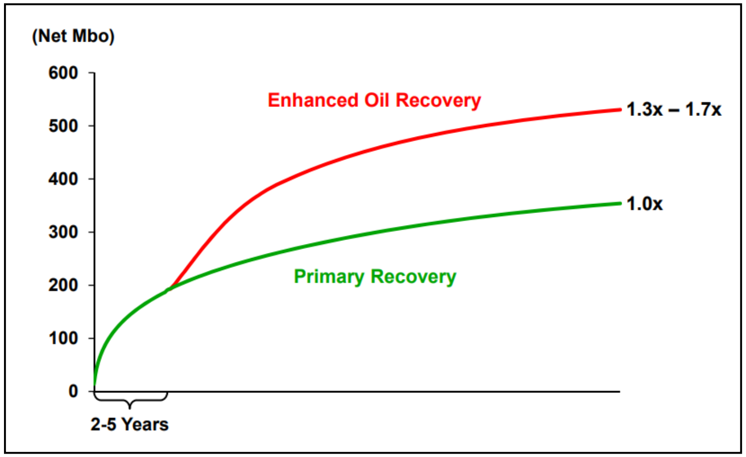
A handful of field pilots are testing (or are planning to test) the viability of injecting gas for increasing tight oil recovery efficiency over primary depletion methods.

Except for high-level information from EOG Resources on the performance of some of their cyclic gas injection field projects, little information on the actual performance of these field pilots exists in the literature.

Active and Planned EOR Field Projects: Eagle Ford Shale

Source: Chesapeake Energy, 2018.

Primary versus Enhanced Oil Recovery: Eagle Ford Shale



Source: EOG Resources, 2017.

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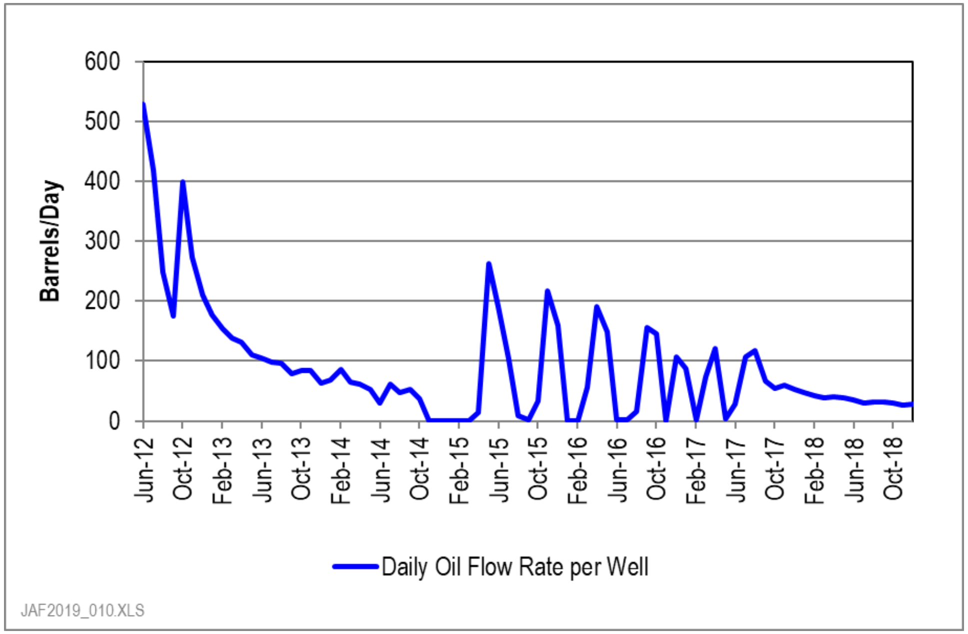
Primary and Cyclic Gas Injection: Four Martindale L&C Lease Wells

Advanced Resources International (ARI) analyzed the performance of a 4-well cyclic gas injection pilot in LaSalle County, initiated in November 2014.

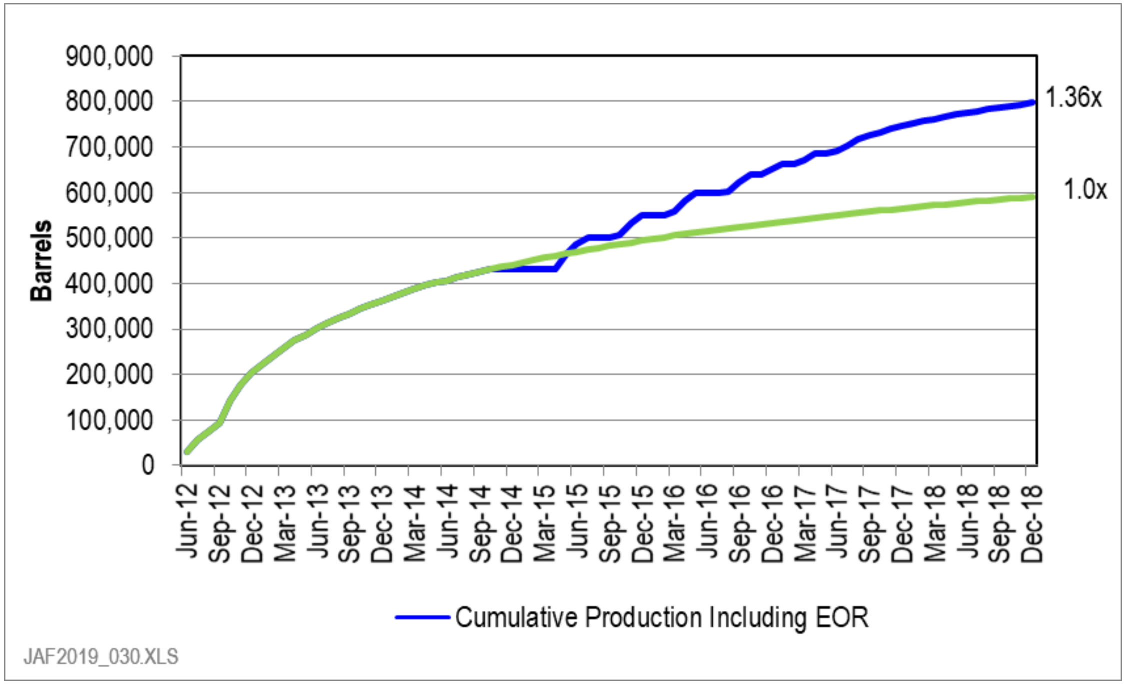
Oil Recovery from Primary and Cyclic Gas Injection – Average Well



Source: Advanced Resources International, 2019

- The four wells had been on primary production for about 2.5 years and together had produced 430,000 barrels of oil.
- To provide a baseline for this cyclic gas injection pilot, ARI created a primary oil recovery “type well” for this lease.
- Four longer-term gas injection and soak cycles and three shorter gas injection and soak cycles were conducted between April 2015 and October 2017.
- The oil production response was positive in each of the seven gas injection cycles, albeit with declining peaks in oil production.

Primary and Cyclic Gas Injection: Four Martindale L&C Lease Wells (Cont'd)



Source: Advanced Resources International, 2019.

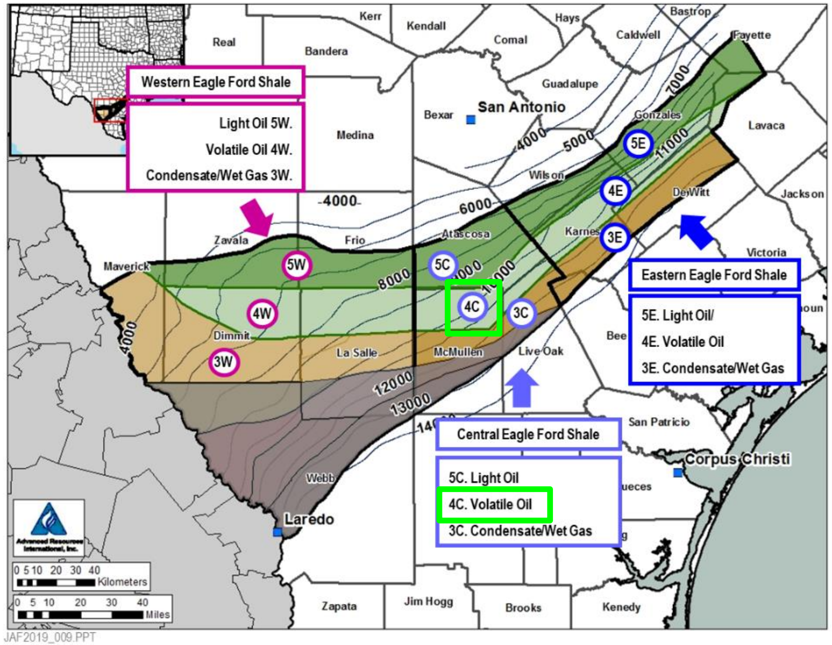
During three plus years of cyclic gas injection, the four Martindale L&C lease wells recovered a total of 370,000 (in addition to the 430,000 barrels of primary recovery), with 210,000 barrels as incremental oil from cyclic gas injection for an uplift of 1.36x.

The 1.36x uplift in oil recovery due to cyclic gas injection is within the range of uplift values reported by EOG Resources.

Eagle Ford Shale Study Area

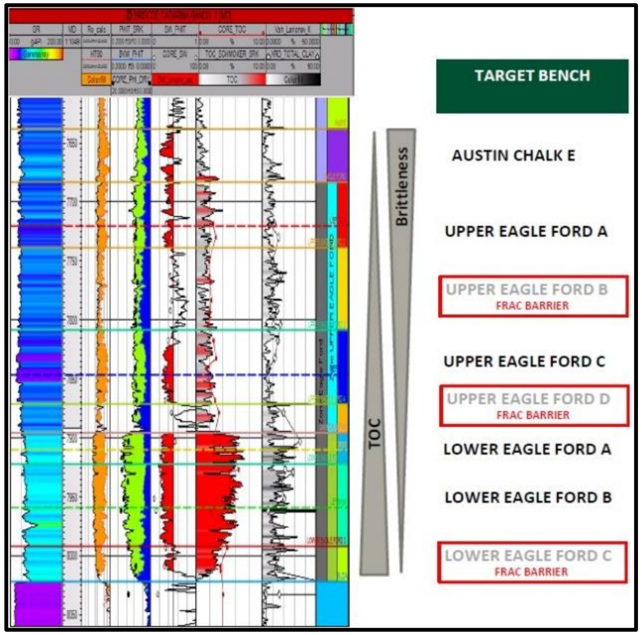
The Advanced Resources' reservoir simulation Study Area is located in north-central McMullen County.

Eagle Ford Shale Oil Dominant Play Areas



Source: Advanced Resources International, 2018.

Upper, Middle and Lower Units of the Eagle Ford Shale



Source: Sanchez Energy, 2017

Study Area Reservoir Properties and OOIP

Lower Eagle Ford Shale Study Area Reservoir Properties

Reservoir Properties	Units
Pattern Area	112 acres
Well Pattern Dimensions	
▪ Length	7,500 ft
▪ Width	650 ft
Depth (to top)	10,000 ft
Net Pay	120 ft
Porosity	
▪ Matrix	9%
▪ Fracture	0.1%
Oil Saturation	
▪ Matrix	80%
▪ Fracture	90%
Saturation Gas/Oil Ratio	1.2 Mcf/B
Formation Volume Factor	1.64 RB/STB
Pressure	6,425 psia
Temperature	260 ^{o} F
Bubble Point	3,456 psia
Formation Compressibility	5 * e $^{-6}$/psi
Oil Gravity	43^{o} API

Source: Advanced Resources International, 2018.

Given the geologic and reservoir properties, the Study Area pattern contains 4.62 million barrels of original oil in-place (OOIP) and 5.54 Bcf of original gas in-place (OGIP).

- OOIP = (112A * 120 ft) * 7758 B/AF (0.091 * 0.80/1.64)
- OOIP = 13,440 AF * 344 B/AF = 4.62 MMB
- OGIP = (4.62 * MMB) * (1.2 Mcf/B) = 5.54 Bcf

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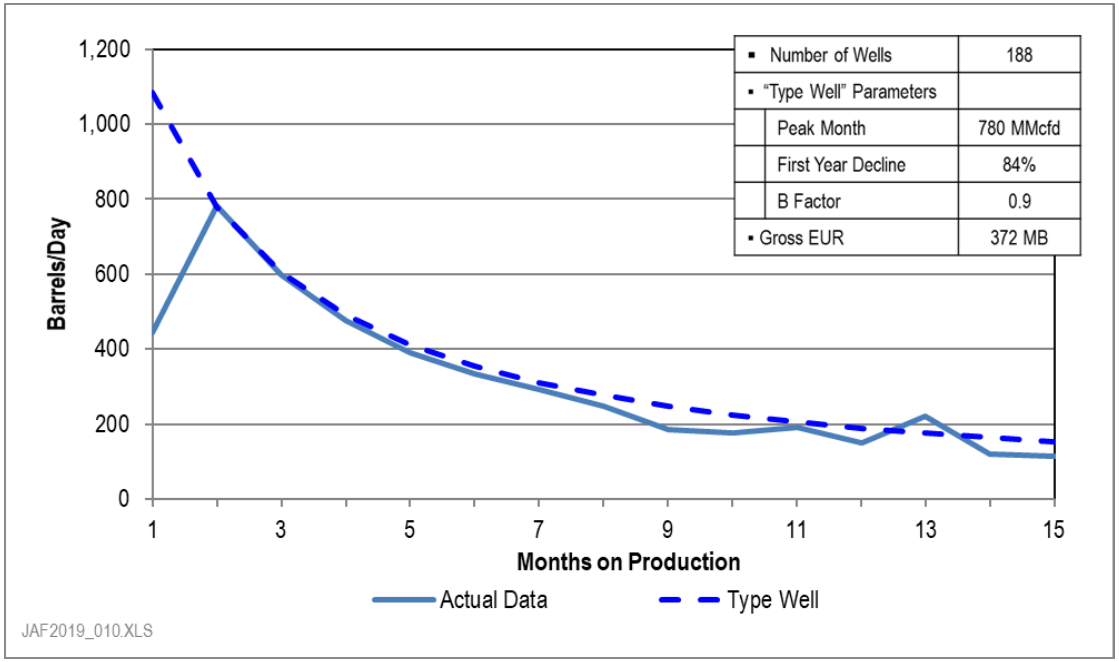
Study Area "Type Well"

Study Area "Type Well" Oil Production



▪ Number of Wells	188
▪ "Type Well" Parameters	
Peak Month	780 MMcfd
First Year Decline	84%
B Factor	0.9
▪ Gross EUR	372 MB

Source: Advanced Resources International, 2019.

The Study Area "type well" represents the composite performance of 188 Hz wells drilled in 2017 and early 2018.

The "type well" in the Study Area has a spacing of 8 wells per 640 acres and a Hz lateral of 7,400 feet. It has an estimated 30-year oil recovery of 372,000 barrels.

Eagle Ford Shale Oil Composition

Lower Eagle Ford Shale Oil Composition Data

	GOR (scf/Bbl)			
	500	1000	1200 (Interpolated)	2000
C1	31.231	44.522	47.929	56.447
N2	0.073	0.104	0.112	0.132
C2	4.314	5.882	6.284	7.288
C3	4.148	4.506	4.598	4.827
CO2	1.282	1.821	1.960	2.306
iC4	1.35	1.298	1.285	1.251
nC4	3.382	2.978	2.874	2.615
iC5	1.805	1.507	1.431	1.24
nC5	2.141	1.711	1.601	1.325
nC6	4.623	3.28	2.936	2.076
C7+	16.297	11.563	10.350	7.316
C11+	12.004	8.94	8.078	5.924
C15+	10.044	7.127	6.379	4.509
C20+	7.306	4.762	4.186	2.745

Source: Modified by Advanced Resources Int'l from Gala, D., and Sharma, M. , 2018.

The oil composition data reflects a saturation gas/oil ratio of 1,200 scf/B.

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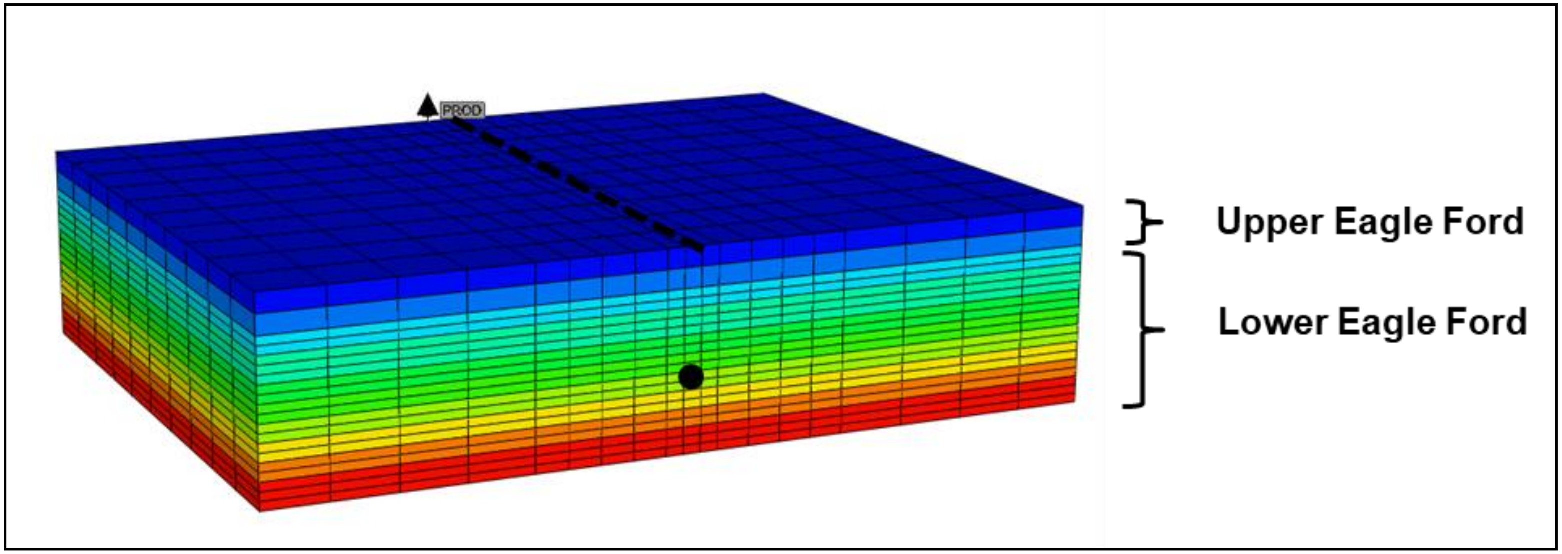
Reservoir Model

The reservoir property and oil composition values (shown previously) were used to populate the compositional reservoir model (GEM) and its 3,800 grid blocks.

Reservoir Model and Grid Blocks Used for Eagle Ford Shale Study

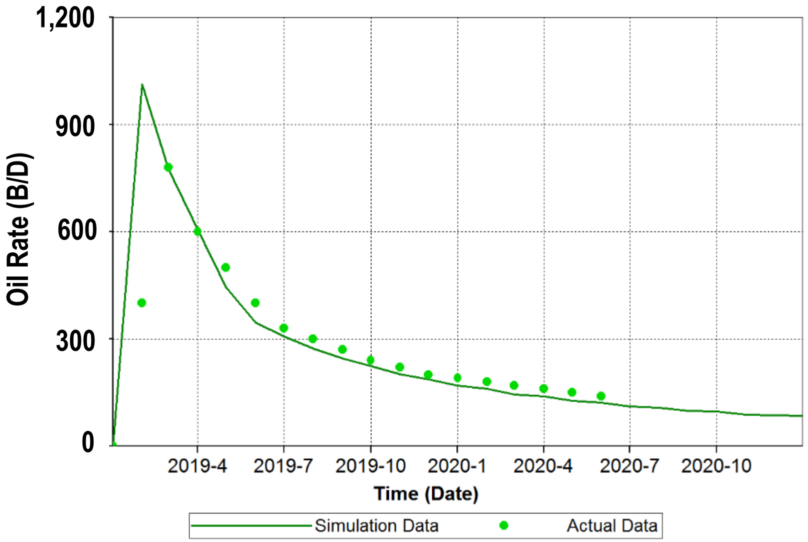


Source: Advanced Resources International, 2019.

History-Matching Oil and Natural Gas Production

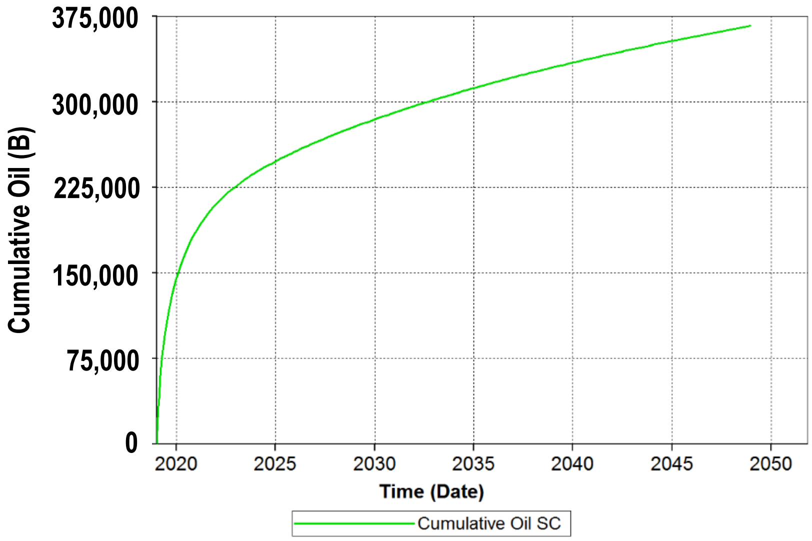
Reservoir simulation achieved an excellent history match with the “type well” for the Study Area, providing a solid base of information on reservoir properties for evaluating cyclic injection of gas for enhancing oil recovery.

History Match of Monthly Oil Production



Source: Advanced Resources International, 2019.

Projected 30 Years of Primary Recovery

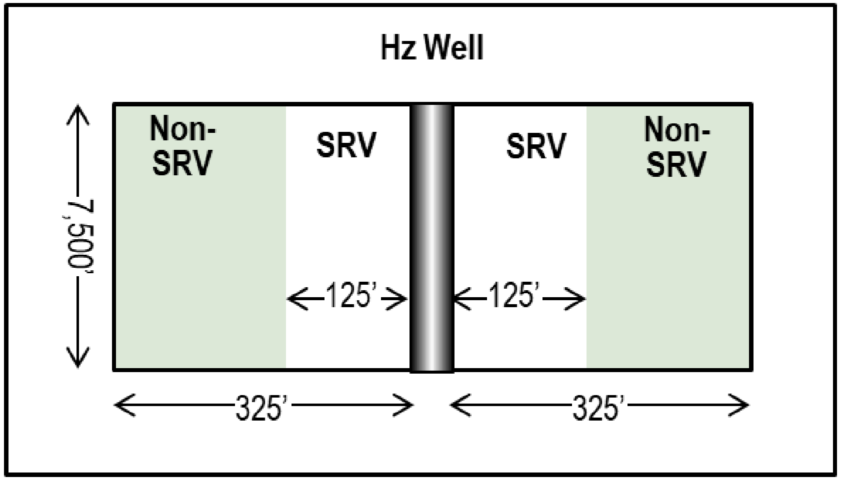


Source: Advanced Resources International, 2019.

Capturing the Impact of Hydraulic Stimulation

SRV Dimensions. The Stimulated Reservoir Volume (SRV) dimensions for the Study Area well, based on history matching of well performance, are illustrated below.

A. SRV Dimensions, Plan View



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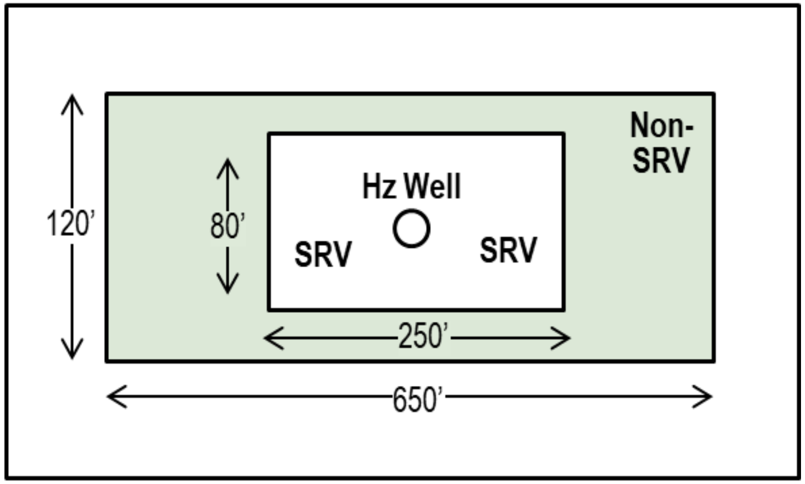
Source: Advanced Resources International, 2019.

B. SRV Dimensions, Side View



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Source: Advanced Resources International, 2019.

Capturing the Impact of Hydraulic Stimulation

Matrix and Fracture Permeability. The matrix and fracture permeability values from history matching of well performance (along the SRV dimensions), were used to history match the Eagle Ford Shale "type well".

Permeability Values Used for History Match

	Matrix
Non-SRV	
• Horizontal	$115 * 10^{-6}$ mD
• Vertical	$11.5 * 10^{-6}$ mD
SRV*	$85 * 10^{-3}$ mD

Source: Advanced Resources International, 2019.

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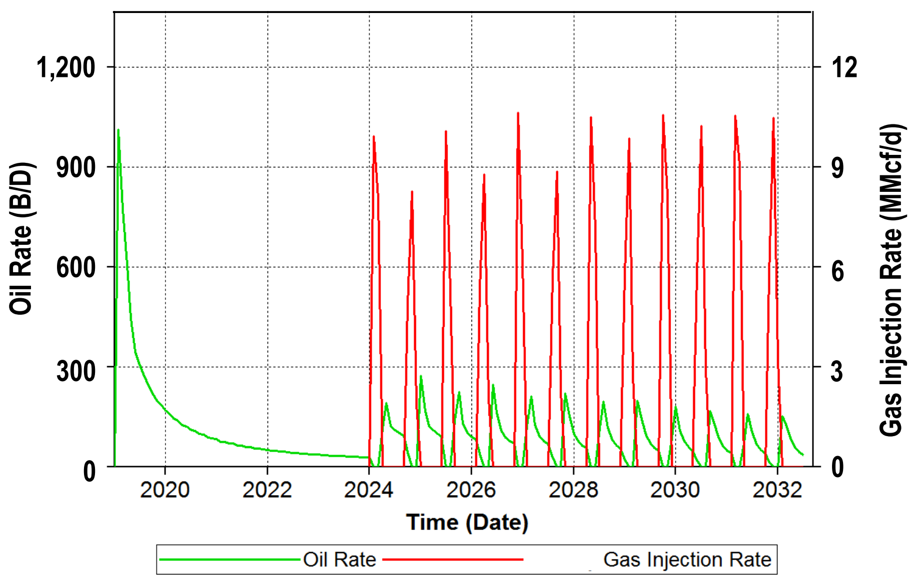
Modeling of Cyclic CO_2 Injection

Primary and Enhanced Oil Recovery: Cyclic CO_2 Injection



Source: Advanced Resources International, 2019.

Cyclic CO_2 injection was initiated in the Study Area well after five years of primary production. At this time, the Hz well had produced 238,000 barrels, about 80 percent of its EUR.

- In cycle one, CO_2 was injected at a constant rate of 10.5 MMcfd for 2 months (BHP limit of 7,000 psia), with a total of 540,000 Mcf of CO_2 injected.
- CO_2 injection was followed by a 2 week soak time and then followed by 6 months of production.
- Eleven additional cycles of CO_2 injection, soak and production followed.

Performance of Cyclic CO_2 Injection: Full Hz Well

Oil Production, CO_2 Injection and CO_2 Production: Full Hz Well

	Cumulative Oil Production (MBbls)		Cumulative CO_2 Injection (MMscf)	Cumulative CO_2 Production (MMscf)
	Total	Incremental		
End of 5-year primary	238		-	*
End of first cycle	262	16	540	300
End of 6th cycle	380	106	3,000	2,420
End of 12th cycle	483	185	6,440	5,600

*A small volume of CO2 (0.6 MMcf) was produced during primary production, as CO_2 is a minor constituent of the reservoir fluids.

Source: Advanced Resources International, 2019.

The 12 cycles of CO_2 injection provided 185,000 barrels of incremental oil recovery (245,000 barrels less 60,000 barrels from continuation of primary recovery for 8.5 years).

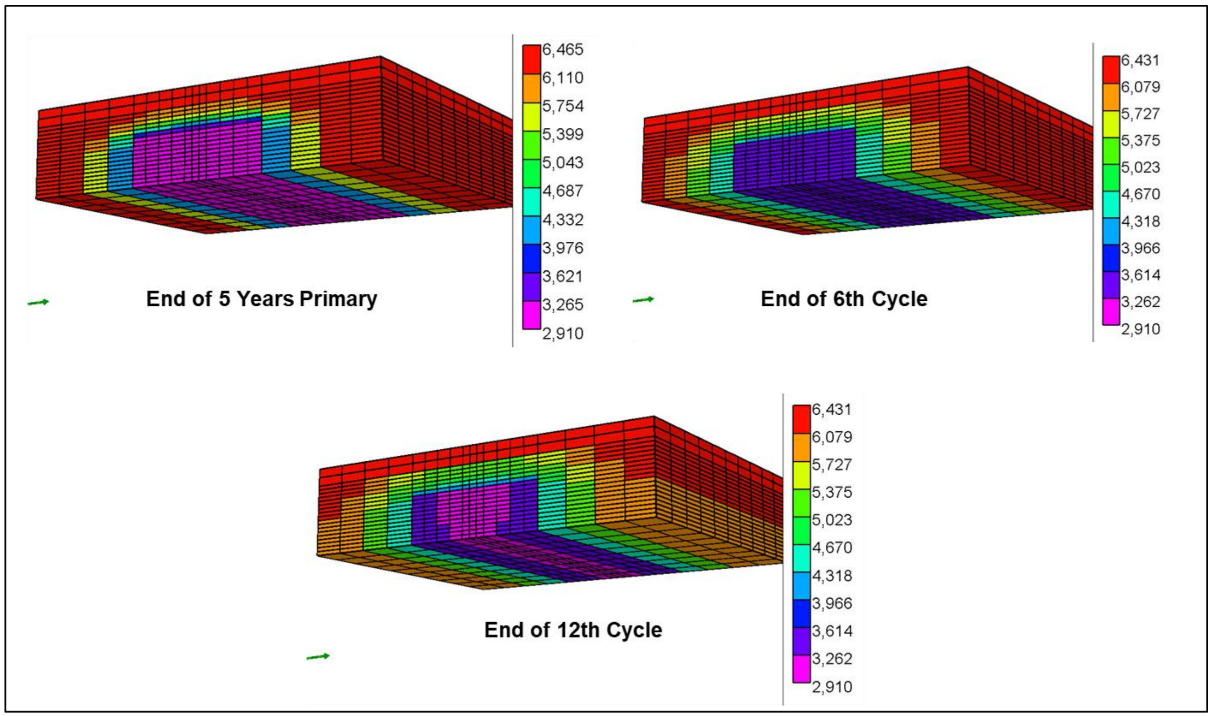
This 12 cycle CO_2 injection project provided a 1.62x uplift to oil production.

((298,000 + 185,000) / 298,000) = 1.62

Reservoir Pressure Profiles

Reservoir pressure profiles at the end of primary production shows substantial declines within the SRV matrix and limited pressure declines in non-SRV matrix blocks. Noticeable pressure declines in the non-SRV matrix blocks are evident at end of 6 and 12 cycles of CO_2 injection.

Pressure Profiles Primary Recovery and Cyclic CO_2 Injection



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Source: Advanced Resources International, 2019.

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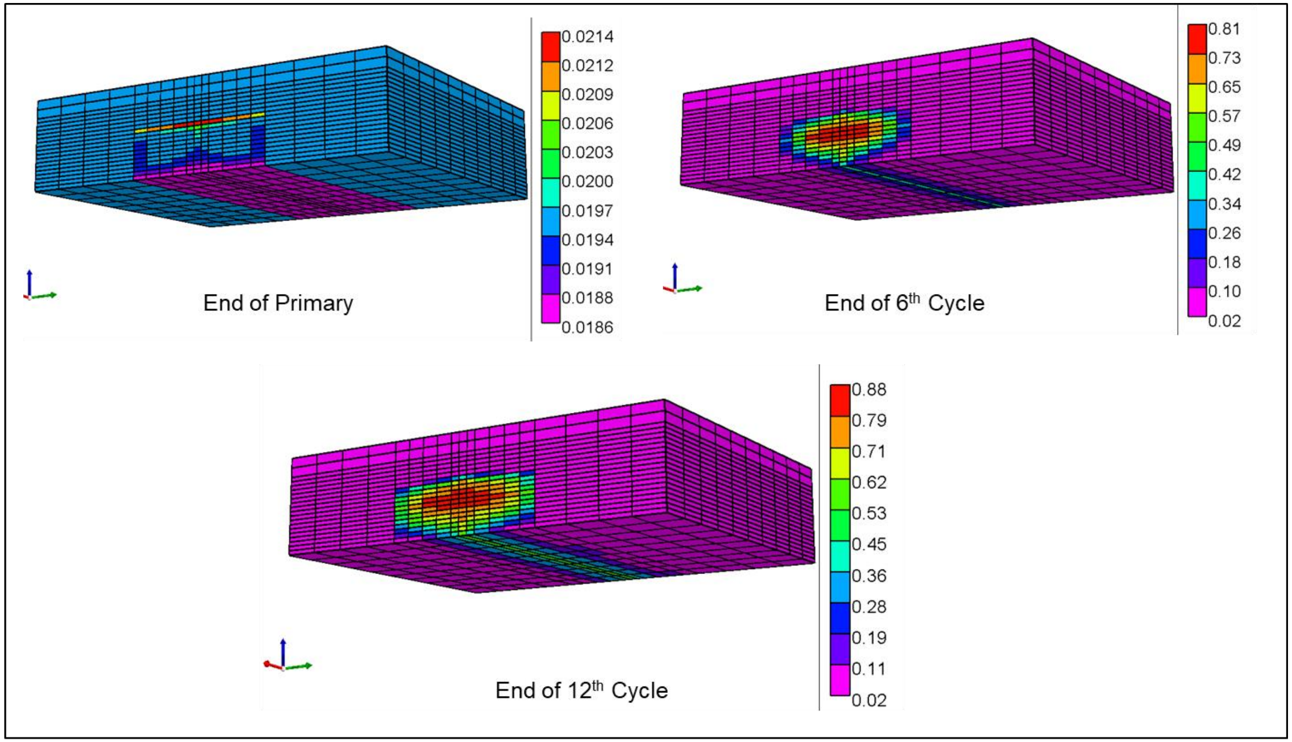
CO_2 Distribution and Storage

At the end of twelve cycles of CO_2 injection and fluid production, CO_2 saturation in the SRV matrix reached 80 percent near the Hz well, declining to 40 to 50 percent at the edges of the SRV.

CO_2 Saturation Profiles Following Cyclic CO_2 Injection



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Source: Advanced Resources International, 2019.

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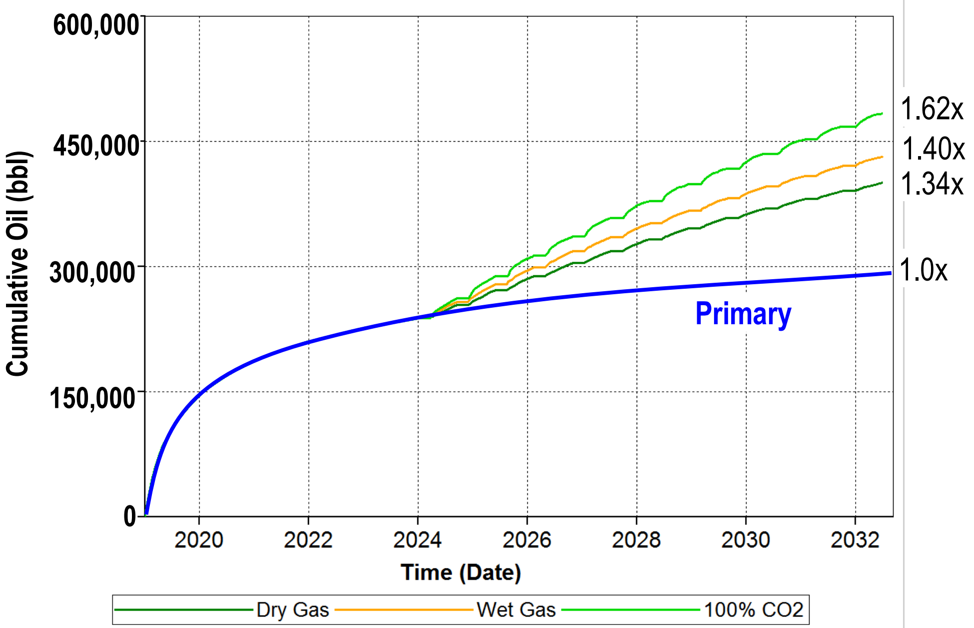
Comparison of Cyclic CO_2, Dry Gas and Wet Gas Injection

Comparison of Cyclic CO_2, Dry Gas and Wet Gas Injection



Source: Advanced Resources International, 2019.

Use of cyclic CO_2 provides a significantly higher "uplift" than using dry or wet gas for enhancing shale oil recovery.

Injection Fluid	"Uplift"
▪ CO_2	1.62
▪ Dry Gas	1.34
▪ Wet Gas	1.40

Performance of Cyclic Gas Injection: Other Shale Oil Basins

Reservoir simulation of cyclic gas injection, using similar methodology as for the Eagle Ford Shale, showed strong improvements in oil recovery from the Wolfcamp (Bench B) and more moderate improvements in oil recovery from the Bakken Shale.

Shale Formation	OOIP (MB)	13.5 Years of Primary Recovery (MB)	Incremental Due to Gas Injection					
			CO_2		Dry Gas		Wet Gas	
			(MB)	"Uplift"	(MB)	"Uplift"	(MB)	"Uplift"
Eagle Ford	4,620	298	185	1.62x	102	1.34x	119	1.40x
Bakken	5,240	363	149	1.41x	40	1.11x	69	1.19x
Wolfcamp (Bench B)	7,630	355	223	1.63x	149	1.42x	169	1.48x

Closing Observations

Oil recovery efficiencies from shale oil formations are low (5% to 9%) using primary (pressure depletion) practices, leaving behind a large remaining oil in-place target for enhanced recovery.

- In geologically favorable settings, cyclic injection of gas can improve shale oil recovery efficiency by 10% to 60% over primary recovery efficiency depending on type of gas injection and shale formation.
- Cyclic injection of CO_2 provides significantly more incremental oil recovery compared to cyclic injection of dry or wet gas.
- Numerous oil recovery mechanisms are involved in cyclic gas injection, including restoring pressure, viscosity reduction, oil swelling and miscibility.
- However, the geologic setting and field development practices need to be favorable for enabling cyclic injection of gas to achieve significant pressure increases (above MMP for CO_2) for effective oil recovery.

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