The Next Phase of the “Shale Oil Revolution”: Storing CO_2 with Shale EOR

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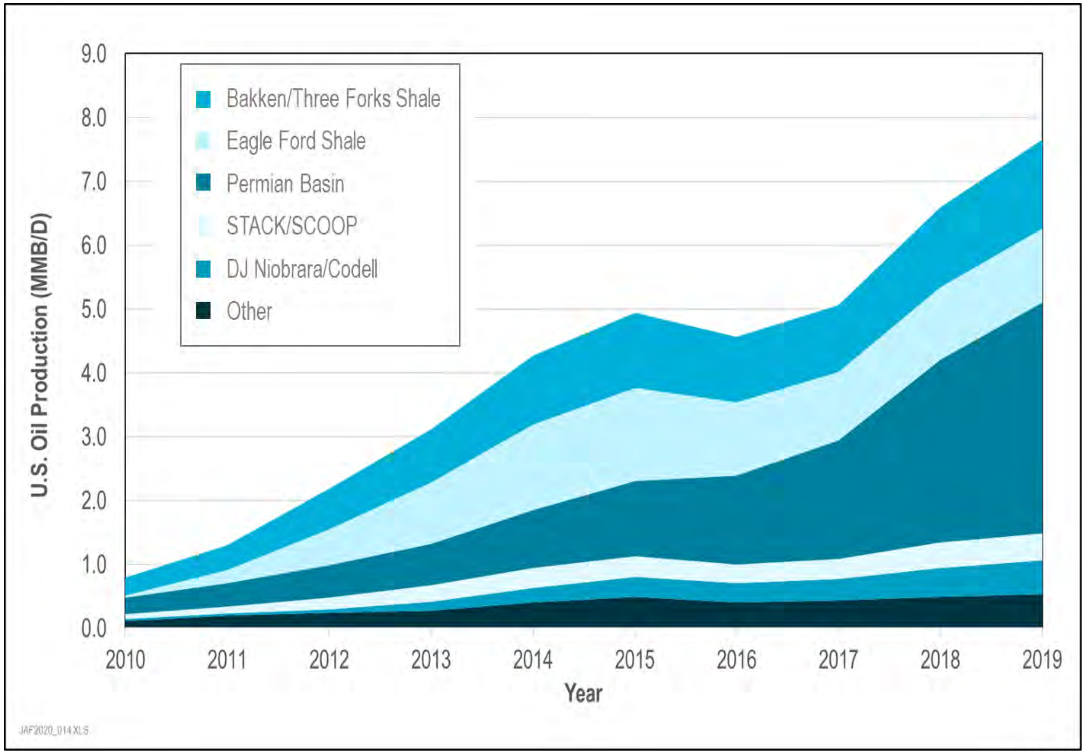
The "Shale Oil Revolution"

The recent decade of growth in domestic shale oil production is without precedent.

U.S. Shale/Tight Oil Production (2010-2019)



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Source: Advanced Resources International Database, 2020.

- From below 1 MMbbls per day a decade ago, shale / tight oil production reached 8 MMbbls per day last year, equal to two-thirds of total domestic oil production.
- Four key shale oil basins:
  - Bakken
  - Eagle Ford
  - Permian (Midland)
  - Permian (Delaware)

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Understanding the Shale Oil Resource

While the growth of shale oil production is well documented, much less is known about other aspects of this important resource:

- *How large is the shale resource in-place?*
- *How much of this large resource is recoverable with current practices?*
- *How much would the use of CO_2 injection (Shale EOR) improve shale oil recovery efficiency?*
- *How much CO_2 could be stored in shale oil formations with CO_2 EOR?*

Answering these questions is the purpose of this study, performed by Advanced Resources International and sponsored by the USEA.

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How Large is the Shale Oil Resource In-Place?

1. Assessing Shale Oil Resource In-Place. Individual resource estimates were established for 51 partitioned areas in four major shale oil basins – Bakken, Eagle Ford, Permian/Midland and Permian/ Delaware– based on:

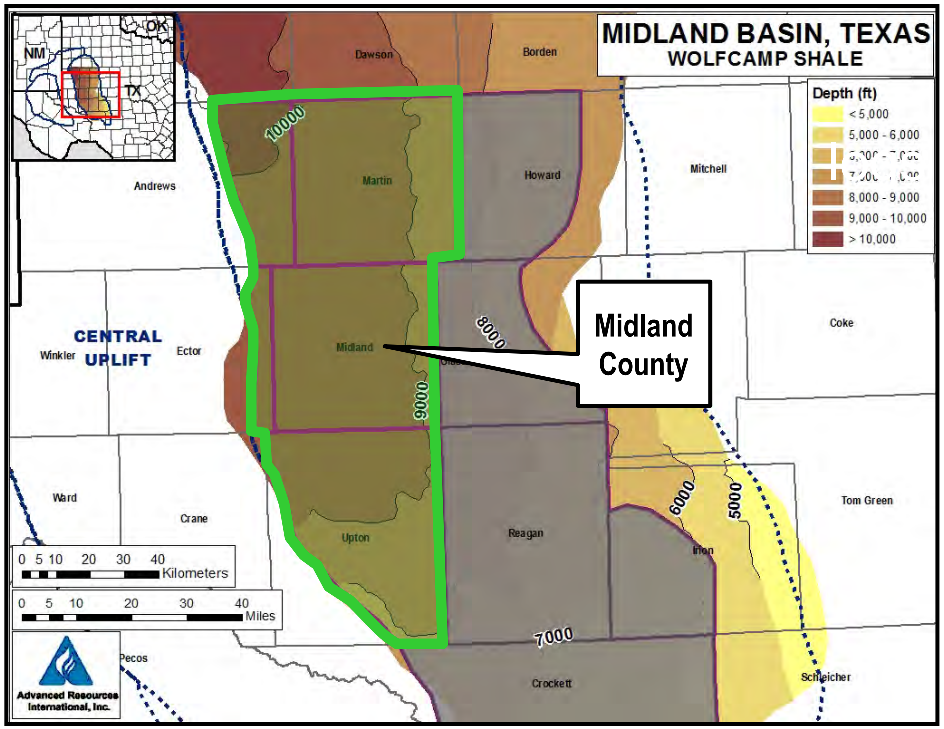
- Mapping of basin depth, gross shale interval, and productive area,
- Log-based assessments of net pay, porosity, and oil/water saturation by lithology (shale, limestone and mixed), calibrated to core,
- Compilation of other key reservoir properties, such as pressure, temperature, gas-oil ratio, oil gravity, among others.

Application of Study Methodology to Midland Basin

The Wolfcamp Shale in Midland County, at a depth of 9,500’, covers a risked area of 820 mi^2.

Bench A has 29.7 MMbbls and Bench B has 57.9 MMbbls of shale oil resource in-place.

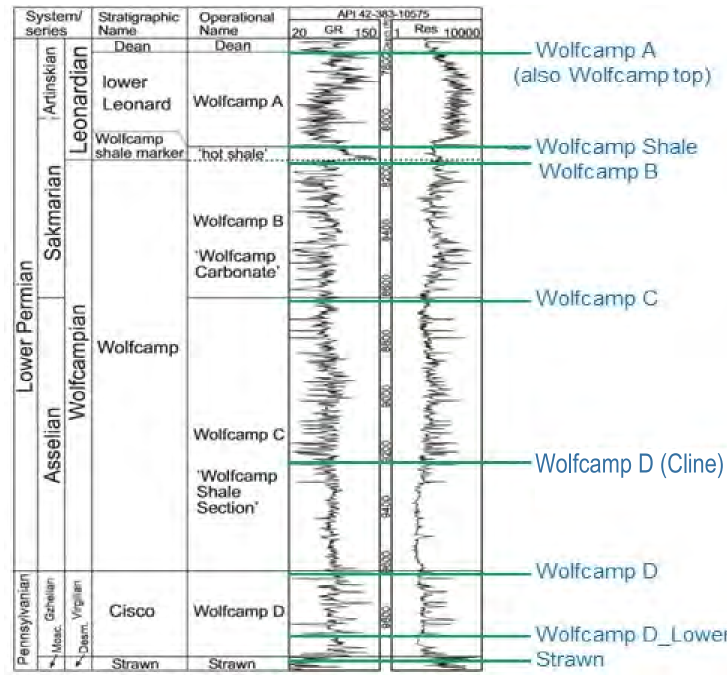
Deep Western Basin Area of the Wolfcamp Shale



Source: Advanced Resources International, 2020.

Midland Basin Stratigraphic Column

(Wolfcamp Benches A and B were individually assessed using a series of well logs)



Rock Units	Net Pay	Porosity	Oil Saturation
Organic Shale	130	4.4%	75%
Mixed Lithology	160	5.0%	44%
Total	290	4.7%	57%

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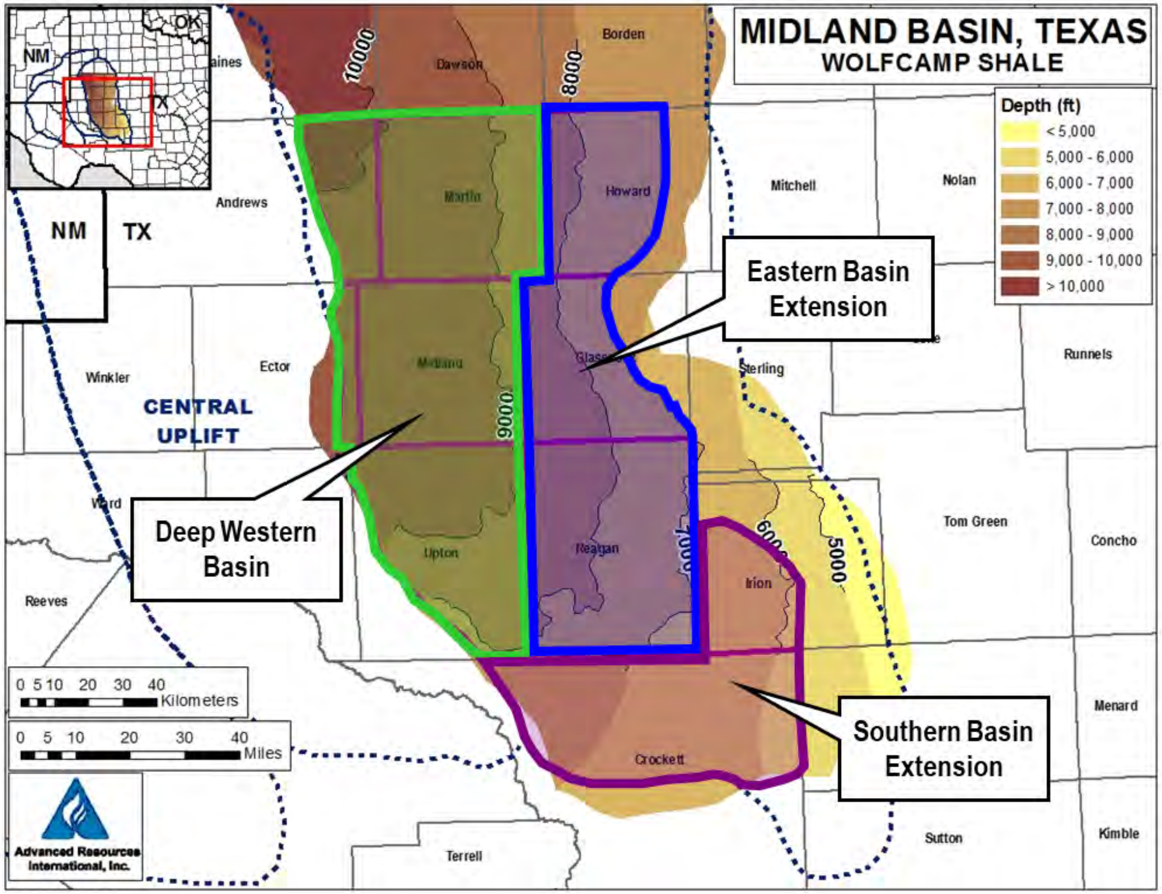
Midland Basin Wolfcamp Shale Resources

Three Geologic Partitions, Wolfcamp Shale Area



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The Midland Basin Wolfcamp Shale was partitioned into Deep Western Basin, Eastern Basin Ext., and Southern Basin Ext. areas, into counties, and then into two benches (A and B).

Volumetric and other reservoir properties were assembled for each of the sixteen assessment areas.

The size of the Wolfcamp Shale resource in-place is 509.1 billion barrels.

Additional tight oil resources exist in the Sprayberry.

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How Much of the Shale Resource is Recoverable?

2. Estimating Recoverable Shale Oil Resources. Reservoir properties and well completion practices, in each of the shale basins, were calibrated using history matching with actual well performance.

- Establish a representative "type well" for primary (pressure depletion) shale oil recovery for each partition (county) in each shale basin.
- Conduct compositional reservoir modeling to calibrate essential reservoir properties and well completion practices with well performance.
- Provide recovery estimates and profiles for oil and water production for each partition (county) in each shale basin and formation.

Application of Study Methodology to Midland Basin

To estimate the recoverable shale resource of Wolfcamp Shale Bench B in a representative area in the Midland Basin, we established a Study Area with reservoir properties shown below:

Wolfcamp Shale Bench B Study Area Reservoir Properties

Reservoir Properties	Units
Pattern Area	180 acres
Well Pattern Dimensions	
▪ Length	9,000 ft
▪ Width	880 ft
Depth (to top)	8,000 ft
Net Pay (All units)*	290 ft
Porosity	
▪ Matrix (Avg)*	4.7%
▪ Fracture	0.1%

Reservoir Properties	Units
Initial Oil Saturation (Avg)*	
▪ Matrix/Fracture	57% / 1%
Saturation Gas/Oil Ratio	0.85 Mcf/B
Formation Volume Factor	1.42 RB/STB
Initial Pressure	4,265 psia
Temperature	159 ^{o} F
Bubble Point	2,800 psia
Formation Compressibility	2.2 * e $^{-5}$/psi
Oil Gravity	39^{o} API

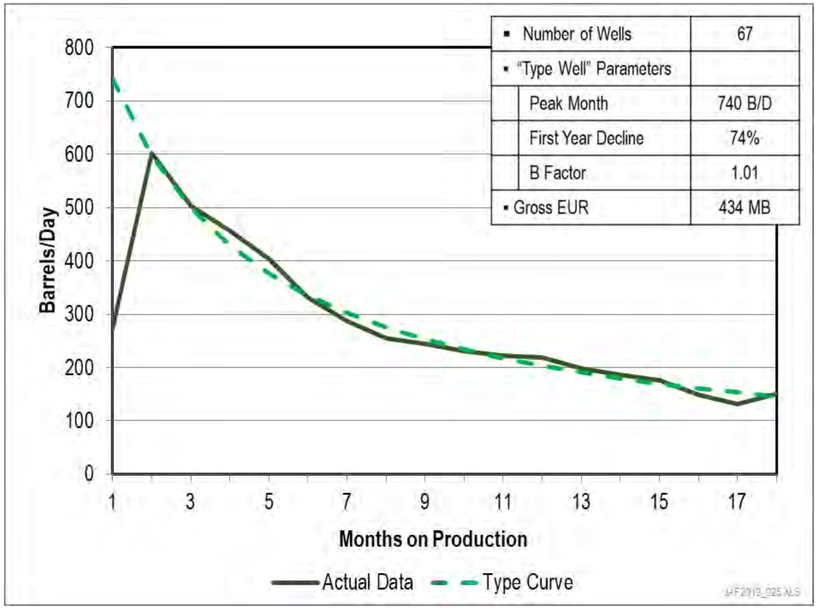
The Study Area contains 7.6 million barrels of original oil in-place (OOIP) and 6.5 billion cubic feet (Bcf) of original gas in-place (OGIP).

Source: Advanced Resources International, 2019.

Type Well for Study Area

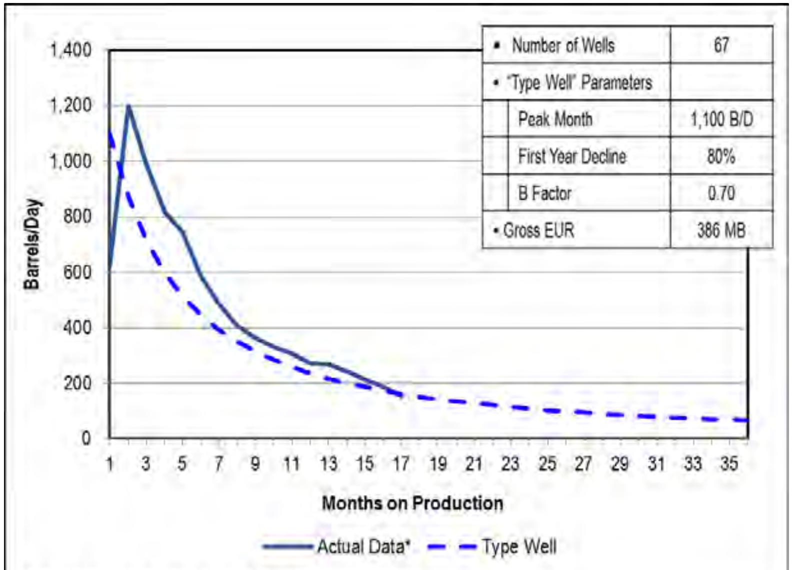
The “type oil well” in the Study Area has a spacing of 180 acres and a Hz lateral of 9,000 ft. It has an estimated 30-year recovery of 434,000 barrels of oil and 386,000 barrels of water, shown below.

Study Area Type Well Oil Production



▪ Number of Wells	67
▪ “Type Well” Parameters	
Peak Month	740 B/D
First Year Decline	74%
B Factor	1.01
▪ Gross EUR	434 MB

Study Area Type Well Water Production



▪ Number of Wells	67
▪ “Type Well” Parameters	
Peak Month	1,100 B/D
First Year Decline	80%
B Factor	0.70
▪ Gross EUR	386 MB

*Actual data includes flow back of 150,000 barrels of water.

Source: Advanced Resources International, 2020.

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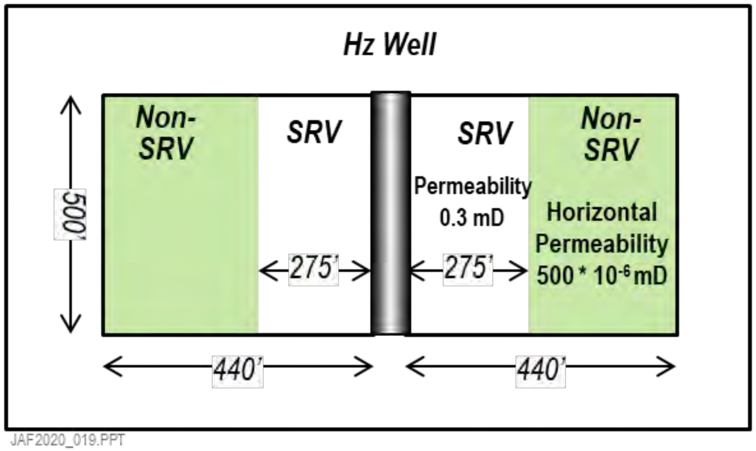
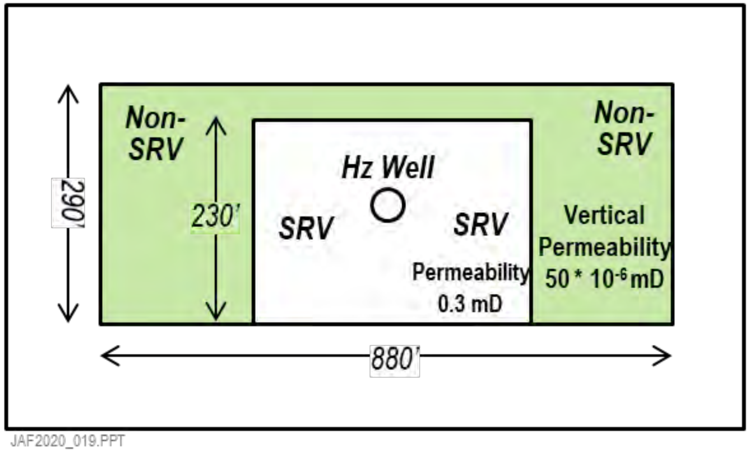
Calibrating Well Performance with Completion Practices

A. SRV Dimensions and Permeability, Plan View



B. SRV Dimensions and Permeability, Side View



The shale oil and water recovery from the Study Area well was calibrated to well completion practices typical for the Wolfcamp Shale in the Midland Basin.

- Horizontal well with 9,000' lateral
- Spacing of 6 wells per 2 sections
- A stimulated reservoir volume (SRV) of 550' by 230'
- An enhanced permeability of 0.3 md in the SRV, with 0. 0005 md in the matrix.

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Recoverable Shale Oil Resources

Only an estimated 84.9 billion barrels of the massive shale oil resource in-place (~6.5%) is technically recoverable with current (primary depletion) practices.

Shale Basin/Formation	Resource In-Place (Billion Barrels)	Primary Recovery	
		(Billion Barrels)	(%)*
1. Williston Basin/Bakken Shale	90.8	10.0	11.1%
2. South Texas/Eagle Ford Shale	139.3	12.6	9.0%
3. Permian Basin			
• **Midland Basin/Wolfcamp Shale**	509.1	26.1	5.1%
• **Delaware Basin/Wolfcamp Shale**	575.7	36.2	6.3%
Total	**1,314.9**	**84.9**	**6.5%**

*Primary Recovery as a % of OOIP.

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How Much Additional Oil Recovery and Storage of CO_2 Could be Achieved with Shale EOR?

3. Evaluating the Performance of Shale EOR Using Cyclic Injection of CO_2:

- Incorporate the reservoir properties and well completion practices from "history matching" well performance using primary (pressure depletion) oil recovery in the Study Area.
- Use the GEM Compositional Reservoir Simulator to model cyclic injection of high-pressure CO_2 for in the Study Area in each shale basin.
- Estimate volumes of incremental oil recovery and storage of CO_2 from Shale EOR using cyclic injection of CO_2.
- Extrapolate modeling results from each Study Area to each shale partition and basin.

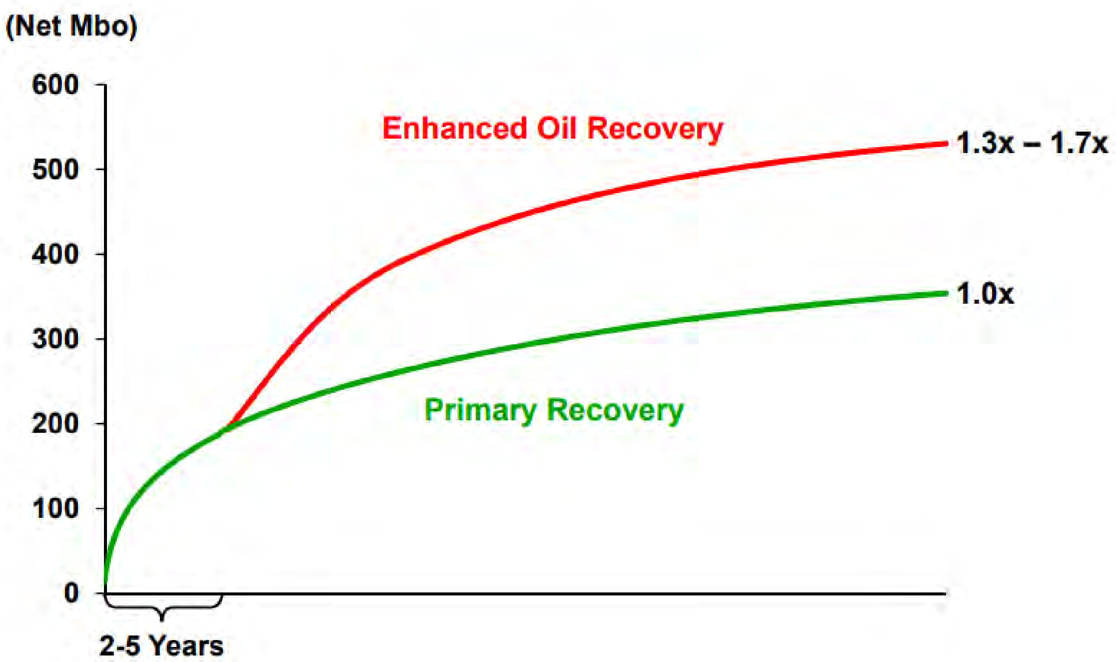
Shale EOR Performance: Industry Information

EOG Resources' Shale EOR Performance.

EOG has conducted cyclic gas injection in 150 wells in Eagle Ford Shale.

The company reported that their 32-well cyclic gas injection field project would add 30% to 70% to primary oil recovery, an uplift of 1.3 to 1.7x.

Primary versus Enhanced Oil Recovery: Eagle Ford Shale



Source: EOG Resources, 2017

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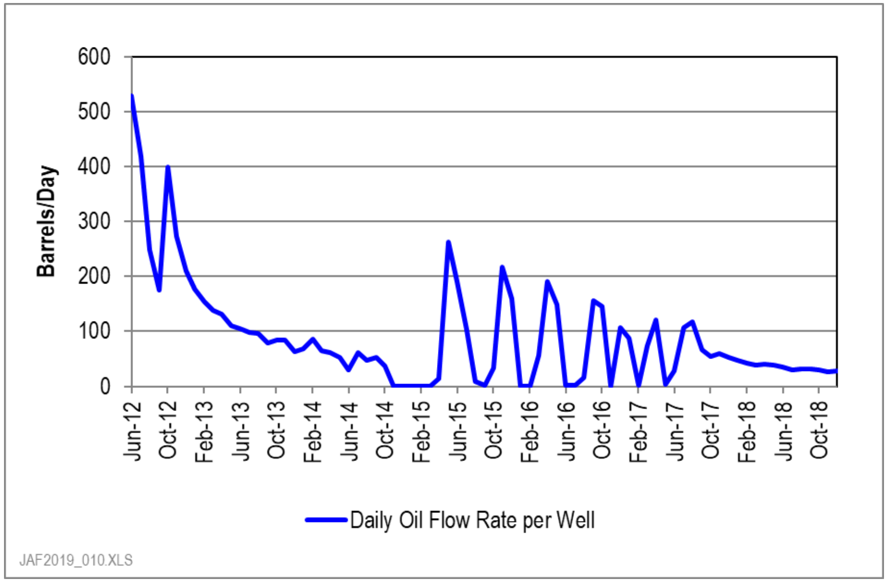
Martindale Unit Cyclic Gas Injection Pilot

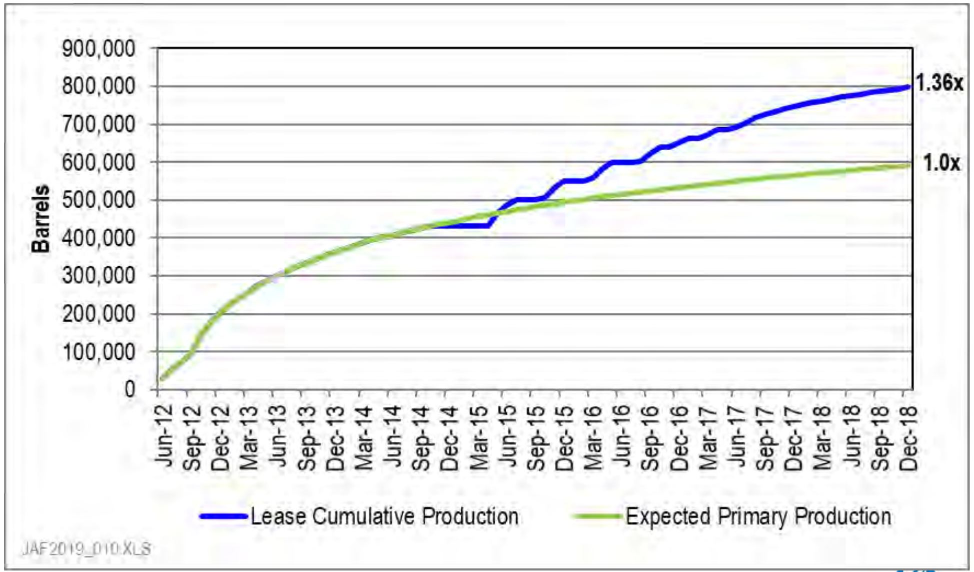
To better understand the performance of cyclic gas EOR, we assembled data and assessed the performance of the Martindale Unit 4-well cyclic gas injection project in the Eagle Ford Shale.

The cyclic gas injection project provided 210,000 barrels of additional oil, an "uplift" of 1.36x to 580,000 barrels from primary oil recovery.

Oil Recovery from Primary and Cyclic Gas Injection – Average Martindale L&C Lease Well



Cumulative Oil Recovery from Primary and Cyclic Gas Injection for Four Martindale L&C Lease Wells



Source: Advanced Resources International, 2020

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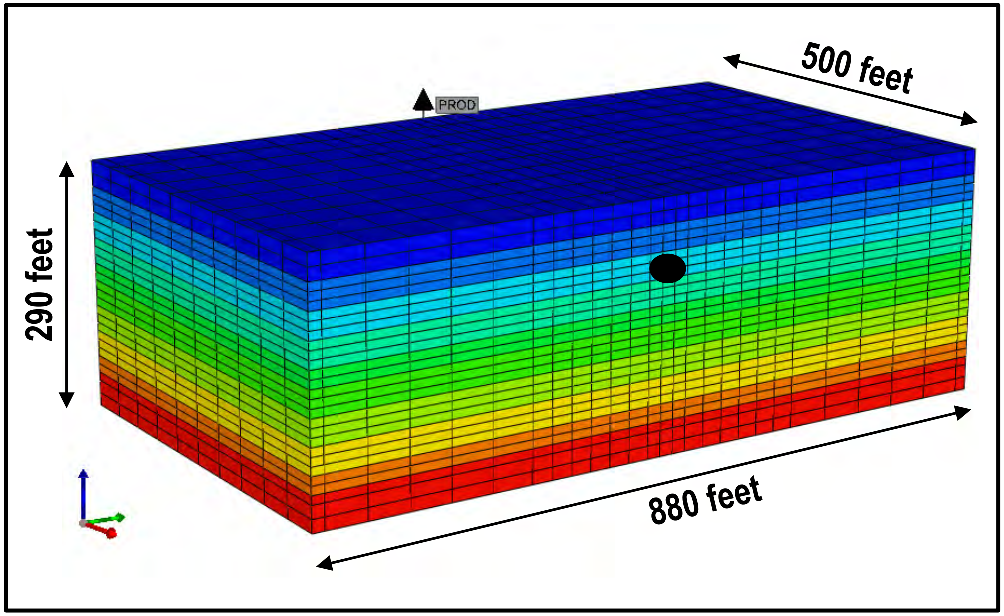
Reservoir Model for Shale EOR Study

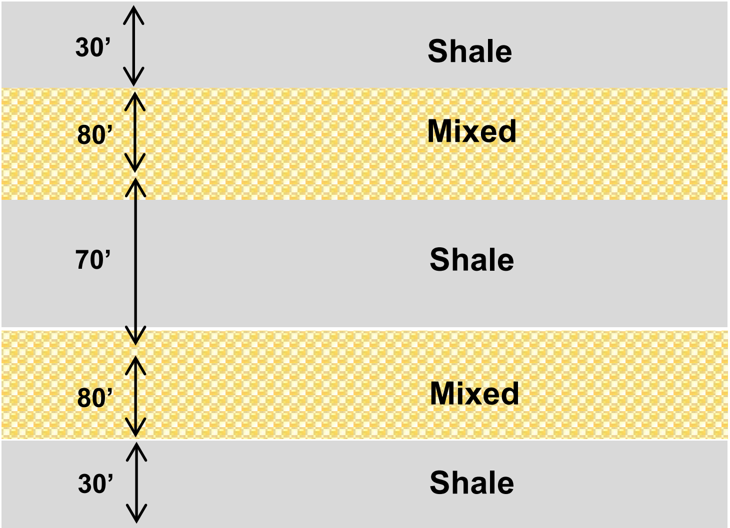
GEM, a compositional EOS reservoir simulator with 7,290 grid blocks, was used to calculate the flow of three-phase, multi-component fluids through the shale reservoir using lithology data from log analysis and values from "history matching".

Model Grid Blocks



Source: Advanced Resources International, 2020.

Reservoir Lithology



Not to scale

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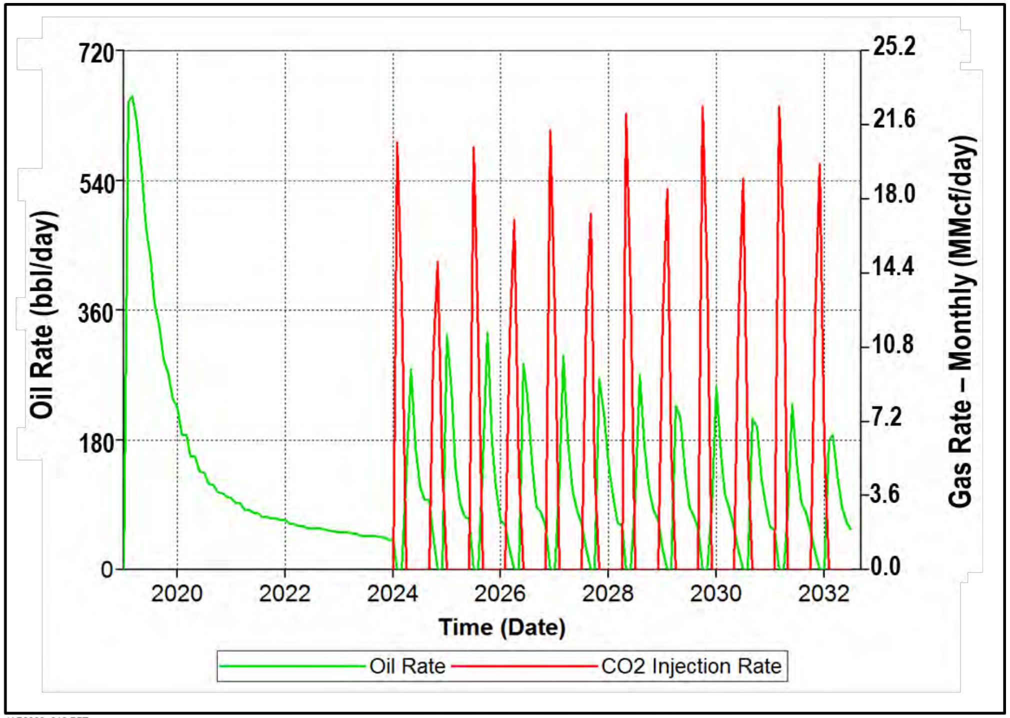
Enhanced Oil Recovery from Cyclic CO_2 Injection

Primary Production and Enhanced Oil Recovery from Cyclic CO_2 Injection



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Source: Advanced Resources International, 2020

Cyclic CO_2 injection was initiated in the Study Area well after five years and 272,000 barrels of primary production, about two-thirds of its EUR.

- In cycle one, CO_2 was injected at 17 MMcfd for 2 months (BHP limit of 4,800 psia).
- CO_2 injection was followed by 2-weeks of soak and 6 months of production.
- Eleven additional cycles of CO_2 injection, soak and production.

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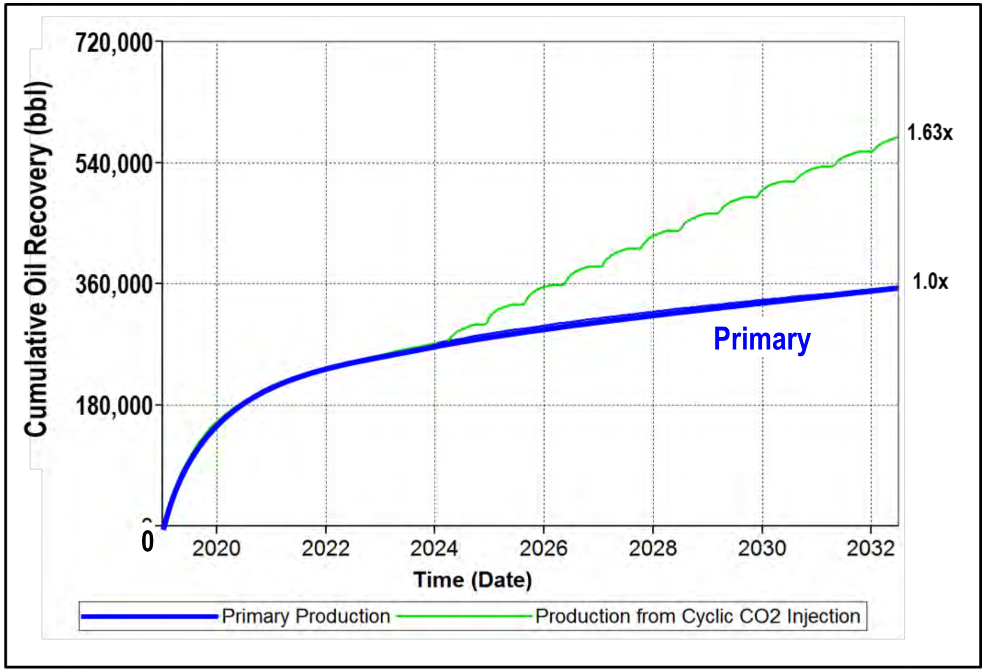
Performance of Cyclic CO_2 Injection: Midland Wolfcamp Shale

Cumulative Oil Production from Primary and Cyclic CO_2 Injection



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Source: Advanced Resources International, 2020.

The 12 cycles of CO_2 injection (over 8.5 years) provided 306,000 bbls of oil recovery (83,000 bbls from continuation of primary and 223,000 bbls from Shale EOR), in addition to 272,000 bbls from primary recovery at start of CO_2 injection.

Cyclic CO_2 injection provided an "uplift" of 1.63x over primary (pressure depletion) production in the Midland Wolfcamp Shale.

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Significant Potential of Shale EOR

While Shale EOR performed well in each of the basins, the Permian's Midland and Delaware Basins accounted for the bulk of incremental oil recovery and CO_2 storage (36 billion bbls of additional oil and nearly 17 billion metric tons of new CO_2 storage capacity.)

Shale Basin/Formation	Incremental Oil Recovery from CO_2 EOR (Billion Barrels)	Storage of CO_2 (Gmt)
1. Williston Basin/Bakken Shale	3.7	1.5
2. South Texas/Eagle Ford Shale	7.6	1.8
3. Permian Basin		
• Midland Basin/Wolfcamp Shale	14.2	6.5
• Delaware Basin/Wolfcamp Shale	21.8	10.0
Total	47.5	19.9

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Closing Comments

While driving record growth in domestic oil production, the aggressive development of shale oil has consumed much of the "core" (higher quality) areas in key shale oil basins:

- **Bakken Shale**. With over 10,000 wells drilled and placed on production, much of the central ("core") area of the Bakken Shale has been consumed.
- **Eagle Ford Shale**. With nearly 20,000 wells on production, the oil-bearing portions of Eagle Ford Shale and its dominant Karnes Trough "core" area are rapidly becoming mature.
- **Permian Basin.** The massive number of rigs working the Midland and Delaware Basins, peaking at nearly 500 in early 2019, and the return to wider well spacings are reducing the number of remaining undeveloped "core" area locations in the Permian Basin.

Given these observations, it is timely to pursue development and application of advanced Shale EOR technologies, if we are to maintain domestic oil production.

Acknowledgements

A portion of the information on resource characterization and reservoir modeling related to cyclic CO_2 EOR in shale oil basins is based on a series of reports previously prepared by Advanced Resources International, Inc. for the U.S. Department of Energy, National Energy Technology Laboratory (U.S. DOE/NETL).

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