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Maximizing Value in a Miscible Gas Huff n Puff Enhanced Oil Recovery Pilot – A Case Study

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Abstract

This study presents a technical evaluation of a large-scale miscible gas huff n puff pilot project, highlighting the reasons for its success over four years of Enhanced Oil Recovery (EOR) operations. Field results show a notable 37% uplift to-date compared to the scenario without EOR.

We built and calibrated a compositional, fully coupled fracture-reservoir model to assess and guide pilot operations. This model was calibrated to completion data, primary production data, and the results of multiple huff n puff cycles, all on a unified and consistent platform. Key model objectives included: 1. characterizing the stimulated rock volume (SRV), 2. properly capturing all mechanisms involved in the complex Huff n Puff process, 3. optimizing huff n puff cycling operations, and 4. estimating uplifts and incremental oil recoveries.

The integration of geomechanics and reservoir models facilitated history matching completion data, primary production, and EOR response. By modeling the hydraulic fracturing process, we effectively estimated well injectivity and captured the behavior of hydraulic fractures, which are influenced by net effective stress on the proppant. Our findings indicate that unpropped portions of the hydraulic fractures may open and close during gas cycling, potentially leading to inefficient gas recovery. This modeling approach helped us avoid such issues.

The calibrated model was used to perform a parametric evaluation to optimize injection cycling. Sensitivity analyses allowed us to estimate target injection pressures, volumes, and flowback strategies, guiding us into maximizing economic value.

Modeling results indicate that greater gas volumes do not always translate into increased value. While oil rate uplift improves with higher gas injection volumes, diminishing economic returns may be observed beyond certain thresholds. Field observations and the modeling study also indicate that Gas Utilization Factors (GUFs) are expected to rise in every cycle. Consequently, gas injection requirements significantly increase in subsequent cycles to achieve similar well responses, while oil production peaks decline with each cycle due to depletion in the near-fracture SRV.

This study presents a robust modeling framework for the design, evaluation, optimization, and economic enhancement of Miscible Gas Huff n Puff pilots in unconventional reservoirs. The insights gained are critical for informing future EOR projects and maximizing recovery efficiencies. As oil production from unconventional oil basins in the United States continues to experience decline, EOR becomes increasingly

critical. EOR will have a substantial impact on increasing recoveries, accelerating production, and extending asset life for the unconventional plays in the United States, unlocking billions of barrels in additional recoverable resources.

Introduction

Enhanced Oil Recovery (EOR) represents a significant opportunity for oil and gas companies operating in the USA's shale plays, offering enhanced production rates and improved resource recovery. Rather than just a strategic choice, EOR serves as a holistic approach to address technical, economic, operational, and environmental challenges, providing companies with essential tools to maximize asset value while meeting the evolving expectations of stakeholders and regulators.

In unconventional reservoirs with nano Darcy permeability, economically viable production often depends on horizontal multi-fractured wells. However, primary depletion typically results in low recovery rates, ranging from 4% to 16%. This leaves vast untapped resources estimated in the hundreds of billions of barrels, often deemed technically and economically unrecoverable without interventions to lower residual oil saturation in pore spaces.

One effective technique for enhancing recovery in unconventional reservoirs is intermittent miscible gas injection, commonly known as Huff n Puff gas injection. This EOR method can significantly improve production rates, extend field lifespans, and enhance resource recovery. In a landscape where oil demand is rising and many unconventional oil reservoirs are plateauing or declining, efficient hydrocarbon exploitation becomes crucial. Additionally, EOR can mitigate environmental impacts by maximizing output from existing wells, thereby reducing the need for new drilling or refracturing of older, less optimized wells. However, successful EOR implementation requires careful consideration of costs, technology, and environmental factors.

The case for adopting EOR in unconventional resources is compelling:

Increased Recovery: EOR methods can recover a substantial portion of hydrocarbons trapped in unconventional reservoirs, significantly boosting production rates. Successful pilot projects across North America showcase the potential for both technical and economic achievements, as highlighted by Malo et al. 2019 and others. Notably, our internal estimates suggest that incremental oil recovery within black and volatile oil windows across various unconventional oil basins could be in the billions.

Production Acceleration and Asset Life Extension: In a competitive energy market, economic viability is essential. Miscible Huff n Puff EOR technology not only enhances recovery rates but also extends the economic life of existing assets. This technique ensures sustainable production and guards against premature asset abandonment, ultimately providing stable and consistent revenue streams. For instance, several industry pilots, including those by EOG and Continental Resources, have shown average monthly production volumes during Huff n Puff that exceed primary expectations by 3 to 5 times (Hoffman, 2018 and Malo et al, 2019).

Value Enhancements in Production Streams: Huff n Puff EOR enhances production value by enriching gas cycles, increasing the recovery of light hydrocarbons, and boosting the heating value of gas streams.

Reduced Operational Footprint: By improving the efficiency of existing wells, EOR can lower the demand for new drilling and refracturing, thereby minimizing land disturbance and environmental impact. The optimization of injection and production processes through advanced technology can lead to cost savings and improved profitability, enhancing competitive positioning.

Technology Development: Ongoing research and innovation in EOR for unconventional resources will advance reservoir characterization, modeling, and monitoring technologies. Companies with strong technical capabilities and partnerships with academic institutions will be better positioned to exploit the vast EOR potential in North America's unconventional oil plays. Government incentives, including tax credits, further support the optimization of recovery methods. Huff n Puff EOR has demonstrated success across both conventional and unconventional reservoirs for decades, with recent pilot projects in unconventional basins showcasing significant recovery and production improvements. Advances in reservoir modeling and gas injection technologies, including gas/foam injection, have the potential to further enhance recovery efficiency.

Operational Optimization: Huff n Puff EOR is a dynamic tool, allowing companies to adapt to fluctuating market conditions. A well-structured EOR technology portfolio enables real-time adjustments to strategy in response to oil and gas price volatility, bolstering resilience in a rapidly changing industry.

Despite its advantages, challenges remain:

Technical Complexity: Implementing EOR in unconventional reservoirs requires advanced engineering and geological expertise. Many technical questions still need to be addressed to improve consistency in results and development.

Cost and Market Considerations: EOR projects incur expenses related to specialized equipment, gas, and operational intricacies. Maintaining a favorable gap between EOR implementation costs and revenue from increased production is crucial for project feasibility and profitability.

In summary, EOR presents a compelling avenue for unlocking the potential of unconventional resources, addressing the need to enhance production from aging assets while meeting increasing energy demands and promoting environmental responsibility. Investing in Huff n Puff EOR technology offers multifaceted competitive advantages, including improved recovery, prolonged asset life, cost efficiency, adaptability to market dynamics, technical excellence, and risk mitigation. This strategic emphasis positions unconventional oil companies for sustained success in an ever-evolving oil and gas landscape.

The benefits of Miscible Gas Injection Enhanced Oil Recovery (EOR) in unconventional resources strongly advocate for continued technological development due to significant potential rewards. Many basins remain in the early phases of piloting or evaluating Miscible Gas Injection Huff n Puff EOR, concentrating on optimizing pilot performance and assessing technical merits for future field expansion. This paper presents criteria for pilot selection and presents a thorough technical evaluation of a pilot performance through integrated compositional fracture/reservoir modeling. This detailed modeling enabled our teams to optimize operations and maximize value, even in initial evaluation stages.

Theory and/or Methods

A Huff n Puff project involves injecting miscible gas into an existing well to raise near-reservoir pressure (huff) and dissolve gas in the oil. This is followed by a brief soaking period, after which the energized reservoir fluids are produced (puff). Figure 1 illustrates the process.

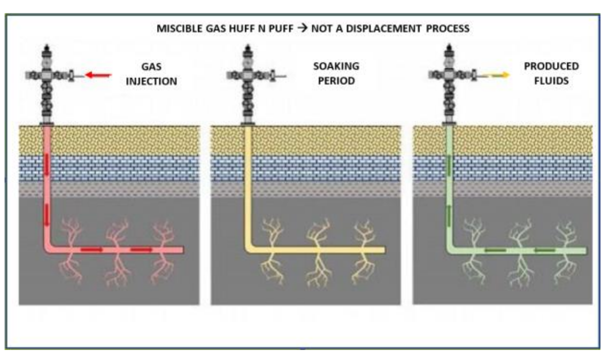


Figure 1. Illustration of the miscible gas huff n puff process (Eltahan et al. 2020)

The literature identifies several key mechanisms enabling miscible gas Huff and Puff in black and volatile oil systems. These main mechanisms include:

- Oil swelling
- Viscosity reduction
- Near-fracture oil vaporization
- Pressure support

Hoffman et al. (2019) utilized an idealized modeling approach to quantify the individual contributions of each mechanism, highlighting oil swelling as the primary driver in black oil systems. Figure 2 summarizes key results from their research.

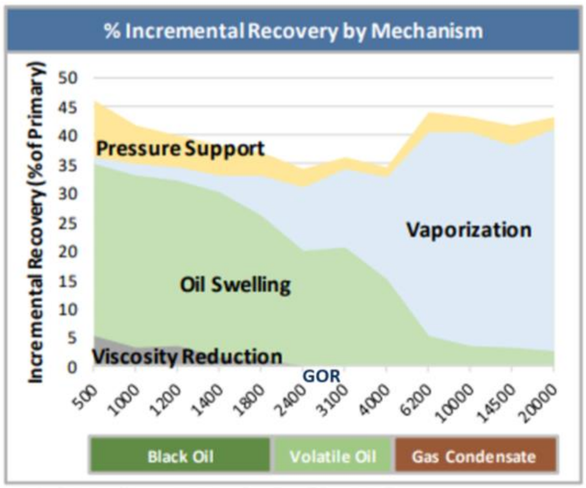


Figure 2. Mechanisms in the incremental recoveries of miscible gas huff n puff (Hoffman et al, 2019)

While idealized modeling provided valuable insights into the contributions of the primary mechanisms for incremental oil recovery, likely identifying the most significant factors, there are additional effects that may also influence recovery, including but not limited to:

- Stress-dependent permeability effects.
- Potential reopening of hydraulic fractures during gas injection.
- Proppant resettlement due to high-pressure cycling.
- Proppant damage during cycling.
- Fracture communication with offsetting wells, which can lead to gas leakage and loss of containment.
- Potential hysteretic behavior of capillary pressures and relative permeability effects.

This list is not exhaustive, as other factors may also play a role. The factors listed above, relevant to high-pressure gas cycling, can be challenging to quantify due to the complexities associated with reservoir geomechanics.

Pilot Screening Criteria and Selection Process

EOR field development hinges on successful execution of one or more pilots. Pilots can have varying objectives which must be clearly defined before their planning and execution.

Initial pilots focus on demonstrating the technical feasibility of the EOR process, while subsequent pilots focus on delineating the applicability of the process in the basin and the technical and economic potential for field expansion. Once an EOR field development is sanctioned, its execution may occur in phases to optimize the EOR process during the execution early stages.

Early Huff and Puff pilots are typically designed to assess the technical and economic feasibility of the process. They are often conducted in one or just a few wells, located in prolific areas of a field, to minimize the complexities associated with multi-well communication and facilitate the interpretation of the reservoir response and behavior. Inter-well communication effects are often evaluated in subsequent delineation pilots (if necessary).

Our pilot screening process starts with a preliminary assessment and ranking of prospects within a basin. This evaluation uses proxies to assess factors such as miscibility, containment, injectivity, depletion, and contacted surface areas. The most promising candidates undergo a detailed analysis, using integrated compositional fracture-reservoir modeling for a comprehensive evaluation.

Proper pilot screening and selection necessitates thorough evaluation by a skilled, multidisciplinary team comprising professionals from geology, geophysics, petrophysics, reservoir, production, facilities engineering, land, legal, and other relevant fields. Continental's comprehensive EOR screening process emphasizes key factors that greatly impact the successful design of a pilot project. Here’s a summary of the criteria for pilot selection.

1. Fluid characterization and miscibility estimation
2. Evaluation of containment potential
3. Gas injectivity assessment
4. Estimation of Original Oil In Place (“OOIP”) and gas-oil contact areas
5. Estimation of the Stimulated Rock Volume (“SRV”) depletion
6. Assessment of gas source availability and transmission capacity
7. Detailed review of well design and well integrity
8. Examination of land and legal constraints impacting the project

Technical evaluation is typically underpinned by integrated compositional fracture/reservoir modeling.

We briefly describe below each of the critical factors evaluated in a pilot selection:

1. Fluid characterization and miscibility evaluation:

The Huff n Puff process focuses on injecting gas to alter the near-surface reservoir volume composition, increasing fluid compressibility rather than displacing fluids. Therefore, accurate representation of fluid phase behavior and interactions require proper fluid characterization through Equation of State (EoS) modeling. EoS models must be calibrated to relevant black oil suite tests and enhanced oil recovery (EOR) experiments, such as swelling and slim tube. Swelling tests are crucial for modeling processes in depleted near-fracture zones during Huff n Puff operations, while slim tube testing may capture displacement behavior through coalescing propped hydraulic fracture networks when more than one well is involved. Although swelling tests are generally more representative, slim tube tests remain valuable for understanding fluid behaviors in specific field conditions.

When evaluating miscibility, target injection pressures often aim to approach First Contact Miscibility Pressure [MMP_{FC}] defined as the pressure at which in-situ fluids and the injectant exist as a single phase, regardless of their mixing proportions. First contact miscibility pressures are strongly dependent on the injectant fluid composition. Leaner gases (< 1,100 BTU/SCF) require higher injection pressures to reach first contact miscibility, while richer hydrocarbons or CO_2 need significantly lower pressures to achieve miscibility, making the process more efficient but at an additional cost.

The potential use of CO_2 for unconventional Huff n Puff pilots has attracted a lot of attention in recent years as the technique offers both incremental oil recovery and CO_2 sequestration benefits. CO_2 is an excellent solvent, and its implementation is very attractive from a technical perspective. However, there are technical and economic challenges for its implementation at scale. Tables 1 and 2 compare the advantages and disadvantages of CO_2 vs. hydrocarbon gas cycling. Please keep in mind, that learnings from an EOR huff 'n puff pilot using lean hydrocarbon gas can be valuable for estimating the benefits of other solvents, such as rich hydrocarbon gas or CO_2, through compositional reservoir simulation.

Table 1. Advantages of using CO_2 as injectant.

	CO_2	**Hydrocarbon gas**
$MMP_{[MC]}$	✓ ~ 2,500 – 3,500 psia	❖ ~3,000 – 5,500 psia
Gas Utilization Factor (GUF)	✓ Lower GUF (More efficient)	❖ Higher GUF (Less efficient)
Sequestration	✓ Added sequestration benefit	❖ Marginal sequestration (if any)
Tax credits	✓ Federal sequestration incentives (up to $85/Ton) ✓ Some states may provide tax incentives	✓ Some states may offer EOR incentives

Table 2. Disadvantages of CO_2 as injectant.

	CO_2	**Hydrocarbon gas**
Source	❖ Limited availability	✓ More readily available
Transportation	❖ Significant investments often required	✓ Typically requires less investments for transportation
Well integrity	❖ May require costly metallurgies and well designs	✓ Less likely to produce issues as most wellbores are designed for the service
Surface Facilities	❖ Req. significant investments for effluent treatment	✓ Effluent is ready to the treated in existing processing units
Equipment	❖ Req. specialized equipment for treatment and compression	✓ More readily available and less expensive
Flow assurance	❖ May cause asphaltene precipitation and/or other flow assurance issues	✓ Less prone to cause flow assurance issues

It's important to consider equipment limitations regarding maximum discharge pressures and to ensure bottom hole pressures remain low enough to avoid fracturing the reservoir and/or reopening unpropped hydraulic fractures. In most injection processes, maximum bottom hole pressures are set at ~ 90% of SHmin or at the initial reservoir pressure, typically aiming to approach MMP_{FC}.

While multi-contact miscibility (MMP_{MC}) is less critical in unconventional miscible gas EOR, it remains relevant. Fracture connections between offsetting wells can facilitate oil displacement through coalescing fractures, but it's important to note that miscible gas injection Huff n Puff is not considered a displacement process. Proper selection of the injectant and target injection pressures is paramount for a successful project.

2. Evaluation of containment potential

A successful project requires a thorough assessment of the reservoir's ability to retain gas under pressure while minimizing leakage. This includes evaluating the reservoir structure to ensure there are no significant faults or extensive natural fracture networks that could compromise containment. Additionally, it involves assessing communication with offset wells to maintain gas concentration in the well(s) targeted for enhanced oil recovery (EOR) stimulation.

3. Gas injectivity assessment

Well injectivity must enable high-rate gas injection to shorten injection periods and minimize production deferrals. Complex modeling is required to properly assess well injectivity. Typically, well productivity, measured by the Linear Flow Parameter (LFP), serves as a proxy in the screening process. Although well productivity and injectivity are not always directly correlated due to positive PDP effects, wells with higher LFP often make better candidates for injection.

4. Estimation of Original Oil In Place ("OOIP") and gas-oil contact areas

Wells with larger contacted surface areas are preferred to provide the necessary scale to produce meaningful enhanced oil recovery potential. For smaller legacy completions, enhanced oil recovery may necessitate simultaneous gas injection into multiple wells to achieve economically viable results for field development.

5. Estimation of the Stimulated Rock Volume ("SRV") depletion

Estimating depletion levels is crucial. Depletion must be limited to ensure oil swelling is the dominant recovery mechanism rather than vaporization. Vaporization can result in an inefficient recovery process requiring substantial gas volumes for meaningful incremental oil recovery. The authors speculate that there is a window of opportunity for implementing a successful EOR project where the primary mechanism is swelling and not vaporization.

6. Assessment of gas source availability and transmission capacity

Access to gas sources and transmission lines is vital for a pilot, given the limited transmission pipeline infrastructure present in most unconventional basins. Surface facilities must be upgraded to support the required injection rates and volumes, along with increased production rates.

7. Detailed review of well design and well integrity

Effective pilot selection requires a thorough evaluation of well integrity. Most Huff and Puff EOR pilots involve injecting and producing through tubing, with packer installation to ensure annular isolation.

8. Examination of land and legal constraints affecting the project

Involving land, legal, and other non-technical disciplines early is essential to assess pilot location feasibility. This collaboration addresses royalty and tax quantification to satisfy operators, landowners, government agencies, and other stakeholders.

Comprehensive evaluation of a Huff n Puff pilot requires detailed modeling to assess pilot potential and expected incremental recoveries under different operating scenarios. The case study presented in this paper describes a thorough evaluation performed for one of our pilots.

Pilot Description – Our Case Study

A single well was selected for an initial pilot to serve as proof of concept and to optimize operating conditions for maximizing oil production. The goal of this pilot was to gauge reservoir response before considering interactions with offsetting wells in a multi-well environment.

The selected well had produced for 3.25 years before gas injection began. The pilot well was located in the black oil window of the basin, with an initial GOR of approximately 750 SCF/STB and an oil API gravity of 43 degrees. The pilot was designed to inject lean gas from a nearby transmission line (~ 1,050 BTU/SCF) with a target pressure close to the original reservoir pressure during gas cycling.

An isolated well serves as an ideal candidate for gas containment. The well was completed using a modern high-intensity completion, with estimates projecting significant oil recovery during primary production. The large contacted surface areas enabled extensive EOR stimulation and ensured the necessary injectivity.

RTA estimates indicated that the well was in boundary-dominated flow, with the average reservoir pressure slightly above the original bubble point before gas injection began. The gas-oil ratios at the start of gas injection were modestly above the well's initial GOR.

Geology

Data from petrophysical logs, core samples, and dipole sonic logs from an adjacent pad provided excellent information for characterizing the reservoir. The petrophysical logs, calibrated to core data, estimated the main reservoir's average porosity at approximately 6% and water saturation at around 35%. The stress profile derived from a dipole sonic log, calibrated to DFIT, indicated that the target reservoir is confined between two strong vertical barriers, with an effective stimulated reservoir thickness of about 42 ft. Figure 3 illustrates the interpreted stress profile.

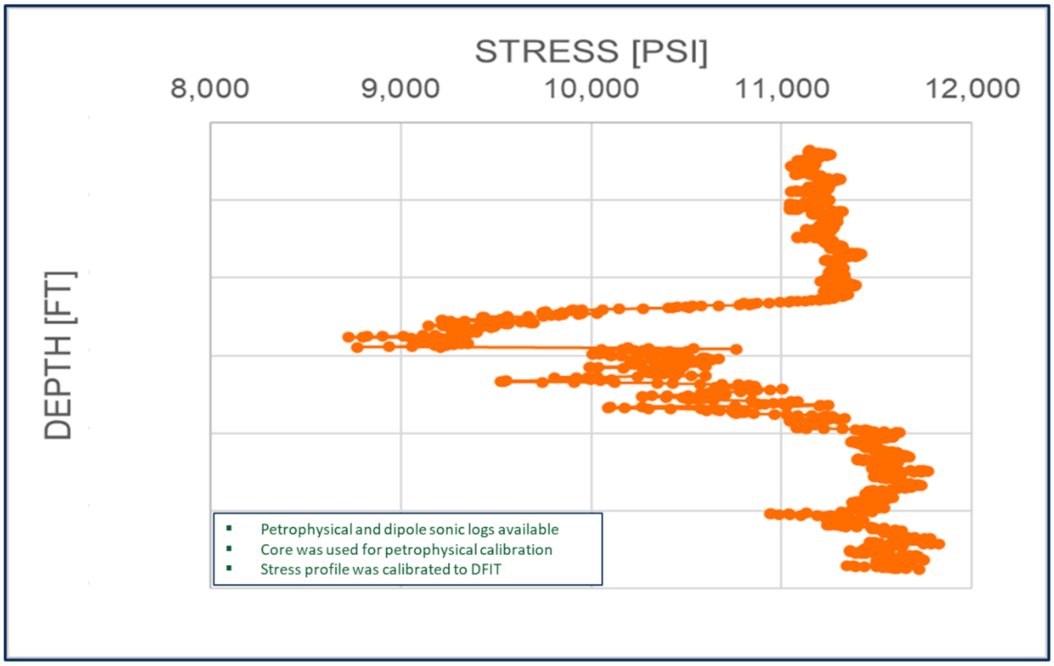


Figure 3. Estimated stress profile for the target zone

Pilot performance

The well exhibited a strong response to the cyclic gas injection huff-and-puff process. Relevant production observations during the cycling are listed below:

1. First-cycle oil production rates during the puff were approximately five times higher than pre-enhanced oil recovery (EOR) rates, following initial gas injection to target pressure.
2. Peak oil production after the first cycle approached 90% of the well's maximum initial production, almost effectively re-establishing its maximum oil output after ~ 3.25 years of production.
3. Multiple huff-and-puff cycles implemented over the years have consistently shown positive results.
4. Peak oil rates during subsequent cycles declined by approximately 15% relative to the previous cycle.
5. During each individual cycle, the evolution of fluid properties indicates that vaporization is the dominant mechanism very early in a puff cycle, while swelling becomes more pronounced thereafter. API gravities of the effluent are high at the start of a puff but approach original API gravities toward the end of the cycle, reflecting changing fluid mechanisms and dynamics and indicating successful access to near-fracture fluids and the achievement of miscibility.
6. Gas injectivity was not an issue; gas could be injected at full compressor delivery capacity.
7. Each cycle required more gas to reach target pressures, resulting in increased gas utilization factors.
8. Water production rates also decreased significantly during the gas cycling process.

Figure 4 shows the oil rates observed during the cycling process, while Figure 5 compares pilot response against a scenario without EOR. Results show an estimated uplift of ~ 37% after the first six cycles, demonstrating both increased recovery and production acceleration.

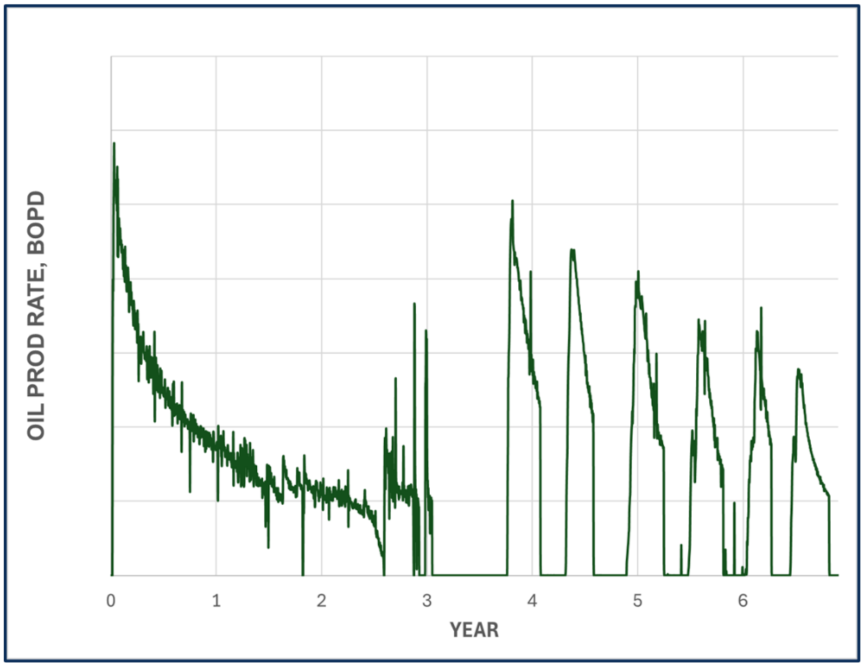


Figure 4. Oil production profile for the pilot.

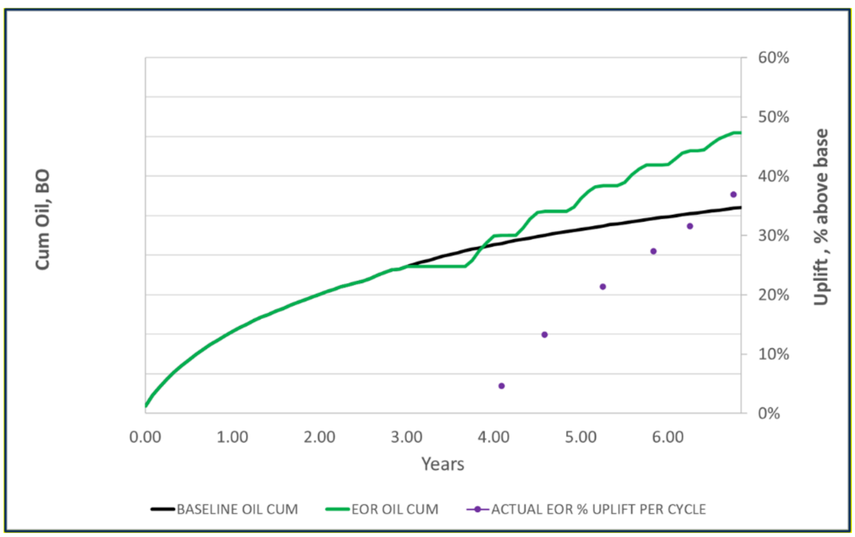


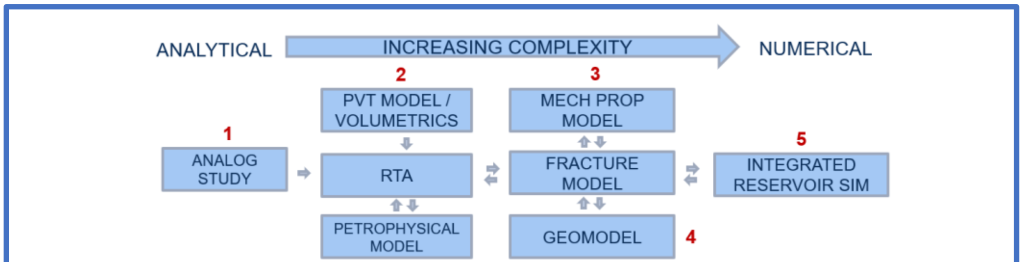
Figure 5. Oil cumulative production and estimated uplift.

Model build and calibration

Simulations were conducted using an integrated hydraulic fracturing and reservoir simulator (McClure et al., 2025) designed to continuously model the full lifecycle of a well, from initial stimulation, to primary depletion, and then to miscible gas injection Huff n Puff. The model is fully coupled. Mass and momentum balance equations are solved while also rigorously calculating geomechanical interactions, including dynamic stress shadowing and depletion-induced poroelastic stress changes.

Modeling objectives included: 1. Characterizing the stimulated rock volume, 2. Inform the optimization of huff-and-puff cycling operations, and 3. Forecast uplifts and incremental oil recoveries.

The model was built and calibrated using the workflow outlined by Zaghloul et al. (2024) and illustrated in Figure 6. This workflow necessitates a thorough evaluation of geology, petrophysics, geomechanics, and production data before proceeding with detailed integrated modeling. Notably, Rate Transient Analysis (RTA) provided estimates of permeability and contacted pore volume, serving as an excellent starting point for model calibration and accelerating the history matching process.



STAGE	IDENTIFICATION	DESCRIPTION
1	ANALOG ANALYSIS	Check if wells to be modelled are representative of a broader type curve region. Define locations impacted by study
2	RTA / VOLUMETRICS	Material balance analysis. Review if DCA makes sense from the thermodynamic point of view. Initial estimate of propped effective reservoir areas grounded on some assumptions.
3	GEOMODEL	Static reservoir description
4	FRACTURE MODEL	Fracture geometries based on geomechanics and mechanical properties
5	INTEGRATED RESIM	Dynamic reservoir simulation fully integrating both material balance and geomechanics

Figure 6. Integrated modeling workflow (Zaghloul et al., 2024).

Hydraulic fracturing results

The target well was completed using a modern design, featuring stages with 4 clusters spaced 70 feet apart and a pumped sand intensity of 2,000 lbs/ft. Fracture modeling revealed very long extensional hydraulic fracture geometries reaching up to 4,300 ft, with significant asymmetric growth due to strong containment. Model results are aligned with empirical field observations, where offset completions have affected wells up to 5,000 ft away in several cases.

Propped geometries covered only a small fraction of the hydraulic fracturing growth, approximately 950 ft. Fracture containment facilitated the accumulation of high proppant concentrations near the wellbore, leading to outstanding fracture conductivities and low proppant conductivity degradation over time.

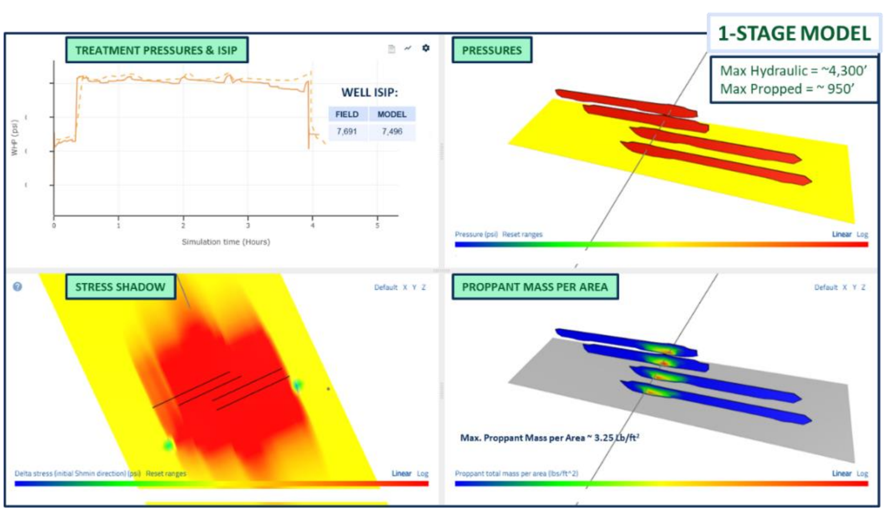


Figure 7. Fracture modeling summary.

The model matched, with reasonable accuracy, treatment pressures and instantaneous shut-in pressures observed in the field. Figure 7 illustrates fracture geometries for a representative stage and summarizes key fracture modeling results.

Production matching

Modeling hydraulic fracturing, completion fluid leak off, primary production, and cyclic miscible gas injection Huff n Puff using a unified platform, and utilizing the same set of parameters throughout, provides confidence and reassurance results are much less non-unique than traditional modeling methods. This consistency will likely translate into enhanced model predictability. Attributes adjusted to calibrate the behavior included:

1. Permeability
2. Relative Permeability Curves
3. Maximum immobilized proppant mass per area
4. Time-dependent conductivity degradation
5. Reversible pressure-dependent permeability in the near-fracture area during the injection processes. In this modeling exercise, the same reversible positive PDP used to match fracture leak-off process also allowed matching gas injection huff cycles.
6. Model grid size near the fractures. This allowed for estimating the stimulated near fracture volumes and capturing the physical dispersion process of the injection fluid into the near fracture area with numerical dispersion.

Figure 8 compares the actual well performance with model results. Results show a reasonable match.

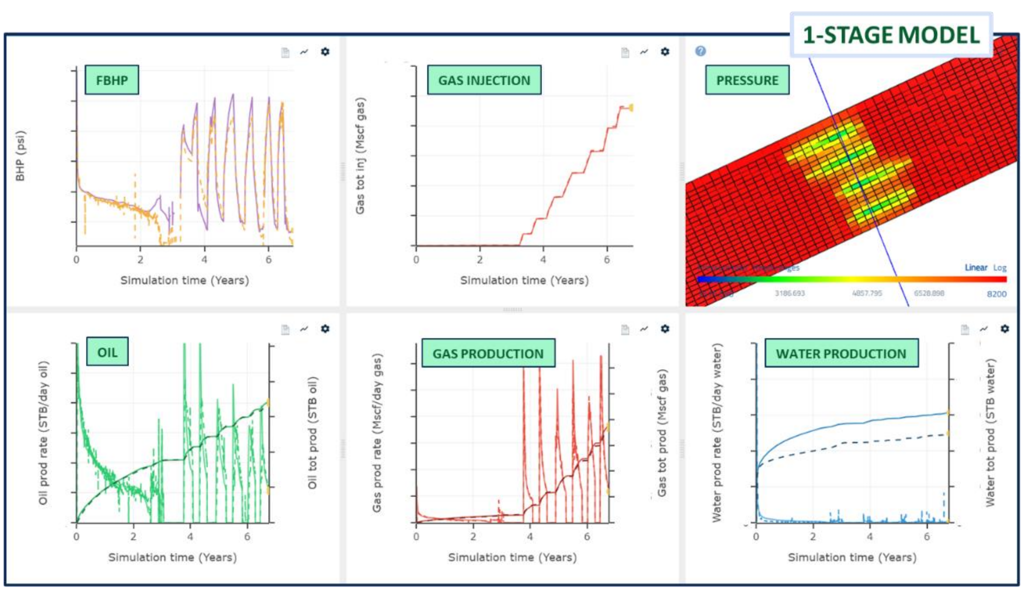


Figure 8. Production history match.

The following insights were obtained through integrated reservoir modeling:

1. The model demonstrated oil swelling as a dominant mechanism in the early cycles. Gas injection increased pressure to near-original reservoir levels in the near-fracture zone. The fraction of light hydrocarbons in the near-fracture oil significantly increased, enhancing oil compressibility and reducing viscosity.
2. Gas saturation in the near-fracture area rose with subsequent cycles, with vaporization becoming increasingly important. Higher gas saturations near the fractures led to a reduction in residual oil due to vaporization.
3. Stress-dependent permeability increases in the near-fracture area were significant during injection. The reduction in net effective stress during gas injection effectively enhanced near-fracture permeability and well injectivity. This same stress-dependent permeability profile was also applied to model the completion leak-off process and gas injection, boosting confidence in the evaluation.
4. Water production was suppressed during the huff and puff process. Our modeling suggests that critical gas saturation builds in the near-fracture areas of zones with significant water saturation, decreasing water phase mobility and reducing water production.
5. Limited gas migration was observed beyond the propped fracture tips due to cyclic stress changes in the fractures, with gas trapped in that area not being efficiently recovered.
6. The model did not suggest any proppant resettlement at the stress levels achieved in our model sensitivities.

Dynamic fracture behavior can significantly impact injection and production of a well, and therefore a fully coupled model is essential for accurately capturing fracture conductivity behavior during gas cycling. A coupled fracture/reservoir modeling approach offers the benefit of properly capturing the following effects:

1. Fracture Conductivity Behavior: Proppants undergo significant changes in net effective stress during gas cycling. A fully coupled approach allows us to properly capture fracture conductivity variations during the injection and production cycle.

2. Fracture Network Behavior: Models must include both unpropped and propped sections of fracture networks. At high injection pressures, unpropped fractures sections near propped tips may reopen, allowing gas to access zones that will close during production, making the process inefficient. Stress calculations along fractures are crucial for estimating reopening potential during gas cycling.

3. Impact of Depletion: Pressure depletion will reduce stress levels in areas stimulated by the EOR process. Depletion may alter, potentially shifting, near-fracture stress-dependent permeability behavior during injection.

4. Potential for Proppant Resettlement: Cyclic stress on proppants during the Huff n Puff process may lead to proppant damage and/or resettlement. A fully coupled approach helps estimate the likelihood and potential impact of damage or resettlement on production and recovery.

This integrated methodology ensures a comprehensive understanding of hydraulic fracture dynamics and enhances model accuracy.

The model described herein was useful for evaluating pilot performance and guiding operational decisions during cycling to optimize recovery. It was used to estimate responses at various target pressures and gas injection volumes, enabling us to:

- Determine required gas injection volumes for different target pressures in subsequent cycles.
- Anticipate gas recovery after each huff cycle and final blowdown.

- Calculate gas utilization factors for each cycle.
- Estimate incremental recovery for each cycle.

Economics for each scenario were run to help decide the following:

- Optimal operational conditions to maximize value for each cycle.
- Timing for cessation of cyclic gas injection operations, and
- Assessing ultimate recovery.

The model proved to be an effective tool for forecasting behavior under various operating conditions, assisting in the optimization of our huff and puff cycles. Model sensitivities were conducted with varying target injection pressures. The results allowed us to estimate required gas injection volumes, expected gas utilization, and estimated uplifts for each cycle. These findings are illustrated in Figure 9.

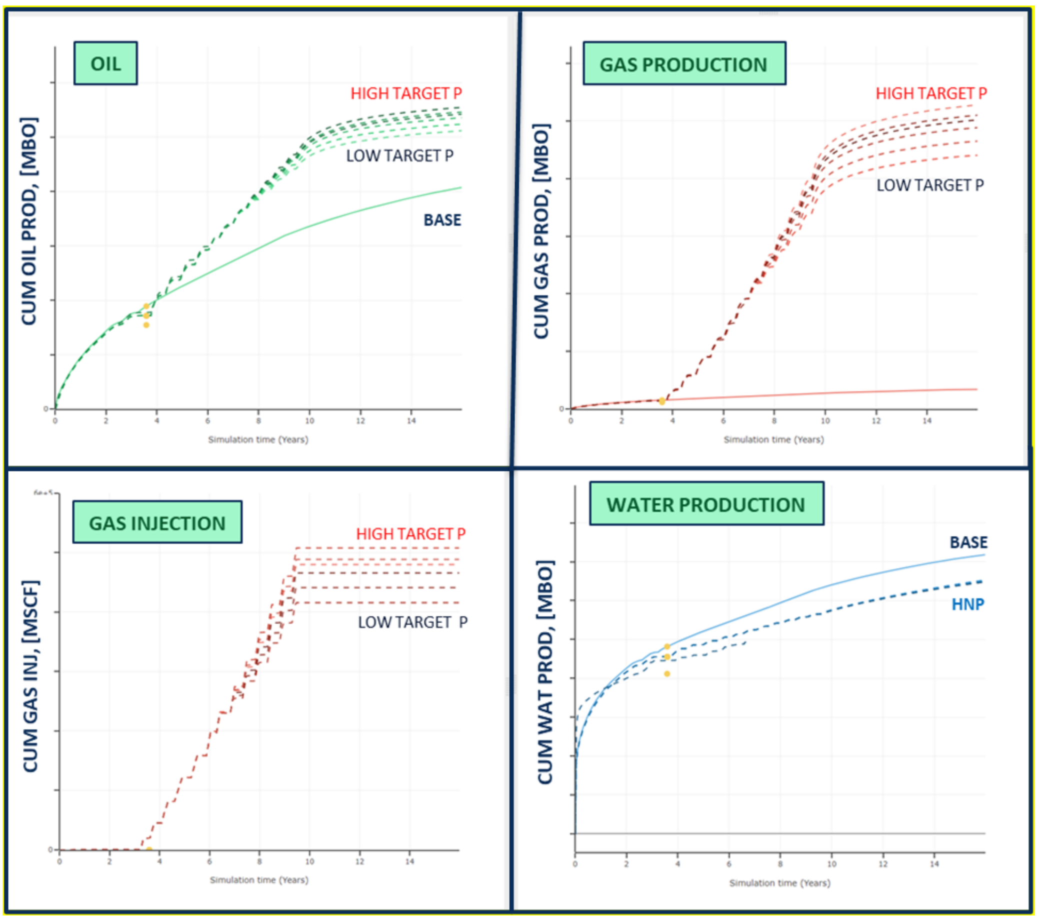


Figure 9. Sensitivities to maximum target injection pressures

Figures 10a, 10b, and 10c present the trends observed in the model sensitivity runs conducted at different target pressures. The model allowed us to estimate the gas required to reach the selected target pressure for each cycle, with gas requirements increasing due to near-fracture region depletion. Results indicated that additional gas injection led to increased recoveries; however, more gas injection is not necessarily better for economic recovery. Gas efficiency decreases with increased gas volumes injected, resulting in diminishing returns. The plots show how gas efficiency evolved with cycling, with utilization factors increasing significantly during the process.

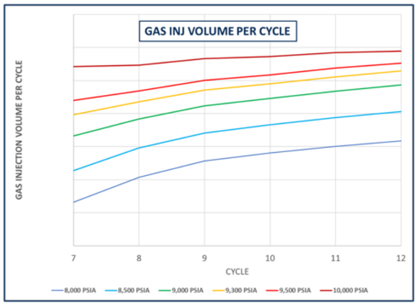


Figure 10a. Estimated Gas injection Volume.

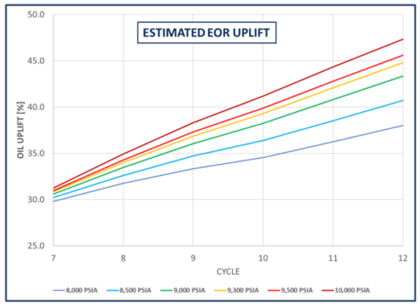


Figure 10b. Estimated Oil Uplift.

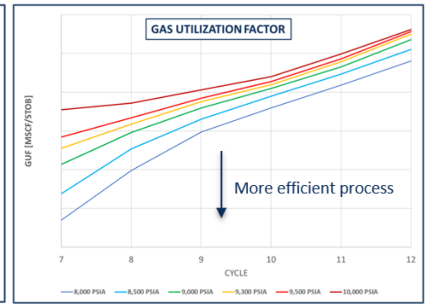


Figure 10c. Estimated Gas Utilization Factor

At Continental Resources, models are treated as live documents, routinely updated to advance our understanding of the pilots.

Conclusions

In summary, our pilot study has yielded significant insights into the dynamics of gas injection and recovery processes within unconventional reservoirs. The findings not only demonstrate the great potential for enhanced oil recovery through miscible gas huff n puff but also underscore the complexities involved in managing gas injection strategies. Below, we outline the key conclusions derived from our evaluation, highlighting critical aspects that will inform future efforts in optimizing incremental oil recovery.

- Our pilot study showcased great injectivity and outstanding gas containment, achieving pressures that approached initial reservoir conditions and near first contact miscibility. The implementation of the miscible gas injection huff and puff technique in this prolific well led to a resulting incremental oil recovery among the best for unconventional huff and puff pilots.
- While increased gas injection may enhance uplifts, it's essential to recognize that more gas is not necessarily better. Uplifts do increase with injection pressures, but there exists a point of diminishing economic returns that must be carefully managed.
- Gas cycling efficiency tends to decline with Huff n Puff cycling. Gas utilization factors are expected to continue to increase with each cycle. Early cycles exhibit more swelling and less vaporization, which ultimately results in more efficient recoveries at the start of a pilot.
- During each individual cycle, the evolution of fluid properties indicates that vaporization is the dominant mechanism very early in a puff cycle, while swelling becomes more pronounced thereafter. API gravities of the effluent are high at the start of a puff but approach original API gravities toward the end of the cycle, reflecting changing fluid mechanisms and dynamics and indicating successful access to near-fracture fluids and the achievement of miscibility.
- Oil production peaks decrease by approximately 15% with every subsequent cycle, largely due to depletion in the stimulated reservoir volume, indicating the importance of strategic resource management.

- Gas injection requirements increase significantly with subsequent cycles, largely to account for depletion after each cycle. Careful planning is necessary to optimize resource allocation and recovery efficiency.
- The full coupling of geomechanics and reservoir models enabled us to match completion, primary production, and enhanced oil recovery (EOR) using a consistent platform, enhancing our understanding of reservoir dynamics. This consistent approach adds rigor and confidence in the results and forecasts.
- Modeling the hydraulic fracturing leak-off process proved useful for estimating initial gas injectivity, providing a more realistic picture of reservoir behavior.
- Fracture conductivities are a function of net effective stress on the proppant, and fully coupled modeling allowed us to properly capture this behavior, ensuring more accurate predictions.
- Portions of the hydraulic fractures (unpropped) may open and close during gas cycling depending on target pressure. Gas injected in this manner may not be efficiently recovered, highlighting the need to carefully manage maximum injection pressures and the need for fully integrated modeling.
- The potential for proppant resettlement can only be evaluated through an integrated approach, emphasizing the complexity of hydraulic fracturing systems. In this case, the modeling did not show potential for resettling at the evaluated target injection pressures.
- Water production was effectively suppressed during the huff and puff process. Our modeling suggests that critical gas saturation builds in the near fracture areas of wet zones, which suppresses water production.

This comprehensive analysis highlights the intricate interplay between gas injection parameters, reservoir conditions, and production efficiency. Continued optimization of modeling approaches and management strategies will be essential for maximizing recovery outcomes in unconventional reservoirs.

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