Numerical Optimization of CO_2-EOR Process in Partially Depleted Oil Reservoirs

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Abstract

A field-scale compositional reservoir flow model was developed for assessing the performance of active CO_2 flood and optimizing both oil production and CO_2 storage. The Southwest Carbon Partnership on Carbon Sequestration (SWP), a US Department of Energy-funded investigation (Project # DE-FC26-05NT42591), has partnered with Chaparral Energy to perform CO_2 storage efficacy investigations at Farnsworth Unit (FWU), Ochiltree, Texas.

A geological framework and history matched models constructed from geophysical, geological and engineering data acquired from FWU were the basis for all reservoir simulations and the optimization method.

An optimization approach consisting of a proxy was constructed with a polynomial response surface method (PRSM). Experimental design was used to link uncertain parameters to the objective function. Control variables considered in this study included: water alternating gas cycle and ratio, production rates and bottom-hole pressure of injectors and producers. Other key parameters considered in the modeling process were CO_2 purchase, gas recycle and addition of infill wells. The PRSM proxy model was "trained" with a series of training simulations.

The proxy model reduced the computational cost significantly. The validation criteria of the reduced order model ensured accuracy in the dynamic modeling results. The prediction outcome suggested robustness and reliability of the genetic algorithm for optimizing both oil recovery and CO_2 storage.

The reservoir modeling approach used in this study illustrates an improved approach to optimizing oil production and CO_2 storage. This study may serve as a benchmark for potential CO_2–EOR projects in the Anadarko basin and/or geologically similar basins throughout the world.

Motivation for this Work

- Ampomah et al 2016 (SPE-179528) presented a scenario-based model to study different injection strategies effects on oil recovery and CO_2 storage
- Their work showed a possibility of recovering more than **30% of OOIP incremental oil beyond waterflood and storing 75% of purchased CO_2**
- **This work** seeks to use and advanced optimization procedure with a multi-objective function to improve prediction of CO_2 storage and/or oil recovery and determine the best-case scenario to optimize both storage and recovery

FWU Reservoir Production History

- First discovery well drilled by Unocal in October 1955
- Initial reservoir pressure at datum of 4900 ft was 2203 psig
- Original bubble point pressure was 2059 psig
- OOIP ~120 MMSTB
- Secondary recovery started 1964
- Tertiary recovery started 2010

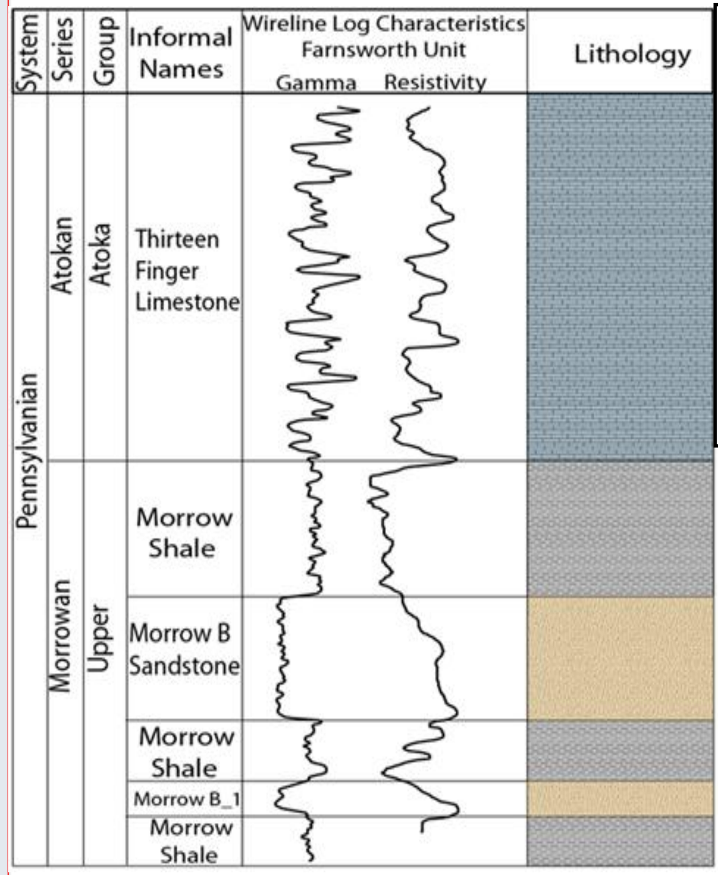
Development Strategy (Baseline & Optimized Case)

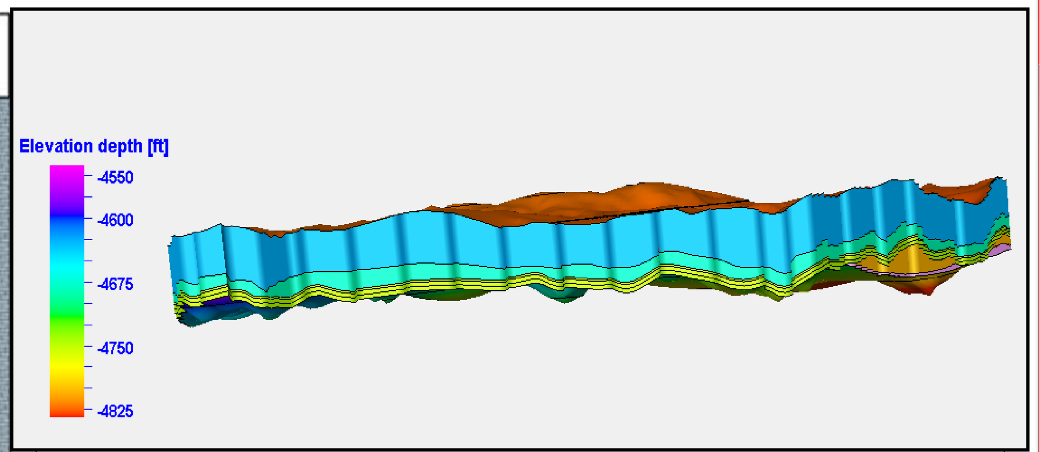
- Convert all injectors to WAG wells (25 wells) using both purchased and recycled CO_2
- Decrease volume of purchased CO_2 from 2022 to 2030
- Inject only recycled gas after 2030.

Conclusions

1. A real time reservoir performance model has been developed by using a fast proxy methodology which can reduce computational costs without compromising on accuracy
2. The use of a complex multi-objective function demonstrated optimum operational variables that yielded results of 95% of CO_2 stored and more than 80% of OOIP oil recovered at FWU.
3. The approach developed can be used to examine different facets of EOR projects and applied to other engineering and science disciplines

Geological Model



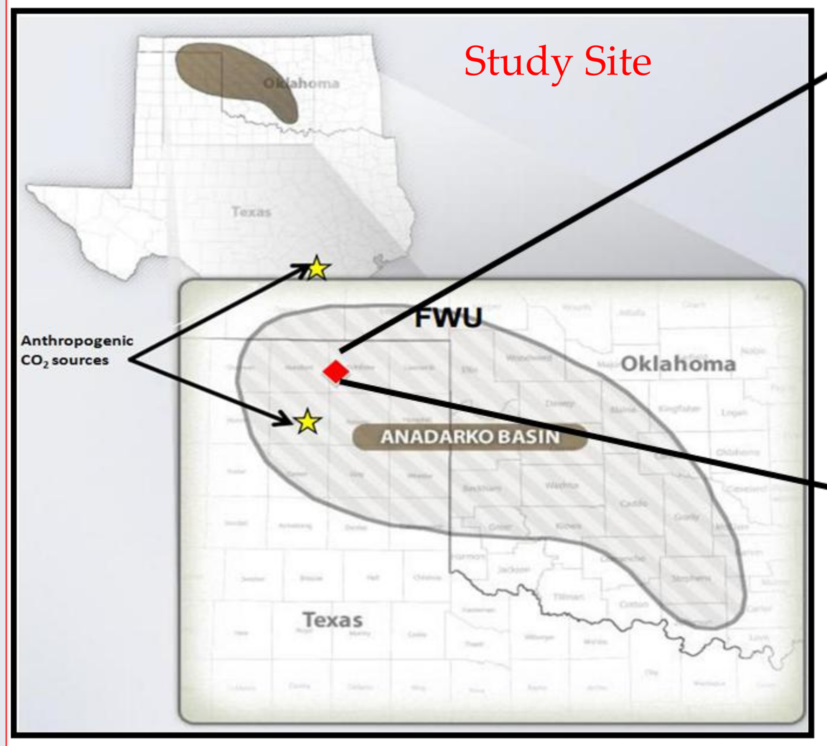


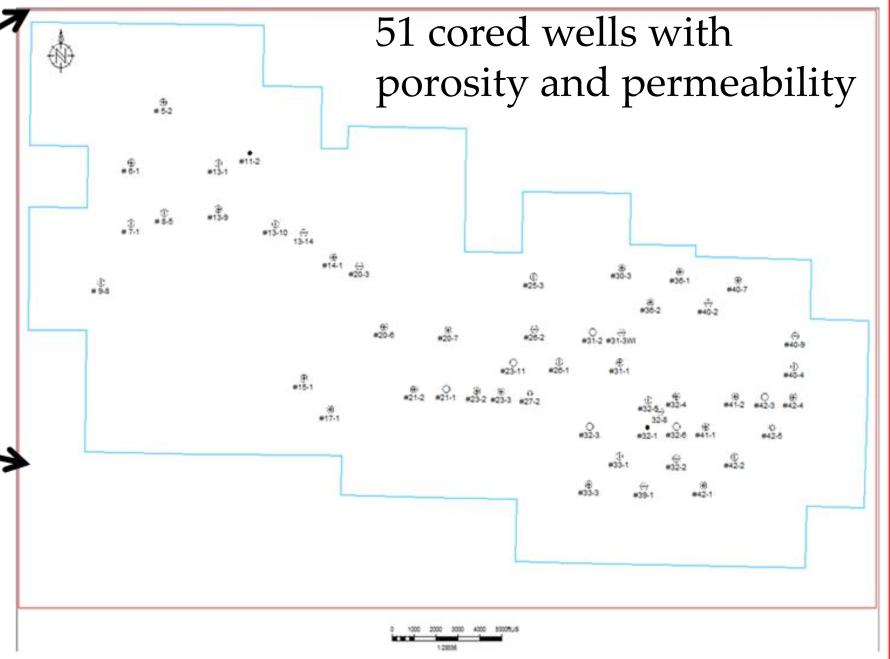
Model Statistics

- Grid Cells 82*78*5
- Grid Dimensions 200ft*200ft
- Total # cells 31,980

The stratigraphic column shows a type log at FWU with formations included in the static model . The structural model is shown at the right.

Property Modeling





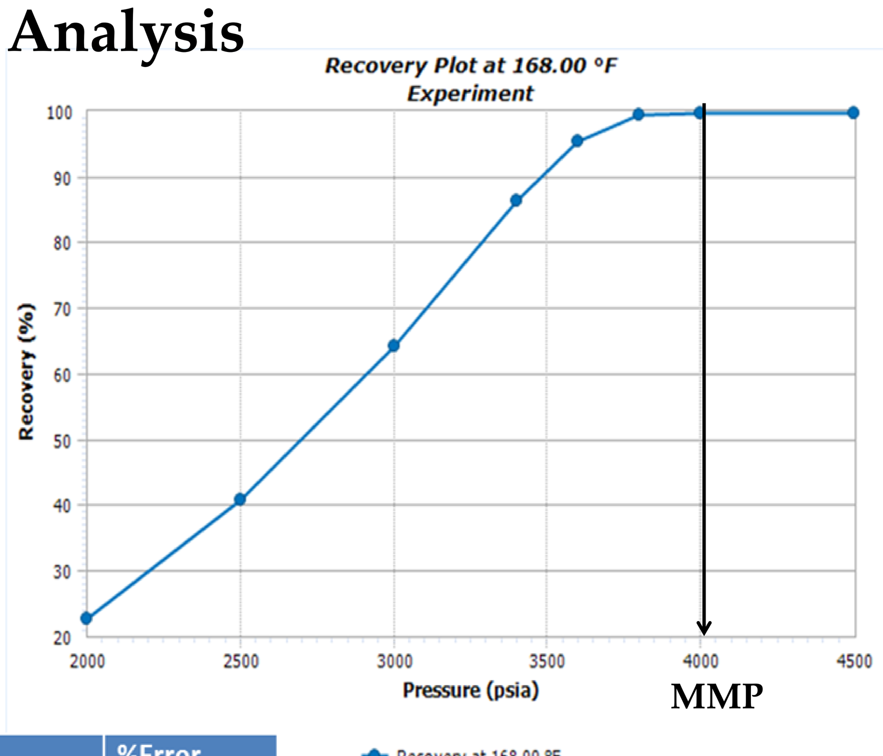
51 cored wells with porosity and permeability

51 cored wells with porosity and permeability were used to construct a static model to study CO_2 performance in the unit. The two main anthropogenic CO_2 sources (stars in figure above left) are a fertilizer plant and an ethanol plant. Reservoir properties are shown in the table at left.

Property	Range	Mean
Porosity, frac	0.092 –0.247	0.146
Permeability, mD	0.01 - 181	58

FWU Reservoir Fluid Analysis

Properties	Units	% Error
Saturation Pressure	psia	2.84
Oil Density	g/cc	1.3
Vapor Z-factor		0.22
GOR	Mscf/stb	1.58
Gas Gravity		2.39
Liquid Viscosity	cp	9.7



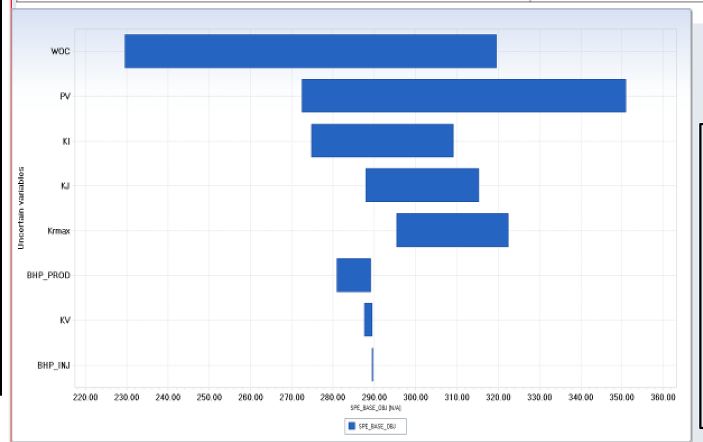
Properties	Units	Observed	Before Regression	After Regression	%Error
MMP	psia	4200	3038.4	4008.8	4.5

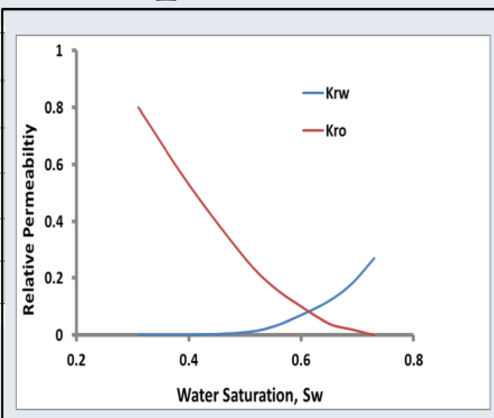
A fluid sample from the FWU was analyzed and calibrated to the equation of state to assist in compositional modeling. A slim tube simulation experiment was used to compute the MMP and compared to lab estimation.

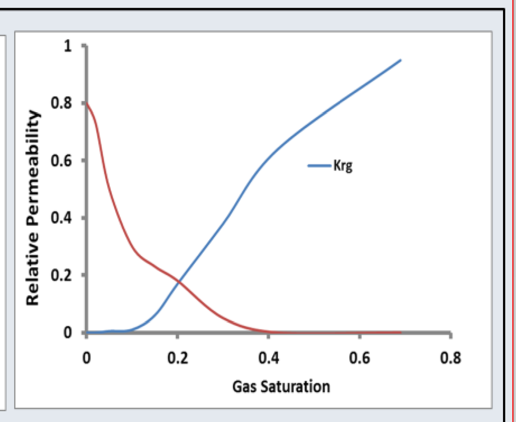
Simulation & Optimization Models

Initialization parameters

P_{init}, psig @ Datum Depth	2203
P_{bubble}, psig @ Datum Depth	2059
Datum Depth(subsea), ft	4900
GOR, Mscf/stb	0.345
Temperature, °F	168
Initial Water saturation	0.31

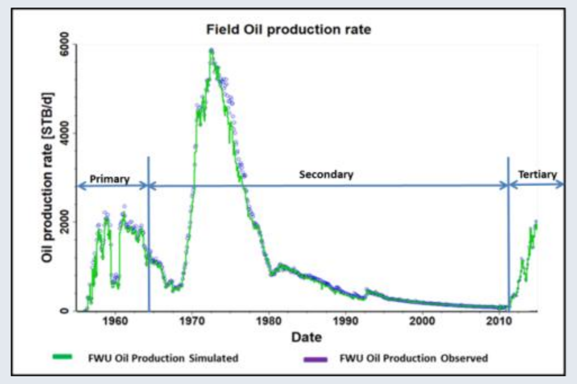




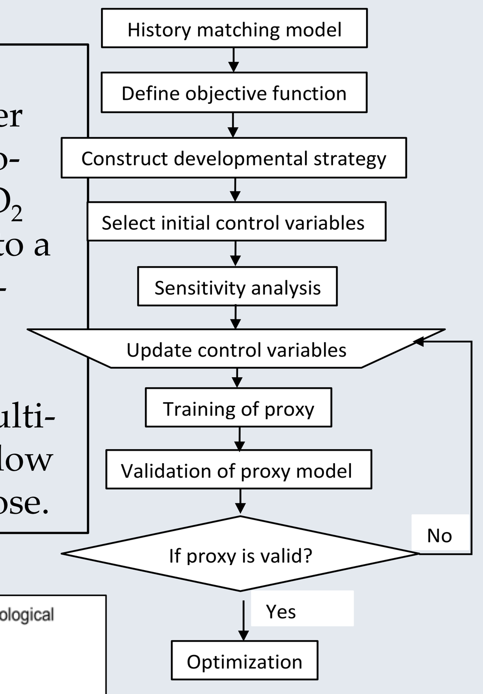


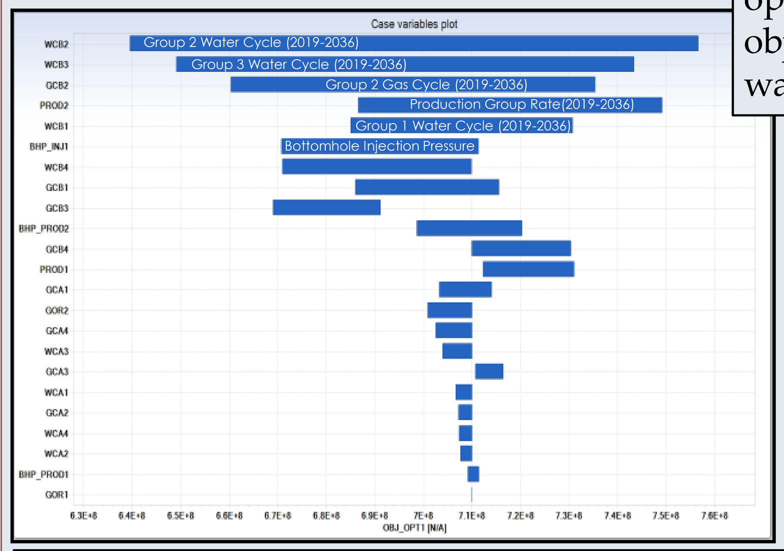
The figure above shows oil-water and gas-oil binary pair relative permeability curves used in modeling. The tornado chart, left, shows the sensitivity of reservoir parameters towards the objective function in the history matching (HM) process. Water-oil contact and pore volume are the most sensitive parameters.

Simulation vs Observed



After HM, an optimization approach using reduced order models was constructed to co-optimize oil recovery and CO_2 storage. This was compared to a baseline case with a scenario-based model. The flow chart (right) summarizes the optimization workflow. A multi-objective function, shown below was developed for this purpose.





To co-optimize CO_2 storage and oil recovery under geological uncertainty

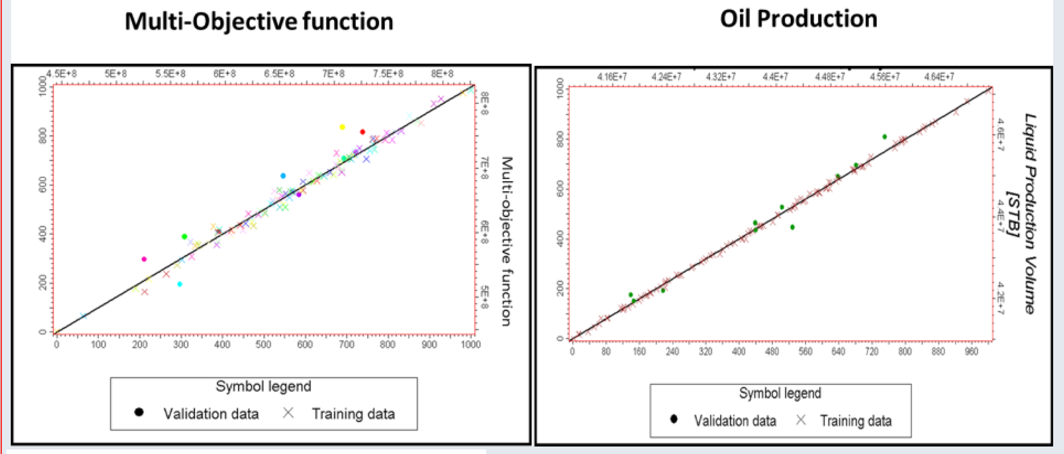
- Multi- Objective function (F):

$$w_1 \times FOPT + w_2 \times FGIT$$

where
w = weight assigned to vector
FOPT = Cumulative oil production
FGIT = Cumulative gas injection which is mostly CO_2

Sensitivity analysis (tornado chart above) was used to reduce the number of control variables to 12. Training simulations were performed to construct a proxy model. Validation plots of the objective function and oil production are shown below. The good match along the equiline signifies a successful proxy.

Proxy Validation



After a successful proxy is achieved, the response surface polynomial equation is used for the optimization process using a genetic algorithm. The table below compares baseline and optimized cases. A sample result (left-hand table) shows a small difference between simulated and response surface results.

Variables	Input Value
$BHP_INJ1	4585.0
$BHP_PROD2	1735.0
$GCB1	9.5
$GCB2	7.0
$GCB3	9.0
$GCB4	5.8
$PROD1	2318.2
$PROD2	2417.7
$WCB1	0.9
$WCB2	0.4
$WCB3	0.3
$WCB4	0.2
Response	866216577
Simulated	878114112
% Error	1.35

Results	Units	Baseline case	Genetic Optimized case
CO2 Purchased	BScf	58	58
CO2 Production Cumulative	BScf	230	238
Recycle	BScf	215	235
CO2 Injection Cumulative	BScf	273	293
Total Storage*	BScf	43	56
% Storage	%	75	95
Cumulative Oil Production	MMstb	43.62	48.80
% Oil Recovery	%	72.70	81.40

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