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ANNUAL EVENT

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Optimization of CO_2/CH_4 Injection for GHG Sequestration and Enhanced Oil Recovery

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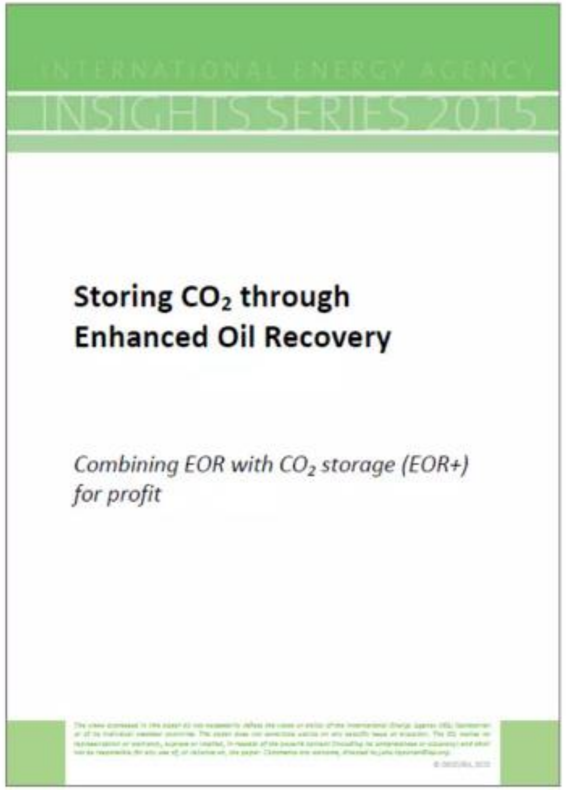
Introduction

- **Adding Storage to CO_2-EOR: EOR+**
  - **Co-exploit CO_2 storage and enhanced oil recovery**
  - **Utilize captured CO_2 to offset capture cost**
  - **Three Models**

Scenario	Incremental Recovery (%)	Utilization (tCO_2/bbl)
Conventional EOR+	6.5	0.3
Advanced EOR+	13	0.6
Maximum Storage EOR+	13	0.9


INTERNATIONAL ENERGY AGENCY
INSIGHTS SERIES 2015
Storing CO_2 through Enhanced Oil Recovery
Combining EOR with CO_2 storage (EOR+) for profit

IEA Insights Paper (2015)

Introduction

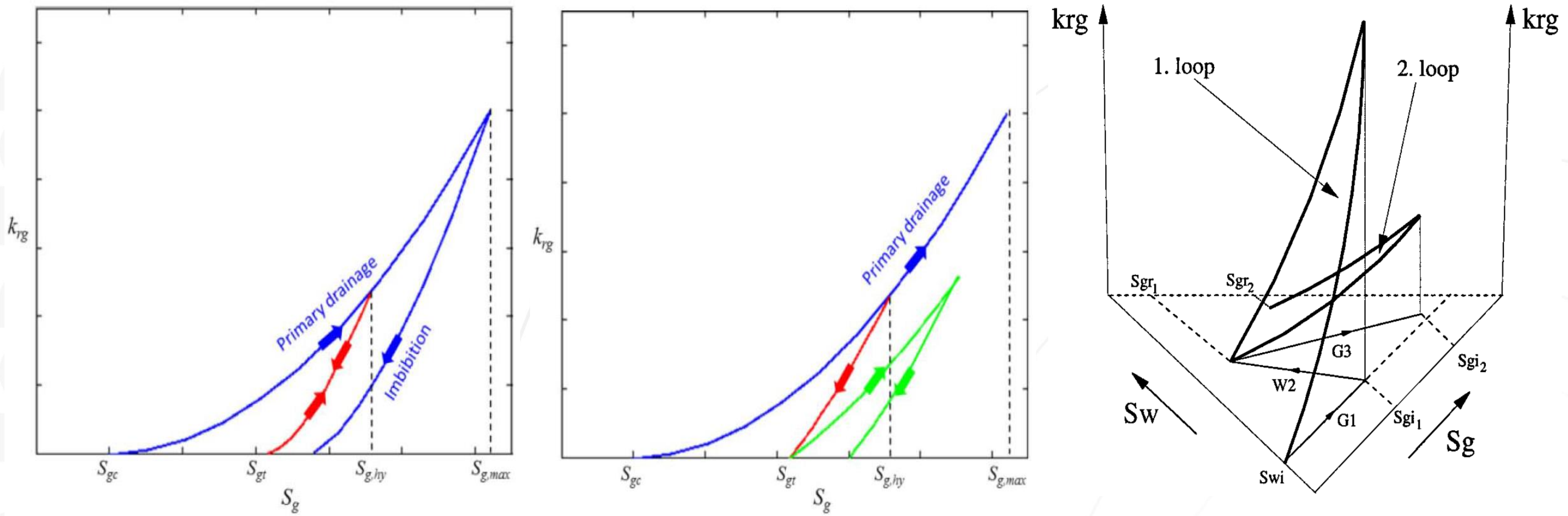
- **CH_4 in Oil Field**
  - CH_4 is by-product of oil extraction
  - CH_4 was flared to atmosphere for decades but recently crackdown on methane from oil and gas industry is initiated
  - Global Warming Potential (GWP) is 28 times that of CO_2
  - Sequestration of CO_2 and CH_4 benefits environment and economics
  - Affects the performance of CCS-EOR
    - ✓ Displacement and sweep efficiency
    - ✓ CO_2 trapping mechanism

Introduction

- **Objectives**
  - **Investigate the effects of CO_2/CH_4 co-injection**
    - ✓ **Oil Recovery**
    - ✓ **CO_2 Trapping Mechanism**
  - **Optimization of the injection strategy**
    - ✓ **Max. Recovery & Storage**
    - ✓ **Max. Recovery**
    - ✓ **Max. Storage**

Methodology

- ➢ **Three-Phase Hysteresis Model for Residual Trapping**



(a) Two-phase hysteresis model **(b) Three-phase hysteresis model** **(c) Hysteresis loops for gas**

(Larsen et al., 1998)

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Methodology

➢ Three-Phase Hysteresis Model for Residual Trapping

- Gas permeability during drainage process

$$k_{rg}^{drain}(S_g, S_w^I, S_g^{start}) = [k_{rg}^{input}(S_g) - k_{rg}^{input}(S_g^{start})]\left(\frac{S_{wi}}{S_w^I}\right)^{\alpha} + k_{rg}^{imb}(S_g^{start})$$

- Gas permeability during imbibition process

$$k_{rg}^{imb}(S_g) = k_{rg}^{drain}(S_{gf} + S_g^{end})$$

(Larsen et al., 1998)

Methodology

- **Solubility Model for Solubility Trapping**
  - **Fugacity**

$$f_{i,w} = y_{i,w} H_i \text{ with } i = 1, \dots, n_c$$

  - **Henry's constant**

$$\ln H_i = \ln H_i^s + \frac{1}{RT} \int_{p_{\mathrm{H_2O}}^s}^{p} \bar{v}_i dp$$

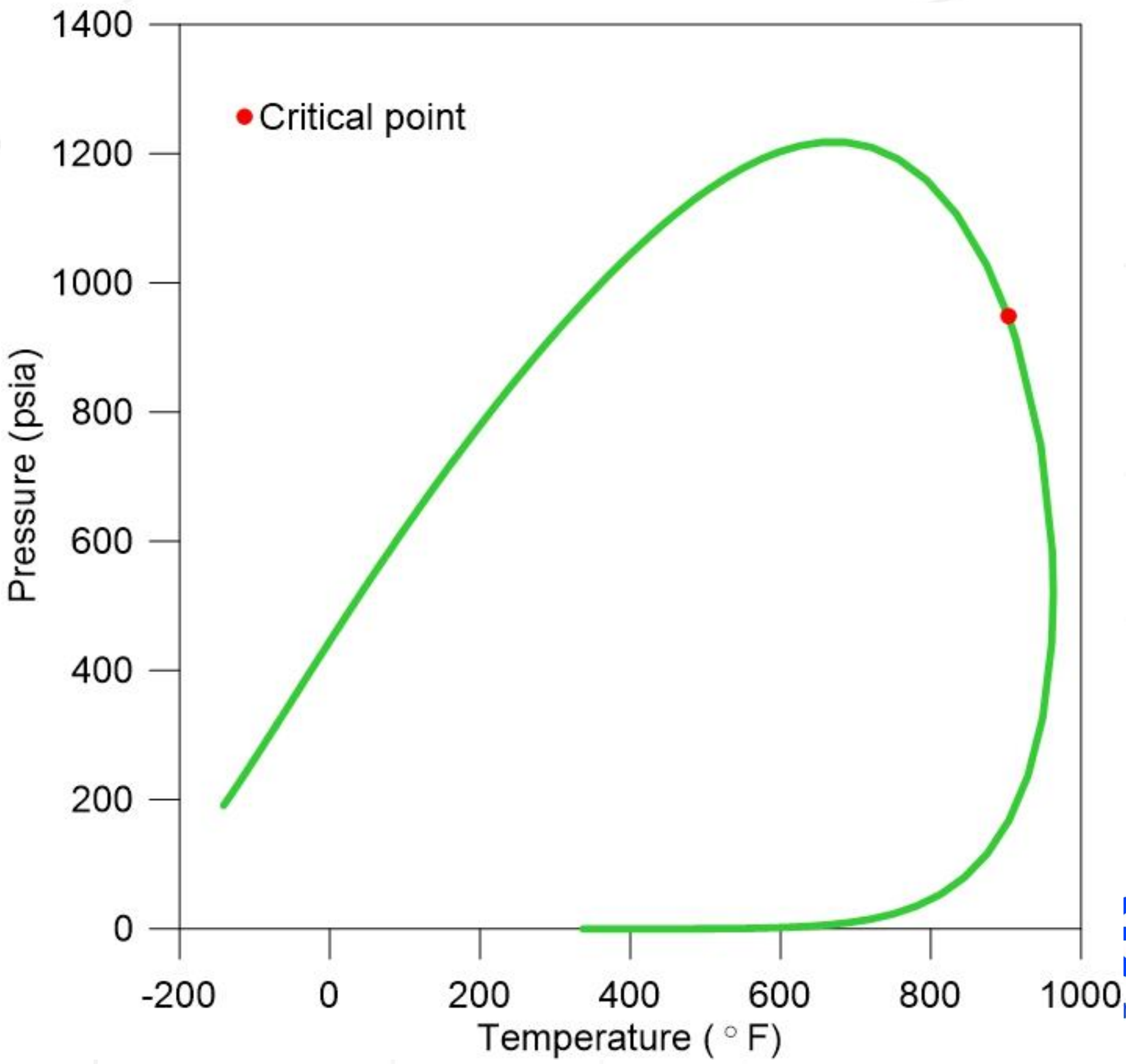
$$\ln H_i^s = \ln p_{\mathrm{H_2O}}^s - D\left(T_{r,\mathrm{H_2O}}\right)^{-1} + E\left(1 - T_{r,\mathrm{H_2O}}\right)^{0.355}\left(T_{r,\mathrm{H_2O}}\right)^{-1}$$

$$+F\exp\left(1 - T_{r,\mathrm{H_2O}}\right)\left(T_{r,\mathrm{H_2O}}\right)^{-0.41}$$

Results

➢ Fluid Modeling

Components	Mole Fraction
N_2	0.0207
CO_2	0.0074
H_2S	0.0012
CH_4	0.0749
C_2H_6	0.0422
C_3H_8	0.0785
$i\text{-}C_4H_{10}$	0.0158
C_4H_{10}	0.0497
$i\text{-}C_5H_{12}$	0.0201
C_5H_{12}	0.0258
$C_{6\text{-}9}$	0.2155
$C_{10\text{-}17}$	0.2202
$C_{18\text{-}27}$	0.1027
C_{28+}	0.1252
Total	1



Results

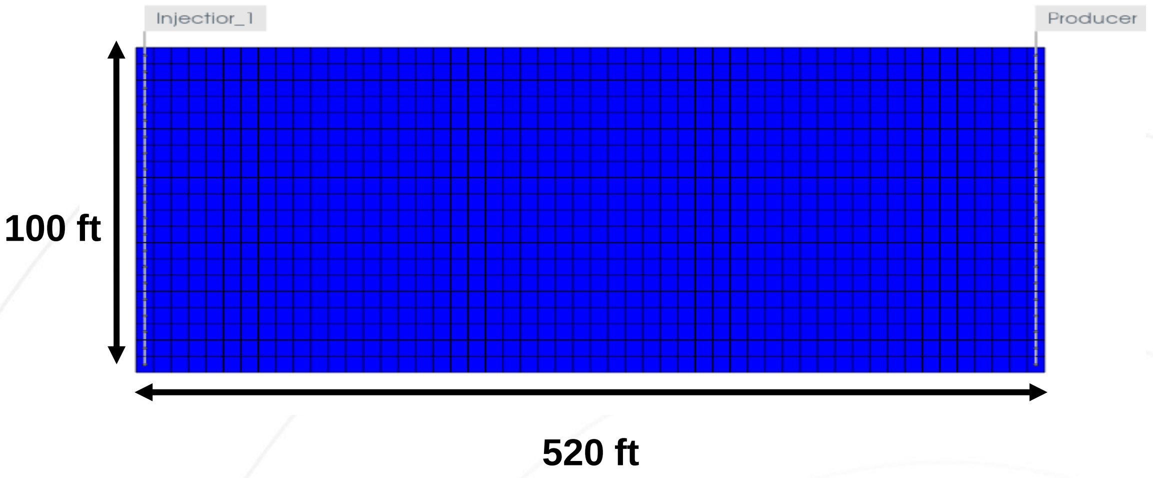
➢ Fluid Modeling

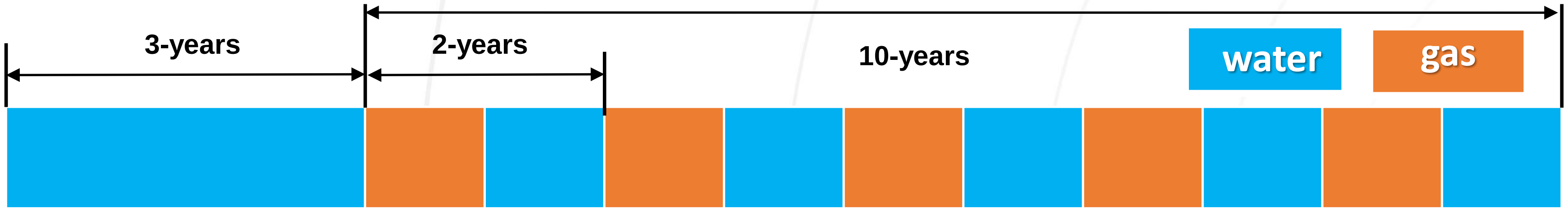
Parameters	Weyburn	Fluid Model	Difference (%)
Saturation Pressure (psi)	713	713	0.08
Oil Density at Saturation Pressure (lb/ft^3)	50.3	50.3	0.09
Viscosity at Saturation Pressure (cp)	1.76	1.76	0.0
Formation Volume Factor (ft^3/scf)	1.12	1.108	1.07
API (◦)	31	34.48	-11.23
MMP with CO_2 (psi)	2,060	2,016	2.09

Results

➢ Reservoir Modeling

Parameters	Values
Depth (ft)	4,000
Initial reservoir pressure (psi)	4,000
Reservoir temperature (°F)	145
Permeability in I, J, K-direction (md)	50, 50, 5
Porosity	0.3
Initial oil saturation	0.6
Initial water saturation	0.3
Pore volume injected (PV)	2.5

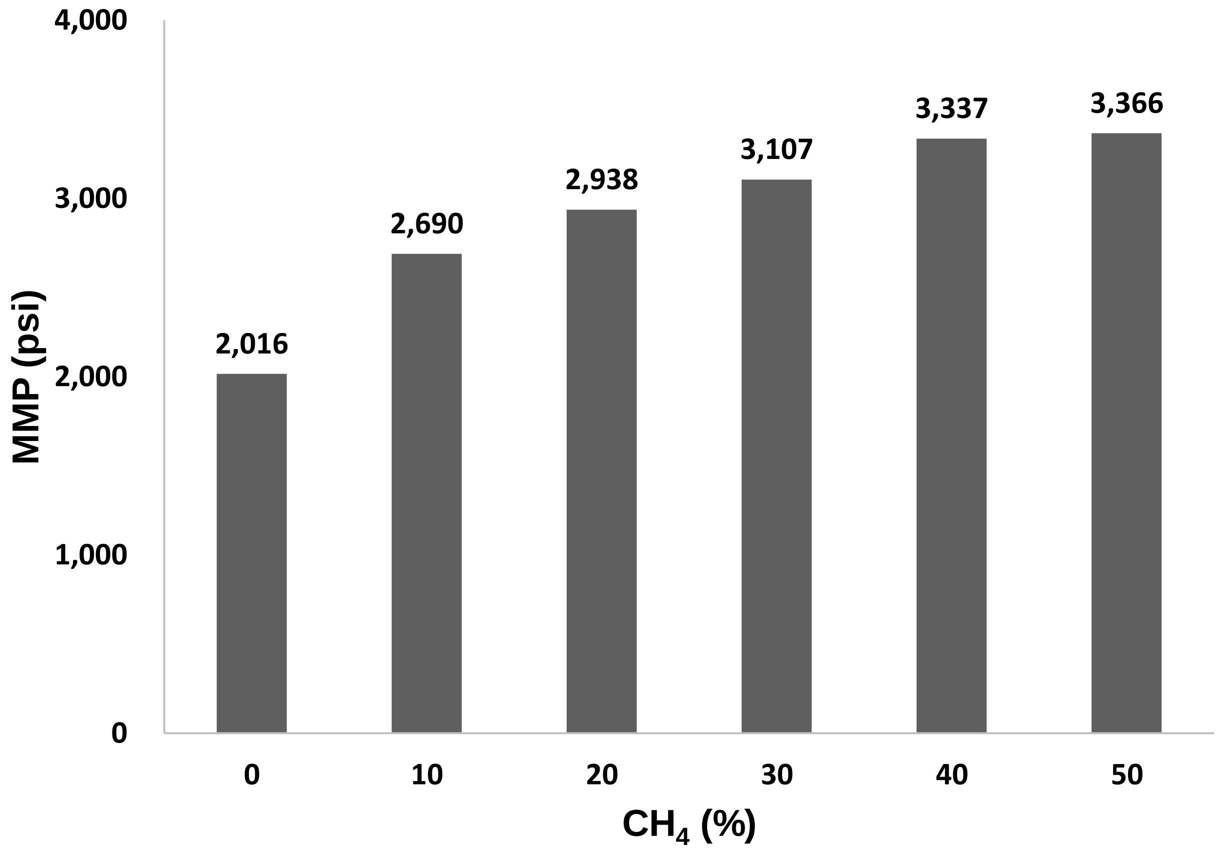




Results

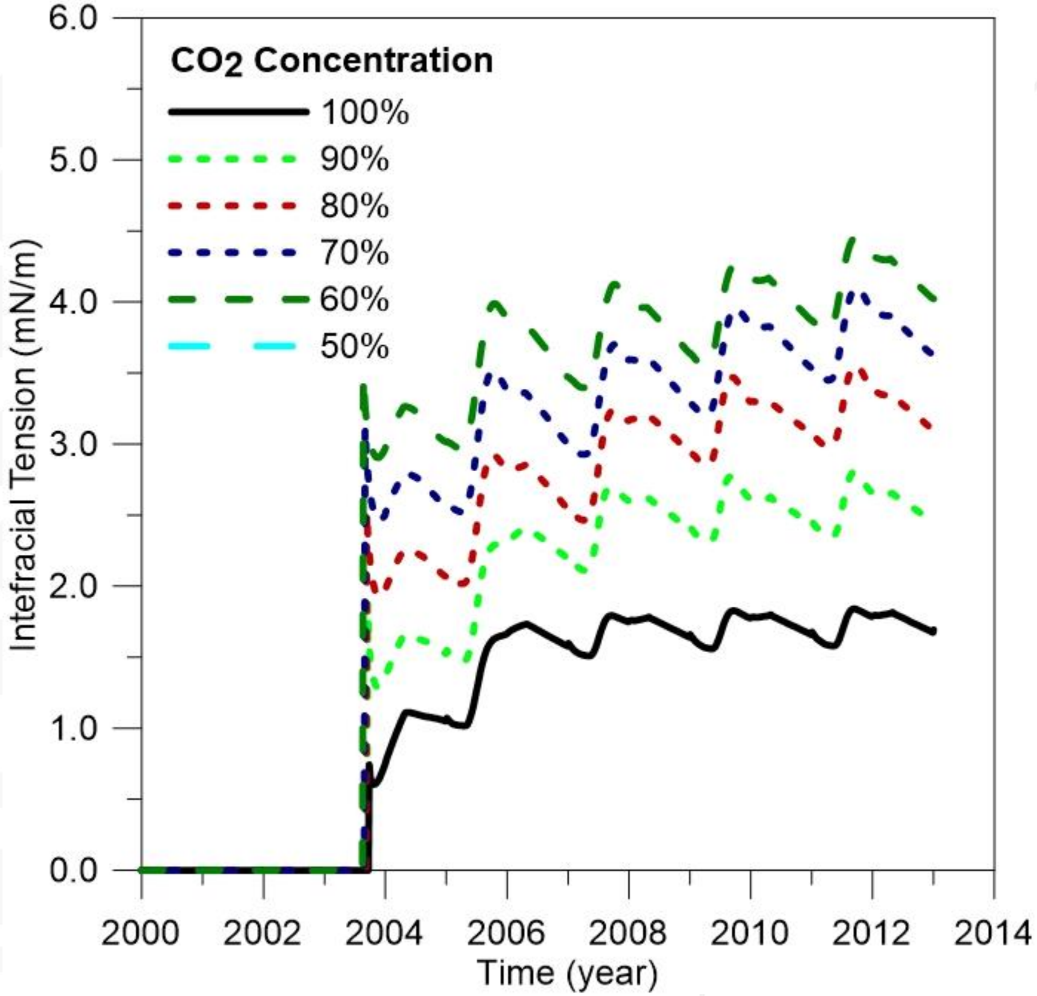
- **Minimum Miscibility Pressure (MMP)**

Components	MMP (psi)
CO_2 100%	2,016
CO_2 90% + CH_4 10%	2,609
CO_2 80% + CH_4 20%	2,938
CO_2 70% + CH_4 30%	3,107
CO_2 60% + CH_4 40%	3,337
CO_2 50% + CH_4 50%	3,366

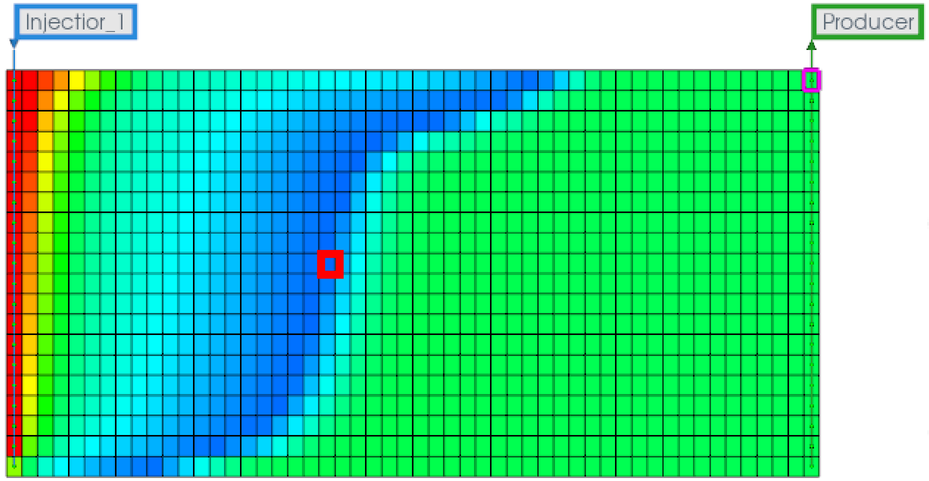


Results

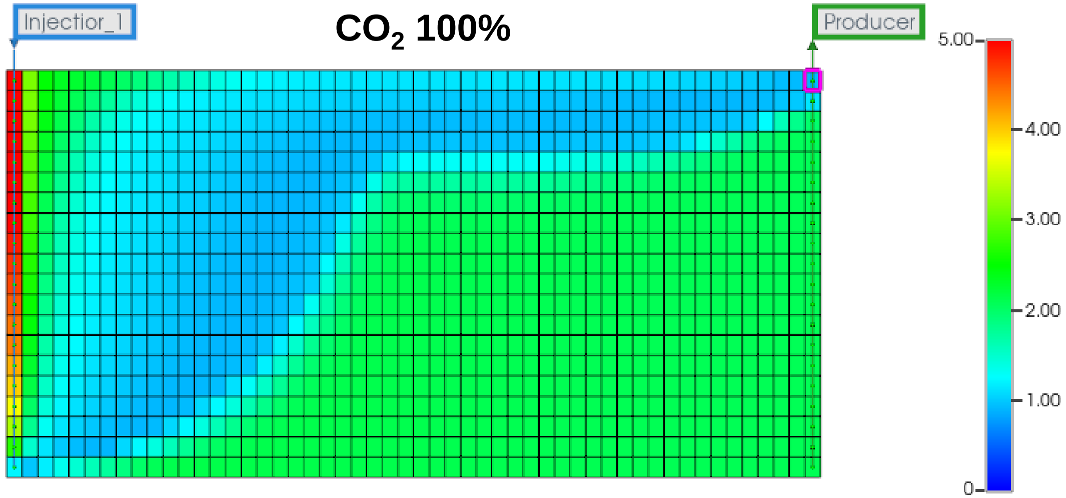
- ➢ **Interfacial Tension (IFT)**



- ➢ **Oil Viscosity**



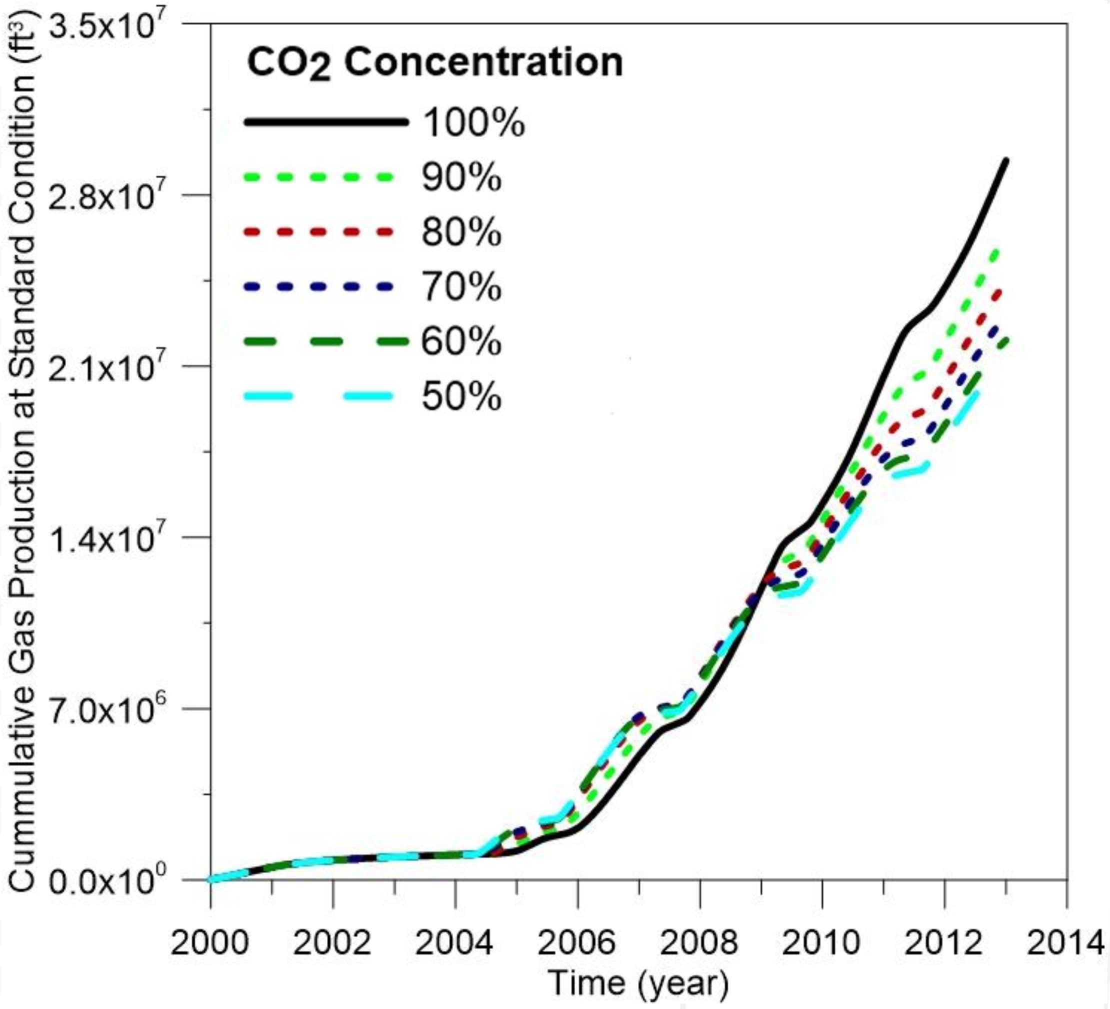
CO_2 100%



CO_2 50%

Results

➢ Cumulative Gas Production



Case	Breakthrough Time
CO_2 100%	2005.01.14 (1,840 day)
CO_2 90% + CH_4 10%	2004.10.11 (1,745 day)
CO_2 80% + CH_4 20%	2004.08.12 (1,685 day)
CO_2 70% + CH_4 30%	2004.07.03 (1,645 day)
CO_2 60% + CH_4 40%	2004.06.01 (1,613 day)
CO_2 50% + CH_4 50%	2004.05.04 (1,585 day)

→ Early Breakthrough

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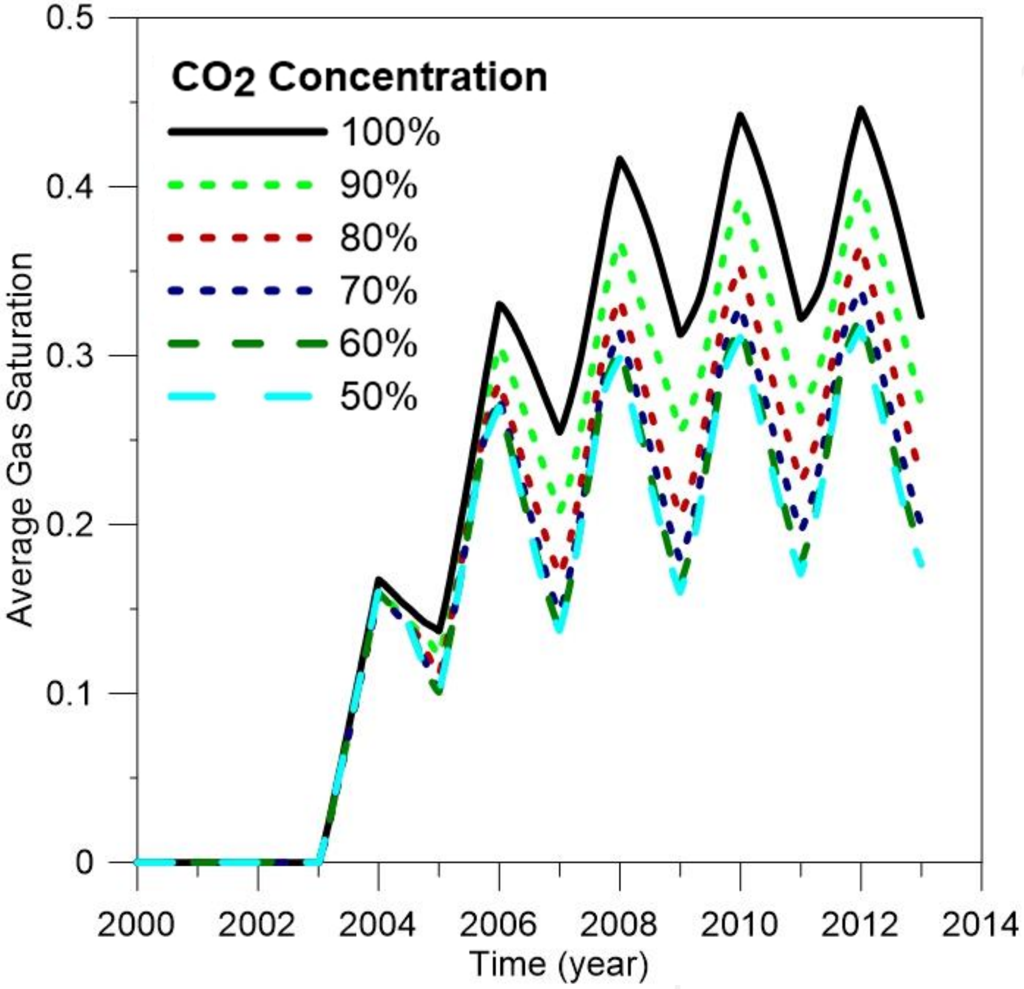
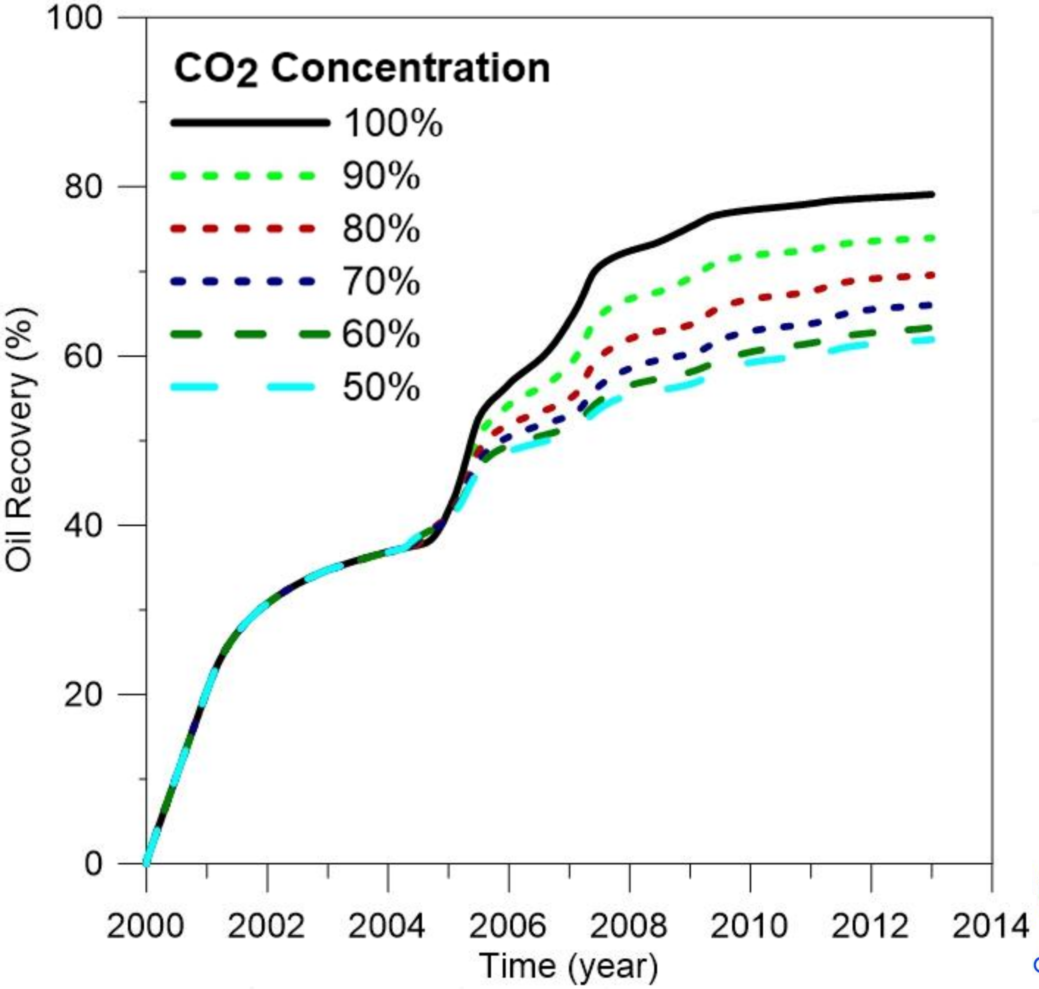
Results

- **Average Gas Saturation**

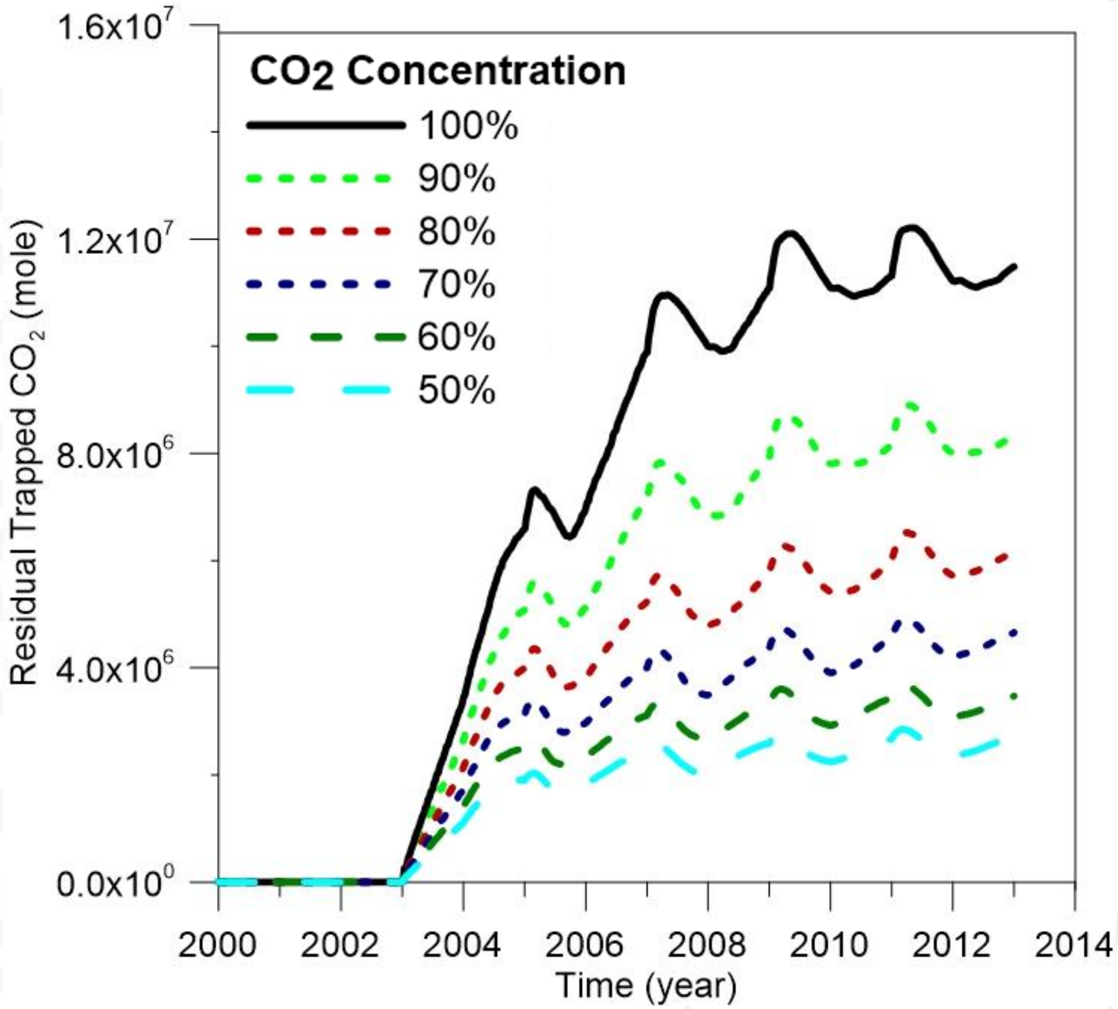


- **Oil Recovery**

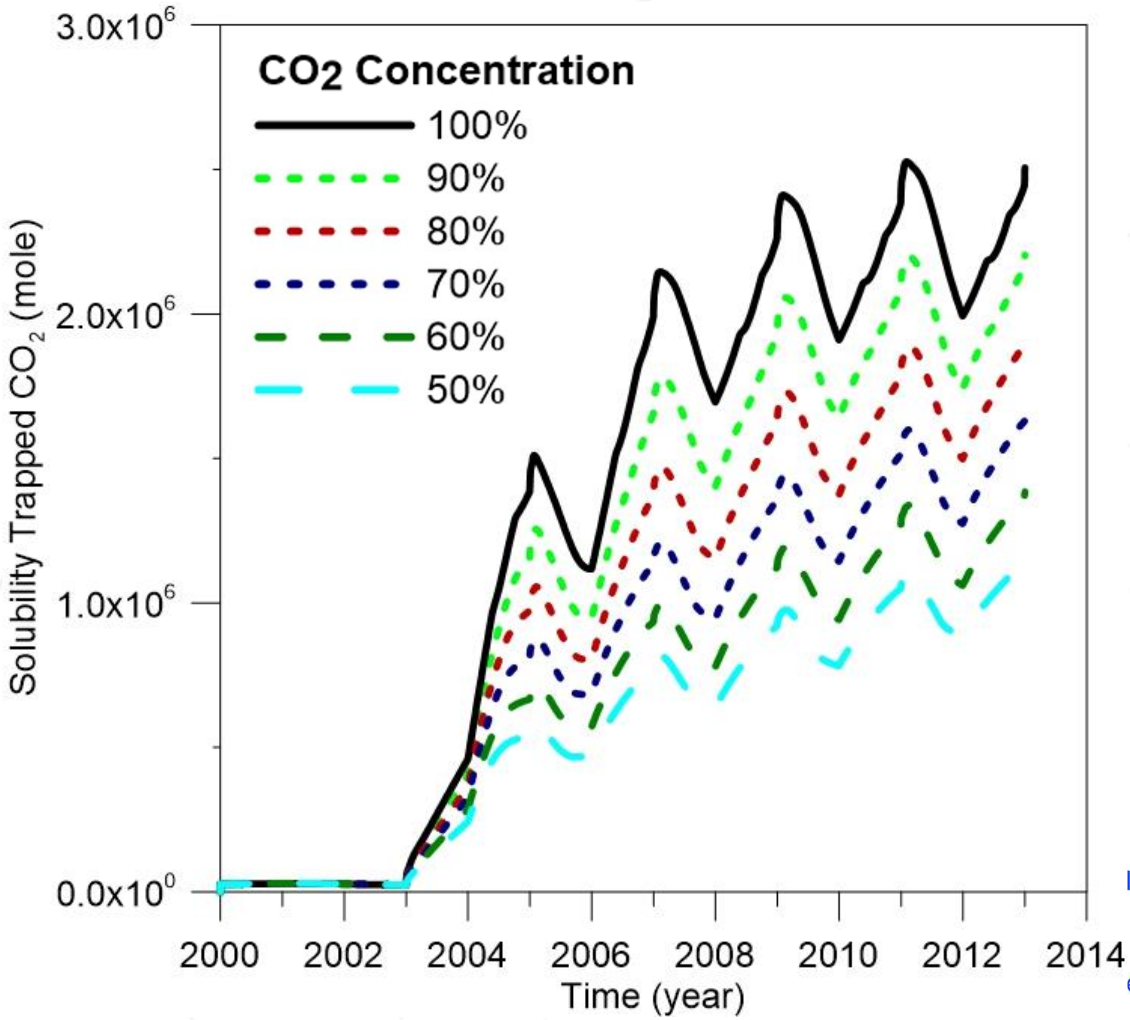


Results

- Residual Trapped CO_2

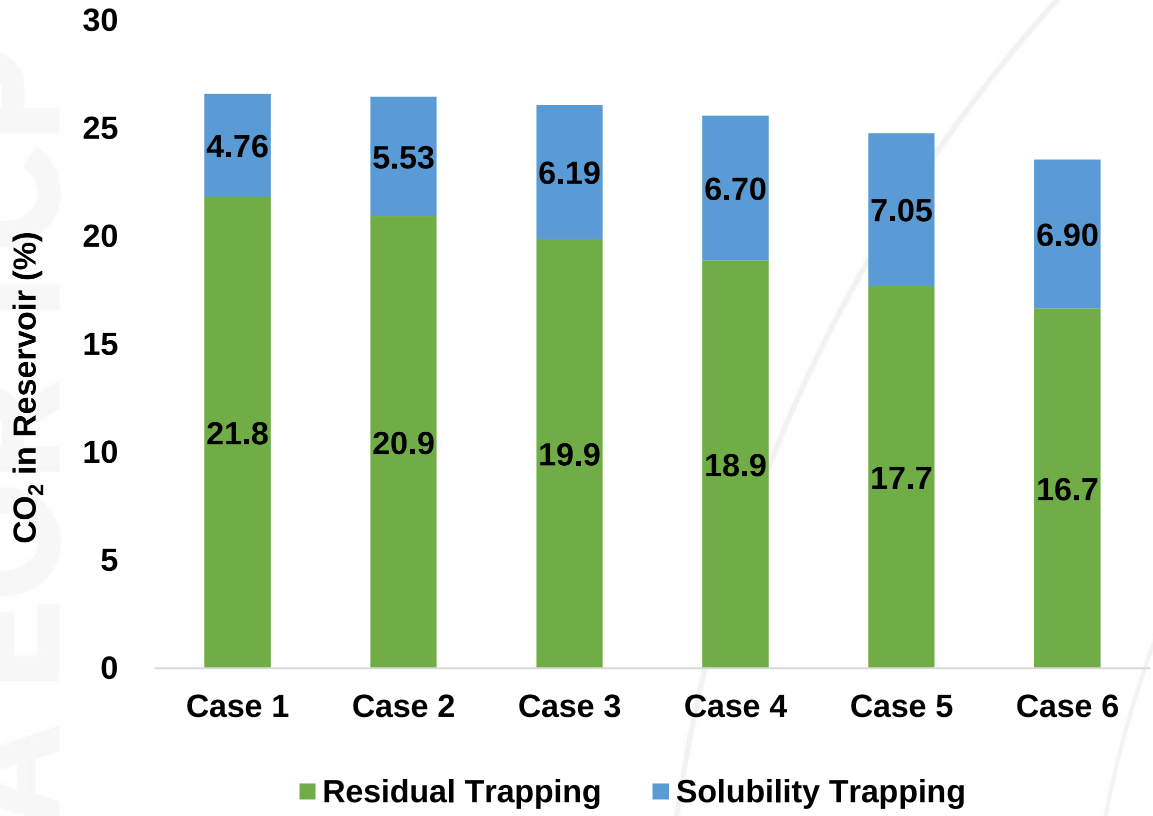


- Solubility Trapped CO_2

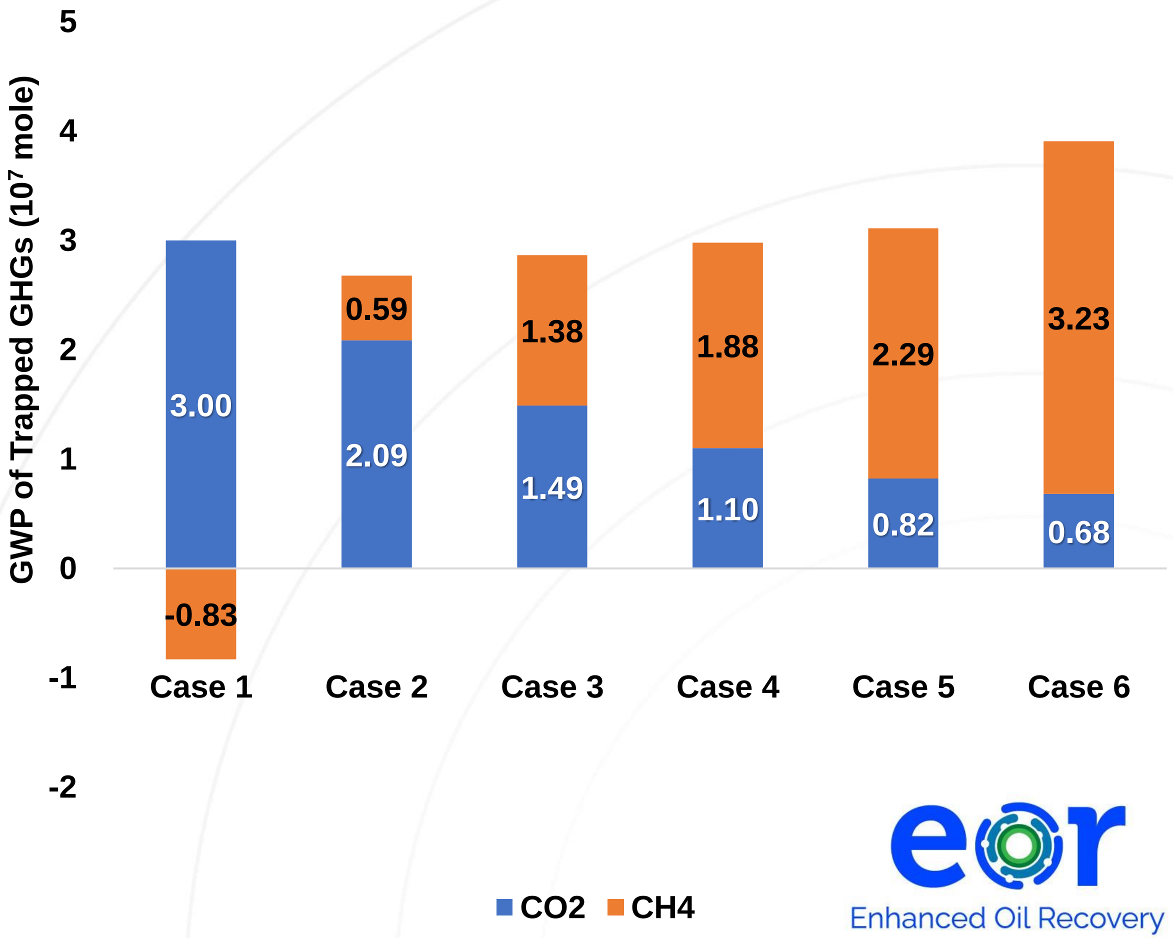


Results

➢ Stored CO_2



➢ GWP of Trapped GHGs



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Results

Scenario	Incremental Recovery (%)	Utilization (tCO_2/bbl)
Conventional EOR+	6.5	0.3
Advanced EOR+	13	0.6
Maximum Storage EOR+	13	0.9

Case	Incremental Recovery (%)	Utilization (tCO_2/bbl)	GWP of Stored GHG (10^7 mole)
CO_2 100%	35.8	0.19	2.17
CO_2 90% + CH_4 10%	30.7	0.31	2.68
CO_2 80% + CH_4 20%	26.3	0.42	2.86
CO_2 70% + CH_4 30%	22.7	0.52	2.98
CO_2 60% + CH_4 40%	20.0	0.63	3.11
CO_2 50% + CH_4 50%	18.7	0.72	3.91

Results

➢ Optimization

- Parametric studies: Injection scenarios

Case	Water Injection Rate at Reservoir Condition (bbl/day)	Cycle Duration (month)	Gas Injection Rate at Reservoir Condition (ft^3/day)
a) CO_2 100% b) CO_2 90% + CH_4 10%	5 – 25	3 6 12 18 24	50 - 120 (0.6 – 1.4 PV)

- Object functions
  - ✓ Maximize recovery
  - ✓ Maximize storage
  - ✓ Maximize both recovery & storage

Results

➢ **Optimization for (a) CO_2 100%**

Object Function	Pre-Water Injection Rate at Reservoir Condition (bbl/day)	Water Injection Rate at Reservoir Condition (bbl/day)	Gas Injection Rate at Reservoir Condition (ft^3/day)	Water Duration (month)	Gas Duration (month)	Oil Recovery (%)	Stored CO_2 (10^7 mole)	Utilization (tCO_2/bbl)
Recovery	5	22	120	3	24	83.3	2.8	0.45
	5	21	120	6	24	83.3	2.3	0.40
	5	17	120	3	24	83.0	2.8	0.45
	5	19	120	12	24	83.0	2.7	0.36
Storage	15	25	120	3	18	83.0	2.9	0.44
	21	25	120	3	18	83.1	2.9	0.44
	18	25	120	3	18	82.9	2.9	0.44
	18	25	120	3	18	82.9	2.9	0.44
Recovery & Storage	21	25	120	3	24	83.1	2.7	0.45
	17	20	118	3	24	82.7	2.8	0.45
	22	25	119	24	24	81.8	2.9	0.31
	25	23	120	3	24	82.8	2.7	0.45

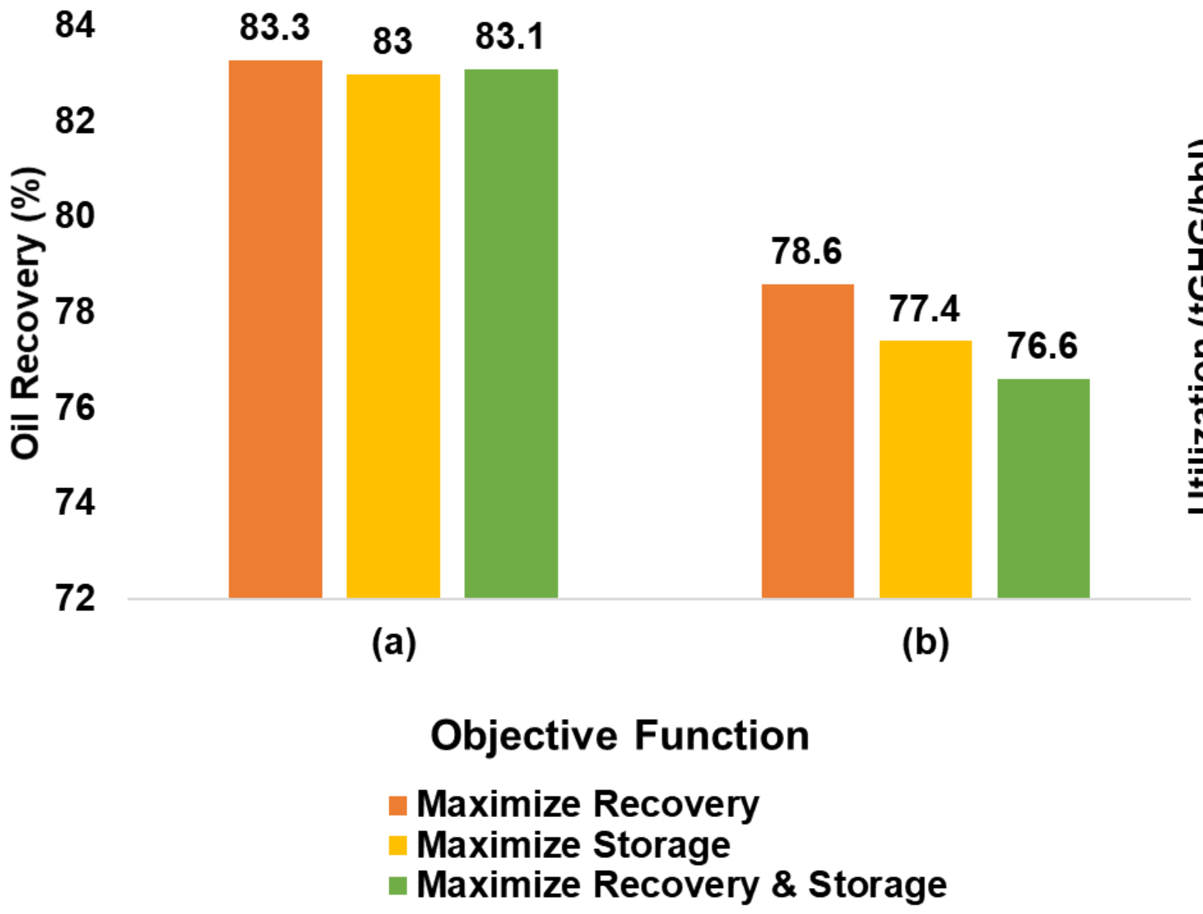
Results

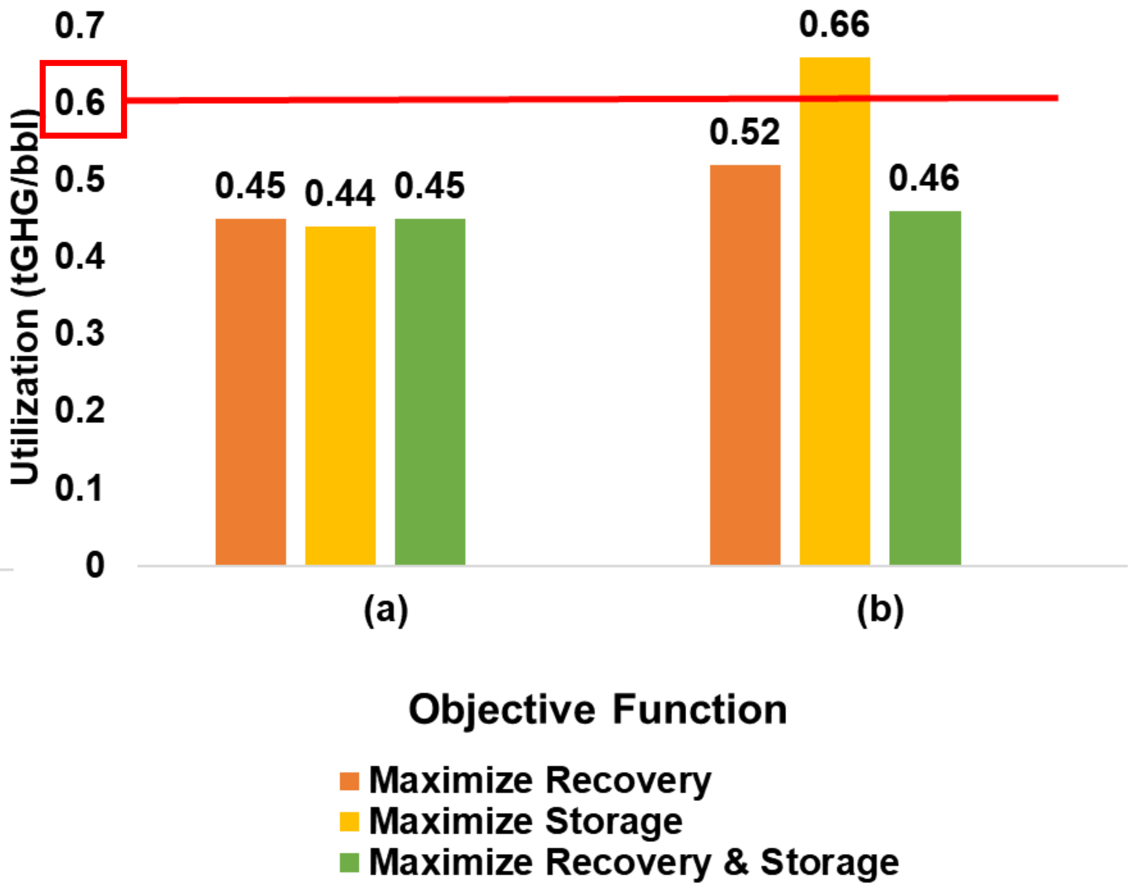
➢ **Optimization for (b) CO_2 90%+CH_4 10%**

Object Function	Pre-Water Injection Rate at Reservoir Condition (bbl/day)	Water Injection Rate at Reservoir Condition (bbl/day)	Gas Injection Rate at Reservoir Condition (ft^3/day)	Water Duration (month)	Gas Duration (month)	Oil Recovery (%)	Stored CO_2 (10^7 mole)	Utilization (tGHG/bbl)
Recovery	5	25	120	3	6	78.6	1.7	0.52
	14	25	120	3	6	78.4	1.7	0.52
	5	25	120	3	12	78.3	1.7	0.61
	5.8	25	120	6	12	78.2	1.9	0.54
Storage	5.5	5	120	3	24	77.4	2.2	0.66
	5.2	5	120	3	24	77.5	2.2	0.66
	5.4	5	120	3	24	77.3	2.2	0.66
	5.8	5	120	3	24	77.2	2.2	0.66
Recovery & Storage	7	13	120	24	24	76.6	2.1	0.46
	5	25	120	24	24	77.6	2.1	0.46
	7	19	120	24	24	77.3	2.1	0.46
	5	25	120	6	24	78.2	1.9	0.54

Results

➢ Optimization





Conclusion

- **Increasing concentration of CH_4 was found to decrease the oil recovery and carbon storage efficiency.**
- **Compared to 100% CO_2, addition of 10% CH_4 resulted in a 5.2% reduction in oil recovery.**
- **As CH_4 fraction increases, the trapped GWPs are increased up to 90%.**
- **Using the Advanced EOR+ approach, the equivalent net utilization of GHG was calculated.**
- **Case (b) met the Advanced EOR+ criteria with a net utilization of 0.6 higher.**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