Optimization of Geological Storage of CO_2 and Enhanced Oil Recovery

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Outline

- Research Objectives and Methodology
- General Background
- Model Validation and Small-scale Simulation Studies
- Experimental Design and Method of Response Surfaces
- Field-Scale Water-Alternating-Gas (WAG) Simulations
- Summary and Conclusions

Research Objectives and Methodology

Objective

➢ **Investigate effect of hysteresis and Water-Alternating-Gas process (WAG) parameters to optimize oil recovery and amount of CO_2 sequestered in compositional simulation of 3D heterogeneous fields**

Methodology

➢ **Sensitivity analysis is preformed to investigate the effect of uncertainties in the considered parameters**

➢ **Apply statistical analysis such as Design of Experiment (DOE) and Method of Response Surfaces (MRS) to achieve efficient studies**

Coupled CO_2 Sequestration and EOR

- **Enhanced Oil Recovery Goals**
  - **Maximize Oil Recovery**
  - **Minimize Amount of CO_2 Injected**
  - **Maximize Profit**
- **Geological CO_2 Sequestration Goals**
  - **Maximize Amount of CO_2 Sequestered**
  - **Store for Thousands of Years without Leakage**
  - **Minimize Costs**
- **Co-optimization Is Needed to Meet Both Goals**

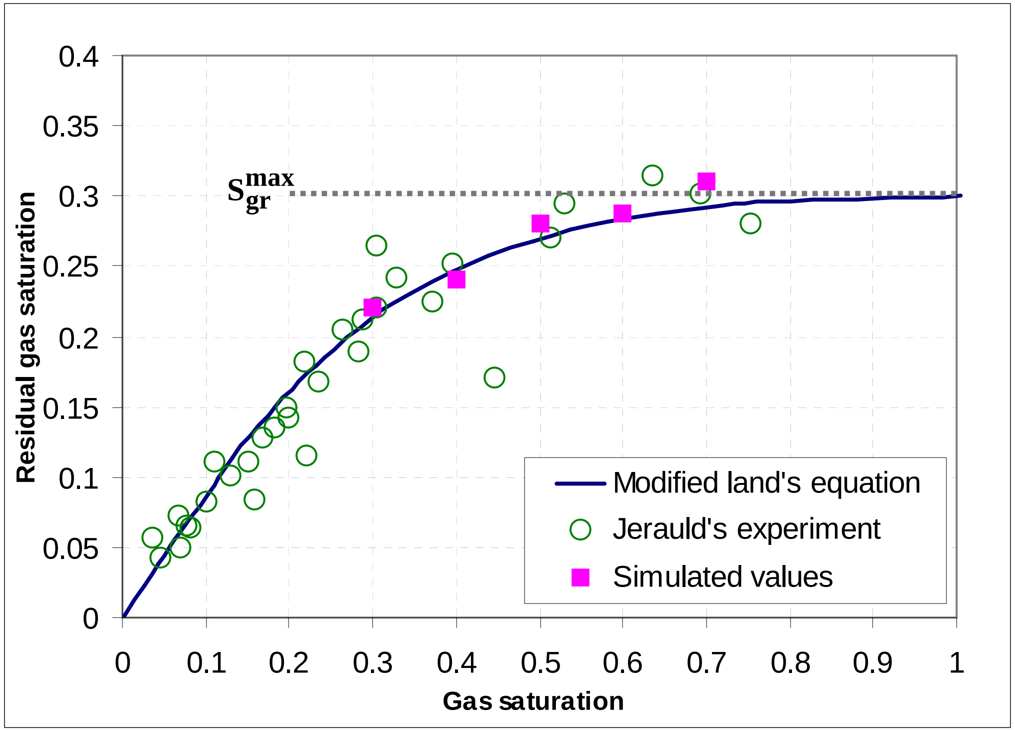
Simulator Description

- Compositional Equation of State Model (PR-EOS)
- Multidimensional, Multicomponent, Multiphase
- Hysteresis in Relative Permeability
- Solubility of CO_2 in Brine
- Geochemistry Models (GEM-GHG)
  - Precipitation reactions & Dissolution
- Explicit, Fully Implicit, and Adaptive Implicit Formulations
- Handling Complex Reservoirs
  - ✓ Corner Point Grid Blocks
  - ✓ Local and Hybrid Grid Refinement

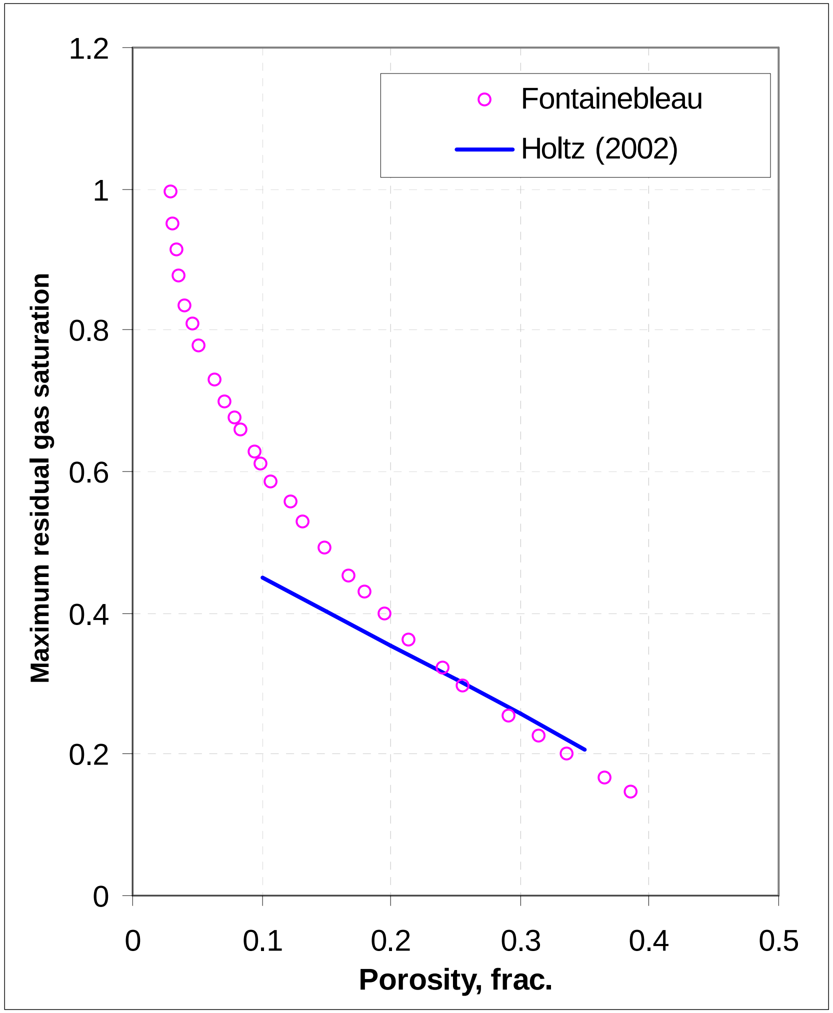
Hysteresis Model

- **Modified Land's Equation:**

$$\frac{1}{S_{gr}^{max}} - \frac{1}{S_{g}^{max}} = \frac{1}{S_{grh}} - \frac{1}{S_{gh}}$$



Correlation between maximum residual gas saturation, S_{gr}^{max}, and porosity

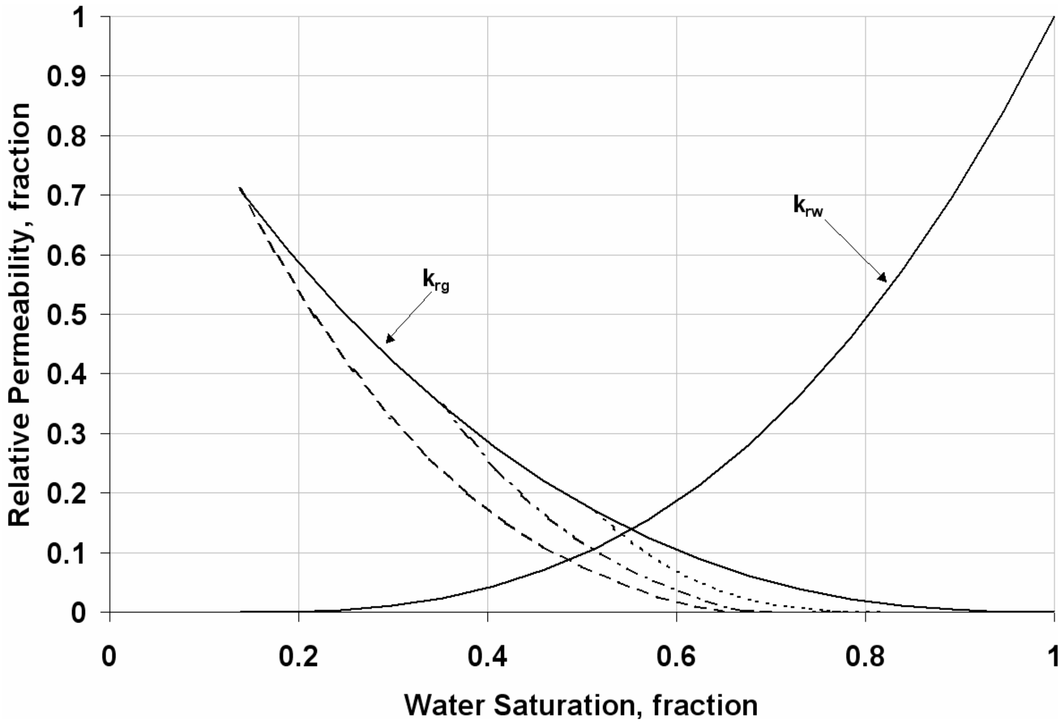


Hysteresis in Gas Relative Permeability

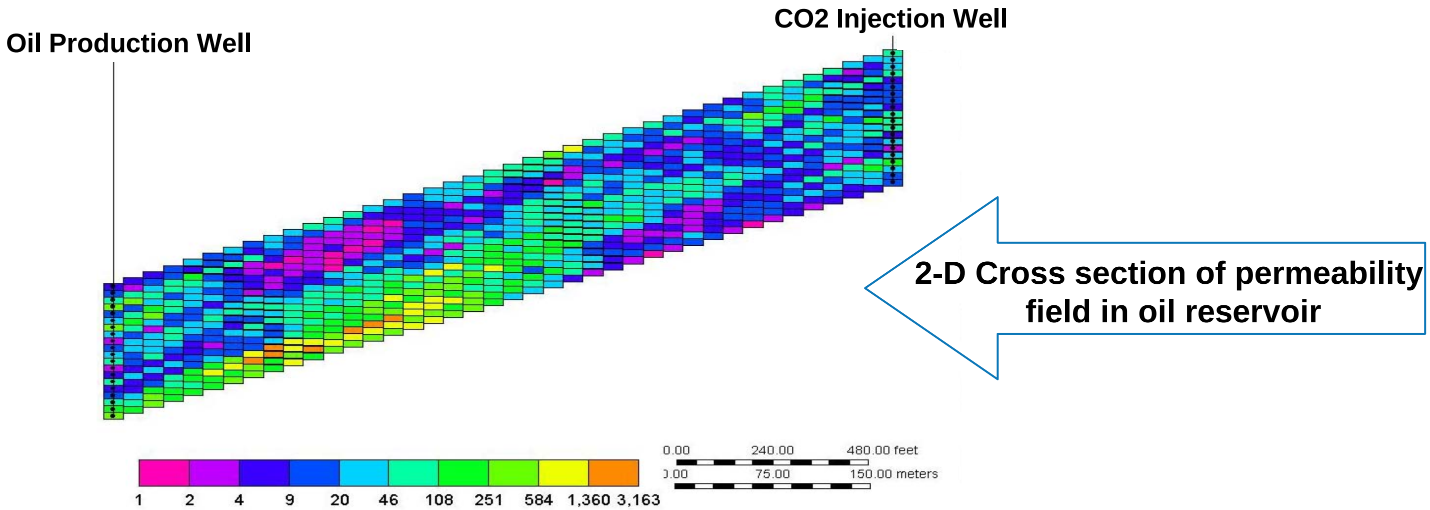
- **Jerauld's (1996) Gas Relative Permeability Model**

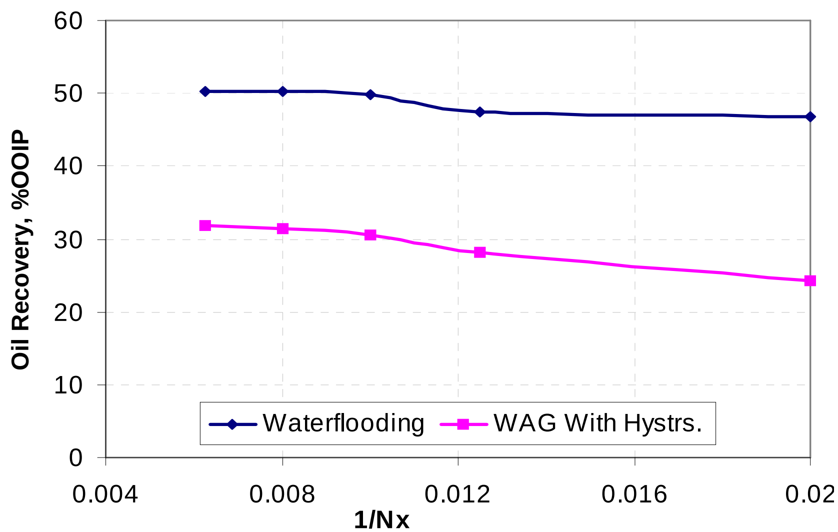
$$k_{rg} = \frac{(1+C_{g2})\left(\frac{S_g(\text{shifted}) - S_{gr}}{1-S_{gr}}\right)^{Cg1}}{1+C_{g2}\left(\frac{S_g(\text{shifted}) - S_{gr}}{1-S_{gr}}\right)^{C_{g1}(1+1/C_{g2})}}$$

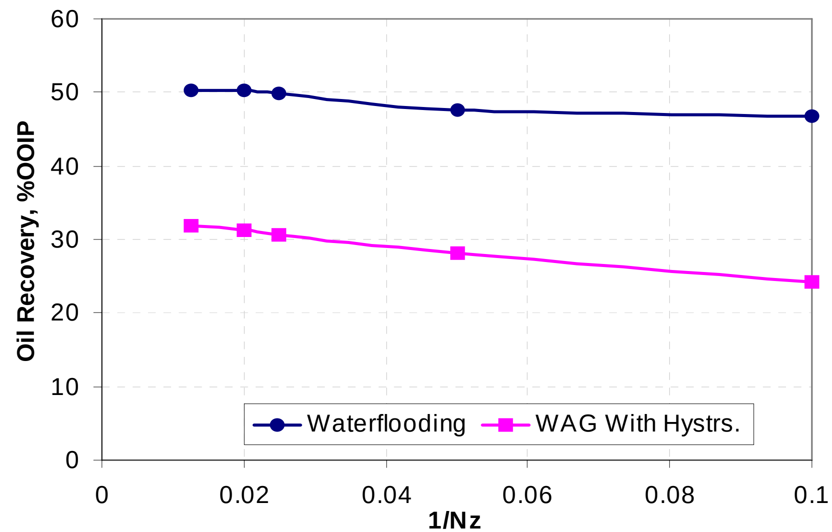
$$S_g(\text{shifted}) = S_{gr} + \frac{(S_g - S_{grh})(S_{gh} - S_{gr})}{(S_{gh} - S_{grh})}$$



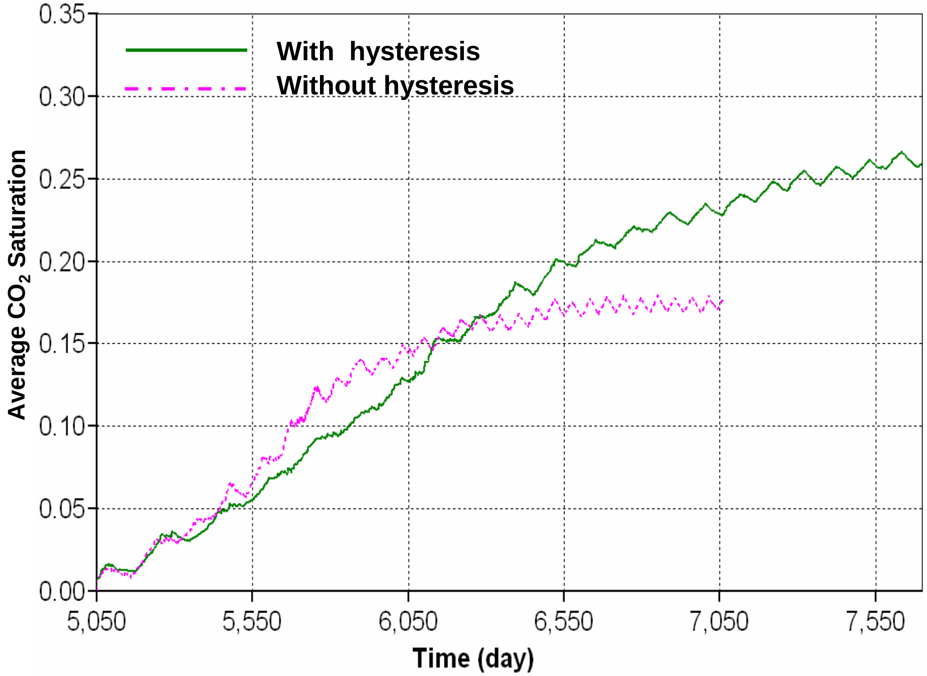
Convergence of 2D Simulations





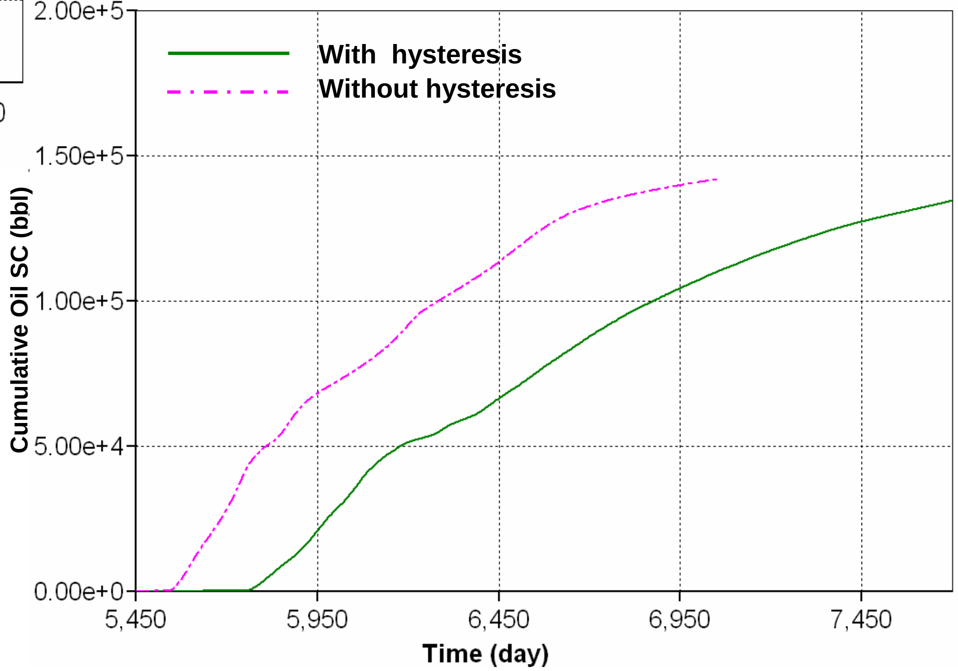


2-D Cross-sectional Simulations of CO2 Injection with a WAG Ratio of 1 with a max GOR=30 MCF



Sensitivity of Ave. CO_2 Saturation to Hysteresis

Sensitivity of Oil Recovery to Hysteresis



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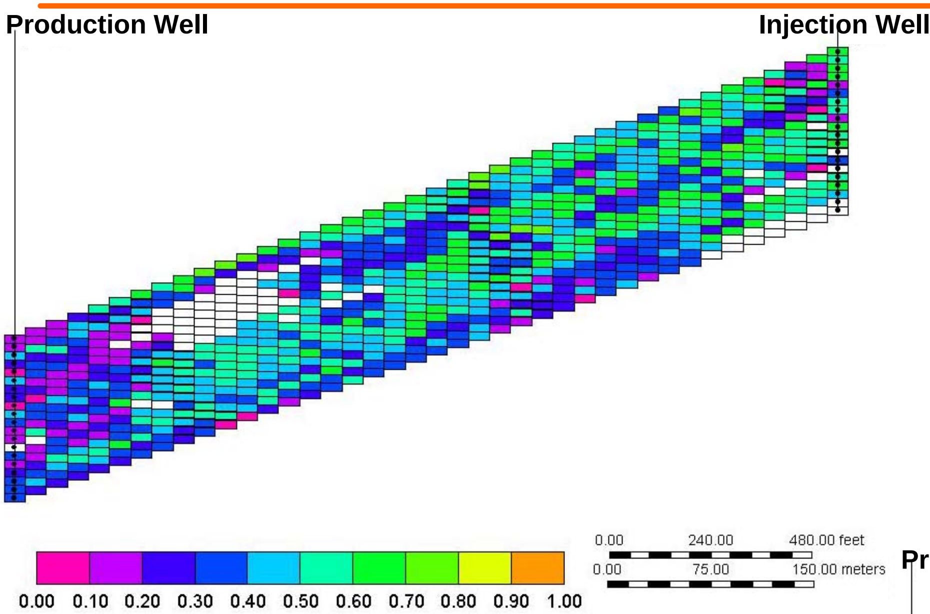
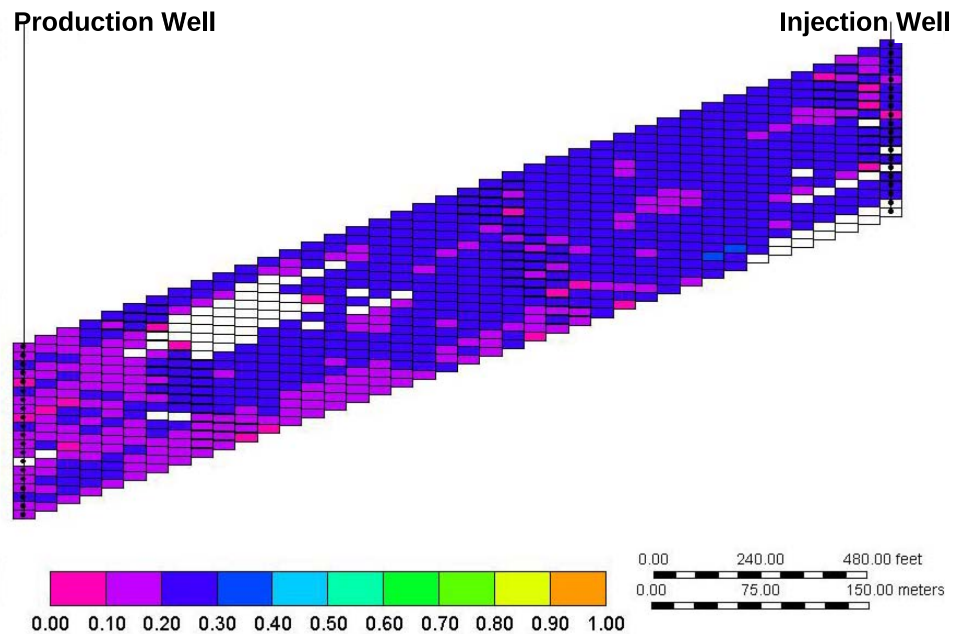
Gas Saturation Distribution



Gas (CO_2) Saturation (Historical maximum)

Trapped Gas (CO2) Saturation



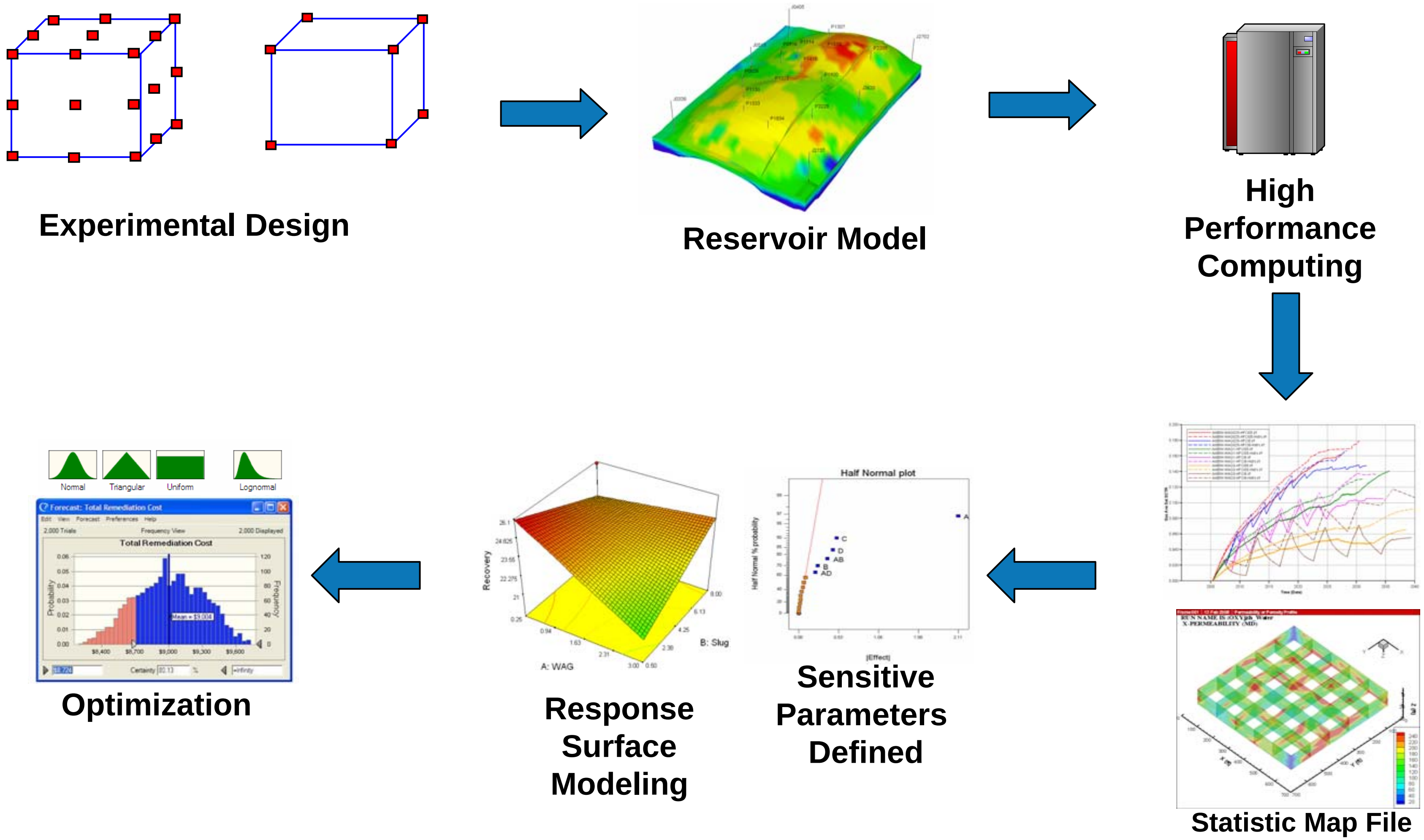
Field-Scale Simulations

- Quantifying the effect of WAG parameters (e.g. WAG ratio and CO_2 slug size) and hysteresis as well as reservoir heterogeneity in the WAG injection processes for coupled CO_2-EOR and sequestration studies

- Experimental design and method of response surfaces to optimize the flood with range of uncertainties for each parameter and interaction among different parameters
    - ✓ Six different parameters with their range of uncertainty
    - ✓ Two level fractional factorial design
    - ✓ Three objective functions (Responses)

- Stochastic permeability fields with the same reservoir fluid, relative permeability, and hysteresis data used in the 2-D cases.

Experimental Design



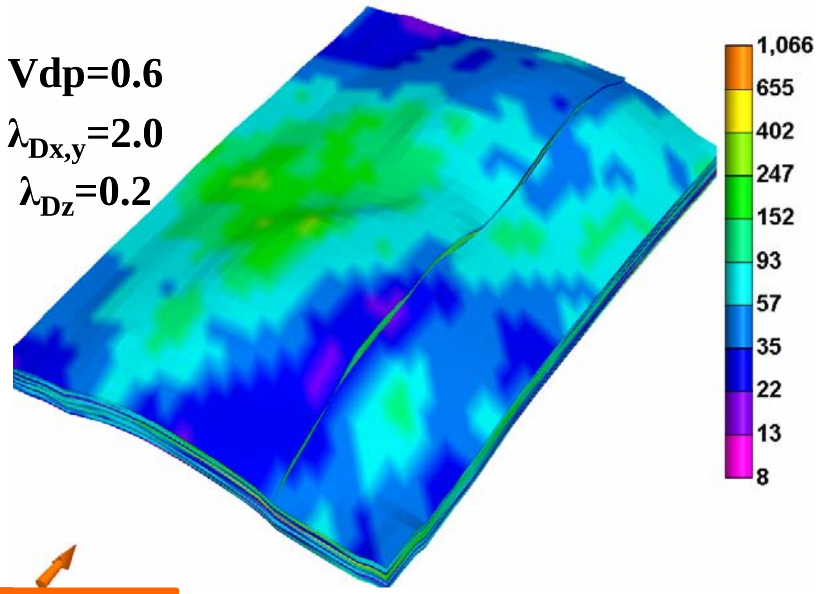
Sensitivity Parameters and Simulation Cases

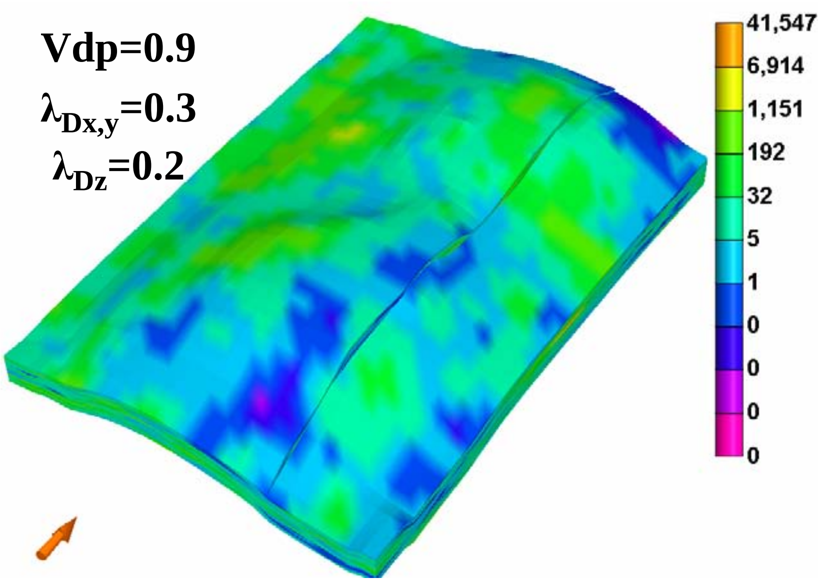
Factor 1 WAG Ratio (0.25-3.0)	Factor 2 Slug Size (0.5-8.0)	Factor 3 V_{dp} (0.6-0.9)	Factor 4 Hysteresis (D1-D2)	Factor 5 $\lambda_{Dx,y}$ (0.2-2.0)	Factor 6 λ_{Dz} (0.3-0.4)

D1: Hysteresis applied

D2: Hysteresis not applied

- **Initially two objective functions defined:**
  - ✓ **Oil Recovery,** %OOIP
  - ✓ **CO_2 Saturation,** frac. P.V.





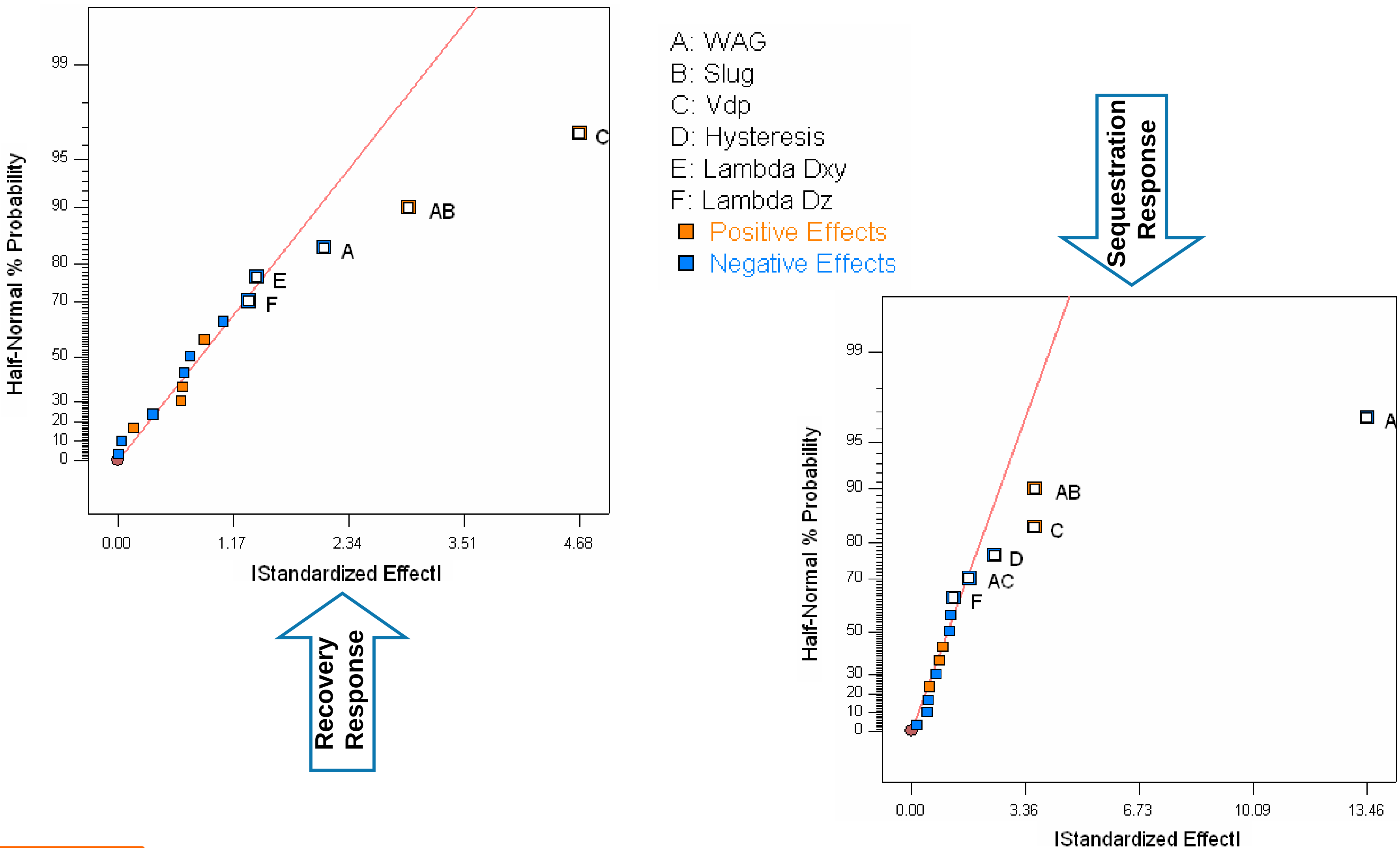
Simulation Results

Run #	Duration Of WAG Flood, yrs	Response 1: Oil Rec., %OOIP	Response 2: CO2 Sat., frac.	Response 3: $ Value	
				$/MCF Stored	$/STB Prod.
1	15	23.3	0.26	0.88	8.7
2	4.8	16.9	0.16	1.04	8.2
3	4.6	20.5	0.21	0.97	8.4
4	8.8	21.3	0.18	1.3	9.5
5	41	22.7	0.12	0.41	9.9
6	35	25.9	0.25	1.06	6.7
7	44	21.3	0.08	0.45	6.1
8	21	14.7	0.07	0.21	3.6
9	52	19.6	0.07	2.58	8.7
10	2.1	19.8	0.21	1.02	8.6
11	18	20.3	0.06	0.43	5.8
12	54	20.0	0.09	2.18	5.4
13	4.7	15.9	0.16	1.00	8.3
14	18	14.9	0.04	0.21	3.6
15	21	19.4	0.10	0.41	6.0
16	38	25.8	0.26	1.03	6.4

Parameters for Discounted Cash Flow Analysis

Oil Price	$35 /bo
Oil Price Increase	10 %
Royalty	12.5 %
CO_2 Price	$0.85 /mcf
Op. Cost Inflation	1.5 %
Recycle Cost	$0.35 /mcf
Lift Cost	$0.2 /bbl
Discount Rate	12 %
Fed. Tax Rate	32 %
EOR Tax Credit	20 %

Sensitive Parameters



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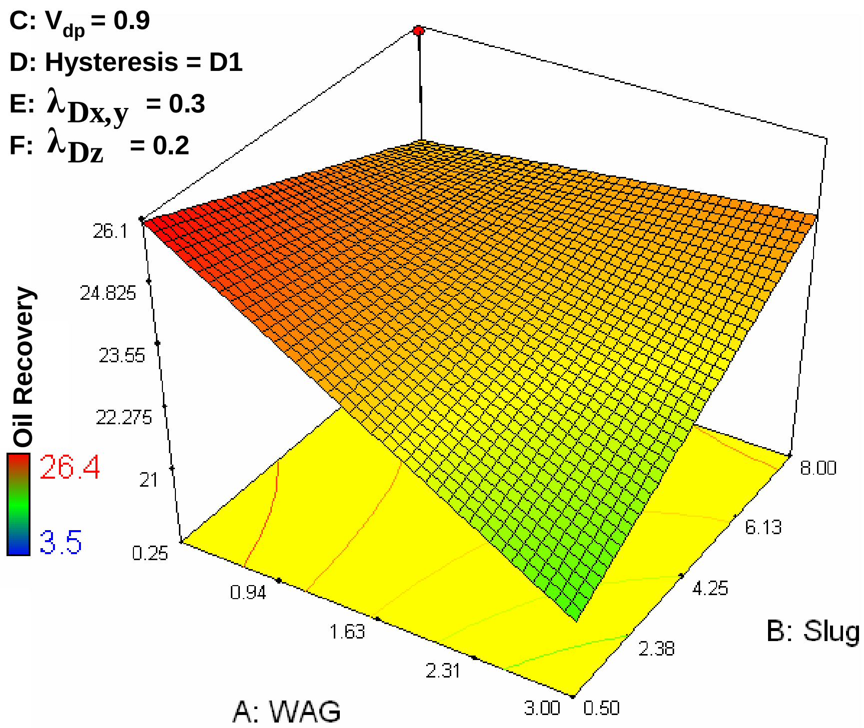
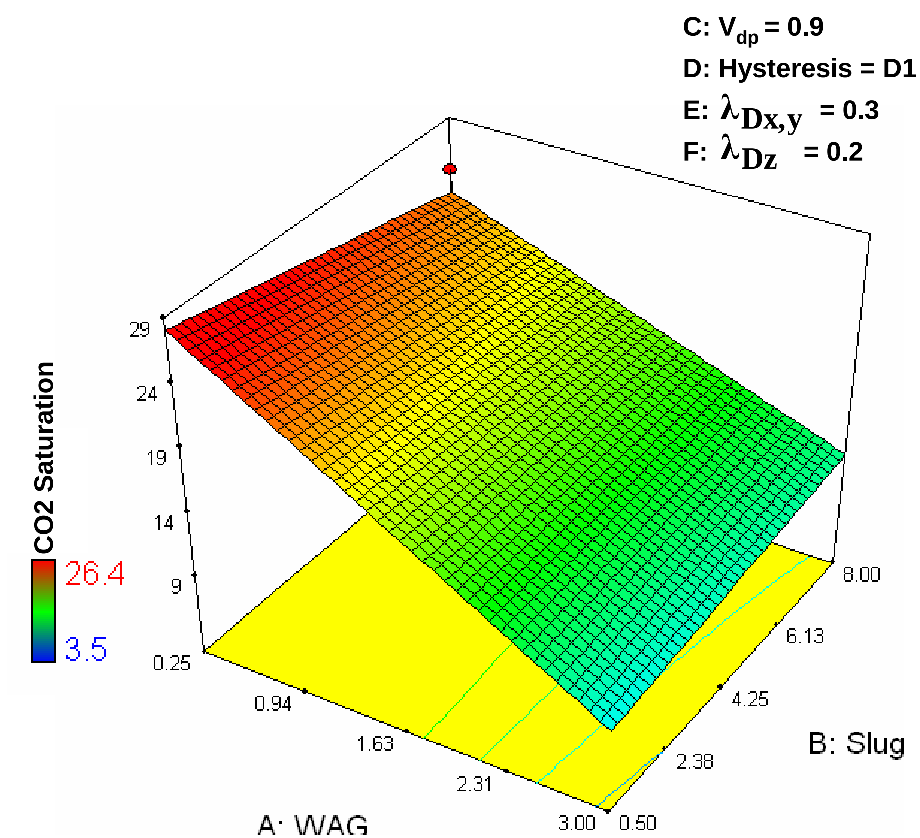
Response Surfaces





Optimization- Suggested Runs

Objectives →	Maximizing Oil Recovery	Maximizing CO_2 Storage	Maximizing Profit	Equal weight for oil recovery and CO2 storage
Factor 1 **A: WAG Ratio**	0.26	0.29	3	0.25
Factor 2 **B: % Slug Size**	0.63	1.51	8	0.57
Factor 3 **C: V_{dp}**	0.9	0.88	0.6	0.9
Factor 4 **D: Hysteresis**	**D2 (Not Applied)**	**D1(Applied)**	**D1(Applied)**	**D1(Applied)**
Factor 5 **E: $\lambda_{Dx,y}$**	0.3	1.33	0.3	0.45
Factor 6 **F: λ_{Dz}**	0.2	0.23	0.4	0.2
Oil Recovery, % OOIP	25.9	24.3	18.6	25.2
CO2 Saturation, frac. P.V.	25.5	28.0	6.2	26.6
$ Value: **$/MCF** CO_2 Stored	1.1	1.4	0.42	0.95
$ Value: **$/STB** Prod.	6.9	6.2	8.7	6.7

Summary

- The optimized values for all objective functions predicted by Design of Experiment and Response Surface Method are close to the values obtained by an exhaustive simulation study but with a very efficient computational time

- Compositional reservoir simulation in conjunction with experimental design can be used to efficiently optimize both CO_2 storage and oil recovery

Conclusions

- Hysteresis has a very large impact on the behavior of CO_2 in terms of both oil recovery and storage in heterogeneous oil reservoirs

- CO_2 storage is greater for
  - ✓Oil reservoirs with low heterogeneity
  - ✓Low WAG ratio
  - ✓Small CO_2 slug sizes

- Profit from CO_2 EOR is greater for
  - ✓Oil reservoirs with low heterogeneity
  - ✓High WAG ratio
  - ✓Large CO_2 slug sizes