Simplified Predictive Models for CO_2 Sequestration Performance Assessment

DE-FE-0009051

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Transforming Technology through Integration and Collaboration
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Presentation Outline

- Benefit to the Program / Stakeholders
- Project Overview
- Technical Status
  - Reduced physics based modeling
  - Statistical learning based modeling
  - Reduced order method based modeling
  - Uncertainty and Sensitivity Analysis
- Accomplishments to Date
- Summary

Benefit to the Program

- Research will develop and validate a portfolio of simplified modeling approaches to predict the extent of CO_2 plume migration, pressure impact and brine movement for a semi-confined system with vertical layering
- These approaches will improve existing simplified models in their applicability, performance and cost
- The technology developed in this project supports the following programmatic goals: (1) estimating CO_2 storage capacity in geologic formations; (2) demonstrating that 99 percent of injected CO_2 remains in the injection zone(s); and (3) improving efficiency of storage operations

Benefit to Stakeholders

- Provide ***project developers*** with simple tools to screen sites and estimate monitoring needs
- Provide ***regulators*** with tools to assess geological storage projects quickly without running full-scale detailed numerical simulations
- Enable ***risk assessors*** to utilize robust, yet simple to implement, reservoir performance models
- Allow ***modelers*** to efficiently analyze various CO_2 injection plans for optimal well design/placement

Project Overview

Goals and Objectives

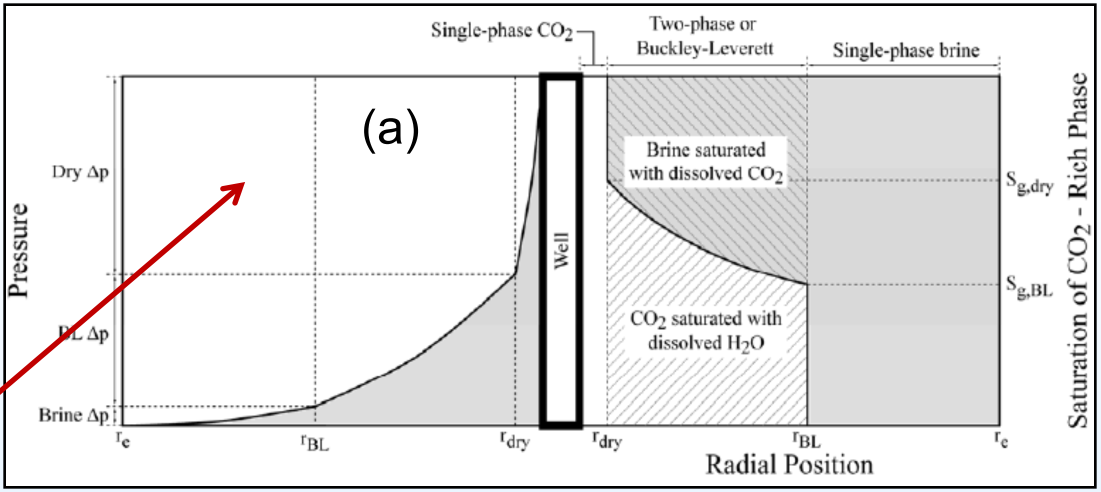
Objective ⇨ Develop and validate a portfolio of simplified modeling approaches for CO_2 sequestration in deep saline formations

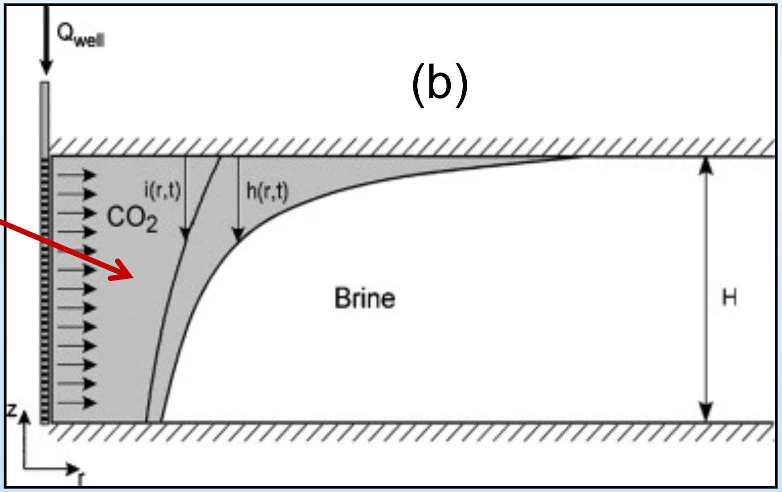
- **Reduced physics-based modeling** - where only the most relevant processes are represented
- **Statistical-learning based modeling** - where the simulator is replaced with a "response surface"
- **Reduced-order method based modeling** - where mathematical approximations reduce computational burden
- **Uncertainty and sensitivity analysis** – to validate the simplified modeling approaches for probabilistic applications

Reduced Physics Based Models

Background

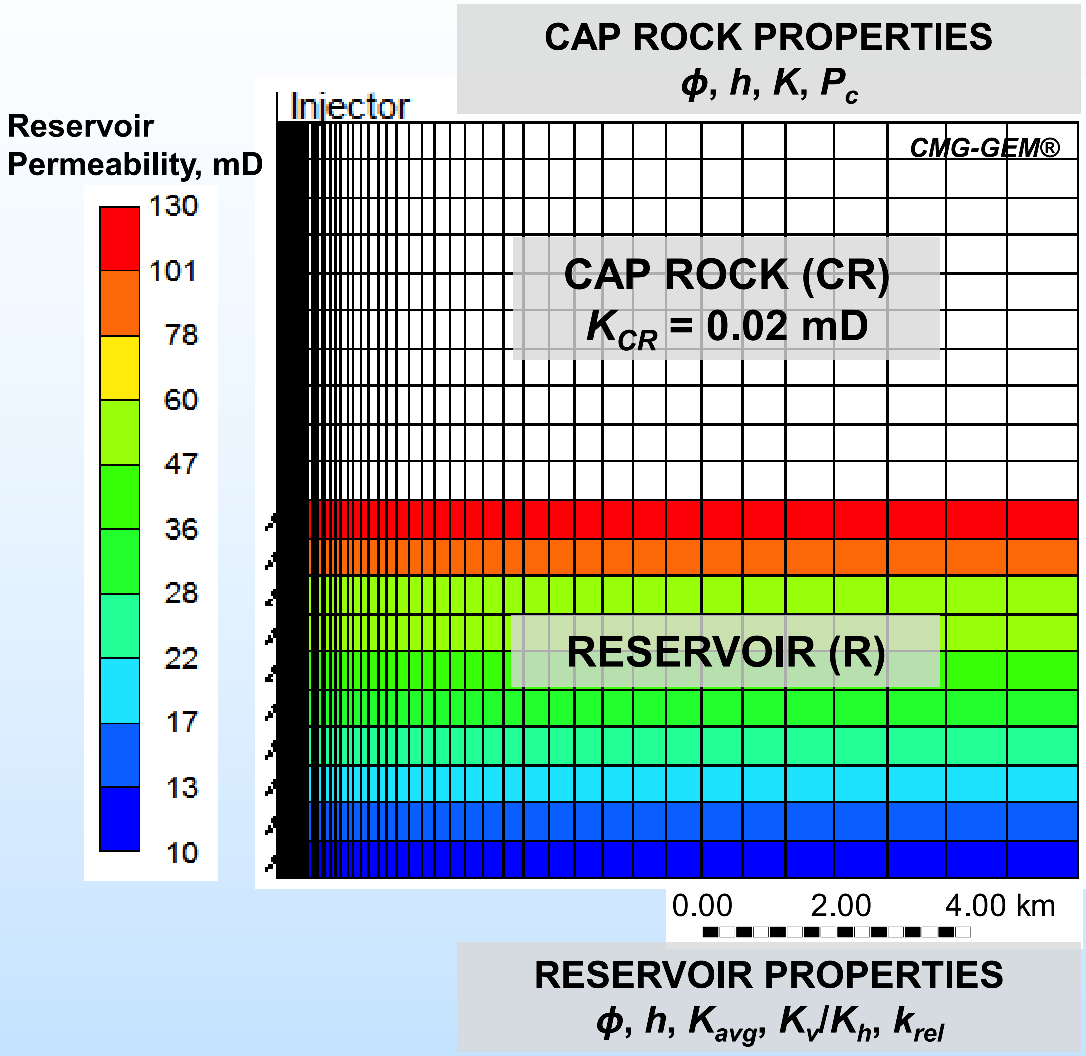
- Useful alternative to simulators if "macro" behavior is of interest
- Analytical models of radial injection of supercritical CO_2 into confined aquifers
  - **(a) Fractional flow** model (Burton et al., 2008; Oruganti & Mishra; 2013)
  - **(b) Sharp interface** model (Nordbotten & Celia, 2008)
- Require extension for semi-confined systems with vertical permeability layering (based on detailed simulations)

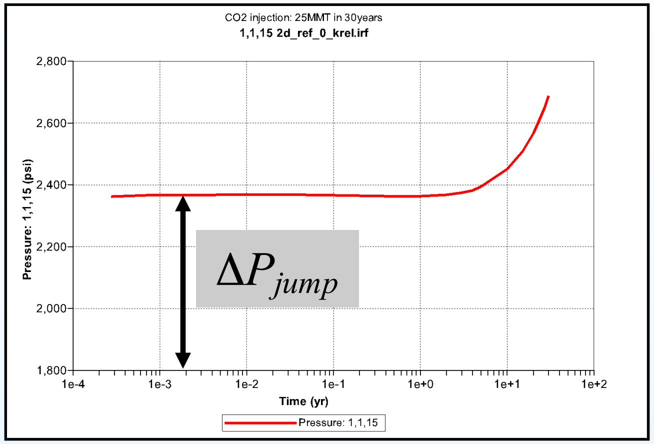




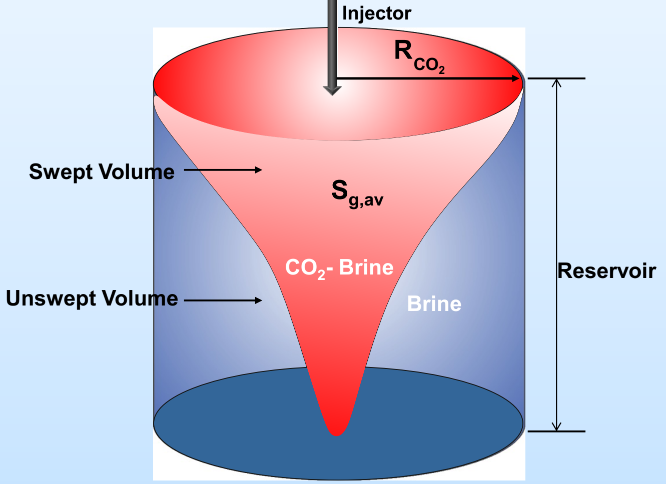
Reduced Physics Based Models

Approach (using CMG-GEM)





$S_{g,av}$ = Average Gas Saturation in Swept Volume



$$E_v = \frac{\text{Swept Volume}}{\text{Swept Volume + Unswept Volume}}$$

Reduced Physics Based Models

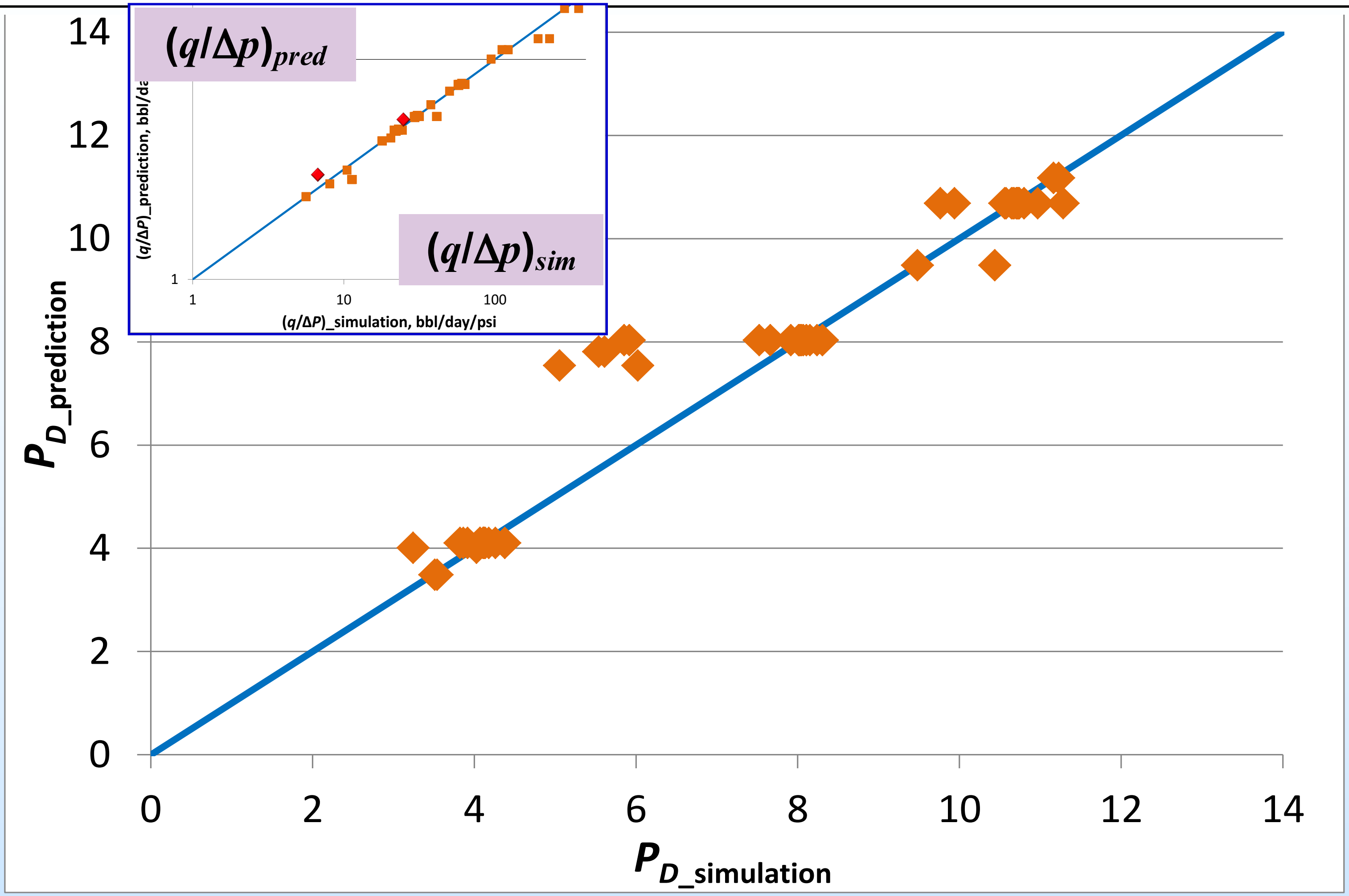
Simulation Scenarios

	Parameter	Description	Units	Reference value (0)	Low value (-1)	High value (+1)	Comments
1	h_R	Thickness of reservoir	m	150	50	250	
2	h_{CR}	Thickness of caprock	m	150	100	200	
3	$k_{avg,R}$ (k_R)	Average horizontal permeability of reservoir	mD	46	12	220	
	V_{DP}	Dykstra-Parson's coefficient	--	0.55	0.35	0.75	Correlated with $k_{avg,R}$
4	$k_{avg,CR}$ (k_{CR})	Average horizontal permeability of caprock	mD	0.02	0.002	0.2	
5	k_V/k_H	Anisotropy ratio	--	0.1	0.01	1	
6	q	CO_2 Injection rate	MMT/yr	0.83	0.33	1.33	
	L	Outer radius of reservoir	km	10	5	7	Correlated with q
7	f_R	Porosity of reservoir	--	0.12	0.08	0.18	
8	f_{CR}	Porosity of caprock	--	0.07	0.05	0.1	
9	I_v	Indicator for permeability layering	--	Random	Increasing from top	Increasing from bottom	

Deriving insights into performance metric behavior → *Quantifying functional relationships between variables based on sensitivity analysis* → *Validating simplified model to check for robustness*

Reduced Physics Based Models

Dimensionless Injectivity – Predictive Model



$$P_D = 10.3 + 0.59\frac{df_g}{dS_g} + 3.41V_{DP} + 1.23\frac{df_g}{dS_g}V_{DP} - 0.34\left(\frac{df_g}{dS_g}\right)^2 - 8.89V_{DP}{}^2$$

Reduced Physics Based Models

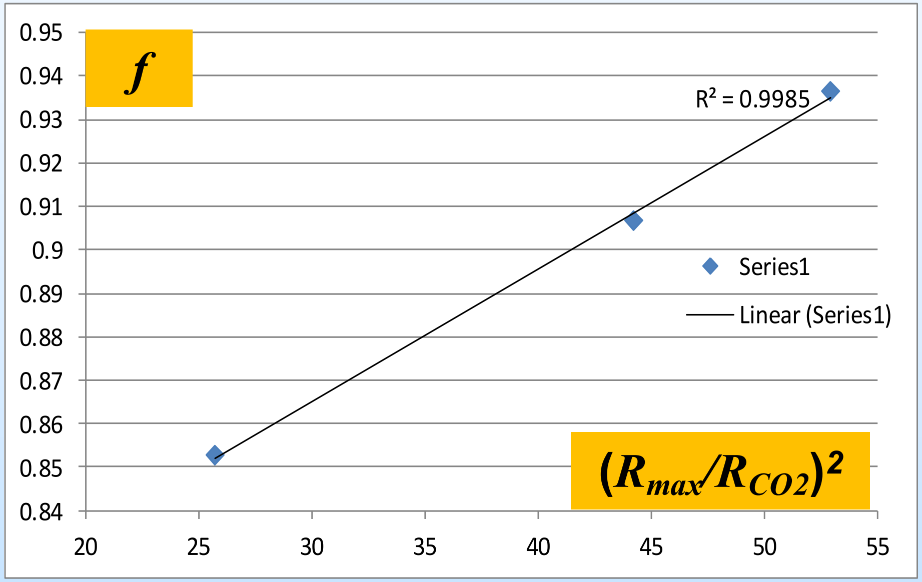
Average Reservoir Pressure – Predictive Model

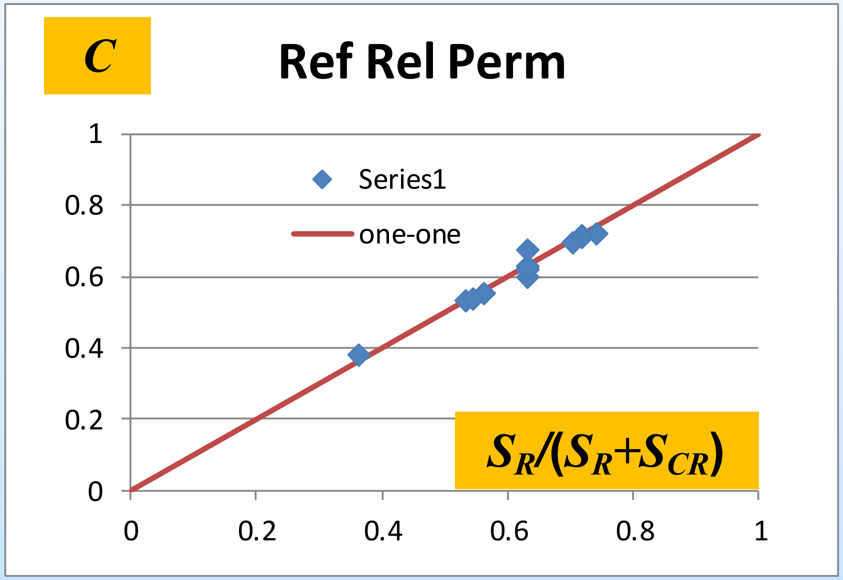
$$\overline{P}_D = f\,2\pi t_{DA}$$

$$\overline{P}_D = fC2\pi t_{DA}$$

For a closed/ no-caprock system
f depends on relative permeability

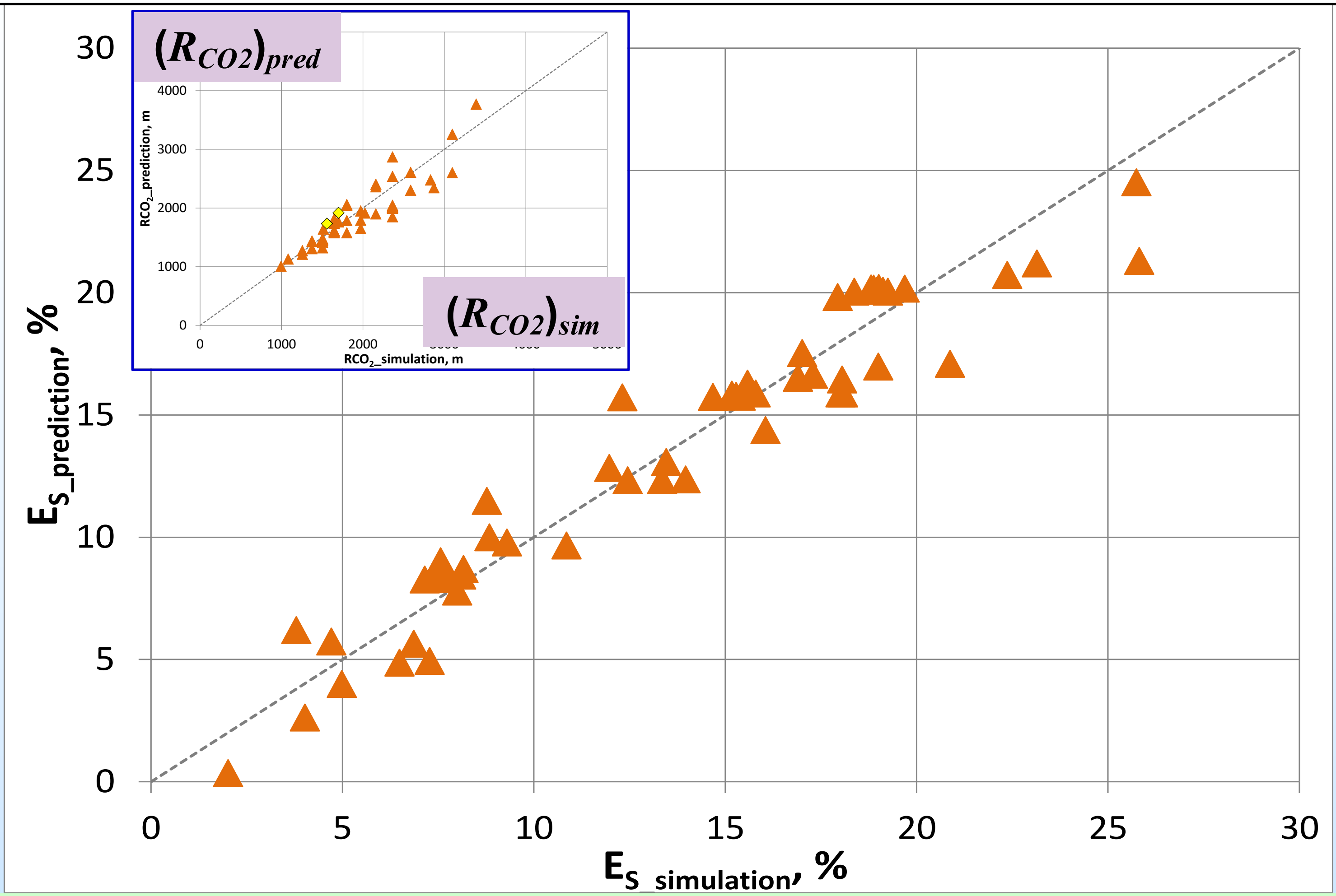
C depends on ratio of reservoir storativity to total storativity





Reduced Physics Based Models

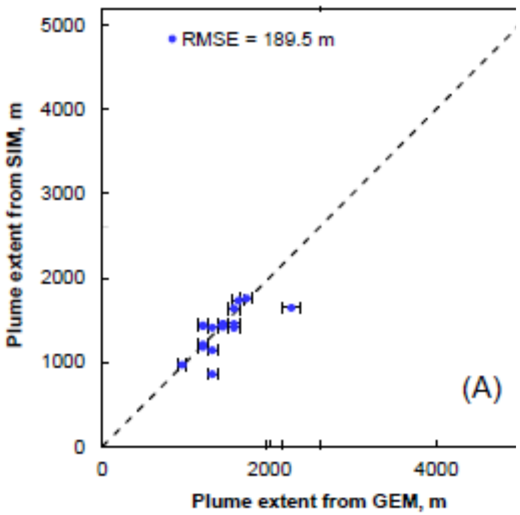
Storage Efficiency – Predictive Model



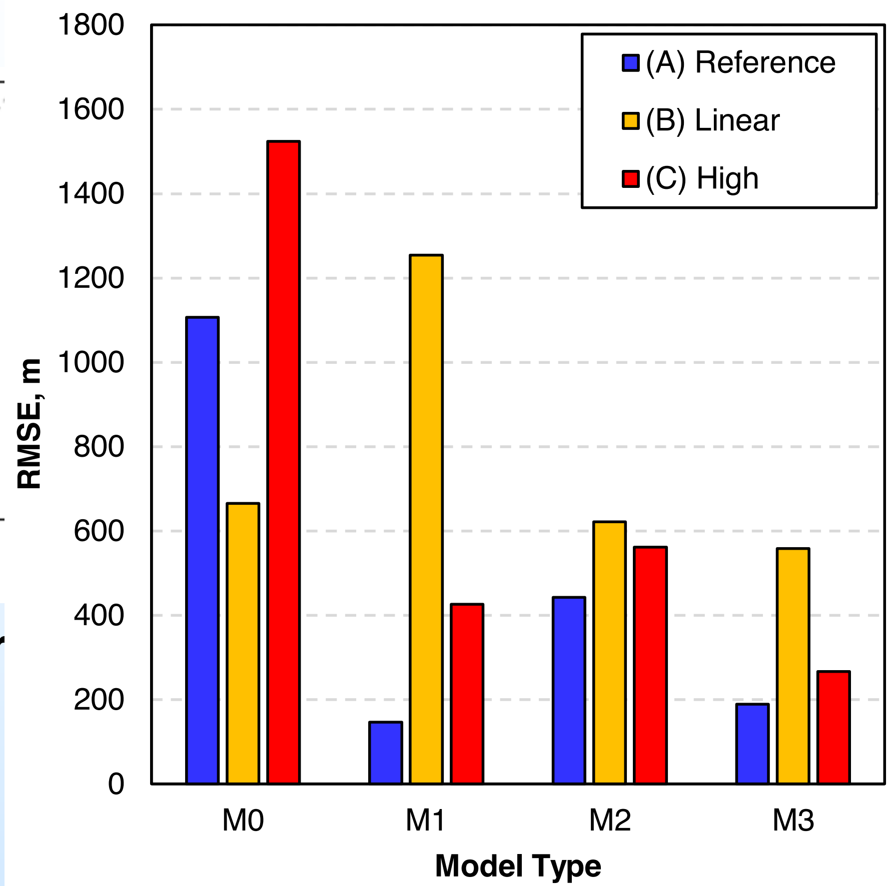
$$E_S = 30.7 + 0.435\frac{df_g}{dS_g} + 29.24L_C - 22.02V_{DP} - 11.2N_g + 4.59\frac{df_g}{dS_g}V_{DP} - 25.21L_C V_{DP} - 0.692\left(\frac{df_g}{dS_g}\right)^2 + 6.11N_g{}^2$$

Reduced Physics Based Models

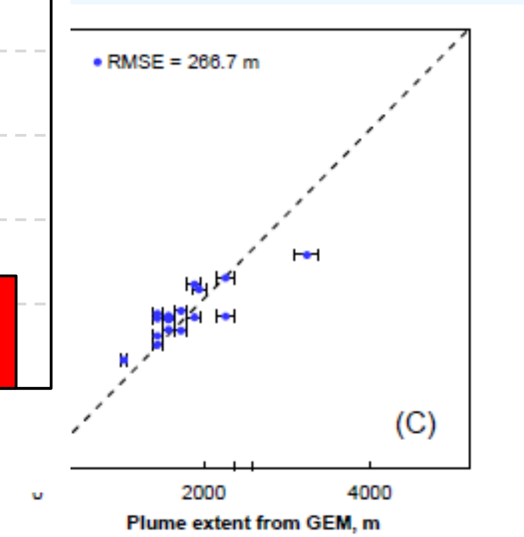
Sharp Interface Model Evaluation



(A) Reference rel per



erage gas saturation
plume tip calculation



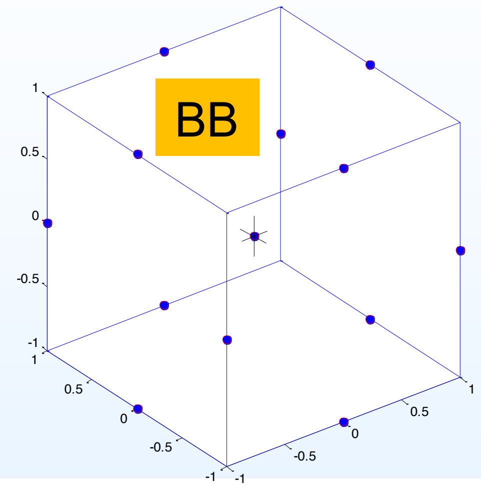
(C) High rel perm

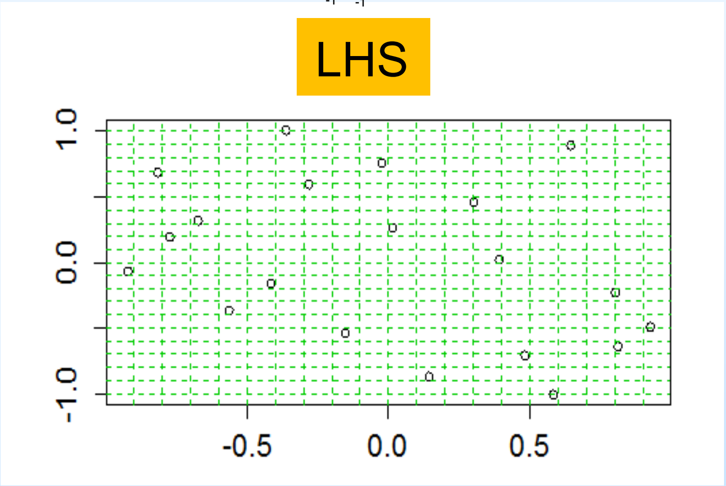
Model M0: sharp interface model
Model M1: sharp interface model + average gas saturation
Model M2: sharp interface model + Bingham-Reid mixing law
Model M3: sharp interface model + average gas saturation + Bingham-Reid mixing law

Statistical Learning Based Models

Background

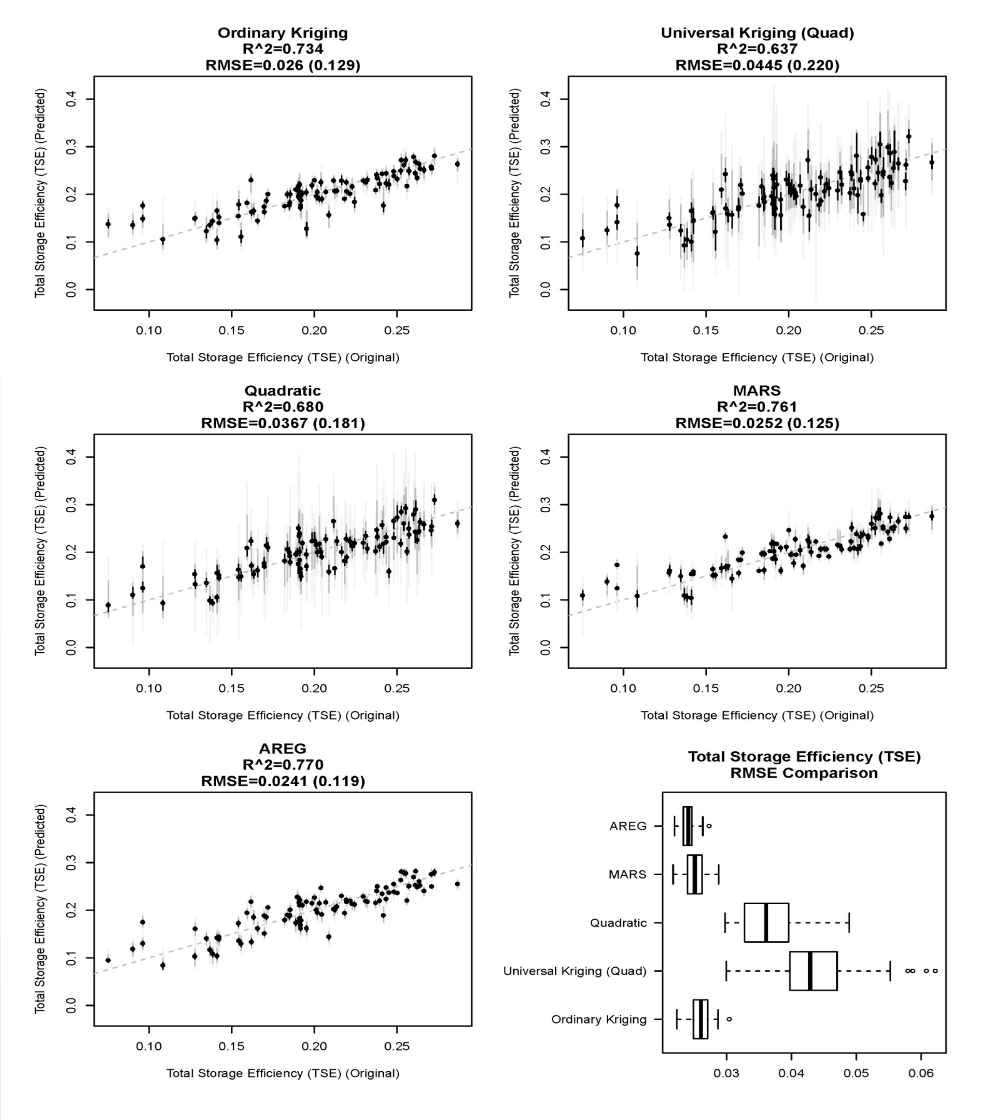
- **Goal** ⇨ replace physics-based model with statistical equivalent
- **Experimental design** ⇨ selection of points in parameter space to run limited # of computer experiments
- **Response surface** ⇨ functional fit to input-output data to produce "proxy" models for plume radius and reservoir pressure buildup
- Two common options
  - Box-Behnken (BB) design
    3-pt + quadratic response surface
  - Latin Hypercube sampling (LHS)
    multi-point + higher-order model





Statistical Learning Based Models

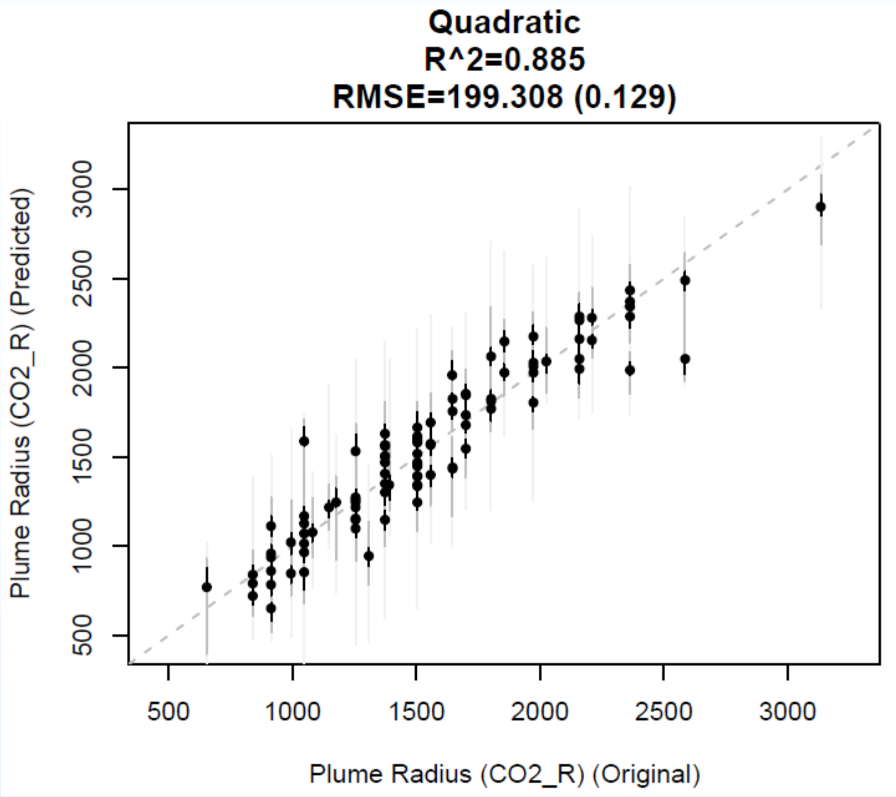
Box Behnken Design – Metamodeling



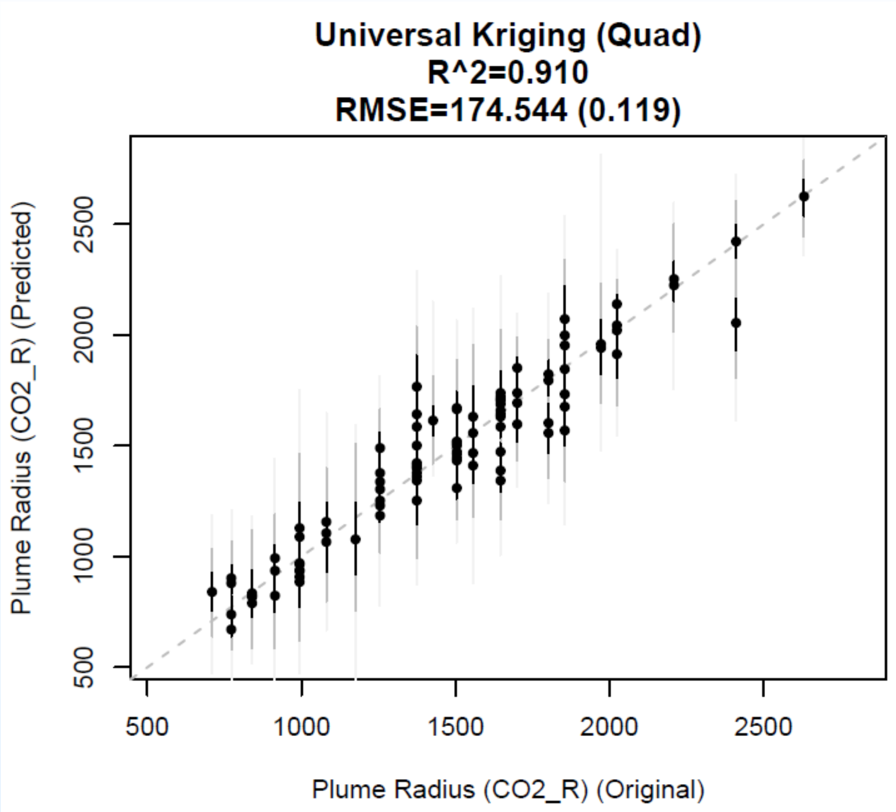
- Data from 2-D GEM simulations of CO_2 injection into closed volume
- 97 run Box-Behnken design with 9 factors
- 4 different meta-models
  - Quadratic
  - Kriging
  - MARS
  - Adaptive regression
- **Cross validation using 5 mutually exclusive subsets (78 training + 19 test data points) with 100 replicates**

Statistical Learning Based Models

Proxy Models – Plume Radius



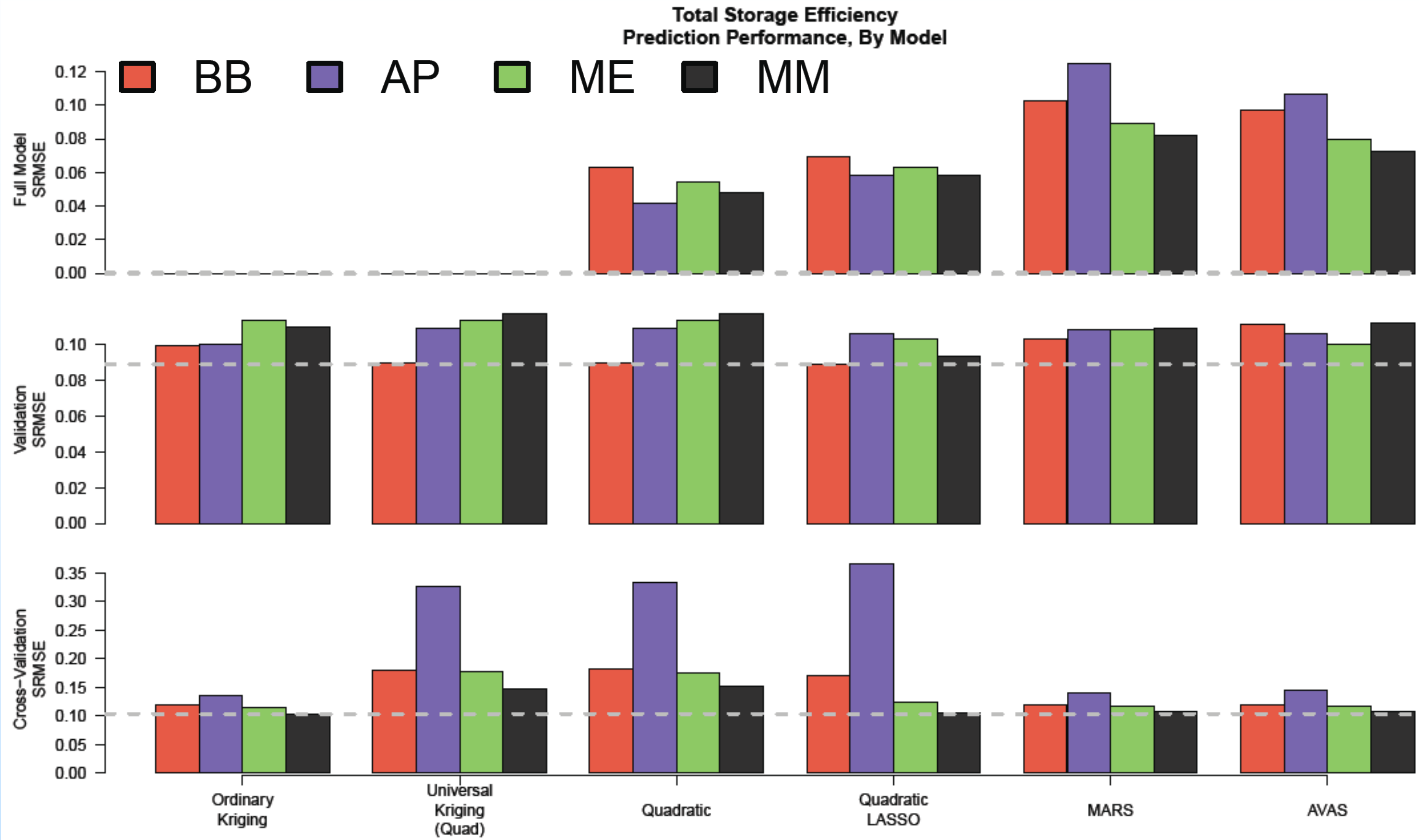
Box-Behnken Design



LHS Design

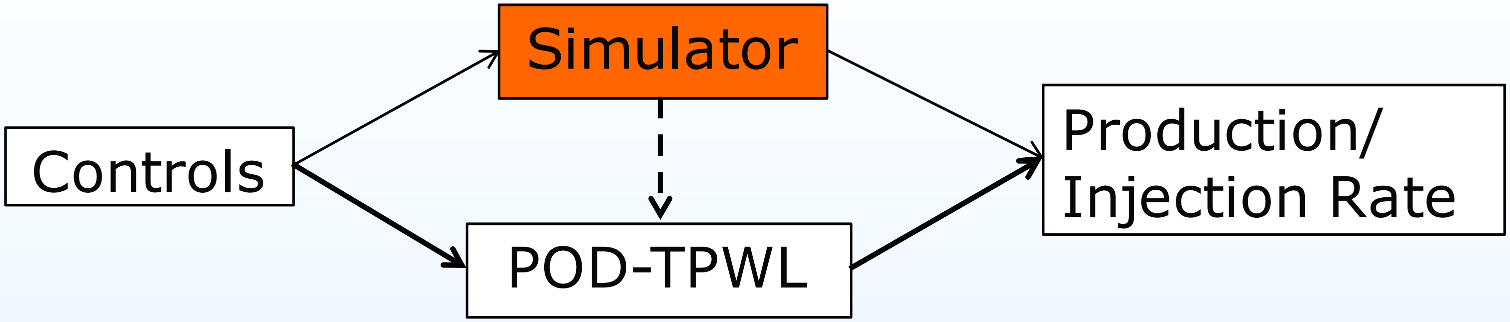
Statistical Learning Based Models

Proxy Model Evaluation



Reduced Order Method Based Models

Background (1)



- Proper Orthogonal Decomposition (POD)
  - Represent high-dimensional state vectors (e.g., pressure & saturation in every grid block) with small number of variables by feature extraction
- Trajectory Piecewise Linearization (TPWL)
  - Predict results for new simulations by linearizing around previous (training) simulations

Reduced Order Method Based Models

Background (2)

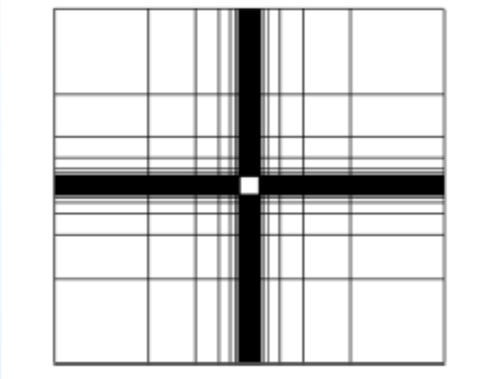
Order reduction		Nonlinearity treatment		Linear expressions w/ 100s of variables
⇩		⇩		⇩
POD	+	TPWL	=	POD-TPWL

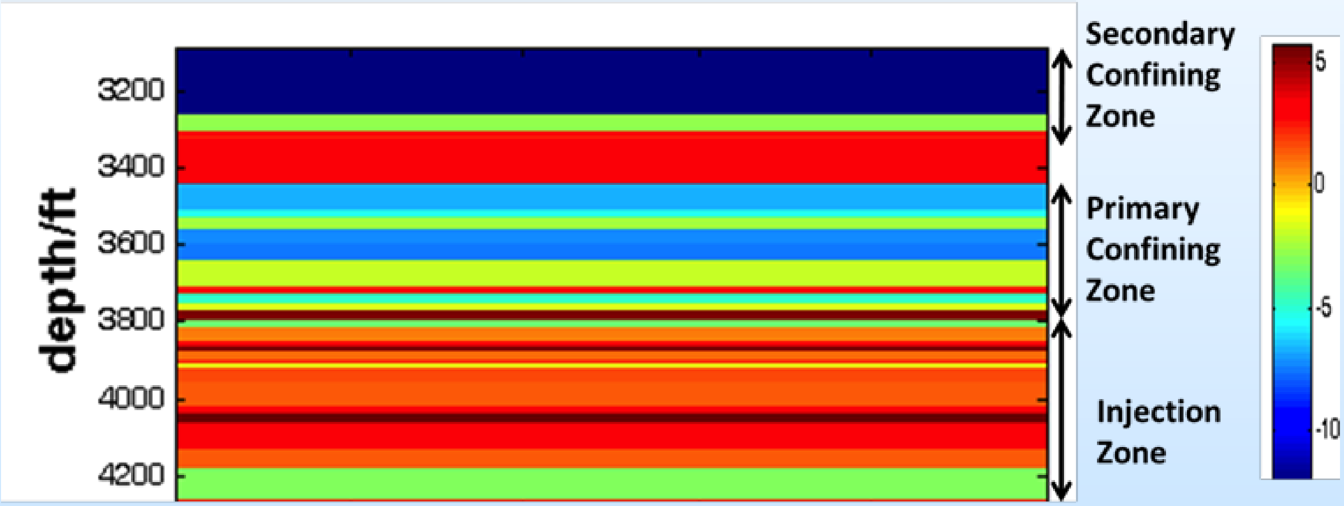
- Retain the physics of the original problem
- Overhead is required to build the POD-TPWL model
- Evaluation of POD-TPWL model takes only seconds
- Applied previously to oil-water problems for optimization and history matching (Cardoso and Durlofsky 2010, 2011; He *et al*. 2011, 2013)

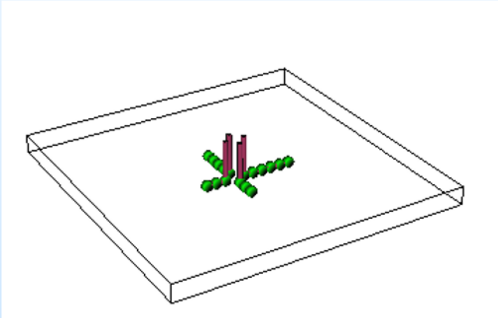
Reduced Order Method Based Models

4-Horizontal Well Problem (CO_2 Storage)

Idealized problem based on CO_2 Storage in Mt Simon sandstone planned for the FutureGen 2.0 site

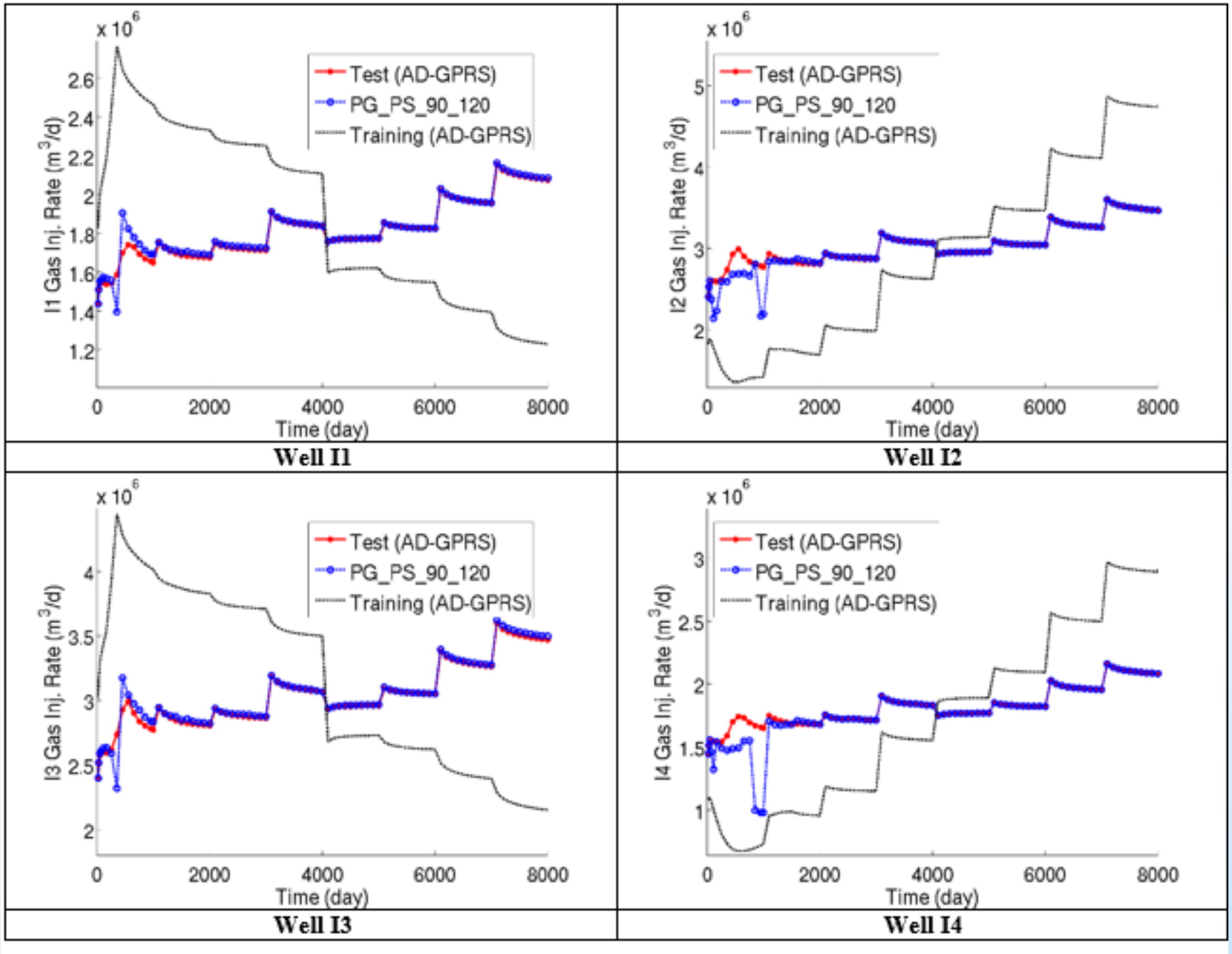






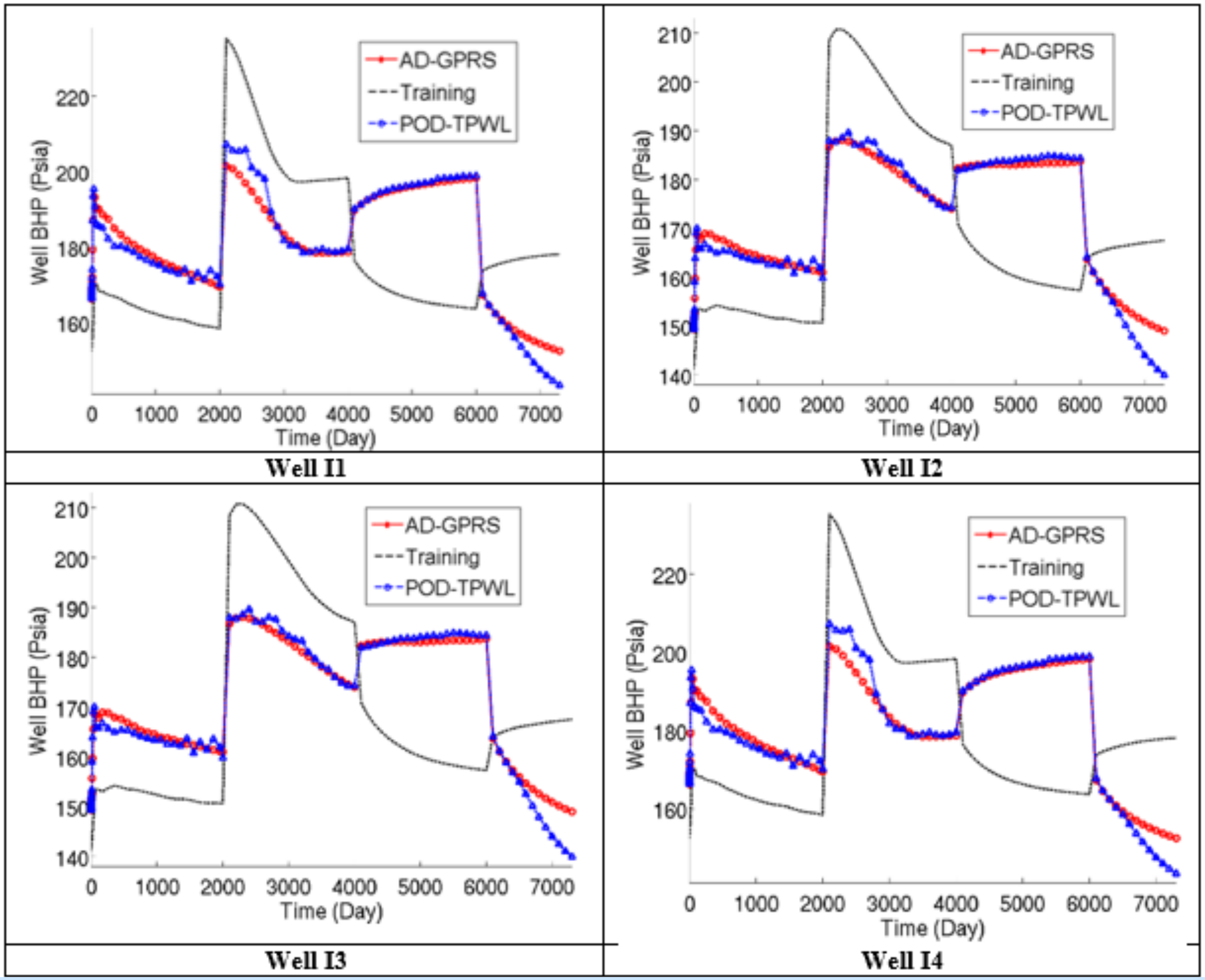
Reduced Order Method Based Models

POD-TPWL Performance: BHP Control for Wells



Reduced Order Method Based Models

POD-TPWL Performance: Rate Control for Wells



Runtime speedup factor ~ 370 for 3D POD-TPWL case (compared to full-order AD-GPRS simulation)

Reduced Order Method Based Models

POD-TPWL Performance: Geological Perturbation

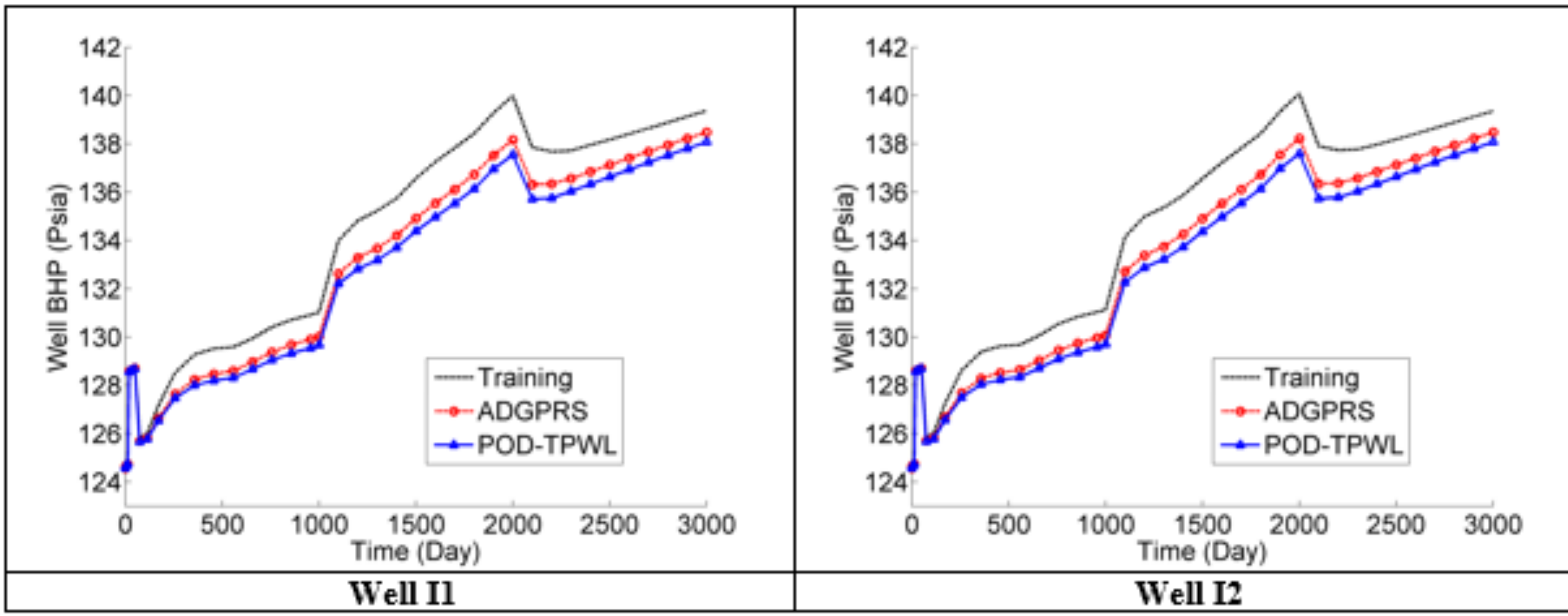


Fig. 27. CO_2 injection well BHPs for test case (geological perturbation example).

Results demonstrate that the approach is able to capture basic solution trends

Uncertainty and Sensitivity Analysis

Problem Definition

Inputs:

- Slope of CO_2 fractional flow curve
- Initial P, T
- CO_2 injection rate
- Time of injection
- Reservoir thickness
- Average porosity
- Radial extent of reservoir
- Reservoir permeability anisotropy ratio
- Total compressibility
- Caprock thickness
- Caprock porosity
- Layer permeability arrangement indicator

Models:

‘**A**’ – Box-Behnken fitted with quadratic polynomial model

‘**B**’ – Maximin LHS fitted with kriging model

‘**C**’ – simplified physics-based models

Cumulative distribution functions (CDFs) evaluated for performance metrics:

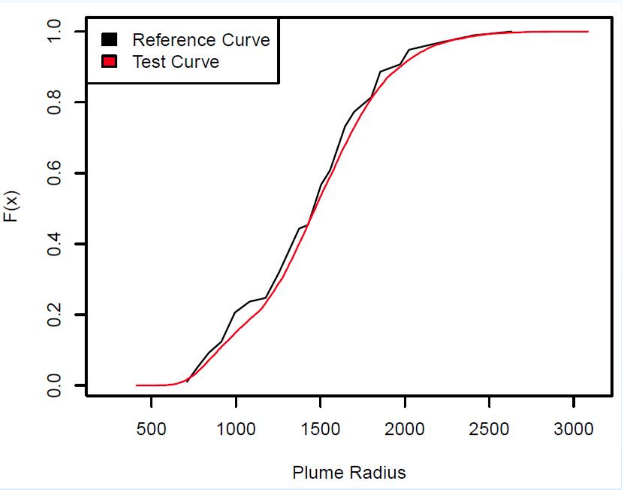
R_{CO2},
ΔP_{Ravg}

Uncertainty and Sensitivity Analysis

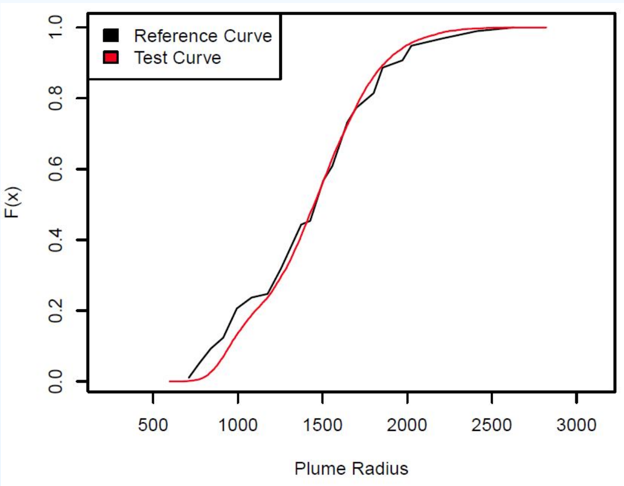
Simplified Model Performance

Plume Extent at End of Injection

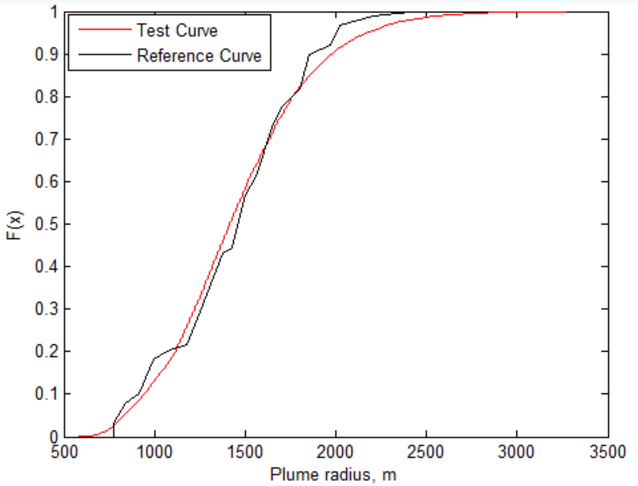
Model ‘A’



Model ‘B’



Model ‘C’



Simplified models can capture full range of outcomes predicted by full-physics model

Accomplishments to Date

RPBM

- Developed simplified predictive models for dimensionless injectivity, average reservoir pressure buildup and CO_2 plume migration extent (storage efficiency)

SLBM

- Compared performance of different metamodeling approaches for building proxy models
- Evaluated experimental design (Box-Behnken) and sampling design (Latin Hypercube sampling) schemes

ROMBM

- Demonstrated applicability of POD-TPWL for CO_2 injection into saline aquifers using a compositional simulator
- Evaluated different well constraints and effects of geologic reservoir heterogeneity

RPBM and SLBM models validated using uncertainty and sensitivity analysis

Synergy Opportunities

- Complements discussions on model complexity by Princeton U. vis-à-vis the limits of applicability of simplified v/s full physics models
- Complements discussions on response surface uncertainty analysis by U. Wyoming vis-à-vis various statistical techniques for model building
- Provides inputs to LANL discussion regarding use of science-based simplified (abstracted) models in performance and risk assessment

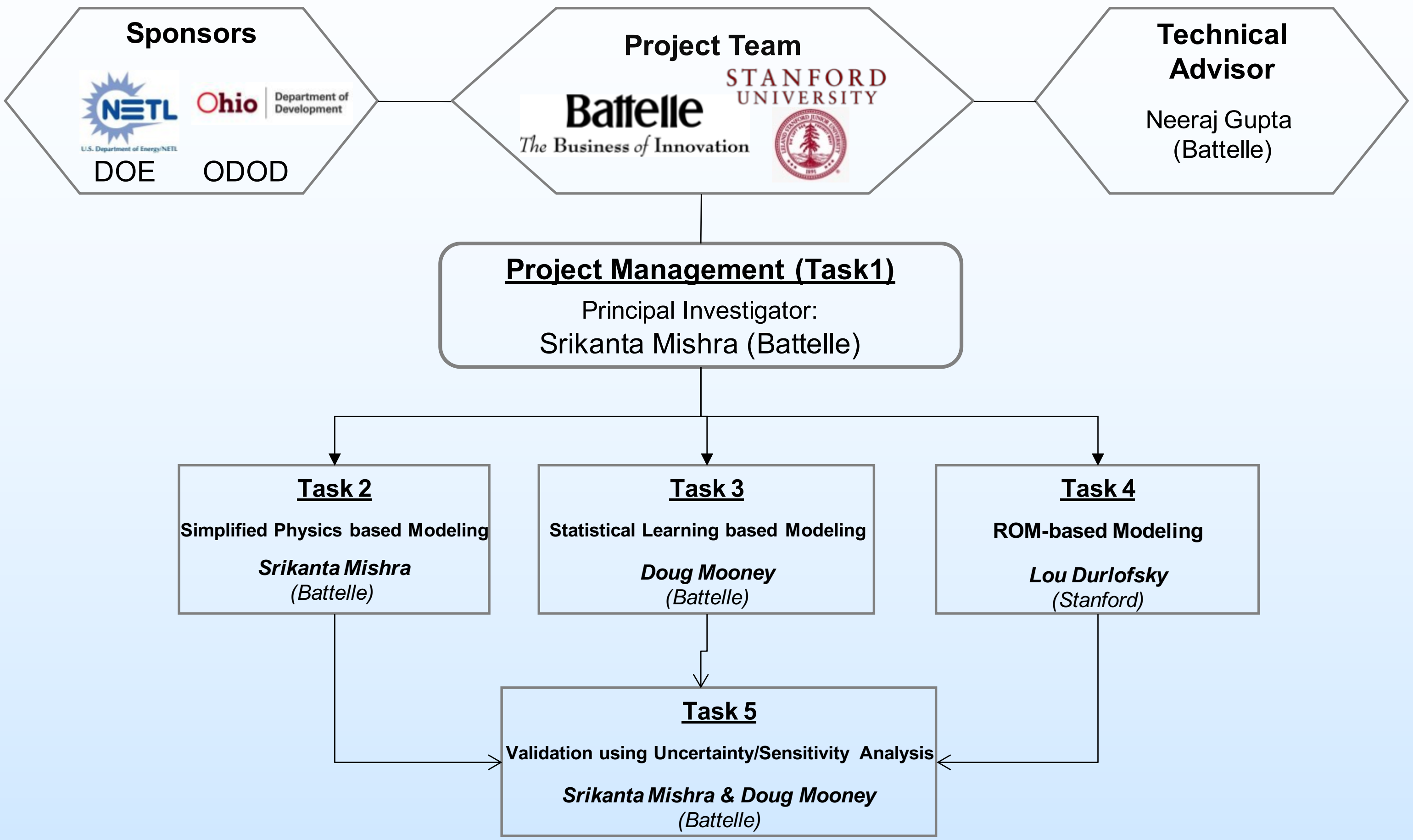
Summary

- Successful development of simplified predictive models for layered reservoir-caprock systems
  - Reduced physics models for injectivity and plume radius
  - Improved proxy modeling workflow using BB/LHS designs
  - Application of POD-TPWL scheme to CO_2-brine systems
- Benefits to stakeholders
  - Site developers, regulators ⇨ simplicity, limited data
  - Modelers, risk assessors ⇨ computational efficiency

Appendix

These slides will not be discussed during the presentation, but are mandatory

Organization Chart



Project Manager – William O'Dowd (DOE)

Gantt Chart

Task Name	BP1 10/2012-09/2013				BP2 10/2013-09/2014				BP3 10/2014-09/2015			
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1: Project Management												
1.1 Project Management & Planning												
1.2 Update Project Mgmt. Plan	X											
1.3 Progress Reporting	X	X	X	X	X	X	X	□	□	□	□	□
1.4 Project Controls												
1.5 Deliverables and Reporting												
Task 2: Simplified physics based modeling												
2.1 Numerical experiments												
2.2 Models for two-phase region behavior												
2.3 Models for pressure buildup												
Task 3: Statistical learning based modeling												
3.1 Design matrix generation												
3.2 Computer simulations												
3.3 Analysis of computer experiments												
Task 4: ROM-based modeling												
4.1 Black-oil ROM procedures												
4.2 Compositional ROM procedures												
Task 5: Validation using UA/SA												
5.1 Problem definition												
5.2 Probabilistic simulation												
5.3 Analysis of results												

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