Simplified Predictive Models for CO_2 Sequestration Performance Assessment

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Developing the Technologies and
Infrastructure for CCS

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Presentation Outline

- Benefit to the Program / Stakeholders
- Project Overview
- Technical Status
  - Simplifed physics based modeling
  - Statistical learning based modeling
  - Reduced order method based modeling
- 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

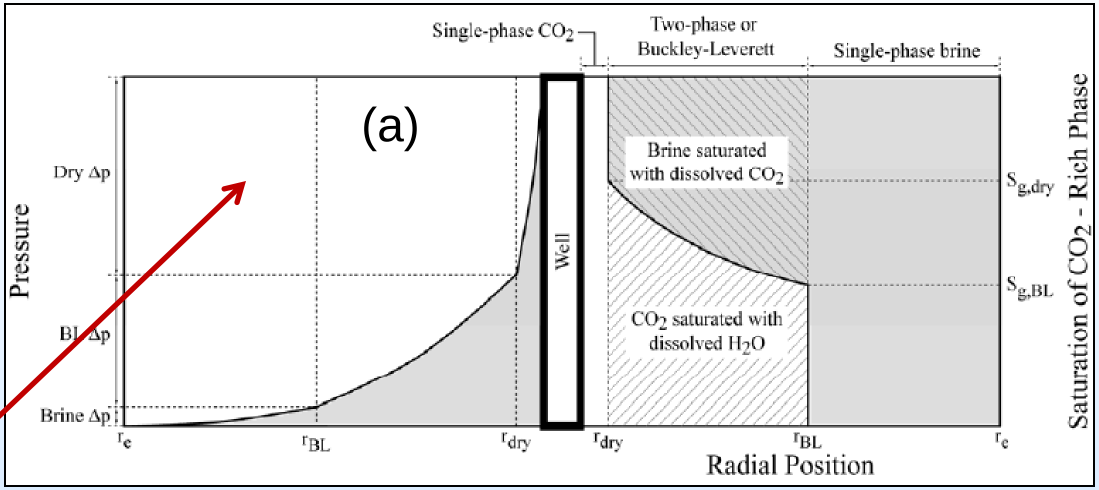
- Provide ***project developers*** with simple tools to screen sites and estimate monitoring needs
- Provide ***regulators*** with tools to assess geological storage projects quickly without running full-scale detailed numerical simulations
- Enable ***risk assessors*** to utilize robust, yet simple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

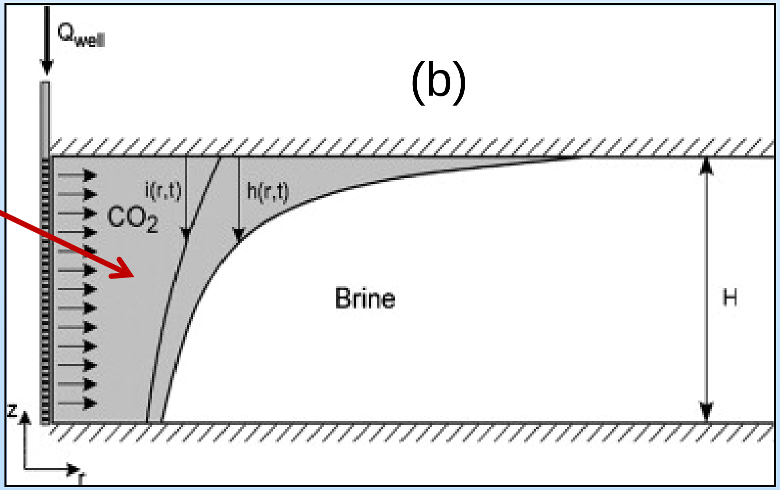
Project Overview
Goals and Objectives

- **Objective** ⇨ Develop and validate a portfolio of simplified modeling approaches for CO_2 sequestration in deep saline formations
  - **Simplified physics-based modeling** - where only the most relevant processes are modeled
  - **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

Simplified 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 layering (based on detailed simulations)

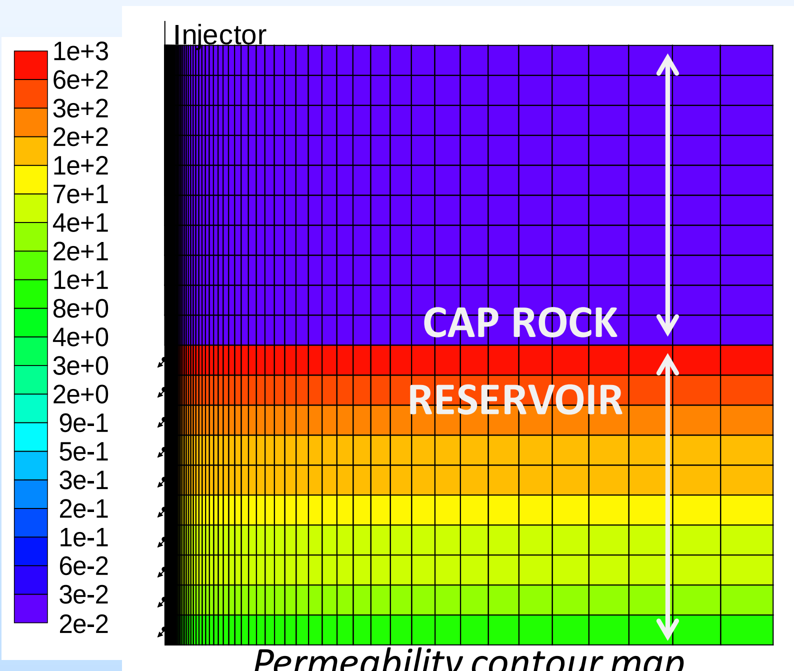




Simplified Physics Based Models
Approach (using GEM)

INPUT VARIABLES

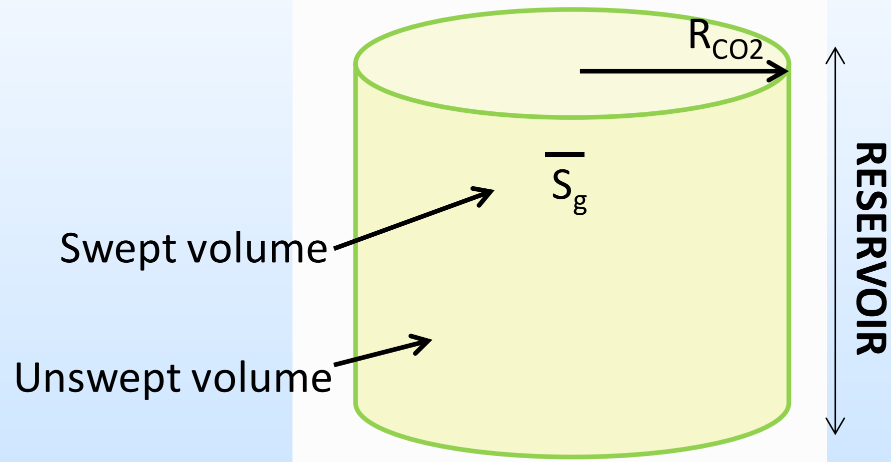
CAP ROCK PROPERTIES:
Ø, h, <K>, P_c,

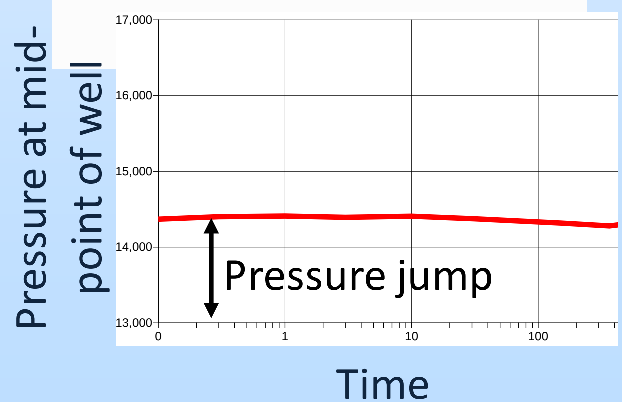


Permeability contour map

RESERVOIR ROCK PROPERTIES:
Ø, h, <K>, K_v/k_h, K_{rel}

PERFORMANCE METRICS



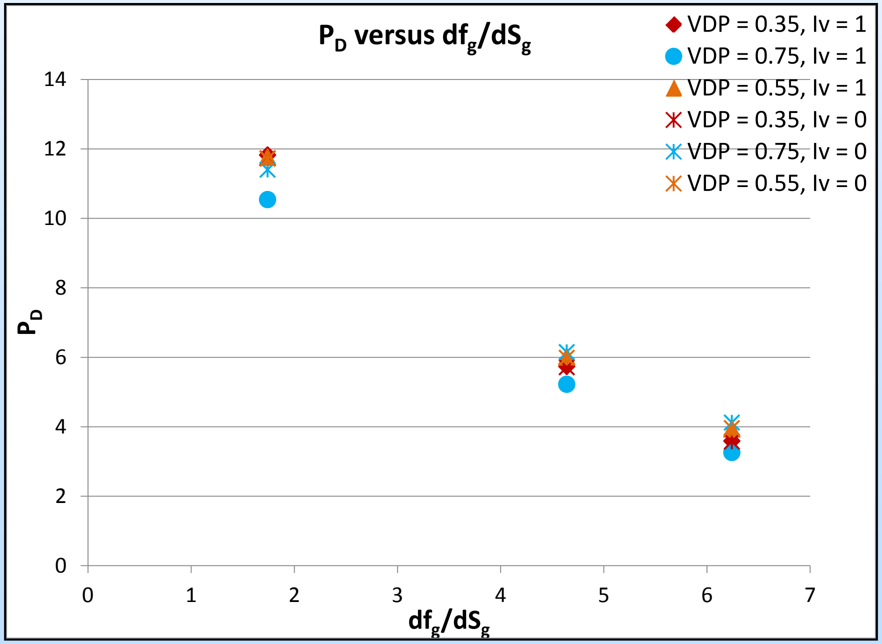


Simplified Physics Based Models

Dimensionless Injectivity

$$\Delta P_{tot} = \frac{q_{CO_2}}{2\pi kH}\left[\frac{\ln(r_{dry}/r_w)}{1/\mu_g} + \frac{\ln(r_{BL}/r_{dry})}{M_{BL}} + \frac{\ln(r_e/r_{BL})}{1/\mu_w}\right]$$

$$P_{D,jump} = \frac{2\pi kH}{q\mu_w}\Delta P_{jump}$$



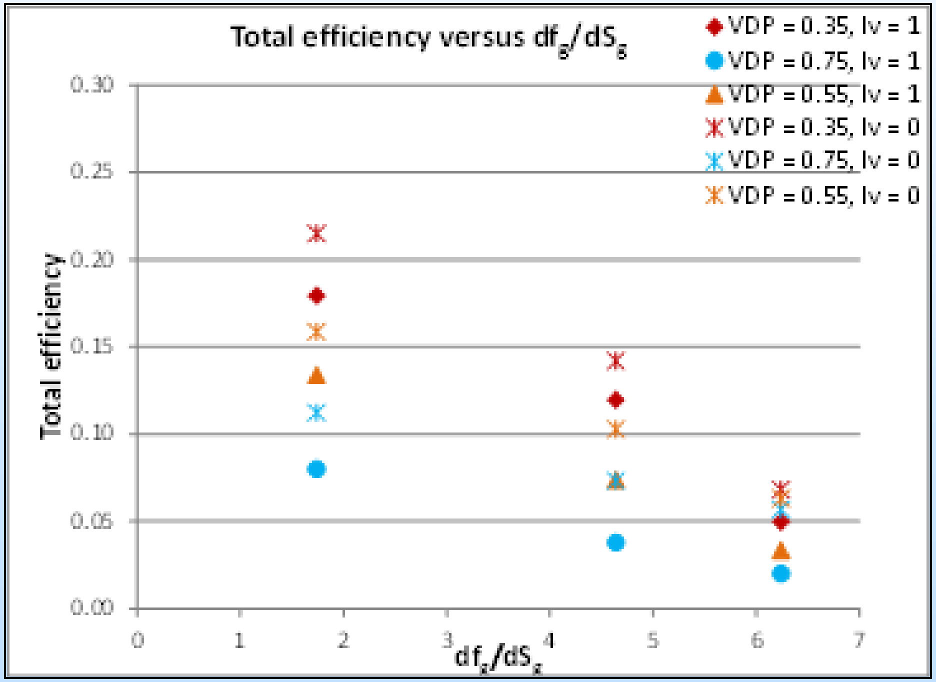
If P_D can be predicted, then q v/s ΔP relationship can be established

Next steps ⇨ Fitting data $P_D = f\{df_g/dS_g; V_{DP}, I_v\}$

Simplified Physics Based Models

Sweep Efficiency

$$R_{CO_2}^2 = \frac{Q}{\pi\phi H \bar{S}_g E_v} = \frac{Q}{\pi\phi H E_s}$$



If E_S can be predicted, then R_{CO2} can be estimated

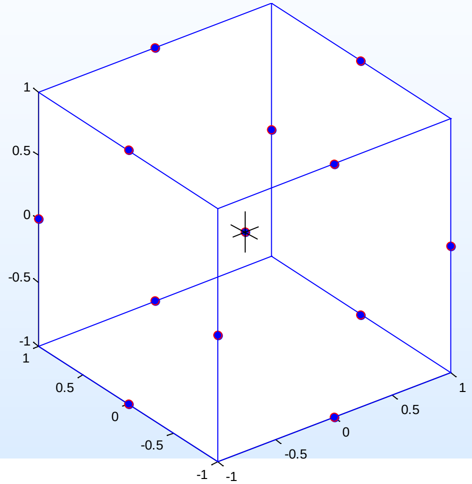
Next steps ⇨ Fitting data

$E_S = f\{df_g/dS_g; V_{DP}, I_{v,} N_G\}$

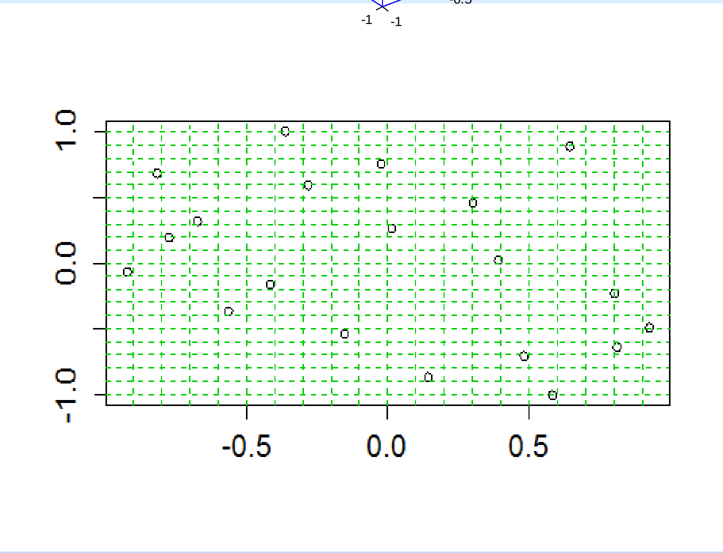
Statistical Learning Based Models

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” model
- Two common options
  - Box-Behnken (BB) design
    3-pt + quadratic response surface
  - Latin Hypercube sampling (LHS)
    multi-point + higher-order model



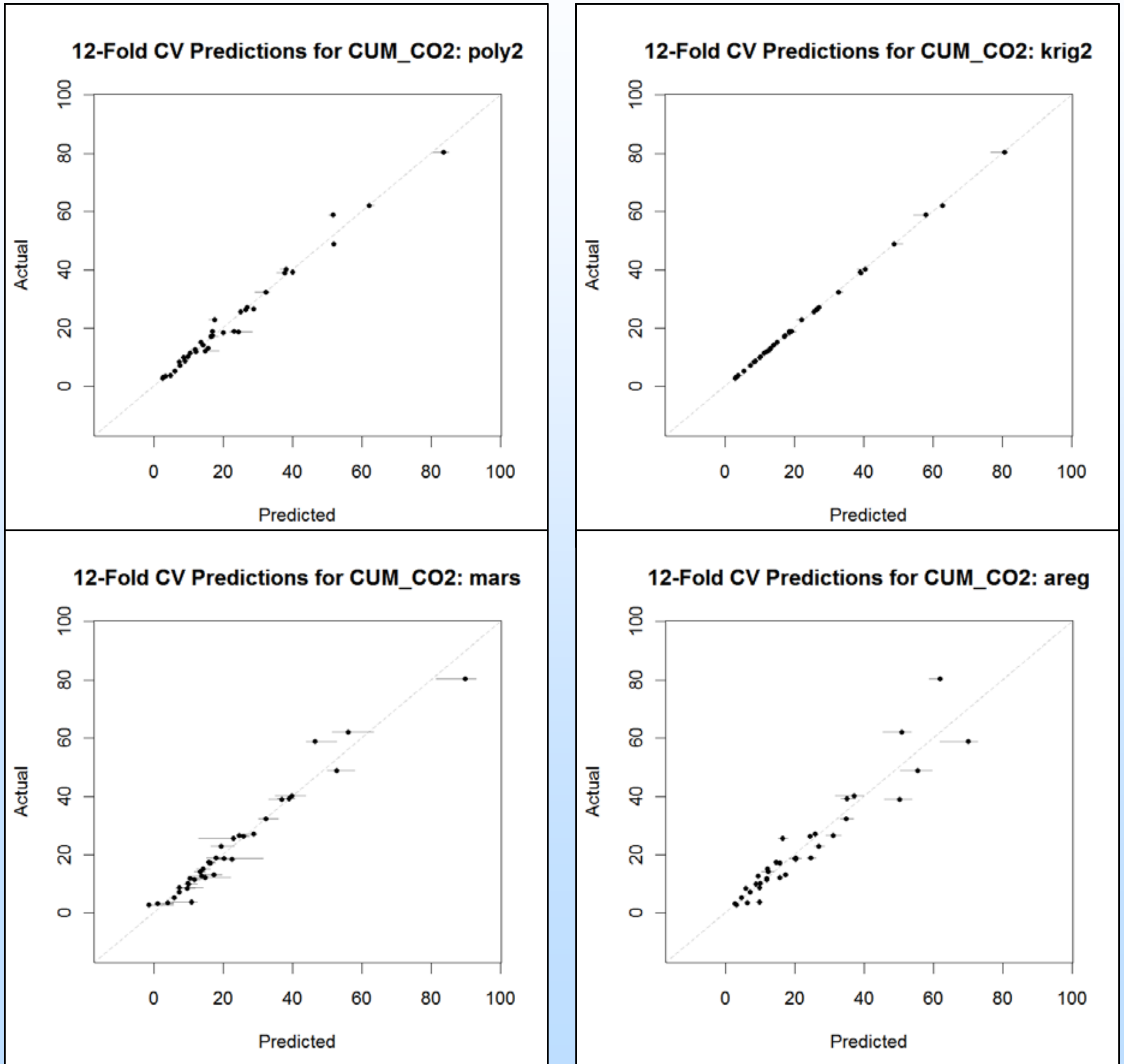
BB



LHS

Statistical Learning Based Models

Example - Metamodel Fits

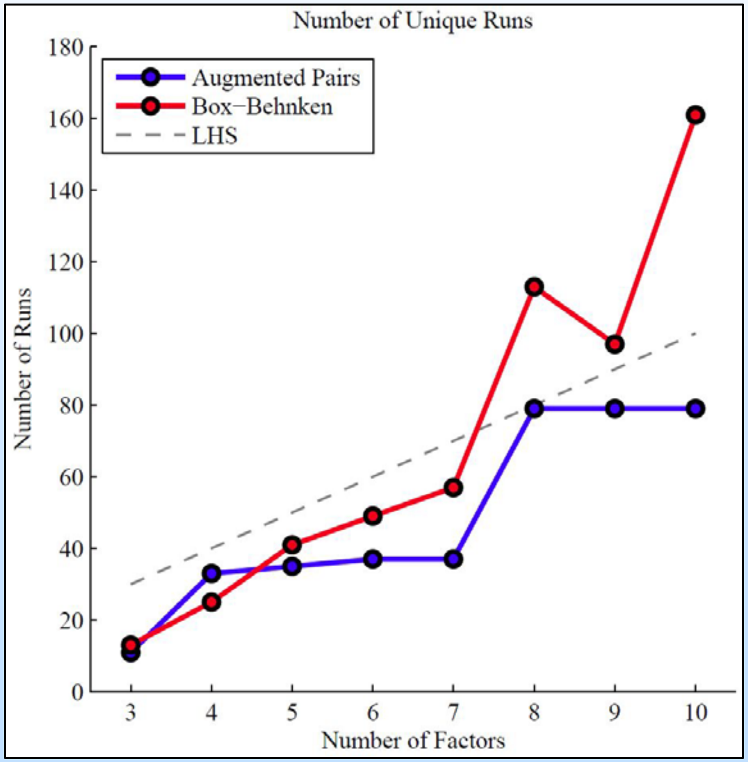


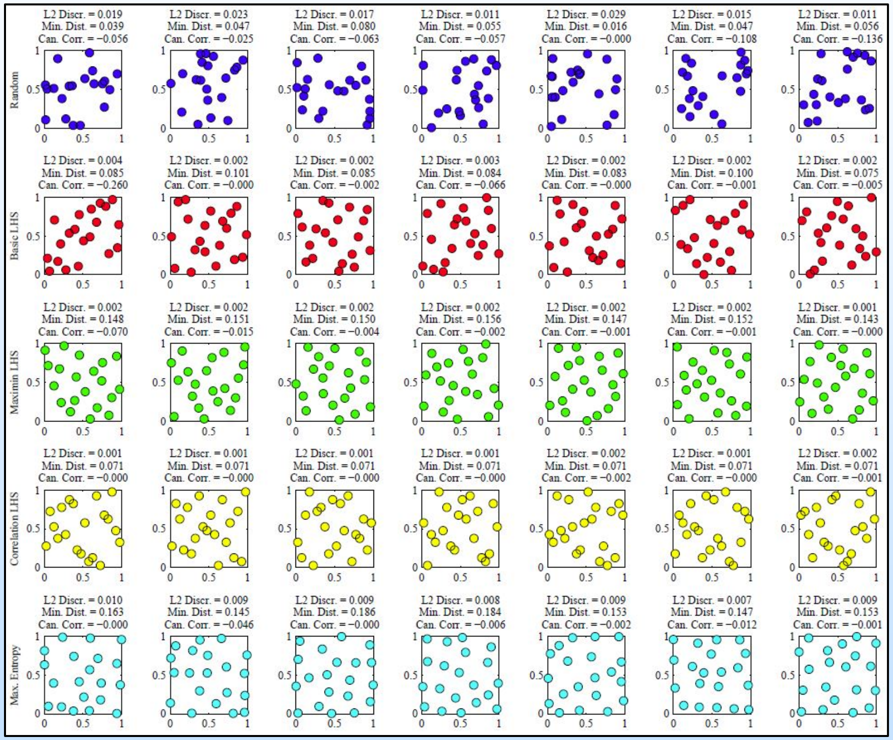
- Data from 2-D STOMP simulations of CO_2 injection into closed systems (Arches province)
- 36 run full-factorial design
  - 3 stratigraphic columns (injection depth)
  - 4 well patterns
  - 3 permeability groups
- Cross validation using 12 mutually exclusive subsets (33 training + 3 test data points) with 100 replicates
- Similar results for CO2_R and PCT_CO2

Statistical Learning Based Models

Generation of Experimental Designs

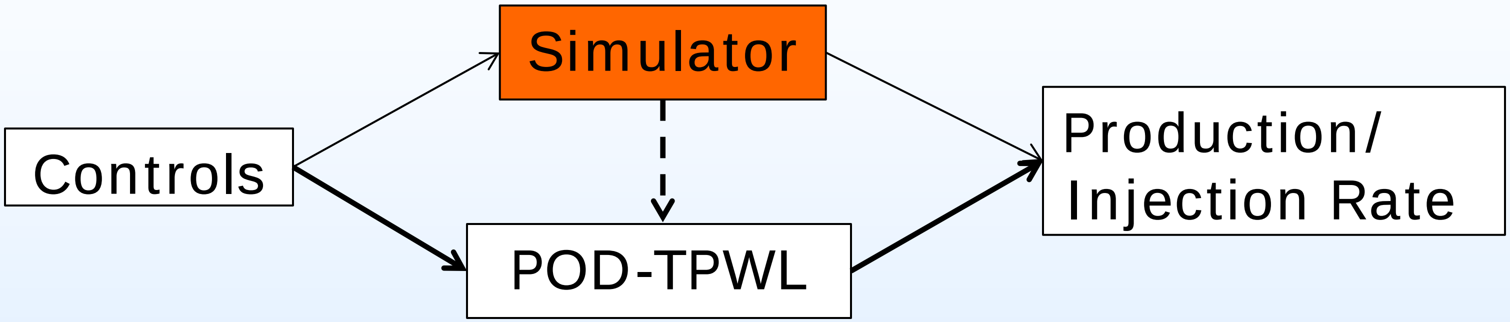
Box-Behnken Alternative





Alternative Space-Filling Designs

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

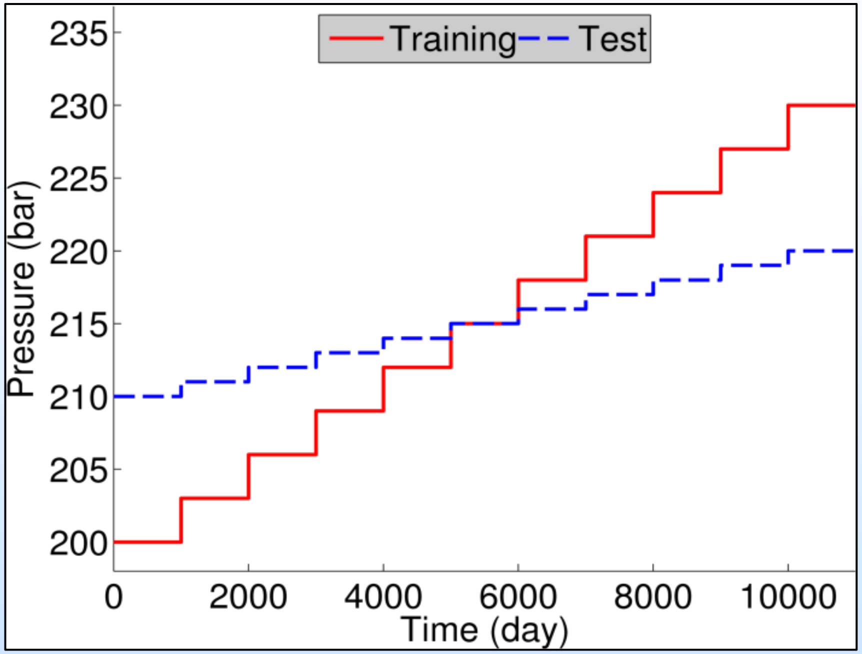
Background (2)

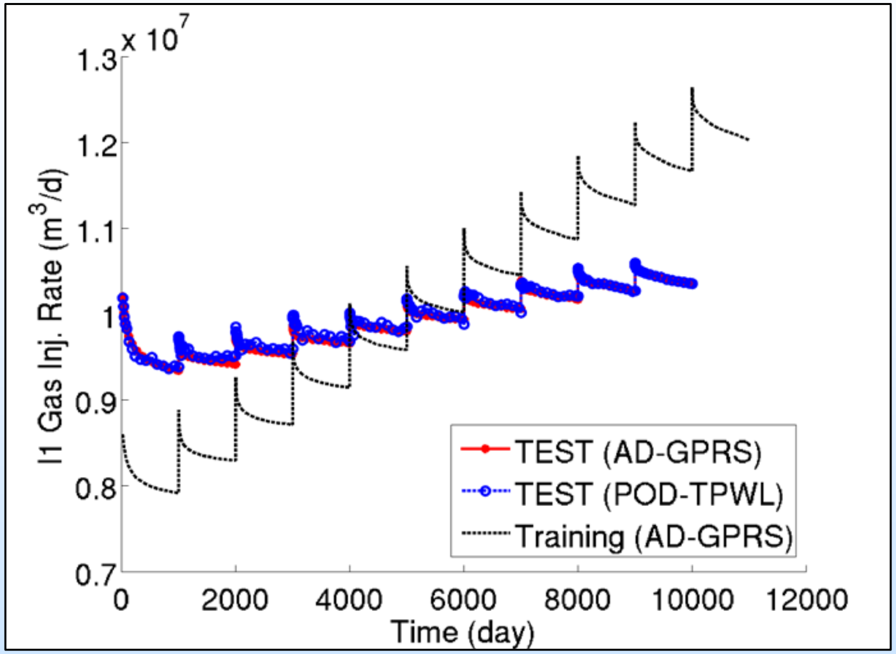
Order reduction		Nonlinearity treatment		Linear expressions w/ 100s of variables
⇩		⇩		⇩
POD	+	TPWL	=	POD-TPWL

- 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

Example – POD-TPWL Performance





	AD-GPRS	POD-TPWL Construction	POD-TPWL (Test)
Run Time	~120s	~360s	~2s

Accomplishments to Date

SPBM

- Completed sensitivity analyses to identify factors influencing reservoir/caprock pressure buildup and CO_2 plume migration
- Identified possible predictive model functional forms for dimensionless injectivity and CO_2 storage efficiency

SLBM

- Completed evaluation of metamodeling techniques (2^{nd} order polynomial, kriging, MARS, ACE)
- Completed Box-Behnken design based simulations for generating response surface based simplified models

ROMBM

- Investigated applicability of POD-TPWL for CO_2 injection into saline aquifers using a compositional simulator
- Evaluated different constraint reduction approaches

Summary

SPBM

- Developed insights into two-phase region injectivity and sweep based on detailed simulations
- Next FY's work will focus on insights for pressure buildup and developing predictive models

SLBM

- Evaluated metamodeling techniques and approaches for generating experimental designs
- Next FY's work will focus on fitting metamodels to BB and LHS simulations and comparing their predictions

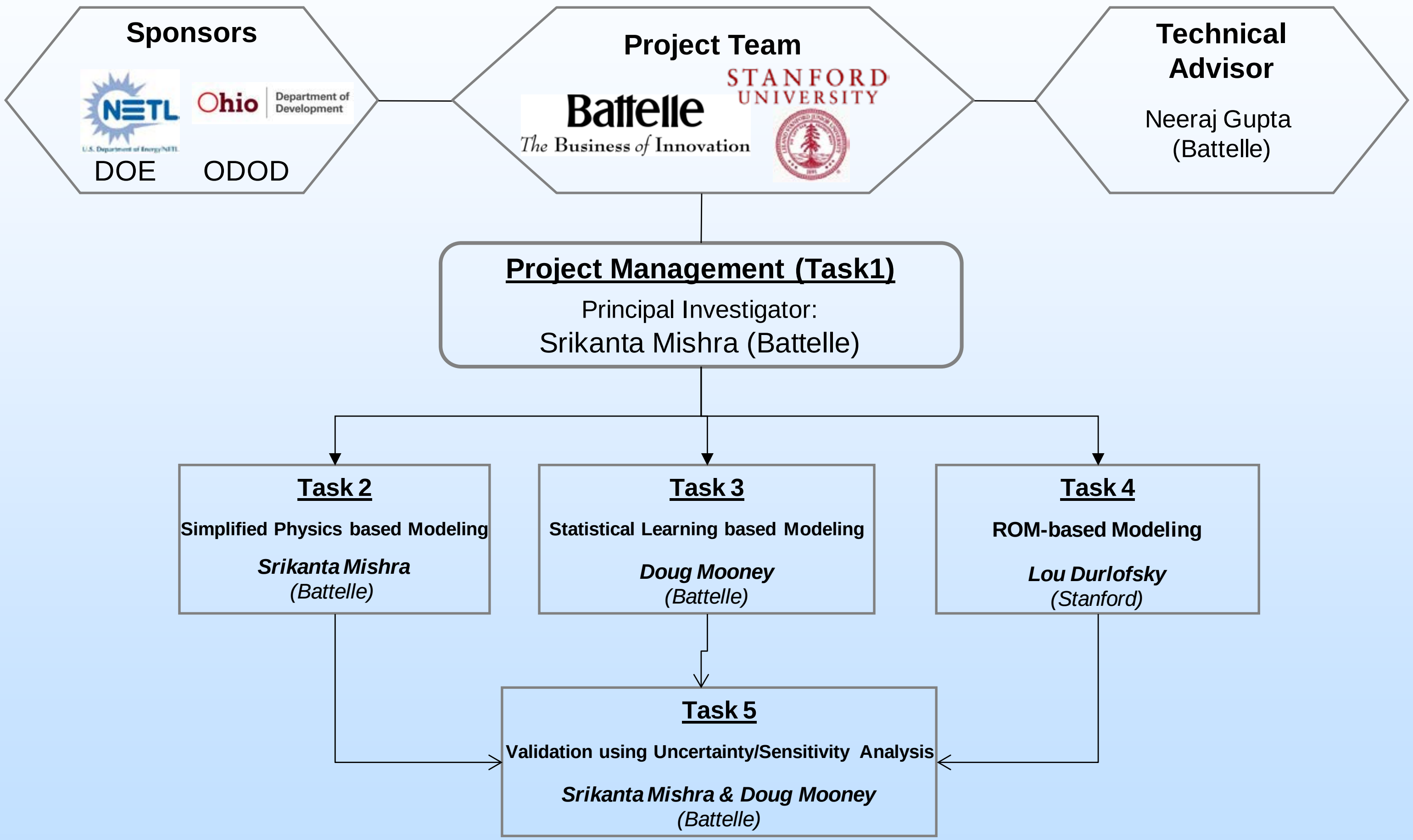
ROMBM

- Implemented POD-TPWL for saline aquifer CO_2 injection
- Next FY's work will focus on improving accuracy, stability and robustness of selected POD-TPWL schemes

Appendix

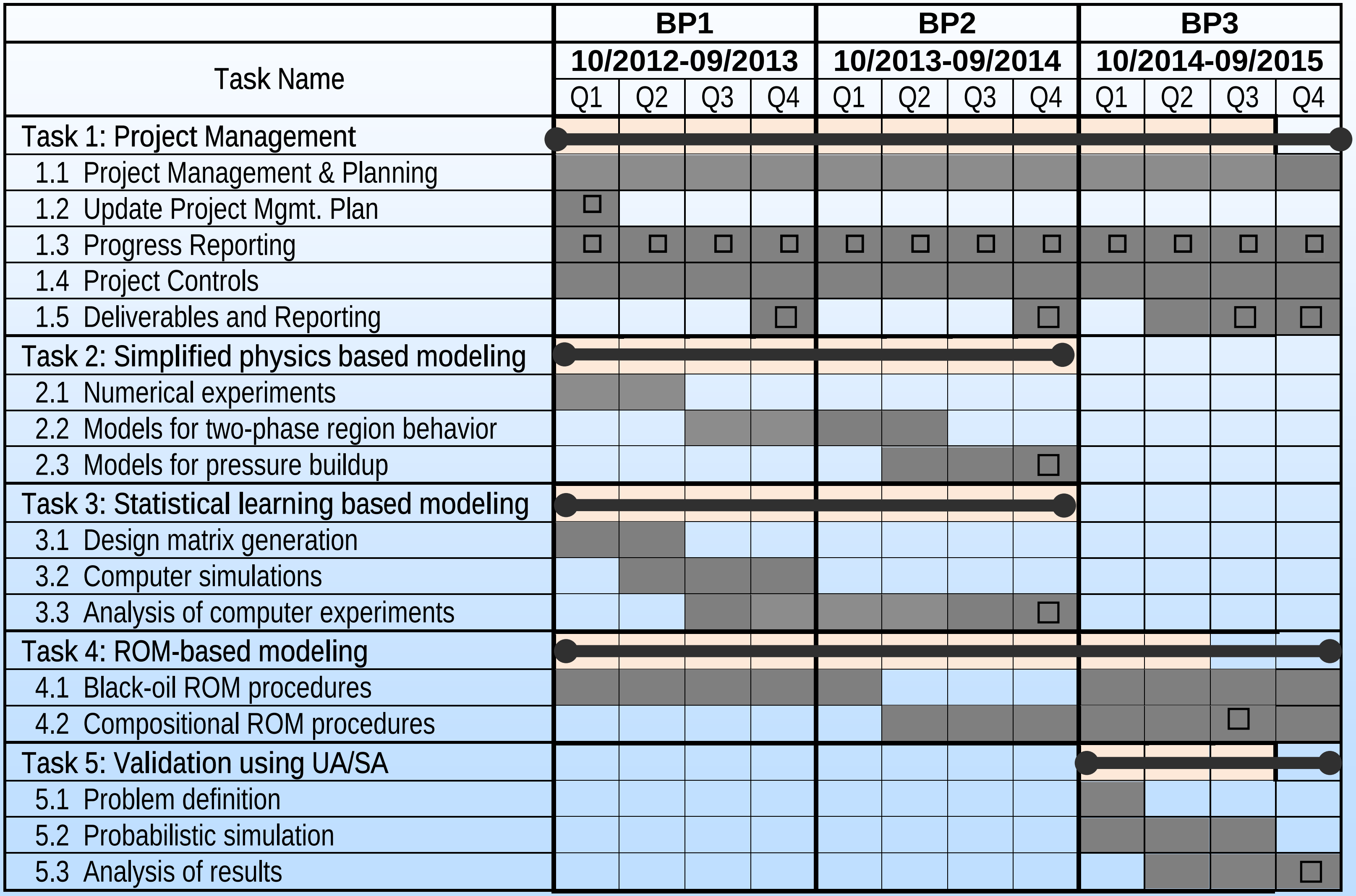
These slides will not be discussed during the presentation, but are mandatory

Organization Chart



Project Manager – Michael McMillian (DOE)

Gantt Chart



BP1
10/2012-09/2013
BP2
10/2013-09/2014
BP3
10/2014-09/2015
Task Name
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
1.3 Progress Reporting
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

Bibliography

- Journal, multiple authors:

  - Schuetter, J., Mishra, S. and Mooney, D., 2013, Evaluation of metamodeling techniques for CO2 geologic sequestration. Computers and Geoscience (to be submitted).
  - Ravi Ganesh, P. and Mishra, S., 2013, Simplified predictive modeling of CO_2 geologic sequestration in saline formations: insights into key parameters governing buoyant plume migration and pressure propagation. SPE Reservoir Evaluation and Engineering (to be submitted).