PS Fundamental Analysis of Heterogeneity and Relative Permeability on CO_2 Storage and Plume Migration*

Nathan Moodie[1], Brian McPherson[1], Si-Yong Lee[1], and Prashanth Mandalaparty[1]

Search and Discovery Article #80330 (2013)**
Posted October 29, 2013

*Adapted from a poster presentation given at AAPG Rocky Mountain Section Meeting, Salt Lake City, Utah, September 22-24, 2013

[1]University of Utah, Salt Lake City, Utah (nathan.moodie@m.cc.utah.edu)

Abstract

Relative permeability is a critical flow parameter for accurate forecasting of long-term behavior of CO_2 in the subsurface. In particular, for clastic formations, small-scale (cm) bedding planes can have a significant impact on multiphase CO_2-brine fluid flow, depending on the relative permeability relationship assumed. Such small-scale differences in permeability attributable to individual bedding planes may also have a substantial impact on predicted CO_2 storage capacity and long-term plume migration behavior. Relative permeability model calibration in this study was accomplished by analyzing previously published laboratory-scale measurements of relative permeability of Berea sandstone. A core-scale model of the flow test was created in TOUGHREACT to elucidate the best-fit relative permeability formulation that matched experimental data. Among several functions evaluated, best-fit matches between TOUGHREACT flow results and experimental observations were achieved with a calibrated van Genuchten-Mualem function. Using best-fit relative permeability formulations, a model of a small-scale Navajo Sandstone reservoir was developed, implemented in TOUGHREACT with the ECO_{2h} module. The model was one cubic meter in size, with eight individual lithofacies of differing permeability, instigated to mimic small-scale bedding planes. The model assumes that each lithofacies has a random permeability field, resulting in a model with heterogeneous lithofacies. Three different relative permeability functions were then evaluated for their impact on flow results for each model, with all other parameters maintained constant. Results of this analysis suggest that CO_2 plume movement and behavior are directly dependent on the specific relative permeability formulation assigned, including the assumed irreducible saturation values of CO_2 and brine. Model results also illustrate that, all other aspects held constant, different relative permeability formulations translate to significant contrasts in CO_2 plume behavior.

Fundamental analysis of heterogeneity and relative permeability on CO_2 storage and plume migration

Nathan Moodie, Brian McPherson, Si-Yong Lee, Prashanth Mandalaparty

Introduction

Data for the relative permeability of CO_2 and water/brine for most reservoir rocks is lacking in the current literature. Relative permeabilities of the Navajo sandstone in particular have not been measured, or at least are not published. One of our research goals was to investigate the validity of using experimentally-derived relative permeability functions for a well-known formation, in this case the Berea sandstone, to calibrate a relative permeability function effective for modeling CO_2 behavior in Navajo sandstone.

Numerical Model

Relative Permeability Parameters

	Linear	van Genuchten - Pruess[1]	van Genuchten - Krevor[11]
Lambda - λ	n/a	0.457	0.67
Water i-sat. (S_{lr})	0.2	0.15	0.2
Gas sat. (S_{gs})	1	n/a	n/a
Water Sat. (S_{ls})	1	1	1
CO2 i-sat. (S_{gr})	0.05	0.1	0.05

1 Values are from Pruess et.al. (1999)

11 Values are modified to match the Berea sandstone as measured by Krevor et.al. (2011)

Layer Data - Core Flood and Bedform Models

Layer Name	TOUGH code	Permeability mD	Permeability m^2	Standard deviation mD	Standard deviation m^2
Berea Model					
Core	core	300	2.96E-13	n/a	n/a
Navajo Models					
Wind ripple lamina	WRL0x	280	2.76E-13	119	1.17E-13
Wind ripple lamina/Grain flow	WRLGx	388	3.83E-13	171	1.69E-13
Grain flow	GF00x	560	5.53E-13	311	3.06E-13
Course lag	CL00x	5346	5.28E-12	2329	2.30E-12

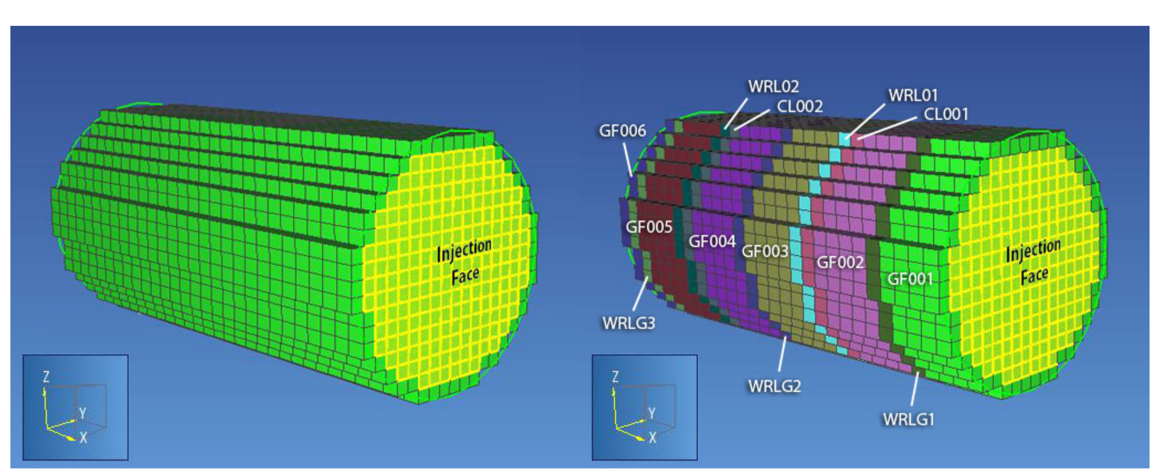
Core flood model has dual injection (COM1,COM3) along one face of the model. There are 193 injection cells

Core Scale Model - Injection Rates

% flow H_2O	% flow CO_2	mass flow per cell (Kg/s) COM1 H_2O	mass flow per cell (Kg/s) COM3 CO_2
1	0	1.28E-06	0.00E+00
0.95	0.05	1.22E-06	1.81E-08
0.9	0.1	1.16E-06	3.63E-08
0.8	0.2	1.03E-06	7.25E-08
0.7	0.3	8.99E-07	1.09E-07
0.5	0.5	6.42E-07	1.81E-07
0.3	0.7	3.85E-07	2.54E-07
0.2	0.8	2.57E-07	2.90E-07
0.1	0.9	1.28E-07	3.26E-07
0.05	0.95	6.42E-08	3.45E-07
0	1	0.00E+00	3.63E-07

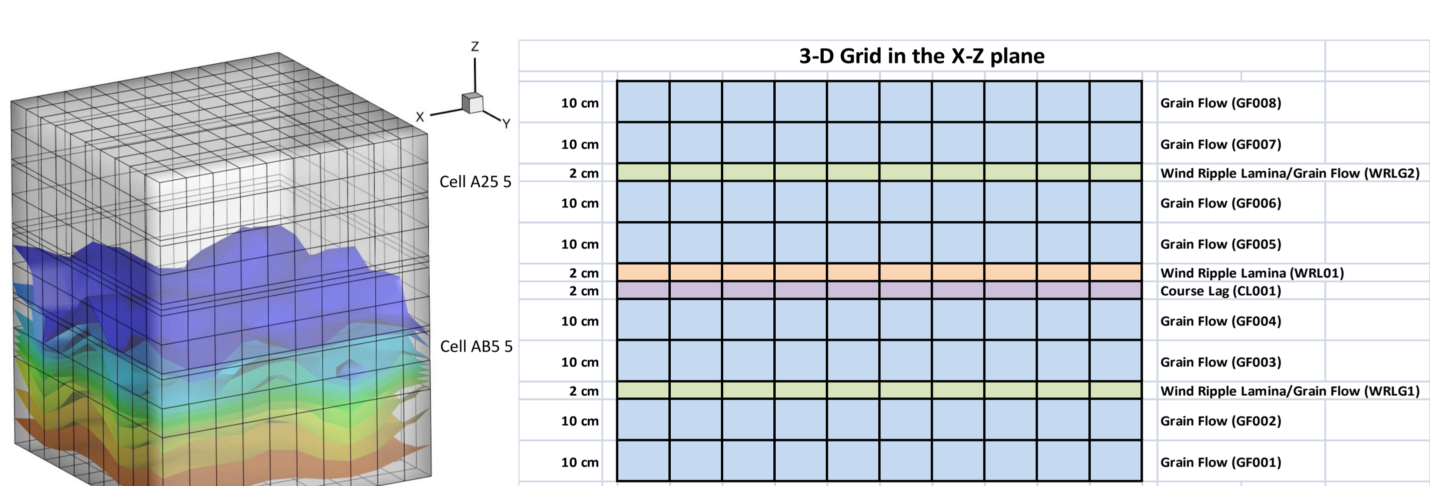
Model Domain – Core Flood Model

- Total dimensions are 2 inches in diameter by 4 inches long
- 20x20x28 cells with a cell volume of 2.87E-08 m^3



Model Domain – Navajo Bedform Model

- Total dimensions are 1 meter by 1 meter by 0.88 meters with 10x10x12 cells
- Cell volume of 1.0e-03 m3 for the GF00x layers and 2.0E-04 m3 for the WRLGx, WRL0x, and CL00x layers.
- There are no injection cells in the Bedform model. There is a dummy layer at the bottom of the model with 50% CO_2 saturation.



Relative Permeability Curve fitting

To get a fair representation of the experimental relative permeability data for Berea sandstone, a single cell "batch" model was created and specific CO_2 mass fractions were assigned. The relative permeability data was then plotted against the Berea sandstone experimental data to determine which relative permeability function and associated parameters gave the best fit. While the Brooks-Corey function gave the best fit it was not a function that was part of TOUGH2. The van Genuchten function gave almost as good a fit so it was used to represent the experimental Berea sandstone curve as measured by Krevor et.al. (2011).

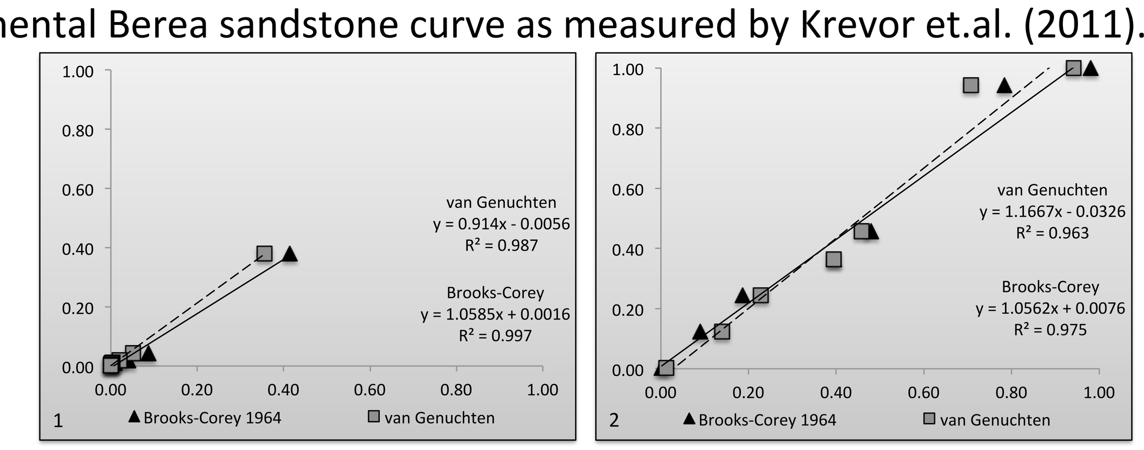
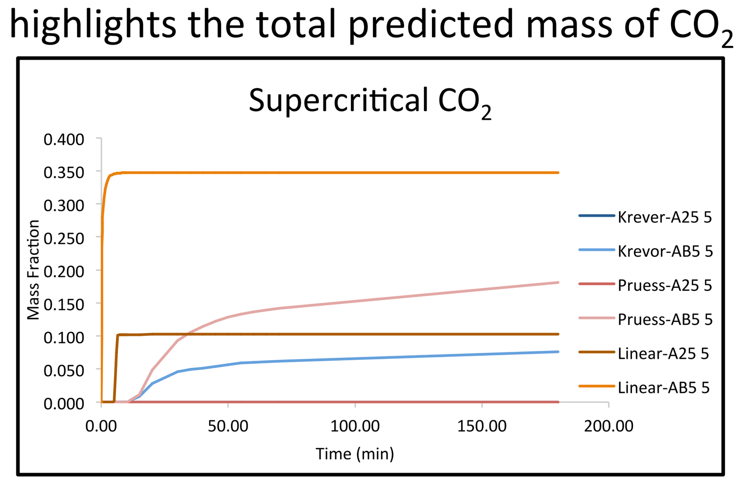


Chart 1,2. Relative permeability of gas, chart 1, and water, chart 2, predicted by the Brooks-Corey and van Genuchten-Mualem functions compared to measured Berea Sandstone data. The x-axis is the fit experimental relative permeability data and the y-axis is the predicted relative permeability data from the functions listed.

Navajo Sandstone Bedform Model Results

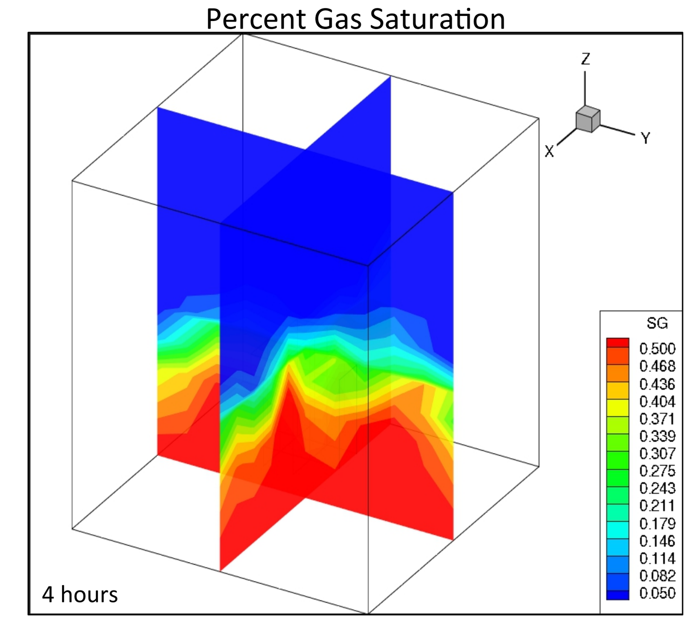
The plots show the supercritical CO_2 saturation for the whole domain and the chart highlights the saturation values at two location in the model; cell AB5 5 is near the bottom and cell A25 5 is near the top of the model domain. The table highlights the total predicted mass of CO_2 at the end of the simulation.



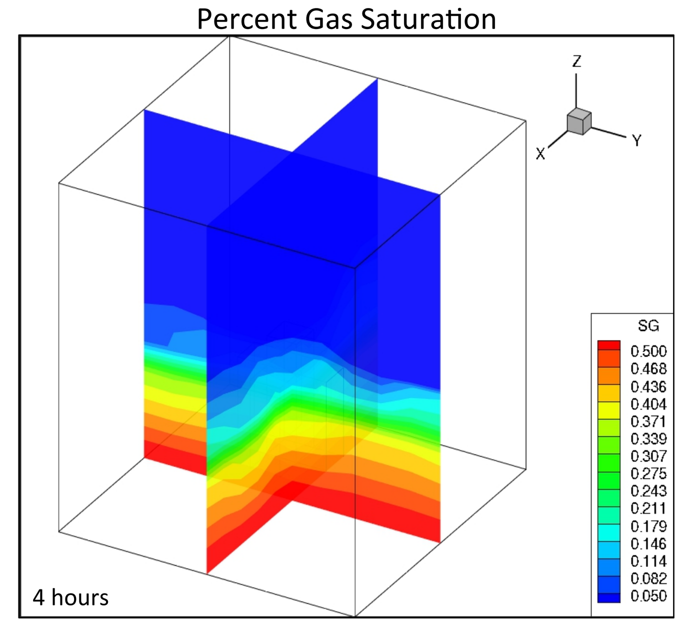
Total CO_2 Predicted at 10kPa

	Supercritical (Kg)	Dissolved (Kg)
Krevor	4.906	2.814
Pruess	8.720	2.750
Linear	27.721	4.953

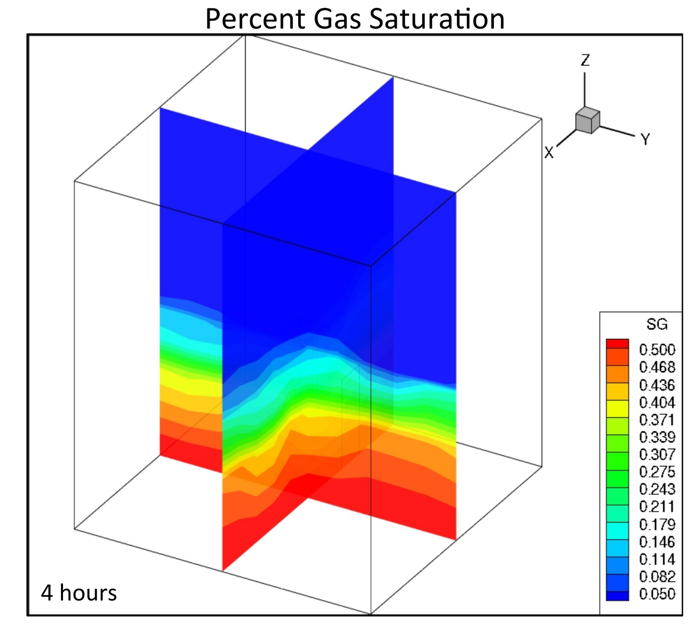
Linear Curve
Percent Gas Saturation



van Genuchten- Krevor
Percent Gas Saturation



van Genuchten – Pruess Curve
Percent Gas Saturation



Conclusions

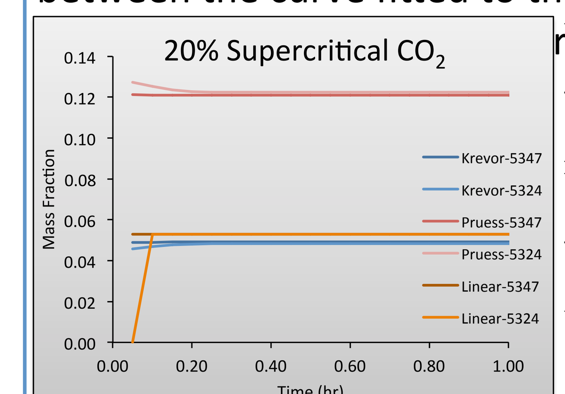
The results of this analysis has shown that the choice of relative permeability function and the parameters used in that function can have a huge impact on predicted CO_2 plume migrations, phase behavior, and storage capacity. It was clear that having experimentally derived relative permeability curves for the target reservoir is essential for getting accurate predictions of the amount of CO_2 and phase behavior. Our study has indicated that supercritical phase CO_2 is very sensitive to the relative permeability curve used in the numerical simulation.

Core Flood Model Results

Berea Sandstone Core model — Navajo Sandstone Core model

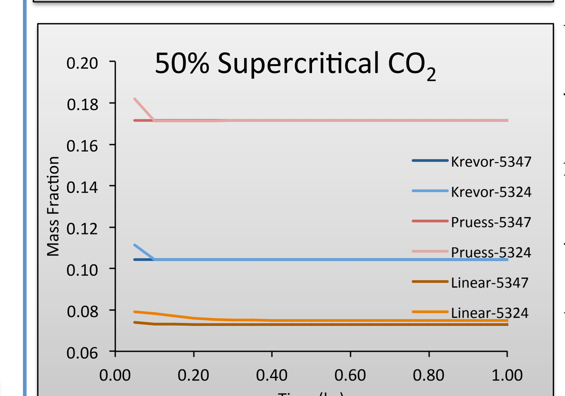
The charts show the mass fraction of CO_2 at two location in the core, cell 5347 is near the injection face and cell 5324 is near the other end of the core. The tables show the average difference in mass of predicted CO_2 between the curve fitted to the Krevor et.al. (2011) experimental data and the curves using the Linear and rs.

Berea Sandstone Core model



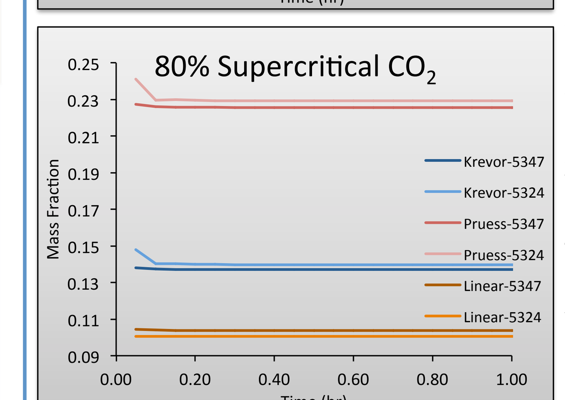
Supercritical CO_2 at 20% fraction flow	Difference (g)	
Pruess	0.031	1.23%
Linear	-1.875	-74.37%

Dissolved CO_2 at 20% fraction flow	Difference (g)	
Pruess	-0.033	-1.86%
Linear	0.100	5.62%



Supercritical CO_2 at 50% fraction flow	Difference (g)	
Pruess	0.069	1.13%
Linear	-4.929	-81.08%

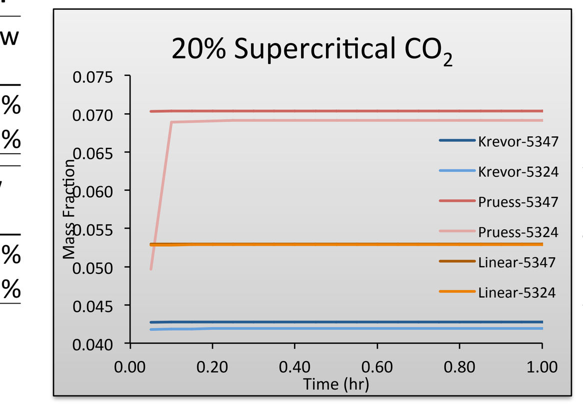
Dissolved CO_2 at 50% fraction flow	Difference (g)	
Pruess	-0.003	-0.17%
Linear	0.157	8.60%



Supercritical CO_2 at 80% fraction flow	Difference (g)	
Pruess	-0.539	-5.55%
Linear	-6.886	-70.87%

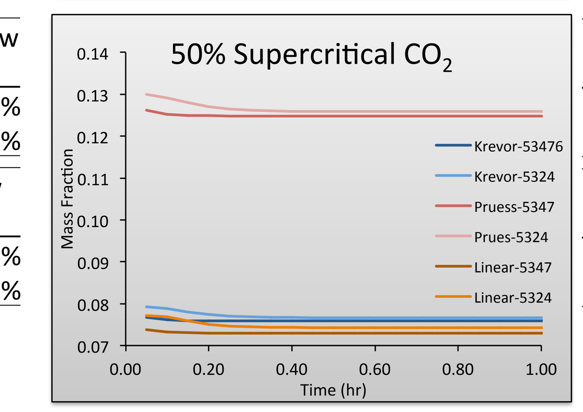
Dissolved CO_2 at 80% fraction flow	Difference (g)	
Pruess	0.041	2.13%
Linear	0.174	9.07%

Navajo Sandstone Core model



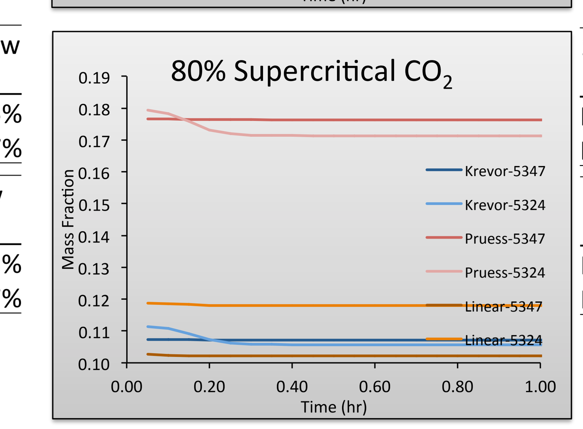
Supercritical CO_2 at 20% fraction flow	Difference (g)	
Pruess	0.274	64.94%
Linear	0.107	25.39%

Dissolved CO_2 at 20% fraction flow	Difference (g)	
Pruess	-0.044	-2.86%
Linear	-0.018	-1.14%



Supercritical CO_2 at 50% fraction flow	Difference (g)	
Pruess	0.626	58.69%
Linear	-0.018	-1.90%

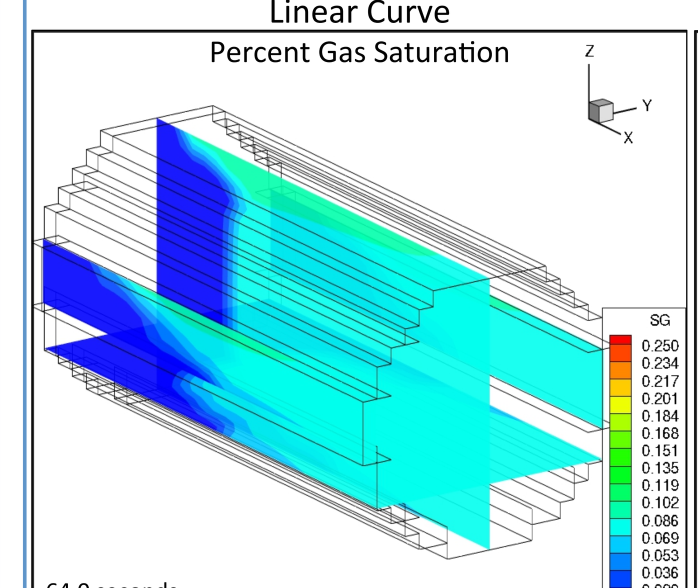
Dissolved CO_2 at 50% fraction flow	Difference (g)	
Pruess	-0.086	-5.28%
Linear	0.003	0.17%



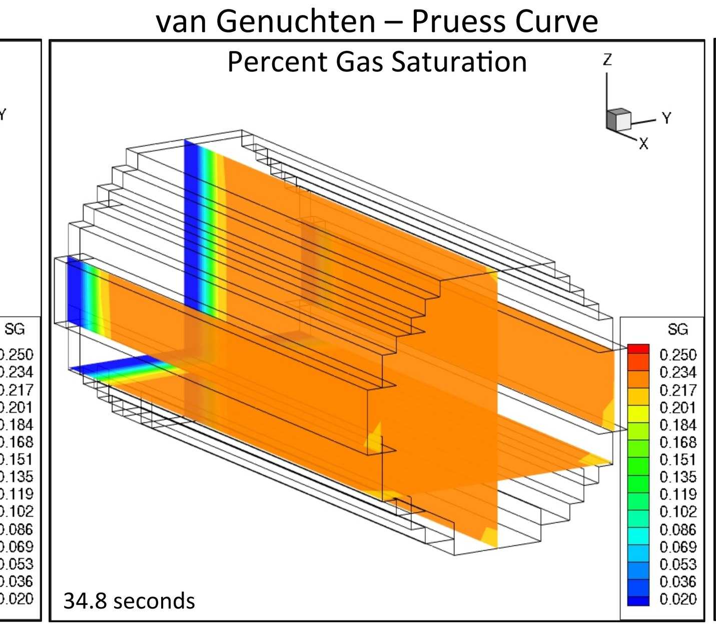
Supercritical CO_2 at 80% fraction flow	Difference (g)	
Pruess	1.551	64.36%
Linear	-0.115	-4.79%

Dissolved CO_2 at 80% fraction flow	Difference (g)	
Pruess	-0.130	-7.64%
Linear	0.009	0.51%

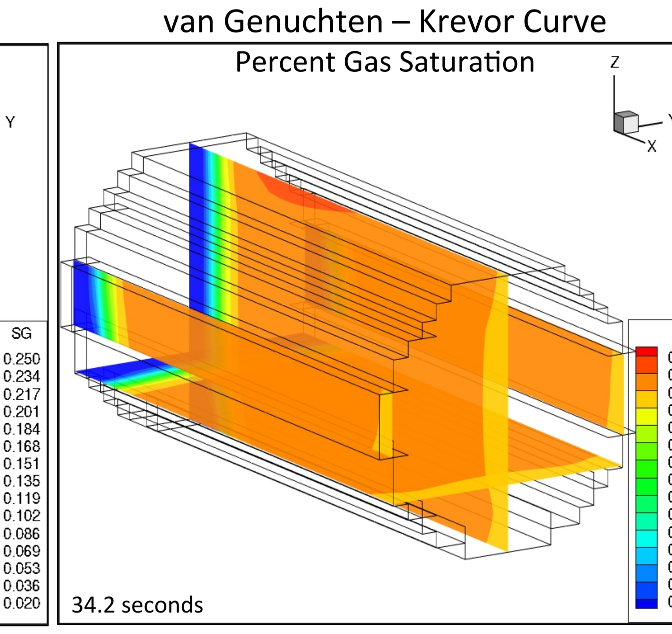
Berea Model – 50% H_2O 50% CO_2
Linear Curve
Percent Gas Saturation



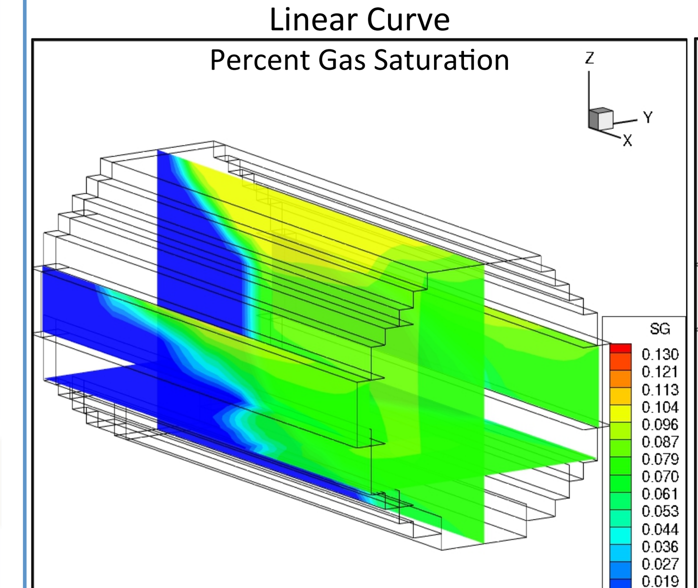
Berea Model – 50% H_2O 50% CO_2
van Genuchten – Pruess Curve
Percent Gas Saturation



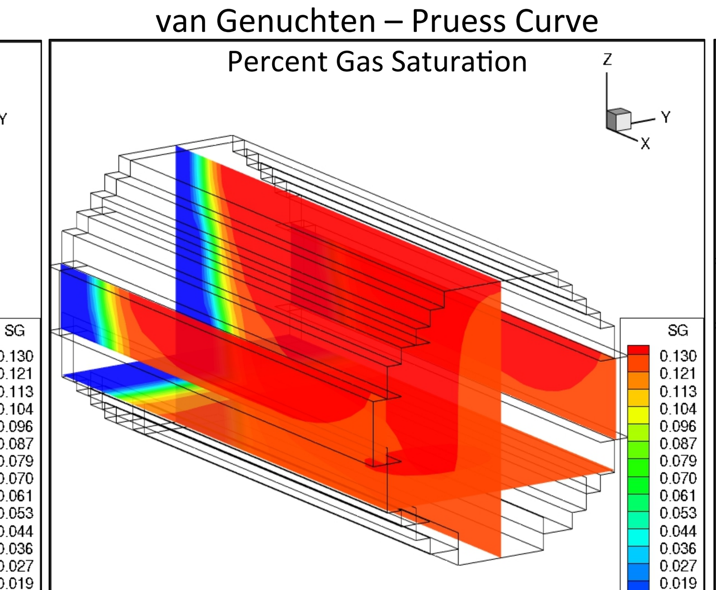
Berea Model – 50% H_2O 50% CO_2
van Genuchten – Krevor Curve
Percent Gas Saturation



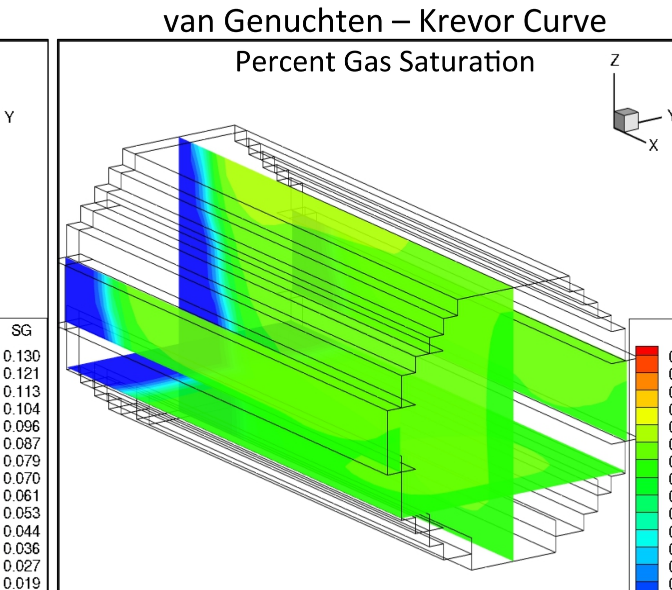
Navajo Model – 50% H_2O 50% CO_2
Linear Curve
Percent Gas Saturation



Navajo Model – 50% H_2O 50% CO_2
van Genuchten – Pruess Curve
Percent Gas Saturation



Navajo Model – 50% H_2O 50% CO_2
van Genuchten – Krevor Curve
Percent Gas Saturation



Acknowledgement

Southwest Partnership

University of Utah
201 Presidents Circle Room 201
Salt Lake City, Utah 84112
nathan.moodie@m.cc.utah.edu

BERKELEY LAB
LAWRENCE BERKELEY NATIONAL LABORATORY

TOUGH2