Maximization of Permanent Trapping of CO_2 in the Highest-Porosity Formations of the Rock Springs Uplift

Project Number: FE0004832

Mohammad Piri and Felipe Pereira

University of Wyoming

U.S. Department of Energy

National Energy Technology Laboratory
Carbon Storage R&D Project Review Meeting
Developing the Technologies and Building the Infrastructure for CO_2 Storage

August 2013

Presentation Outline

- Benefit to the Program
- Project Overview
- Technical Status
  - o Experimentation: core-flooding and IFT/CA
  - o Pore-scale modeling modeling
- Accomplishments to Date
- Summary

Benefit to the Program

- Program goal:
  - ‘Develop technologies that will support industries’ ability to predict CO_2 storage capacity in geologic formations to within ±30 percent.’

- Benefits statement:
  - The research project is focused on performing reservoir conditions experiments to measure steady-state relative permeabilities, residual saturations, interfacial tensions, and contact angles to inform models at pore, core, and reservoir scales. These can then be used to develop improved understanding of displacement mechanisms leading to design of strategies to maximize trapping.

Project Overview:
Goals and Objectives

- Goal:
  - The overall goal of this project is to provide information that will assist in maximizing the permanent trapping of supercritical CO_2 ($scCO_2$), and co-contaminants (referred to as 'mixed $scCO_2$') in deep saline aquifers.
- Objectives:
  - Measurement of reservoir conditions drainage and imbibition relative permeabilities, irreducible brine and residual mixed $scCO_2$ saturations and relative permeability scanning curves (hysteresis).
  - Characterization of wettability through measurements of contact angles and interfacial tensions under reservoir conditions.
  - Development of physically-based dynamic core-scale pore network model.
  - Development of new, improved high-performance modules for the UW-team simulator to provide new capabilities to the existing model in order to include hysteresis in the relative permeability functions, geomechanical deformation and an equilibrium calculation (for mixed $scCO_2$).
  - Validation of the compositional reservoir model against well-characterized unsteady-state core-flooding experiments.
  - Numerical study of long term permanent trapping of mixed $scCO_2$, through high-resolution numerical experiments taking into account reservoir heterogeneity, saturation history, dissolution, capillary trapping and geomechanical deformation.

Technical Status

Project includes two major groups of tasks (6 UW faculty members):

1. Experimentation and Modeling: Pore and Core Scales

- Task 2: Relative permeability measurements at reservoir conditions
- Task 3: IFT and CA measurements at reservoir conditions
- Task 4: Dynamic pore-scale modeling to predict k_r and P_c functions

2. Modeling and Simulation: Core and Field Scales

- Task 5: Reservoir modeling activities
- Task 6: Development of the UW-team compositional simulator
- Task 7: Geomechanics model development
- Task 8: Field-scale numerical experiment

Experimentation and Modeling
Pore and Core Scales

- Measurement of relative permeability functions
- Measurements of IFT and CA

- Development dynamic, parallel pore-scale network models

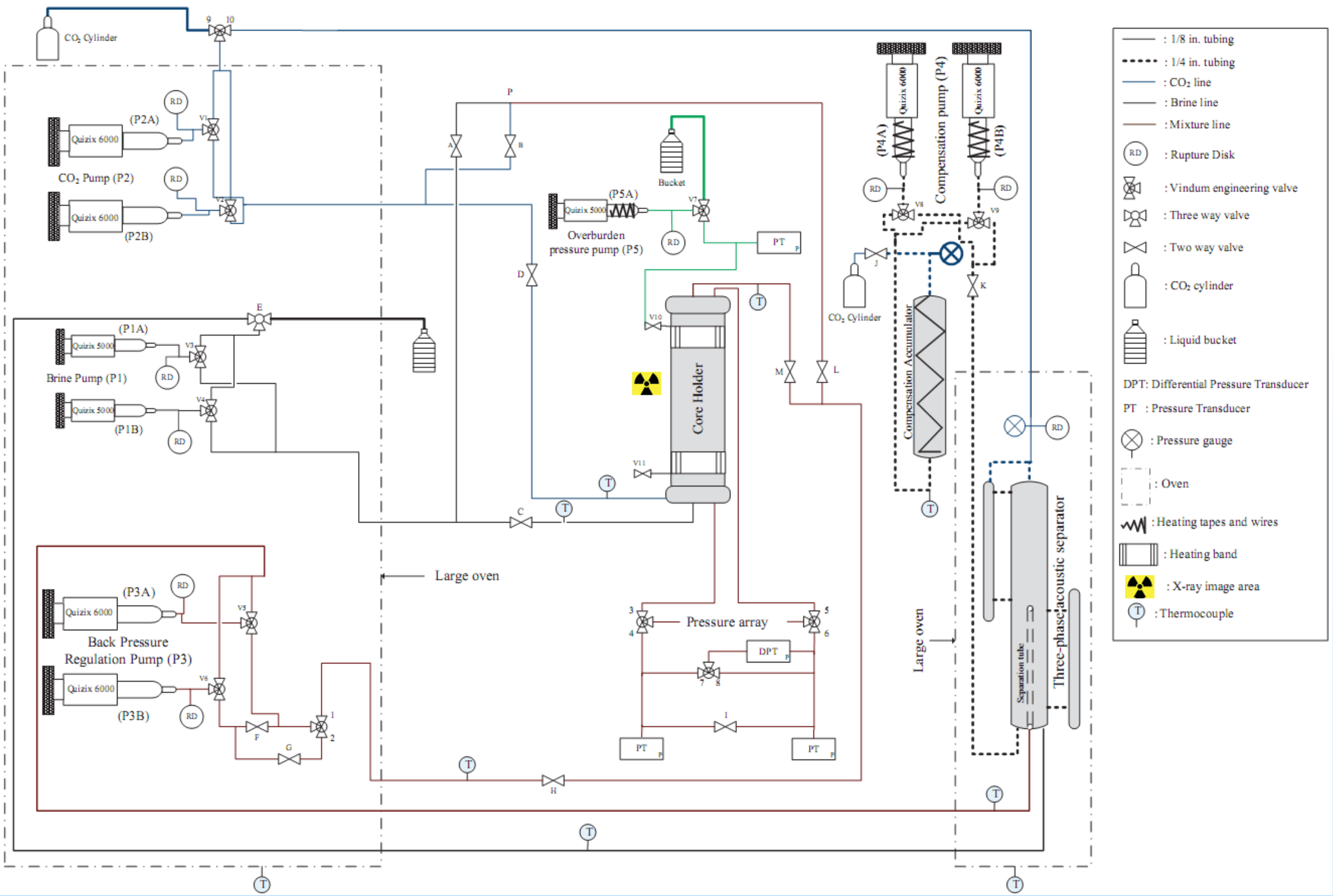
Measurement of $scCO_2$/brine steady-state drainage & imbibition relative permeabilities (Task 2)

CT scanner in vertical and horizontal orientations

Measurement of $scCO_2$/brine steady-state drainage & imbibition relative permeabilities (Task 2)

Vertical positioning system

Measurement of $scCO_2$/brine steady-state drainage & imbibition relative permeabilities (Task 2)



Core samples (Category A)

Nugget sandstone

- Core length: 14.8 cm
- Core diameter: 3.8 cm
- Porosity: 14.3 %
- Permeability (Brine): 312 mD
- Pore volume: 24.0 cc

Berea sandstone

- Core length: 15.0 cm
- Core diameter: 3.8 cm
- Porosity: 20.1 %
- Permeability (Brine): 50 mD
- Pore volume: 34.19 cc

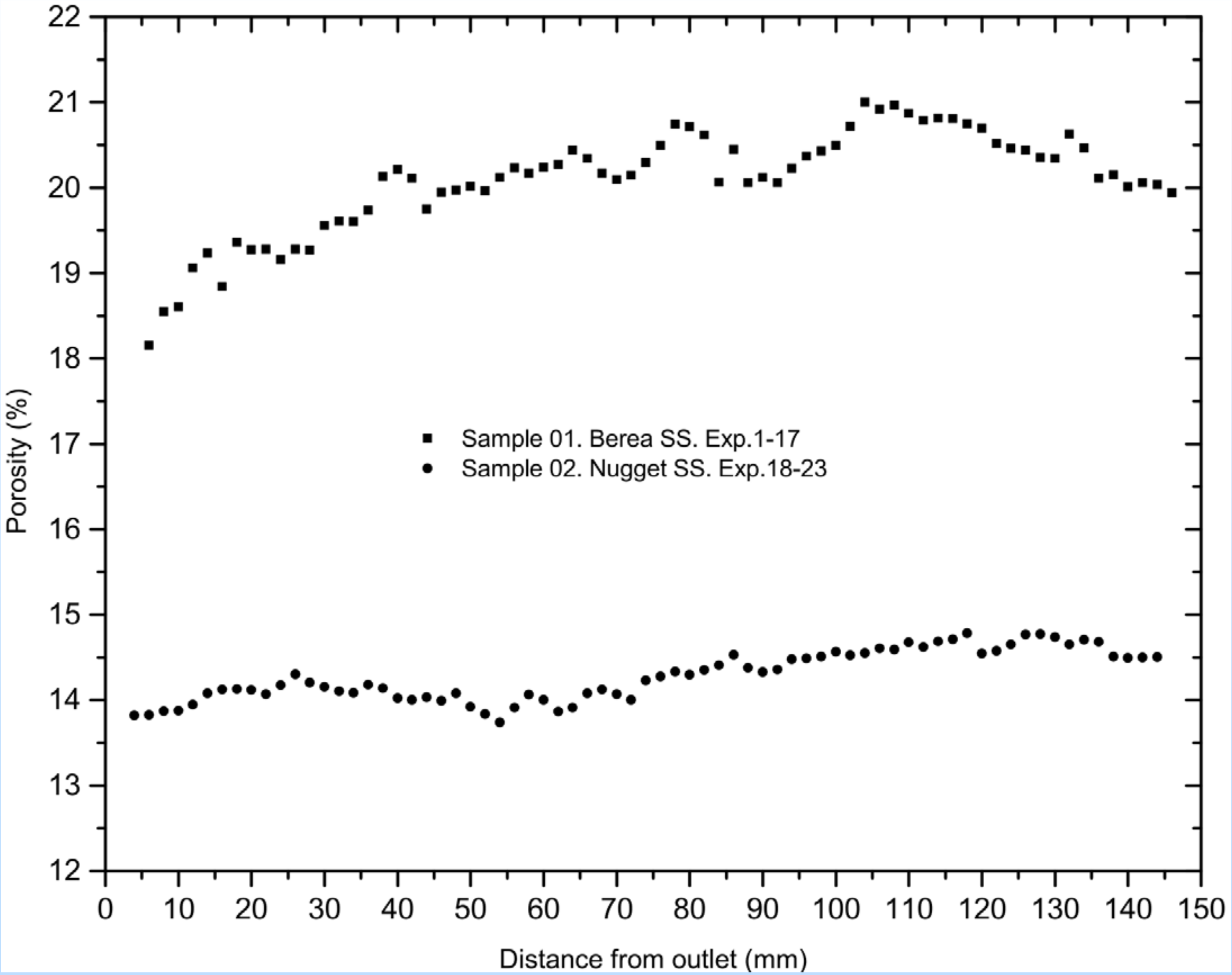
3.8 cm

14.8 cm

3.8 cm

15.0 cm

Core samples (Porosity)



Core-flooding conditions (Category A)

Gaseous Condition (group 1)

- Pressure: 3.46 MPa
- Temperature: 20 ° C
- Overburden pressure: 4.82 – 5.86 MPa

Supercritical Condition (group 2)

- Pressure: 11.0 MPa
- Temperature: 55 ° C
- Overburden pressure: 12.7 – 13.1 MPa

➢ Typical capillary number: 1.03×10^{-5}

➢ Sleeve: Viton (Teflon+ Aluminum foil)

➢ Wetted material: Hastelloy

➢ O-rings: Ultra High Molecular Weight (UHMW)- AFLAS

➢ Core-holder: Hassler type

➢ Brine composition:
- 10.0 wt% NaI
- 5.0 wt% NaCl
- 0.5 wt% $CaCl_2$

Fluid properties (Category A)

Fluid	Pressure MPa	Temperature °C	Viscosity cP	Density gr/cm^3	CO_2/Brine IFT mN/m*
Supercritical CO_2	11.0	55	0.044	0.393	38.15
Gaseous CO_2	3.46	20	0.016	0.081	51.24
Brine	11.0	55	0.91	1.126	-
Brine	3.46	20	1.57	1.125	-

Flow rates (Category A)

Experimental flow rates for CO_2 and chase brine injections

1- CO_2 injection

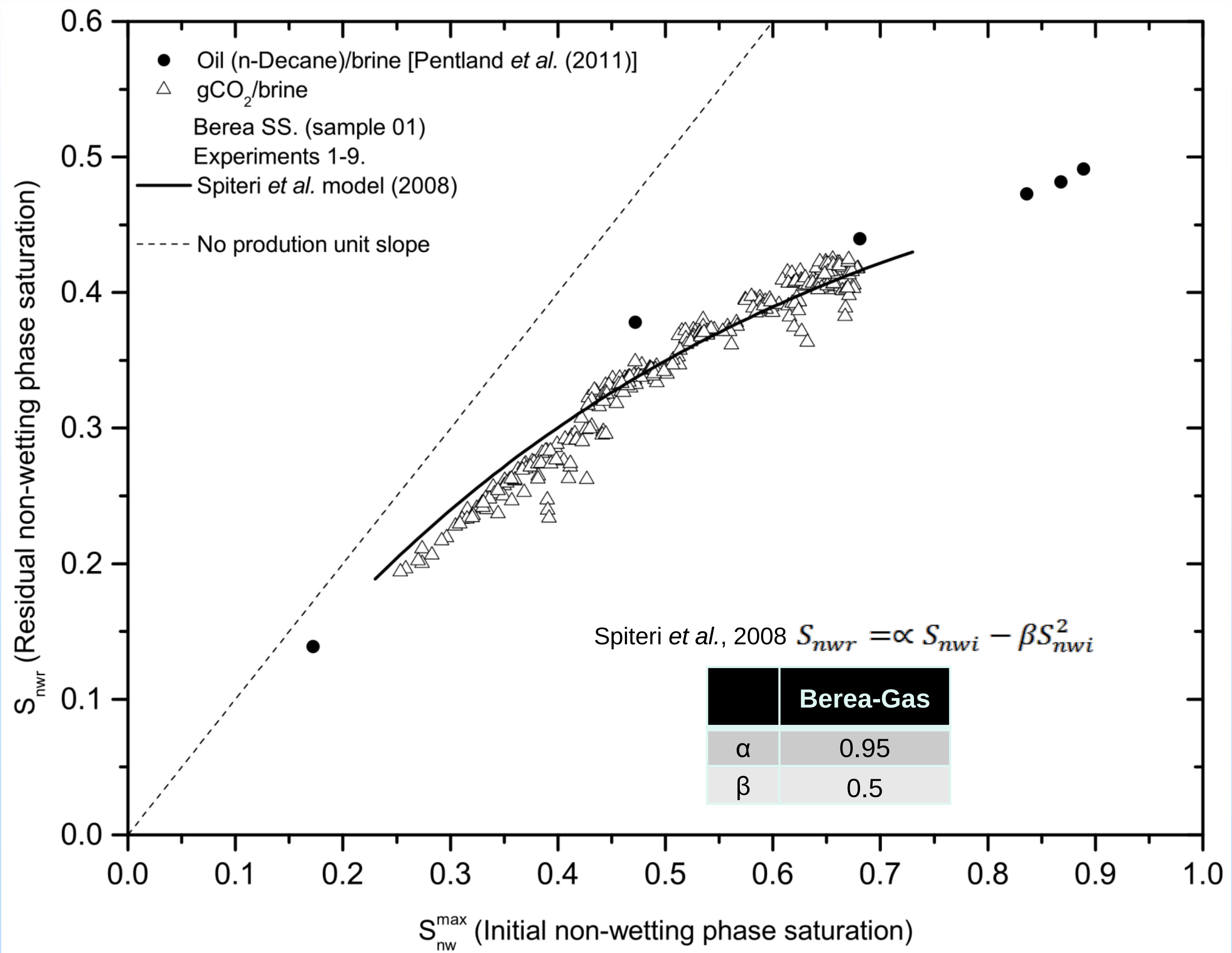
Sample	NWP	WP	0.125 cm^3/min	0.25	0.5	1.0	2.5	5	10	15	20	30	60	100	120
01-Berea SS	$scCO_2$	Brine		•	•	•	•	•	•	•	•				
01-Berea SS	gCO_2	Brine	•	•	•		•		•			•	•	•	•
02-Nugget SS	$scCO_2$	Brine		•	•	•	•	•	•						

2- Chase brine injection

- 1- Brine flow rate: Q_b=0.05-0.5 cm^3/min
- 2- Gradual increase in flow rate

- 1- 46 unsteady-state drainage and imbibition experiments
- 2- Full recirculation condition for all the experiments **regardless of flow rate**

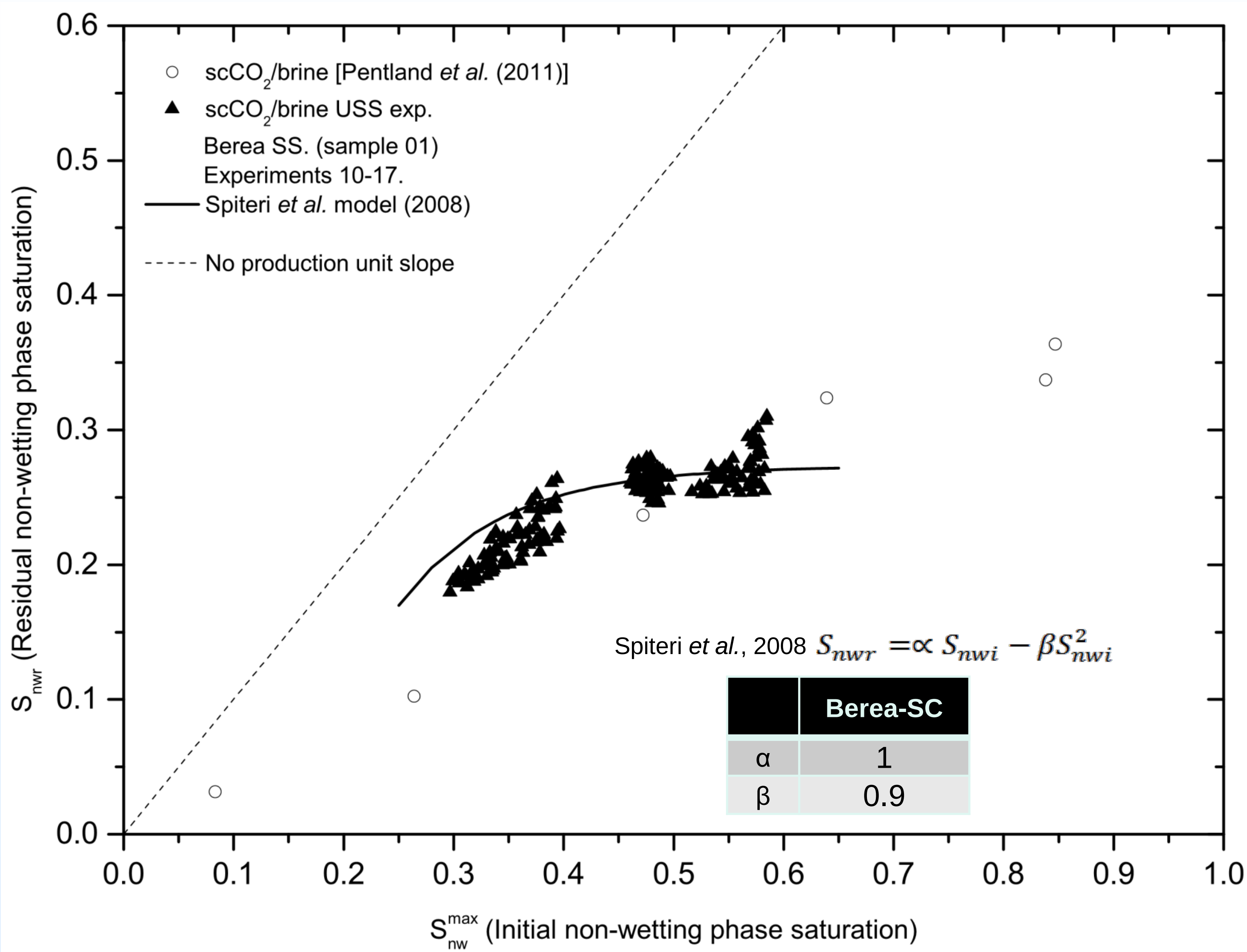
Results (Effect of S_{CO2}^{max} on S_{CO2r} – Berea SS)



Spiteri *et al.*, 2008 $S_{nwr} = \propto S_{nwi} - \beta S_{nwi}^2$

	Berea-Gas
α	0.95
β	0.5

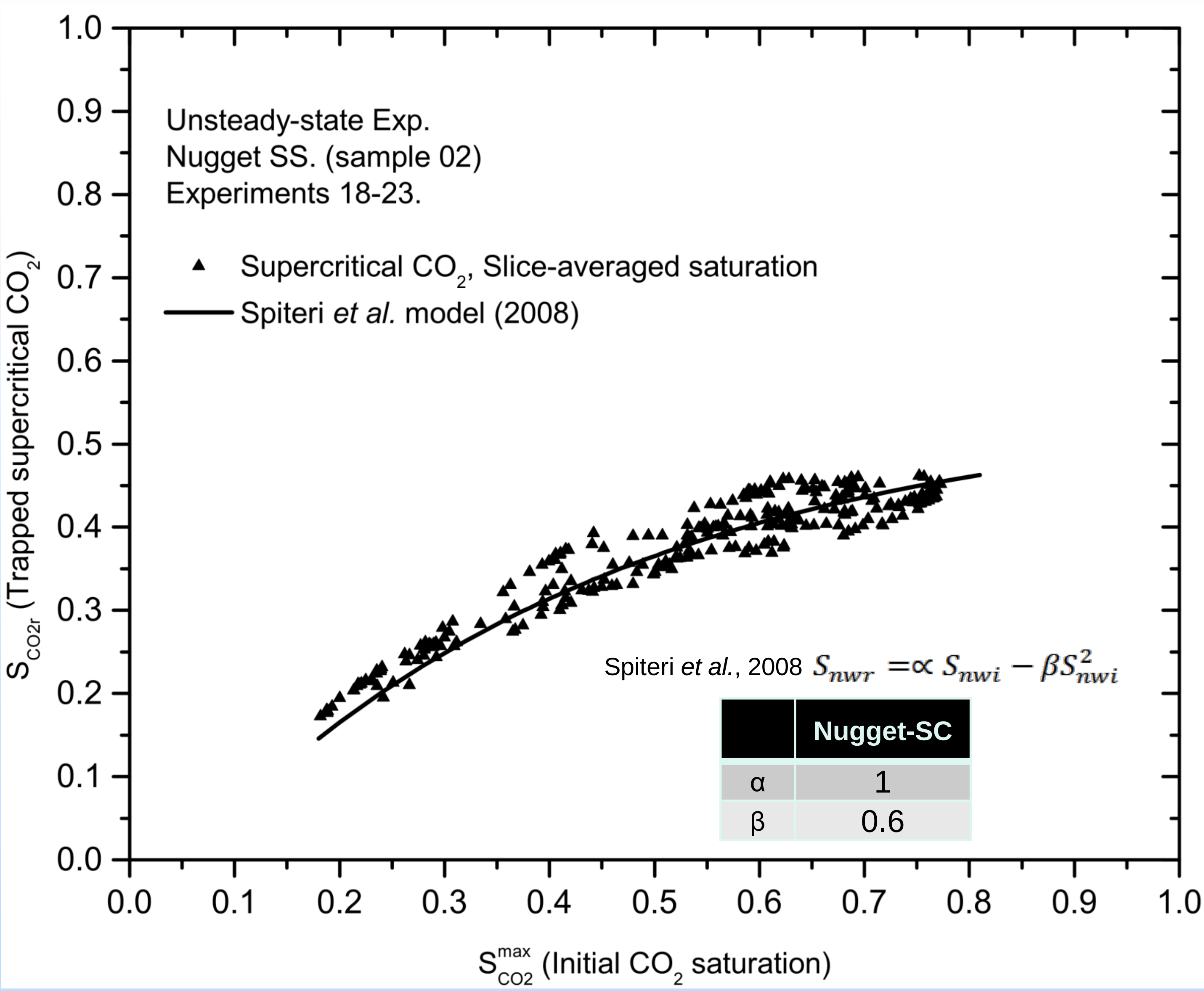
Results (Effect of S_{CO2}^{max} on S_{CO2r} – Berea SS)



Spiteri *et al.*, 2008 $S_{nwr} = \propto S_{nwi} - \beta S_{nwi}^2$

	Berea-SC
α	1
β	0.9

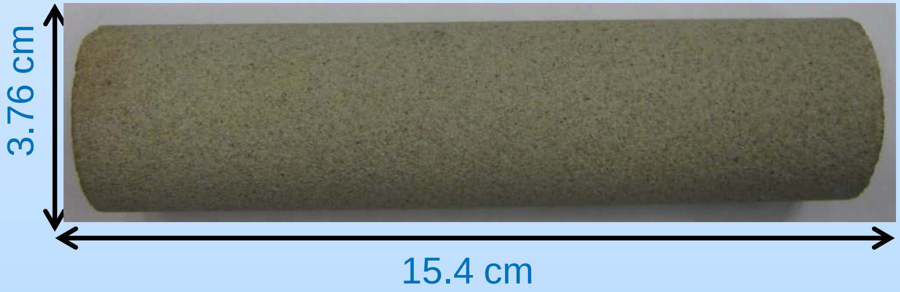
Results (Effect of S_{CO2}^{max} on S_{CO2r} – Nugget SS)



Core sample (Category B)

Berea sandstone

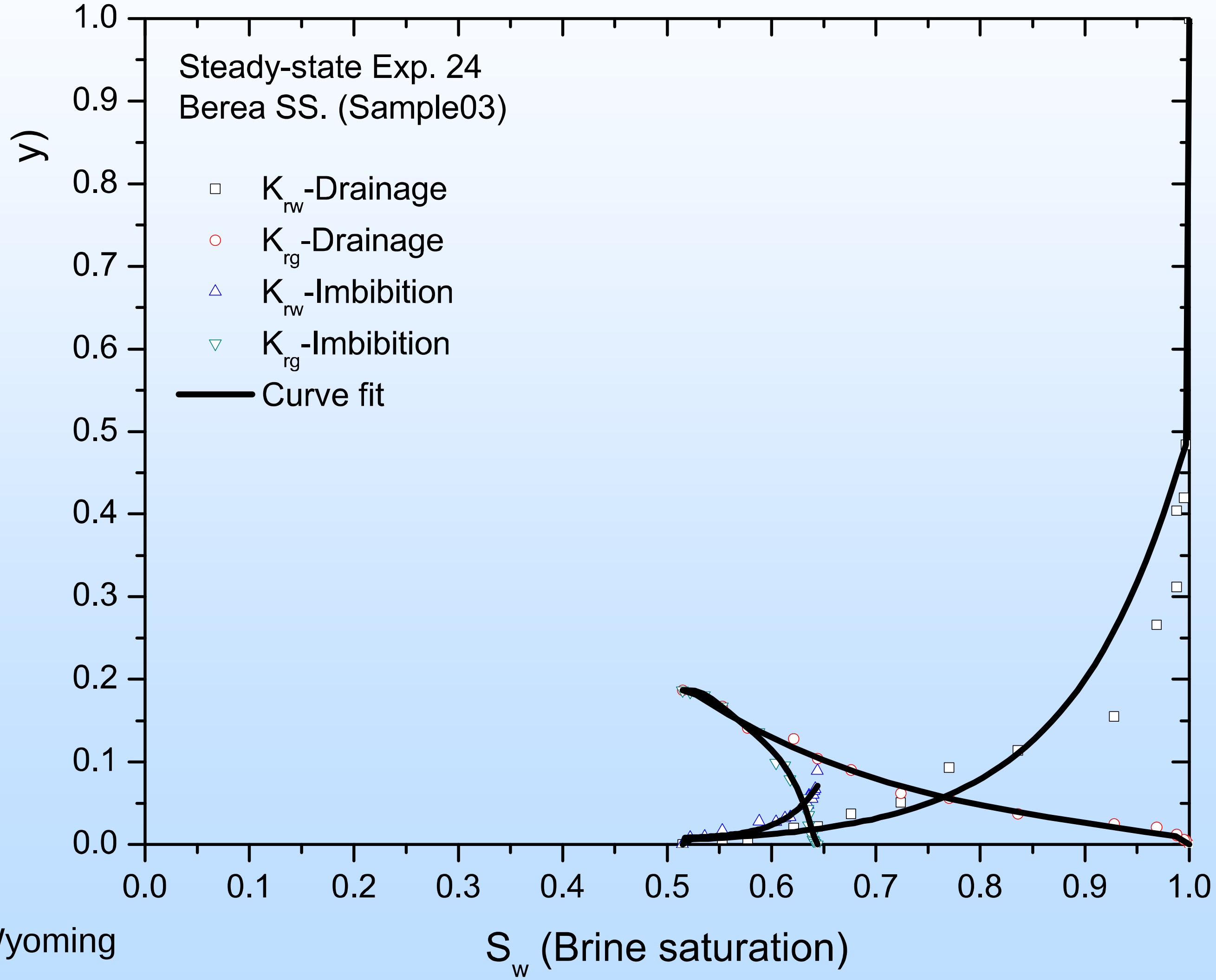
- Core length: 15.4 cm
- Core diameter: 3.76 cm
- Porosity: 21.2 %
- Permeability (Brine): 612 mD
- Pore volume: 36.3 cc



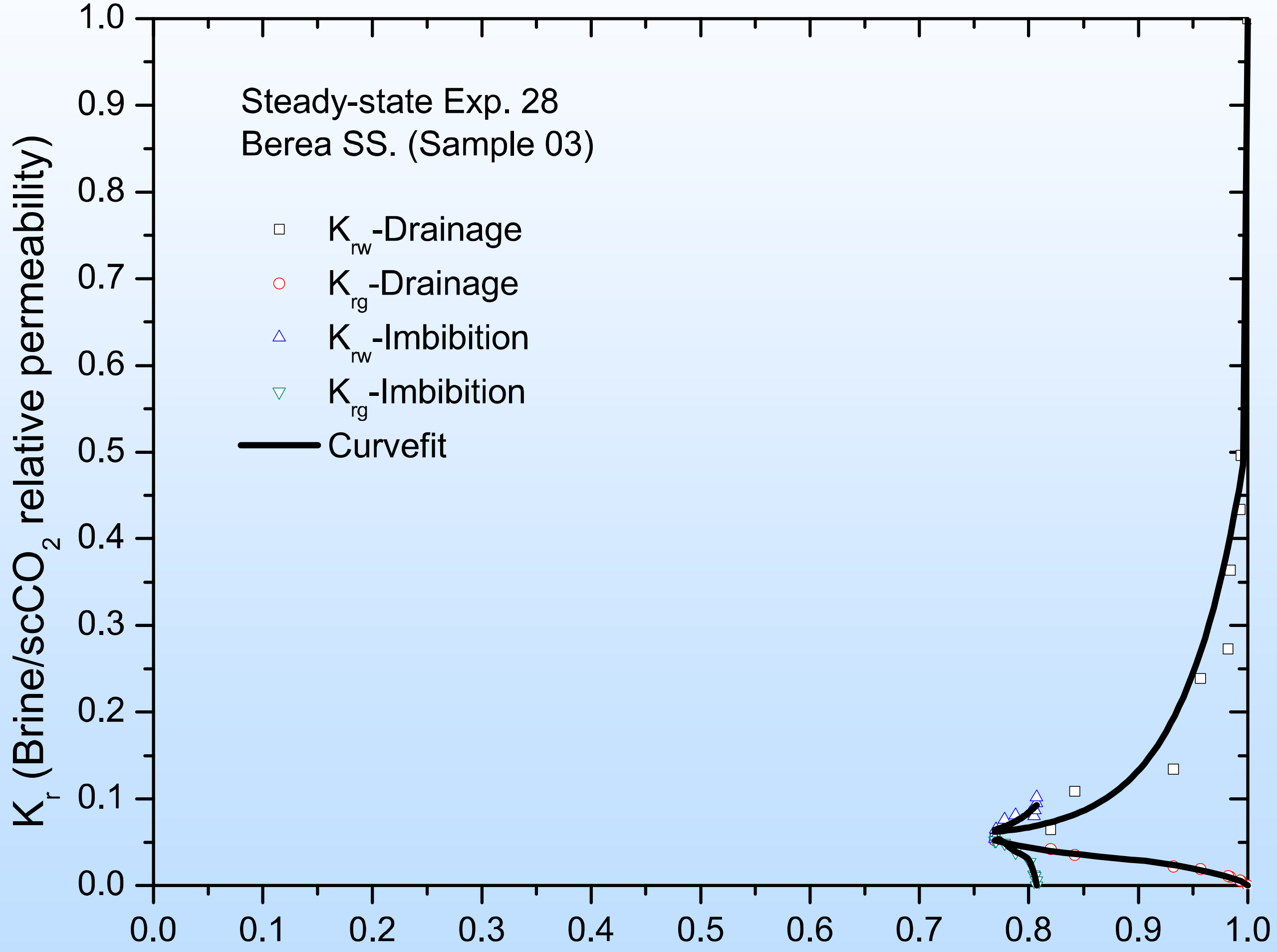
Experimental Conditions

- Temperature: 55.0 ° C
- Pressure: 11 MPa
- Overburden Pressure: 13.1 MPa
- $scCO_2$ flow rate: 0 – 5.0 cc/min
- Brine flow rate: 0.45 – 0.0 cc/min (Drainage)
- Brine flow rate: 0 – 0.25 cc/min (Imbibition)
- Typical capillary no. ≤ 2.5×10^{-6}

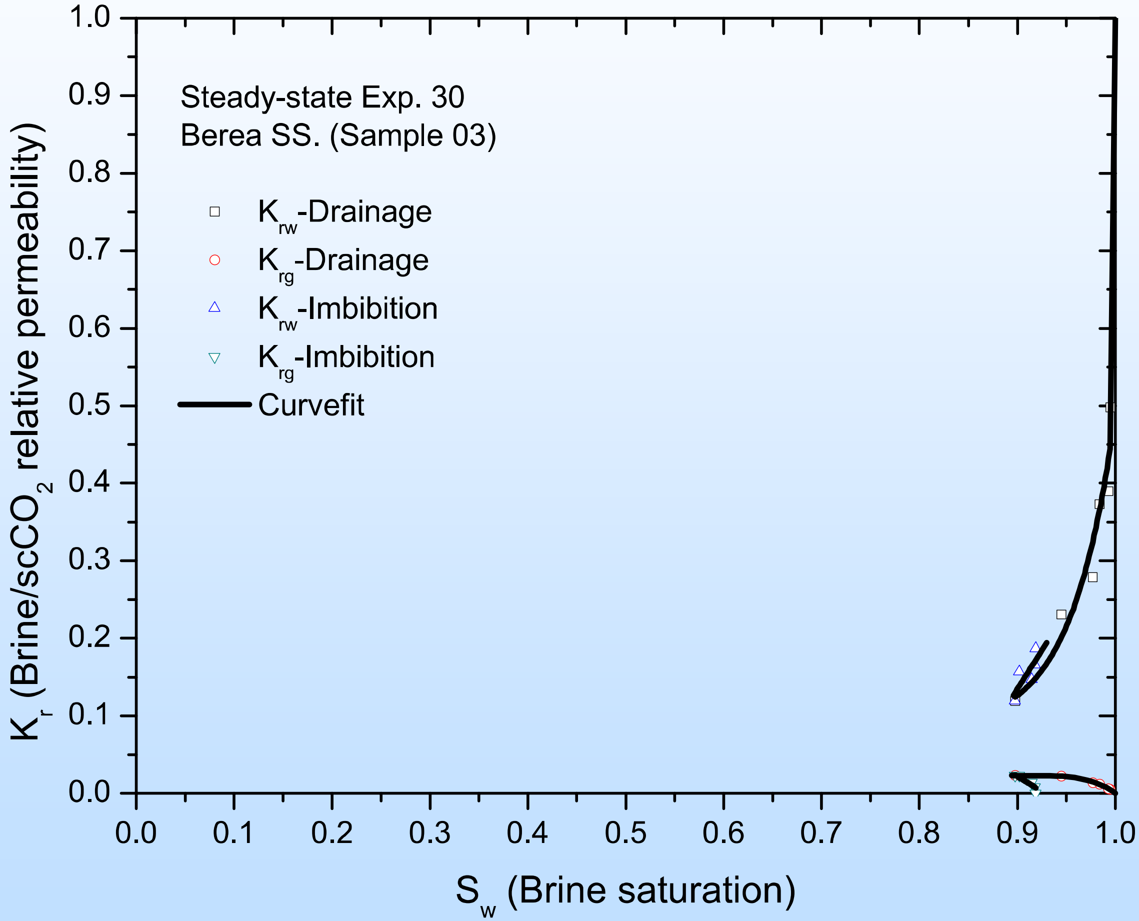
Measurement of $scCO_2$/brine steady-state drainage & imbibition relative permeabilities (Task 2)



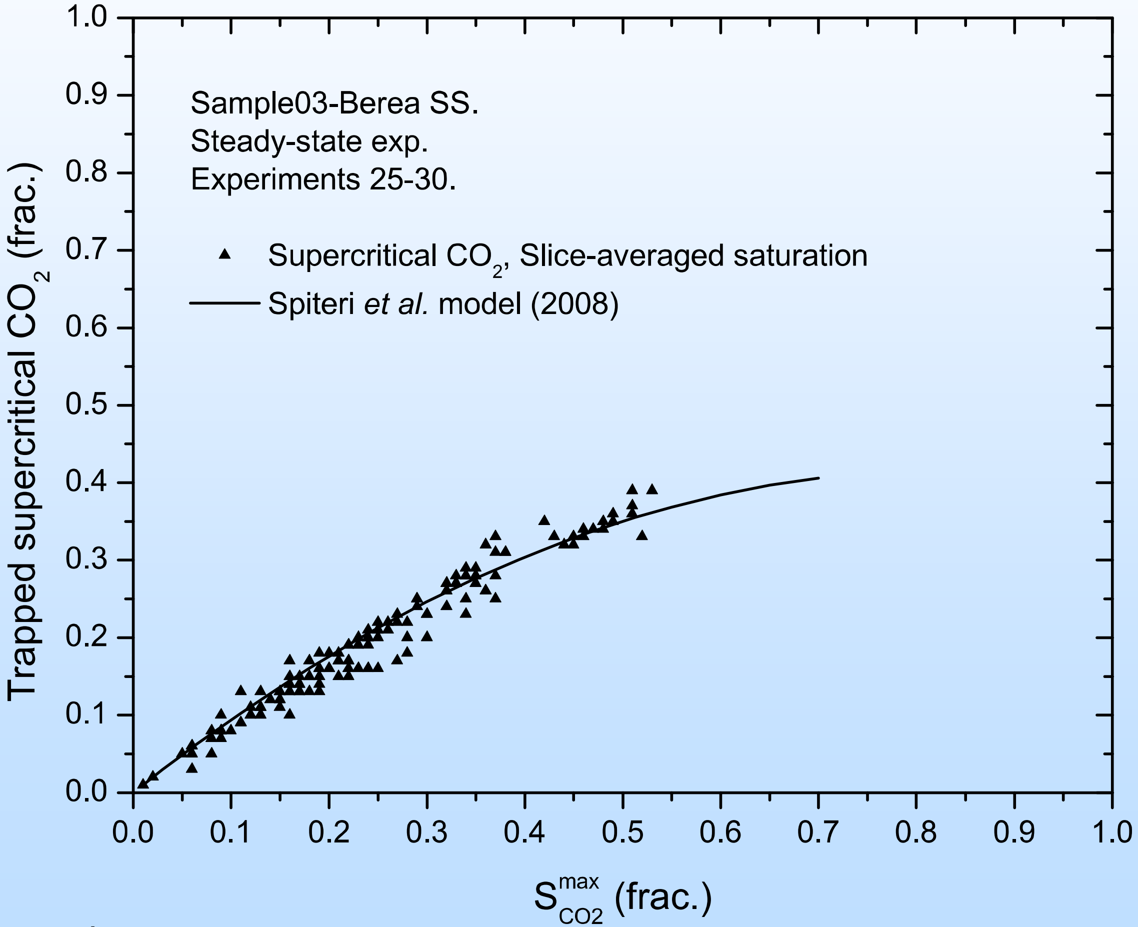
Measurement of $scCO_2$/brine steady-state drainage & imbibition relative permeabilities (Task 2)



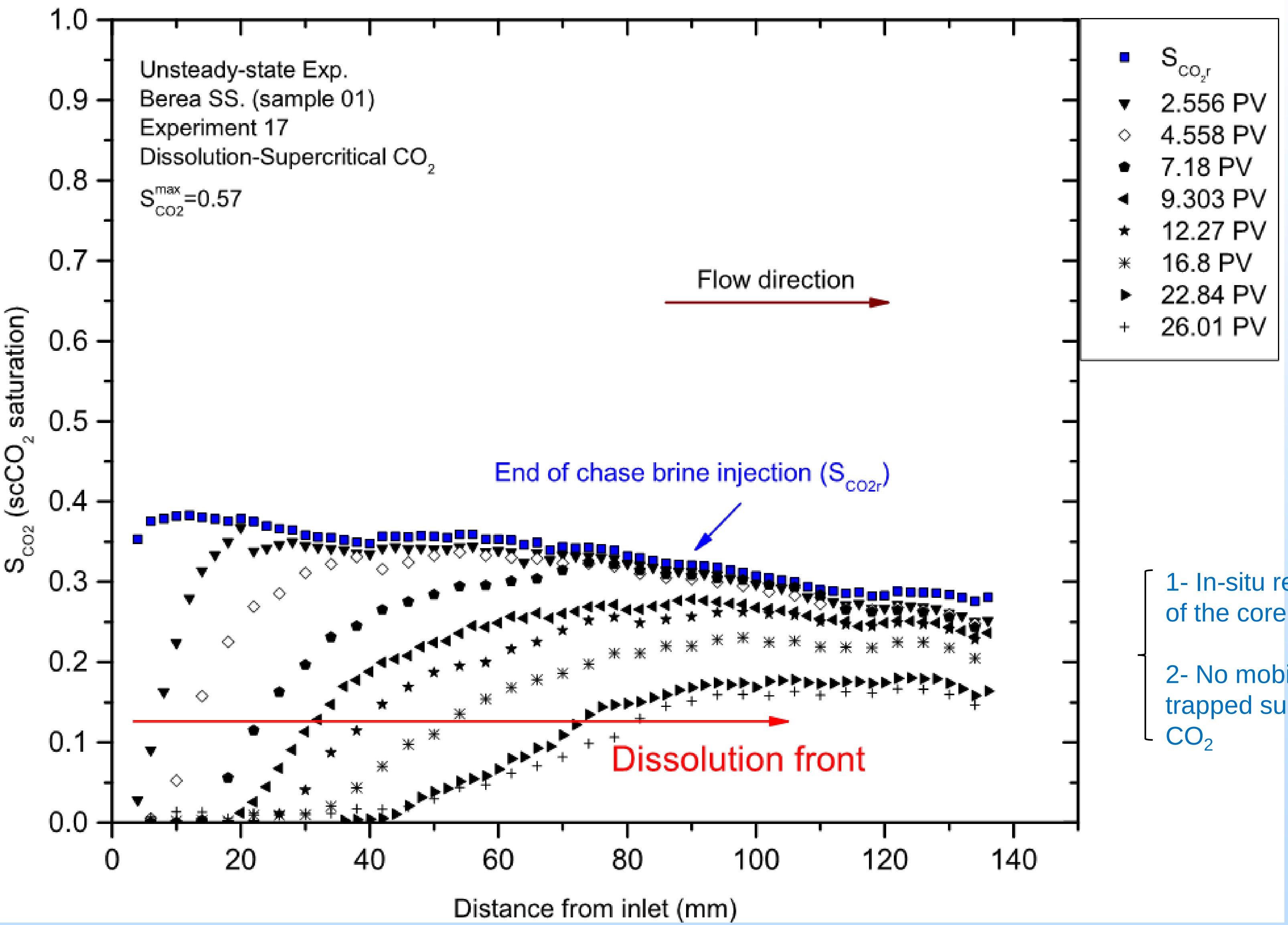
Measurement of $scCO_2$/brine steady-state drainage & imbibition relative permeabilities (Task 2)



Measurement of $scCO_2$/brine steady-state drainage & imbibition relative permeabilities (Task 2)



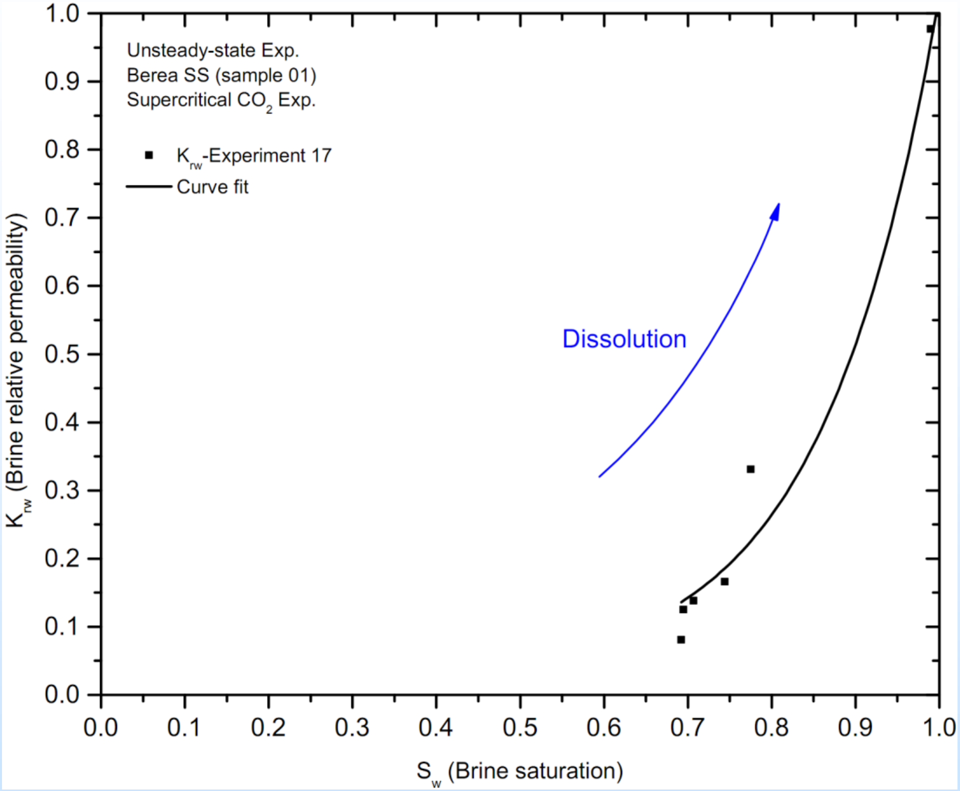
Results (Dissolution or in-situ re-saturation)

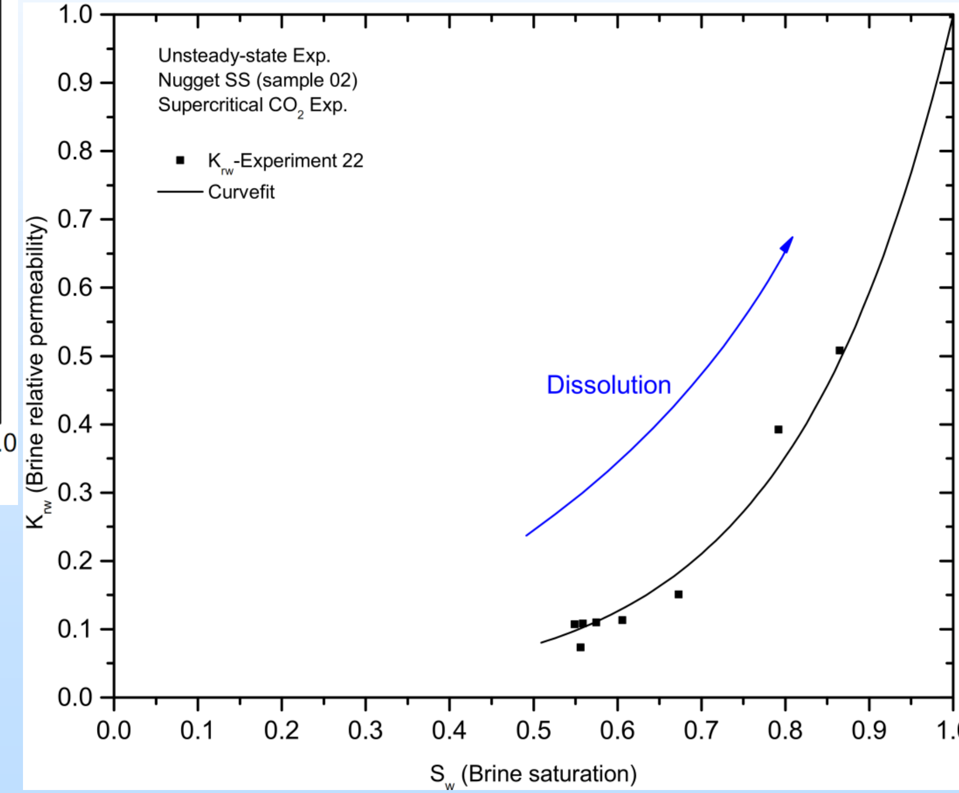


1- In-situ re-saturation of the core with brine

2- No mobilization of trapped supercritical CO_2

Results (Dissolution relative permeability)

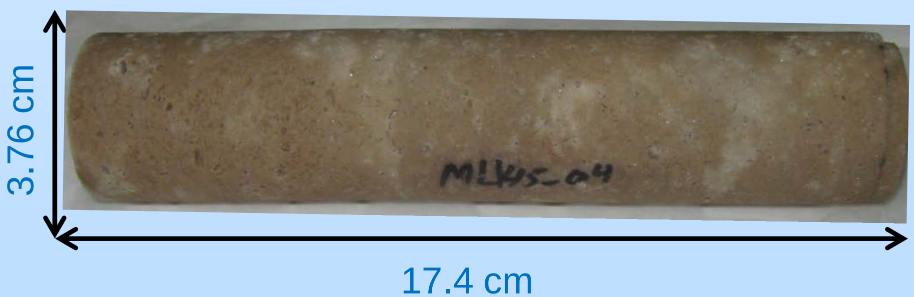




Core sample (Category C)

Madison limestone

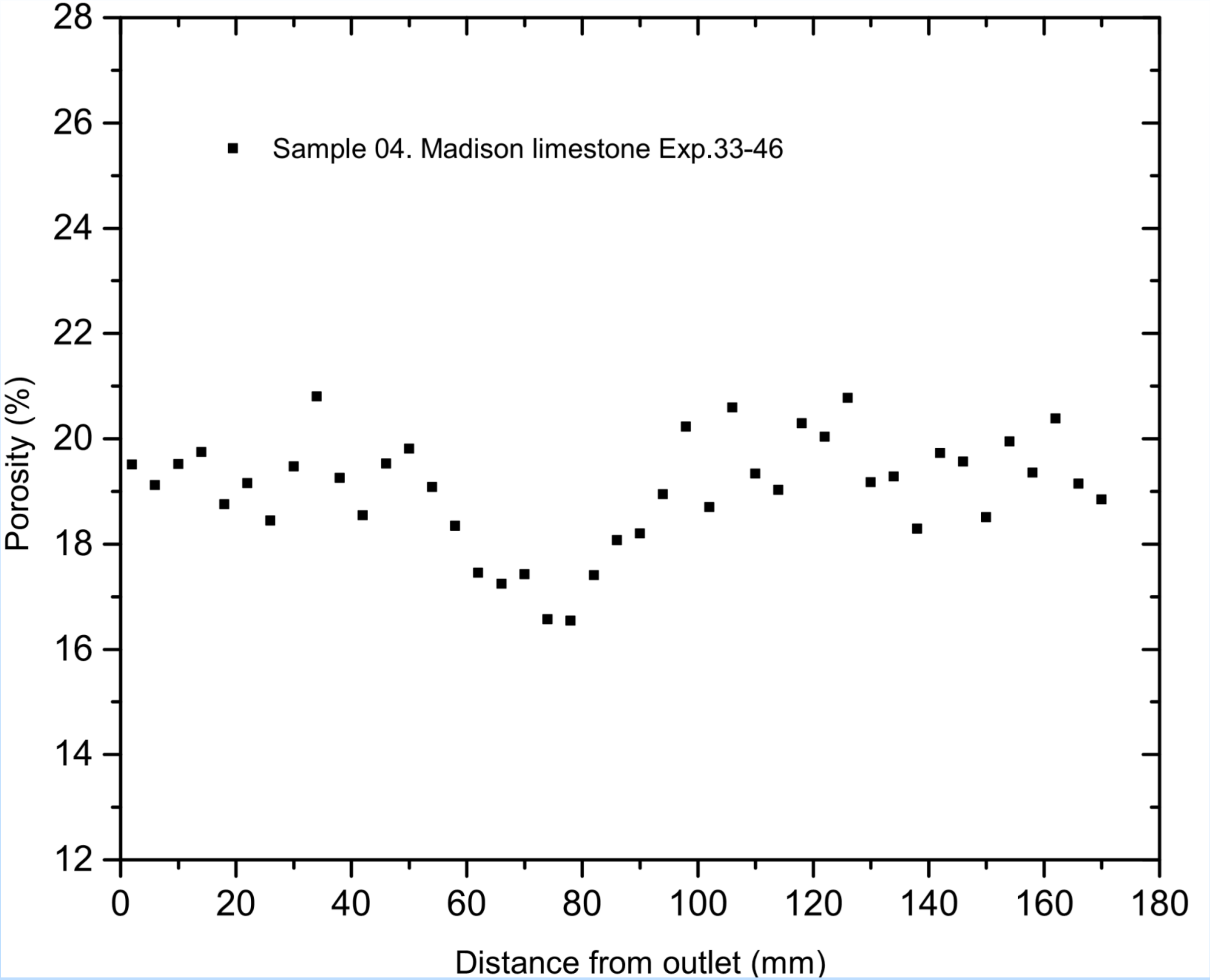
- Core length: 17.4 cm
- Core diameter: 3.76 cm
- Porosity: 19.03 %
- Permeability (Brine): 13.6 mD
- Pore volume: 36.77 cc



Experimental Conditions

- Temperature: 60.0 ° C
- Pressure: 19.6 MPa
- Overburden Pressure: 21.37 MPa
- $scCO_2$ flow rate: 0 – 0.1 cc/min
- Brine flow rate: 0.03 – 0.2 cc/min (Drainage)
- Brine flow rate: 0.03 – 0.16 cc/min (Imbibition)
- Typical capillary no. ≤ 7.5×10^{-7} (Cap.-dom.)
- Typical capillary no. > 10^{-5} (Visc.-dom.)

Madison limestone (Porosity)



Fluids and materials (Category C)

Fluids:

- Pure CO_2
- Pure SO_2: 1200 ppm
- Brine:
  - 50000 ppm NaI
  - 36500 ppm NaCl

Material:

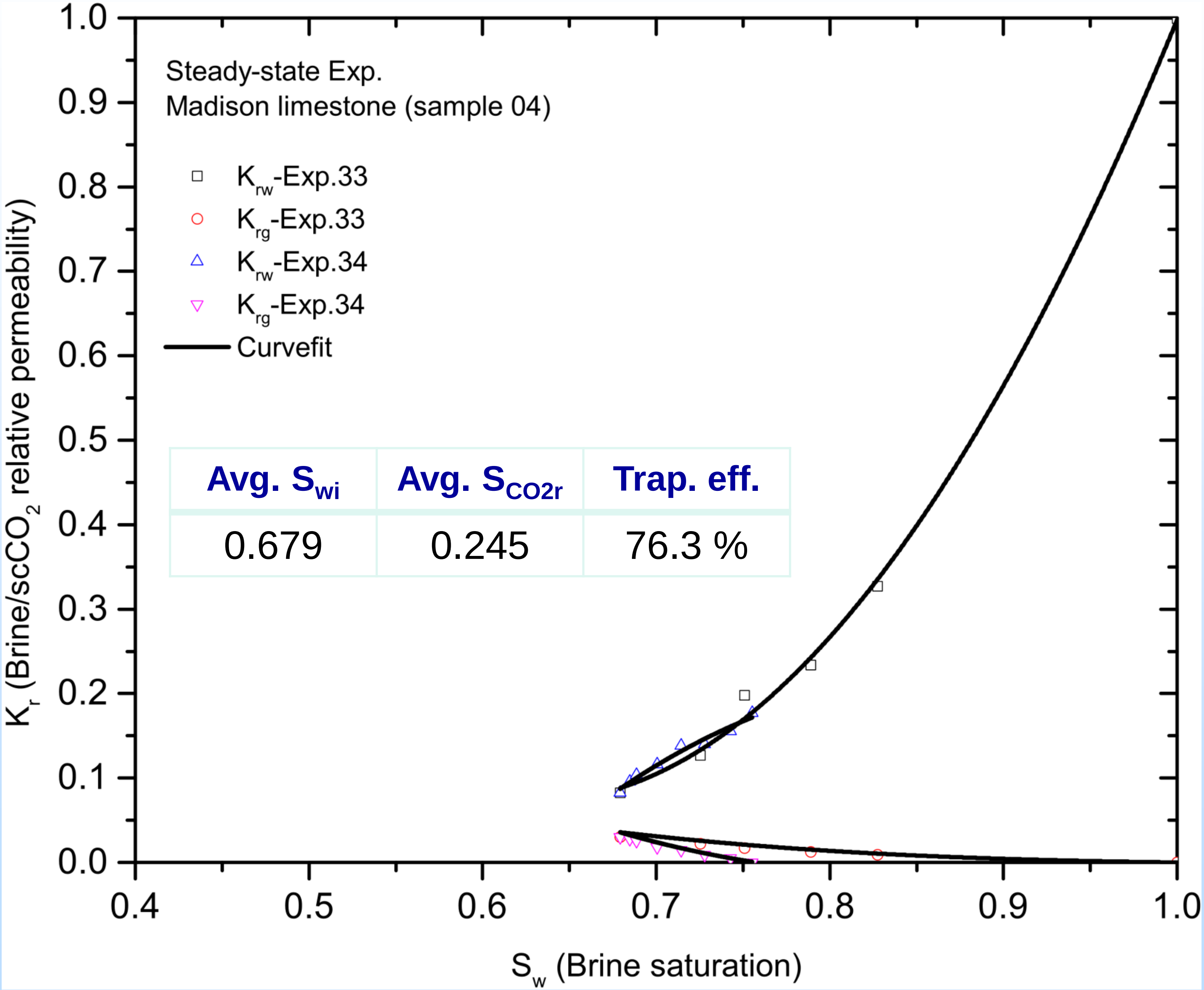
- Sleeve: AFLAS* (Teflon+ Aluminum foil)
- Wetted material: Hastelloy
- O-rings: AFLAS
- Core-holder: Hassler type

*: The AFLAS materials specifically designed for SO_2+CO_2 experiments

Fluid properties (Category C)

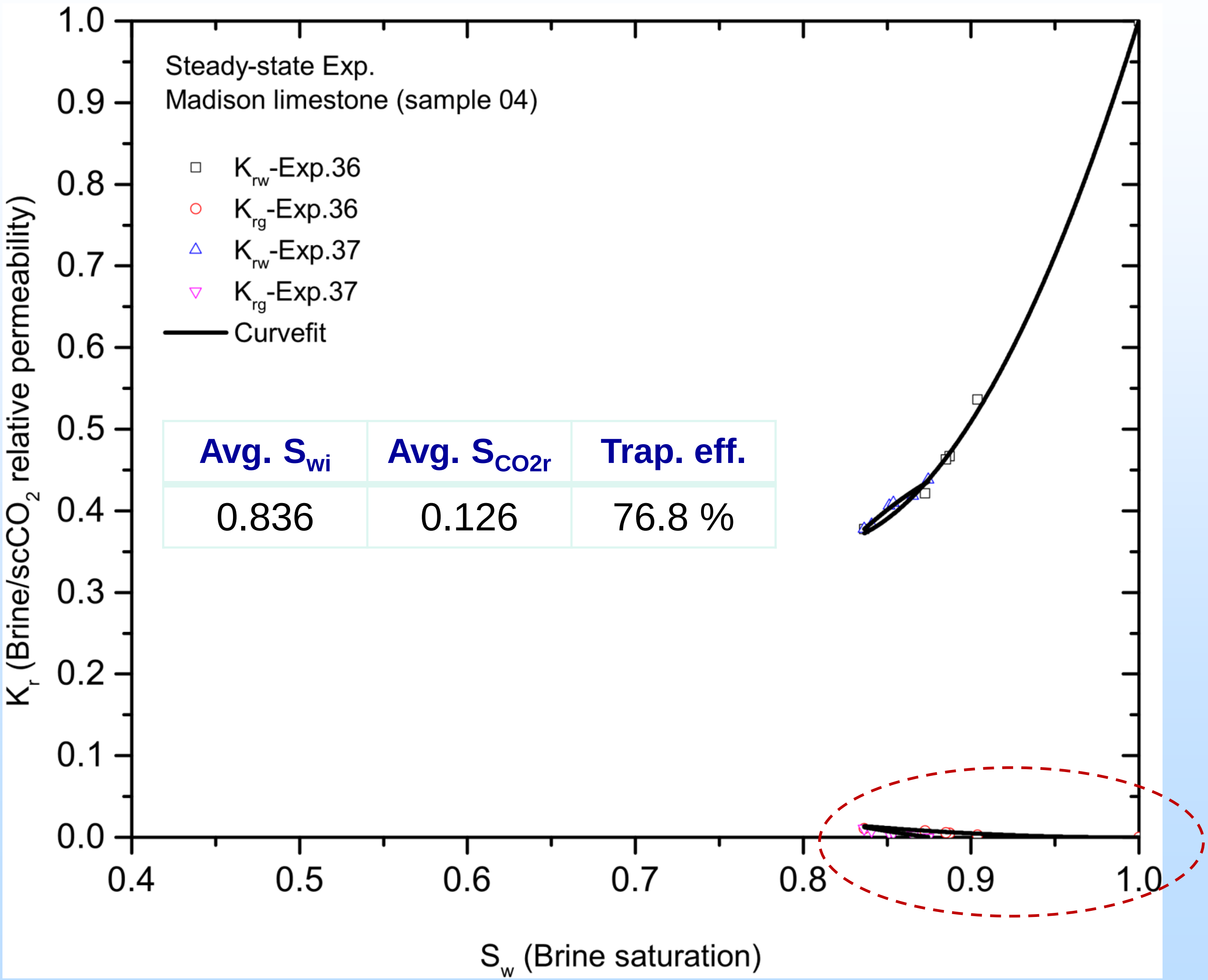
Fluid	Pressure MPa	Temperature °C	Viscosity cP	Density gr/cm^3	CO_2/Brine IFT mN/m*
$scCO_2$ –rich phase	19.16	60	0.0692	0.70	28.1
Brine-rich phase	19.16	60	0.635	1.05	-

Results (Steady-state relative permeability–Half cycle)



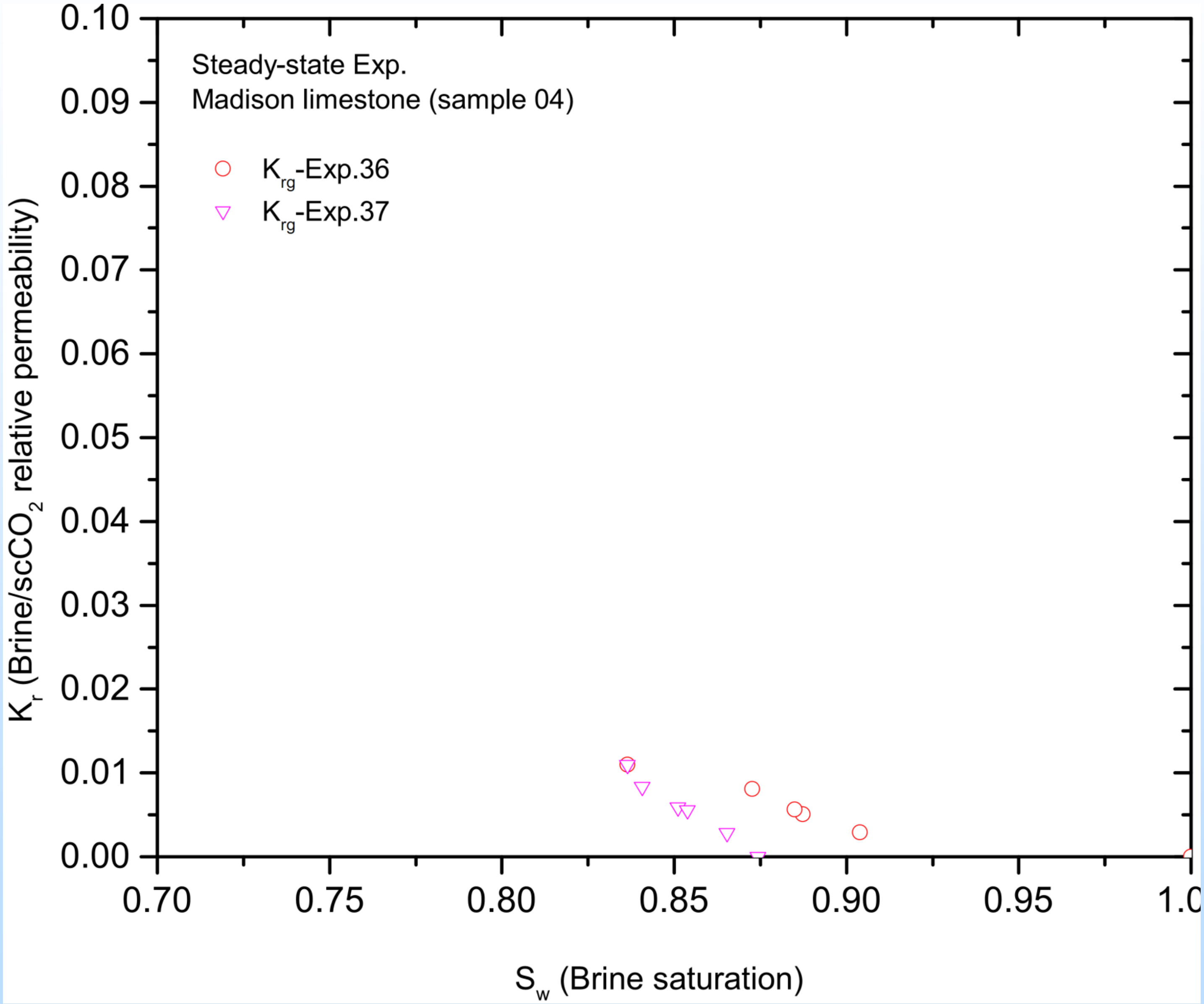
Avg. S_{wi}	Avg. S_{CO2r}	Trap. eff.
0.679	0.245	76.3 %

Results (Steady-state relative permeability–1/4 cycle)

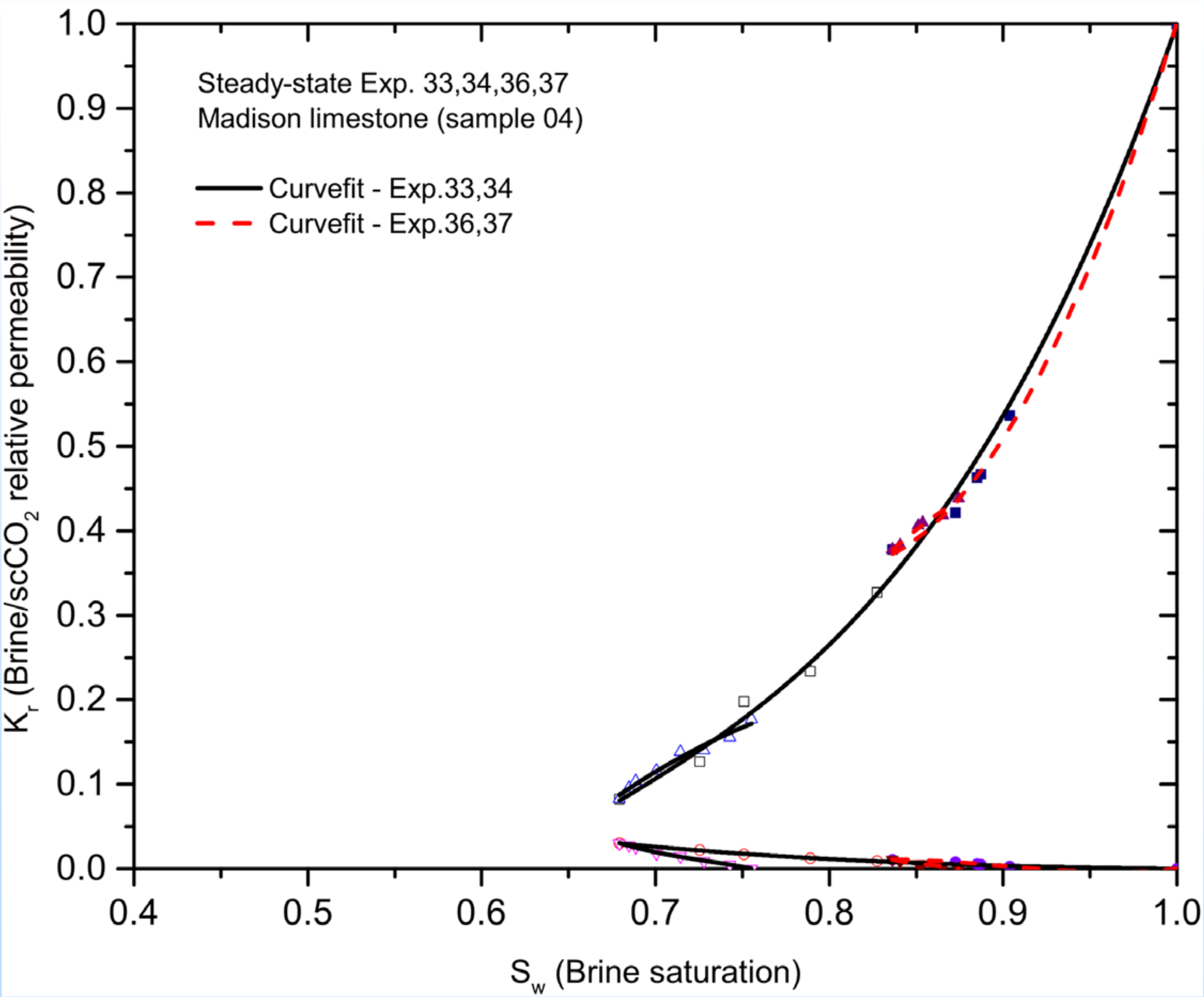


Avg. S_{wi}	Avg. S_{CO2r}	Trap. eff.
0.836	0.126	76.8 %

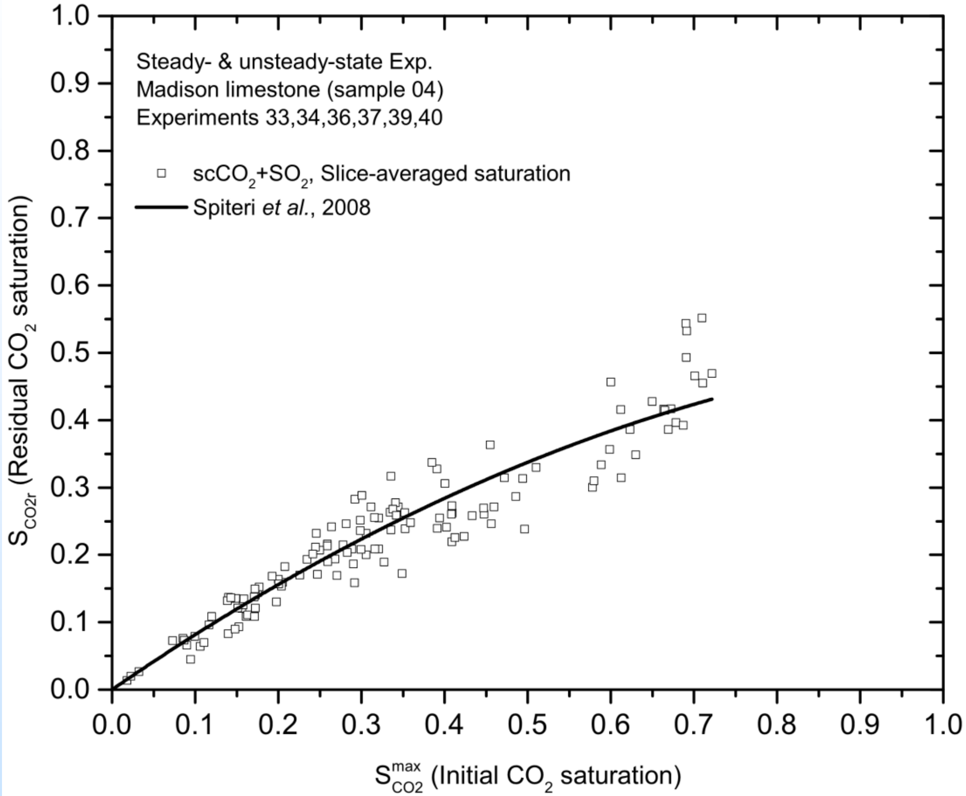
Results (Steady-state relative permeability–1/4 cycle)

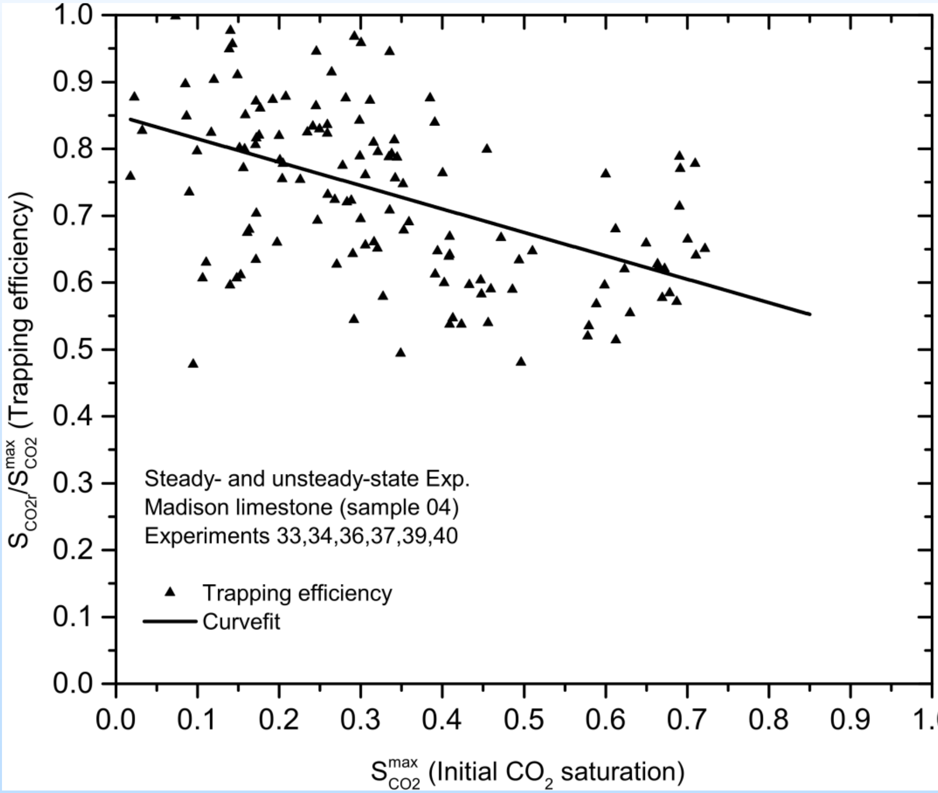


Results (Steady-state relative permeability–Both cycles)



Results (Effect of S_{CO2}^{max} on S_{CO2r} - Trapping efficiency)

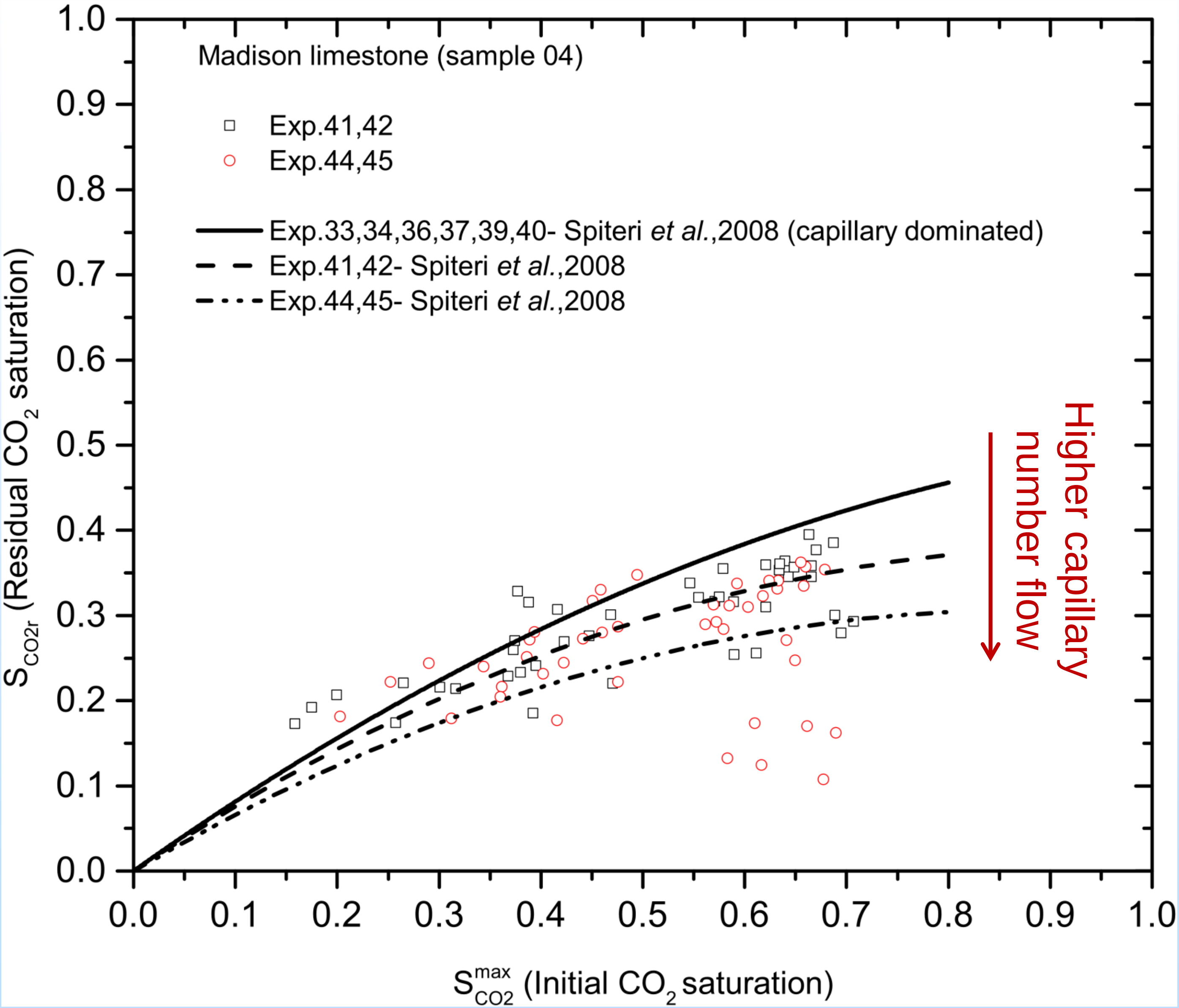




Spiteri *et al.*, 2008 $S_{nwr} = \propto S_{nwi} - \beta S_{nwi}^2$

	Madison Limestone
α	0.85
β	0.35

Results (Dynamic effects exp.- Category C-3)



Accomplishments to Date

1. Milestones 1-6 were completed:
    - Update Project Management Plan - Hold kickoff meeting of PIs with govt. partners
    - Acquisition of rock samples and micro-CT images for pore-level network model
    - Measurement of unsteady-state core-flooding experimental data required for code validation
    - Measurement of steady-state relative permeabilities for code validation
2. A new state-of-the-art IFT and contact angle apparatus was built from scratch and validated
3. Development of fully parallel dynamic pore-scale network model is nearing completion
4. Development of hysteresis model was completed
5. Development of phase equilibrium calculation module for $scCO_2$, SO_2, and brine is nearing completion
6. Development of compositional simulator was completed
7. Code validation for the UW-Team simulator (Milestones 5) is on track for completion in September
8. Active dissemination of findings through publications and presentations in scientific meetings

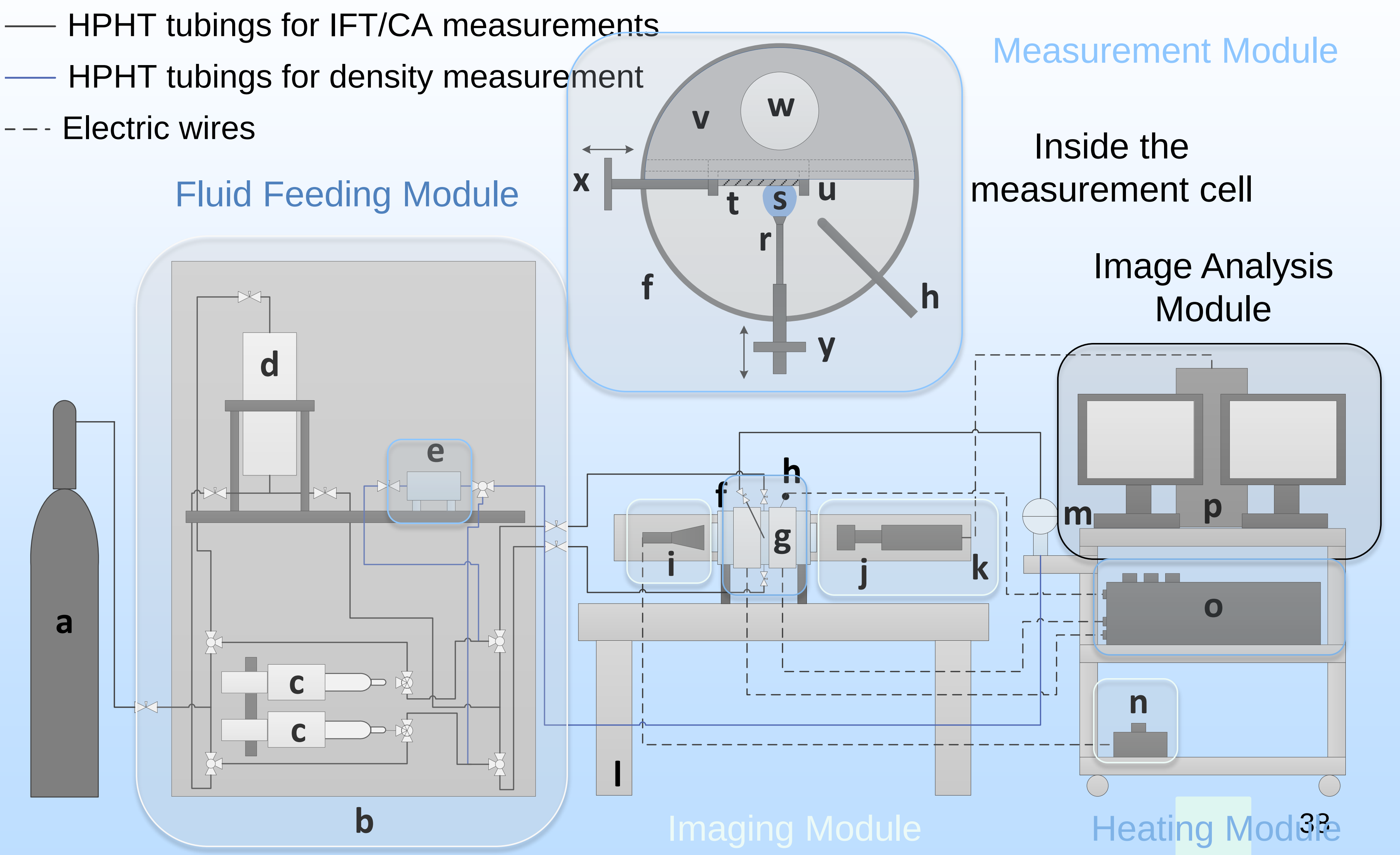
Summary

- Key findings
  - Significant fractions of initial CO_2 in place can be stored through residual trapping
  - Lower initial CO_2 saturation leads to higher trapping efficiency ($R=S_{CO2r}/S_{CO2}^{max}$)
  - Trapping efficiency between 49 to 83% of CO_2 in place
  - Accurate numerical approximation of transport problems with hysteresis

- Future Plans
  - Develop a fully parallel version of the phase equilibrium module
  - Dynamic pore-scale modeling of imbibition in large networks
  - Completion of geomechanics module
  - Compositional reservoir simulations on large computer clusters, UQ studies

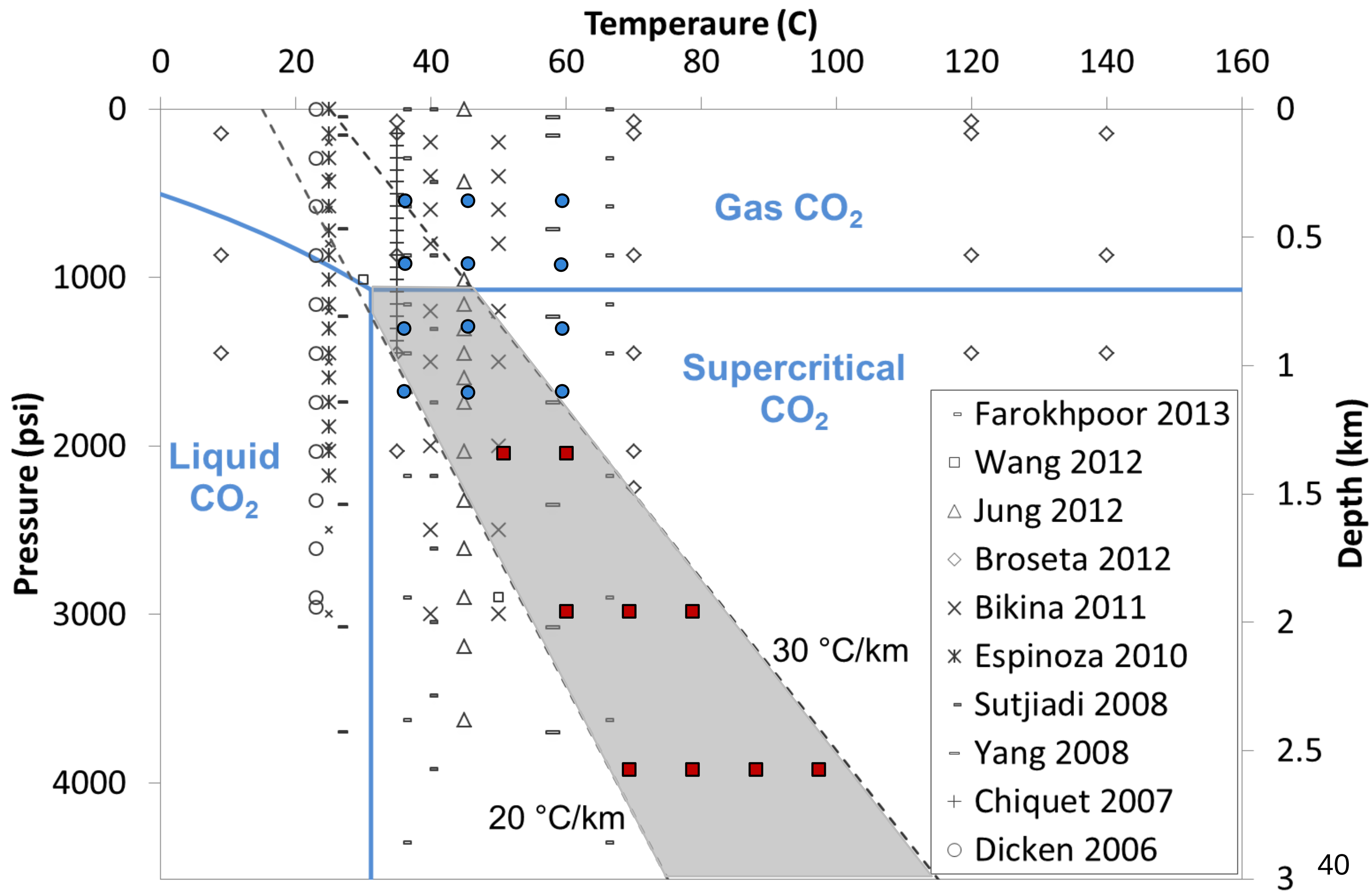
Thank you

IFT/CA Experimental Setup

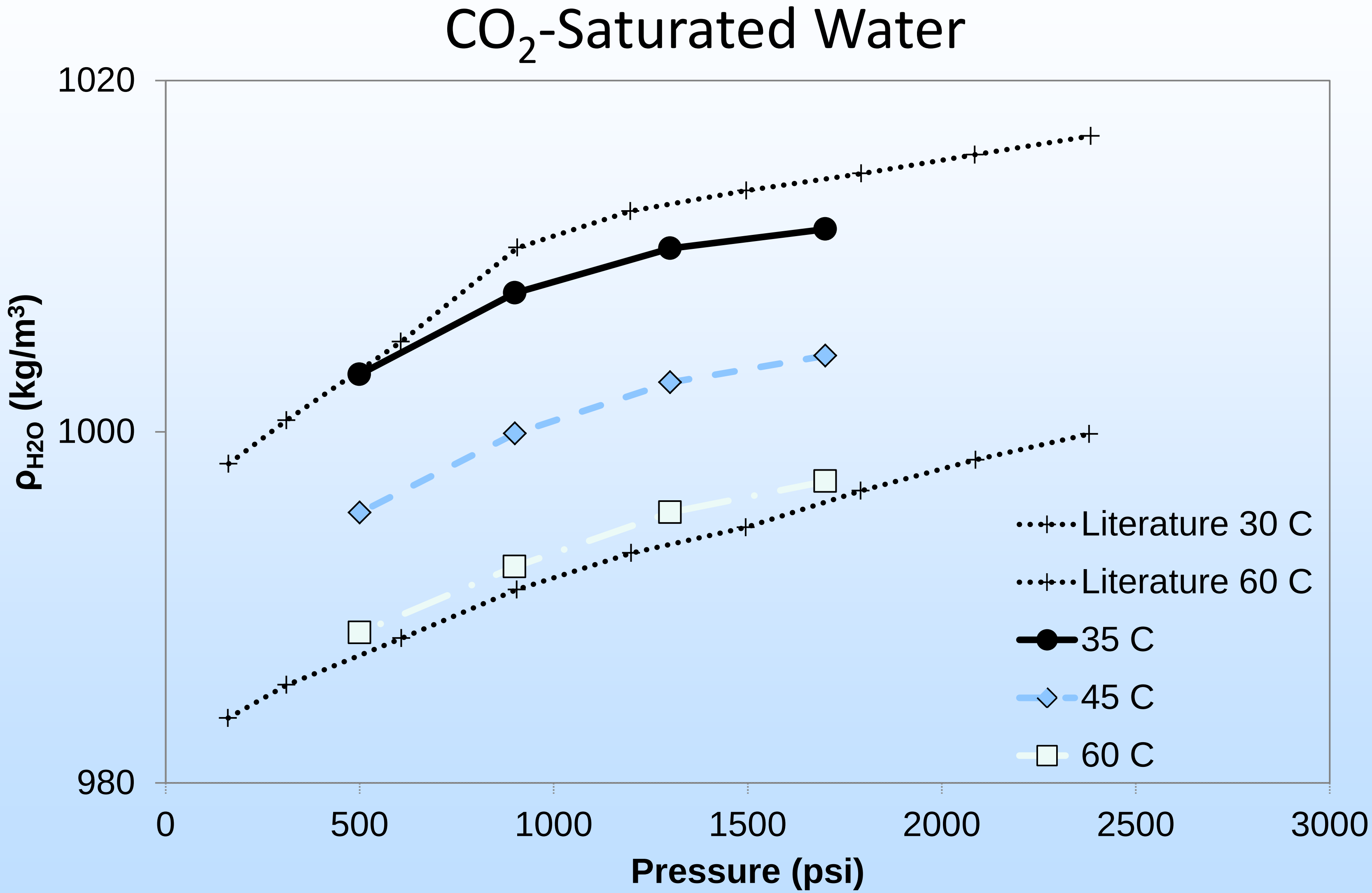


Experimental Setup (cont.)

Contact Angle and IFT Measurements

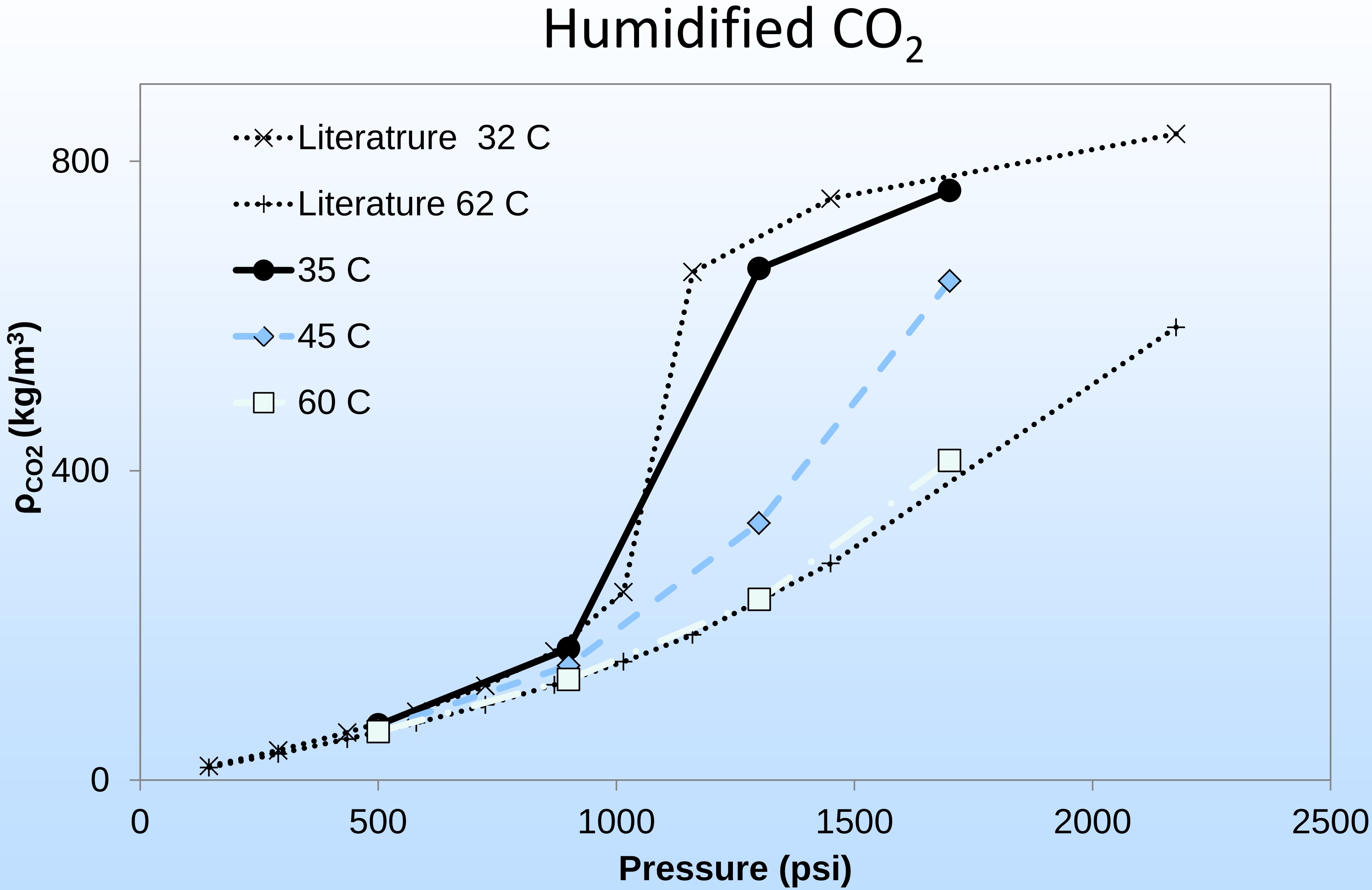


Densities (CO_2/Water system)



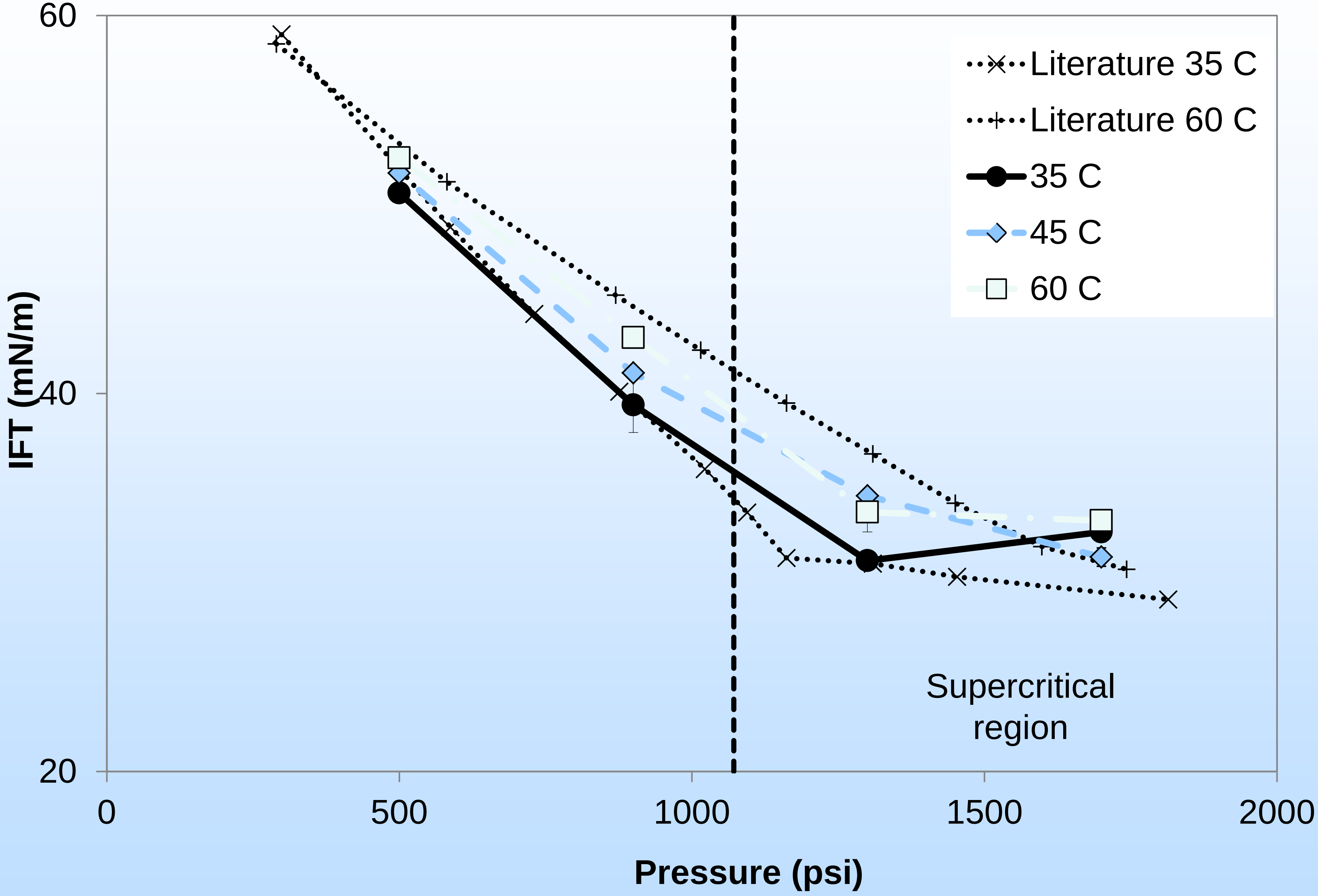
Hebach A., Oberhof A., Dahmen N., *J. Chem. Eng. Data*, 49, 950-953, 2004

Densities (CO_2/Water system)



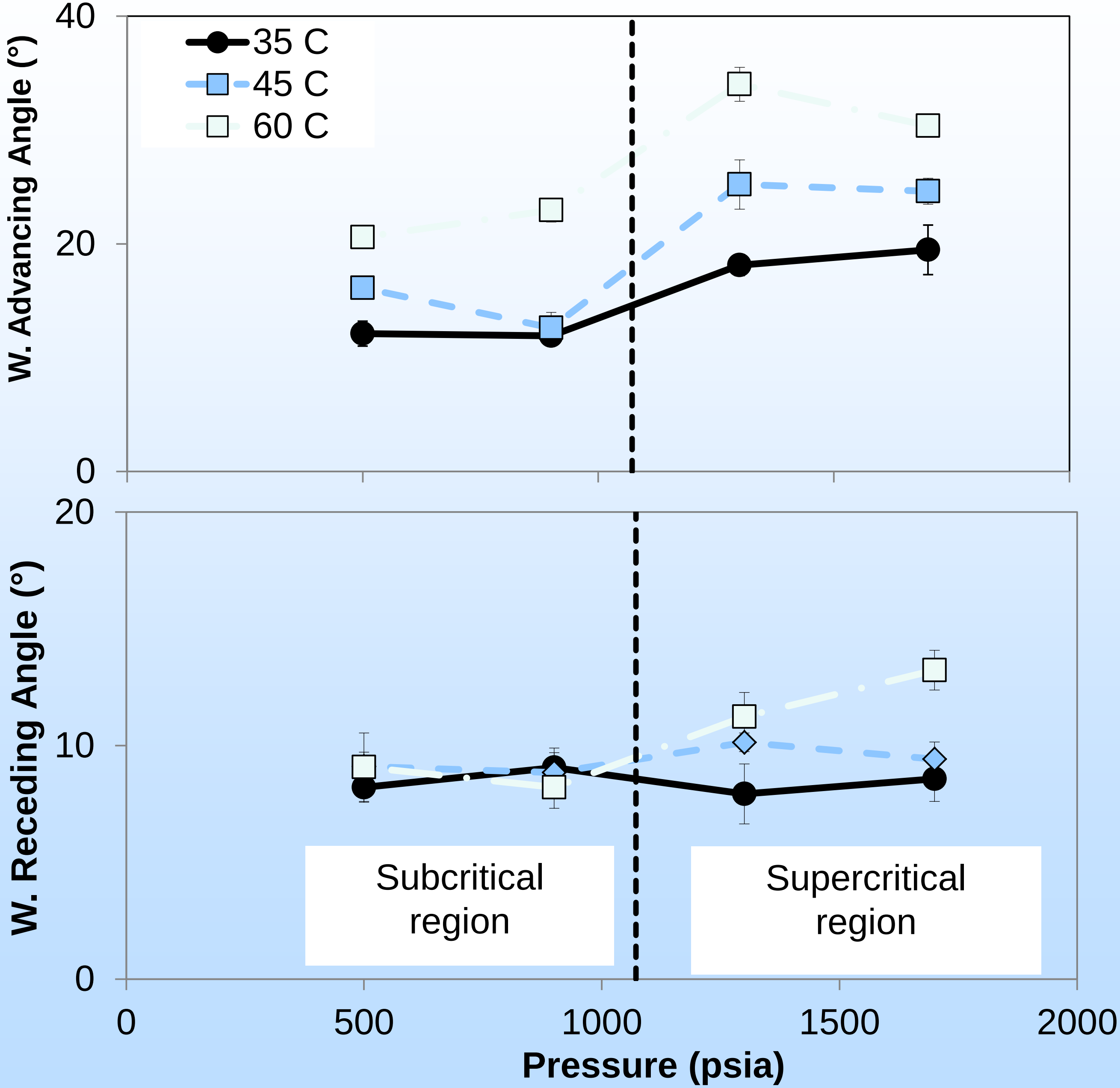
Span R., and Wagner W., *J. Phys. Chem. Ref. Data*, 25 (6), 1509-1596, 1996

IFT (CO_2/Water)



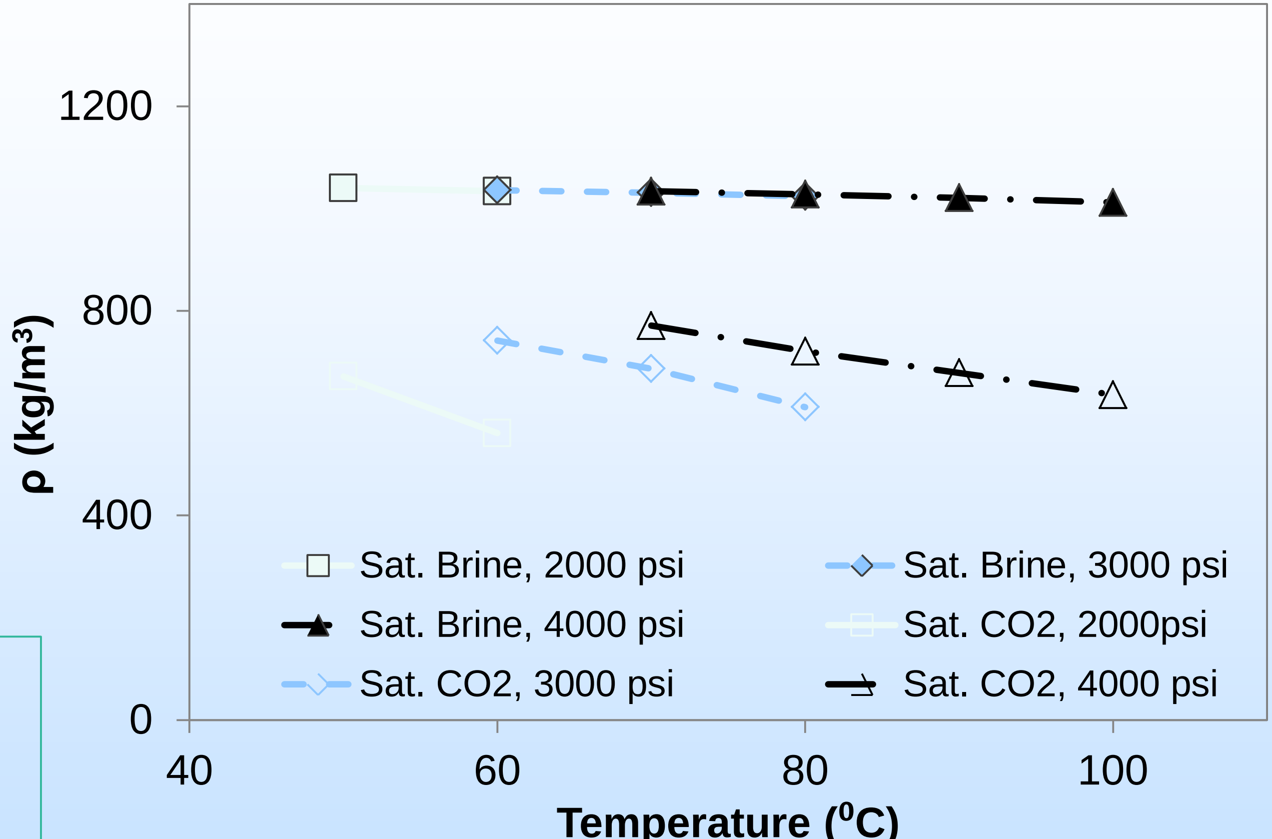
Hebach, A., Oberhof A., Dahmen N., Kogez A., Ederer H., and Dinjus E., *J. Chem. Eng. Data*, 47, 1540-1546, 2002

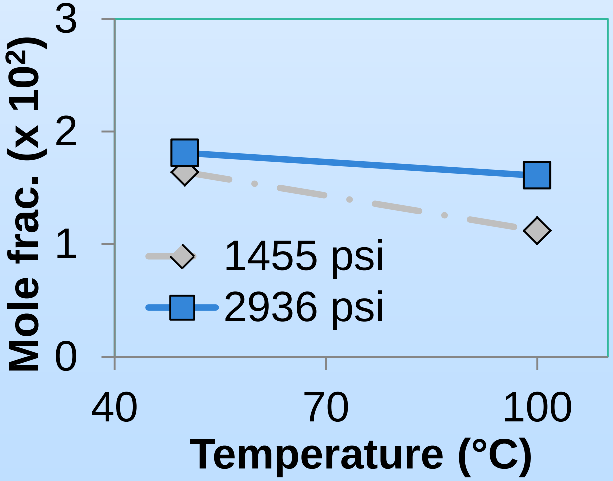
IFT-CA (CO_2/Water/Quartz system)



Results (Effect of P and T for sc-CO_2)

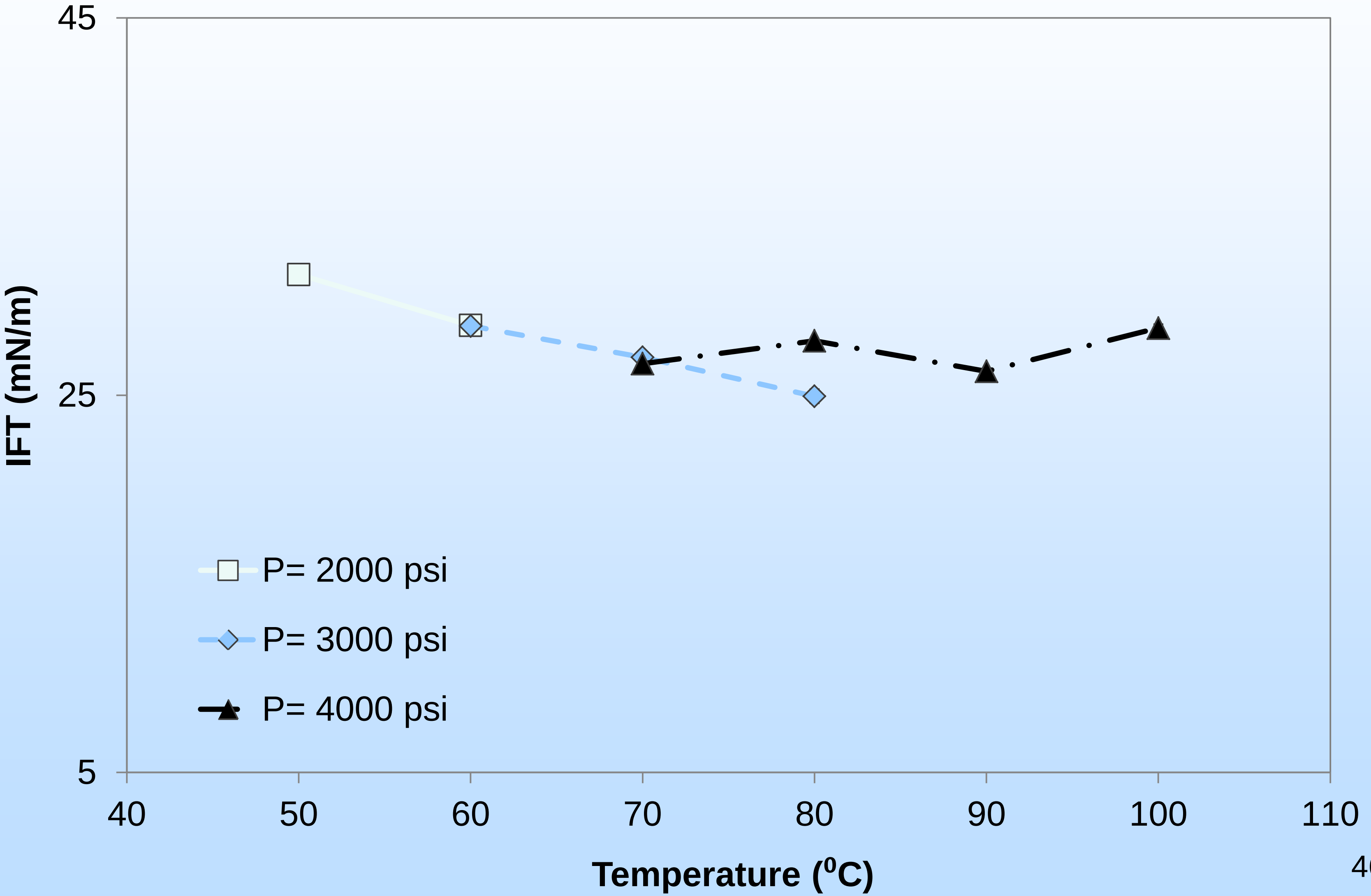
- I=1M NaCl
- Pure CO_2



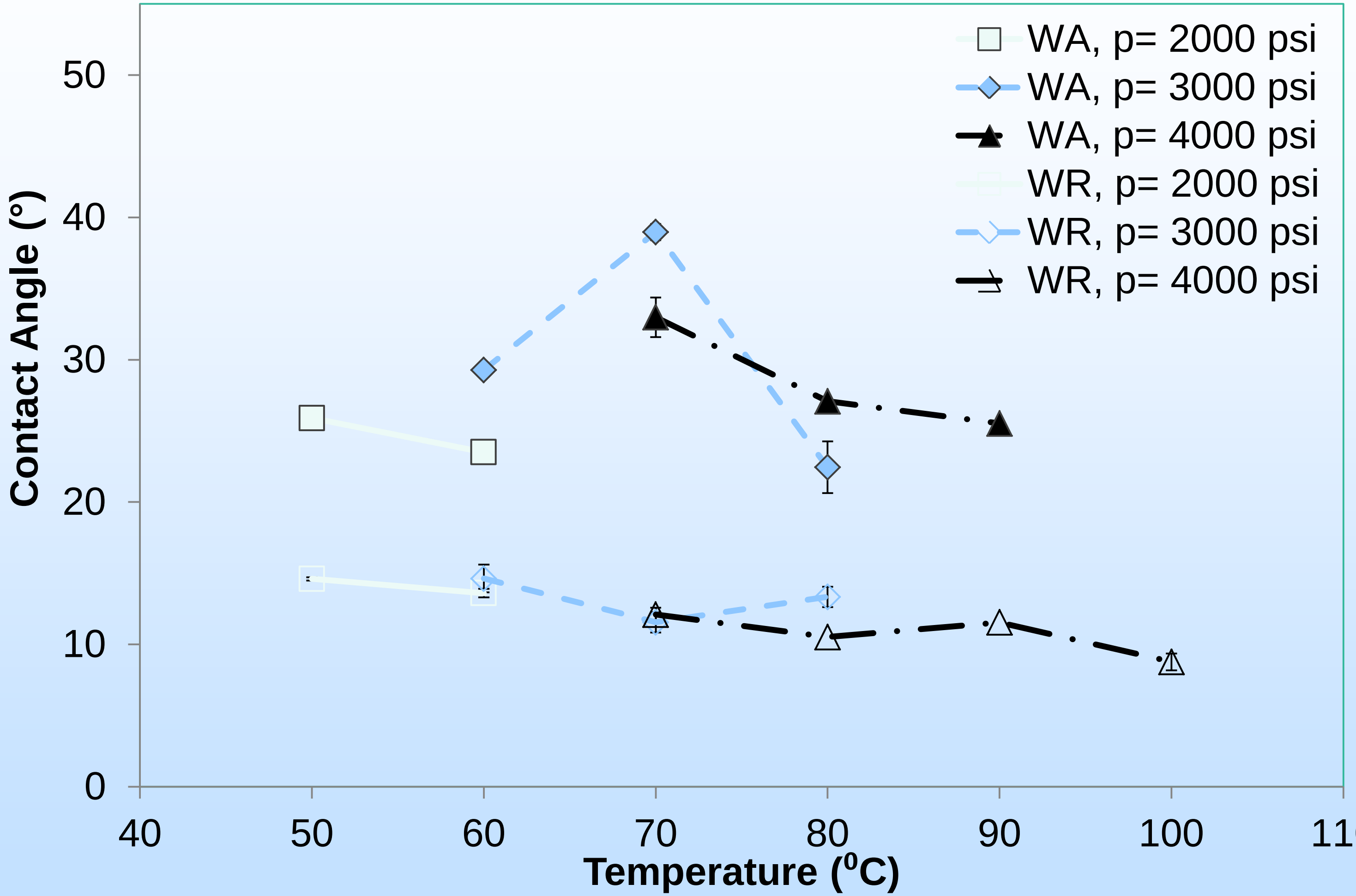


Koschel D., Coxam J-Y, Rodier L., and Majer V.,, 2006, Fluid Phase Equilibria, 247, 107-120

Results (Effect of P and T for sc-CO_2)



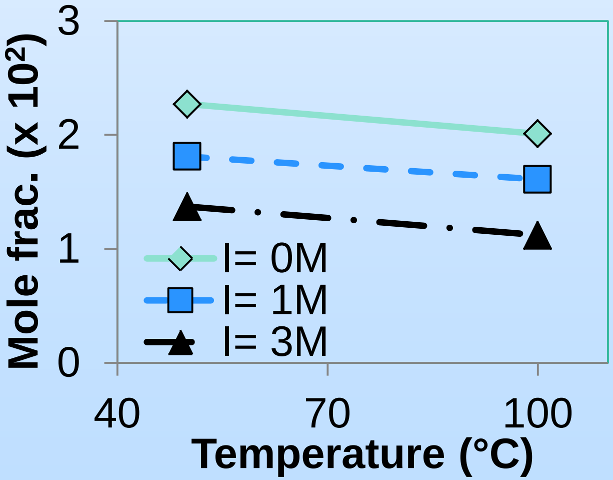
Results (Effect of P and T for sc-CO_2)

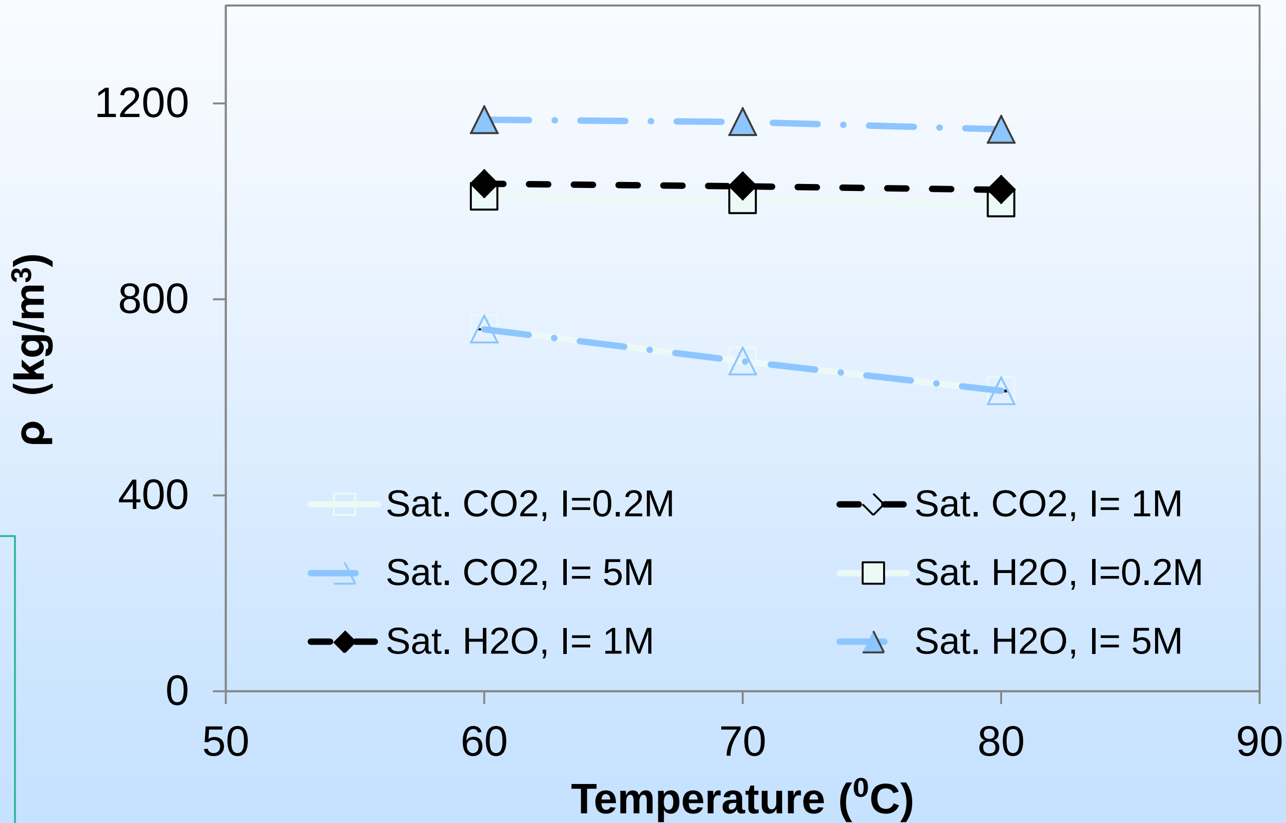


Results (Effect of Salinity)

- P=3000 psi
- Pure CO_2

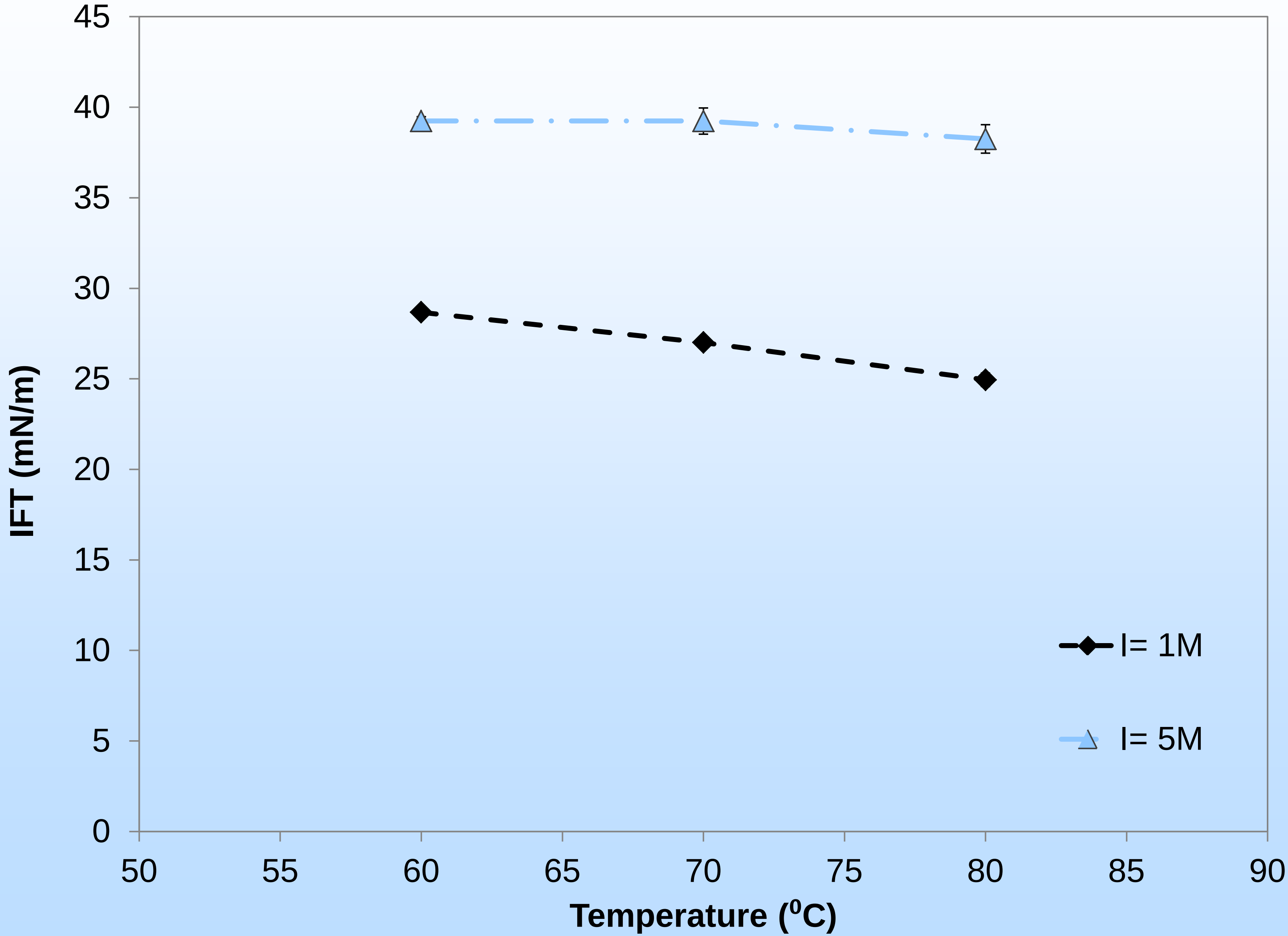
I (M)	I (ppm)
0.2	11688
1	58440
5	292200



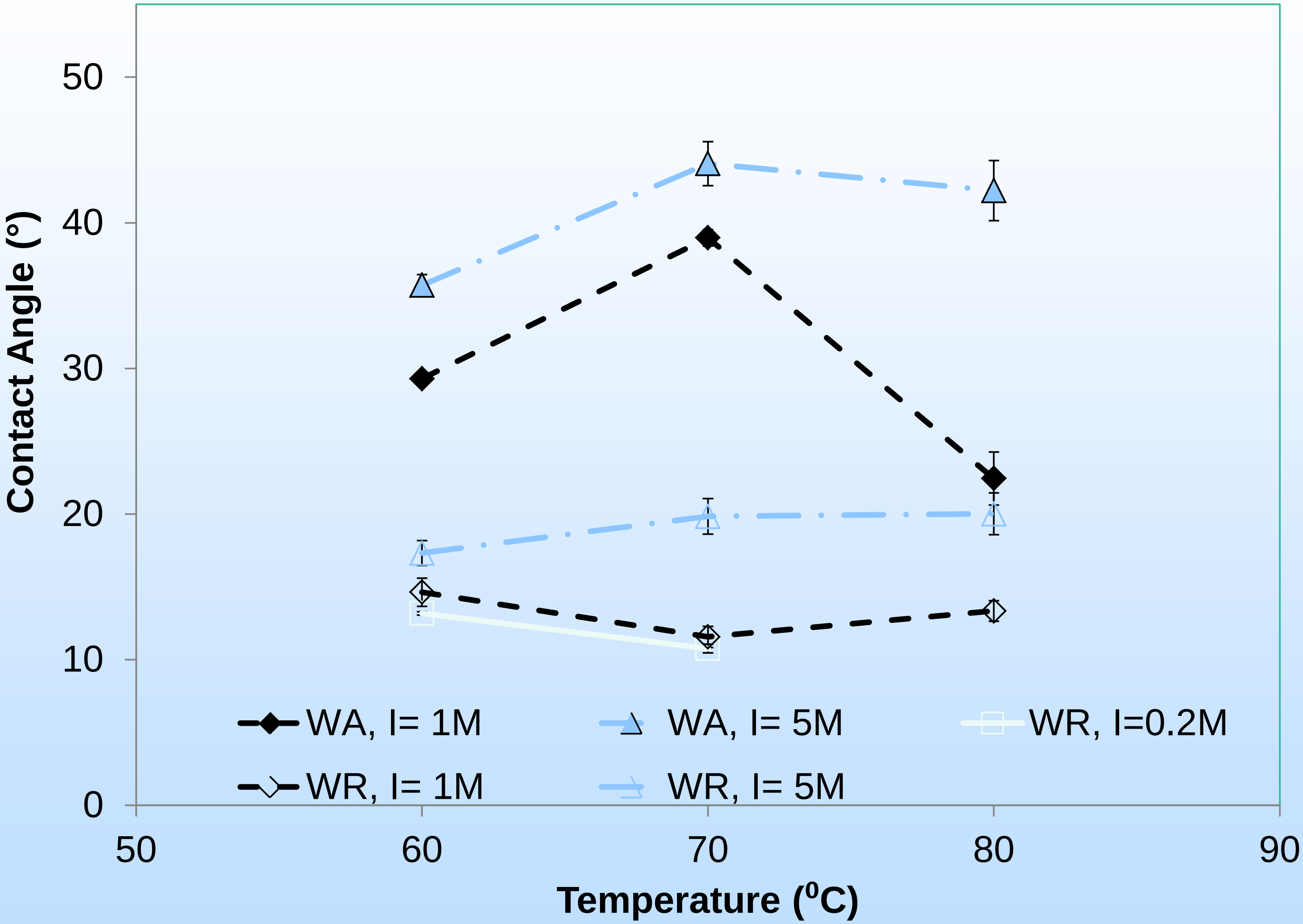


Michael K., et. al., IJGGC, 4, 659-667, 2010
Koschel D., Coxam J-Y, Rodier L., and Majer V.,, 2006, Fluid Phase Equilibria, 247, 107-120

Results (Effect of Salinity)



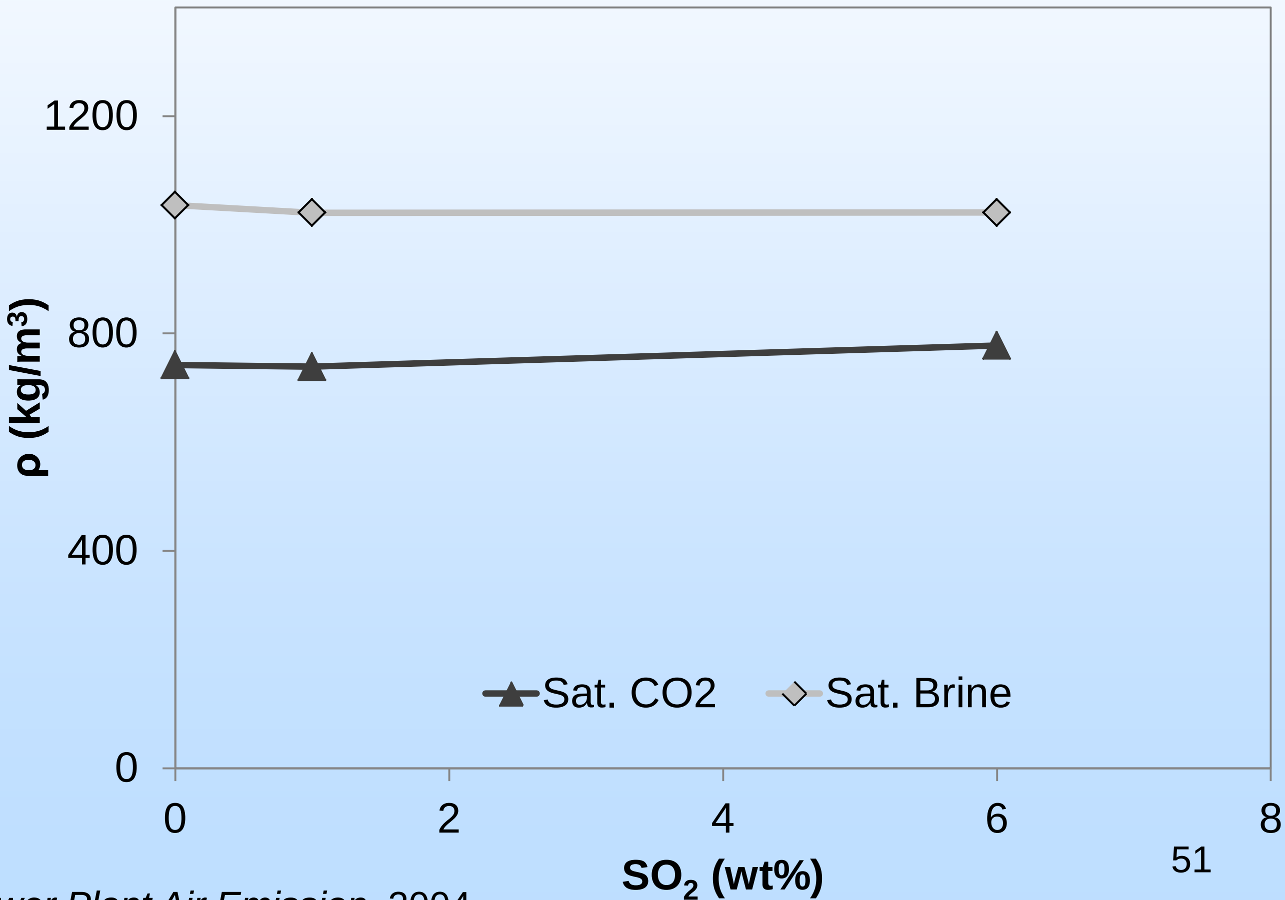
Results (Effect of Salinity)



Results (Effect of SO_2)

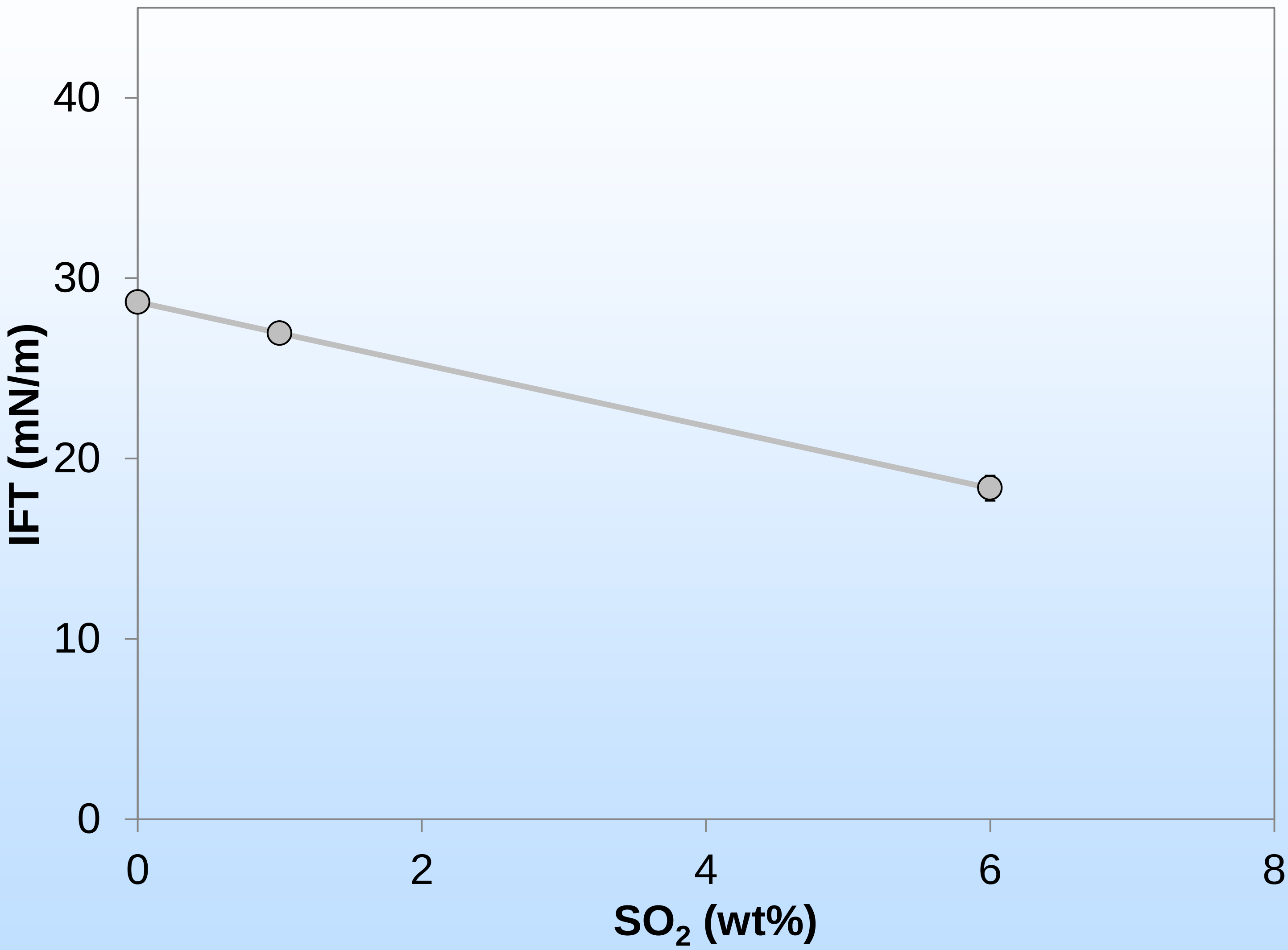
Emission stream from N.A. power plants has SO_2/CO_2 ratio ranging between 0.02 to 8 wt% with an average of 0.6 wt%.

- P=3000 psi
- T=60 ° C
- I=1 M



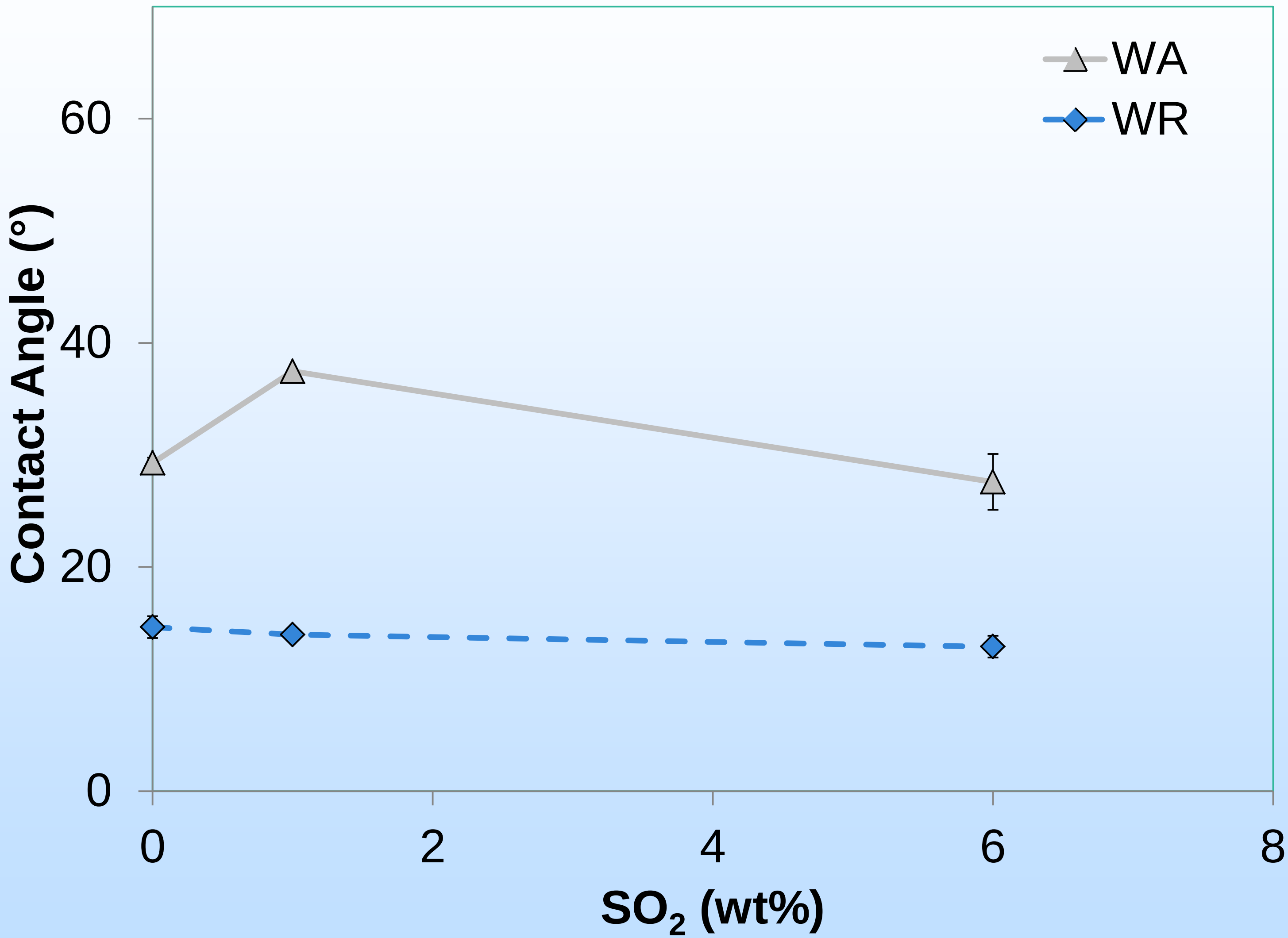
Miller P.J., Van Atten C., *N. A. Power Plant Air Emission*, 2004

Results (Effect of SO_2)



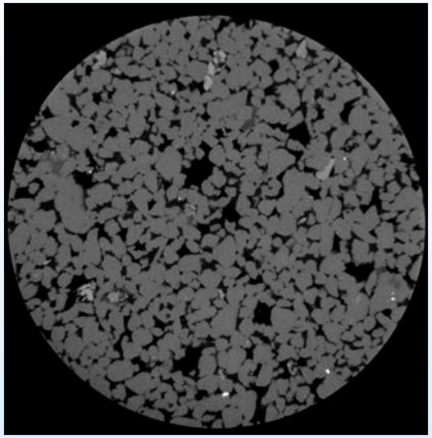
T. Tarbuck and G. Richmond, *J. Am. Chem. Soc.*, 128, 10, 3256–3267, 2006.
V. Shah, D. Broseta, G.Mouronval, and F.Montel, Int. J. Greenhouse Gas Control, 2, 4, 594–604, 2008.

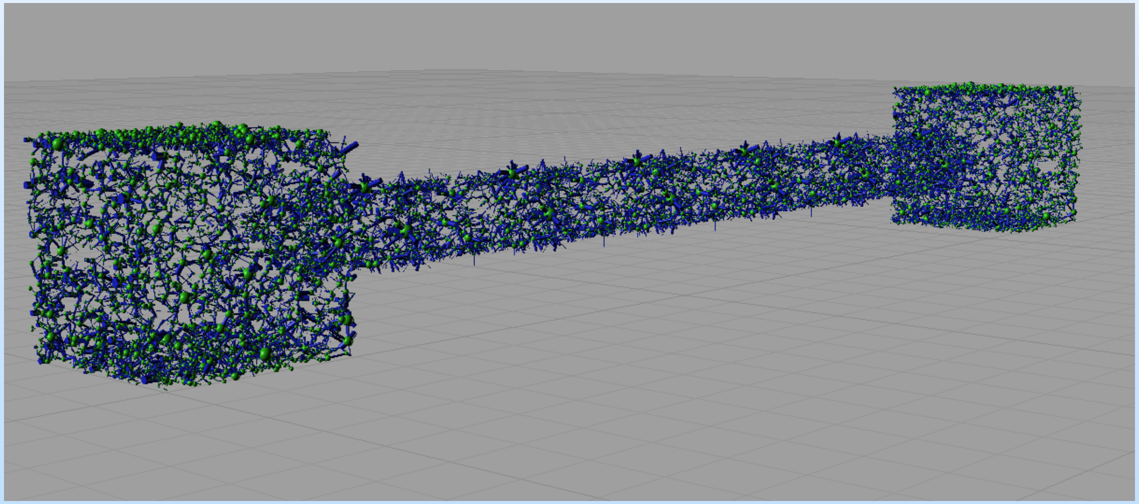
Results (Effect of SO_2)



D. Broseta, N. Tonnet, and V. Shah, *Geofluids*, vol. 12, no. 4, pp. 280–294, 2012.

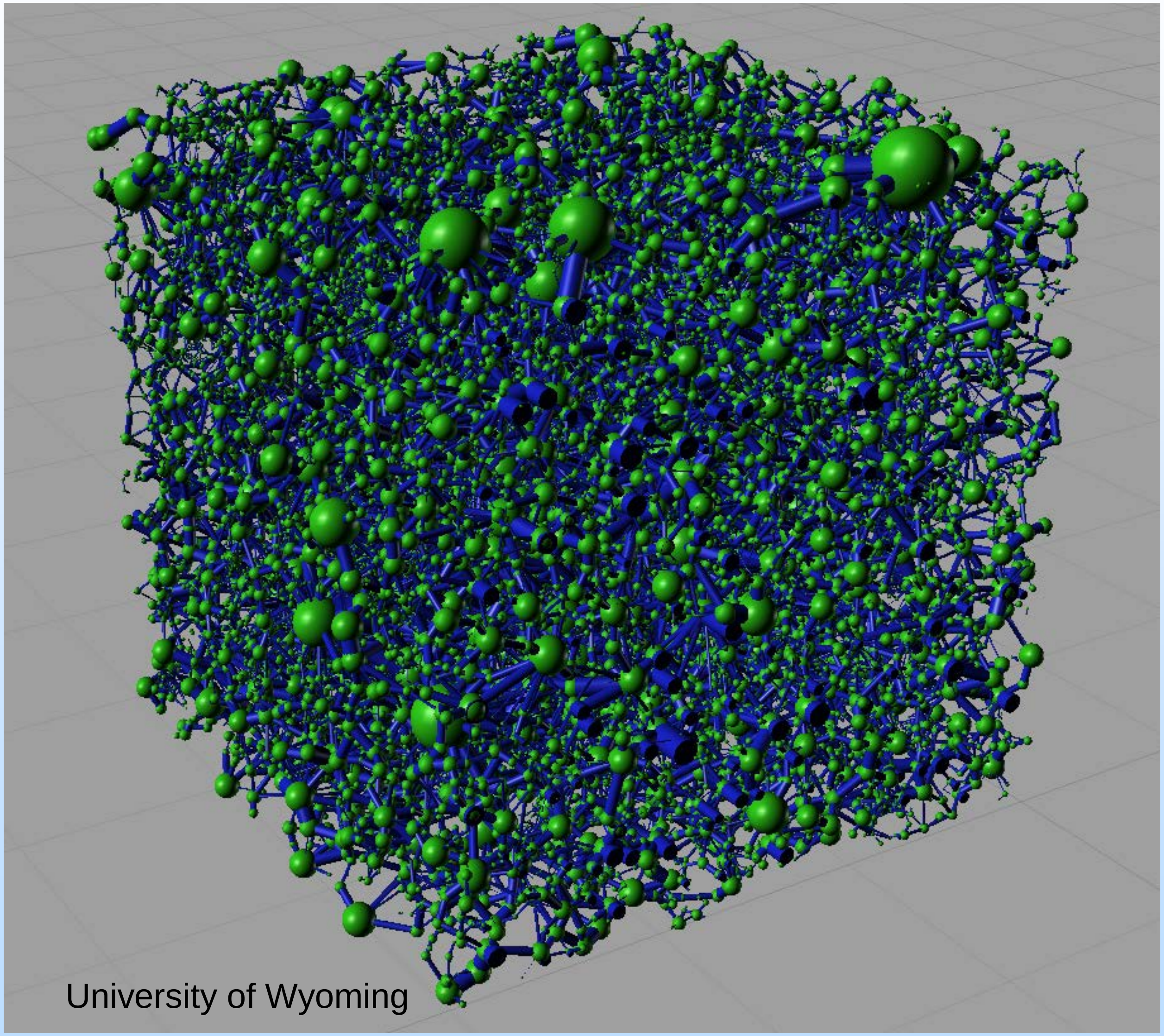
Development of physically-based dynamic pore-scale network model (Task 4)





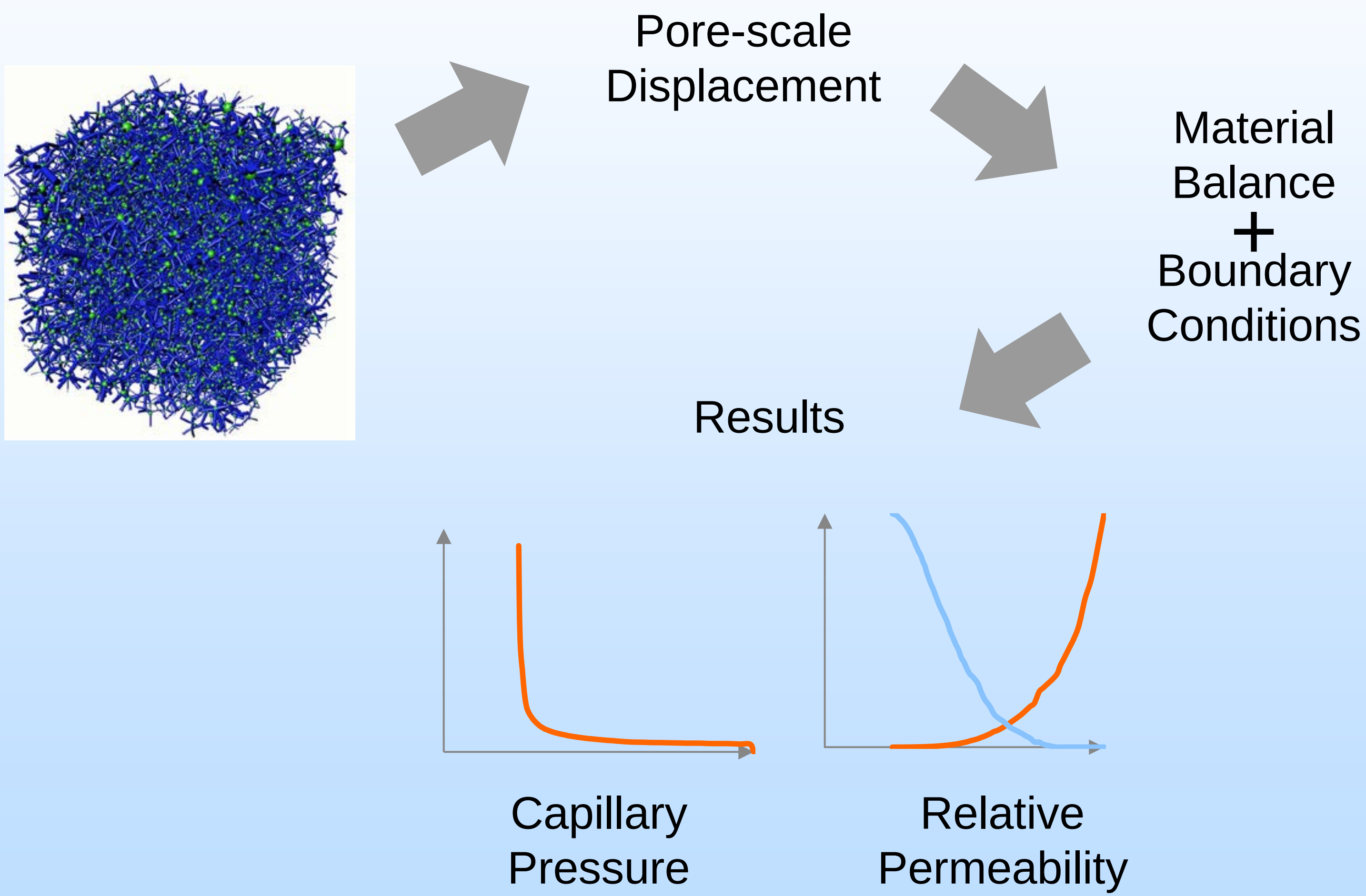
Millions of pores and throats. They represent the size, distribution and connectivity of micro pores.

Development of physically-based dynamic pore-scale network model (Task 4)

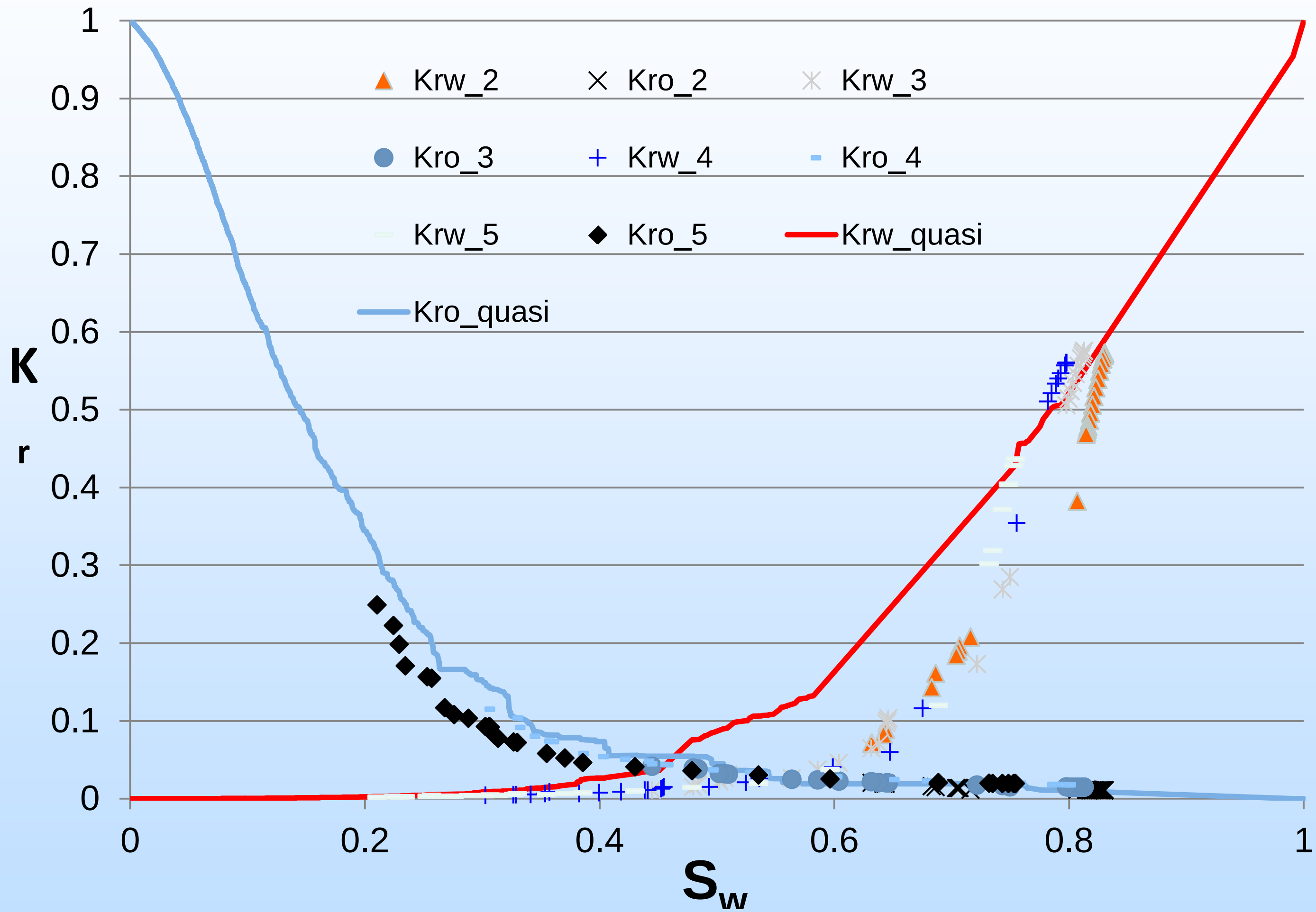


Equivalent pore network constructed for Bentheimer Sandstone using high-resolution microtomography images.

Development of physically-based dynamic pore-scale network model (Task 4)



Development of physically-based dynamic pore-scale network model (Task 4)



Modeling and Simulation
Core and Field Scales

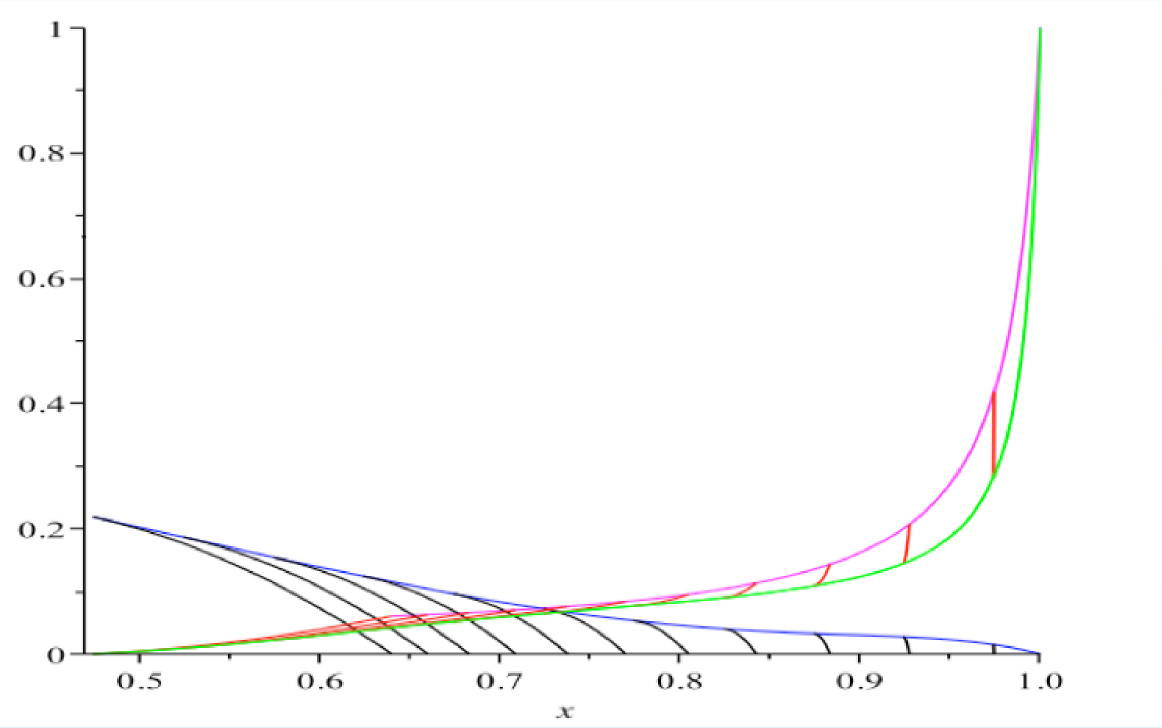
- Reservoir Modeling Activities
- Development of the UW-team Simulator

Reservoir Modeling Activities (Task 5)

- Relative permeability hysteresis
  - Construction of a mathematical model of two-phase relative permeability hysteresis measured experimentally at deep reservoir conditions
  - Analysis of its wave structure, by solving the associated Riemann problem, and development of an appropriate numerical procedure for its simulation
  - Code verification

Reservoir Modeling Activities
Relative Permeability Hysteresis

- Two-phase relative permeability functions constructed to fit the experimental data



Brine saturation (x) vs. permeabilities (y).

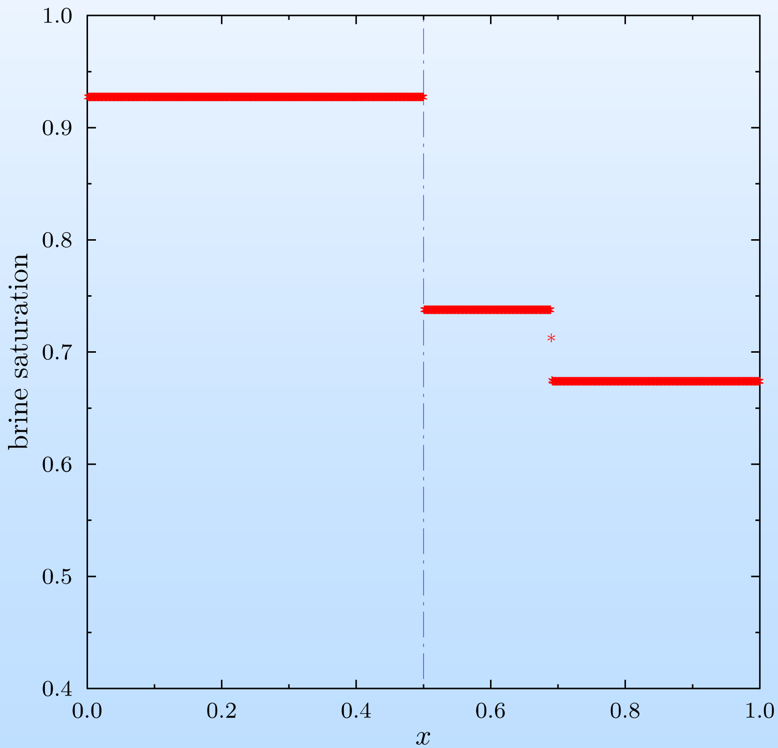
Reservoir Modeling Activities
Relative Permeability Hysteresis

- Mathematical analysis (Riemann solutions) vs. numerical solutions

o Fully nonlinear system describing mass conservation and hysteresis effects

o Example:
- Gravity points to the left
- Solution: Stationary discontinuity and a right-propagating shock

o Naive numerical schemes: incorrect answer



Development of the UW-team simulator

(Tasks 6 and 7)

- Multi-phase, multi-component, compositional model for CO_2 injection development

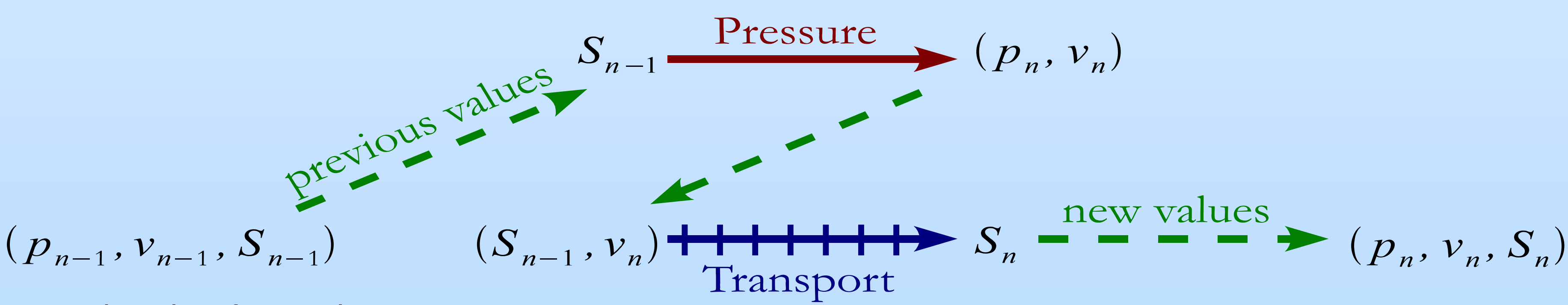
o To be used both at the core scale (model validation) and field scale (prediction of injected CO_2 location)

o Educational tool: code development (graduate course developed and taught), HPC

Development of the UW-team simulator
Strategy for discretization

- Operator splitting:
  - The problem is decomposed into components representing relatively simple physics
  - Accuracy: adequate numerical methods for distinct PDEs
  - Computational efficiency: distinct time steps for distinct physical processes

Example: 2-phase flows



Development of the UW-team simulator
Numerical methods

- Locally conservative procedures:

- **Hyperbolic systems:** Explicit, high-resolution Central Schemes
  - Riemann solvers not needed
  - Naturally parallelizable in CPU-GPU machines
  - Correct solutions: hysteresis

- **Elliptic and parabolic problems:** Mixed finite elements
  - Accurate velocity fields in the presence of rapidly varying coefficients
  - Parallelization through multiscale mixed methods in CPU-GPU machines

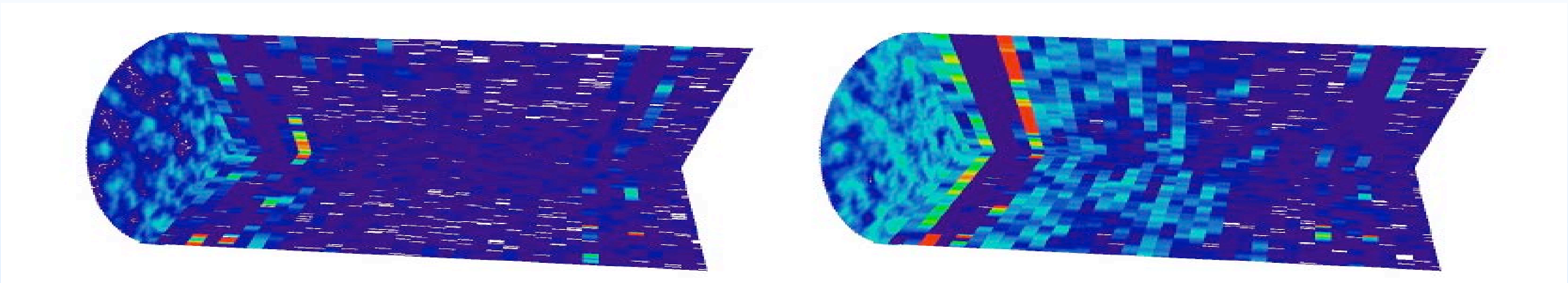
Development of the UW-team simulator
Model validation: Bayesian framework

- Context
  - Characterization at the mm scale
  - Prediction at the core scale
  - Goal: validation of the compositional model at the Darcy scale against experimental data

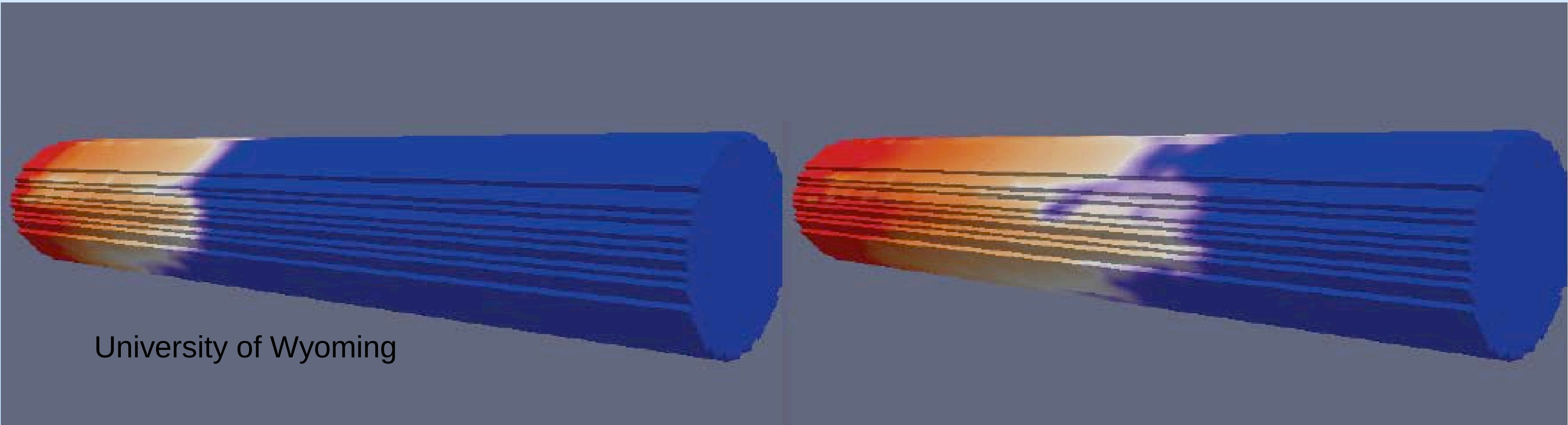
- The framework for UQ: MCMC/MC
  - Static data: porosity field at the mm scale (perm. field unknown)
  - Dynamic data: saturation fields at the mm scale, pressure drop, production curve

Development of the UW-team simulator
Model validation: Bayesian framework

Reservoir-conditions drainage experiment



Simulation results



University of Wyoming

Accomplishments to Date

1. Milestones 1-6 were completed:
    - Update Project Management Plan - Hold kickoff meeting of PIs with govt. partners
    - Acquisition of rock samples and micro-CT images for pore-level network model
    - Measurement of unsteady-state core-flooding experimental data required for code validation
    - Measurement of steady-state relative permeabilities for code validation
2. A new state-of-the-art IFT and contact angle apparatus was built from scratch and validated
3. Development of fully parallel dynamic pore-scale network model is nearing completion
4. Development of hysteresis model was completed
5. Development of phase equilibrium calculation module for $scCO_2$, SO_2, and brine is nearing completion
6. Development of compositional simulator was completed
7. Code validation for the UW-Team simulator (Milestones 5) is on track for completion in September
8. Active dissemination of findings through publications and presentations in scientific meetings

Summary

- Key findings
    - Significant fractions of initial CO_2 in place can be stored through residual trapping
    - Lower initial CO_2 saturation leads to higher trapping efficiency ($R=S_{CO2r}/S_{CO2}^{max}$)
    - Trapping efficiency between 49 to 83% of CO_2 in place
    - Accurate numerical approximation of transport problems with hysteresis

- Future Plans
    - Develop a fully parallel version of the phase equilibrium module
    - Dynamic pore-scale modeling of imbibition in large networks
    - Completion of geomechanics module
    - Compositional reservoir simulations on large computer clusters, UQ studies

Thank you