NETL Hydrate Program
Peer Review

26-27 August 2008

Comparative Assessment of Advanced Gas Hydrate Production Methods

Pacific Northwest National Laboratory

International Hydrate Code Comparison

Battelle, Pacific Northwest Division

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Project Structure and Status

Project Management

Quarterly and Annual Reports (Ongoing)
Teleconferences (Ongoing)

Closed Domain Problems

Problem 1 “Nonisothermal Multifluid Transition to Equilibrium” (Completed)
Problem 2 “Closed-Domain Hydrate Dissociation” (Completed)

One-Dimensional Open Domain Problems

Problem 3 “Dissociation in a 1-D Open Domain” (Completed)
Problem 4 “Gas Hydrate Dissociation in a 1-D Radial Domain - Similarity Solutions” (Completed)

Two-Dimensional Open Domain Problems

Problem 5 “Gas Hydrate Dissociation in a 2-D Radial Domain” (Completed)
Problem 7 “Long-Term Simulations for Mt Elbert and PBU L-Pad ‘Like’ Deposits” (Ongoing)

Validation Problem

Problem 6 “Analysis of Modular Dynamic Formation Test Results from the Mount Elbert Stratigraphic Test Well, Milne Point, Alaska (Completed)

Project Structure and Status

Project Management

- Research Management Plan (Completed)
- Quarterly and Annual Reports (Ongoing)

Technology Status Assessment

- Assessment Report (Completed)

Numerical Simulation of Natural Gas Hydrate Production

- Simulator Development and Verification (Completed)
- Natural Gas Hydrate Production Technology Assessment (Completed)
- Portable, Scalable Implementation of STOMP-HYD (Ongoing)

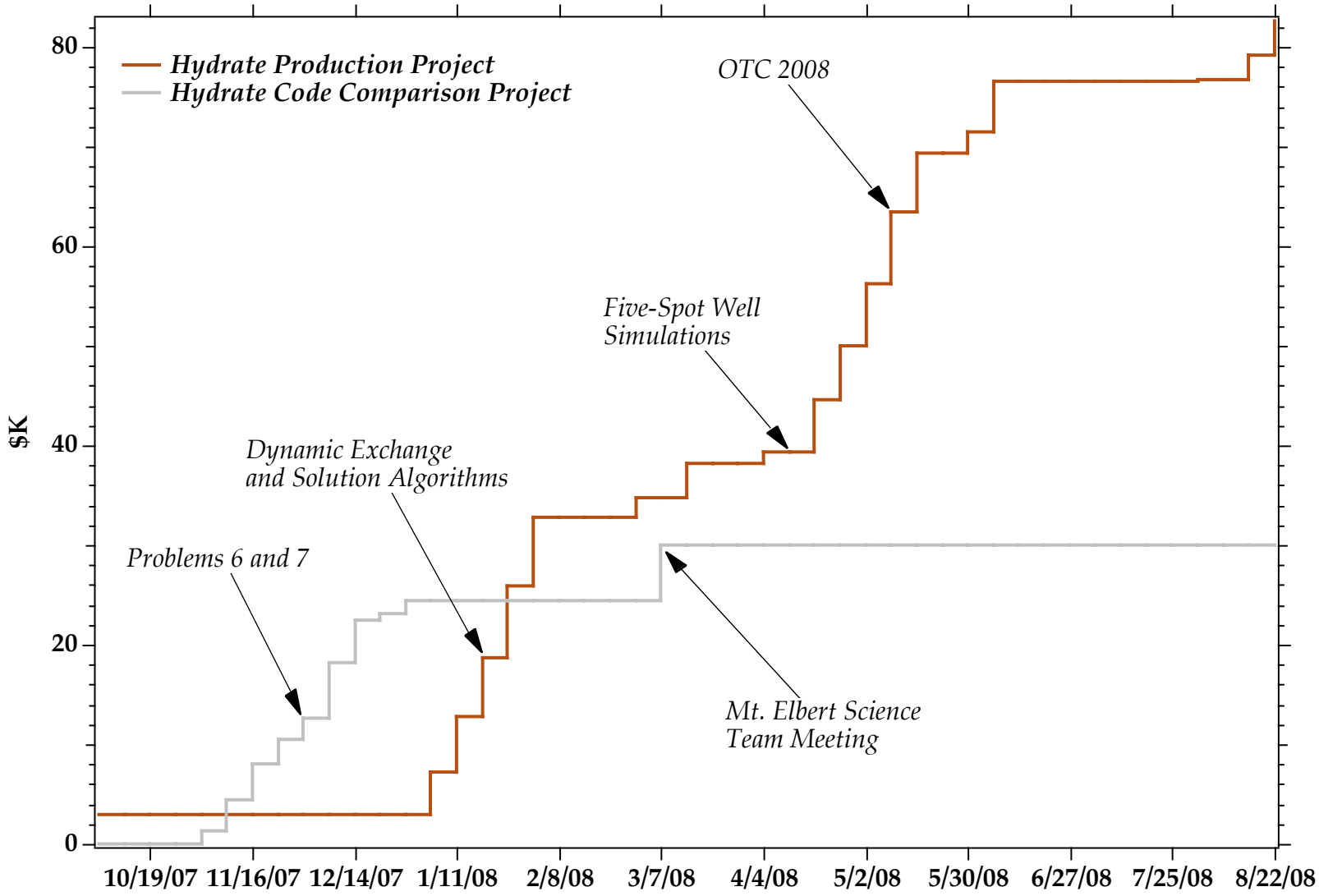
Reservoir Simulation with Alaska North Slope Field Data

- Conceptual Model Development (Pending)
- Conventional Production Technologies (Pending)
- Enhanced Gas Hydrate Recovery Technologies (Pending)
- Direct CO_2 Exchange Production Technologies (Pending)

Final Report

- Project Summary Report (Pending)

Project Costs



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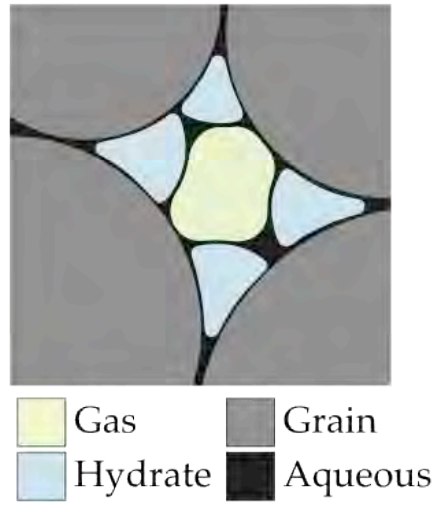
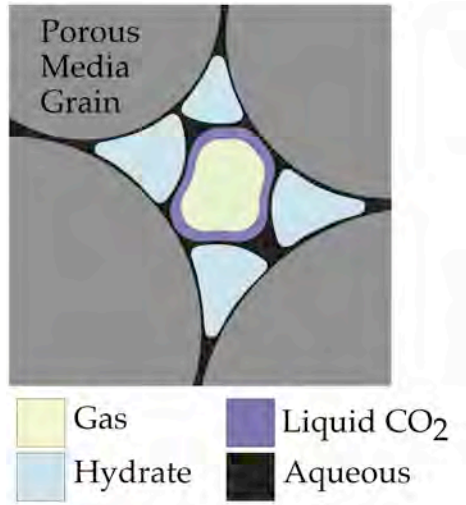
Simulator Development

STOMP-HYD (equilibrium exchange of guest molecules)
- Core Version
  - 3 unknowns (energy, water, CH_4)
  - 4 phases (aqueous, gas, hydrate,ice)
- Plus CO_2
  - 4 unknowns (energy, water, CH_4, CO_2)
  - 5 phases (aqueous, gas, liquid CO_2, hydrate, ice)
- Plus Inhibitor
  - 5 unknowns (energy, water, CH_4, CO_2, inhibitor)
  - 5 phases (aqueous, gas, liquid CO_2, hydrate, ice)
- Hydrate Independent
  - hydrate saturation function of temperature and bulk equilibrium temperature
  - considered pore-size distribution via retention characteristics
- Hydrate Dependent
  - hydrate saturation primary variable
  - equilibrium temperature independent of pore-size

STOMP-HYDk (kinetic exchange of guest molecules)
- Core Version
  - 6 unknowns (energy, water, mobile CH_4, mobile CO_2, hydrate CH_4, hydrate CO_2)
  - 5 phases (aqueous, gas, liquid CO_2, hydrate, ice)





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Publications

Technology Status Assessment Report

(http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/reports/NT42666_TSA.pdf)

International Symposium on Gas Hydrate Production

White, M. D. and B. P. McGrail. 2006. " STOMP-HYD: A New Numerical Simulator for Analysis of Methane Hydrate Production from Geologic Formations," In Proceedings of *2nd International Symposium on Gas Hydrate Technology*, 1-2 November 2006, KIGAM, Daejeon, Korea.

Offshore Technology Conference 2008

White, M. D., and B. P. McGrail. 2008. "Numerical Simulation of Methane Hydrate Production From Geologic Formations via Carbon Dioxide Injection." In Proceedings of *Offshore Technology Conference*. PNWD-SA-8114, Battelle—Pacific Northwest Division, Richland, WA.

International Conference on Gas Hydrates 2008

Wilder, J. W., G. J. Moridis, S. J. Wilson, M. Kurihara, M. D. White, Y. Masuda, B. J. Anderson, T. S. Collett, R. B. Hunter, H. Narita, M. Pooladi-Darvish, K. Rose, and R. Boswell. 2008. “An international effort to compare gas hydrate reservoir simulators,” In Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, Canada, July 6-10, 2008.

Anderson, B. J., J. W. Wilder, M. Kurihara, M. D. White, G. J. Moridis, S. J. Wilson, M. Pooladi-Darvish, Y. Masuda, T. S. Collett, R. B. Hunter, H. Narita, K. Rose, and R. Boswell. 2008. “Analysis of modular dynamic formation test results from the ‘Mount Elbert’ stratigraphic test well, Milne Point, Alaska,” In Proceedings of the 6th International Conference on Gas Hydrates (ICGH 2008), Vancouver, British Columbia, Canada, July 6-10, 2008.

STOMP Overview

Operational Modes

- STOMP-W, -WA, WAE -- Water-Air-Energy Operational Modes
- STOMP-WO, -WOA, WOAE -- Water-Oil-Air-Energy Operational Modes
- STOMP-WS, -WSA, WSAE -- Water-Salt-Air-Energy Operational Modes
- STOMP-WCS, -WCSE -- Water-CO2-Salt-Energy Operational Modes
- STOMP-WCMSE -- Water-CO2-CH4-Salt-Energy Operational Modes

Implementations

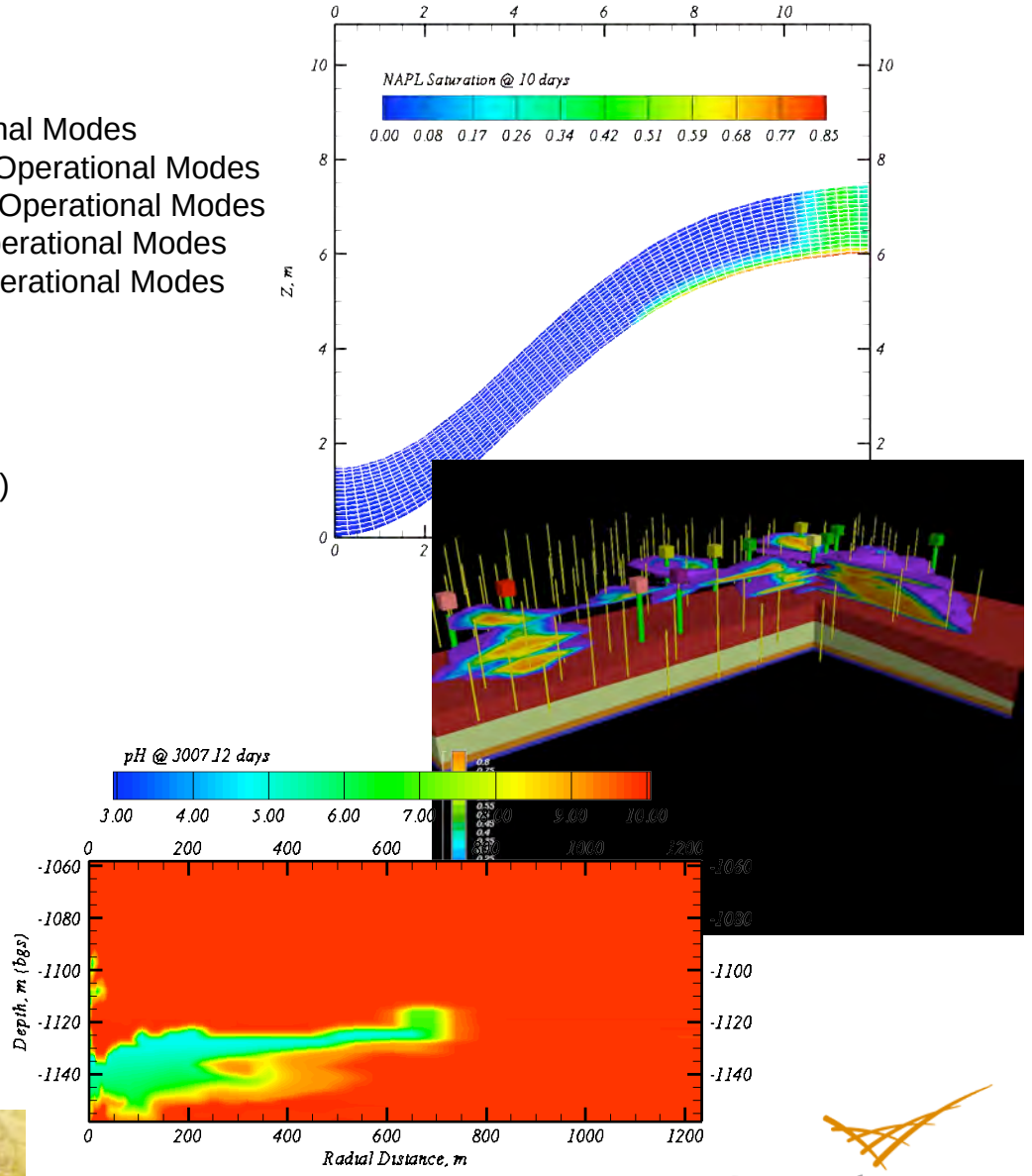
- Sequential (FORTRAN 77)
- Scalable (Fortran 90, MPI, PETSc, FP, Global Arrays)

Licensing and Quality Assurance

- Academic, U.S. Gov., Foreign Gov., Industrial
- Documentation (Guides, Website, Publications)
- Short Courses (University Sponsored)
- DOE Order 414.1C (System Safety Software)

Future

- Geologic CO_2 sequestration
- Hydrocarbon production
- Petascale computing and beyond



STOMP Subsurface Transport Over Multiple Phases

http://stomp.pnl.gov

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STOMP-WAE, WNE

Hanford Site SX-Tank Farm

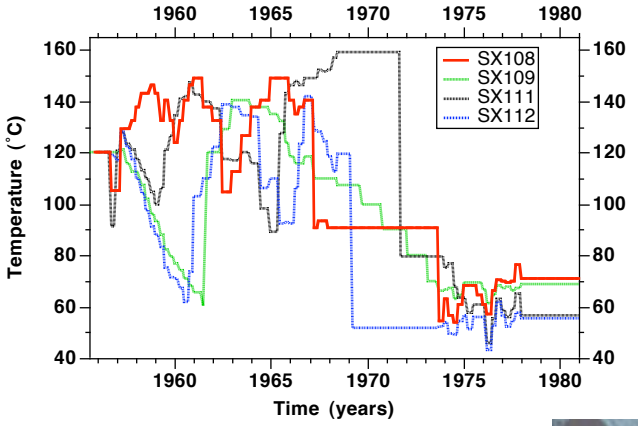
- Historical Simulation from 1955 to 2000
- Coupled Thermal and Hydrologic System

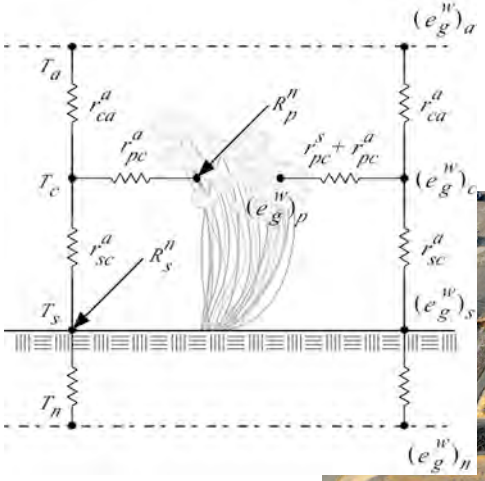
Hanford Site Surface Barriers

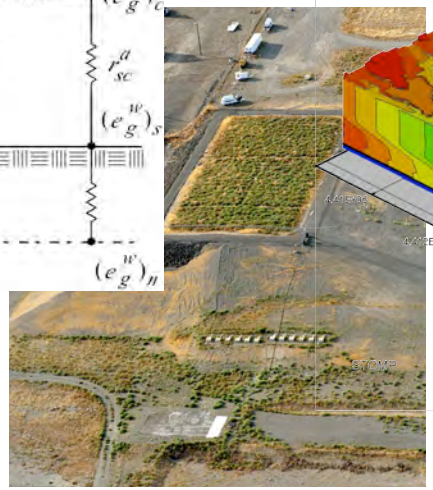
- Engineered Surface Barriers
- Sparsely Vegetated Surface

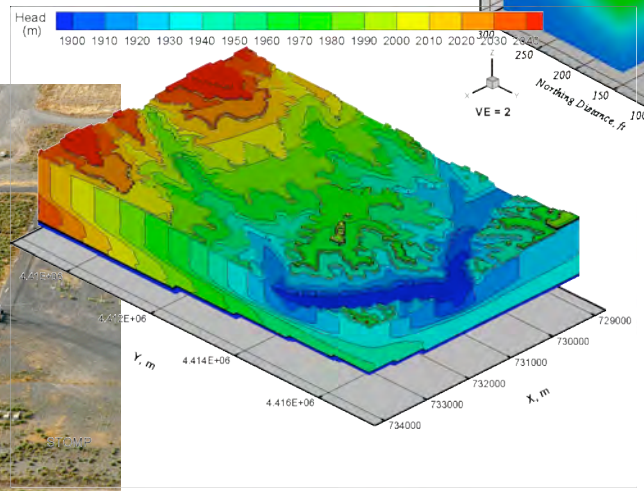
Piceance Basin Intermediate Scale Modeling

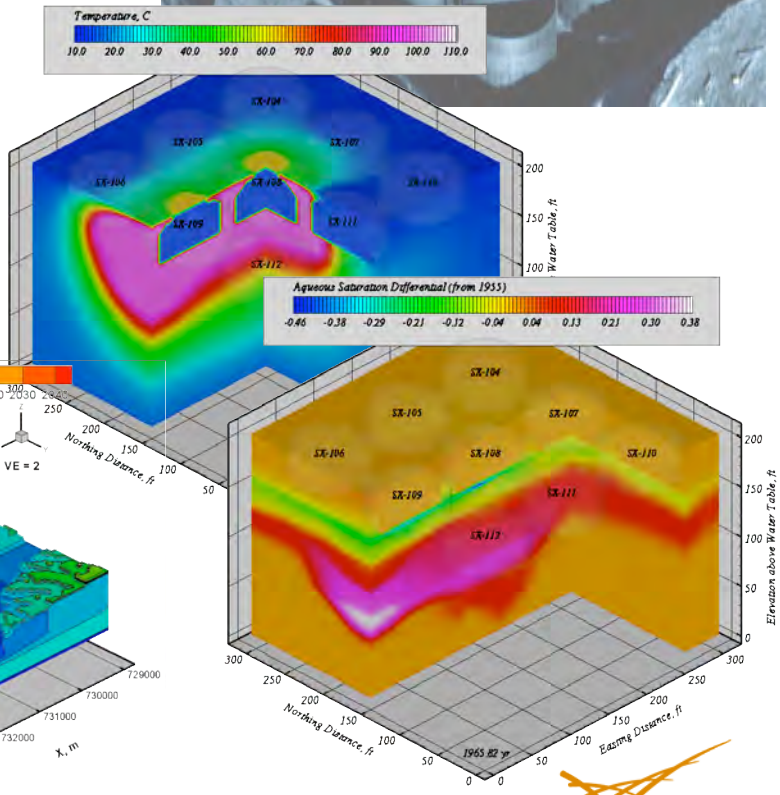
- Chevron, PNNL, LANL, and INL Environmental CRADA
- Thermal Plume and Reactive Transport between Pod and Basin Scales











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STOMP-WO, WOA, WON, WOAE

Hanford Site Z9 Crib

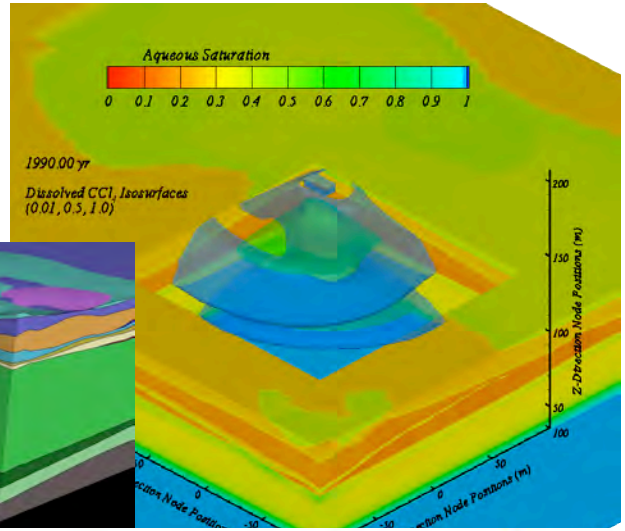
- Historical Simulation from 1965 to 2000
- Soil Vapor Extraction

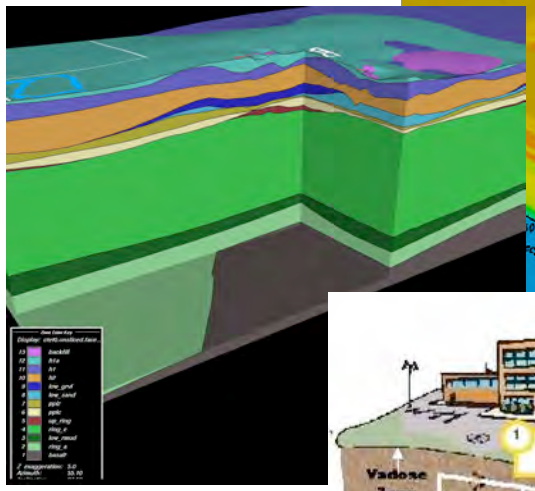
Brooklawn and Scenic Superfund Sites

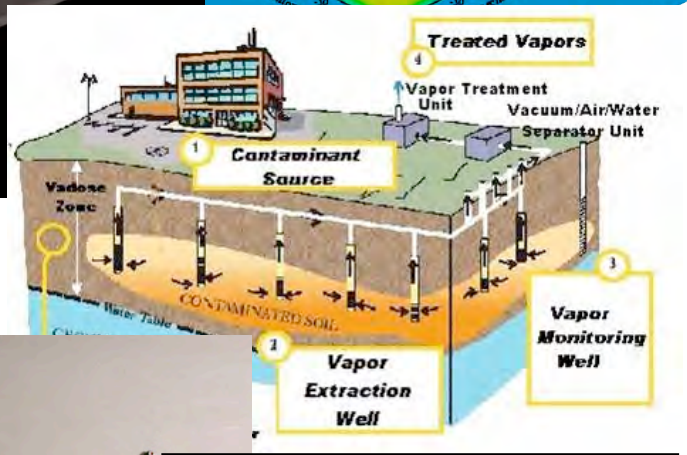
- Multifluid Recovery Wells
- DNAPL Migration
- Fluctuating Water Table

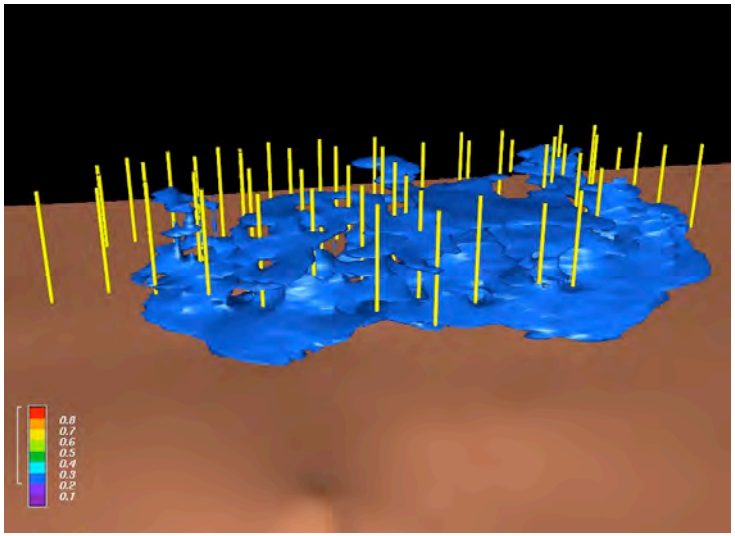
Laboratory Flow Cell Validation

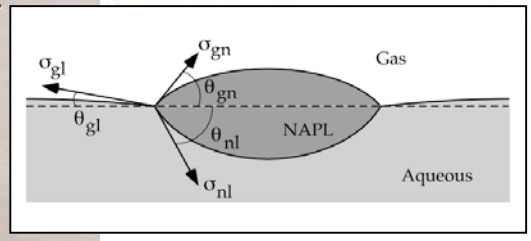
- Vadose Zone Residual NAPL
- Heterogeneous Soil Systems
- Iterative Theory Development and Validation
- Experiment and Remediation Technology Design











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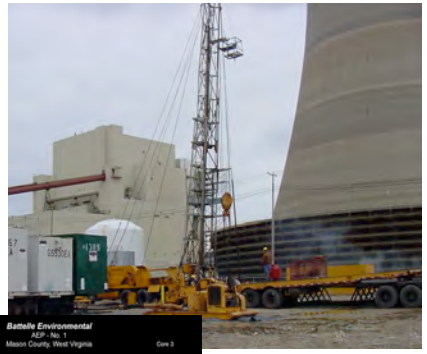
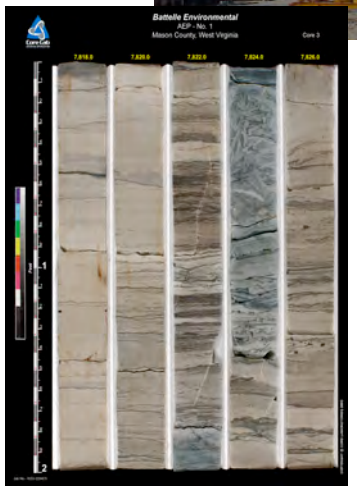
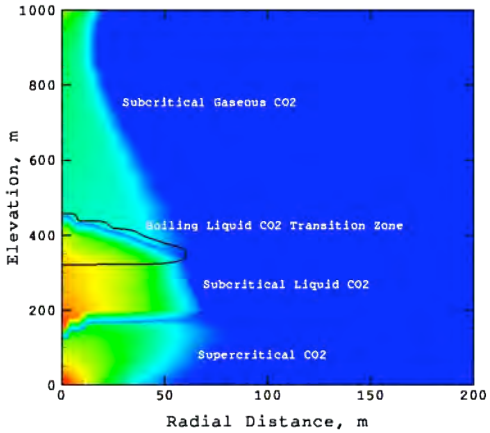
STOMP-CO2, CO2e, CO2ae

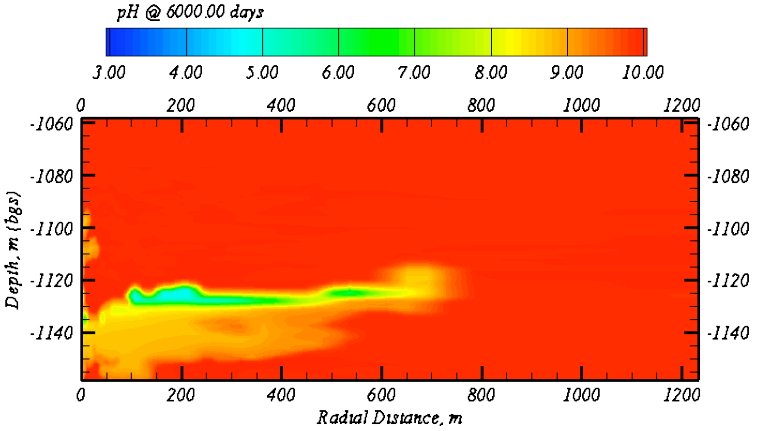
Applications

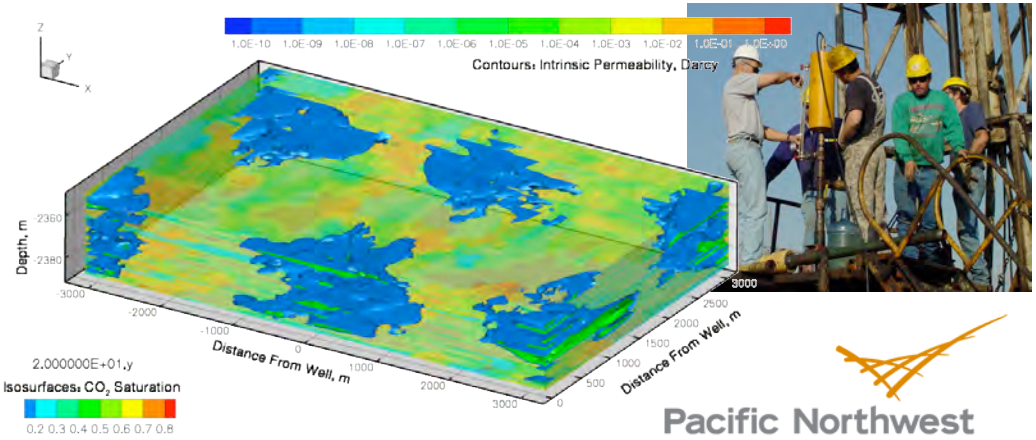
- GeoSeq Intercomparison Problems
- Supercritical CO_2 Injection Experiments
- Columbia River Basin
  - Grande Ronde Basalt
- AEP Mountaineer Power Plant Site
  - Rose Run Formation
  - Copper Ridge Formation
- FutureGen Site Selection Process
  - Brazos, Texas
    - Travis Peak Formation
    - Woodbine Formation
  - Mattoon, Illinois
    - Mount Simon Formation
  - Odessa, Texas
    - Queen Formation
    - Delaware Mountain Formation
  - Tuscola, Illinois
    - Mount Simon Formation
- Midwest Regional Carbon Partnership
  - Michigan Site
    - Bass Islands Dolomite Formation
- Alaska North Slope, Milne Point
  - C Unit











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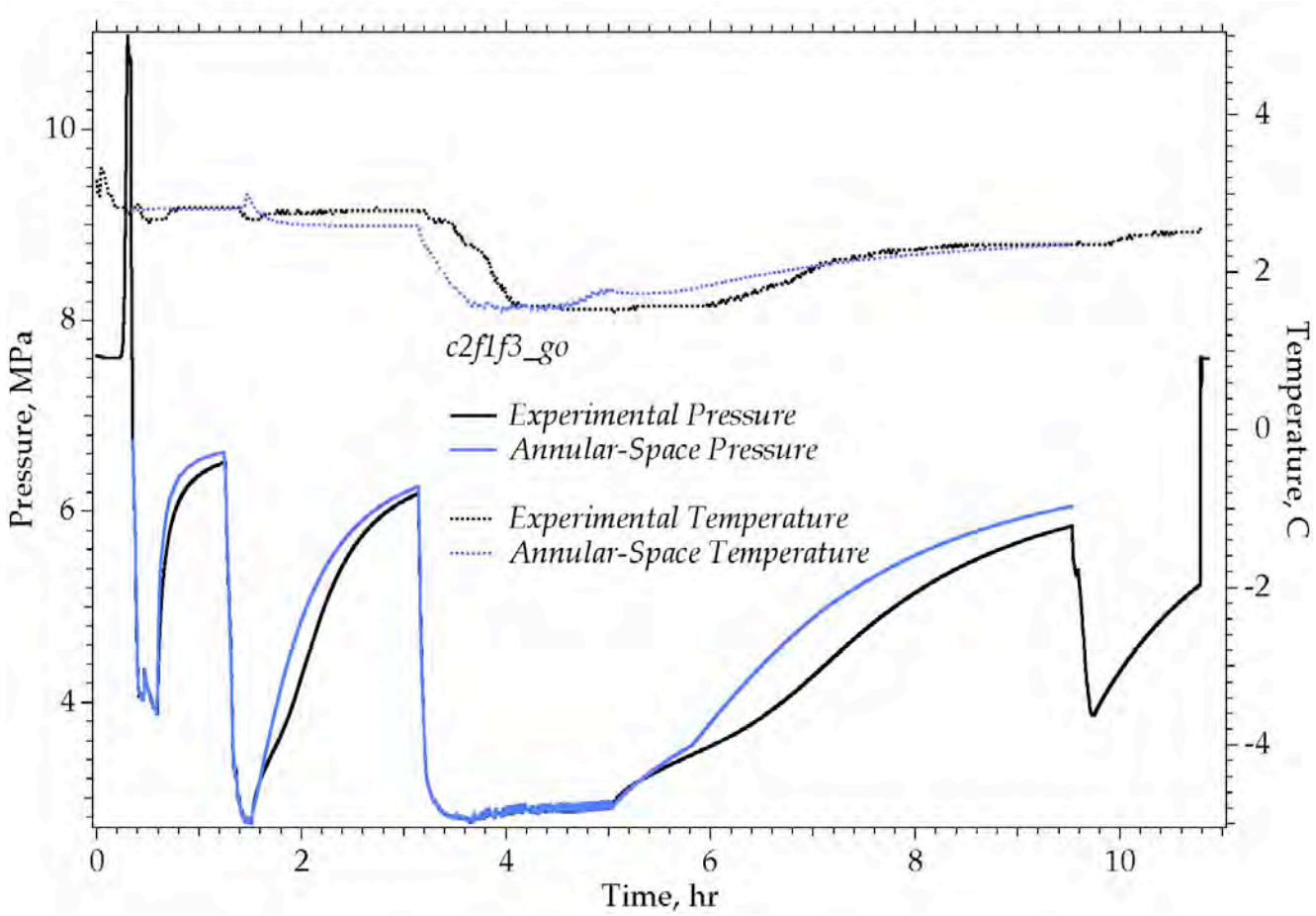
Project Outcomes

Project Management

Open scientific exchange of simulation concepts, approaches and techniques with the code comparison group

Validation Problem

Problem 6 “Analysis of Modular Dynamic Formation Test Results from the Mount Elbert Stratigraphic Test Well, Milne Point, Alaska



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Simulation Challenges and Gaps

Numerical Execution

- Nonlinearities in Constitutive Equations
- Phase Appearances and Disappearances
- Convergence Behavior
- Execution Speeds

Assumptions

- Pore-Filling Gas Hydrate
- Non-Zero Aqueous Saturation
- Equilibrium Gas Hydrate Dissociation/Formation

Scientific Gaps

- Relative Permeability as a Function of Phase Saturations and Hydrate Morphology
- Thermal Conductivity as a Function of Phase Saturations and Hydrate Morphology
- Mechanical Properties as a Function of Phase Saturations and Hydrate Morphology

Validation Needs

- Dynamic Laboratory Experiments
- Field-Scale Pilot and Production Tests

Project Outcomes: Constitutive Equations

No Liquid CO_2

$$\bar{\bar{s}}_l = \frac{\frac{s_l}{\left(1 - s_h - s_i\right)} - s_{lr}}{\left(1 - s_{lr}\right)} = func\left[\beta_{gl}\left(P_g - P_l\right)\right]; \text{ where } \beta_{gl} = \frac{\sigma_{ref}}{\sigma_{gl}}$$

$$P_n = \frac{\beta_{nl} P_l + \beta_{gn} P_g}{\beta_{nl} + \beta_{gn}}; \text{ where } \beta_{gn} = \frac{\sigma_{ref}}{\sigma_{gn}}$$

Liquid CO_2

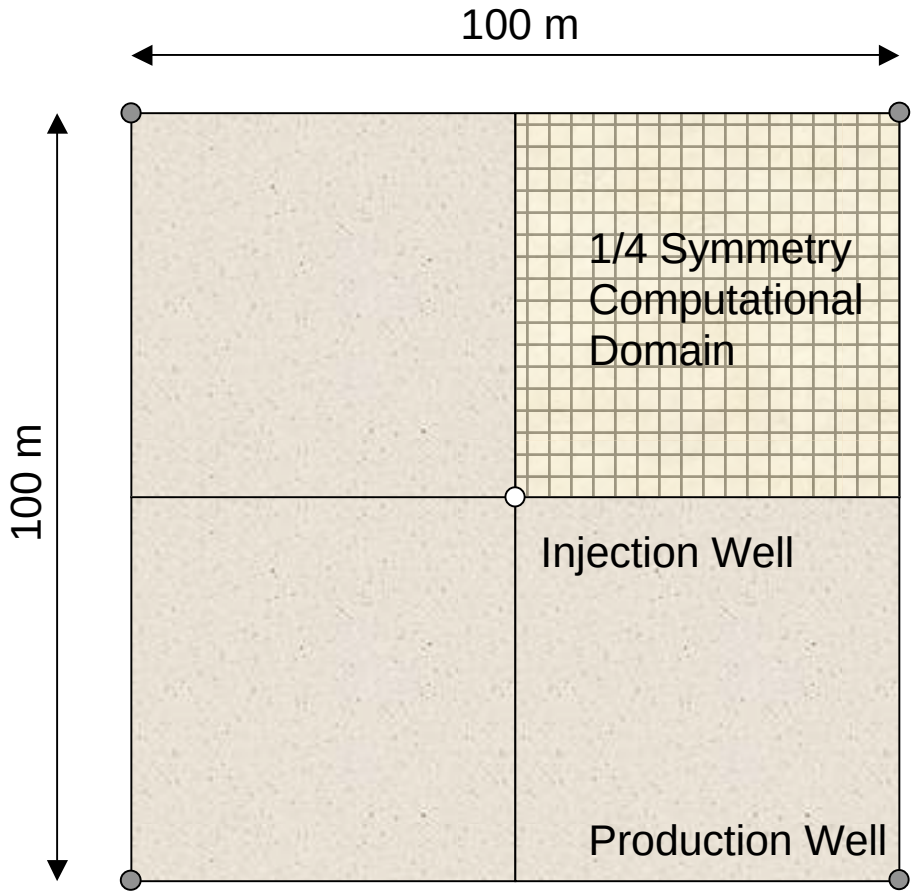
$$\bar{\bar{s}}_l = \frac{\frac{s_l}{\left(1 - s_h - s_i\right)} - s_{lr}}{\left(1 - s_{lr}\right)} = func\left[\beta_{nl}\left(P_n - P_l\right)\right]; \text{ where } \beta_{nl} = \frac{\sigma_{ref}}{\sigma_{nl}}$$

$$s_n = s_t - s_l \text{ ; where } \bar{\bar{s}}_t = \frac{\frac{s_t}{\left(1 - s_h - s_i\right)} - s_{lr}}{\left(1 - s_{lr}\right)} = func\left[\beta_{gn}\left(P_g - P_n\right)\right]$$

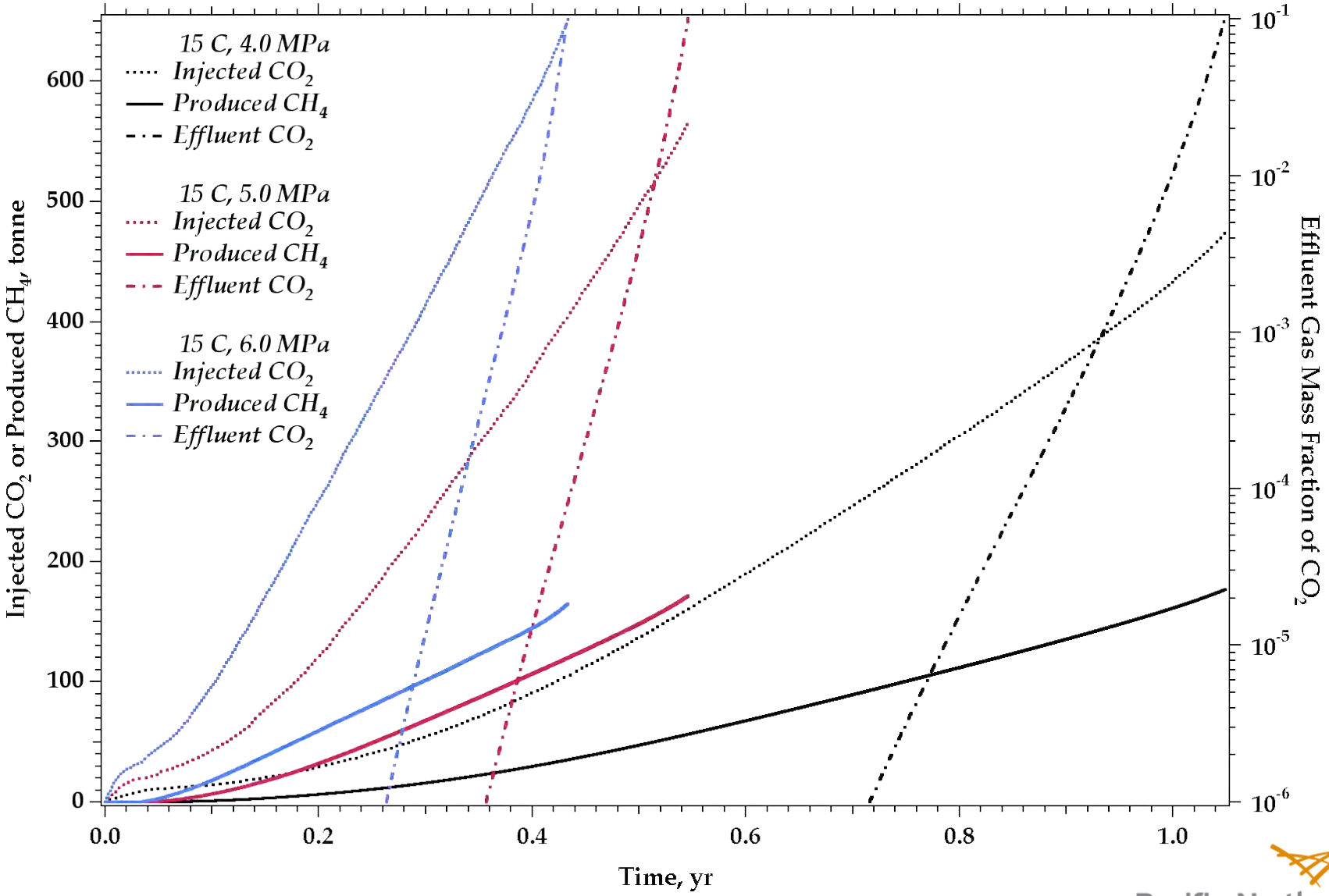
5-Spot Well Production

Scenarios

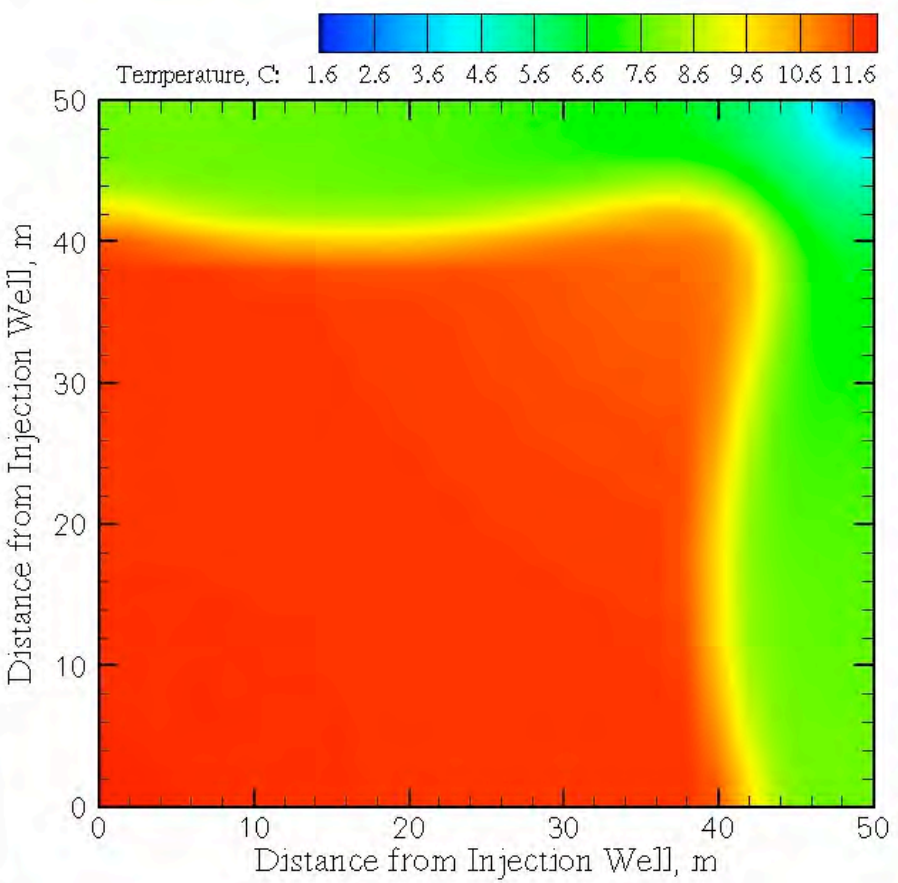
- Formation Type = sandstone
- Formation Thickness = 1 m
- Intrinsic Permeability = 1 Darcy
- Porosity = 0.35
- Compressibility = 6.25e-10 1/Pa
- Formation Pressure = 6 MPa
- Formation Temperature = 3 C
- Depressurization to 3 MPa
- CO_2 Injection Conditions
  - 15 C, 4 MPa (5.3 C, gas)
  - 15 C, 5 MPa (14.3 C, gas)
  - 15 C, 6 MPa (22.0 C, liquid)
- CO_2 breakthrough at 0.01 effluent gas mass fraction

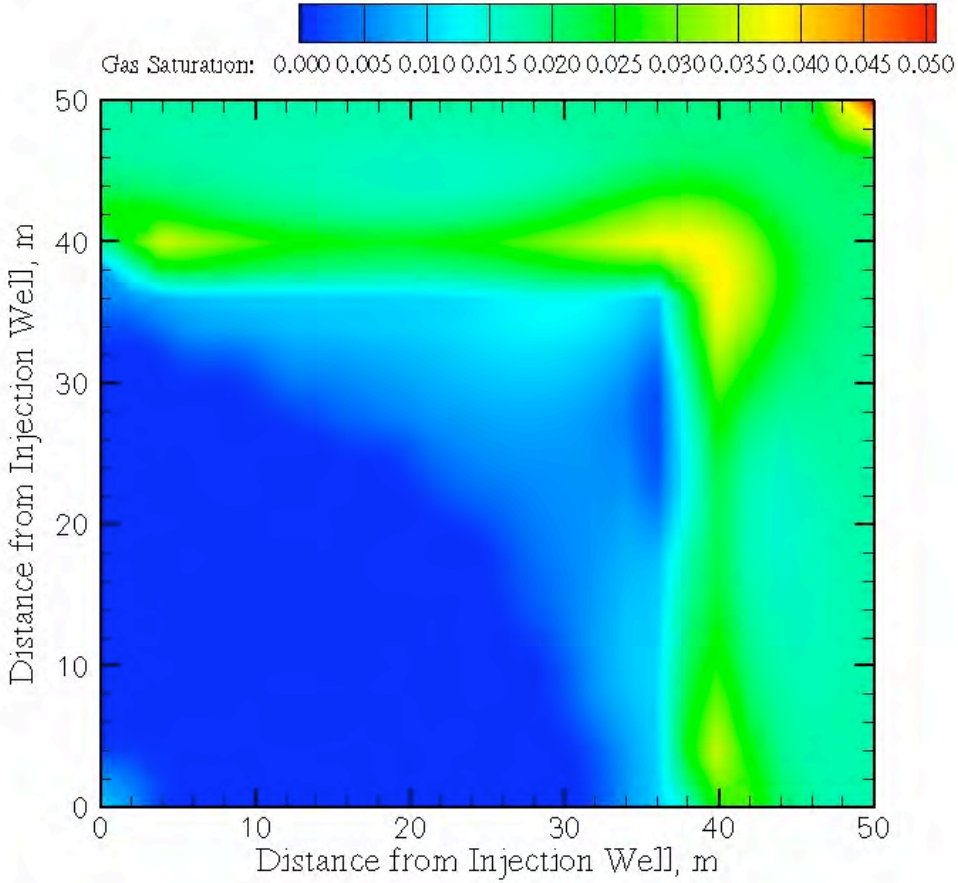


CH_4 Production



Temperature and Gas Saturation





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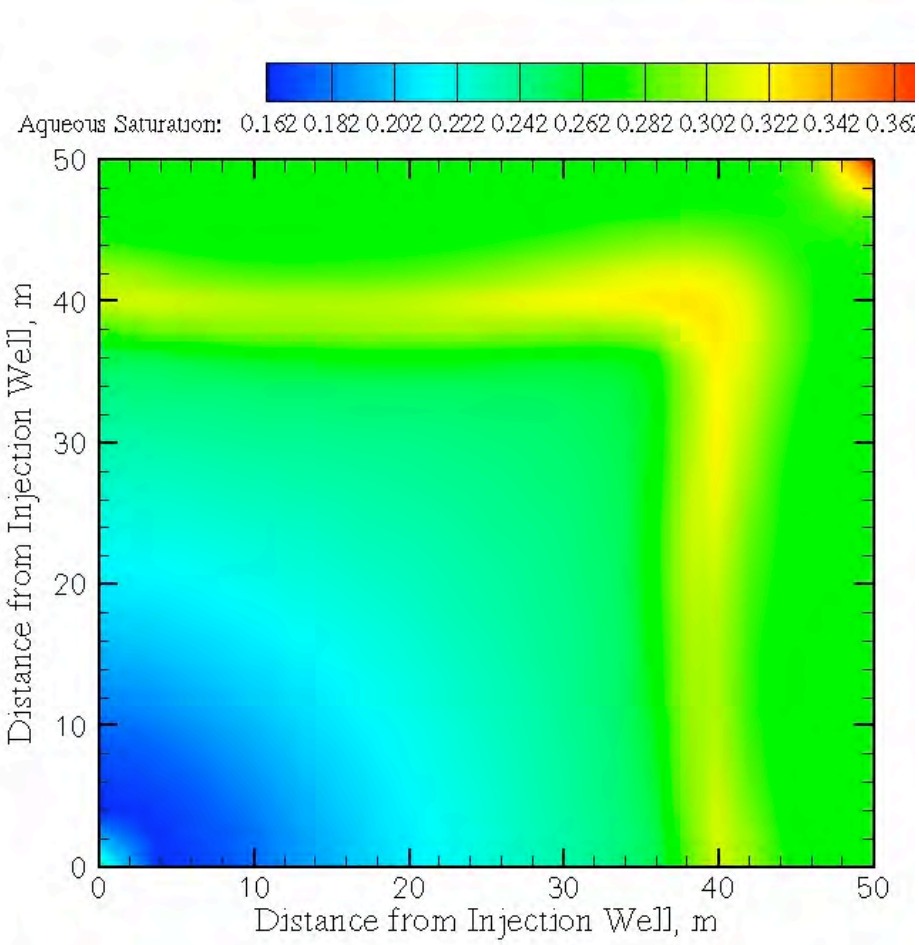
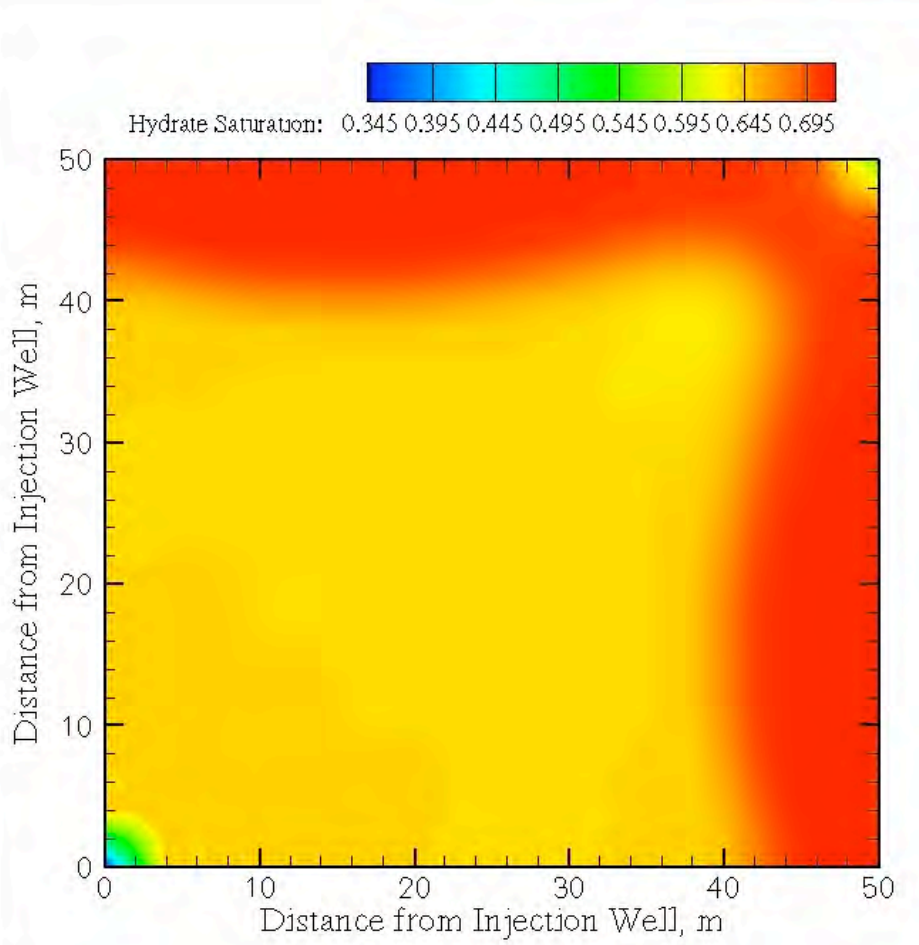
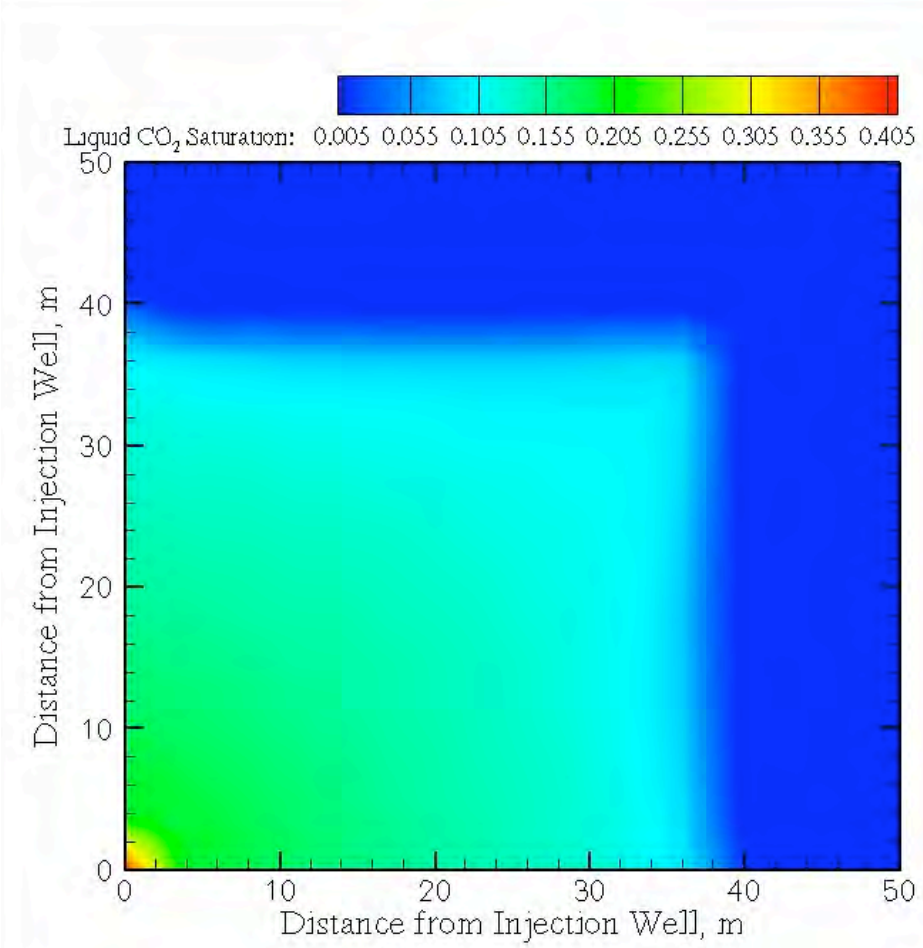
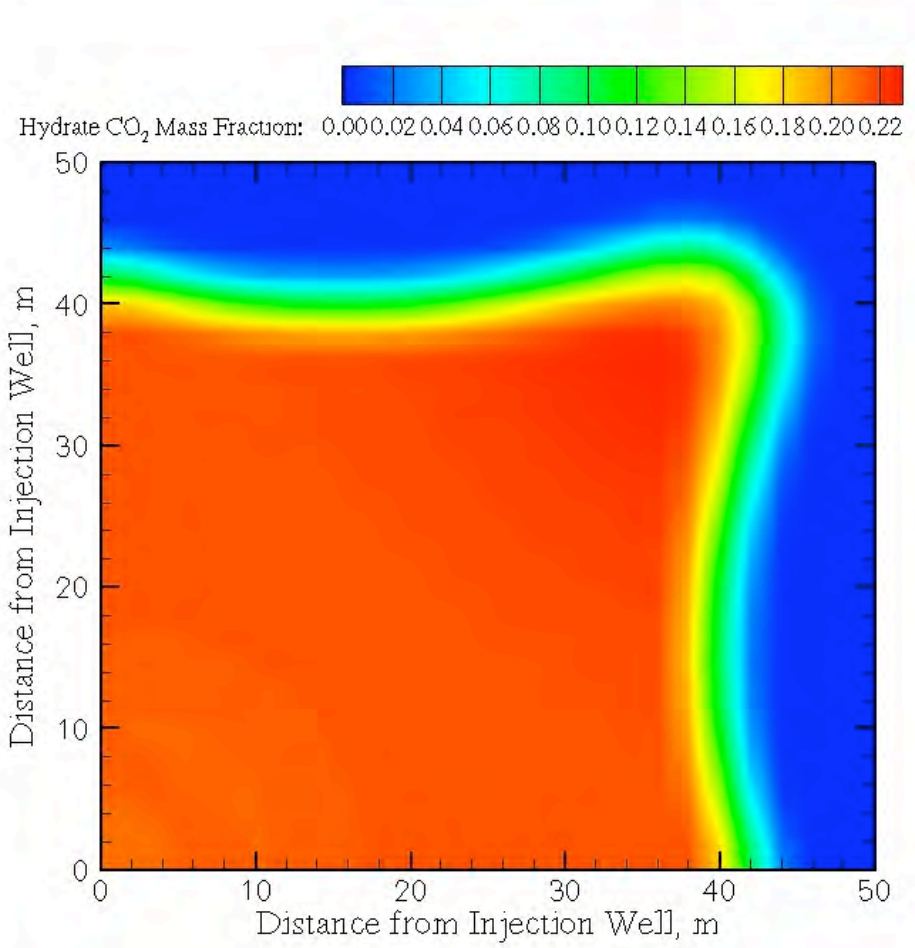
Aqueous and Hydrate Saturation





Liq. CO_2 Sat. and Hydrate CO_2 Mass Frac.





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Simulation Assumptions and Summary

Assumptions

Kinetics of the direct exchange of hydrate formers (i.e., CO_2 with CH_4) ignored, but will be considered in the future by tracking mobile and hydrate components separately.

Cage occupancies of the sI structure ignored, but will be considered in the future by tracking small and large cage occupancies of hydrate components.

Summary

Preliminary depressurization to a point above the freezing point of the aqueous phase opens pore space for mobile fluids.

Controlling secondary hydrate formation is critical to prevent pore plugging.

Heat transfer into the production zone not required.

Total CH_4 production (roughly 50% of available) independent of injection pressure.

Research Directions

Development

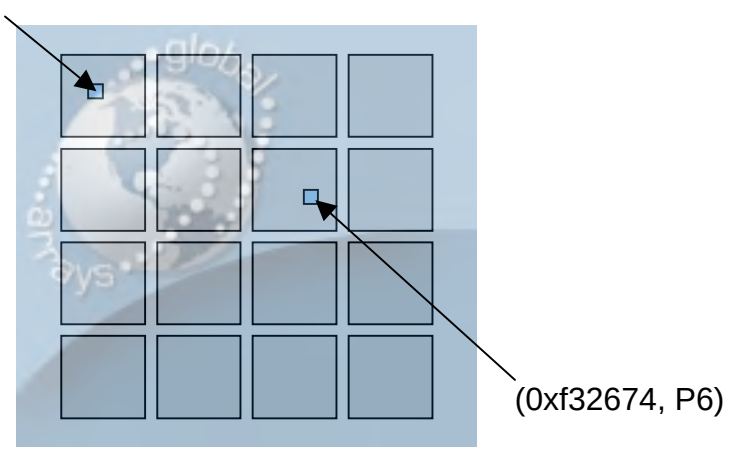
- Geomechanics: SEGMech Module
- Geochemistry: ECKEChem Module

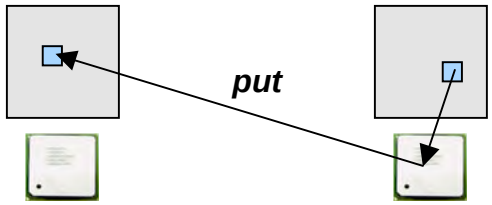
Validation

- Laboratory-Scale Experiments
  - Exchange Kinetics
  - Cage Occupancies

Scalable Computing

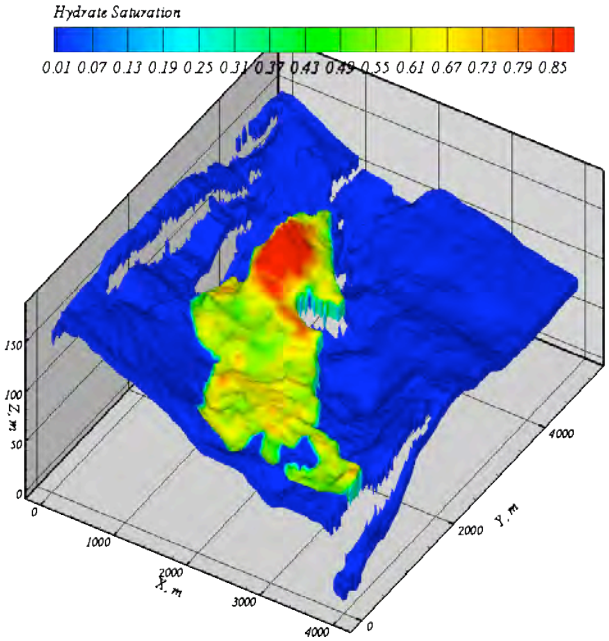
- Global Arrays
  - Shared-Memory Programming
  - One-Side Communications

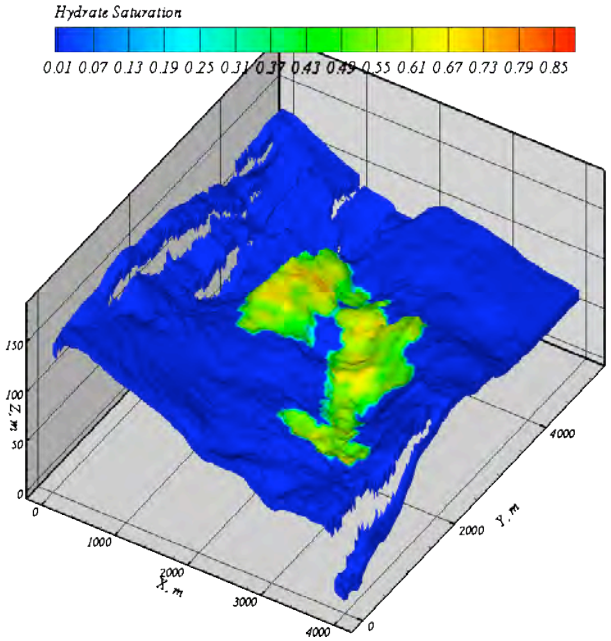




one-sided communication

message passing





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