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Annual Review
Project FWP 72688
Coupled Hydrologic, Thermodynamic, and Geomechanical Processes of Natural Gas Hydrate Production

September 6, 2019

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Pacific Northwest National Laboratory

U.S. DEPARTMENT OF ENERGY BATTELLE

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Topics

- NETL Sponsored Research
  - Tasks and Objectives
  - Accomplishments
  - Outcomes and Lessons Learned
  - Future Research
- Collaborative Research
  - Tasks and Objectives
  - Accomplishments
  - Outcomes and Lessons Learned
  - Future Research

NETL Sponsored Research Tasks and Objectives

BP1-Task 1.0 Project Management

Communication and coordination with NETL project manager on progress against budget and time schedules and alterations to the Project Management Plan, including submission of quarterly reports.

BP1-Task 2.0 IGHCCS2

Second international gas hydrate code comparison study focused on coupled thermal-hydrologic-thermodynamic-geomechanical processes for natural gas hydrate systems

BP1-Task 3.0 STOMP-HYDT-KE Parallelization

Programming implementations for computing on multiple processor computers for both shared-memory and distributed-memory computer architectures for the PNNL developed STOMP-HYDT-KE (Subsurface Transport Over Multiple Phase HYDrate Ternary with Kinetic Exchange) numerical simulator.

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NETL Sponsored Research Accomplishments BP1-Task 2.0 IGHCCS2

Principal Investigators

Mark White, PNNL; Tim Kneafsey, LBNL; and Yongkoo Seol, NETL

17 Participating Institutes

NETL Sponsored Research Accomplishments BP1-Task 2.0 IGHCCS2

Benchmark Problems

Benchmark Problem 1 – Similarity Solutions: Hydrate Dissociation in a Radial Domain

Problem Champion: Mark White, PNNL

Benchmark Problem 2 – Extended Terzaghi Problem

Problem Champion: Shubhangi Gupta, GEOMAR

Benchmark Problem 3 – Radial Production

Problem Champions: Matthew Reagan and Alejandro Queiruga, LBNL

Benchmark Problem 4 – Nankai Trough

Problem Champion: Sayuri Kimoto, Kyoto University

Benchmark Problem 5 – Isotropic Consolidation with Hydrate Dissociation

Problem Champions: Shun Uchida, RPI; Xueri Gai, NETL; Jeen-Shang Linn, Pitt; Evgeniy M. Myshakin, NETL and Yongkoo Seol, NETL

IGHCCS2 2ND INTERNATIONAL GAS HYDRATE CODE COMPARISON STUDY

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NETL Sponsored Research Accomplishments BP1-Task 2.0 IGHCCS2

Submissions against the Benchmark Problems

Abbreviation	Institute	Teaming	Problem Submissions	Computer Code(s)
Cambridge	University of Cambridge	Cambridge + JOGMEC + UCB		Berkeley-Cambridge THM model – COMSOL FEM Code
GEOMAR	GEOMAR Helmholtz Centre for Ocean Research Kiel	GEOMAR	1, 2,	TCHM Code for Methane Hydrate Systems
GT	Georgia Institute of Technology	GT + Ulsan		
JLU	Jilin University	JLU	1, 2, 3	HydrateBiot
JOGMEC	Japan Oil, Gas and Metals National Corporation	Cambridge + JOGMEC + UCB		
KAIST	Korea Advanced Institute of Science and Technology	KAIST		K-Hydrate with FLAC2D/FLAC3D
Kyoto	Kyoto University	Kyoto	4	COMVI-MH
LBNL	Lawrence Berkeley National Laboratory	LBNL	1, 2, 3	T+H with STONE
LLNL	Lawrence Livermore National Laboratory	LLNL + Tongji	1, 2, 3, 4, 5	GEOS
NETL	National Energy Technology Laboratory	NETL + Pitt + RPI	1, 2, 3, 4, 5	MIX3HRS-GM
Pitt	University of Pittsburgh	NETL + Pitt + RPI	1, 2, 3, 4, 5	MIX3HRS-GM
PNNL	Pacific Northwest National Laboratory	PNNL	1, 2, 3, 5	STOMP-HYDT-KE with GeoMech
RPI	Rensselaer Polytechnic Institute	NETL + Pitt + RPI	1, 2, 3, 4, 5	MIX3HRS-GM
SNL	Sandia National Laboratories	SNL	1	PFLOTRAN
Southampton	National Oceanography Centre Southampton, University of Southampton	Southampton + UPC		CODE_BRIGHT + Hydrate-CASM
TAMU	Texas A&M University	TAMU		CODE_BRIGHT-HYDRATE and T+M(AM)
Tongji	Tongji University	LLNL + Tongji	1, 2, 3, 4, 5	GEOS
UCB	University of California, Berkeley	Cambridge + JOGMEC + UCB	1, 2, 3, 4, 5	Berkeley-Cambridge THM model – COMSOL FEM Code
Ulsan	University of Ulsan	GT + Ulsan	1, 2, 3, 4, 5	Geo-COUS
UTA	University of Texas at Austin	UTA	1	UT_HYD

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NETL Sponsored Research Accomplishments BP1-Task 2.0 IGHCCS2

Publication Status

- Abstract (White, Kneafsey, Seol)
- ✓ Introduction (Waite)
- ✓ Participants and Computer Codes (White)
- ✓ Benchmark Problem 1 (White)
- ✓ Benchmark Problem 2 (Gupta)
- ✓ Benchmark Problem 3 (Reagan and Queiruga)
- Benchmark Problem 4 (Kimoto)
- ✓ Benchmark Problem 5 (Uchida et al.)
- ✓ Outcomes for Participants (White, Kneafsey, Seol, Waite)
- Conclusions (White, Kneafsey, Seol)

IGHCCS2
2nd International Gas Hydrate Code Comparison Study

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NETL Sponsored Research Accomplishments BP1-Task 3.0 STOMP-HYDT-KE Parallelization

Shared Memory Parallelization

OpenMP

Lis Linear System Solver

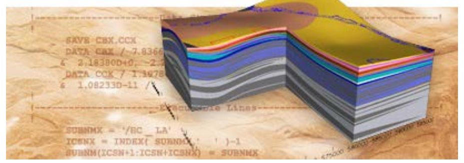
Distributed Memory Parallelization

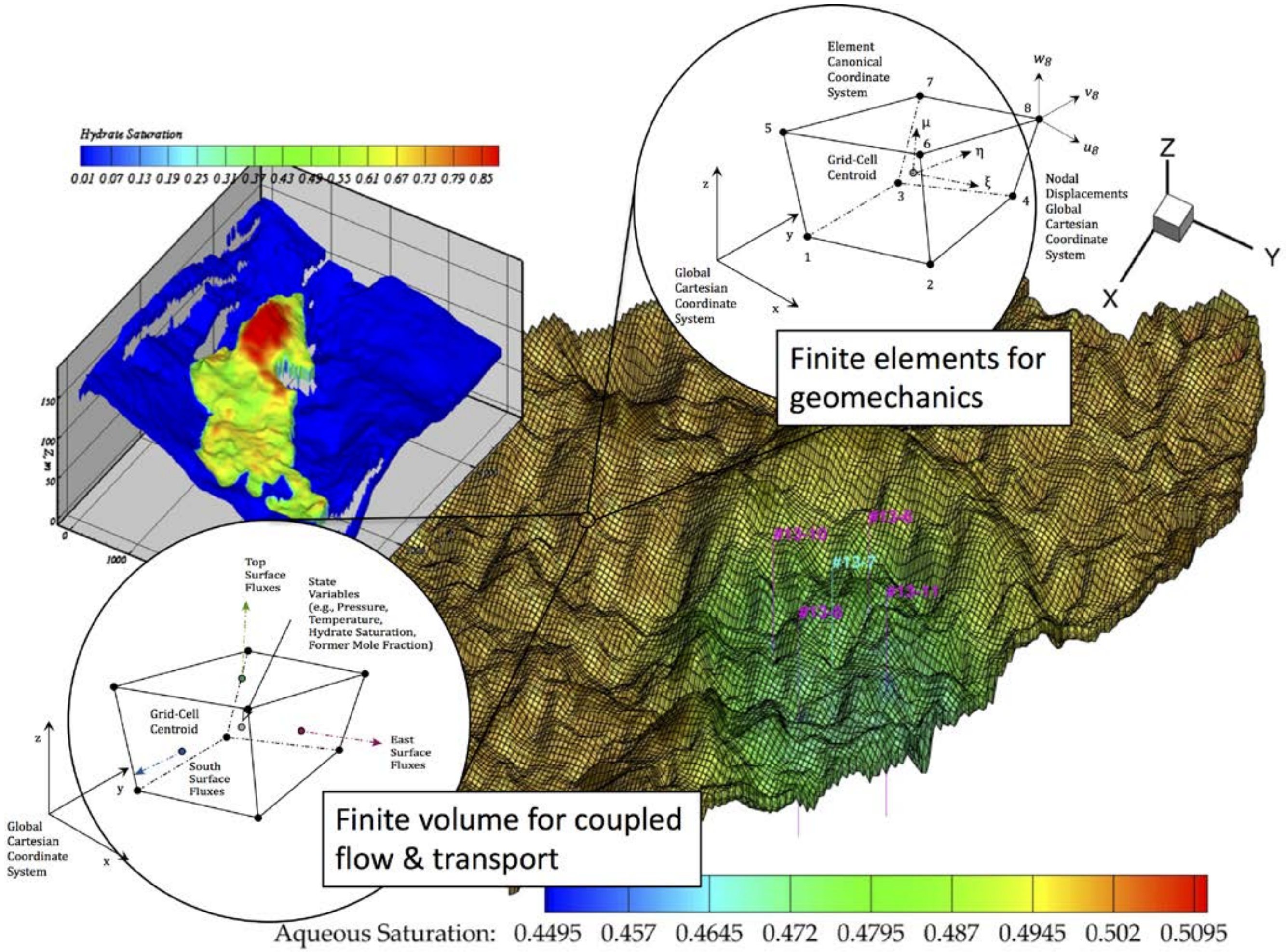
Global Arrays

Conversion of GA routines to MPI to eliminate the dependency on GA

PETSc Linear System Solver

STOMP-HYDT-KE





NETL Sponsored Research Outcomes and Lessons Learned

Benefits to Participants and DOE

Resolution of coding errors

Implementation of gas hydrate capabilities into legacy codes (i.e., GEOS and PFLOTRAN)

More than cursory understand of modeling approaches and code capabilities of international institutes

Identification of needed improvements in simulation capabilities

Comparisons against modeling approaches (e.g., general physics versus built for purpose, equilibrium versus kinetic formulations, finite element versus finite volume, radial geomechanics versus two-dimensional domains).

Legacy of solved hydrate problems for future code development efforts

Creation of an international scientific community for modeling gas hydrate systems

NETL Sponsored Research Outcomes and Lessons Learned

Lessons Learned

Solution Submission Redistribution to Problem Champions

- Error – Distributed LBNL results for Benchmark Problem 2 with the wrong units for vertical displacement
- Lesson – Extra diligence is required in handling study participants results

Presentation of Analytical Results

- Error – Incorrectly calculated undrained bulk modulus in the analytical solution for Benchmark Problem 3 and presented results to the study participants
- Lesson – Verify calculations with the problem champions before presenting the results

Teaming Arrangements

- Error – Incorrectly associated University of Ulsan with Georgia Tech from publications
- Lesson – Verify actual teaming arrangements with study participants

NETL Sponsored Research
Future Research

Numerical Modeling of Staged Depressurization in Units D and B

Cylindrical geometry with radially homogeneous properties and saturations

Forecast of produced water and gas

Exploration of intrinsic permeability, effective permeability models, relative permeability models, and bound water

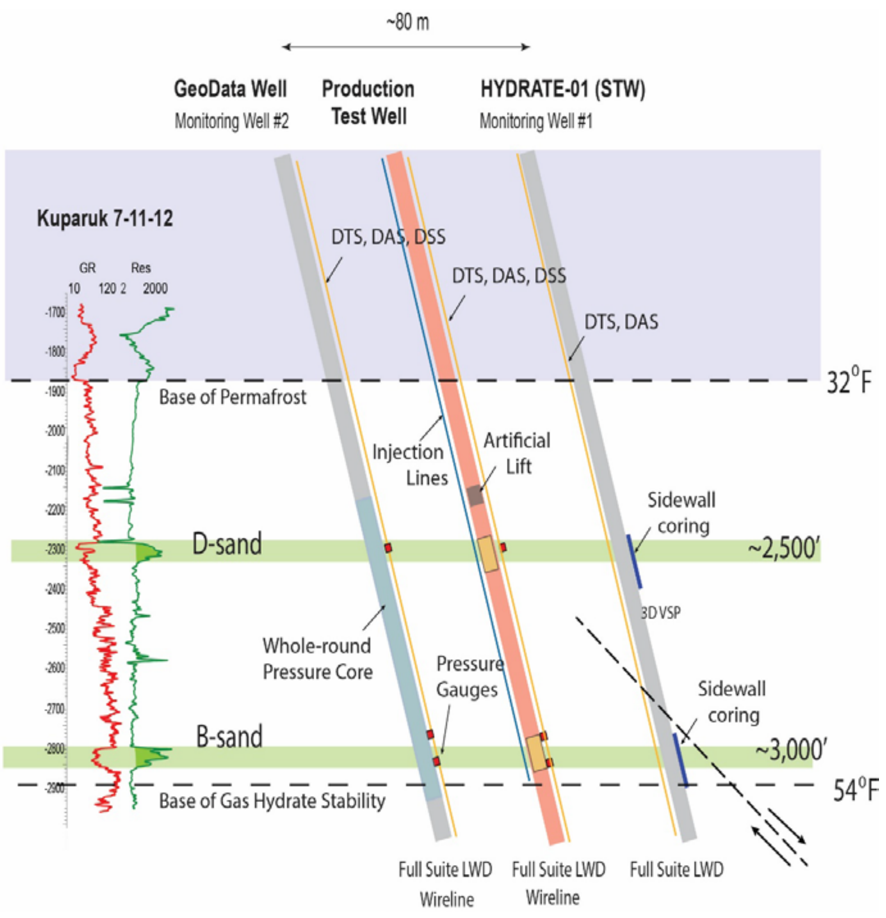
Numerical Modeling of Gas Injection into Monitoring Wells

3D Cartesian geometry with horizontally homogeneous properties and saturations

Potential use of well model

Pure nitrogen injection at different stages of depressurization

Flue-gas injection at different stages of depressurization



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Collaborative Research Tasks and Objectives

Assessment of Nitrogen or Air Injection

Previous simulations demonstrated the potential for flattening the production rates with combined depressurization and pure nitrogen injection, but the economics of pure nitrogen injection makes the technology commercially unviable.

Recognizing the risks associated with air injection, this project seeks to explore the use of air or flue gases for combined depressurization and gas injection.

Required the development of CH_4-O_2-N_2 hydrate equilibria data and conversion of the mobile phases of STOMP-HYDT-KE.

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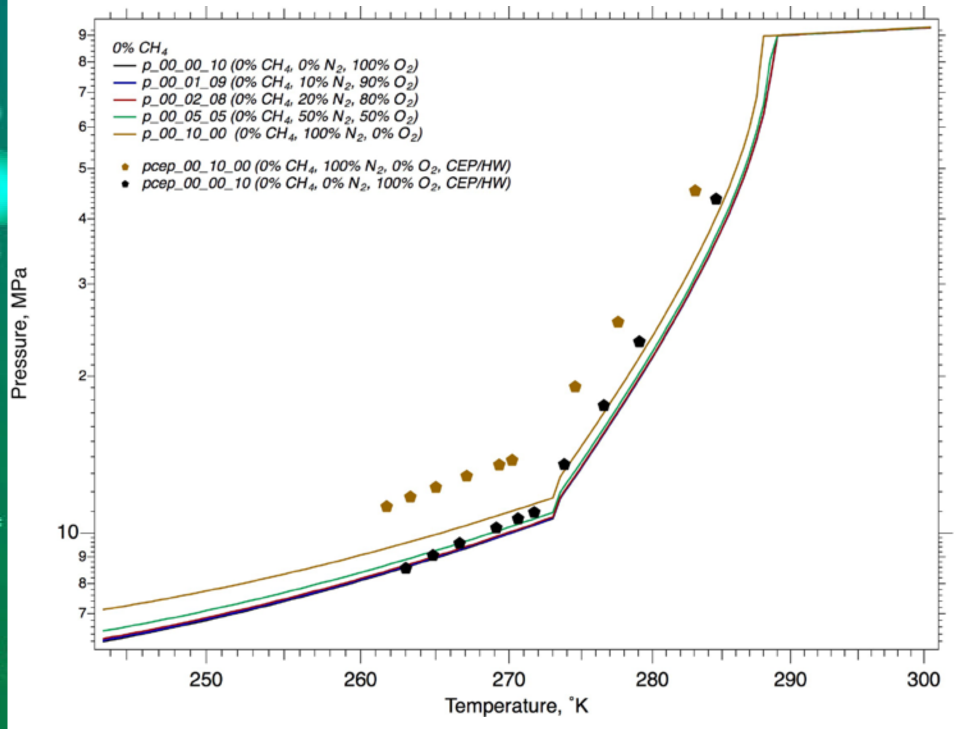
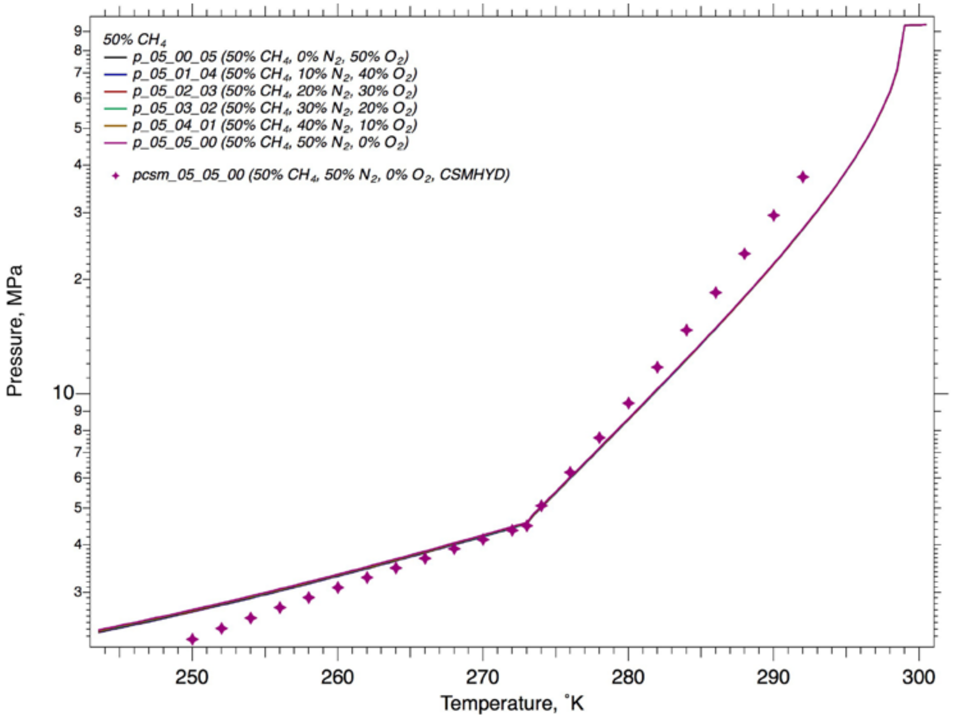
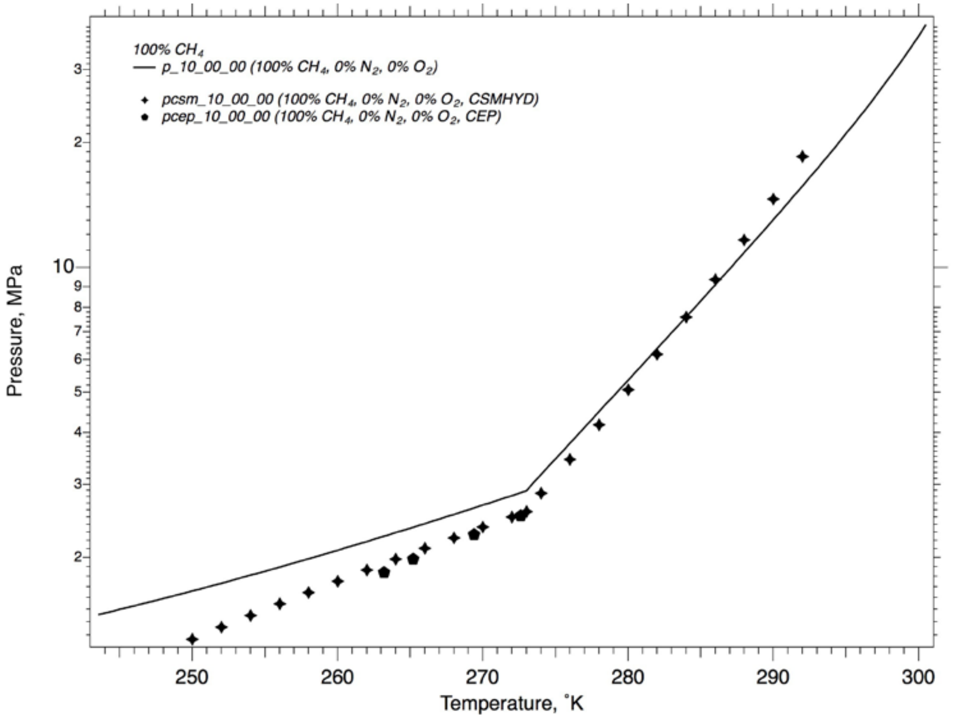
Collaborative Research Accomplishments Assessment of Nitrogen or Air Injection

- Development of CH_4-O_2-N_2 Gas Hydrate Equilibria
  - Computer code based on chemical potential across phases
  - Draft manuscript in preparation, entitled "Methane Hydrate Reservoir Modeling with Self-consistent Kihara Parameters."







NETL Sponsored Research Accomplishments Assessment of Nitrogen or Air Injection

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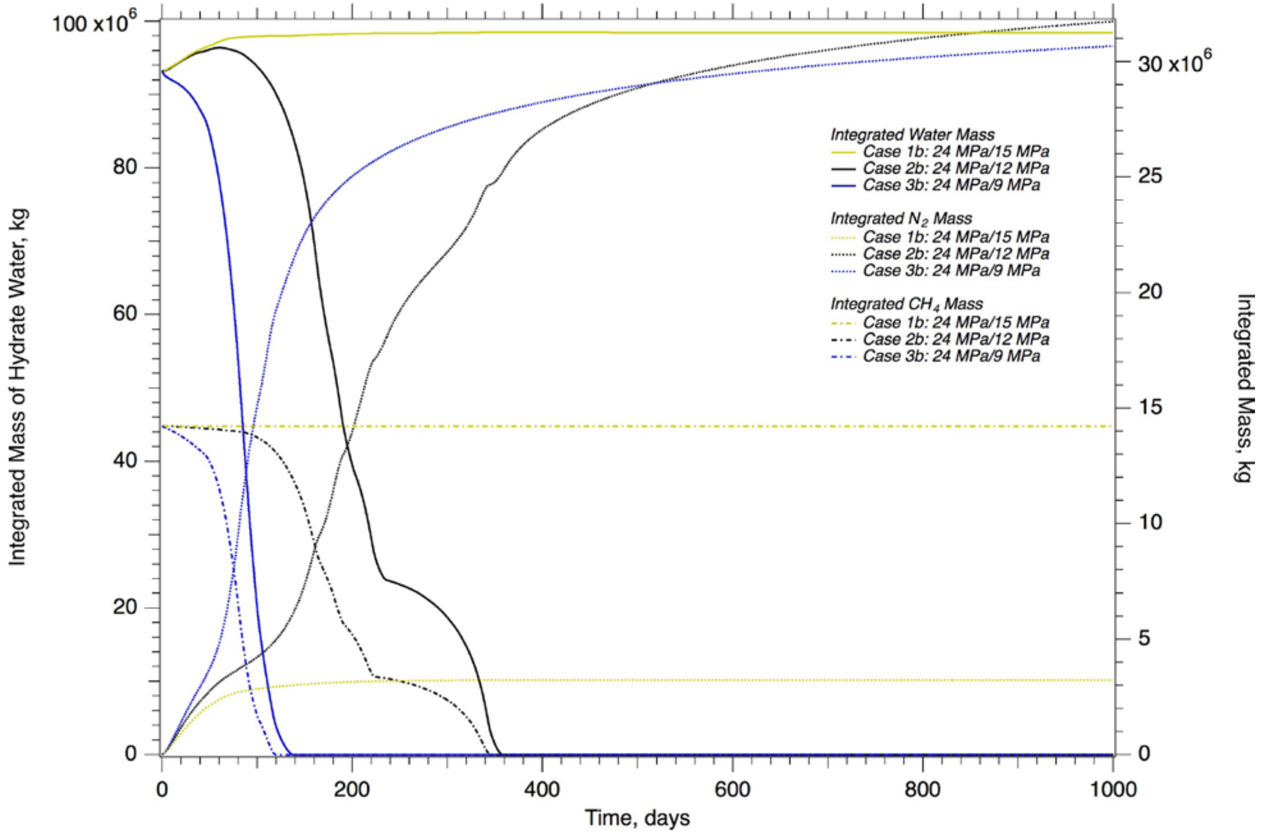
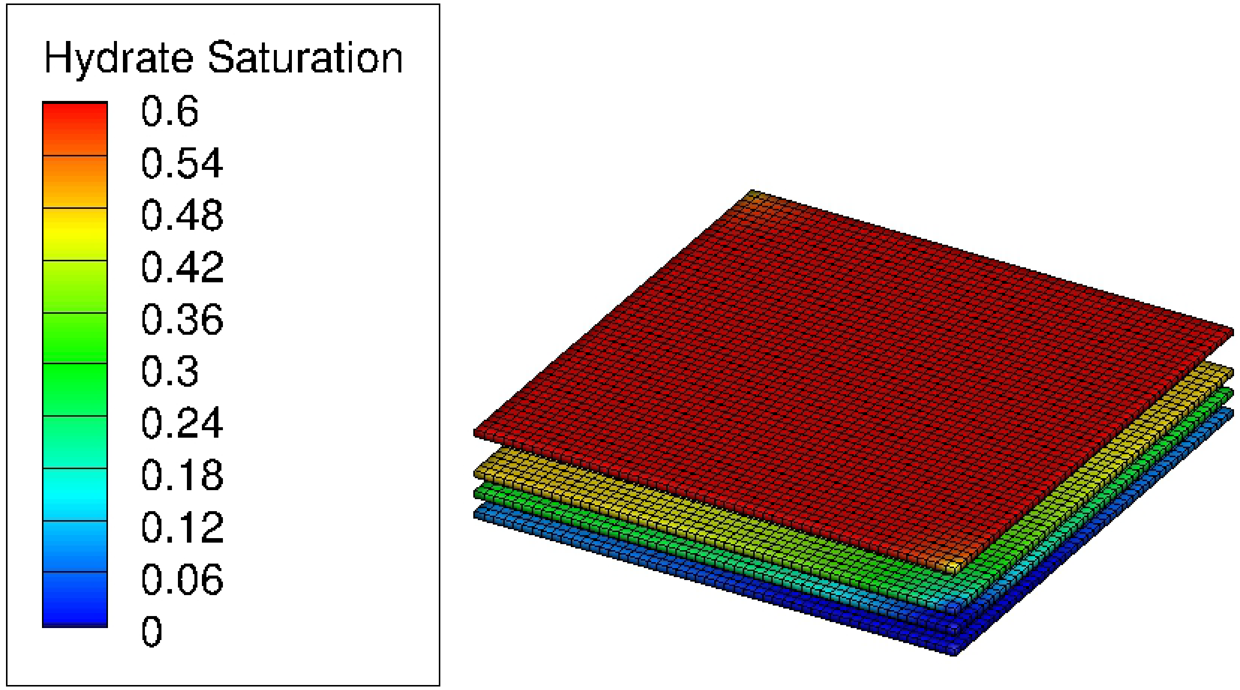
한국지질자원연구원 KIGAM Korea Institute of Geoscience and Mineral Resources

- Development of CH_4-O_2-N_2 Gas Hydrate Reservoir Simulation Capabilities
  - Conversion of STOMP-HYDT-KE from CH_4-CO_2-N_2 (three phase) to CH_4-O_2-N_2 (two phase)
  - Application of the new simulator to assess nitrogen and air injection in the Ulleung Basin





Collaborative Research Outcomes and Lessons Learned

Outcomes

Pure nitrogen and air injection perform similarly in affecting natural gas hydrate dissociation and production.

Nitrogen can be used as a surrogate for oxygen when modeling gas injection into natural gas hydrate reservoirs

Flue gas looks promising due to its cost, low flammability risk, and moderate carbon dioxide concentration (i.e., below nonaqueous liquid phase conditions).

Lessons Learned

Nonequilibrium modeling approaches allow for guest molecule swapping investigations, but are computationally expensive (i.e., 9 unknowns per grid cell).

Research sponsored by other nations are not always publicly available.

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Collaborative Research Future Research

KIGAM
Korea Institute of Geoscience and Mineral Resources

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한국지질자원연구원 · Korea Institute of Geoscience and Mineral Resources · KIGAM

Mark White
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Date: July 29, 2019

Dear Dr. Mark White:

During previous collaboration between KIGAM and PNNL from 2007, we made a remarkable progress in a Gas Hydrate Simulation. With respect to the new proposal to DOE, Korea Institute of Geoscience and Mineral Resources (KIGAM) is highly interested in the simulation study on the Alaska North Slope:

- Implementation of the well models developed for STOMP-CO2 and STOMP-GT into STOMP-HYDT-KE
- Simulation of the depressurization experiments, with consideration of the intrinsic and relative permeability parameter space
- Simulations of gas injection into the monitoring wells, after a period of depressurization

Additionally, KIGAM would like to utilize the STOMP-HYDT-KE simulator as a shadow reservoir simulations in the Ulleung Basin at the pilot scale, as a complementary simulator.

As you know, Korean GH project performed by KIGAM is now preparing next phase with GHDO and Korean government. The work scope and funds for future collaboration project is subject to approval by GHDO and Korean government. If you have any other questions, please feel free to contact us(Joo Yong Lee: jyl@kigam.re.kr, Won Suk Lee: wslee@kigam.re.kr).

Yours sincerely,

Lee, joo yong

Project Manager, Gas Hydrate Exploration & Production Study

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Future Research

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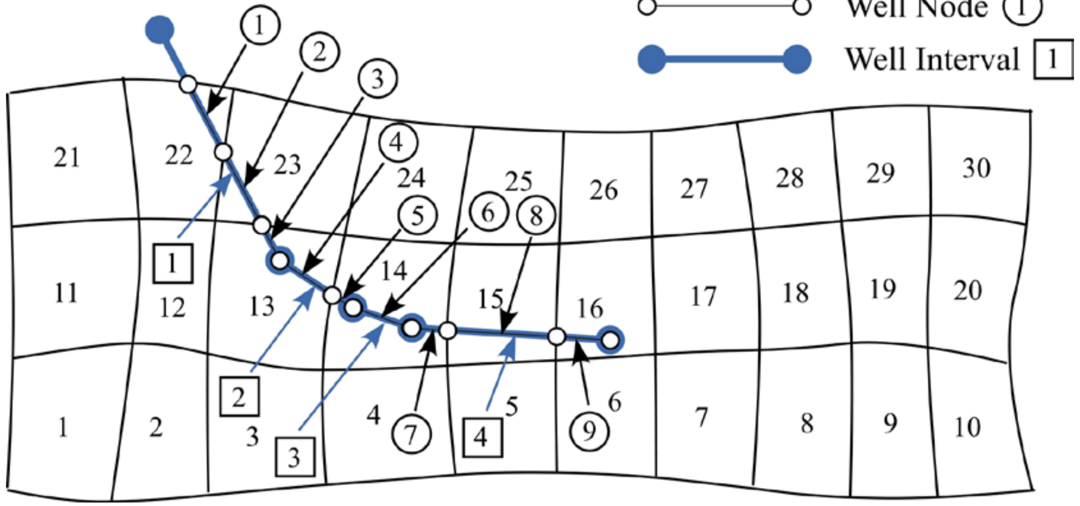
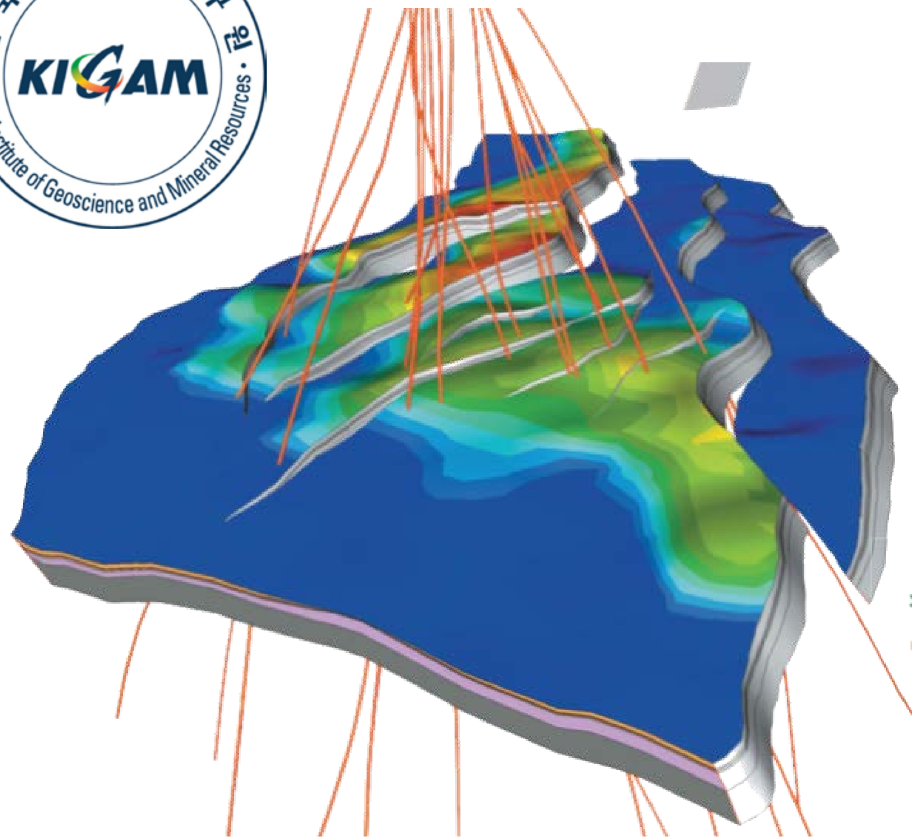
KIGAM 한국지질자원연구원 Korea Institute of Geoscience and Mineral Resources

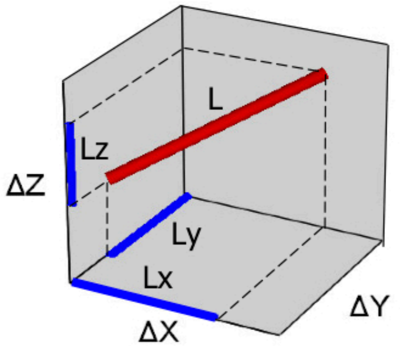


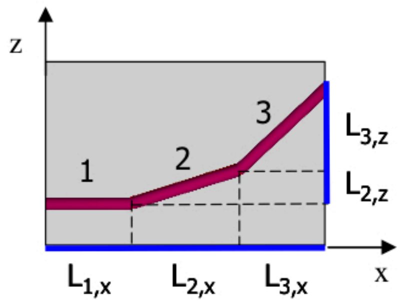
$$WI_x = \left[\frac{2\pi\sqrt{k_y k_z}\,L_x}{\ln\left(\frac{r_{o,x}}{r_w}\right)+s}\right];\ r_{o,x} = 0.28\left[\frac{\left(\Delta z^2\left\{\frac{k_y}{k_z}\right\}^{1/2}+\Delta y^2\left\{\frac{k_z}{k_y}\right\}^{1/2}\right)^{1/2}}{\left(\left\{\frac{k_y}{k_z}\right\}^{1/4}+\left\{\frac{k_z}{k_y}\right\}^{1/4}\right)}\right]$$

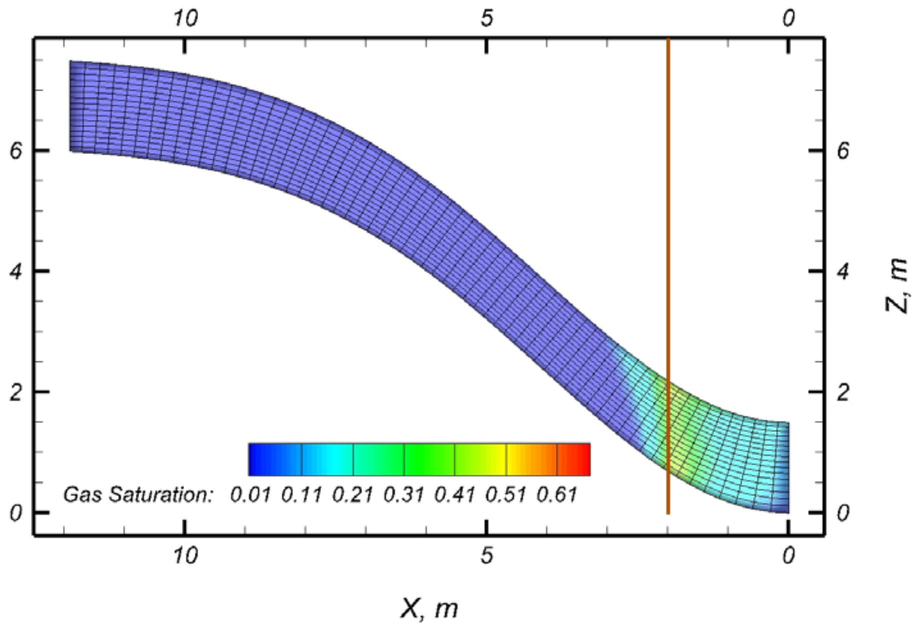
$$WI_y = \left[\frac{2\pi\sqrt{k_x k_z}\,L_y}{\ln\left(\frac{r_{o,y}}{r_w}\right)+s}\right];\ r_{o,y} = 0.28\left[\frac{\left(\Delta z^2\left\{\frac{k_x}{k_z}\right\}^{1/2}+\Delta x^2\left\{\frac{k_z}{k_x}\right\}^{1/2}\right)^{1/2}}{\left(\left\{\frac{k_x}{k_z}\right\}^{1/4}+\left\{\frac{k_z}{k_x}\right\}^{1/4}\right)}\right]$$

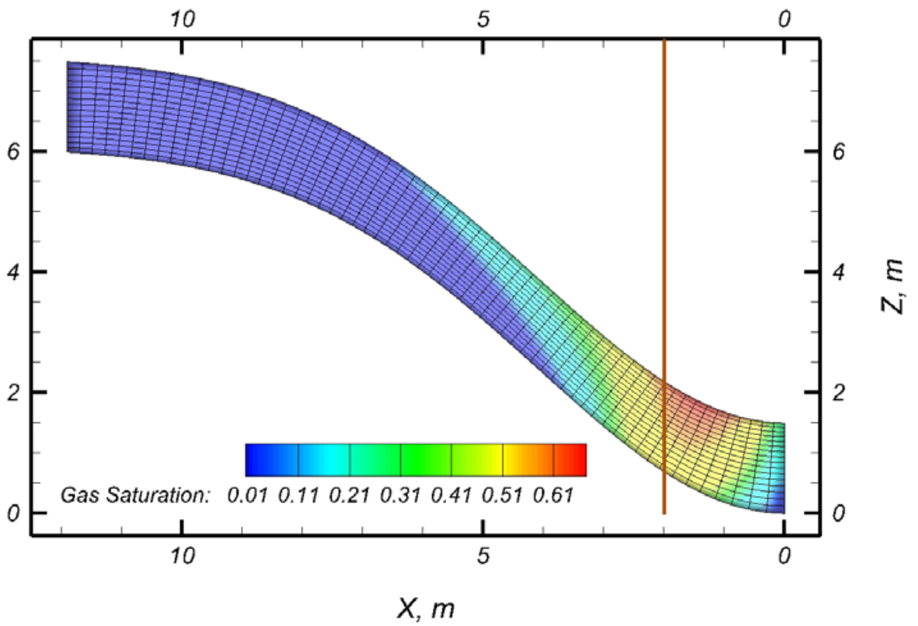
$$WI_z = \left[\frac{2\pi\sqrt{k_y k_x}\,L_z}{\ln\left(\frac{r_{o,z}}{r_w}\right)+s}\right];\ r_{o,z} = 0.28\left[\frac{\left(\Delta y^2\left\{\frac{k_x}{k_y}\right\}^{1/2}+\Delta x^2\left\{\frac{k_y}{k_x}\right\}^{1/2}\right)^{1/2}}{\left(\left\{\frac{k_x}{k_y}\right\}^{1/4}+\left\{\frac{k_y}{k_x}\right\}^{1/4}\right)}\right]$$











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Questions?

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