Natural Gas Hydrate Research at NETL RIC

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NETL RIC

U.S. Department of Energy
National Energy Technology Laboratory
Resource Sustainability Project Review Meeting
October 25 - 27, 2022

Presentation Outline

- NETL R&IC Hydrate Portfolio Overview
- Major Accomplishments
- Project Summary
- Lesson Learned
- Collaborations and Opportunities
- Bibliography

Project Overview

Project Goals:

- Provide the state-of-the-art experimental, modeling, and economic analysis to support planning and execution of long-term field gas production tests, predicting environmental implications and developing long-term projection of US energy asset.
- Provide pertinent, high-quality information that benefit the development of geological and numerical models and methods for predicting the behavior of gas hydrates in natural and production conditions.

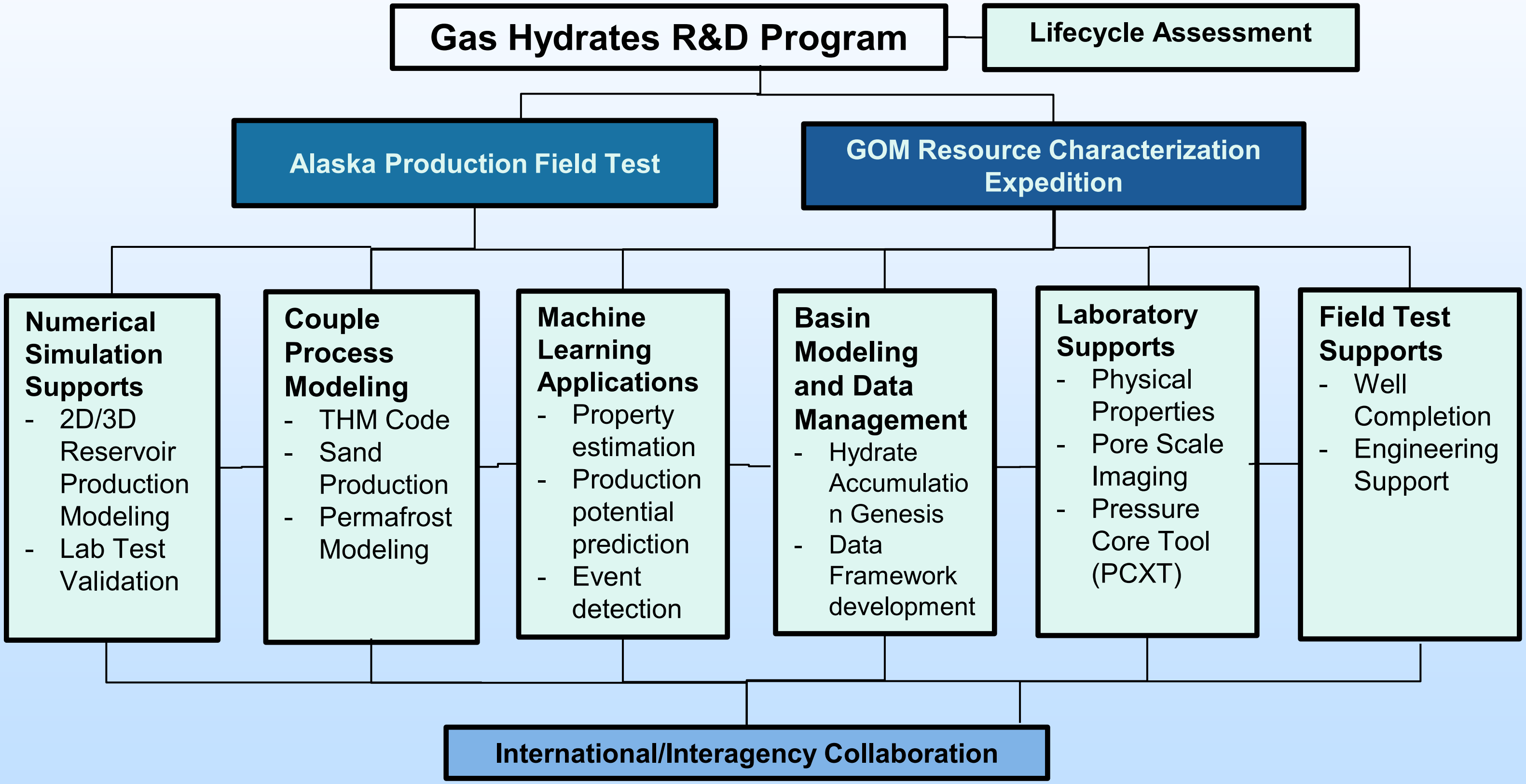
EY22 Funding: $2.02M ($0.75M + $1.27M Carryover)

Overall Project Performance Dates: 04/01/2022 – 03/31/2023

Project Participants:

- FE HQ Division Director; Vanessa Nunez-Lopez
- FE HQ Project Manager: Gabby Intihar
- NETL Technology Manager: John Roger
- NETL Senior Fellow: Ale Hakala
- NETL Program Manager: Sandra Borek
- NETL R&IC TPL: Yongkoo Seol
- NETL R&IC Researchers
- LRST Site Support Researchers
- ORISE Fellows
- Universities: West Virginia Univ., RPI, Georgia Tech, Pitt, Stanford, TAMU

NETL R&IC Hydrate Portfolio



Gas Hydrates R&D Program

Lifecycle Assessment

Alaska Production Field Test

GOM Resource Characterization Expedition

Numerical Simulation Supports
- 2D/3D Reservoir Production Modeling
- Lab Test Validation

Couple Process Modeling
- THM Code
- Sand Production
- Permafrost Modeling

Machine Learning Applications
- Property estimation
- Production potential prediction
- Event detection

Basin Modeling and Data Management
- Hydrate Accumulation Genesis
- Data Framework development

Laboratory Supports
- Physical Properties
- Pore Scale Imaging
- Pressure Core Tool (PCXT)

Field Test Supports
- Well Completion
- Engineering Support

International/Interagency Collaboration

NETL R&IC Hydrate Portfolio

Project Area	Tasks	Goals
Numerical Simulation Supports	• **(Task 2)** Gas Production Prediction Supports with 2D/3D reservoir models	• Economical recoverability for long-term gas production and recommendations on planning, execution, and analysis
Coupled Processing Modeling	• **(Task 3, 13)** THCM Code development and Modeling • **(Task 11, 13)** Sand Production Modeling	• THCM simulator for methane hydrate reservoir modeling
Machine Learning Applications	• **(Task 9)** Well log data analysis for key parameter estimation and lithofacies/hydrate morphology recognition for both permafrost and deep-sea	• Efficient and accurate parameter estimations using new ML technique for large data analysis and model development
Basin and Petroleum System Modeling	• **(Task 6)** New basin model and data system for ANS accumulations	• Hydrate Accumulation Genesis in ANS and new data framework for 3D Model and ML applications
Laboratory Experimental Supports	• **(Task 4)** Hydrological/Geomechanical Property • **(Task 5)** Pressure Core Analysis and Tool Development • **(Task 5)** Multiscale (Core/Pore) Testing and Imaging	• Relevant input for numerical simulations • Fundamental knowledge on gas hydrate and its responses
Field Production Test Supports	• **(Task 7)** Shut In Procedure/Well Completion Method • **(Task 8)** Engineering Support for field test design and operation	• Engineering support needed for the planning and operation of the ANS production well test
Life Cycle Assessment	• **(Task 12)** Refining the previous assessment of the total CO2 emissions associated with the gas production and consumption from ANS	• Evaluate key contributors to the GHG emissions and the environmental impact of gas hydrate production
Interagency and International Collaboration	• **(Task 2, 5, 7, 8, 11)** Reservoir simulations, Pressure Core Working Group	• Supporting success of domestic and international exploration and expedition

NETL R&IC Hydrate Portfolio

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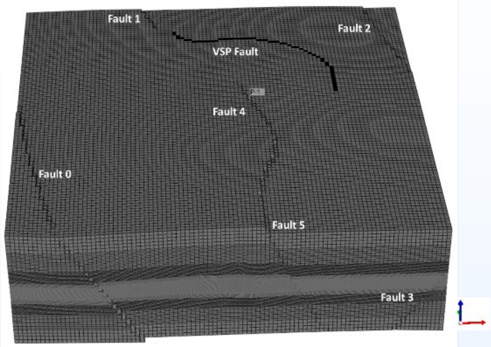
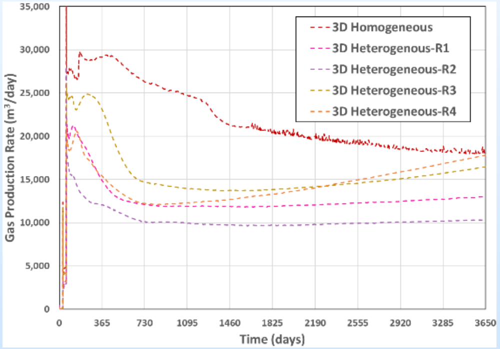
2D/3D Numerical Simulation Support for upcoming field testing at the PBU Kuparuk 7-11-12 pad on Alaska North Slope

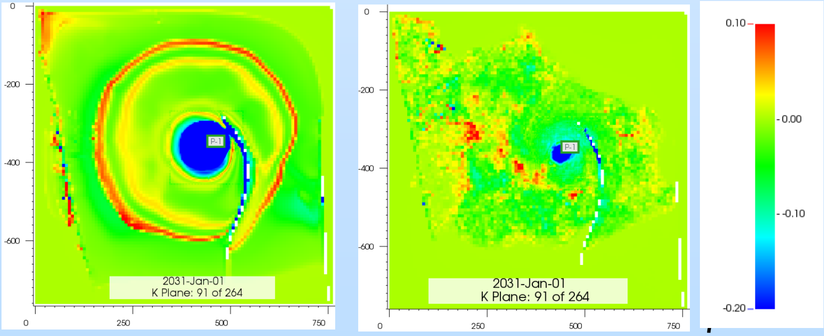
- **Goal**: Evaluate reservoir productivity at various depressurization scenarios and provide relevant predictions for operation planning and test execution
- **Challenges**: Uncertainty and complexity in physical properties, heterogeneity in reservoir geologic characteristics, impacts of operational events (e.g., shut-in, rates of pressure drawdown)
- **Approach:** Multiple scenarios and sensitivity cases considering uncertainties in fault transmissivity, well design, and seal/reservoir unit properties are simulated using 2D and 3D models.
- **Results/Accomplishments:**
  - 2D model with a 500-m radius provides close predictions with 3D simulation results.
  - 3D heterogeneous models provide reduced reservoir performance compared to a lateral homogenous model.
  - Imposing sealing faults around a wellbore causes increase of gas and decrease of water production during first 2 years of depressurization compared for a case with default fault properties.
- **Implications**: Practical tool to predict and assess gas production potential and to support field test planning and operation. Low-cost way to evaluate multiple scenarios, well designs, and simulation cases.



3D Kuparuk model showing faults



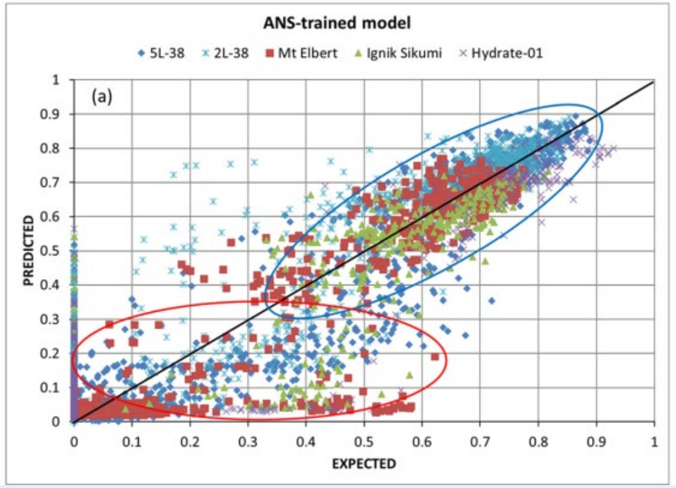
Gas production using 3D laterally homogenous and several realizations of 3D heterogenous models



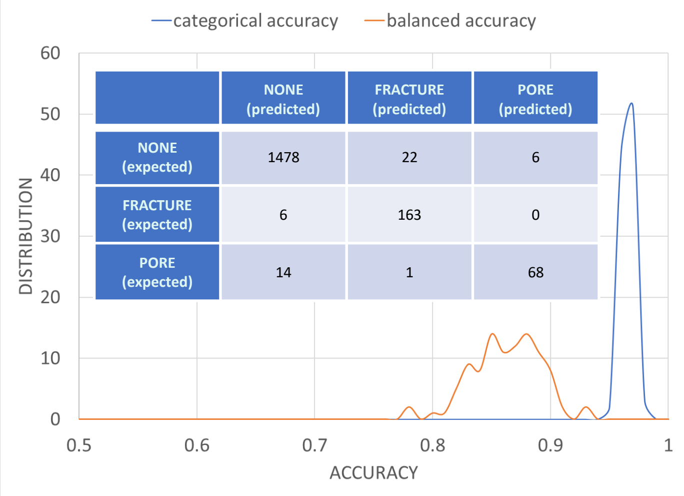
Top views across the top of the perforated interval showing hydrate reformation in homogenous (left) and heterogenous (right) models

Machine Leaning Applied to Gas Hydrate Reservoir and Basin Characterization

- **Machine Learning (ML) Approaches**: Provide the ability to identify and exploit underlying dependencies between input well log data and target variables that are not readily available through physics-driven models
- **Application of ML techniques in Gas Hydrate Research**:
  - Characterize gas hydrate reservoir and basin regions using well logs, seismic and other geologic and geophysical (G&G) data,
  - Spatial variability of hydrological and geophysical properties from a wellbore to develop reservoir models capturing 3D spatial heterogeneity of reservoir
- **Results/Accomplishments**:
  - Application of machine learning to characterize gas hydrate reservoirs in Mackenzie Delta (Canada) & on the Alaska North Slope (USA). (Paper published in Computational Geosciences 26 (2022) 1151-1165: https://doi.org/10.1007/s10596-022-10151-9)
    - ML gas hydrate saturation prediction in permafrost settings using up to six well logs (80% - 90% accuracy)
  - Application of machine learning to assess saturations & morphology in marine gas hydrate-bearing sediments. (Poster presented on 2022 October 25 at Resource Sustainability Project Review Meeting).
    - ML recognition of pore-filling and fracture-filling gas hydrate in marine sediments (approximately 85% accuracy)
- **Implication to DOE Natural Gas Hydrates Program** to obtain high precision data on gas hydrates in their natural environment and under production scenarios that secures future exploration of gas hydrate as future U.S. energy source



Expected versus predicted hydrate saturations for Mackenzie Delta & Alaska North Slope wells

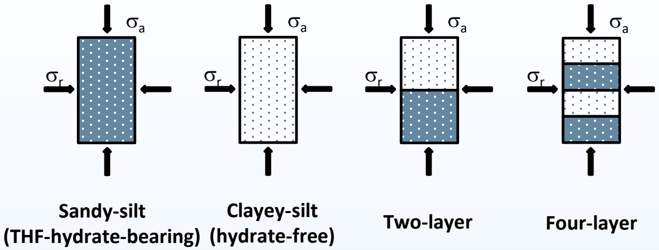


	NONE (predicted)	FRACTURE (predicted)	PORE (predicted)
NONE (expected)	1478	22	6
FRACTURE (expected)	6	163	0
PORE (expected)	14	1	68

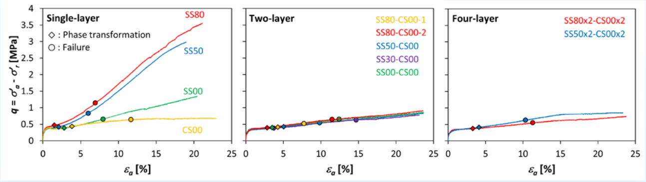
Hydrate morphology classification accuracies & categorical results on validation data from six NGHP-02 wells

Mechanical Property Characteristics of Layered Hydrate-Bearing Sediments

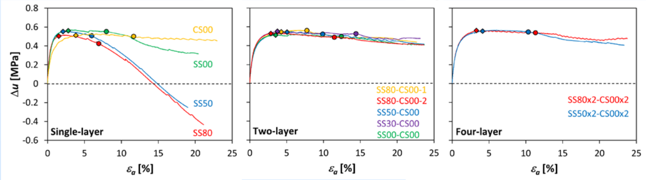
- **Goal**: Characterize mechanical behavior of layered hydrate-bearing sediments (HBS) and provide homogenized mechanical property inputs for reservoir mechanical simulations
- **Challenges**: layered sample preparation with hydrate; and prolonged experimental duration on multiple cases and slow progress on deformation
- **Approach:**
  - Two distinct layers: clayey-silt & sandy-silt for seal and hydrate-bering layers of marine reservoirs,
  - Consolidated-undrained (CU) triaxial compression test on 1, 2, and 4-layer cores;
  - CT-scanning to observe core deformation;
  - Monitor mechanical deformation over time
- **Results/Accomplishments:**
  - Stress-strain relationship (*q,* deviator stress vs ε_a, axial strain); pore pressure(Δu, excess pore pressure vs. ε_a); stress path; CT-images
  - Dominant effect from hydrate-free clayey-silt layer on mechanical/hydraulic behavior of layered system
- **Implications**: Mechanical properties of interbedded system is complex and may need further experiments and modeling for proper production prediction.



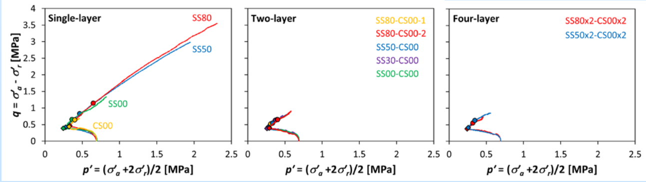
Frozen core in membrane



Stress-strain relationship

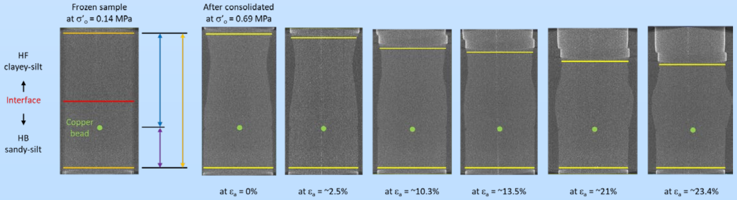


Pore pressure development



Stress path

Triaxial chamber on industrial CT-scanner



Displacement between base, bead, and top during CU triaxial compression test

Two-layer specimen after depressurization

Pressure Core Characterization and Visualization Tools in NETL Gas Hydrate Laboratory

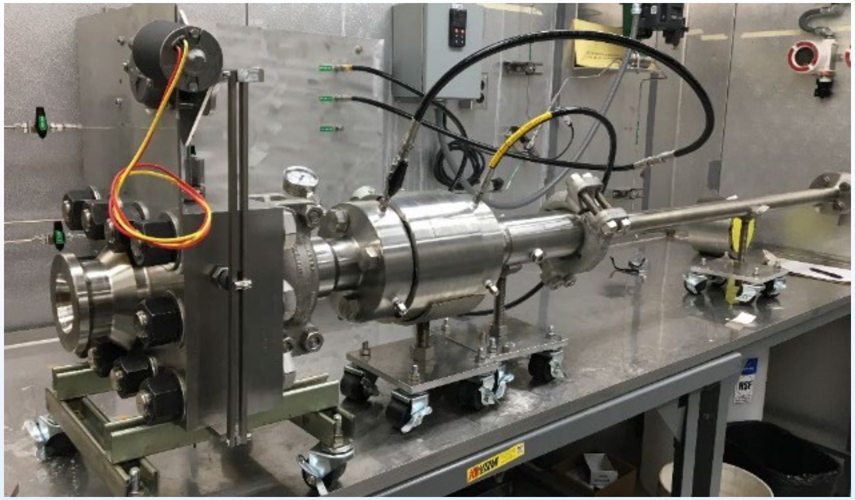
- **Goal**: Characterizing HBS at pore and core scale in the form of pressure cores retrieved from the natural hydrate-bearing sediments to understand interactions between hydrate and its hosting geologic matrix.

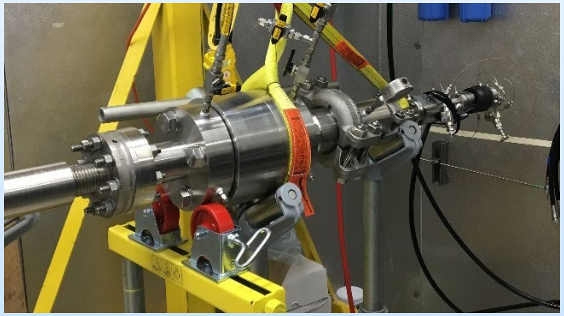
- **Challenges**: Experimental complexity associated with hydrate stable pressure and temperature condition, and the sample heterogeneity which should be carefully reviewed before testing.

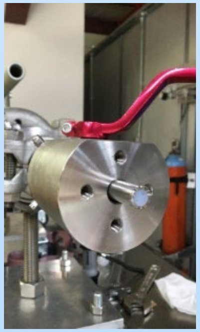
- **Approach:** A suite of tool set to manipulates and characterizes natural hydrate bearing cores, as well as visualize methane hydrate in natural sediment pores with high resolution at its *in-situ* condition.

- **Results/Accomplishments:** The PCXT (pressure core characterization and X-ray CT visualization tools) with new chambers (TSC, APS), currently processing pressure cores retrieved from Gulf of Mexico was tested. Upgraded PCXT for Alaska pressure cores.

- **Implications**: The tool set will be utilized to analyze pressure cores from Alaska (2022-2023) and Gulf of Mexico (2021-2022, 2023), which will be the key input for numerical reservoir simulation of gas production potential.







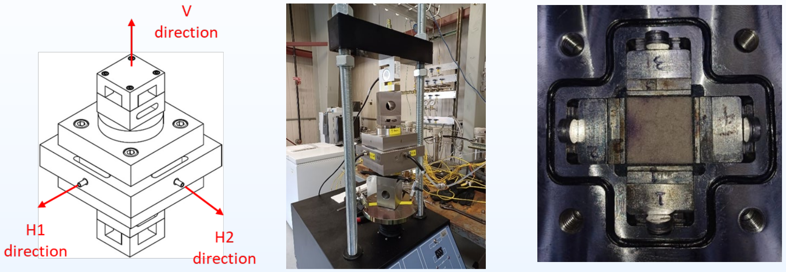
Anisotropic Permeability Cell

Triaxial Stress Chamber

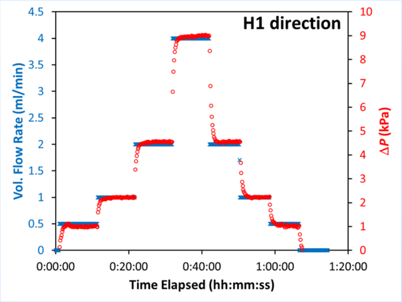
Permeability Anisotropy in Natural Hydrate-Bearing Sediments

- **Goal**: Experimentally measure vertical and horizontal permeabilities of natural rock & sediment and provide permeability anisotropy data for reservoir modeling
- **Challenges**: No existing standard testing protocols/equipment; Trimming cylindrical natural sample down to cube
- **Approach:** Customize a permeator that can measure permeabilities of a cube sample in three orthotropic directions; develop permeability anisotropy data bases for numerical modeling
- **Results/Accomplishments:** Permeability anisotropy measurements of natural rock & sediment that are often layered and heterogeneous.
- **Implications**: This experimental study provides direct permeability measurements of sediments from current focused testing sites (NGHP02, GOM2, and Alaska) and can eventually fills the knowledge gaps relevant to permeability anisotropy in natural geologic deposits.

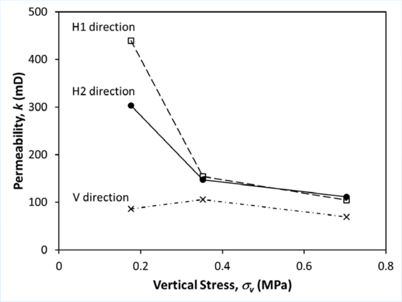
Rendering of Anisotropy Permeability Chamber (APC) (Left); APC on load frame (middle); and sand sample in APC (right).



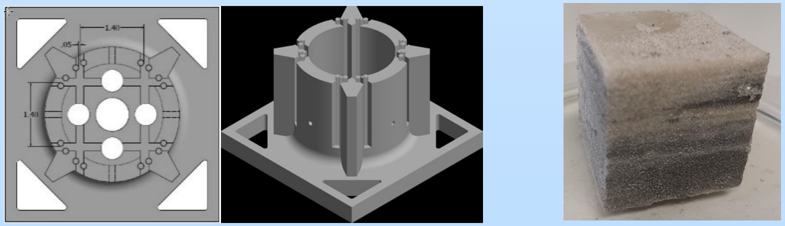
ΔP development a horizontal direction at different flow rates



Anisotropic permeabilities measured at different vertical stress



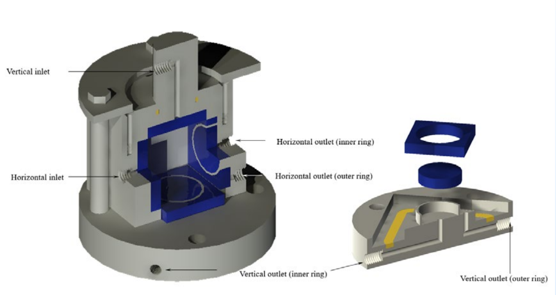
Rendering of cube-cutting holder (left); and cube sample cut from cylindrical frozen sand (right)



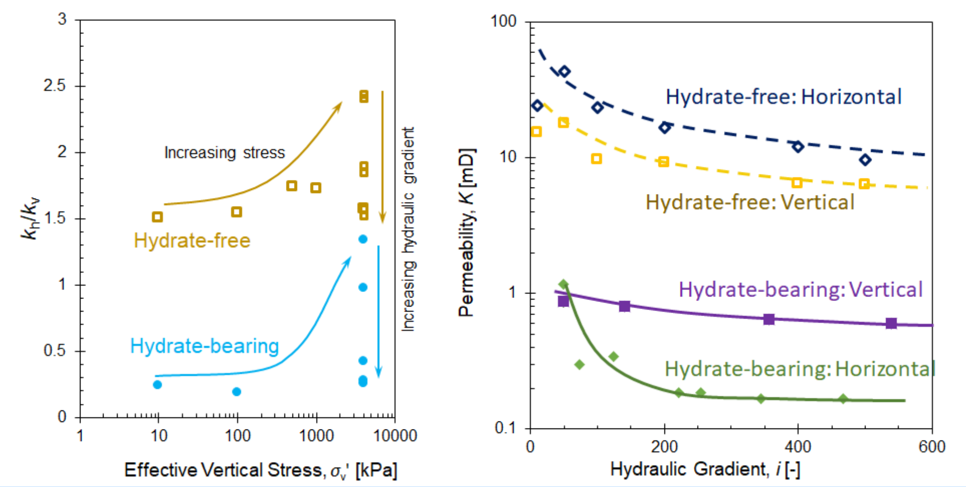
Permeability Anisotropy in Natural Hydrate-Bearing Sediments

- **Goal**: Quantify vertical and horizontal permeability in natural sediments and provide physical models for reservoir modeling
- **Challenges**: No existing standard testing protocols/equipment; sediments layering and heterogeneity
- **Approach:** Customize unique testing devices for synthesized, conventionalized or frozen pressure cores; develop novel pore network modeling and computational fluid dynamics schemes
- **Results/Accomplishments:** Permeability anisotropy measurements; impacts of stress to permeability anisotropy; impacts of hydraulic gradient to measured permeability.
- **Implications**: Experimental and numerical results attained through this task provide novel solutions to quantify permeability anisotropy in natural sediments and provide direct measurements for sediments from GOM2 (and Alaska in near future) testing sites.

Customized setup: Permeability anisotropy cell for natural core (left) and synthesized layered sediments (right).



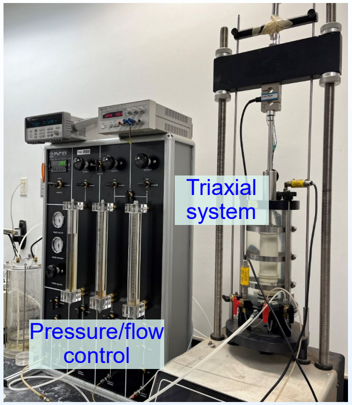
GOM2 core testing: Permeability anisotropy as a function of stress (left) and hydraulic gradient (right), with and without hydrate.



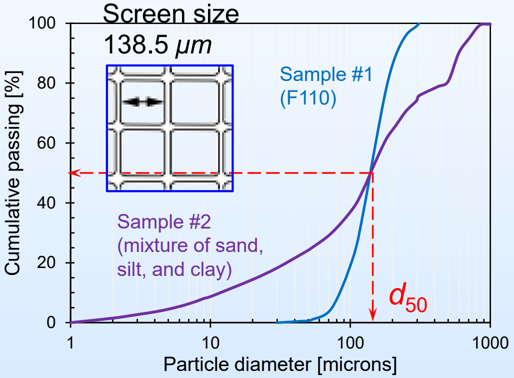
Solids Migration during Gas Production from Hydrate-Bearing Sediments

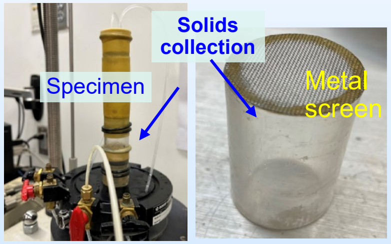
- **Goal**: Experimentally determine the critical hydraulic gradient and mass loss under various stress and flow conditions for hydrate-bearing sediments, and develop a *lab-validated* sand production model for reservoir simulations
- **Challenges**: No calibrated sand migration models for hydrate-bearing sediments
- **Approach:** Customize a unique testing device for sand migration in triaxial loading; develop novel numerical schemes
- **Results/Accomplishments:** Mass loss and permeability evolution in sediments subjected to various stresses and flow conditions. Numerical validation study is in progress. Further tests with hydrate are in progress.
- **Implications**: A wider grain size distribution tends to render more solids migration; Higher deviatoric stress and hydraulic gradient exacerbate solid migration. Help to validate numerical model and plan for field testing.

A customized triaxial system to allow controls of stresses and hydraulic gradients while measuring collected soil mass.

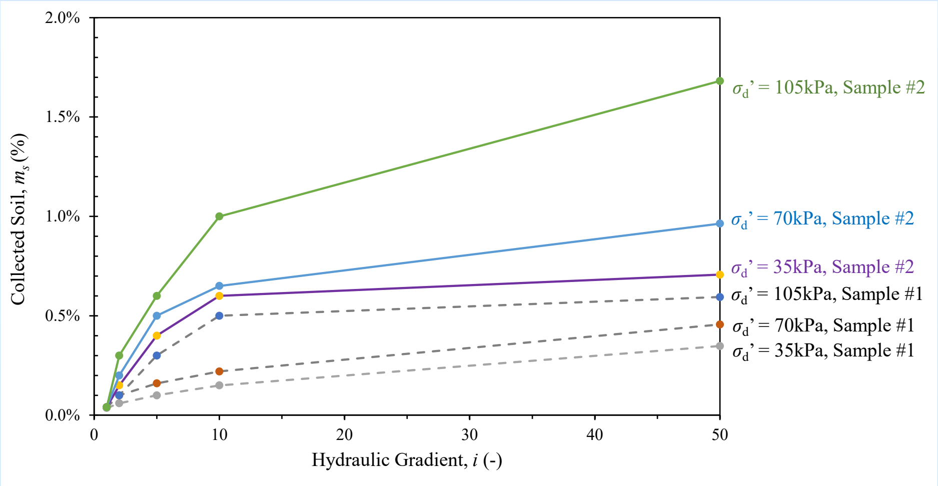


Grain size distribution of two tested specimens with identical mean grain size, which approximates the screen opening.





Solids migration measured under various stress and flow conditions



Project Summary

Project Area	Key Outcomes	Future Work
Numerical Simulation Supports	• 2D/3D Geological Models for Kuparuk Site • Production simulations for fixed/staged production scenarios with TOUGH+/CMG-STARS • Sensitivity analysis for various production scenarios	• 3D Modeling for Kuparuk with updated input (geologic features and laboratory data) • Model validation with field acquired data from production test
Coupled Processing Modeling	• Fully coupled reservoir simulator to be completed • Sensitivity studies to identify major parameters for sand production	• Fully coupled THM simulations for Kuparuk site with both geomechanical deformation and particle transport
Machine Learning Applications	• Well log data analysis and parameter estimations for NGHP-02	• *ON HOLD*
Basin and Petroleum System Modeling	• Compiled and cataloged a database of 582 digital well logs for the ANS	• 1D burial and thermal history models along the Eileen-Prudhoe Bay
Laboratory Experimental Supports	• Pressure Core Analysis and Tool Development • Multiscale (Core/Pore) Testing and Imaging • Hydrological/Geomechanical Property	• Relevant input for numerical simulations for ANS and GOM • Fundamental knowledge on gas hydrate and its responses
Field Production Test Supports	• Shut In Procedure/Well Completion Method • Engineering Support	• Engineering support needed for the planning and operation of the ANS production well test
Life Cycle Assessment	• Refined the previous assessment of the total CO2 emissions associated with the gas production and consumption from ANS hydrate reservoir	• Complete a comprehensive NETL LCA report on the gas hydrate production in the northern Alaska region
Interagency and International Collaboration	• Code comparisons, Core Analysis Working Group	• Supporting success of domestic and international exploration and expedition

Lessons Learned

- 3D reservoir modeling is critical to include complicated geologic features and to refine practical 2D models.
- Characterization of pressure core is challenging, as well as collecting cores, transporting and storing, and manipulating. Sophisticated tools for characterization, visualization, and analysis is essential.
- Contribution from both reservoir modeling and laboratory characterization is the key supporting the large field tests and expedition.
- Understanding complicated THM processes occurring in the hydrate reservoir, in particular, on thinly interbedded sediment reservoir is critical and characterizing and modeling coupled processes is important for successful development.

Collaborations & Opportunities

- Collaborations:
  - Reservoir modeling for coupled processes: JOGMEC, LBNL, TAMU
  - Laboratory test and comparison : AIST, LBNL, UTA, GT
  - Pressure core working group: AIST, USGS, UTA, GT
  - Life cycle analysis; WVU, UGSG
  - Machine learning application: JOGMEC, USGS, India
- Information sharing for advanced comprehensive analysis and improved test design and execution: Code comparison studies, inter-laboratory comparison study, discussion groups, well log data analysis
- New Research Area: global climate change impacts, carbon-neutral methane production, industrial applications

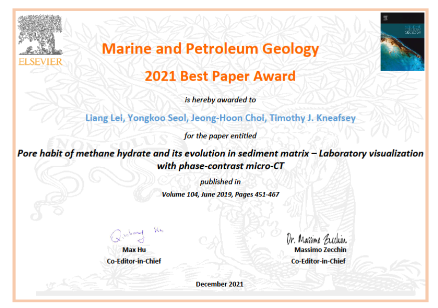
Publications (21-22)

- Lei, L., Park, T., Jarvis, K., Pan, L., Tepecik, I., Zhao, Y., Ge, Z., Choi, J.H., Gai, X., Galindo-Torres, S.A. Boswell, R., and Seol, Y., 2022. Pore-scale observations of natural hydrate-bearing sediments via pressure core sub-coring and micro-CT scanning. Scientific reports, 12(1), pp.1-17.
- Myshakin, E., Garapati, N., Seol, Y., Gai, X., Boswell, R., Ohtsuki, S., Kumanagi, K., Sato, M., Okinaka, N. Numerical Simulations of Depressurization-Induced Gas Hydrate Reservoir (B1 Sand) Response at the Prudhoe Bay Unit Kuparuk 7-11-12 Pad on the Alaska North Slope, *Energy Fuels*, 2022, 36(5), 2542–2560 https://doi.org/10.1021/acs.energyfuels.1c04099
- Boswell., R., Yamamotto, K. Tamaki, M., T. S. Collett, G. J. Moridis, E. M. Myshakin, New Insights into the Occurrence and Implications of Mobile Water in Gas Hydrate Systems, *Energy Fuels*, 2022, 36(5), 2447–2461 10.1021/acs.energyfuels.1c04101
- Chong, L., Singh, H., C. Gabriel Creason, E. M. Myshakin, Application of machine learning to characterize gas hydrate reservoirs in Mackenzie Delta (Canada) and on the Alaska north slope (USA), *Computational Geosciences*, 2022, 26(5):1-15; 10.1007/s10596-022-10151-9, May, 2022.
- Uchida, S., Seol, Y. and Yamamoto, Koji, Sand Migration simulation during gas production from gas hydrate reservoir at Kuparuk 7-11-12 site in the Prodhoe Bay Unit, Alaska, *Energy and Fuels,* 2022 Accepted*.*
- Zhang, L., Dong, H., Dai, S., Kuang, Y., Yang, L., Wang, J., Zhao, J. and Song, Y., 2022. Effects of depressurization on gas production and water performance from excess-gas and excess-water methane hydrate accumulations. Chemical Engineering Journal, 431, p.133223.
- Kim, J., Seol, Y. and Dai, S., 2021. The coefficient of earth pressure at rest in hydrate-bearing sediments. *Acta Geotechnica*, pp.1-11.
- Seol, Y., L. Lei, K. Jarvis, D. Hill, J. H. Choi, T. Park, X. Gai, G. Wunderlich, B. Grey, and C. McArdle (2021), Tools for pressure core sub-coring and pore-scale micro-CT (computed tomography) scans, *Scientific Drilling*, 29, 59-67, doi:10.5194/sd-29-59-2021.
- Singh, H., Seol, Y., Myshakin, E. M., Prediction of gas hydrate saturation using machine learning and optimal set of well-logs, *Computational Geosciences*, 2021, 25(1), 1-17 https://doi.org/10.1007/s10596-020-10004-3

– The BEST PAPER AWARD in 2021 in *Marine and Petroleum Geology*.

Pore Habit Of Methane Hydrate And Its Evolution In Sediment Matrix – Laboratory Visualization With Phase-contrast Micro-CT, Lei et al.,(2019)

– 7 Abstracts submitted for presentation at ICGH10



ELSEVIER

Marine and Petroleum Geology

2021 Best Paper Award

is hereby awarded to

Liang Lei, Yongkoo Seol, Jeong-Hoon Choi, Timothy J. Kneafsey

for the paper entitled

Pore habit of methane hydrate and its evolution in sediment matrix – Laboratory visualization with phase-contrast micro-CT

published in

Volume 104, June 2019, Pages 451-467

Max Hu
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December 2021

Appendix

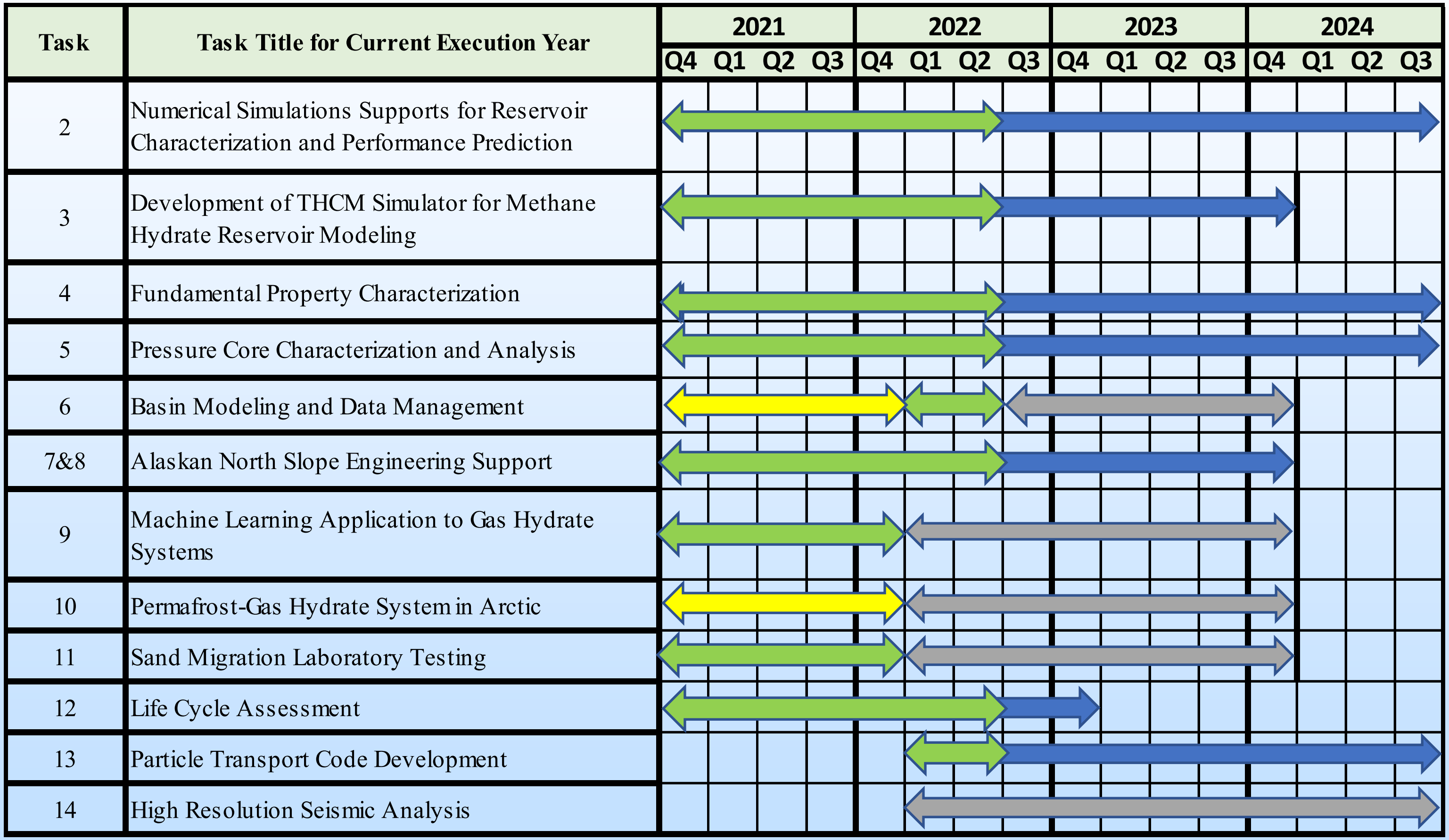
- Organization Chart
- Gantt Chart

Organization Chart

- NETL Technology Manager: John Roger
- Senior Fellow(s): Ale Hakala
- R&IC TPL(s): Yongkoo Seol
- R&IC PI(s): Yongkoo Seol, Ray Boswell
- FE HQ Division Director: Vanessa Nunez-Lopez
- FE HQ Project Manager: Gabby Intihar
- Program Manager: Sandra Borek

Task #	Task Leads	Team Members
Z	Sandra Borek	Sean Sanguinito (LRST)
2	Yongkoo Seol	Evgeniy Myshakin (LRST), Nagasree Garapati (UNH), Leebyn Chon (LRST)
3	Yongkoo Seol	Evgeniy Myshakin (LRST), Ali Zidane (LRST) Shun Uchida (RPI),
4	Yongkoo Seol	Jeong Choi (LRST), Karl Jarvis (LRST), Sheng Dai (GT)
5	Yongkoo Seol	Mathias Pohl (LRST), Karl Jarvis (LRST), Jeong Choi (LRST)
6	Yongkoo Seol	Gabe Creason (ORISE), Leebyn Chong (LRST)
7&8	Ray Boswell	Jim Kirksey (MESA), Alana Sheriff (MESA)
9	Yongkoo Seol	Evgeniy Myshakin (LRST), Leebyn Chong (LRST)
11	Yongkoo Seol	Sheng Dai (GT), Shun Uchida (RPI), Evgeniy Myshakin (LRST),
12	Yongkoo Seol	Nagasree Garapati (UNH), Evgeniy Myshakin (LRST),
13	George Moridis	Students at TAMU

Gantt Chart



Task	Task Title for Current Execution Year	2021				2022				2023				2024			
		Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
2	Numerical Simulations Supports for Reservoir Characterization and Performance Prediction	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
3	Development of THCM Simulator for Methane Hydrate Reservoir Modeling	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦			
4	Fundamental Property Characterization	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
5	Pressure Core Characterization and Analysis	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
6	Basin Modeling and Data Management	🟨	🟨	🟨	🟨	🟨	🟩	🟩	▨	▨	▨	▨	▨	▨			
7&8	Alaskan North Slope Engineering Support	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦			
9	Machine Learning Application to Gas Hydrate Systems	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨			
10	Permafrost-Gas Hydrate System in Arctic	🟨	🟨	🟨	🟨	🟨	▨	▨	▨	▨	▨	▨	▨	▨			
11	Sand Migration Laboratory Testing	🟩	🟩	🟩	🟩	🟩	▨	▨	▨	▨	▨	▨	▨	▨			
12	Life Cycle Assessment	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟦	🟦							
13	Particle Transport Code Development						🟩	🟩	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
14	High Resolution Seismic Analysis						▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨

🟥 Go/No-Go TimeFrame
⬛ Project Completion

Current Progress as of OCt. 2022 🟩 On Schedule 🟨 Delayed

▨ On Hold 🟦 Planned