NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

DOE Award No.: FP00008138

Quarterly Research Performance Progress Report
(Period Ending 9/30/2019)

NUMERICAL STUDIES FOR THE CHARACTERIZATION OF RECOVERABLE RESOURCES FROM METHANE HYDRATE DEPOSITS

Project Period (August 1, 2018 to Open)

Submitted by:
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Signature

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U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

Office of Fossil Energy

RESEARCH PERFORMANCE PROGRESS REPORT

DISCLAIMER

ACCOMPLISHMENTS:

Task 1. Project Management Plan

Status: Ongoing

A Draft PMP was submitted for Budget Period #1 in July 2018, with a revised FWP and SOPO.

Task 2. Code Maintenance, Updates, and Support

Status: Ongoing

The three-part paper series documenting the TOUGH+HYDRATE/Millstone suite was published in Q3:

Moridis, G.J., Reagan, M.T., Queiruga, A.F., "Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part I: The Hydrate Simulator," *Transport in Porous Media*, **128**, 405-430, doi: 10.1007/s11242-019-01254-6.

Queiruga, A.F., Moridis, G.J., Reagan, M.T., "Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part II: Geomechanical Formulation and Numerical Coupling" *Transport in Porous Media*, **128**, 221-241, doi: 10.1007/s11242-019-01242-w.

Reagan, M.T., Queiruga, A.F., Moridis, G.J., "Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part III: Application to Production Simulation," *Transport in Porous Media*, **129**, 179-202, doi: 10.1007/s11242-019-01283-1.

An invited talk concerning the TOUGH+Millstone coupling was presented in Q2:

In the course of parameterizing the datasets needed for the ML-based model development (Task 4), a recent empirical model for the properties of mixtures of liquid water, salt, and gas was found in the literature. The empirical model was implemented in TOUGH+Hydrate to further improve the accuracy of the density formulations in the current state-of-the-art simulator, and will be included in the next release of the T+M simulator.

Task 3. Support of DOE's Field Activities and Collaborations

Subtask 3.1: Design support for a DOE-led field test in the North Slope of Alaska
Status: Ongoing

We began discussions about the upcoming field test in Q4, and received data in August 2019.

An initial analysis suggested the system, particularly Unit B, could be separated into discrete zones/layers, with uniform hydrate saturation and/or other properties within each zone. However, consultation with DOE and USGS suggested that the data was sufficiently accurate to map directly onto a very fine (0.5 ft) vertical meshing, with each vertical subdivision/layers as measured considered to be a separate rock/material type for maximum flexibility in defining local system properties. This maximizes fidelity to the field data.

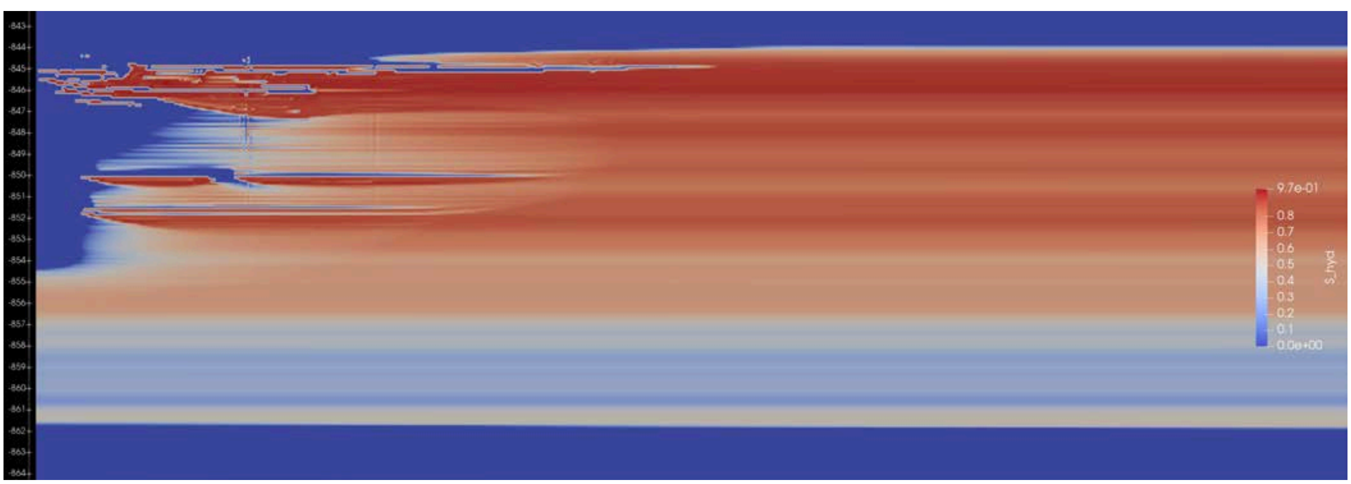
The result was a finely-meshed 2-D cylindrical/axisymmetric system, with a *z*-discretization as fine as 0.1 m in the Unit B hydrate zone. The system was extended outward to r = 800 m, and to a vertical extent of 250 m, encompassing both the Unit B and the less productive Unit D, plus associated overburdens and underburdens. The total mesh size was thus 641 x 343 elements in (r,z). All boundaries, vertical and lateral, were considered open/flowing barring further data. For the reference production case, we assumed a 10 m perforated interval at the top of the system, with bottom-hole pressure declining in increments of 2 MPa every 30 days to a final production P_w = 2.8 MPa.

Evaluation of the production performance and potential is accomplished by monitoring the following key parameters during the field test period: the amounts (rates and cumulative masses) of (1) gas release from hydrate dissociation, (2) gas production and (3) water production, as well as (4) the provenance of the produced gas. These define the criteria that enable assessment of hydrate deposits as desirable production targets: high gas production (the absolute criterion) and low water-to-gas ratio (the relative criterion). A large set of additional parameters is also monitored: (5) the accumulation of free gas in the reservoir, (6) the inflows of water from the boundaries and (7) the spatial distributions of pressure, temperature and phase saturations in the reservoir. The pressure, temperature and phase saturations are also monitored at several locations where observation wells can be measured. Although earlier studies have indicated that adverse geomechanically-induced changes (i.e., subsidence and declines in porosity and permeability) are likely to be limited during production from hydrates in arctic settings because of the mitigating effect of the stiffness of the overlying permafrost, geomechanical parameters (stresses, strains and displacements) and their effects on flow are also monitored, with emphasis in the vicinity in the well where the maximum disturbances are expected to occur and the probability of mechanical instability is at its highest.

Preliminary results for the reference case and several sensitivity cases were presented to the DOE team in October, 2019.

The preliminary results indicated:

1. The system exhibits significant H_2O production and inefficient depressurization (i.e., reduced hydrate dissociation) because of significant/persistent H_2O inflows from the permeable boundaries.
2. If the production strategy of step-wise pressure decline is replaced with a fast linear decline in bottomhole pressures, this yields higher gas production, but also higher H_2O production.
3. The effect of relative permeability parameters is significant in terms of gas and H_2O production, but not so in terms of water-to-gas ratio (still poor). However, this defines the envelope of possible production estimates.
4. Varying the length of the production interval was shown to be inconclusive (up to this point), as production is affected by the considerable S_H variability with depth.



As a general conclusion: water production is a pervasive issue for this system, and production operation management or well construction can have only minor effects on H_2O production. Our analysis of the system continues in Q1 of FY20, with more results pending.

Subtask 3.2: Activities in support of DOE international gas hydrate collaborations
Status: Ongoing

Our group finished in Q3 the paper for the JMPG Special Edition on the India Gas Hydrates program, and the paper remains in press pending the completion of the special issue.

Subtask 3.3: Participation in the Code Comparison Study
Status: Ongoing

LBNL contributed solutions to Problems #1, #2, and #4, and designed Problem #3. We participated in regular teleconferences with study leaders and other simulation teams. The insights gained from the CCS have led to the development of a new code testing and validation system for TOUGH+HYDRATE (see Task 2), as well as motivating us to perform addition evaluations of the TOUGH+ code architecture, numerical methods, and other issues.

The Problem #3 formulation and the analysis of the results included a mesh-convergence study for both TOUGH+HYDRATE and the TOUGH+HYDRATE+Millstone flow-geomechanical suite. This is the first such study that we are aware of, and contributes to the understanding of the mesh generation methodologies used to create reservoir models for TOUGH+HYDRATE and other Darcy-based hydrate reservoir simulators.

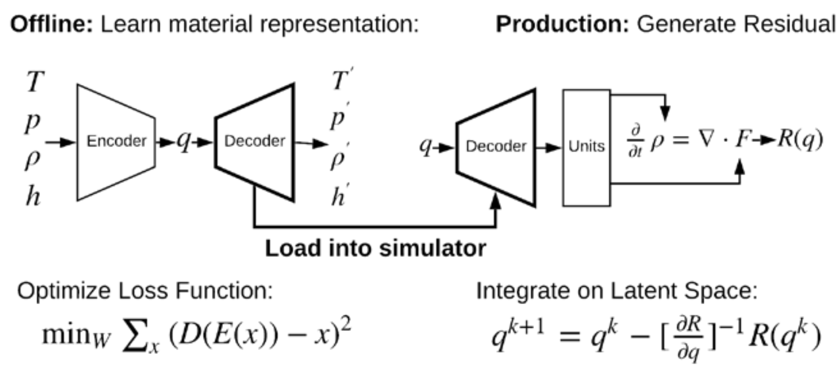
Work related to Problem 3, plus our additional analysis of mesh-convergence issues for hydrate simulators, has been accepted for presentation at the 2019 AGU Fall Meeting:

"Validation And Testing Of Coupled Flow-Thermal-Mechanical Hydrate Reservoir Models," OS34A: Geomechanics of Hydrate-Bearing Reservoirs: Laboratory Testing, Numerical Modeling, and Field Testing on Gas Production and Geohazard II.

Task 4. Exploration of High-Efficiency Modeling Methods for Hydrate Reservoir Simulation
Status: Ongoing

In this quarter, we have made major progress on the machine learning based approach to solving multiphase, multicomponent reservoir simulation problems. The general direction of this line of work has been demonstrating the use of differentiable programming in scientific and engineering applications.

The new multiphase simulator was extended to include flux connections between decoder-based cells. At this stage, the flux connections implement basic linear Darcy flow, also implemented in TensorFlow. For the first stage, the simulator will mix currently used derived formulas with the ML-based decoders for the phase state representation. Extending the simulator to learn new flux laws for hydrate reservoirs requires new experimental datasets.

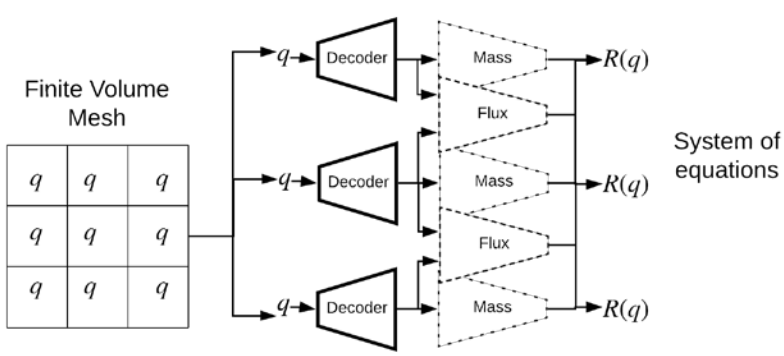


The work was submitted to the American Geophysical Union conference in December and accepted for an oral presentation:

"A Trainable Simulator: using unsupervised learning in conjunction with computational methods to rewrite our equations, applied to multiphase flow." IN44A: Incorporating Physics and Domain Knowledge to Improve Explainability, Reliability, and Generalization of Machine Learning Models I."

In addition, the work will be presented as an invited presentation at the 2020 SIAM Conference on Mathematics of Data Science:

"On the Interpretation of Learning Dynamical Systems," Mini Symposium on Machine Learning and Physical Science.



Exploratory work on learning flux representations for transport equations was performed using Burgers' equation as a known benchmark. A deep learning approach has been successfully demonstrated to learn a nonlinear convolutional module that solves the discretized equation.

The learning suite was published open source to Github at:

https://github.com/afqueiruga/nn_1d_pde

and a preprint of the analysis, "Studying Shallow and Deep Convolutional Neural Networks as Learned Numerical Schemes on the 1D Heat Equation and Burgers' Equation" is on arXiv as https://arxiv.org/abs/1909.08142, which is being prepared to be submitted to a conference.

Task 5. Publications, Tech Transfer, and Travel
Status: Ongoing

No new submitted publications in this quarter.

Conference travel to date:

1. Mastering the Subsurface, Carbon Storage and Oil and Natural Gas Conference, Pittsburgh, PA 13-16 August 2018.
2. Machine Learning in Solid Earth Geoscience, Santa Fe, Nevada, March 2019
3. SIAM Conference on Mathematical & Computational Issues in Geosciences, Houston, Texas, March 2019
4. "Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits," Addressing the Nation's Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting, Pittsburgh, PA, 26-30 August 2019.

Milestone Table

Milestone Title	Milestone Description	Planned Completion Date	Actual Completion Date	Status / Results
PMP	Maintenance and update of the Project Management Plan	August 30, 2018	Included with SOPO 7/25/18	Submitted
Deliverable	Updated versions serial and parallel versions of the T+H/Millstone code	May 30, 2019	April, 2019	Three-paper series describing software published in TiPM.
Deliverable	Report describing the design and performance of the proposed field test.	August 31, 2019	October 7, 2019	Preliminary results presented to DOE in October 2019. Simulations ongoing after receipt of data
Deliverable	Completion participation in the code comparison study; contributions to reports and publications	August 31, 2019		IGHCCS continues into FY20.
Deliverable	An assessment of the feasibility, effectiveness and robustness of ROMs	August 31, 2019		Development of the ML-based modeling techniques (with associated publications) will be completed in Q1 FY20.

PRODUCTS:

Publications to date (this FWP):

1. Moridis, G.J., Reagan, M.T., Queiruga, A.F., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part I: The Hydrate Simulator,” *Transport in Porous Media*, **128**, 405-430, doi: 10.1007/s11242-019-01254-6.
2. Queiruga, A.F., Moridis, G.J., Reagan, M.T., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part II: Geomechanical Formulation and Numerical Coupling” *Transport in Porous Media*, **128**, 221-241, doi: 10.1007/s11242-019-01242-w.
3. Reagan, M.T., Queiruga, A.F., Moridis, G.J., “Simulation of Gas Production from Multilayered Hydrate-Bearing Media with Fully Coupled Flow, Thermal, Chemical and Geomechanical Processes Using TOUGH+Millstone, Part III: Application to Production Simulation,” *Transport in Porous Media*, **129**, 179-202, doi: 10.1007/s11242-019-01283-1.
4. Moridis, G.J., Reagan, M.T., Queiruga, A.F., Collett, T.S., Boswell, R., Evaluation of the Performance of the Oceanic Hydrate Accumulation at the NGHP-02-9 Site of the Krishna-Godavari Basin During a Production Test and Under Full Production, *J. Marine and Petroleum Geology,* in press, doi: 10.1016/j.marpetgeo.2018.12.001.
5. Moridis, G.J., Reagan, M.T., Queiruga, A.F., Kim, S.J., System response to gas production from a heterogeneous hydrate accumulation at the UBGH2-6 site of the Ulleung basin in the Korean East Sea, *J. Pet. Sci. Eng.,***178**, 655-665. doi: 10.1016/j.petrol.2019.03.058.

Presentations to date (this FWP):

1. “Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits,” Mastering the Subsurface, Carbon Storage and Oil and Natural Gas Conference, Pittsburgh, PA 13-16 August 2018.
2. “Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits,” project wrapup meeting. 28 September 2018.
3. "Machine Determination of Better Representations of Multiphase Equation of States for Subsurface Flow Simulation" at Machine Learning in Solid Earth Geosciences, 18-22 March 2019 in Santa Fe, NM.
4. “Fully Coupled Multimesh Algorithms for Nonisothermal Multiphase Flow and Mechanics in Geological Formations,” **(invited)** SIAM Conference on Mathematical & Computational Issues in Geosciences, Houston, Texas, March 2019.
5. “Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits,” Addressing the Nation’s Energy Needs Through Technology Innovation – 2019 Carbon Capture, Utilization, Storage, and Oil and Gas Technologies Integrated Review Meeting, Pittsburgh, PA, 26-30 August 2019.

SPECIAL REPORTING REQUIREMENTS:

N/A

BUDGETARY INFORMATION:

Actual Cost (this quarter)	Actual Cost (cumulative for BP)	Funds available (for the BP)	Balance of unspent funds (for the BP)	Actual Cost (cumulative for the full FWP)	Funds available (for the full FWP)	Balance of unspent funds (for the full FWP)
$105,888	$423,903	$500,000	$76,097	$423,903	$500,000	$76,097

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