NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

DOE Award No.: ESD12010

Quarterly Research Performance Progress Report

(Period Ending 3/31/2018)

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

Project Period (April 1, 2012 to open)

Submitted by:
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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 PMP was submitted for Budget Period #6 in March 2017. A revised FWP and SOPO was submitted on July 31, 2017. A revised for the new, extended BP #6 was submitted in August, 2017.

Task 2. Code Maintenance, Updates, and Support

Subtask 2.6:

Status: Ongoing, task expanded 7/31/2017

Development of the new Millstone geomechanical code has been ongoing, and has now been tested in real-world simulation problems associated with other tasks in the FWP. A new capability for static post-processing of pre-existing T+H simulation was added in the previous quarter, and was used in this quarter on the results of the India NGHP studies described in Task 3.

The release of the new coupled T+H/Millstone platform was accompanied by the submission of three papers that document 1) T+H code development, 2) Millstone code development, and 3) testing of the latest coupled simulator:

1. Moridis, G.J., Reagan, M.T., Queiruga, A.F., “The TOUGH+Millstone Code for the Analysis of Coupled Flow, Thermal, Chemical and Geomechanical Processes in Hydrate-Bearing Geologic Media, Part I: The Hydrate Simulator,” submitted to *Transport in Porous Media*.
2. Queiruga, A.F., Moridis, G.J., Reagan, M.T., “The TOUGH+Millstone Code for the Analysis of Coupled Flow, Thermal, Chemical and Geomechanical Processes in Hydrate-Bearing Geologic Media, Part II: Numerical Algorithms and the Stone Geomechanical Simulator,” submitted to *Transport in Porous Media*.
3. Reagan, M.T., Queiruga, A.F., Moridis, G.J., “The TOUGH+Millstone Code for the Analysis of Coupled Flow, Thermal, Chemical and Geomechanical Processes in Hydrate-Bearing Geologic Media, Part III: Application to Production Simulation,” submitted to *Transport in Porous Media*.

Note that the papers were originally submitted to *Computers and Geosciences*, but a new “open source only” policy (in reality, a “free download only” policy) now prevents licensed codes like TOUGH+HYDRATE from being used in published papers for that journal.

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

Subtask 3.6: Detailed Analysis of the Production Potential of Hydrates Deposits Offshore India

Status: Ongoing

The latest versions of the T+H and Millstone codes, developed in Task 2, has been used for ongoing simulations of the India NGHP Site 9 production test. In this quarter, the team completed all but one of the simulations of Site 9 production scenarios, with and without coupled geomechanics, using data and geological models developed in consultation with NETL, USGS, and Indian scientists. The final simulations have been in progress for several months and will be completed in April 2018 (Q3). Problems caused by purely technical issues were overcome, and recent delays were solely the result of the extremely long execution times required to properly model the system, with multi-million-timestep simulations consuming close to 1 million CPU-hours. We continue to use a pay-per-use supercomputer system (Lawrencium) that provides us easy access, but the number of processors we can use is subject to user load. Also, the cost of this system (which can be several thousand dollars a month at peak use), is billed out of project funds.

The reason for these very short time steps continues to be the extreme variation in permeability between the hydrate-bearing layers (~1.0 mD or less) and the hydrate-free sand (~10.0D). The 4-order difference in permeability causes a multitude of problems: the very fine radial discretization along the hydrate-free sand lenses result in practically zero pressure differences between adjacent grid elements, making the computation of gradients and derivatives both difficult and inaccurate for the Jacobian needs of the fully implicit model in TOUGH+HYDRATE. These conditions that are particular to Site 9 drastically aggravate an already difficult, non-linear problem of coupled flow, thermal and geomechanical processes, and lead to the very long execution times that we are experiencing. Scenarios involved multiple wells at varying

spacing have shown greatly improved numerical behavior, as they result in more dramatic depressurization of the system and reduced water inflow.

As of March 31, a total of six cases have been simulated:

1) New reference case, involving a single vertical well, using the new layered system and updated reservoir properties
2) New open case with the permeable interlayer excluded from the perforated interval of the well
3) New closed case, simulating a pattern of wells at 1000 m spacing (r = 500 m)
4) New closed case, simulating a pattern of wells at 200 m spacing (r = 100 m)
5) New closed case, simulating a pattern of wells at 150 m spacing (r = 75 m)
6) New open case, simulating a single vertical well but with a reduced permeability of 1.0 D in the hydrate-bearing sands.

Cases 4 and 5 have been completed to 540 days (the duration of the field test). Case 2 has been stopped after 50 days of production after initial analysis indicated that the results were essential identical to the new reference case after a few days of production. Case 3 is currently (March 31) at 350 days, having consumed over 175,000 CPU-hours of cluster time, and continues to be the most challenging of the five cases to simulate due to the unique combination of high water production at early times and slow transition to strong depressurization after five months of production (leading to increased productivity after 250 days). We will run Case 3 until sufficient data is available to evaluate the system, or until 540 days. Case 1, the reference case, was suspended at t = 200 d after results indicated that high water flows from the boundaries via the interlayer, aquifer, and through open pathways through the hydrate layers were preventing effective depressurization of the system and thus production rates that fail to increase with time. The newest Case 6, with reduced-permeability sands, resulted in a more numerically tractable simulation (larger timesteps), but also suffered from water inflow problems as there are still highly permeable pathways suppressing the depressurization of the reservoir.

The results from these simulations will be submitted to the journal special issue associated with the India NGHP in late April 2018. The results will also be presented in a confidential report to the NGHP leadership in April. Preliminary results from this work were also presented as part of the keynote address at the 2018 Gordon Conference on Natural Gas Hydrates, and at an invited talk at the National University of Singapore.

Subtask 3.7: Participation in the Code Comparison Study of Coupled Flow, Thermal and Geomechanical Processes

Status: Ongoing

The LBNL team has been participating in the regular meetings, and presented our capabilities on December 7. Matt Reagan and Alejandro Queiruga are designing Problem #3, a variation of a standard axisymmetric coupled flow-mechanical test problem.

Task 4. Assessment of Resource Recoverability From Natural Hydrate Deposits

Subtask 4.4:

Status: Ongoing

Work on Subtask 4.4 continued in Q2. The work focused on simulations of the production behavior of horizontal wells in sloping systems. The geomechanical consequences of production and post-production re-equilibration were assessed for each case, and results suggest there is little or no chance of slope failure during the production cycle. The results were submitted as a conference paper:

Moridis, G.M., Reagan, M.T., Queiruga, A.F., "Geomechanical Stability and Overall System Behavior of Sloping Oceanic Accumulations of Hydrates Responding to Dissociation Stimuli, OTC-24896-MS,*Proc.* Offshore Technology Conference-Asia, 20 March 2018."

The results were also presented at the Offshore Technology Conference Asia in March 2018, and highlighted in the keynote address at the 2018 Gordon Conference on Natural Gas Hydrates.

Milestone Table

Milestone Title	Milestone Description	Planned Completion Date	Actual Completion Date	Status / Results
PMP	Maintenance and update of the Project Management Plan	April 30, 2016, March 30, 2017	Included with BP#6 SOPO 3/15/17	Updated 30 days after receipt of added BP #6 funding
Deliverable	Report and presentation(s) regarding the results of the initial Subtask 3.6 simulations	June 30, 2017	Results to date presented at ICGH 9 on June 26-30, 2017.	Subtask 3.6 extended and expanded to cover a wider range of scenarios and parameters through July 2018,
Deliverable	Completed T+H/ROCMECH Code Updates	December 31, 2016	March 27, 2018**	ROCMECH found to be incompatible with cylindrical well simulations (i.e., India NGHP studies). Development suspended in May 2016 with the beginning of Millstone development. **T+H/Millstone v1.0 completed in March 2018.
Deliverable	Submission of a report on the preliminary studies of offshore Indian hydrates	May 31, 2017	May 2017	Report submitted.
Deliverable	Completion of the analysis and submission of a paper evaluating the production performance of slanted wells	July 31, 2016	March 16, 2018	Paper submitted to 2018 Offshore Technologies Conference Asia. Presented May 2, 2018.
Deliverable	Submission of a paper on the expected long-term fate and transport of released gas following the cessation of operations	July 31, 2016	December 12, 2016; June 30, 2017	Results presented as a poster at AGU Fall Meeting. Paper submitted to ICGH 2017 and presented June 30, 2017.

Deliverable	A paper (jointly with T. Kneafsey) on the design and analysis of the planned experiments.	May 31, 2017	Pending	Delays in experiments have resulted in a delay in producing a paper. We are currently evaluating completed tests.
Deliverable	Updated versions serial and parallel versions of the T+M/Millstone code	July 31, 2018	March 27, 2018	Three papers describing T+H/Millstone submitted to Transport in Porous Media.
Deliverable	Completion of analyses and participation in the code comparison study	July 31, 2018	Ongoing	Problem #1 completed in Q2. CCS expected to continue into FY19.
Deliverable	Submission of a report on the ongoing studies of offshore Indian hydrates	Jul 31, 2018	April 13, 2018	Report submitted to NGHP; Report condensed into paper submitted to JMPG.
Deliverable	Submission of a report on the evolution of subsidence and strategies to mitigate production problems	Jul 31, 2018	Ongoing	Work ongoing

PRODUCTS:

Publications to date (this BP):

Reagan, M.T., Moridis, G.J., Seim, K.S., "Fast Parametric Relationships for the Large-Scale Reservoir Simulation of Mixed CH4-CO2 Gas Hydrate Systems," *Computers and Geosciences*, **103**, 191-203, 2017.

Moridis, G.J., Reagan, M.T., Queiruga, A.F., "Long-Term System Behavior Following Cessation of Gas Production from Hydrate Deposits," *Proc.* 9th Int. Conference on Gas Hydrates, Denver, CO, 1-3 June 2017.

Moridis, G.J., Queiruga, A.F., Reagan, M.T., "The T+H+M Code for the Analysis of Coupled Flow, Thermal, Chemical and Geomechanical Processes in Hydrate-Bearing Geologic Media," *Proc.* 9th Int. Conference on Gas Hydrates, Denver, CO, 1-3 June 2017.

Moridis, G.J., Reagan, M.T., Queiruga, A.F., "The TOUGH+Millstone Code for the Analysis of Coupled Flow, Thermal, Chemical and Geomechanical Processes in Hydrate-Bearing Geologic Media, Part I: The Hydrate Simulator," submitted to *Transport in Porous Media*.

Queiruga, A.F., Moridis, G.J., Reagan, M.T., "The TOUGH+Millstone Code for the Analysis of Coupled Flow, Thermal, Chemical and Geomechanical Processes in Hydrate-Bearing Geologic Media, Part II: Numerical Algorithms and the Stone Geomechanical Simulator," submitted to *Transport in Porous Media*.

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Moridis, G.M., Reagan, M.T., Queiruga, A.F., Geomechanical Stability and Overall System Behavior of Sloping Oceanic Accumulations of Hydrates Responding to Dissociation Stimuli, OTC-24896-MS,*Proc.* Offshore Technology Conference-Asia, 20 March 2018.

Presentations to date (this BP):

"Long-Term System Behavior Following Cessation of Gas Production from Hydrate Deposits," 9th Int. Conference on Gas Hydrates, Denver, CO, 1-3 June 2017.

"The T+H+M Code for the Analysis of Coupled Flow, Thermal, Chemical and Geomechanical Processes in Hydrate-Bearing Geologic Media," 9th Int. Conference on Gas Hydrates, Denver, CO, 1-3 June 2017.

"Geomechanical Stability and Overall System Behavior of Sloping Oceanic Accumulations of Hydrates Responding to Dissociation Stimuli," OTC-24896 Offshore Technology Conference-Asia, 20 March 2018.

"Modeling at the Reservoir and Field Scales," (invited) Keynote Session, Gordon Research Conference on Natural Gas Hydrates, Galveston, TX, 25 February-2 March 2018.

"Current Advances in Laboratory and Simulation Studies at LBNL," National University of Singapore, 27 March 2018.

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)
$91,136	$382,418	$350,000*	$37,693**	$1,212,307	$1,250,000*	$37,693**

* this includes the additional $150,000 to be added to the FWP for BP #6.
** this includes overlapping funds/carryover between BP #5 and BP#6.

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