Oil & Natural Gas Technology

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2012 Annual Research Progress Report
(April – December 2012)

Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits Project Period (April 2012 – March 2013)

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2012Annual Progress Report

Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits

WORK PERFORMED UNDER
ESD12-010

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Project Period/Duration: April 1, 2012 – March 31, 2013

Period Covered in This Report: April 1, 2012 – December 31, 2012

February 4, 2013

EXECUTIVE SUMMARY

The project accomplishments during the April 1-December 31 reporting period were significant, given the project budget. More specifically: (1) New versions of both the serial and the parallel TOUGH+HYDRATE codes (V1.25, with improved thermodynamics and thermophysical properties, and new control and output capabilities) were released to the public, (2) entirely new versions (V2.0) with new input and output data structures were developed and will be ready for release in mid-2013, along with a paper (currently in preparation) on the subject, (3) two collaborative studies (with KIGAM, Korea) on the evaluation of the production potential of Korean marine hydrates in the Ulleung Basin and of the corresponding geomechanical system behavior were completed, and two related paper are either published or in review, (4) a two-way, fully-coupled flow-thermal-geomechanical simulator (involving TOUGH+HYDRATE and ROCMECH) was developed and tested, (5) two papers on coupled flow-thermal-geomechanical processes in producing hydrate systems were published, (6) the largest study ever conducted of marine hydrate deposit evaluation (requiring solution of 10M equations on clusters and supercomputers) was concluded, a conference paper on the subject was completed, and a paper on the same subject is in review for publication in a scientific journal, (7) studies on gas recoverability from the PBU-L106 site in Alaska were completed and a paper on the subject is in review, and (8) a chapter on the status of gas production from hydrates (in which the PI of the project is the first author) was published by Springer in the book "*Advanced Biofuels and Bioproducts*".

I. GOALS & OBJECTIVES

The overall objective of this project is to continue studies on the characterization and analysis of recoverable resources from gas hydrate deposits, the evaluation of appropriate production strategies for both permafrost and marine environments, and the analysis of the geomechanical behavior of hydrate-bearing sediments, in addition to providing support for DOE's hydrate-related activities and collaborative projects.

The specific objectives describe the scope of work, which includes (a) the maintenance, upgrade and support of numerical simulation codes for the analysis of gas production from hydrates and of the corresponding geomechanical system response, (b) support for DOE's activities and collaborations (including support for a planned field test of gas production from Alaskan hydrates on the North Slope, and collaboration with KIGAM on production from hydrates from the Korean East Sea), and (c) assessment of resource recoverability from natural hydrate deposits in the permafrost and in the oceans, involving an analysis of important factors affecting such gas production and of the corresponding (potentially adverse) geomechanical changes. All these activities meet the DOE program goals.

II. TECHNICAL HIGHLIGHTS

II.1. Task 1: Project Management Plan

The LBNL team worked together with the NETL project manager to maintain and update the project management plan (PMP) originally submitted at FWP approval (and formatted in accordance with the guidance provided by NETL). Because there was no change in the scope of work or the budget, there were no major modifications to the FWP, so there was no need to update the PMP.

II.2. Task 2: Code Maintenance, Updates, and Support

Subtask II.2.1: Updates, corrections and improvements of the forward hydrate simulation codes

This was the only funded of the three subtasks initially proposed by the LBNL team. All the forward simulation codes were maintained and upgraded. The main included (a) the serial and parallel versions of the TOUGH+HYDRATE code (referred to as T+H and pT+H, respectively), the coupled flow-thermal-geomechanical code T+H+FLAC3D code, and the coupled flow-geophysics T+H+G code.

The new versions of (V1.25) of T+H and pT+H were released in December 2012. These include improved thermodynamics and thermophysical properties, a more streamlined structure that improves computational speed, enhanced description of well and boundary conditions (i.e., time variable rates and properties, described by tables or functions), and and new control and output capabilities. The testing and verification of a new, major upgrade of both the T+H and pT+H codes (V2.0) is nearing completion, and these will be released in mid-2013. The pT+H code was greatly enhanced for the simulation of very large problems, and is now capable of running seamlessly on any multi-processor

computer platform, from a simple desktop PC to clusters to supercomputer systems. Thus, the pT+H code was used for the successful simulation of the largest hydrate problem ever attempted, involving about 2.5M of cells, 10M of simultaneous equations, and over 2000 processors. A paper on the subject, entitled "*The T+H and pT+H V2.0 codes for the description of system behavior of hydrates in geological systems*" is nearing completion, and will be submitted to the journal *Computers and Geosciences*. In the case of the T+H+FLAC3D code (hereafter referred to as T+H+F), we implemented a complete two-way coupling of flow, thermal and geomechanical processes, thus accurately describing quantitatively the interdependence of these processes.

Because of the inadequacy of FLAC3D in the analysis of large problems (brought about by its proprietary nature, which precludes access to the source code and optimization/adaptation for use on clusters and large parallel computer systems), we developed the ROCMECH code, which is a significant update of the older ROCMAS code that had been developed at LBNL in the mid-90s. The ROCMECH code was coupled with the T+H code through an implicit two-way scheme, and can describe coupled flow, thermal and geomechanical processes. The resulting code (named T+H+M) has been fully tested through comparisons to results from the T+H+F simulator, has been used in the analysis of several problems (e.g., the geomechanical impact of production from marine hydrates), and is eminently suitable for parallelization (which will begin when appropriate funding becomes available).

Task Deliverables: Updated versions of the various LBNL codes for forward (predictive) simulations of hydrate-bearing geologic systems, and of the corresponding User's Manuals.
Status: Deliverables were met and exceeded

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

Subtask 3.1: Design support for a field test at the PBU-L106 and Mount Elbert sites, North Slope, Alaska

This task describes LBNL's participation in a DOE-supported field test under consideration, and **focuses on the completion of studies that are already in progress**. The test scenarios that were studied involve long-term gas production from a Class 3 permafrost hydrate deposit (mainly the C-Unit deposit at the site of the PBU-L106 well, at the Mount Elbert site, North Slope, Alaska, and, to a much lesser extent, the hydrate deposit of D-Unit at the same site). LBNL's studies involved evaluation (by means of numerical simulation) of the production potential under various well designs and operation/production regimes, and provided information needed for the design of the field study. Work in this subtask included an analysis of the geomechanical system response during long-term field tests that would be conducted at the two sites

Work on the analysis of the production potential of the PBU-L106 using both vertical and horizontal wells has been completed. The results are in included in the paper "*Evaluation of the Hydrate Deposit at the PBU L-106 Site, North Slope, Alaska, for a Long-Term Test of Gas Production*" (by G. Moridis, M.T. Reagan, H. Anderson-Kuzma, Y. Zhao, K. Boyle, and J. Rector), currently under review for publication in the journal *SPE Reservoir*

Evaluation and Engineering. Additionally, the analysis of geomechanical response of the system during long-term production using both vertical and horizontal wells was completed, and the paper "*Numerical Studies on Coupled Flow and Geomechanics in Hydrate Deposits*" (by J. Kim, G.J. Moridis, D. Yang, and J. Rutqvist), was published in the *SPE Journal* (17(2), 485-501, 2012**,** doi: 10.2118/141304-PA). In this paper, the significant differences between the results from one-way and two-way coupling are clearly demonstrated.

Subtask 3.2: Activities in Support of the Joint U.S.-Korea Gas Hydrate Studies

In this subtask, LBNL staff provided support for joint US-Korea studies on gas production from Korean offshore deposits (mainly in the Ulleung Basin of the Korean East Sea). These studies includes (a) evaluation of the gas production potential of deposits identified during recent scientific cruises in that area, (b) analysis of sensitivity of gas production to important (and relatively uncertain) variables and parameters describing the hydrate deposit and the production operations (including the well design), and (c) investigation of the geomechanical response of the hydrate-bearing formation in the course of production, with emphasis on the determination of the envelope of safe production operations (thus alleviating problems of significant subsidence, yielding and failure of the hydrate-bearing formation, and potentially catastrophic incidents such as well collapse).

Using two sets of data provided by KIGAM, two studies on the evaluation of the production potential of Korean marine hydrates in the Ulleung Basin and of the corresponding geomechanical system behavior were completed. The results are reported in the paper "*Feasibility of Gas Production from a Gas Hydrate Accumulation at the UBGH2-6 Site of the Ulleung Basin in the Korean East Sea*" (by. G. Moridis, J. Kim, M. Reagan and S.J. Kim), which was submitted in late December 2012 is currently in review for publication in the *Journal of Petroleum Science and Engineering*.

Task Deliverables: (1) A minimum of one paper on the proposed long-term production test at the potential test sites focusing on (a) the evaluation of production potential of the deposit and its sensitivity to system properties, production methods/strategies, and design/operational parameters, (b) the geomechanical response of the hydrate system and the wellbore during the test, and (c) the feasibility of using time-lapse geophysical methods to monitor the evolution of hydrate accumulations during production, and thus to manage production; (2) data and information that can be used to design the field test; (3) a minimum of one paper on production from Korean hydrates, accounting for both flow and geomechanical issues.
Status: Deliverables were met and exceeded

II. Task 4: *Assessment of Resource Recoverability From Natural Hydrate Deposits*

The primary focus of the LBNL activities in this task was on the subject of production using horizontal wells. Worn in this task confirmed earlier indications of the significant advantage of such wells in the case of production from Class 2 and Class 3 deposits over production from vertical wells in terms of higher production rates and reduced secondary

hydrate formation (a common occurrence during production from vertical wells). The studies addressed several issues, e.g., (a) the effects of well location relative to distinct reservoir features, (b) the possibility of formation fracturing and the corresponding effects, (c) the suitability and effectiveness of combining depressurization with other production methods, (d) the effect of initial and boundary conditions, and (e) the importance of the magnitude and spatial distribution of various reservoir hydraulic (permeability, porosity) and thermal properties (thermal conductivity, specific heat). Inevitably, some of the results of these studies were included in the publications listed in Task 3.

A conference paper entitled "*Modeling and Numerical Simulation for Coupled Flow and Geomechanics in Composite Gas Hydrate Deposits*" (by J. Kim and G. Moridis) on an analysis of the coupled flow-geomechanical-thermal behavior of such hydrate systems during production using horizontal wells was presented at the 46th during the U.S. Rock Mechanics/Geomechanics Symposium, 24-27 June 2012, Chicago, Illinois. Based on results form studies in this task, the paper entitled "*Coupled Multiphase Fluid Flow and Wellbore Stability Analysis Associated with Gas Production from Oceanic Hydrate-Bearing Sediments*" (by J. Rutqvist and G. Moridis) was also published in mid-2012 in the *Journal of Petroleum Science and Engineering* (92-93**,** 65-81, doi: 10.1016/j.petrol. 2012.06.004).

Of particular importance was the analysis of production performance in highly stratified deposits with alternating sand-clay lenses. The results of the study indicated the challenges facing horizontal wells, and showed potential benefits of angled wells. The results of this study are currently being analyzed, and, when completed, will be submitted for publication in an appropriate scientific journal in 2013.

A significant effort in this task was expended in the analysis of production of challenging hydrates in marine deposits bordering large (and permeable) water bodies. To address this issue, we conducted the largest hydrate simulations ever attempted, involving a very complex 3D geologic structure with pronounced heterogeneity (representing a real system, with data provided by an oil and gas company), about 2.5M of cells, 10M of simultaneous equations, and over 2000 processors. We investigated the production potential of this system using both horizontal and vertical wells, and determined the limited potential of this target because of large water production and low gas production (a result of ineffective pressurization because of the permeable boundaries, which allowed continued water inflow). The results of this study were presented in the paper "*Massively Parallel Simulation of Production from Field-Scale Oceanic Gas Hydrate Deposits*" (by M.T. Reagan, G.J. Moridis, K.L. Boyle, C.M. Freeman, L. Pan, N.D. Keen, and J. Husebo), presented during the September 2012 TOUGH Symposium, and an expanded version of this paper under the title "*Field-Scale Investigation of Feasibility of Gas Production from a Large Oceanic Hydrate Deposi*t" and by the same authors is in review for publication in the journal "Transport in Porous Media".

Additionally, a review paper entitled "*Gas Hydrates as a Potential Energy Source: State of Knowledge and Challenges*" with G. Moridis as the first author was published by a

chapter in the book *Advanced Biofuels and Bioproducts* (pages 977-1035, 2012, Springer, New York, Heidelberg, Dordrecht, London, ISBN 978-1-4614-3347-7, doi: 10.1007/978-1-4614-3348-4) that was released in mid 2012.

Task Deliverables: (1) A minimum of one new paper on gas production using horizontal wells, and (2) a minimum of one new paper on the coupled flow-geomechanical behavior of hydrate-bearing media.
Status: Deliverables were met and significantly exceeded

III. RISK ANALYSIS

The overall risk of not accomplishing the tasks listed is considered to be very small. LBNL and the ESD Hydrates group has a decade's history in hydrate research, with more than 60 peer-reviewed journal publications, and reputation as the world's leading research group on the subject.

Task 1: Project Management and Planning
LBNL and the PI have many years experience with managing integrated projects. *Dr. George Moridis* is a Staff Scientist with the Earth Sciences Division of the Lawrence Berkeley National Laboratory (LBNL), Berkeley, California. He is the Deputy Lead for Energy Resources, and Group Leader for Hydrate and Shale gas/Oil studies. He is also managing some of the largest research projects on shale gas production in the US. He is assisted by Dr. Matthew Reagan, who has significant experience co-managing the same large projects.

The largest risk to project management would be loss of key personnel. This risk is considered low, and is managed by the co-PIs on this project, each of whom have experience in project management and share in working knowledge of this project.

Task 2: Code Maintenance, Updates, and Support
The risk of not accomplishing these tasks is low. The PI is a member of the TOUGH2 developer team, and is in charge of the development of the TOUGH+ family of codes, i.e., the new generation of LBNL codes for the simulation of flow and transport in geologic media. Additionally, he is the main author of the TOUGH+HYDRATE code for the simulation of flow and behavior of hydrate systems, which is the main code targeted for enhancement in this task. The progress to-date indicates that this risk is a non-issue.

Task 3: Support of DOE's Field Activities and Collaborations
The progress to-date on this task indicates that this risk is a non-issue.

Task 4: Assessment of Resource Recoverability From Natural Hydrate Deposits
The progress to-date on this task indicates that this risk is a non-issue.

IV. MILESTONE STATUS

Task 2 -- Code Maintenance, Updates, and Support
Milestone: Complete update of pTOUGH+HYDRATE code and corresponding user manual
Planned Date: 12/31/2012
Actual Completion Date: December 2012
Verification Method: Progress Report documenting various code maintenance and updgrades

Task 3 -- Support of DOE's Field Activities and Collaborations
Milestone: Completion of numerical simulation of production from Korean hydrates and the support of the DOE field test, accounting for both flow and geomechanical issues
Planned Date: 8/31/2012
Actual Completion Date: December 2012
Verification Method: Progress Report documenting submission / publication of papers on the defined subject areas

Task 4 -- Assessment of Resource Recoverability From Natural Hydrate Deposits
Milestone: Submission of two new papers; 1) on coupled flow-geomechanical behavior of hydrate-bearing media, and 2) on production using horizontal wells
Planned Date: 11/31/2012
Actual Completion Date: November 2012
Verification Method: Progress Report Documenting submission / publication of papers on the identified subjects

V. SCHEDULE STATUS

There are no changes in the planned schedule (as set forth in the Project Management Plan submitted with the FWP) vis-a-vis the actual schedule. The project is ahead of schedule in terms of milestones and deliverables.

VI. COST STATUS

Project spending is slightly ahead of schedule, but this is expected given the accelerated pace of work and the progress made thus far. Relevant cost information is shown on the next page.

Cost Plan/Status

		Year 1 Start: End			
Baseline Reporting Quarter		Q2	Q3	Q4	Q1
Baseline Cost Plan					
Federal Share	Task 1	1029	0	0	0
	Task 2	4744.5	4744.5	4744.5	4743
	Task 3	9999.75	9999.75	9999.75	9997
	Task 4	10000.25	10000	10000	9998
Non-Federal Share		0	0	0	0
Total Planned Cost (Federal and Non-Federal)		25773.5	24744.25	24744.25	24738
Cumulative Baseline Cost		$ 25,773.50	$ 50,517.75	$ 75,262.00	$ 100,000.00
Actual Incurred Costs					
Federal Share	Task 1	1000	0	0	
	Task 2	2400	4800	7000	
	Task 3	1000	9700	19485	
	Task 4	1001	10086	27500	
Non-Federal Share		0	0	0	
Non-Federal)		5401	24586	53985	0
Cumulative Incurred Costs		$ 5,401.00	$ 29,987.00	$ 83,972.00	$ 83,972.00
Variance					
Federal Share	Task 1	-0.028182702	0	0	0
	Task 2	-0.494151122	0.011697755	0.47539256	0
	Task 3	-0.8999975	-0.029975749	0.948548714	0
	Task 4	-0.899902502	0.0086	1.75	0
Non-Federal Share		0	0	0	0
Federal)		-2.322233826	-0.009677994	3.173941274	0
Cumulative Variance		-2.322233826	-2.33191182	0.842029453	0.842029453

VII. CONCLUSIONS

The progress made in this project is significant, and ahead of schedule. Thus, (1) new versions of both the serial and the parallel T+H codes (V1.25, with improved thermodynamics and thermophysical properties, and new control and output capabilities) were released to the public, (2) entirely new versions (V2.0) with new input and output data structures were developed and will be ready for release in mid-2013, along with a paper (currently in preparation) on the subject, (3) two collaborative studies (with KIGAM, Korea) on the evaluation of the production potential of Korean marine hydrates in the Ulleung Basin and of the corresponding geomechanical system behavior were completed, and two related paper are either published or in review, (4) a two-way, fully-coupled flow-thermal-geomechanical simulator (involving TOUGH+HYDRATE and ROCMECH) was developed and tested, (5) two papers on coupled flow-thermal-geomechanical processes in producing hydrate systems were published, (6) the largest study ever conducted of marine hydrate deposit evaluation (requiring solution of 10M equations on clusters and supercomputers) was concluded, a conference paper on the subject was completed, and a paper on the same subject is in review for publication in a scientific journal, (7) studies on gas recoverability from the PBU-L106 site in Alaska were completed and a paper on the subject is in review, and (8) a chapter on the status of gas production from hydrates (in which the PI of the project is the first author) was published by Springer in the book "*Advanced Biofuels and Bioproducts*".

The successes in this project are important in the technology development of gas production from hydrates because (a) they provide the numerical tools for the quantitative analysis and evaluation of gas production and its geomechanical impact, and (b) through the numerical studies conducted within the project, they develop the data and insights that are necessary for the determination of the key factors affecting the exploitation of hydrate accumulations in geological media and the design of field tests and, eventually, production operations.

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