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Final Project Report

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

Project Period (April 1, 2012 to September 30, 2018)

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

ESD12-010

Final Project Report

Principal Investigators: George Moridis, Matthew Reagan

GOAL OF THIS REPORT

The intent of the report is to highlight and summarize previously reported or published results generated during the seven-year term of the project, and to report on the completion of the proposed tasks. Please see the referenced papers for additional information at a higher level of detail.

PROJECT SUMMARY

Here we describe the project tasks across multiple Budget Periods (BPs), with a description of the work performed and the resulting deliverables.

Task 1: Project Management Plan

The Recipient shall work 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). In the event of major modifications to the FWP an update of the PMP shall be submitted to the NETL project manager within 30 days. The NETL Project Manager shall have 20 calendar days from receipt of the revised PMP to review and provide comments to the Recipient. Within 15 calendar days after receipt of the NETL Project Manager's comments, the Recipient shall submit a final revised PMP to the NETL Project Manager for final review and approval.

Subtask 1.1. Budget Period (BP) #1: January 2012 – December 2012

Task Duration: 1/1/2012 to 2/1/2012

Subtask 1.2. Budget Period (BP) #2: July 2013 – June 2014

Task Duration: 7/1/2013 to 8/1/2013

Subtask 1.3. Budget Period (BP) #3: August 2014 – July 2015

Task Duration: 8/1/2014 to 8/31/2015

Subtask 1.4. Budget Period (BP) #4: August 2015 – July 2016

Task Duration: 8/1/2015 to 7/31/2016

Subtask 1.5. Budget Period (BP) #5: March 2016 – May 2017

Task Duration: 3/1/2016 to 4/30/2016

Subtask 1.6. Budget Period (BP) #6: April 2017 – September 2018

Task Duration: 4/1/2017 to 9/30/2018

Accomplishments and deliverables:

The LBNL team worked together with the NETL project manager, and completed the maintenance and update of the project management plan (PMP) of BP#1 within the specified time frame and budget. The PMP and associated milestone list was updated each Budget Period under consultation with the Project Manager.

Task 2: Code Maintenance, Updates, and Support

The forward codes (i.e., codes for predictive studies of system behavior) developed within the framework of the hydrate project are the following:

- (a) The serial TOUGH+HYDRATE code (hereafter referred to as the T+H code) for the simulation of the thermodynamic states, fluid flow and heat transport in geologic media on serial computational platforms.
- (b) The parallel version of the TOUGH+HYDRATE code (hereafter referred to as the pT+H code) for use across a variety of multiprocessor computational platforms, i.e., from multi-processor desktop computers to clusters and massively parallel supercomputers.
- (c) The coupled T+H+M codes, which allows the concurrent study of geomechanical processes, fluid and heat flow and thermodynamic states in a hydrate system undergoing changes, the interaction between hydraulic (porosity and permeability) and geomechanical (stresses and strains) parameters, and examination of geomechanical stability.

In order to maintain the state-of-the-art status of the codes and their ability to accurately describe phenomena and processes in hydrate-bearing geologic media, recent developments (originating from fundamental research, laboratory studies, or data from field tests) need to be incorporated into the codes as they become available, and the corresponding manuals have to be updated. Potential errors in the codes and in the manuals necessitate correction as information from the users of the codes reaches the LBNL code development team. Additionally, suggestions from the user community about new features and overall improvements merit attention. This subtask addressed these issues. In addition, it developed geomechanical codes more powerful and more flexible than the FLAC3D commercial simulator used in earlier work.

We incorporated code corrections and updates as listed above, however, most of the effort in this task was about improving the performance (with an emphasis on execution speed) in items (b) and (c), because these are the most commonly used and computationally intensive codes. Because of the tremendous computational requirements that the numerical description of hydrate behavior in geologic media, the serial T+H code in item (a) is now used as a reference code (into which all additions and modifications are implemented for testing and validation), and its application is limited to the solution of small problems by users that do not have access to multi-processor

computational platforms. The pT+H code has become the main workhorse for large-scale production simulation.

The proliferation of multi-core desktop computer architecture has resulted in the use of pT+H on multi-processor platforms ranging from PCs to workstations to clusters to supercomputers. Because of the near-linear improvement in the code performance as a function of the number of processors, execution times can be reduced by orders of magnitude, but they are still very large in absolute terms (often requiring several days of continuous execution to complete a single run). Thus, significant effort was invested in improving pT+H performance by addressing issues unrelated to the number of processors: (a) the domain decomposition technique (currently accomplished by the MPI package), and (b) the use of faster, more efficient parallel solvers.

Subtask 2.1. Budget Period (BP) #1: January 2012 – December 2012

Task Duration: 1/1/2012 to 12/31/2012

Given the budget available for this task in BP #1, after an evaluation of the various options, activities focused on three major areas: (a) the development of T+H, and (b) corrections and improvements in both the standard versions of T+H (serial) and pT+H (parallel) codes. Activity (a) was co-supported by other projects, so the significant leveraging provided the impetus for this needed development. Activity (b) led to improved versions of the codes with new boundary options, enhanced output capabilities, and a much more powerful pT+H version that allowed simulations of over 9M equations using over 2,000 processors on the fastest supercomputer at the National Energy Research Supercomputer Center (NERSC) of LBNL.

Accomplishments and deliverables

- (1) An improved serial T+H code, with the corresponding updated User's manual.
- (2) An improved/enhanced parallel pT+H code that could run on the biggest clusters and supercomputers. This code became the standard tool for the very large simulations performed in Budget Periods 1, 3, 4, 5, and 6.

Subtask 2.2. Budget Period (BP) #2: July 2013 – June 2014

Task Duration: 7/1/2013 to 6/30/2014

Activities on code maintenance and update focused on the TOUGH+HYDRATE “universal” code (uT+H), i.e., a version of the code that can be run without any modification on either serial or any multi-processor platform (thus eliminating the need for maintaining two very different versions of code). The intent was to eliminate the need to maintain and support two very different versions of the code, create improvements in execution speeds by using more than a single processor. Work on the uT+H of the hydrate code began in FY2012, and a prototype was developed. The budget (\$9K) did not allow the completion of the task to the full satisfaction of the research team, as there are lingering issues of portability and inconsistent solver performance.

Accomplishments and deliverables

A prototype of uT+H, and the updated User's Manual.

Subtask 2.3. Budget Period (BP) #3: August 2014 – July 2015

Task Duration: 8/1/2014 to 7/31/2015

The limited budget for the task did not allow the completion of this task in BP #2, as it turned out to be more challenging than initially expected. Thus, in BP #3, activities on code maintenance and update focused on attempted development of uT+H, a version of the code that could be run on any serial or multi-processor platform. This included work on (a) the portability of the code (operation on any single- or multi-processor platform), and (b) the resolution of issues stemming from the uneven/inconsistent solver performance after the incorporation of the PETSc package.

Other activities in this task included (c) the updating of the current version of the uT+H User's as well as the organization of a training course to teach the use of the current versions of T+H to national and international hydrate scientists. The training course has been announced, and 40+ scientists have already registered.

Accomplishments and deliverables

- (1) The uT+H code was upgraded with the introduction of new solvers and was tested against a suite of very large problems. The corresponding manuals have also been completed using a new format that is reflective of the modular structure of the code. However, performance on parallel machines was not sufficient to replace pT+H as the MPI-parallel base code.
- (2) A well-attended training course for T+H with participants from national and international organizations was conducted at LBNL in September 2014.

Subtask 2.4. Budget Period (BP) #4: August 2015 – July 2016

Task Duration: 8/1/2015 to 7/31/2016

In this BP we introduced updated thermodynamics based on the most recent advances in hydrate science and made corrections and improvements based on feedback from the various users of the codes from all over the world.

The recently developed T+M code [Kim and Moridis, 2014] is used to evaluate the coupled flow-thermal and geomechanical behavior of hydrate systems under production, and is composed of the T+H code (describing the hydrate behavior) and the ROCMECH code (describing the geomechanics of the system). We further integrated the ROCMECH geomechanical code into the T+H structure for seamless application to the solution of coupled flow-thermal-geomechanical processes.

Accomplishments and deliverables

- (1) The LBNL simulation team developed and released to the public updated versions of the serial and parallel versions of the T+H and T+M codes for simulations of hydrate-bearing geologic systems (coupled flow-thermal-geomechanical processes), and the corresponding User's Manuals.
- (2) In September 2015, LBNL staff conducted in Berkeley a training course on the use of the T+H/T+M codes, within the framework of the 2015 TOUGH Symposium.

Subtask 2.5. Budget Period (BP) #5: March 2016 – May 2017

Task Duration: 3/1/2016 to 12/31/2016

We updated the T+H code and T+M codes, which further couples the T+H code with the ROCMECH code for geomechanics. The update and code expansion included the full spectrum of

possibilities: improved thermodynamics, advanced matrix solution methods, additional output options, additional geomechanical failure criteria to describe pore collapse or fracture development, enhanced boundary conditions and/or initial conditions, etc. We expanded the current gridding capabilities through a reengineered MeshMaker that introduces heterogeneous 3D grids, including options to remove or add geometrically complex subdomains, plus adds the ability to generate flow meshes, geomechanical meshes, and visualization meshes with a single consistent toolkit. The new capabilities in visualization allow the true volume rendering of TOUGH+ meshes and simulation results at large scales (up to millions of elements in 3D). Such visualizations are were extensively in future tasks for this and other projects.

Accomplishments and Deliverables

- (1) Updated versions of the serial and parallel versions of the T+H and T+M codes for simulations of hydrate-bearing geologic systems (coupled flow-thermal-geomechanical processes), and the correspondingly modified user's manuals.
- (2) Development and release of the (a) MeshMaker V2.0 facility, a completely rewritten gridding code for the creation and visualization of meshes of complex geometries of heterogeneous systems, and (b) of the corresponding User's Manual. The new MeshMaker was documents in a conference paper and a report/user's manual.

Moridis, G.J. and N. Keen, MeshMaker V2.0S And V2.0P: New Grid Generators For Complex Heterogeneous Domains in TOUGH2/TOUGH+ Simulations, *Proc. TOUGH Symposium 2015*, Lawrence Berkeley National Laboratory, Berkeley, California, September 28-30, 2015.

Moridis, G.J., User's Manual of the MeshMaker V2.0 Code: A Mesh Generator for Domain Discretization in Simulations of the TOUGH+ and TOUGH2 Families of Codes, Report LBNL-1005134, Lawrence Berkeley National Laboratory, Berkeley, CA, 2016.

Moridis, G.J., "User's Manual for the HYDRATE v1.5 Option of TOUGH+ v1.5: A Code for the Simulation of System Behavior in Hydrate-Bearing Geologic Media," Lawrence Berkeley National Laboratory report LBNL-6869E, February 2016.

Subtask 2.6. Budget Period (BP) #6: April 2017 – September 2018

Task Duration: 4/1/2017 to 9/30/2018

In the final BP, we continued development of the new geomechanical codebase, where fully coupled geomechanical analysis of the latest set of hydrate reservoirs is now enabled by a *new* simulation framework. The previous generation of mechanical solvers employed to study this class of problems was based around a one-to-one coupling between the elements of the FEM mesh and the grid cells of the Integral Finite Difference Method (IFDM) grid with the option of only 3D Cartesian-element systems. Efficient solution of the flow component of the hydrate-bearing reservoirs requires size-gradated structured meshes, resulting in element with long/skinny aspect ratios. While radial axisymmetry (for the description of single-well problems) is treated in the IFDM formulation, the FEM formulation of the previous coupled simulator (T+H plus the ROCMECH geomechanical code) required a 3D-wedge-shaped domain, which introduced a geometric error on top of further ill-conditioning. As a result, solving the mechanical aspects of

the hydrate reservoir resulted in a linear system that was too ill-conditioned and would often not converge. Attempts to solve the mechanical system by increasing the computational power using MPI-parallel processing and the advanced PETSc solver also ran into convergence issues, with the additional burden of parallel load-balancing for the ill-conditioned matrices.

To address these issues, a new geomechanical framework, named Millstone, was developed and coupled with the T+H code. Two core changes to the code formulation required a complete rewrite: (1) a separate mesh can be used for the mechanical solution, and, (2) formulations for plane-strain and axisymmetry using 2D elements are included in addition to standard 3D Cartesian formulations. By removing the one-to-one element to grid cell requirement, two separate meshes can be generated that are high-quality for each of their respective numerical methods, avoiding the long-and-skinny elements that create conditioning problems. The axisymmetric formulation for the description of the performance of single-well problems (a common occurrence in the study of gas production from hydrates) removes the geometric error introduced by the wedge-like representation. This yields significant speed improvements by reducing in the number of the unknowns by one third, in addition to the associated improvement in the stability, conditioning and accuracy of the solution. These improvements (made possible by the use of the two different grids) are also observed in the simulations of Cartesian 3D systems. However, the additional flexibility comes at the computational cost of projection and interpolation of data between meshes.

The new coupled simulator was used in mission-critical studies analyzing the production potential of offshore hydrate deposits involved in international collaborations of the US Department of Energy, and has yielded very interesting (and never-reported-before) results that may have dramatic implications for the production behavior of such systems. The main problem facing the new coupled code is the slowness of the execution speed: it often requires 2-3 weeks of continuous execution to cover less than 6 months of production from a modestly-sized problem (<60,000 elements), with the Millstone solutions taking longer than the T+H solutions. The need for drastically increasing the execution speed cannot be overemphasized.

An additional feature of Millstone is the ability to perform 1-way coupling between T+H and geomechanics using standard T+ output files. This allows the analysis of very large problems where fully coupled simulation is impractical (due to time and resource constraints), and also allows re-analysis of previously generated outputs. Thus we can leverage previous production simulation work and add geomechanical analysis without re-running the flow simulations.

Debugging of the TOUGH+HYDRATE/Millstone combination continued through the end of the project. Inspired by discussions in the IGHCCS2 meetings, we developed a new set of test problems for T+H. These test problems are designed to auto-run after code compilation, automatically testing whether code upgrades or modifications affect the validity of the code and results. In addition, we performed additional convergence testing, to establish a formal baseline for mesh discretization decisions. The results were reported to the IGHCCS2 group to inform other teams' code development and testing strategies.

Deliverables

(1) Updated versions of the serial and parallel versions of the T+H and T+M/Millstone codes for simulations of hydrate-bearing geologic systems (coupled flow-thermal-geomechanical processes), and the updated User's Manuals.

(2) Submission and revision of a three-part series of publication documenting the new codebase:

Moridis, G.J., Queiruga, A.F., Reagan, M.T., “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,” in revision for *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,” in revision for *Transport in Porous Media*.

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,” in revision for *Transport in Porous Media*.

(3) The new coupled codebase was used for simulations in an additional paper:

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-Godawari Basin During a Single and Multi-Well Production,” *J. Marine and Petroleum Geology*, in press.

(4) An additional conference paper resulted from this work:

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, 25-30 Jun 2017.

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

Subtask 3.1: Design support for a DOE-led field test

This task encompassed LBNL’s participation in a DOE-supported field test under consideration, and involved the continuation of studies that have been in progress for a number of years. The test scenarios that include long-term gas production from a permafrost-associated hydrate deposit on the North Slope, Alaska. LBNL’s support involves evaluation of the production potential under various well designs and operation/production regimes, and provides information needed for the design of the field study.

Work in this subtask also included an analysis of the geomechanical system response during long-term field tests that would be conducted at the two sites. Studies that began in FY2009 have already indicated limited geomechanical response of the hydrate-bearing media and its overburden because of the stiffness of the permafrost at the two potential test sites. This subtask completed investigations on the following subjects:

(1) The evolution of stresses and strain during the dissociation-fueled production, their impact on the reservoir properties (porosity and permeability), and the cumulative effect on production.

(2) The possibility of formation failure, yielding, and shear dilation, and their potential impact on production. Note that localized formation failure may result in fracture development and, consequently, on the enhancement of permeability and production rate.

(3) The evolution of the near-well geomechanical regime, and the possibility of wellbore and formation failure in that region. Such failures can have a critical effect on production, ranging from increasing sand production (a mild problem) to catastrophic well instability or collapse.

Subtask 3.1.1. Budget Period (BP) #1: January 2012 – December 2012

Task Duration: 1/1/2012 to 9/30/2012

Activities in BP #1 focused on two permafrost-associated hydrate deposits on the North Slope, Alaska: the deposit at the site of the PBU-L106 well, and the colder hydrate deposit of the D-Unit at the Mount Elbert site. Work on this task focused on the comparative analysis of the production potential from the two sites using both vertical and horizontal wells, and an evaluation of the geomechanical system response under gas production (determined to not pose stability problems to nearby structures or to affect the integrity of the well).

Accomplishments and deliverables

(1) Publication of the following journal and conference papers:

Kim, J., G.J. Moridis, D. Yang, and J. Rutqvist, Numerical Studies on Coupled Flow and Geomechanics in Hydrate Deposits, SPE Journal, 17(2), 485-501, 2012 (doi: 10.2118/141304-PA)

Kim J., and G.J. Moridis, Modeling and Numerical Simulation for Coupled Flow and Geomechanics in Composite Gas Hydrate Deposits, 46th U.S. Rock Mechanics/Geomechanics Symposium, 24-27 June 2012, Chicago, Illinois.

Kim, J., G.J. Moridis, and J. Rutqvist, “Coupled Flow and Geomechanical Analysis for Gas Production in the Prudhoe Bay Unit L-106 Well Unit C Gas Hydrate Deposit in Alaska, Journal of Petroleum Science and Engineering,” 92-93, 143-157, 2012.

(2) Data and information that can be used to design the field test: these are included in the published papers, in papers under preparation, and in the reports submitted to the DOE management.

Subtask 3.1.2. Budget Period (BP) #2: July 2013 – June 2014

Task Duration: 7/1/2013 to 6/30/2014

Work in this subtask was to include studies focused on the planning of future potential production field tests at locations not previously considered or investigation of issues that have not been covered in earlier studies of PBU L-Pad and Mt. Elbert sites, with specific site(s) or issues to be investigated defined through mutual agreement between LBNL and NETL. In BP#2, effort went toward reanalyses of PBU L-Pad data and extension of previous simulations over longer time periods, including shut-in of the reservoir after production.

Accomplishments and Deliverables

The work resulted in the following presentation:

“Long-Term Fate of Hydrate-Bearing Reservoirs During and After Production,” (poster)
B21G-0510, AGU Fall Meeting 2016, San Francisco, CA, 12-16 Dec 2016.

Subtask 3.1.3. Budget Period (BP) #3: August 2014 – July 2015

Task Duration: 10/1/2014 to 7/31/2015

Work in this subtask focused only on revision of the papers from earlier Budget Periods, due to a very limited task budget.

Accomplishments and Deliverables

One hydrate-related paper was finalized:

Reagan, M.T., Moridis, G.J., Freeman, C.M., Pan, L., Boyle, K.L., Keen, N., Husebo, J.A.,
“Field-Scale Simulation of Production from Oceanic Gas Hydrate Deposits,” *Transport in Porous Media*, 108(1), 151-169, 2015.

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). Such studies included (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). The scope of this task was defined each Budget Period by consultations with US DOE officials involved in the joint project, as well as with Korean scientists.

Subtask 3.2.1. Budget Period (BP) #1: January 2012 – December 2012

Task Duration: 1/1/2012 to 12/31/2012

Activities in BP #1 focused on the investigation of the gas production potential of the hydrate deposit at the UBGH2-6 site of the Ulleung Basin of the Korean East Sea. Using two sets of flow and geomechanical properties of the various formations at the site (obtained from direct measurements or from analogs), two sets of analyses were conducted to estimate gas production and the corresponding geomechanical behavior (a serious concern, given the softness of the sediments at the site).

Accomplishments and Deliverables

The following paper:

Moridis, G.J., Kim, J., Reagan, M.T., Kim, S.J., “Feasibility of Gas Production from a Gas Hydrate Accumulation at the UBGH2-6 Site of the Ulleung Basin in the Korean East Sea,” *J. Petro. Sci. Eng.*, doi: 10.1016/j.cageo.2013.04.001, 2013.

Subtask 3.2.2. Budget Period (BP) #2: July 2013 – June 2014

Effort/Cost: 1.75 man-months/\$70K

Task Duration: 10/1/2013 to 5/31/2014

In the BP #2 component of 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). The main component of this study was support for the development of a design for a short-term (less than 30 days long) field test planned for 2014 in the Ulleung Basin. Additional work in this subtask included the production analysis activities described in the task description component of this section (see above), and investigated the long-term production and geomechanical behavior of the system under production at the site of the field test. Note that laboratory studies in Korea on hydrate-bearing cores from the Ulleung Basin have indicated very different geomechanical properties than the earlier ones provided to LBNL for a preliminary analysis of potential subsidence during production, so the entire issue of production analysis had to be revisited and re-evaluated using the updated parameters.

Accomplishments and Deliverables

(1) A design package on the revised evaluation of production from Korean hydrates, accounting for both flow and geomechanical issues, was delivered to KIGAM in March 2013.

(2) The conference paper:

Moridis, G.J., Reagan, M.T., Kim, J., Kim, S.-J. “System Response During Short- and Long-Term Gas Production from a Gas Hydrate Deposit at the Site of a Planned Field Test in the Ulleung Basin of the Korean East Sea,” OTC 25384, *Proc. 2014 Offshore Technology Conference*, Houston, TX, 5-8 May 2014.

was presented to a special session on hydrates during the 2014 Offshore Technology Conference.

Subtask 3.2.3. Budget Period (BP) #3: August 2014 – July 2015

Task Duration: 10/1/2014 to 2/28/2015

In the BP #3 component of this subtask, LBNL staff developed statistical models of the heterogeneous distributions of the various properties and conditions of the HBS involved in the studies. Using the geological models with the heterogeneous property distributions, the study evaluated by means of numerical simulation the overall system performance during the short-term (14-day long) test of depressurization-induced dissociation for gas production from a hydrate deposit at a site in the Ulleung Basin selected by KIGAM. The study covered the evolution of production during this period, as well as the corresponding geomechanical system response, covering the widest possible spectrum of system behavior.

Accomplishments and Deliverables

A design package on the revised evaluation of production from Korean hydrates, accounting for both flow and geomechanical issues was developed and delivered to KIGAM by February 28, 2015. Large 3D simulations of very heterogeneous realizations of the hydrate deposits (involving over 500K elements and over 2M equations) were conducted on supercomputers to predict the production potential of this deposit and assess its geomechanical response, with the intent of answering the question whether heterogeneous hydrate saturations and flow properties could lead

to well instability (e.g., tilting). The studies included considerations of heterogeneity in hydrate saturation, intrinsic permeability, porosity and geomechanical properties. This was a very demanding and time-consuming process, and the available budget was insufficient to cover the time needed to produce a publication within BP#3. Thus, a large amount of material was collected, and a publication was later prepared in the next BP (#4).

Subtask 3.2.4. Budget Period (BP) #4: August 2015 – July 2016

Task Duration: 10/1/2015 to 3/31/2016

In the BP #4 component of this subtask, LBNL staff concentrated on the analysis of the results collected in BP #3, the preparation of a manuscript based on the results of the study of heterogeneous Ulleung basin hydrate deposit, and the submission to a peer-reviewed scientific publication.

Accomplishments and Deliverables

The analysis of the data from several complex heterogeneous representations of the 3D domain in the Ulleung Basin continued, investigating the fully coupled flow, thermal, chemical and geomechanical behavior of the system. A paper on the response of the heterogeneous Ulleung basin hydrate deposit to production could not be completed in this Budget Period (BP) because of the massive amounts of data it involved.

Subtask 3.2.5. Budget Period (BP) #5: March 2016 – May 2017

Task Duration: 4/1/2016 to 5/31/2017

In the BP #5 component of this subtask, LBNL staff developed a new joint US-Korea collaboration on gas production from Korean offshore deposits, as determined at a meeting held in Denver, CO in April 2016. Such collaborations will include LBNL effort to perform large-scale 3D flow simulations of the evolution of production from promising Ulleung Basin reservoirs, and to assess the geomechanical responses. In this budget period, we completed the analysis of the proposed field test, performed additional sensitivity studies, and began the preparation of a paper described the results.

Accomplishments and Deliverables

The analysis of the data from several complex heterogeneous representations of the 3D domain in the Ulleung Basin was completed, using data from BPs #3 and #4, investigating the fully coupled flow, thermal, chemical and geomechanical behavior of the system. A paper on the proposed production test was later completed, submitted, revised, and published in BP #6:

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 in the Ulleung Basin of the Korean East Sea,” *J. Pet. Sci. Eng.*, *in press*.

Subtask 3.3: Analysis of the results of the Iñik Sikumi field test, North Slope, Alaska

Budget Period (BP) #1: July 2012 – December 2012

Task Duration: n/a

Budget Period (BP) #2: July 2013 – June 2014

Task Duration: 9/1/2013 to 4/30/2014

Task Description

This task involved an analysis of the results of the Ignik Sikumi field test of gas production from hydrates associated with the Alaskan permafrost. More specifically, work in this subtask did not involve an analysis of the earlier part of the test (which involved N₂+CO₂ injection), but focused exclusively on the later phase of the test, which entailed long-term depressurization-induced gas production. This test was conducted in 2012 in collaboration with ConocoPhillips, and resulted in gas production rates that are higher, by an order of magnitude, than flow rates in all earlier field tests (e.g., Mallik tests in 2002, 2007 and 2008).

Work in this subtask included interactions with other organizations (DOE, National Laboratories, USGS, ConocoPhillips) involved in the design and execution of the field tests, as well as in the analysis of the production results and observations.

Accomplishments and Deliverables

The simulations of the late production were completed, but despite significant effort, the LBNL team was unable to obtain a history match that they can consider satisfactory. These history-matching difficulties are attributed to the effects of CO₂ and N₂, which were injected initially into the hydrate formation, and which continued to appear in the production stream in non-trivial quantities even at later times of the production test. It is assumed that either (a) the CO₂ and N₂ had long-lingering effects, or (b) the assumed conditions at the time when these two gases had no further effect were significantly different (in terms of hydrate distribution, pressure and temperature) than the actual field conditions.

Budget Period (BP) #3: August 2014 – July 2015

Task Duration: 11/1/2014 to 5/31/2015

Task Description

This task attempted to complete the analysis of the results of the Ignik Sikumi field test of gas production from hydrates associated with the Alaskan permafrost. Part of the effort also involved an attempt to determine the “initial” conditions for this late-term study, i.e., the pressure, temperature and phase saturations at the time production is assumed to no longer be affected by the initial injection of CO₂ and N₂. This was a challenging task due to the need to make assumptions about the values of the variables describing the “initial” conditions, and also assumptions about the spatial distributions of critical variables such as the hydrate saturation.

Accomplishments and Deliverables

We performed an initial analysis of the results of the Ignik Sikumi study. Difficulty in the analysis and convincing explanation of the results from the numerical study (i.e., behavior distinctly different from earlier studies involving pure CH₄ system produced by depressurization or thermal stimulation) and insufficient resources for a more in-depth analysis have not allowed the submission of a manuscript for publication in a peer-reviewed journal. A paper describing the fast parametric relationships used in the development of the mixed CH₄-CO₂ simulator was submitted to *Computers and Geosciences*.

Budget Period (BP) #4: August 2015 – July 2016

Task Duration: 5/1/2015 to 7/31/2015

Task Description

The small budget available to this task was used to finalize a manuscript and to submit it for publication to a peer-reviewed journal, where it was published in BP#5.

Deliverable

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.

Subtask 3.4: Analysis of the results of the Nankai Trough field test

Although included in the Statement of Project Objectives for several budget periods, this task was never funded.

Subtask 3.5: Preliminary Evaluation of the Production Potential of Hydrates Deposits Offshore India

This task involved a preliminary investigation into the production potential and geomechanical behavior of recently discovered offshore gas hydrate deposits in the Bay of Bengal, India, and is part of a wider U.S.-India collaboration on the subject. This ongoing investigation will involve coupled flow-geomechanical simulations using the coupled T+H (hydrate system behavior - serial and parallel) and geomechanical codes.

Budget Period (BP) #4: August 2015 – July 2016

Task Duration: 12/1/2015 - 2/29/2016

The work under this task developed the input models and performed initial simulation runs in collaboration with the NETL in-house research staff. Within budget *and time* limitations, these simulations determined the production potential of representative deposits in the Basin, and also examine (1) the evolution of stresses and strain during the dissociation-fueled production, (2) the resultant impact on cumulative production, (3) the possibility of formation failure, yielding, or shear dilation, or wellbore failure.

Note that this numerical simulation effort involved scoping calculations to better define the envelope of the expected system behavior by using parameters derived from analogs and spanning the entire spectrum of possible magnitude. Another, far more focused, investigation (requiring an additional budget) addressing the site-specific conditions and properties (flow, thermal and geomechanical) is performed in later Budget Periods.

Accomplishments and Deliverables

The preliminary study was completed in a very short period of time, and the results on the system performance during short- and long-term production regimes were presented during a 3-day meeting in New Delhi, India. The study identified and investigated the impact of all important reservoir parameters and production method specifics, and defined the limits of the envelope of

production potential of the reservoir, of the consequent geomechanical behavior and of the effects on production. The preliminary report was completed at the end of February 2016.

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

Budget Period (BP) #5: March 2016 – May 2017

Task Duration: 3/1/2016 - 5/31/2017

This task was part of a wider U.S.-India collaboration on the development of hydrate deposits, and involved a detailed investigation (in partnership with scientists at NETL) into the production potential and the corresponding geomechanical behavior of recently discovered offshore gas hydrate deposits. This numerical investigation involved the following:

- (1) A complete analysis of two potential sites currently under consideration: Site 9 (primary) and Site 16 (secondary), accounting for all coupled flow, thermal, thermodynamic, and geomechanical processes using the latest updated versions of T+H, pT+H, T+M, and MeshMaker v2.0 to accomplish the task.
- (2) Two different production regimes: A long-term field test of production (lasting 18 months) involving a single vertical well operating in the entire hydrate deposit, and a realistic, commercial-type long-term production regime lasting 10-30 years (or until the exhaustion of the resource), involving multiple wells configured on a regular pattern that covers the entire footprint of the reservoir.
- (3) Two different types of well operation/production: production at a constant bottom-hole pressure, and production at a constant or time-variable rate.
- (4) Thorough sensitivity analyses to all possible parameters and conditions that can significantly affect the production of fluids and the geomechanical behavior of the system. The preliminary analysis in Task 3.5 already provided strong indications of the variables and conditions to be considered: (a) the properties of the media in all the layers/strata in the system from the ocean floor to deep into the underburden beneath the base of the hydrates; (b) the initial distribution of the various phases (aqueous and hydrate), and their spatial distributions; (c) the method of production and the corresponding parameters (the level of the bottom-hole pressure, and the constant or time-variable well production rate); and (d) the specifics of well construction (the length and location of the perforated interval).
- (5) A review, comparison, and evaluation of significant flows and displacements. Thus, inflows into the hydrate system from the overburden and underburden (i.e. permeable boundaries), including the extreme case of water flooding from the seafloor or the deep boundary of the system, were monitored, as well as flows from each of the hydrate layers. Displacements (subsidence or expansion/rise) at key locations and interfaces were captured via coupled geomechanical modeling and monitored in an effort to determine if they exceed the limits of generally accepted norms of safe well operation.

The size and the scope of the studies listed above required extensive simulations on supercomputers using the pT+H and T+M codes. Note that the inputs to this detailed study have been provided through parallel studies conducted by the various partners of the India project: the US Department of Energy and collaborating national laboratories, the US Geological Survey, the Japanese participants (JOGMEG, AIST, etc.), and the various Indian organizations leading the project (ONGC, DGH, MONG, etc.).

Accomplishments and Deliverables

The simulations in this budget period completed the initial analysis, finishing very long runs (to 540 days), studying additional parametric cases and well designs, and using the reference case to study the effects of well shut-in after production. The deliverables included a report (and a corresponding presentation) with a discussion of important reservoir parameters and the limits of the envelope of production potential of the reservoir, of the consequent geomechanical behavior and of the effects on production. A meeting at ICGH 9 in June 2017 set in motion a journal special issue to consolidate publications.

Budget Period (BP) #6: April 2017 – July 2018

Task Duration: 4/1/2017 - 7/31/2018

Work continued in this budget period and involved a detailed investigation (in partnership with scientists at NETL) of the production potential and the corresponding geomechanical behavior of NGHP-02 Site 9. The work involved the following:

- (1) A re-analysis of the Site 9 deposit currently under consideration for a long-term field test, using the most recent data provided by AIST and USGS. As in the previous BP, the analysis accounted for all coupled flow, thermal, thermodynamic, chemical, and geomechanical processes relevant to production. We used the latest versions of T+H, pT+H, T+M (including the new Millstone code), and MeshMaker v2.0 to accomplish the task.
- (2) The simulations re-analyzed the long-term field test (lasting 18 months) investigated in the last BP involving a single vertical well operating in the entire hydrate deposit. We then investigated a commercial-type long-term production regime (lasting until the exhaustion of the resource), involving multiple wells configured on a regular pattern that would cover the entire footprint of the reservoir.
- (3) We focused on production at a constant bottom-hole pressure, based on the results of the preliminary studies.
- (4) We performed sensitivity analyses to all relevant parameters and conditions (as determined in the preliminary studies) that can significantly affect the production of fluids and the geomechanical behavior of the system.
- (5) We sought to quantify the magnitude of water inflows into the hydrate system from the overburden and underburden (i.e. permeable boundaries or permeable release pathways), the seafloor, the deep boundary of the system, and from each of the permeable interlayers.
- (6) We captured displacements at key locations and interfaces via coupled geomechanical modeling to determine if they could exceed the limits of generally accepted norms of safe well operation.
- (7) In addition to the re-assessment of production potential, the new analysis was compared to previous simulations to further understand the importance of key reservoir parameters and reservoir configurations on production potential.
- (8) The LBNL team also contributed to wider collaborations within the hydrate program of the US Department of Energy through participation in meetings/discussions with the national and international team members (NETL, USGS, AIST, ONGC, etc.), including the effort to evaluate new field data, understand interim results, and incorporate new knowledge into the choice/design of simulation scenarios.

The size and the scope of the simulations again required extensive use of supercomputers to run the pT+H and T+M codes. As in previous Budget Periods, the inputs to this detailed study will be provided by parallel studies conducted by the various partners of the India project: the US Department of Energy and collaborating national laboratories, the US Geological Survey, the Japanese participants (AIST, etc.), and the various Indian organizations leading the project (ONGC, DGH, MONG, etc.).

Accomplishments and Deliverables

- (1) A report, and a corresponding presentation given in March 2018, with a determination of important reservoir parameters and the limits of the envelope of production potential of the recharacterized reservoir, the consequent geomechanical behavior, and the effects on production.
- (2) Three publications—two in a special issue devoted to the NGHP-02, and one using earlier results (previous BP) to demonstrate the latest version of the T+H and T+M codes:
 1. 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*.
 2. 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-Godawari Basin During a Single and Multi-Well Production,” *J. Marine and Petroleum Geology*, *in press*.
 3. Boswell, R., Myshakin, E., Moridis, G.J., Konno, Y., Collett, T.S., Reagan, M.T., Ajayi, T., Seol, Y., “Scientific Results of Numerical Simulation of Gas Hydrate Reservoirs in the Offshore of India: National Gas Hydrate Program Expedition-02,” *J. Marine and Petroleum Geology*, *in press*. doi: 10.1016/marpetgeo.2018.09.026, 2018.

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

Budget Period (BP) #6: April 2017 – July 2018

Task Duration: 10/1/2017 - 7/31/2018

This task included the activities of the LBNL team in the course of participation in the 2nd Hydrate Code Comparison Study. This is a study supported by the U.S. Department of Energy (DOE) and aims to evaluate the efficacy, accuracy and overall code performance of several participating codes involving the coupled flow, thermal and geomechanical processes associated with the behavior of hydrates (dissociating or forming) in geologic media.

The study is investigating the code performance in several problems of increasing complexity. These problems, as well as the evaluation criteria, have been decided by consensus, following the successful process of the 1st code comparison study. The study began with very basic problems for which analytical and/or semi-analytical solutions may be available, in an effort to confirm the validity of the basic processes in the codes, and progressed to the simulation of a field test and of core-scale studies. The entire process will be valuable in providing confidence in

the ability of the codes to accurately represent the coupled processes involved in hydrate accumulations under production.

T+H includes several options for the geomechanical component of the coupled code. The first is the oldest geomechanical option of the T+H code and involves the FLAC3D commercial simulator. Although this simulator is one of the two global standards for geomechanical studies it has several shortcomings: because of commercial intellectual property restrictions, communication between the flow/thermal part of T+H and FLAC3D is accomplished by writing and reading external files. Additionally, FLAC3D does not parallelize well, leading to long execution times. Finally, FLAC3D lacks an axisymmetric option, making the study of cylindrical (single well) systems cumbersome and often inaccurate. The 2nd (more recent) option is the ROCMECH, which was developed at LBNL (based on an older geomechanical code) to address the shortcomings of FLAC3D. Because memory is shared between the flow/thermal and the geomechanical component, this is a much faster code and has the additional advantage of having been parallelized. The most advanced option is the Millstone code, also developed at LBNL, which addresses the shortcomings of all previous codes.

Accomplishments and Deliverables

In this Budget Period, LBNL led the development of Problem #3 (axisymmetric flow and geomechanics), including the development of a analytical expression to ground-truth the coupled codes. LBNL also submitted results for Problems #1 and #2.

Task 4: Assessment of Resource Recoverability From Natural Hydrate Deposits

Differences in geologic and geochemical environments can have significant impact on the recoverability of methane hydrate, and dictate the production strategy and practice. The production behavior of hydrate-bearing media using vertical wells has been thoroughly researched by the LBNL team in previous years for earlier FWP (FY2006 through FY2009). Thus, vertical well designs and configurations that enable long-term production from hydrates have been proposed, and the corresponding hydrate system response (in terms of the evolution of the spatial distributions of pressure, temperature and phase saturations) has been investigated to a considerable degree in earlier FWPs in the NETL Hydrates program. Additionally, extensive analysis has provided a good indication of the sensitivity of gas production to a variety of properties (e.g., intrinsic permeability, porosity), conditions (e.g., initial and boundary conditions of pressure, temperature, and phase saturations), dissociation methods (depressurization, thermal stimulation, and inhibitors), production strategies (e.g., production interval location and length, well operations), etc.

Because a significant body of information has already been created on the subject of single vertical well performance and system behavior, the primary focus of the LBNL investigation on novel production methods is now on horizontal wells. Existing information on their performance indicates a significant advantage 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 investigation addresses the effect on production using horizontal and inclined wells, and the coupled flow-thermal-geomechanical behavior of hydrate-bearing media during the gas production process.

Subtask 4.1: Assessment of gas production from different well designs and of the corresponding geomechanical system response

Budget Period (BP) #1: January 2012 – December 2012

Task Duration: 1/1/2012 to 12/31/2012

Activities within this task focused on three major areas indicated through work in the previous FWP: (a) the evaluation of the performance of horizontal wells during production from oceanic deposits, (b) geomechanical system behavior during gas production from hydrate deposits, and (c) analysis of wellbore stability in hydrate accumulations.

Accomplishments and Deliverables

(1) Publication of the following conference papers and later related journal article:

Reagan, M.T., G.J. Moridis, K.L. Boyle, C.M. Freeman, L. Pan, N.D. Keen, and J. Husebo, *Massively Parallel Simulation of Production from Field-Scale Oceanic Gas Hydrate Deposits*, Proceedings, TOUGH Symposium 2012, 17-19 September 2012, Berkeley, CA.

Reagan, M.T., Moridis, G.J., Freeman, C.M., Keen, N., *Massively Parallel Simulation of Production from Oceanic Gas Hydrate Deposits*,” *Proc. International Petroleum Technology Conference*, Beijing, China, 26-28 March 2013.

Reagan, M.T., Moridis, G.J., Freeman, C.M., Pan, L., Boyle, K.L., Keen, N., Husebo, J.A., “*Field-Scale Simulation of Production from Oceanic Gas Hydrate Deposits*,” *Transport in Porous Media*, 108(1), 151-169, 2015.

(2) A new journal article and a book chapter on the coupled flow-geomechanical behavior of hydrate-bearing sediments:

Rutqvist, J. and G.J. Moridis, “*Coupled Multiphase Fluid Flow and Wellbore Stability Analysis Associated with Gas Production from Oceanic Hydrate-Bearing Sediments*,” *J. of Petroleum Science and Engineering*, 92-93, 65-81, 2012. (doi: 10.1016/j.petrol.2012.06.004)

Moridis, G.J., T.S. Collett, R. Boswell, S. Hancock, J. Rutqvist, C. Santamarina, T. Kneafsey, M.T. Reagan, M. Pooladi-Darvish, M. Kowalsky, E.D. Sloan, and C. Coh₂, “*Gas Hydrates as a Potential Energy Source: State of Knowledge and Challenges*,” in: *Advanced Biofuels and Bioproducts*, J.W. Lee (ed.), 977-1035, 2012, Springer, New York, Heidelberg, Dordrecht, London. (ISBN 978-1-4614-3347-7, doi: 10.1007/978-1-4614-3348-4)

(3) In addition, this work led to the following presentations:

“*Massively Parallel Simulation of Field-Scale Oceanic Gas Hydrate Deposits*,” AIChE Spring Meeting, Houston, TX, 1-5 April 2012.

“*Massively Parallel Simulation of Field-Scale Oceanic Gas Hydrate Deposits*,” 2012 TOUGH Symposium, Berkeley, CA, 17-19 September 2012.

“Field-Scale, Massively Parallel Simulation of Production from Oceanic Gas Hydrate Deposits,” OS34A-07, AGU Fall Meeting 2012, San Francisco, CA, 9-13 December 2012.

Subtask 4.2: Assessment of gas production from slanted wells

Budget Period (BP) #2: July 2013 – June 2014

Task Duration: 9/1/2013 to 4/30/2014

Effort/Cost: **(unfunded)**

Although this was an unfunded task, there was significant activity conducted by a graduate student as part of his thesis work toward a MSc degree, and then continued on a much larger scale by the project PI. This effort was at no cost to the project, as the MSc student was supported by his institution, and the involvement of the project PI was done during his own free time.

The simulations (3D, involving millions of elements and equations) in this study on the effectiveness of slanted wells in the production of gas from highly stratified hydrate deposits have been concluded, and the results were analyzed. Such stratified deposits are among the recent GOM discoveries, and slanted wells are an option that demands evaluation given the relative inefficiency of both vertical and horizontal wells.

Budget Period (BP) #3: August 2014 – July 2015

Task Duration: 1/1/2015 to 3/31/2015

Limited (free) time and the absence of support for this task in BP #2 did not allow analysis of the data, and publication of the findings. In this task we focused exclusively on the analysis and publication of the results of the studies on the performance of inclined wells that were completed in Subtask 4.2 in BP #2. However, careful analysis indicated a significant grid orientation and size effect. This resulted in a new set of simulations with finer grids, inclined coordinate systems and much larger (compared to the earlier studies) systems of equations, with measurably different results from the earlier-obtained ones (in BP #2). Additionally, the performance of such wells in the presence of significant heterogeneity was also investigated. The limited resources available to this task did not allow the thorough data analysis required, nor for manuscript preparation.

Accomplishments

A large number of simulations of the behavior/performance of slanted wells in the production of gas from (homogeneous and heterogeneous) hydrate deposits.

Budget Period (BP) #4: August 2015 – July 2016

Task Duration: 3/1/2016 to 4/30/2016

In this task we focused on the analysis and publication of the most promising results of the studies that were completed in BP #2 and #3, including additional simulation to clarify interesting cases, plus limited geomechanical analysis.

Deliverables

A conference paper on gas production using slanted wells in homogeneous/heterogeneous hydrate deposits, including an analysis of the corresponding geomechanical behavior and possible impacts of production on oceanic slope stability.

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. 2018 Offshore Technology Conference-Asia*, 20 March 2018.

The results were also highlighted in an invited presentation:

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

Subtask 4.3: Evaluation of the possibility of uncontrolled releases during hydrate dissociation

Budget Period (BP) #4: August 2015 –July 2016

Task Duration: 3/1/2016 to 7/31/2016

This task investigated the possibility (and the potential consequences) of an uncontrolled gas release during production from hydrates by depressurization. We investigate the possibility of the released gas escaping along permeable faults that intercept the hydrate beds after encountering a pressure gradient that overwhelms the depressurization induced by the production well. We also determined the fate of the released gas upon the cessation of the operations of hydrate dissociation (e.g., of producing wells that induce depressurization) both in the presence and absence of permeable features (such as fractures or faults) within the formation. In the latter study, we determined that (a) the cessation of production will be followed by additional hydrate dissociation that lingers for a substantial time, and that (b) despite the buoyancy of the released gas, its transport through the subsurface and the possibility of emergence at the seafloor is unlikely due to thermal and pressure gradients favored hydrate reformation in the overburden.

Accomplishments and Deliverables

The work resulted in the following presentation:

“Long-Term Fate of Hydrate-Bearing Reservoirs During and After Production,” (poster) B21G-0510, AGU Fall Meeting 2016, San Francisco, CA, 12-16 Dec 2016.

The work also resulted in the following conference paper:

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, 25-30 Jun 2017.

Subtask 4.4: Production Strategies to Avoid Dissociation Constraints During Production from Oceanic Hydrate Deposits

Budget Period (BP) #6: April 2017 – September 2018

Task Duration: 10/1/17 to 9/30/18

A very important observation from the studies conducted with the coupled codes discussed in Task 2.6 is that oceanic hydrates in deposits involving soft sediments (such as muds in interlayers and/or in the overburden) exhibit significant subsidence in the immediate vicinity of vertical wells. While this is challenging, there may be a more adverse effect: the creation of a cylindrical barrier of secondary hydrate at a considerable radius from the well (beyond 10 m)

that begins to emerge as early as 2 months from the onset of production. The permeability of this barrier is very small and ever-diminishing. Earlier published studies (which did not employ full coupling of flow, thermal and geomechanical processes) showed dissociation of the hydrate surface facing the well with simultaneous build-up of the outer surface (facing the interior of the deposit), giving the appearance of a moving boundary that eventually stagnated and disintegrated.

The new coupled code describes a far more complex (and more challenging) situation: the significant subsidence in the vicinity of the well drastically reduces porosity and, consequently, permeability in the space between the well and the barrier. The result of this regime is that dissociation of the surface of the secondary hydrate barrier facing the well ceases, making the hydrate barrier relatively impermeable. This, in turn, significantly affects the hydrate dissociation in, and gas production from, the interior of the hydrate deposit, both of which decline substantially (and may even stop). Note that this is the first time that such a behavior has been observed and reported.

Under this task we will numerically investigate the effectiveness of various strategies to alleviate the problem using the coupled simulator. Such strategies could involve, for example, continuous or periodic warm water injection (thus limiting pressure reduction and subsidence, and reducing the driving force for the creation of the barrier). We will also investigate the performance of horizontal and slanted wells. Such wells distribute the pressure drop over a significantly larger distance and volume. Additionally, the limited thickness of the hydrate layers may prevent the creation of such barriers, or their creation may have a limited effect on hydrate dissociation and gas production. At the same time, increased water production due to inflows from a less-than-impermeable overburden and/or underburden may complicate the situation. The possibility of using warm water injection in a parallel horizontal/slanted wells was also considered.

Accomplishments and Deliverables

The magnitude of the effort required for Subtask 3.6 in this budget period consumed the bulk of the resources allotted for the Budget Period, limiting the number of simulations that could be set-up and performed. Additional work on this subject has been proposed for a follow-on FWP. Analysis of the results described above was discussion in two presentations:

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

“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.

PROJECT BUDGET

Actual Cost for the full FWP	Funds available for the full FWP	Balance of unspent funds (September 2018)
\$1,249,350	\$1,250,004	\$654

PUBLICATIONS

Peer-reviewed papers:

1. Kim, J., G.J. Moridis, D. Yang, and J. Rutqvist, Numerical Studies on Coupled Flow and Geomechanics in Hydrate Deposits, SPE Journal, 17(2), 485-501, 2012 (doi: 10.2118/141304-PA)
2. Kim, J., G.J. Moridis, and J. Rutqvist, "Coupled Flow and Geomechanical Analysis for Gas Production in the Prudhoe Bay Unit L-106 Well Unit C Gas Hydrate Deposit in Alaska," *J. Petroleum Science and Engineering*, 92-93, 143-157, 2012.
3. Moridis, G.J., Kim, J., Reagan, M.T., Kim, S.J., "Feasibility of Gas Production from a Gas Hydrate Accumulation at the UBGH2-6 Site of the Ulleung Basin in the Korean East Sea," *J. Petro. Sci. Eng.*, doi: 10.1016/j.cageo.2013.04.001, 2013.
4. Kneafsey, T. and G.J. Moridis, "X-Ray Computed Tomography Examination Of NGHP Cores And Comparison Of Hydrate Dissociation In NGHP-01 And Mount Elbert Cores: Experimental Observations And Numerical Modeling," *Journal of Marine and Petroleum Geology*, 58, 526-539, 2014.
5. Reagan, M.T., Moridis, G.J., Freeman, C.M., Pan, L., Boyle, K.L., Keen, N., Husebo, J.A., "Field-Scale Simulation of Production from Oceanic Gas Hydrate Deposits," *Transport in Porous Media*, 108(1), 151-169, 2015.
6. 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.
7. 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 in the Ulleung Basin of the Korean East Sea," *J. Pet. Sci. Eng.*, *in press*.
8. Moridis, G.J., Queiruga, A.F., Reagan, M.T., "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," in revision for *Transport in Porous Media*.
9. 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," in revision for *Transport in Porous Media*.
10. 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," in revision for *Transport in Porous Media*.
11. 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-Godawari Basin During a Single and Multi-Well Production," *J. Marine and Petroleum Geology*, *in press*.
12. Boswell, R., Myshakin, E., Moridis, G.J., Konno, Y., Collett, T.S., Reagan, M.T., Ajayi, T.,

Seol, Y., “Scientific Results of Numerical Simulation of Gas Hydrate Reservoirs in the Offshore of India: National Gas Hydrate Program Expedition-02,” *J. Marine and Petroleum Geology*, *in press*. doi: 10.1016/marpetgeo.2018.09.026, 2018.

Conference Papers and Published Reports:

13. Kim J., and G.J. Moridis, Modeling and Numerical Simulation for Coupled Flow and Geomechanics in Composite Gas Hydrate Deposits, 46th U.S. Rock Mechanics/Geomechanics Symposium, 24-27 June 2012, Chicago, Illinois.
14. Reagan, M.T., Moridis, G.J., Boyle, K.L., Freeman, C.M., Pan, L., Keen, N., Husebo, J.A., “Massively Parallel Simulation of Field-Scale Oceanic Gas Hydrate Deposits,” *Proc. 2012 TOUGH Symposium*, Berkeley, CA, 17-19 September 2012.
15. Reagan, M.T., Moridis, G.J., Freeman, C.M., Keen, N., “Massively Parallel Simulation of Production from Oceanic Gas Hydrate Deposits,” *Proc. International Petroleum Technology Conference*, Beijing, China, 26-28 March 2013.
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17. Moridis, G.J. and N. Keen, MeshMaker V2.0S And V2.0P: New Grid Generators For Complex Heterogeneous Domains in TOUGH2/TOUGH+ Simulations, *Proc. TOUGH Symposium 2015*, Lawrence Berkeley National Laboratory, Berkeley, California, September 28-30, 2015.
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Presentations:

In addition to the task-specific conference presentations listed above, this project funded over 40 presentations to various groups and organizations in the US, China, Singapore, India, Germany, Japan, Korea, Saudi Arabia, Taiwan, Australia, New Zealand, and the work and exposure resulted in 30 additional invited presentations funded by the hosts.

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