NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

DOE Award No.: DE-FE00-28966

Research Performance Progress Report

(Period Ending 03/31/2017)

Impact of clays on the compressibility and permeability of sands during methane extraction from gas hydrate

Project Period (10/1/2016 to 9/30/2019)

Submitted by:
Dr. Jongwon Jung


Signature

Louisiana State University, Dept. of Civil and Environmental Engineering
DUNS #075050765
3505C Patrick Taylor Hall
Baton Rouge, LA 70803
Email: jjung@lsu.edu
Phone number: (225) 578-9471

Prepared for:
United States Department of Energy
National Energy Technology Laboratory

Submission Date

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

Office of Fossil Energy

DISCLAIMER

TABLE OF CONTENTS

EXECUTIVE SUMMARY

Background: The quantity of methane potentially recoverable from gas hydrate is large enough to motivate federally-supported production tests in several countries, which in turn motivates studies of reservoir production efficiency. Evaluating long-term production well viability involves modeling permeability evolution in the reservoir sediments around the production well because processes reducing the flow of gas into the production well also reduce the long-term economic viability of the well. Fine particles, such as clays, exist nearly ubiquitously in the permafrost and marine settings that typically host gas hydrate, and fines reacting to fluid flow by migrating and clogging pore throats can reduce flow toward the production well. Many fines are sensitive to variations in pore-fluid chemistry, swelling in reaction to in situ pore brine being displaced by fresh water liberated from hydrates during dissociation. Additionally, fine particles tend to collect at gas/water interfaces created by the multiphase flow of gas and water. Thus, as methane and fresh water flow from the hydrate-dissociation front toward the production well, fine particles in the reservoir sands, interbedded fine-grained layers and seal layers can be swelled, migrated (or both), potentially clogging pathways and limiting flow to the production well.

Objective: This project seeks to provide a quantitative basis for reservoir models to account for the impact of clays and other fine-grained material ("fines") on reservoir compressibility and permeability, two key factors controlling the flow of gas and fluids toward a production well. This overall objective is addressed through a combination of site-specific and more generalized, fundamental science goals:

Site-specific measurement goals: quantify the change in compressibility and permeability due to the reaction of fines to pore-water freshening in sediment from the 2015 NGHP-02 gas hydrates research cruise offshore India.

Fundamental measurements on pure fines goal: distinguish between, and quantify, mechanisms for sediment compressibility and permeability change due to physical and chemical responses of fines to the flow of freshened pore water and gas:

- Chemical response: quantify and catalog the sensitivity of pure fines (fines with only a single component, or "endmember" fines) to pore-water chemistry.
- Physical response: quantify the link between fines migration and clogging during single and multiphase flow.

ACCOMPLISHMENTS

The overall project timeline is shown in Figure 1. This report details activities in the second quarter of Year 1. A full list of milestones and Success Criteria is provided in the Appendix.

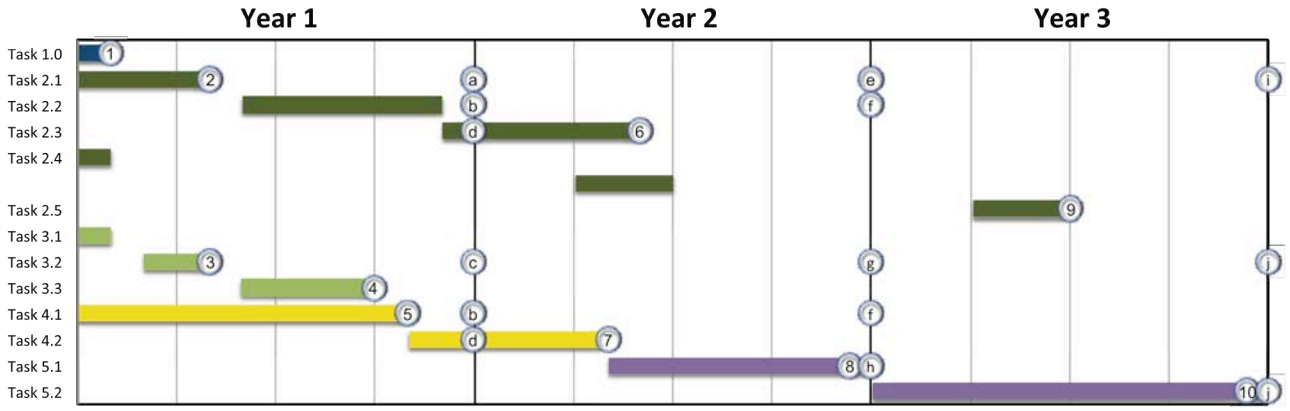

Figure 1: Project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given in the Appendix.

In this quarter, the team benefitted from a group meeting at Louisiana State University. The meeting allowed participants to develop the scope and structure for a conference paper submitted in this quarter. A laboratory tour allowed participants to go over the LSU micromodel set-up to guide the USGS team's plans for creating a similar system (required for Tasks 2.2 and 2.3). Active Tasks this quarter included Tasks 2.1 (Index property analysis of NGHP-02 conventional core sediment), 2.2 (2D microfluidic model visualization of fines migration), 3.2 (Electrical sensitivity of pure, endmember fines), 3.3 (Dependence of compressibility and permeability on pore fluid chemistry in pure, endmember fines) and 4.1 (Dependence of fines migration and clogging on physical conditions in porous media containing pure, endmember fines). A summary of accomplishments for each Task is provided below.

<u>Task 2.1: Index property analysis of NGHP-02 conventional core sediment</u>

The U.S. Geological Survey acquired conventional core material from the India's 2015 National Gas Hydrate field program (NGHP-02). To help interpret planned measurements of the chemical sensitivity and migration behavior of fines from the NGHP-02 study, index property analyses are being carried out on NGHP-02 sediment. Results will be withheld from publication until the NGHP-02 publication moratorium is lifted. Accomplishments this quarter include:

- Planning activities: the transfer of NGHP-02 pressure cores to Woods Hole is ongoing. Cores are on route, but their arrival has been delayed until early in FY17 3Q.
- Data assessment activities this quarter were tied with an ongoing NGHP modeling project led by DOE-NETL.

Task 2.2: 2D Microfluidic model visualization of NGHP-02 fines

This subtask is an opportunity to compare results with 2D micromodeling between LSU (Task 4), and the USGS (Task 2.2). Observations will be made on endmember fines as a function of fines concentration and pore fluid chemistry to examine fines migration and permeability shutdown (clogging). Accomplishments in this initial quarter of activity include:

- Completing the bidding process for a microscope/camera system.
- Acquiring a high-precision syringe pump required to control fluid flow in the 2D micromodel.
- Micromodels have been constructed at LSU (see Task 4.1).

Task 3.2: Electrical sensitivity of pure, endmember fines

Electrical sensitivity provides a means of quantifying the extent to which certain fines will swell in response to changes in pore water chemistry. This swelling can increase the capacity of fines to clog pore throats, and is being studied here separately from migration and mechanical causes of pore-throat clogging by fines (the focus of Task 4). Findings this quarter include:

- Liquid limit and plastic limit tests, upon which the electrical sensitivity value is based, have been made for all endmember fines using three different pore-water fluids: deionized water, brine and kerosene. The

data analysis is complete, and the electrical sensitivity of the fines has been classified as shown in Figure 2. These results were then used in a conference paper (See Task 3.3) to as a basis for distinguishing between the behavior of the fines during compressibility tests.

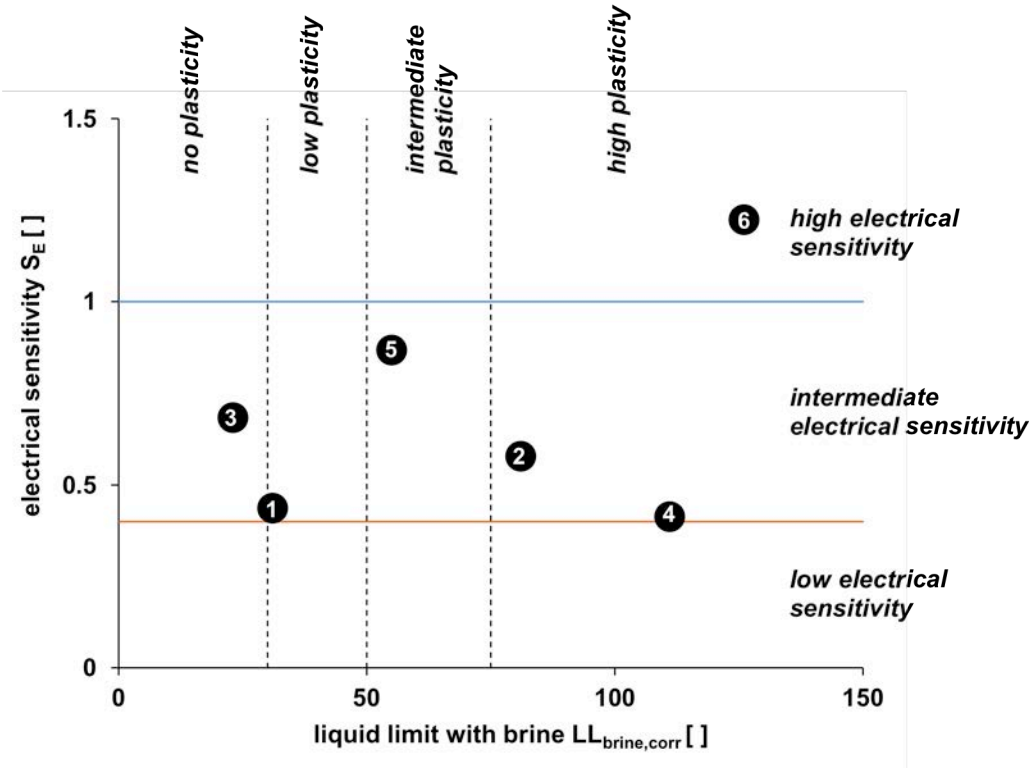

Figure 2: Chart for soil classification based on electrical sensitivity. Numbered black circles represent the endmember fines: (1) silica silt, (2) mica, (3) calcium carbonate, (4) diatoms, (5) kaolin, (6) bentonite.

- Additional sedimentation tests have been conducted using settling tubes designed and built in house to provide insight into the impact of salinity on sediment fabric (the arrangement in which particles collect as sediment). Tests were run with pore fluids between 0 and 2M salinity to provide insight into how interparticle interactions may change during the pore-water freshening that occurs during methane extraction from hydrate-bearing sediments.
- Sedimentation tests show fundamentally different responses to salinity changes between high-aspect ratio fines (kaolin and mica)

relative to silica silt and bentonite. Increasing the brine concentration caused fines to settle in lower void-ratio fabrics, but settlement rates were slowed in kaolin and mica in contrast to the accelerated settlement rates observed for silica silt and bentonite. This dependence on salinity was due to differences in the charge distributions on the fines particles tested. Sedimentation test results were used in a conference paper to assess the compressibility results discussed in Task 3.3.

Task 3.3: Dependence of compressibility and permeability on pore-fluid chemistry in pure, endmember fines

Compressibility and permeability are two critical parameters for describing the ease with which fluid can flow through a formation over the production life of a reservoir. As the reservoir is subjected to increased effective stresses during the pressure draw down required to destabilize the hydrate in situ, reservoir sediment porosity (and hence, permeability) will be lost as the sediment compresses. The relationship between applied stress and the extent of compression is given by the compressibility, which was the focus of laboratory activities in this quarter. Accomplishments include:

- Oedometer-style compression tests have been run at LSU and the USGS on fines for a variety of pore fluids. In this quarter, emphasis was placed on understanding the dependence of compressibility on pore-water salinity. Compression tests were run for all endmember fines for deionized water and 2M brine. Compressibility results in the brine relative to that in pure water were plotted as a function of electrical sensitivity (measured in Task 3.2), and showed a clear compressibility decrease with increasing electrical sensitivity. The results could be explained using results from the sedimentation tests (from Task 3.2) and have been submitted as part of a conference paper for the Ninth International Conference on Gas Hydrates (to be held June 25-30, 2017).

Task 4.1: Dependence of fines migration and clogging on physical conditions in porous media containing pure, endmember fines

Fines existing in coarse-grained material can migrate in pore-fluid flow, collect at pore-throats and clog flow pathways, reducing the overall permeability required for efficient methane extraction from hydrate-bearing sands. In this task, endmember fines are assessed in terms of their mechanical capacity to migrate and clog pores of various sizes relative to the grain size of the fines themselves. Accomplishments this quarter include:

- Fabrication of 2D micromodels at LSU has produced the first units (Figure 3). The fluid flow and imaging systems are also in place. Preliminary measurements to evaluate the system and image integrity are underway.

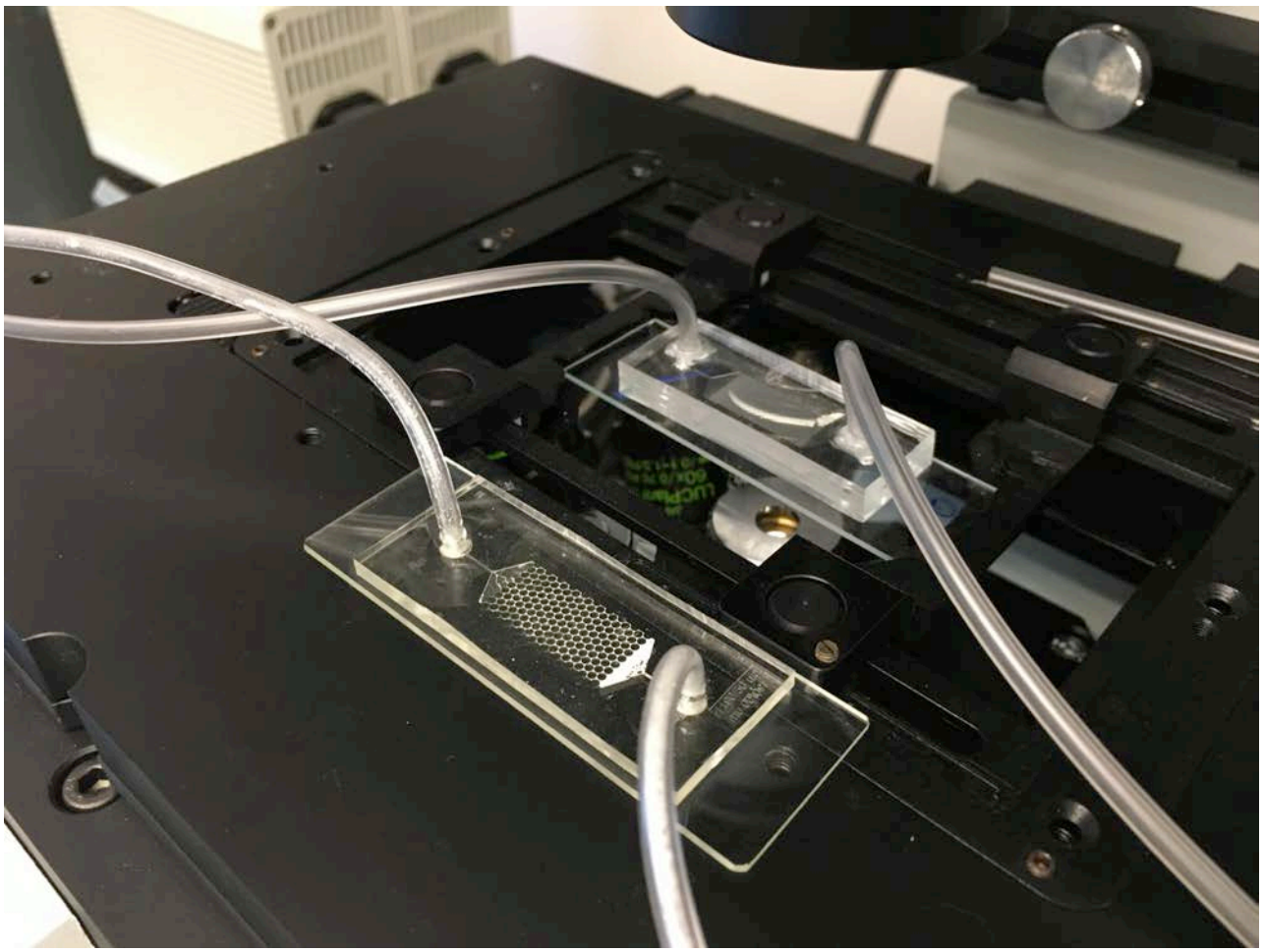

Figure 3: LSU 2D-micromodel observation setup. Two micromodel units, fabricated at LSU, sit atop the microscope imaging stage. A relatively large pore-throat model is in the foreground, with a relatively small pore-throat model in the background. Fluid flow tubes for controlling the inlet and outlet flow have been connected to the units.

PRODUCTS

Jang, J., Waite, W.F., Jung, J., Pore-fluid sensitivity of clays and its impacts on gas production from hydrate-bearing sediments [Abstract]. Accepted for the 9th International Conference on Gas Hydrates, June 25-30, 2017, Denver, Colorado.

Jang, J., Cao, S., Waite, W.F., Jung, J., Impact of pore-water freshening on clays and the compressibility of hydrate-bearing reservoirs during production. Conference paper submitted for the 9th International Conference on Gas Hydrates, June 25-30, 2017, Denver, Colorado.

APPENDIX: PROJECT TIMELINE

The complete Project timeline is shown in Figure A1, with Milestones and Success Criteria listed thereafter.

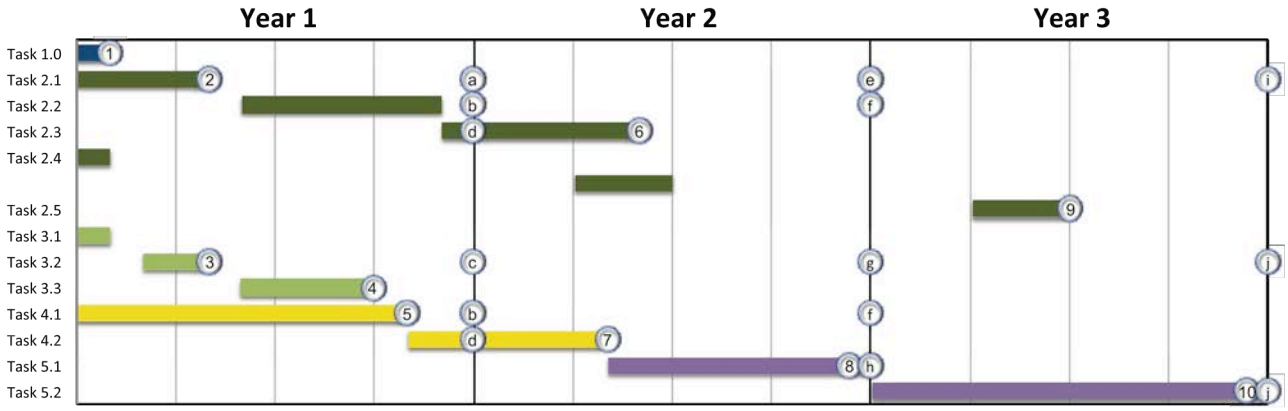

Figure A1: Project timeline, including times of activity (color bars), Milestones (numbered circles) and Success Criteria (lettered circles). A complete list of Milestones and Success Criteria are given below.

Milestones (listed according to the numbers given in Figure A1)

Budget Period 1

1. Task 1, Project Management (LSU/USGS). This task will be completed October 31, 2016 and verified through DOE acceptance of the project SOPO, annual budget forecasts and Project Management Plan.
2. Task 2, Site-specific pore fluid sensitivity study (USGS). This data acquisition component of Task 2 will be completed January 31, 2017 and verified through comparison of NGHP-02 data obtained with available shipboard data from the NGHP-02 cruise offshore India.
3. Task 3, Endmember fines – electrical sensitivity index (USGS). This data acquisition component of Task 3 will be completed January 31, 2017. Results will be verified through duplicate measurements of targeted specimens using LSU equipment, literature comparison where available.
4. Task 3, Endmember fines – dependence of compressibility and permeability on pore fluid chemistry (LSU). This data acquisition component of Task 3 will be completed June 30, 2017. Results will be verified through duplicate measurements of targeted specimens using USGS equipment.
5. Task 4, 2D micromodel studies – mechanical contribution of endmember fines to clogging (LSU). This data acquisition component of Task 4 will be completed July 31,

2017. Results will be verified through duplicate measurements of targeted specimens using USGS equipment.

Budget Period 2

6. Task 2, 2D micromodel studies – mechanical contribution of NGHP-02 fines to clogging (USGS). This data acquisition component of Task 2 will be completed March 1, 2018. Results will be verified through linkages between imaged clogs and measured evolution of pressure and flow parameters.
7. Task 4, 2D micromodel studies – clogging dependence of endmember fines on pore fluid chemistry (LSU). This data acquisition component of Task 4 will be completed January 31, 2018. Results will be verified through duplicate measurements of targeted specimens using USGS equipment.
8. Task 5, 3D visualization of clogging and clog fracturing – dependence on endmember fines (LSU). This data acquisition component of Task 5 will be completed September 30, 2018. Results will be verified through linkages between imaged clogs and measured evolution of pressure and flow parameters.

Budget Period 3

9. Task 2, Site-specific dependence of compressibility and permeability on pore fluid chemistry (USGS). This data acquisition component of Task 2 will be completed March 31, 2019. Results will be verified for brines and freshened pore water by comparisons with pressure core data obtained elsewhere in the NGHP-02 project.
10. Task 5, 3D visualization of clogging and clog fracturing – dependence on pore water chemistry (LSU). This data acquisition component of Task 5 will be completed September 30, 2019. Results will be verified through linkages between imaged clogs and measured evolution of pressure and flow parameters.

Success Criteria (listed according to the letters given in Figure A1)

End of Budget Period 1

a. Subtasks 2.1, 2.4: NGHP-02 fines properties (Offshore India). Index property measurements and liquid limit tests should have begun on NGHP-02 conventional core sediment. Additional index property and liquid limit tests can be run on NGHP-02 material as the material becomes available from pressure cores that were previously dedicated for USGS study during NGHP-02.
b. Subtasks 2.2 and 4.1 (linked): 2D microfluid models – clogging via physical processes. Measurements of clogging by endmember fines should have been run separately by both participants. Results should be quantified in terms of clogging potential due to mechanical activity (fines migration) and geometry (pore throat size relative to grain size of the fines). Results should demonstrate similar behavior within the subset of LSU and USGS tests that are paired for interlaboratory verification purposes.

c. Task 3: Endmember fines assessment of pore fluid chemistry impact on compressibility and permeability. All data for a manuscript detailing the implications of the electrical sensitivity (pore fluid sensitivity) of fines on compressibility and permeability should be in hand, and a conference abstract prepared.
d. Subtasks 2.3 and 4.2 (linked): 2D microfluid models – clogging dependence on pore fluid chemistry. 2D micromodel experiments should have been started by both participants to assess the dependence of clogging by fines in relation to fluid chemistry. Initial comparisons between participants should guide subsequent efforts and dictate any additional tests that may need to be run.

End of Budget Period 2

e. Subtasks 2.1, 2.4: NGHP-02 fines properties (Offshore India). Index property measurements and liquid limit tests should continue on NGHP-02 pressure core sediment as the material becomes available from pressure cores that were previously dedicated for USGS study during NGHP-02. The publication moratorium should have expired in time to allow a conference abstract submission covering the NGHP-02 fines study to date.
f. Subtasks 2.2, 2.3 and Task 4: 2D Micromodel studies of clogging by endmember fines. All data for a manuscript detailing the implications of mechanical and chemical controls on clogging by endmember fines should be in hand. A joint manuscript should be submitted for peer reviewed journal publication, though the review process will likely be ongoing at the end of Budget Period 2.
g. Task 3: Endmember fines assessment of pore fluid chemistry impact on compressibility and permeability. Based on feedback from presenting this material at a conference, a peer-reviewed journal manuscript should have been written and submitted during this budget period, though the review process will likely be ongoing at the end of Budget Period 2.
h. Subtask 5.1: 3D micromodel imagery of the role of endmember fines in clogging, clog fracturing, and relative permeability. This Subtask is a 3D extension of the Subtasks 2.2 and 4.1 2D micromodel tests. By the end of Budget Period 2, comparisons between 2D and 3D observations of fines clogging based on mechanical and geometric factors should be providing insight into how the 2D micromodel results scale up to 3D, and these insights should be captured in a submitted conference abstract.

End of Budget Period 3

i. Subtasks 2.1, 2.4: NGHP-02 fines properties (Offshore India). Index property measurements and liquid limit tests should be complete on NGHP-02 pressure core sediment as the material. Based on feedback from presenting this material at a conference, a peer-reviewed journal manuscript should have been written and submitted during this budget period, though the review process for an NGHP-02 special volume may be ongoing even by the end of Budget Period 3.
j. Tasks 3 and 5: Interaction of fines with pore water – effect of pore water chemistry on index properties and flow behavior of endmember fines. Tying the macroscopic property insights from Task 3 with the 3D pore-scale behaviors observed in Task 5

provides the scientific content for the capstone publication in this project. Based on reviewer feedback from Task 3 and conference feedback from Subtask 5.1, a manuscript covering the interaction between fines and pore water and the subsequent impact on index and flow properties will be submitted.

National Energy Technology Laboratory

626 Cochrans Mill Road
P.O. Box 10940
Pittsburgh, PA 15236-0940

3610 Collins Ferry Road
P.O. Box 880
Morgantown, WV 26507-0880

13131 Dairy Ashford Road, Suite 225
Sugar Land, TX 77478

1450 Queen Avenue SW
Albany, OR 97321-2198

Arctic Energy Office
420 L Street, Suite 305
Anchorage, AK 99501

Visit the NETL website at:
www.netl.doe.gov

Customer Service Line:
1-800-553-7681