NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

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Quarterly Research Performance Progress Report

(Period Ending 3/31/2019)

Advanced Simulation and Experiments of Strongly Coupled Geomechanics and Flow for Gas Hydrate Deposits: Validation and Field Application

Project Period (10/01/2016 to 09/30/2019)

Submitted by:
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Signature

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ACCOMPLISHMENTS

Objectives of the project

The objectives of the proposed research are (1) to investigate geomechanical responses induced by depressurization experimentally and numerically; (2) to enhance the current numerical simulation technology in order to simulate complex physically coupled processes by depressurization and (3) to perform in-depth numerical analyses of two selected potential production test sites: one based on the deposits observed at the Ulleung basin UBGH2-6 site; and the other based on well-characterized accumulations from the westend Prudhoe Bay. To these ends, the recipient will have the following specific objectives:

1). Information obtained from multi-scale experiments previously conducted at the recipient's research partner (the Korean Institute of Geoscience and Mineral Resources (KIGAM)) that were designed to represent the most promising known Ulleung Basin gas hydrate deposit as drilled at site UBGH2-6 will be evaluated (Task 2). These findings will be further tested by new experimental studies at Lawrence Berkeley National Laboratory (LBNL) and Texas A&M (TAMU) (Task 3) that are designed capture complex coupled physical processes between flow and geomechanics, such as sand production, capillarity, and formation of secondary hydrates. The findings of Tasks 2 and 3 will be used to further improve numerical codes.

2) Develop (in Tasks 4 through 6) an advanced coupled geomechanics and non-isothermal flow simulator ($T+M^{AM}$) to account for large deformation and strong capillarity. This new code will be validated using data from the literature, from previous work by the project team, and with the results of the proposed experimental studies. The developed simulator will be applied to both Ulleung Basin and Prudhoe Bay sites, effectively addressing complex geomechanical and petrophysical changes induced by depressurization (e.g., frost-heave, strong capillarity, cryo-suction, induced fracturing, and dynamic permeability).

Accomplished

The plan of the project timeline and tasks is shown in Table 1, and the activities and achievements during this period are listed with Table 2 as follows.

Task 1: Project management and planning

The ninth quarterly report was submitted to NETL on Jan. 30, 2019. Task 2 was completed. LBNL has been actively working on Subtask 3.3, and TAMU is working on Subtask 3.4 with LBNL. TAMU and KIGAM are working on Subtasks 4.1 and 5.2 related to the experiment of Task 2, validation of TOUGH+ROCMECH with the experimental data. The specific status of the milestones is shown in Table 2. Specific achievements including presentation and publication during this period are as follows.

Task 2: Review and evaluation of experimental data of gas hydrate at various scales for gas production of Ulleung Basin

Subtask 2.1 Evaluation of Gas hydrate depressurization experiment of 1-m scale

This task was completed previously. During this quarter, we found the data obtained from the single sand-layer hydrate system, which will be used for numerical validation tests, too.

Subtask 2.2 Evaluation of Gas hydrate depressurization experiment of 10-m scale

This task was completed.

Subtask 2.3 Evaluation of Gas hydrate depressurization experiment of 1.5-m scale system in 3D

This task was completed.

Fig. 2.3.1 Vertical deformation of the sediment sample measured by a laser displacement gauge during the experiment

Subtask 2.4 Evaluation of gas hydrate production experiment of the centimeter-scale system

This task was completed.

Task 3: Laboratory Experiments for Numerical Model Verification

Subtask 3.1: Geomechanical changes from effective stress changes during dissociation

This task was completed.

Subtask 3.2 Geomechanical changes from effective stress changes during dissociation – sand

This task was completed.

Subtask 3.3 Geomechanical changes resulting from secondary hydrate and capillary pressure changes

In Quarter 2, we completed 2 subtasks. After some preliminary capillary pressure stone testing, we have assembled a realistic setup in a sleeve in a pressure vessel with attached feedthroughs.

We have opted to run stainless steel tubing into the vessel and through the vessel wall, and modify the endcap to fun two pass throughs. Once inside the sample, the connection to the host Nylon tubing will be made. One of these would contain capillary pressure tubing, while the other would function as normal. Saturating and familiarization testing with 5 bar and 15 bar stones has been performed.

Subtask 3.4 Construction of the Relative Permeability Data in Presence of Hydrate

In reservoir simulation technology, it is a common practice to capture multi-phase flow dynamics using relative permeability curves. However the nature of these curves are not well established for the simulation of the depressurization process. The current relative permeability curves are based on correlations developed in the absence of hydrate and they may not be suitable for the representation of the flow. In this subtask, apart from the work on geo-mechanics, we plan to perform multi-phase flow studies at varying levels of hydrate saturation in order to construct relative permeability curves that are suitable for the depressurization.

Methane hydrate will be formed in the laboratory in stages, ranging from no hydrate to the level of hydrate saturation when the porous medium is impermeable. Effective permeability and relative permeability values will be measured at each stage. At each stage both mass balance and x-ray computed tomography (CT) will be used.

Current Progress

The design of the measurement setup is completed recently. Detailed steps for the sand preparation are being decided. The preparation of the sand pack is important for a uniform residual water saturation in the sand pack, when the water is displaced with gas, so that a uniform methane hydrate forms in the sand pack, rather than its clusters. This is to be done with a drainage process that is currently being developed.

Secondly, the procedure to measure the permeability are defined for hydrate free sediment. This will provide a baseline to compare values when hydrate is present.

Previous studies have shown that the injection of the inert gas hydrate dissociates and influence the relative permeability. To predict relative permeability in the presence of hydrate, the hydrate saturation should stay the same for all flow ratios. So, one important consideration for the measurements is the requirement to have a stable hydrate saturation during the flow measurement stage. For this purpose our team has recently developed a new procedure to control the hydrate saturation in the sand pack during the flow measurements. To accomplish this, we propose to use a mixture of helium and methane. From literature review, and in-house experiments, helium is inert to methane hydrates. The only effect that helium has is to change the partial pressure of methane in the system. When the partial pressure of methane is reduced to below the equilibrium pressure of pure methane hydrate, then the hydrate dissociates. For example, at 1 degree Celsius, the equilibrium pressure of methane hydrate is near 400 psi; thus, if the partial pressure of methane in the He/CH_4 mixture falls below this value, hydrate will dissociate, but if it is above this value, then it will be stable. Therefore, during hydrate formation, partial pressure of methane will be high enough to form hydrates in the sand pack, and during the flow experiments the partial pressure of the mixture will be just above that of the equilibrium pressure—thus freezing the hydrate at a desired saturation.

A New Procedure for the Relative Permeability Measurements in Presence of Hydrates

To measure permeability and relative permeability in a sand pack in the presence of methane hydrate at different hydrate saturations, we propose the following procedure. The experiments and data collection will be done during May 2019 at the LBNL facilities.

A. Sand Pack Preparation

1. Mix sand and silt
2. Pack sand in rubber sleeve
3. Apply confining pressure

B. Preparation of Gas Phase Mixtures

4. Make 2 coils of tubing.
6. Connect each coil to the tanks of Mixture 1 and Mixture 2.
7. Connect other ends of the coils to a valve then to a T fitting.
8. Connect T fitting to the gas inlet port of the permeability setup.
9. Place the coils into cold water bath at the cell temperature and circulate water.

C. Relative Permeability Measurements in the Absence of Hydrate

10. Set the dry sand pack temperature to a constant value, e.g., 25 C
11. CT scan dry sand pack
12. Vacuum sand pack
13. Flood with CO2 at low pressure
14. Vacuum sand pack again
15. Inject Methane to max pressure desired.
16. CT scan system with fully gas saturated sand pack
17. Vacuum sand pack
18. Flood with CO2 at low pressure
19. Vacuum sand pack again
20. Inject water at a pressure, e.g., 900 psi
21. Flow water to fully saturate
22. CT Scan fully saturated sand pack
23. Measure steady-state single-phase water permeability
24. Continue flowing water and add methane/helium mixture at the inlet to measure water/gas relative permeability using steady-state method
    a. Using two syringe pumps, inject water and use a third to draw water out at a fixed ratio of total flow rate. Using a gas injection pump inject methane at constant pressure
    b. CT scan at fixed times, and at each volume ratio.

c. Measure the effective permeability curves at the set saturations

d. Continue increasing the injected gas volume going through steps 24 a-c at fixed water gas ratios. At minimum of 2 points other than the end points.

e. Measure single-phase gas permeability at the irreducible water saturation

f. Construct the relative permeability curves

25. Pressurize system to xxx psi with mixture 2, (methane/helium mixture) (excess Methane)

26. CT Scan system

27. Cool the system to 1C to form hydrate

D. Relative Permeability Measurements in the Presence of Hydrate

28. CT scan during hydrate formation at set time frame

29. Allow the system to equilibrate

30. Measure single-phase methane/helium (mixture 1) permeability in the presence of hydrate

    a. CT scan during this measurement at set interval

31. Displace helium/methane mixture 1 with water and measure water permeability in the presence of hydrate

    a. CT Scan during this time

32. Perform steady-state water/gas relative permeability using helium/methane mixture 1 in the presence of hydrate

    a. a. Using two syringe pumps, inject water and use a third to draw water out at a fixed ratio of total flow rate. Using a gas injection pump inject methane at constant pressure

    b. CT scan at fixed times, and at each volume ratio.

    b. CT Scan at fixed times

    c. Construct relative permeability curves

    d. Continue increasing the injected helium/methane mixture 1 volume going through steps 32 a-c for at least 4 points of water gas ratios.

    e. Measure single-phase gas permeability

    f. CT scan

    g. Construct the relative permeability curves permeability in the presence of hydrate

E. Increase Hydrate Saturation Level

33. Flush with water

34. CT Scan

35. Flush with helium/methane mixture 1 to prevent hydrate formation

36. Displace helium/methane mixture 1 with methane and allow new hydrate formation

37. Repeat Steps 29-31 to produce higher level of water saturation

38. Allow the system to equilibrate at higher hydrate saturation

39. CT scan during hydrate formation

40. Repeat 32-39 till impermeable

Subtask 3.5 Identification of Hysteresis in Hydrate Stability

This subtask was competed.

Task 4: Incorporation of Laboratory Data into Numerical Simulation Model

Subtask 4.1 Inputs and Preliminary Scoping Calculations

We have further been analyzing the new data obtained from the sand layer system of Subtask 2.1. Specifically, in Subtask 2.1, we have extracted the data of pressure and displacement when the depressurization is 20% (DP=20%), along with the data of DP 30%, which we extracted in the previous quarter. Those data are shown in Subtask 5.1 (Figs 5.1 and 5.2), more discussed in Subtask 5.1.

Furthermore, we have analyzed the data of Subtask 2.3, and identified that displacement after around 1300 min was not measured (Figs. 4.1). The bottom hole pressure decreased linearly, but it did not reach the constant pressure unlike Subtask 2.1. Just like Subtask 1, we will match the simulated displacement result with the measured data (the right of Fig. 4.1), imposing the pressure boundary condition (the left of Fig. 4.1).

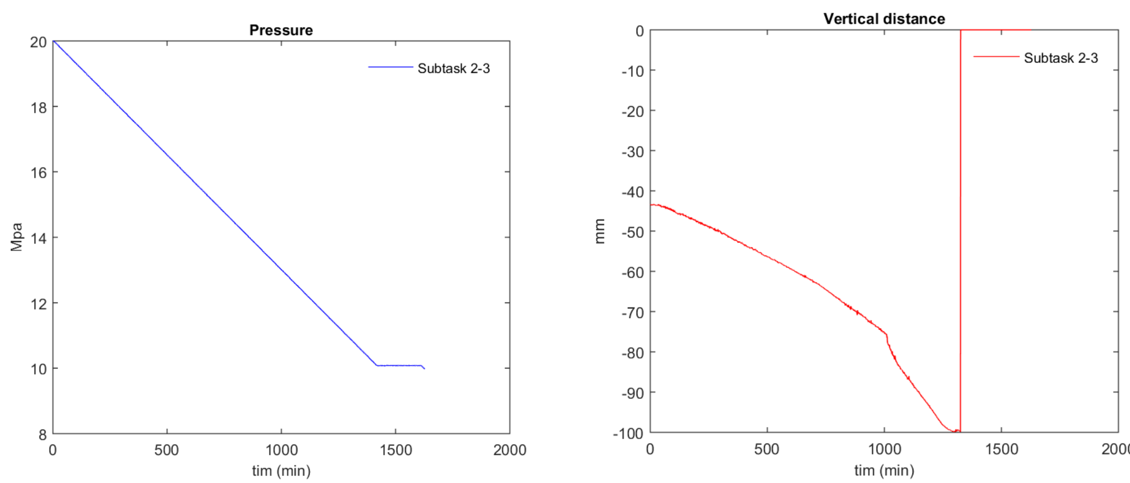

Fig. 4.1 Experimental results of Subtask 2.3: Pressure (left) and displacement (right).

Subtask 4.2 Determination of New Constitutive Relationships

No further progress has been made during the quarter.

Subtask 4.3 Development of Geological Model

No further progress has been made during the quarter.

Task 5: Modeling of coupled flow and geomechanics in gas hydrate deposits

Subtask 5.1 Development of a coupled flow and geomechanics simulator for large deformation

This task was completed.

Subtask 5.2 Validation with experimental tests of depressurization

Continuing the previous work, we have been validating T+M (TOUGH+ROCMECH), matching parameters of geomechanics and flow by using the data of the single sand-layer system of Subtask 2.1. We imposed the constant pressure at the bottom boundary (instantaneous pressure drop), as the depressurization was applied at the bottom in the experiment. Figs. 5.1 and 5.2 are the experimental results used for validation. Note that the same sample was used in the experiment.

For validation, we first considered the following uncertain parameters: initial hydrate saturation, permeability, drained elastic geomechanics moduli at SH=0% and 100%. SH means the hydrate saturation. We use the linear interpolation when estimating the geomechanics moduli at a certain hydrate saturation. Fig. 5.3 shows that the numerical results are good agreement with the experimental results, validating T+M. If we honor the pressure constraint more accurately, particularly at early times for DP=20%, we can obtain better agreement between numerical and experimental results.

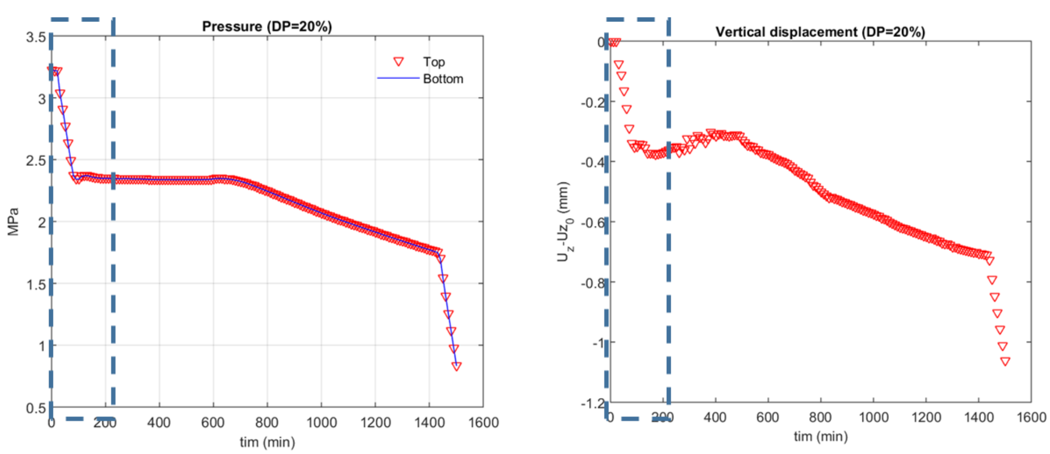

Fig. 5.1 Experimental results of Subtask 1 (DP=20%): Pressure (left) and displacement (right). The blue dotted area means the interval used for validation of T+M.

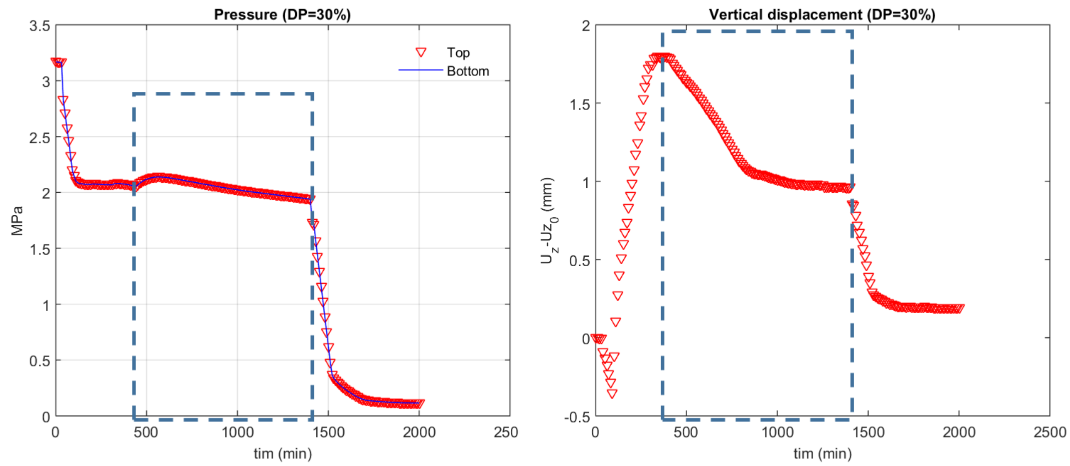

Fig. 5.2 Experimental results of Subtask 1 (DP=30%): Pressure (left) and displacement (right).

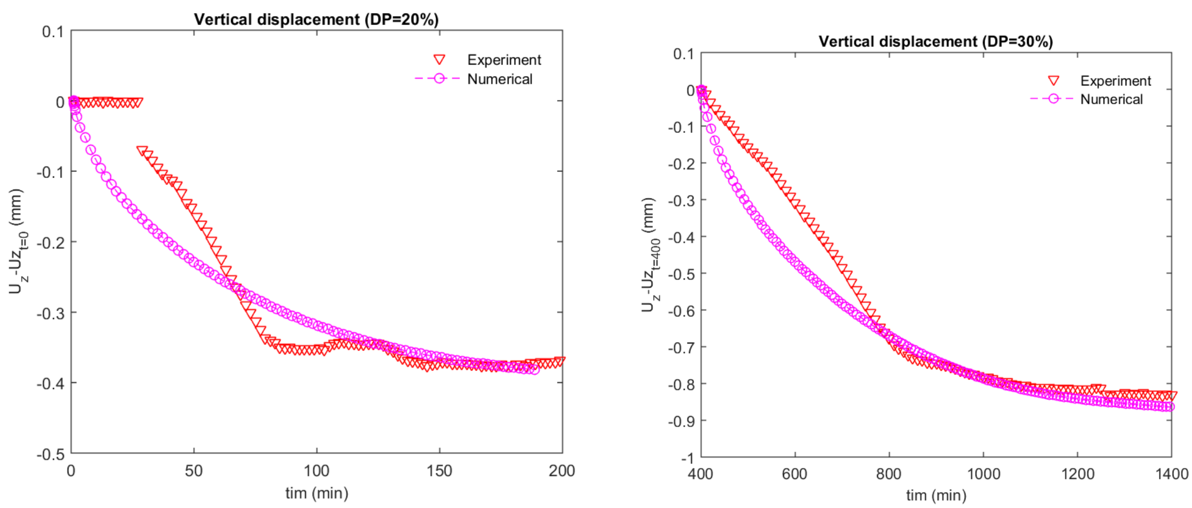

Fig. 5.3 Comparison between numerical and experimental results. Left: DP=20%. Right: DP=30%.

Subtask 5.3 Modeling of sand production and plastic behavior

No further progress was made during this quarter.

Subtask 5.4 Modeling of induced changes by formation of secondary hydrates: Frost-heave, strong capillarity, and induced fracturing

No further progress was made during this quarter.

Subtasks 5.5 and 5.6 Field-scale simulation of PBU L106 and Ulleung Basin

No further progress was made during this quarter.

Task 6: Simulation-Based Analysis of System Behavior at the Ignik-Sikumi and Ulleung Hydrate Deposits

No further progress was made during this quarter.

PRODUCTS

We have organized a mini-symposium in SIAM (Society for Industrial Applied Mathematics) Conference on Mathematical & Computational Issues in the Geosciences, titiled Recent Advances in Computational Modeling of Coupled Flow and Geomechanics in the Subsurface Environment (with Dr. Sanghyun Lee, Florida State University at Tallahassee, and Dr. George Moridis, TAMU) Mar. 11-14, 2019.

We have also made some presentations as follows.

Yoon S., Kim J., 2019, The Modeling of Fault Activation and Induced Seismicity by using Coupled Flow-geomechanics Simulation and its Field Application, SIAM Conference on Mathematical & Computational Issues in the Geosciences, Houston, TX, Mar. 11-14

Kim J., Lee S., Moridis G.J., 2019, Advanced Simulation for Strongly Coupled Non-isothermal Flow and Geomechhanics for the Gas Hydrate Deposits, SIAM Conference on Mathematical & Computational Issues in the Geosciences, Houston, TX, Mar. 11-14

The fund was acknowledged.

Continuing the previous activity of the web-conference, all parties of TAMU, LBNL, KIGAM have been participating in the 2nd International Gas Hydrate Code Comparison Study teleconference (IGHCCS2) held every two weeks online.

BUDGETARY INFORMATION

Table 3 shows the information of the budget for this project and the expenditure up to 3/31/2019. The expenditure by TAMU and cost-share from KIGAM are accurate while the expenditure by LBNL might not be accurate. We have fixed LBNL's expenditure at the previous quarter. For detailed information of the budget and expenditure, refer to the financial status report separately submitted to NETL by each institution.

Table 1 – Initial project timeline and milestones (Gantt Chart)

	FY17				FY18				FY19			
Quarter	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task 1.0. Project Management/Planning	A											
Task 2.0. Experimental study of gas hydrate in various scales for gas production of Ulleung Basin												
Subtask 2.1. Depressurization of 1 m scale in 1D				B								
Subtask 2.2 Depressurization of 10-m scale in 1D							C					
Subtask 2.3. Depressurization of 1.5-m scale in 3D										D		
Subtask 2.4. Revisit to the centimeter-scale system												
Task 3.0. Laboratory Experiments for Numerical Model Verification												
Subtask 3.1. Effective stress changes during dissociation				E								
Subtask 3.2. Sand production								F				
Subtask 33. Secondary hydrate and capillary pressure changes												G
Subtask 3.4. Relative Permeability Data												
Subtask 3.5. Hysteresis in Hydrate Stability												
Task 4.0. Incorporation of Laboratory Data into Numerical Simulation Model												
Subtask 4.1. Inputs and Preliminary Scoping Calculations									H			
Subtask 4.2. Determination of New Constitutive Relationships												
Subtask 4.3. Development of Geological Model												
Task 5.0. Modeling of coupled flow and geomechanics in gas hydrate deposits												
Subtask 5.1 Development of a coupled flow and geomechanics simulator for large deformation				I								
Subtask 5.2 Validation with experimental tests of depressurization										J		
Subtask 5.3 Modeling of sand production and plastic behavior								K				
Subtask 5.4 Frost-heave, strong capillarity, and induced fracturing												L
Subtask 5.5 Field-scale simulation of PBU L106												
Subtask 5.6 Field-wide simulation of Ulleung Basin												
Task 6.0. Simulation-Based Analysis of System Behavior at the Ignik-Sikumi and Ulleung Hydrate Deposits												M

Table 2. Milestones Status

Milestone	Description	Planned Completion	Actual Completion	Status / Comments
Task 1 Milestones				

Milestone A	Complete the kick-off meeting and revise the PMP	12/31/17	1/14/2017	Kickoff meeting held 11/22/17, revised PMP finalized 1/17/17
Task 2 Milestones				
Milestone B	Complete analysis of 1 m-scale experiment in 1D and validation of the cm-scale system (FY17, Q4)	9/30/2017		Completed.
Milestone C	Complete analysis of 10m-scale experiment in 1D	6/30/2018		Completed.
Milestone D	Complete analysis of 1.5m-scale experiment in 3D			Completed.
Task 3 Milestones				
Milestone E	Complete geomechanical changes from effective stress changes during dissociation and construction of the relative permeability data	9/30/2017		Completed
Milestone F	Complete geomechanical changes from effective stress changes during dissociation (sand production) and hysteresis in hydrate stability	9/30/2018		Completed
Milestone G	Complete geomechanical changes resulting from secondary hydrate and capillary pressure changes	9/30/2019		
Task 4 Milestones				
Milestone H	Complete inputs and preliminary scoping calculations, determination of New Constitutive Relationships, development of Geological Model	12/31/2018		Ongoing
Task 5 Milestones				
Milestone I	Complete development of a coupled flow and geomechanics simulator for large deformation, validation with experimental tests of Subtasks 2.1 and 2.4.	9/30/17		Completed
Milestone J	Validation with experimental tests of Task 2 and 3	3/31/2019		Ongoing
Milestone K	Complete modeling of sand production and plastic behavior, validation with experimental tests of Subtasks 2.2	9/30/2018		Ongoing
Milestone L	Complete field-scale simulation of the Ulleung Basin and PBU L106	9/30/2019		
Task 6 Milestones				
Milestone M	Complete Task 6	9/30/2019		

Table 3 Budget information

Baselinie Reporting Quarter	Budget Period 1							
	Q1		Q2		Q3		Q4	
	10/01/16-12/31/16		01/01/17-03/31/17		04/01/17-06/30/17		07/01/17-09/30/17	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baselinie Cost Plan								
Federal (TAMU)	$37,901	$37,901	$57,809	$95,711	$43,967	$139,678	$34,206	$173,884
Federal (LBNL)	$18,750	$18,750	$18,750	$37,500	$18,750	$56,250	$18,750	$75,000
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972	$6,986	$20,958	$656,986	$677,944
Total Planned	$63,637	$63,637	$83,545	$147,183	$69,703	$216,886	$709,942	$926,828
Actual Incurred Cost								
Federal (TAMU)	$0	$0	$10,235	$10,235	$57,085	$67,321	$54,167	$121,488
Federal (LBNL)	$0	$0	$0	$0	$0	$0	$8,500	$8,500
Non-Federal Cost Share	$0	$0	$6,986	$6,986	$6,986	$13,972	$156,986	$170,958
Total incuured cost	$0	$0	$17,221	$17,221	$64,071	$81,293	$219,653	$300,946
Variance								
Federal (TAMU)	($37,901)	($37,901)	($47,574)	($85,475)	$13,118	($72,357)	$19,961	($52,396)
Federal (LBNL)	($18,750)	($18,750)	($18,750)	($37,500)	($18,750)	($56,250)	($10,250)	($66,500)
Non-Federal Cost Share	($6,986)	($6,986)	$0	($6,986)	$0	($6,986)	($500,000)	($506,986)
Total variance	($63,637)	($63,637)	($66,324)	($129,961)	($5,632)	($135,593)	($490,289)	($625,882)

Baselinie Reporting Quarter	Budget Period 2							
	Q1		Q2		Q3		Q4	
	10/01/17-12/31/17		01/01/18-03/31/18		04/01/18-06/30/18		07/01/18-09/30/18	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baselinie Cost Plan								
Federal (TAMU)	$42,481	$42,481	$35,307	$77,788	$46,367	$124,155	$39,908	$164,063
Federal (LBNL)	$18,750	$18,750	$18,750	$37,500	$18,750	$56,250	$18,750	$75,000
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972	$6,986	$20,958	$6,986	$27,944
Total Planned	$68,217	$68,217	$61,043	$129,260	$72,103	$201,363	$65,644	$267,007
Actual Incurred Cost								
Federal (TAMU)	$35,832	$35,832	$31,662	$67,494	$35,510	$103,004	$86,971	$189,974
Federal (LBNL)	$45,952	$45,952	$18,130	$64,082	$0	$64,082	$4,990	$69,072
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972	$506,986	$520,958	$6,986	$527,944
Total incuured cost	$88,770	$88,770	$56,778	$145,548	$542,496	$688,044	$98,947	$786,990
Variance								
Federal (TAMU)	($6,650)	($6,650)	($3,645)	($10,294)	($10,857)	($21,151)	$47,062	$25,911
Federal (LBNL)	$27,202	$27,202	($620)	$26,582	($18,750)	$7,832	($13,760)	($5,928)
Non-Federal Cost Share	$0	$0	$0	$0	$500,000	$500,000	$0	$500,000
Total variance	$20,552	$20,552	($4,265)	$16,288	$470,393	$486,681	$33,302	$519,983

Baselinie Reporting Quarter	Budget Period 3							
	Q1		Q2		Q3		Q4	
	10/01/18-12/31/18		01/01/19-03/31/19		04/01/19-06/30/19		07/01/19-09/30/19	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baselinie Cost Plan								
Federal (TAMU)	$43,543	$43,543	$36,189	$79,733	$47,526	$127,259	$41,209	$168,468
Federal (LBNL)	$18,750	$18,750	$18,750	$37,500	$18,750	$56,250	$18,750	$75,000
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972	$6,986	$20,958	$6,986	$27,944
Total Planned	$69,279	$69,279	$61,925	$131,205	$73,262	$204,467	$66,945	$271,412
Actual Incurred Cost								
Federal (TAMU)	$46,338	$46,338	$47,068	$93,406				
Federal (LBNL)	$6,658	$6,658	$39,707	$46,365				
Non-Federal Cost Share	$6,986	$6,986	$6,986	$13,972				
Total incuured cost	$59,982	$59,982	$93,761	$153,743				
Variance								
Federal (TAMU)	$2,795	$2,795	$10,878	$13,673				
Federal (LBNL)	($12,092)	($12,092)	$20,957	$8,865				
Non-Federal Cost Share	$0	$0	$0	$0				
Total variance	($9,297)	($9,297)	$31,835	$22,538				

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