NATIONAL ENERGY TECHNOLOGY LABORATORY

OIL & GAS

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Quarterly Research Performance Progress Report

(Period Ending 12/31/2018)

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 eighth quarterly report was submitted to NETL on Oct. 30, 2018. KIGAM provided the additional data of the completed Subtask 2.1 for TAMU in order to perform Subtasks 4.1 and 5.2. LBNL has been actively working on Subtask 3.3. 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. TAMU, KIGAM, and LBNL are also actively working on Subtasks 4.2, 4.3, 5.5, and 5.6. The specific status of the milestones is shown in Table 2. Specific achievements including 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 previously.

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

This task was completed previously. Here, we further describe the experimental results, which are closely related to Subtask 4.1, focusing on depressurization experiment after gas hydrate formation. Deformation of the sediment sample during the experiment was measured using a laser displacement gauge mounted on a high pressure cell cover. The vertical deformation of the sediments measured from the laser displacement gauge during the entire period from the brine circulation to the depressurization test is shown in Fig. 2.3.1. Vertical deformation was measured only during the first depressurization due to measurement errors, and it was observed that about 35 mm of the deformation has occurred. The first depressurization is the period during which most of the water is produced by the GH dissociation. It is inferred that the sediment deformation occurred due to the dissociation of load-bearing hydrate.

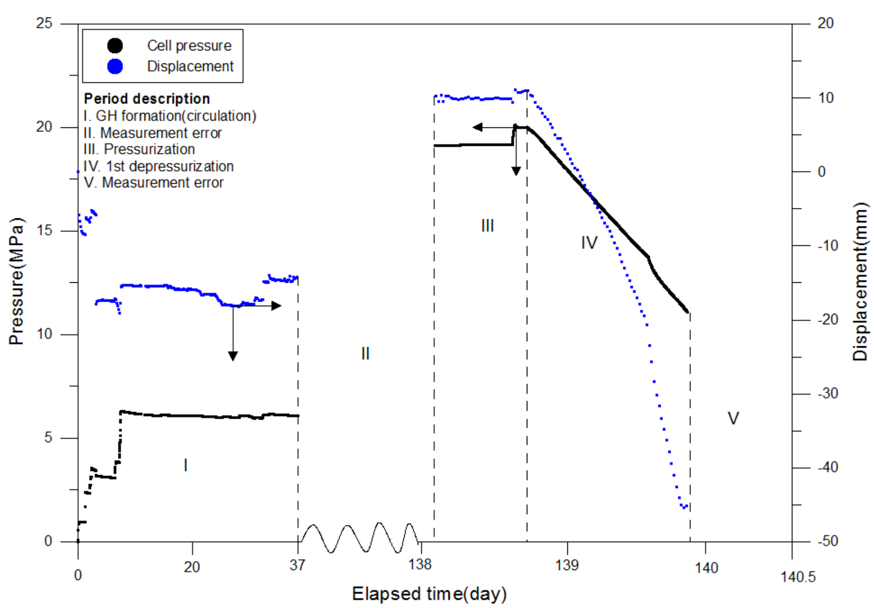

Fig. 2.3.1 Vertical deformation of the sediment sample measured by a laser displacement gauge during the experiment

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

This task was completed previously.

Task 3: Laboratory Experiments for Numerical Model Verification

Subtask 3.1: Geomechanical changes from effective stress changes during dissociation

This task was completed, previously.

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

We evaluated our new of capillary pressure "stones" made by SoilMoisture Equipment (Fig. 3.3.1). We have concerns about the tubing used, and are engineering solutions for application. We have designed and tested techniques to control a temperature gradient and to place our capillary stones in a layered system. This work was in coordination with other projects and uses the results from these to extend the work here.

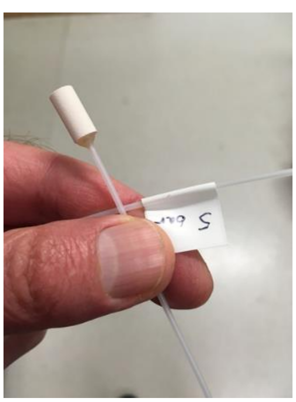

Fig. 3.3.1 Experimental equipment.

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

We are outlining the following experimental procedure, communicating with LBNL.

1. Measure water/gas relative permeability of the sand pack with no hydrate
2. Produce hydrate in the sand pack at residual water saturation
3. Measure water/gas relative permeability
    a. Measure methane relative permeability
    b. Flush with helium
    c. Measure water relative permeability
4. Then flush again with helium
5. Then add methane
6. Repeat cycle 2-6

Each cycle produces layers of hydrate, by which the hydrate saturation increase by the residual water saturation, and the process continue until the sand pack is 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 been analyzing the new data obtained from the sand layer system of Subtask 2.1, because the sand layer system (homogeneous) is less complicated for matching numerical simulation than the sand-mud layer system (heterogeneous). We made the correction that values of the percentage are not saturation but the level of depressurization, denoted by 'DP.' From Fig. 4.1.1., we found subsidence after the pressurization is applied after around 200 min. This physical behavior looks simpler (easier to match numerical simulation) than the previous from the sand-mud layer system. We will use this data for Subtask 5.2.

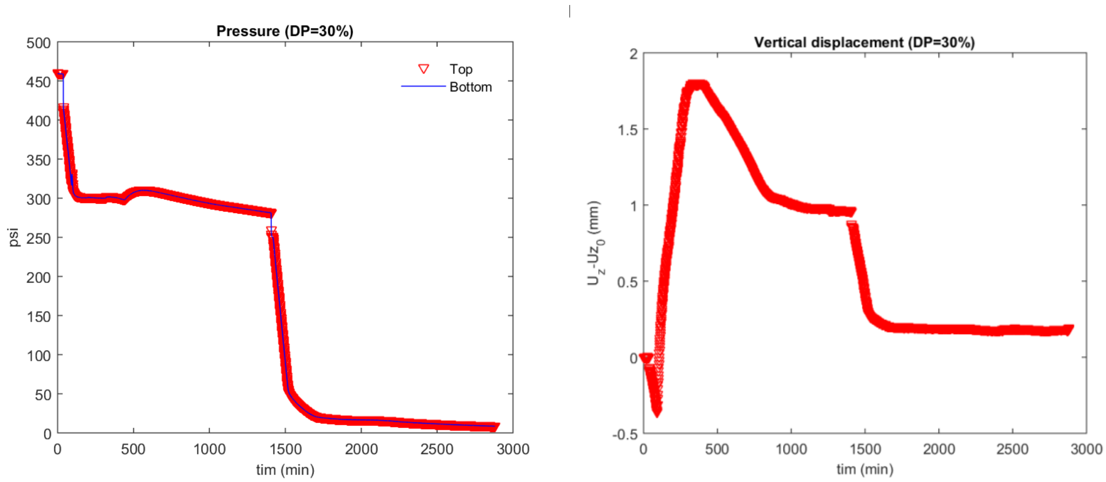

Fig. 4.1.1. Evolutions of pressure (left) and vertical displacement (right).

We have been post-processing and analyzing the data from Subtask 3.5 as follows. Fig. 4.1.2 shows how the equilibrium pressure changes in the presence of the hysteresis. The higher the melting temperature is, the harder it is for the system initially form hydrates while at lower melting temperatures the easier it is. The quadratic equation fits the data perfectly, and is valid for temperatures from T_{Phase} up to 46.4C. Fig. 4.1.2 also shows the temperature at which hydrate forms when the hysteresis is present. As with the pressure the same trend is seen, the higher the melting temperature is, the harder it is for hydrate to form while the lower melting temperature the easier it is.

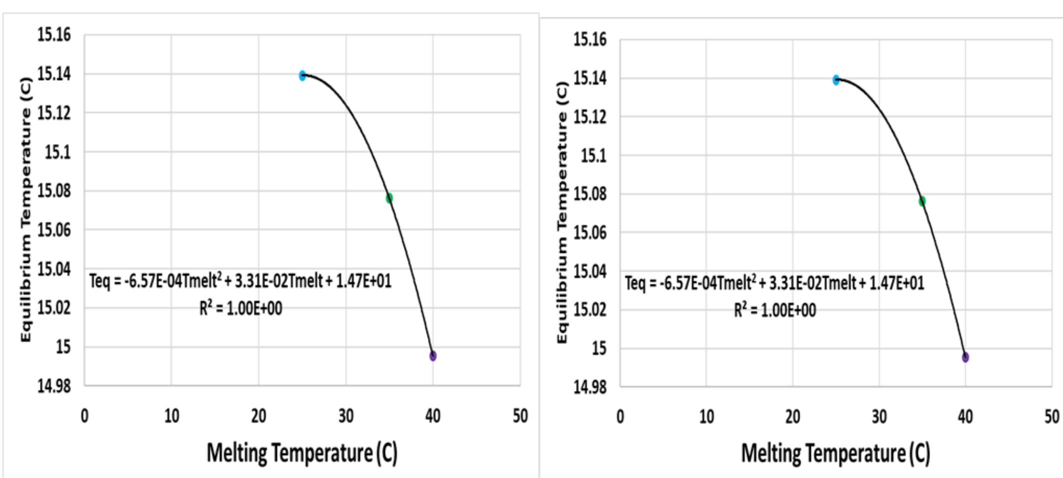

Fig. 4.1.2: Equilibrium pressure and temperature versus maximum melting temperature in presence of hysteresis

Subtask 4.2 Determination of New Constitutive Relationships

Continuing to the above analysis, in order to implement the hysteresis, a shift in the pressure-temperature phase diagram is needed. This is done in Eqs. 5a and 5b. To determine the change in the initial hydrate formation time that the hysteresis causes, the shift in the diagram is estimated in Eqs. 5a and 5b.

$$T_{shift\ melt} = T_{eq} - (-6.57E^{-4}T_{melt}^2 + 3.31E^{-2}T_{melt} + 14.7) \tag{5a}$$

$$P_{shift\ melt} = P_{eq} - (-1.67E^{-1}T_{melt}^2 + 8.39T_{melt} + 1770) \tag{5b}$$

$$T_{eq}^* = T_{shift\ melt} + T_{eq} \tag{6a}$$

$$P_{eq}^* = P_{shift\ melt} + P_{eq} \tag{6b}$$

T_{eq}^* and P_{eq}^*, the modified equilibrium temperature and the modified equilibrium pressure, respectively, are then estimated using equations 6a and 6b. This represents a shift in the phase diagram to the right.

In Fig. 4.2.1, the flow chart for hydrate formation in the presence of hysteresis is illustrated. For the chart, we considered the hydrate formation algorithm of the Tough+Hydrate simulator as the basis. This simulator directly computes the kinetic rate of formation. The necessary modification to the existing algorithm for the presence of the hysteresis is shown in red. The kinetic rate of hydrate formation is computed using the following formulation:

$$\frac{DQ}{dt} = k_o e^{-E_A/RT} A_s \left(P_{eq} \emptyset_{eq} - P_{CH_4} \emptyset\right) y_{CH_4} \tag{9}$$

In this equation the hysteresis comes into play through the driving force which is represented by the parenthesis term. The drive basically represents the tendency of the water-gas system to form hydrate and in this case, it is measured as the difference in the fugacity values of methane in the cages at equilibrium and the methane in the bulk gas. In Eq. 9 these fugacity values are represented by the fugacity coefficients multiplied by their respective pressures, (equilibrium pressure, and partial pressure for methane). The hysteresis should change the equilibrium fugacity of methane in the cages based on the shift in the equilibrium pressure and temperature.

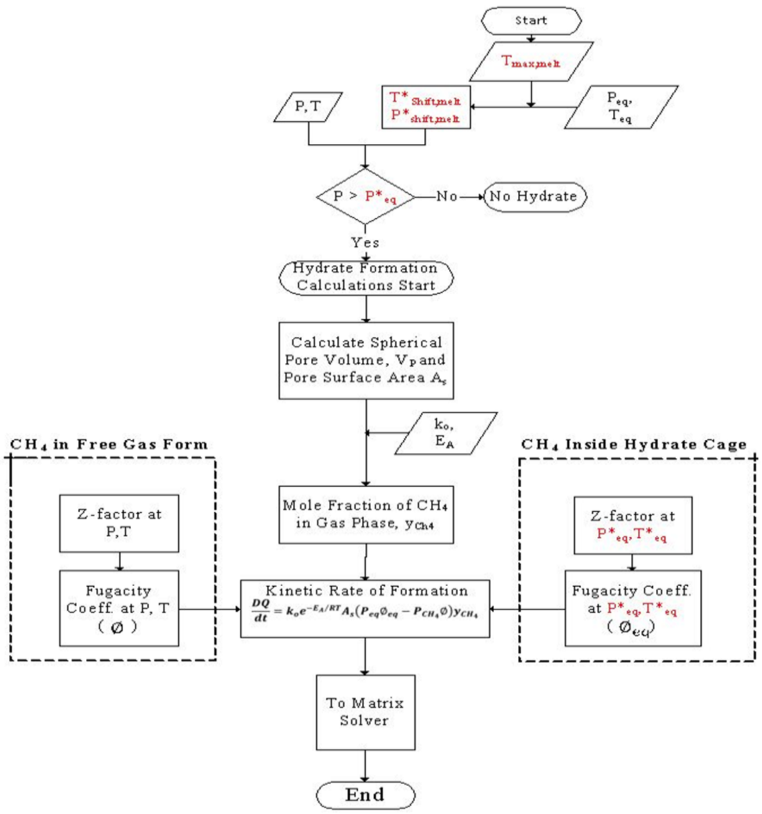

Fig. 4.2.1: Flow chart for Implementing Hysteresis into Tough+Hydrate. Necessary changes in the algorithm due to the presence of hysteresis is shown in red.

Subtask 4.3 Development of Geological Model

We used the geological model based on the axisymmetric domain for Site UBGH2-6 in the Ulleung Basin, which was constructed at the previous quarter. Refer to the previous quarterly report for more details.

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 previously.

Subtask 5.2 Validation with experimental tests of depressurization

Continuing the previous work, we are 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.

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

Continuing to the previous work, we are working on the coupling the fracturing simulator of ROCMECH with TOUGH+Hydrate.

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

Continuing the previous quarter, we have been testing the field-wide simulation of two-way coupled flow and geomechanics for the UBGH2-6 site located in Ulleung Basin from the geological model made in Subtask 4.3.

We have further investigated the behavior of flow and geomechanics for two different values of bottom hole pressure (BHP). From Fig.5.5.1 we identify that low BHP results in fast dissociation of the gas hydrate, inducing fast depressurization. As a result, shown in Fig. 5.5.2, low BHP causes substantial changes in geomechanical behavior.

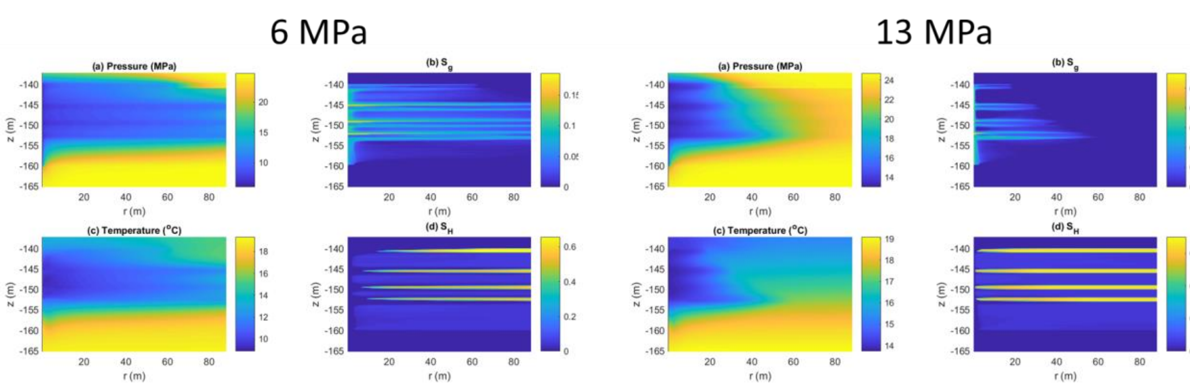

Fig. 5.5.1 Distributions of pressure (a), gas saturation (b), temperature (c), and hydrate saturation (d) after 150day production for BHP (bottom hole pressure) of 6MPa (left) and 13MPa (right)

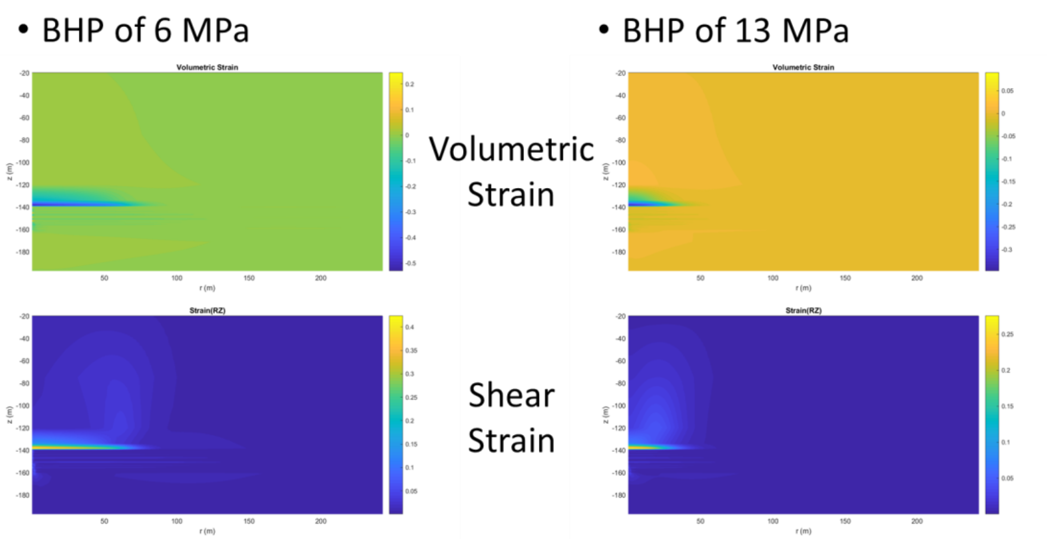

Fig. 5.5.2 Distributions of volumetric (top) and shear (bottom) after 150day production.

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 participated in the AGU (American Geophysical Union) Fall Meeting 2018, and given a presentation related to this project as part of Tech-Transfer activities, as follows.

Yoon, H.C., Kim, J., Lee, J.Y., Field-wide Simulation and Analyses of the Geomechanical Responses Different Depressurizations for the Gas Hydrate Deposit Located in Ulleung Basin, South Korea, AGU (American Geophysical Union) Fall Meeting 2018, Washington D.C., 10-14 Dec. 2018

The fund was acknowledged in the talk in the conference.

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 12/31/2018. The expenditure by TAMU and cost-share from KIGAM are accurate while the expenditure by LBNL might not be accurate. 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		
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	3/31/2019		
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						
Federal (LBNL)	$3,255	$3,255						
Non-Federal Cost Share	$6,986	$6,986						
Total incuured cost	$56,579	$56,579						
Variance								
Federal (TAMU)	$2,795	$2,795						
Federal (LBNL)	($15,495)	($15,495)						
Non-Federal Cost Share	$0	$0						
Total variance	($12,700)	($12,700)						

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