NATIONAL ENERGY TECHNOLOGY LABORATORY
OIL & GAS

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Quarterly Research Performance Progress Report
(Period Ending 09/30/2017)

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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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 the fourth quarter of 2017 are listed as follows along with Table 2.

Task 1: Project management and planning

The third quarterly report was submitted to NETL at July 25. The Budget Period 1 to 2 transition meeting with TAMU, LBNL, KIGAM, NETL was held at July 27. Tasks 2.1 and 2.4 are completed. The corresponding cost-share of the data was also carried out by KIGAM. Task 3.1 is still ongoing due to delay of initial account activation and of device delivery. Task 5.1 is also completed by TAMU. The specific status of the milestones is shown in Table 2.

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

We have completed Subtasks 2.1 and 2.4. We are working on reviewing the data of Subtask 2.2.

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

This task is completed. The description of the experimental set-up and some results was shown in the previous quarterly report. The results data of the experiment are stored in the Excel file, which was sent to TAMU.

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

We initiated this task. We have been reviewing a 10-m scale experimental study, as follows. In this experiment, a 10 meter-scale apparatus was developed to simulate the depressurization-induced gas hydrate production one dimensionally in the field-scale. We investigated the gas production behavior from the viewpoint of the dominating factor by observing the pressure, temperature, and gas production over time in the depressurizing process. The 10 meter-scale apparatus was composed of four major modules, which are tube reactor, fluid control unit, data acquisition unit, and temperature control unit. Fig. 2.1 presents a schematic diagram of the experimental apparatus. The tube reactor in which the unconsolidated sedimentary sample is located is sequentially combined with six steel tubes of 2 m long. The dimensions of the sediment sample are 1.67 cm of the diameter and 13.3 m of the length. Seven K-type thermocouples (from T_1 to T_7) and seven pressure transducers (from P_1 to P_7) for the internal temperature and pressure measurement, respectively, of the sample are equipped at regular intervals in the tube reactor. Each tube is modularized to easily expand the scale of the sample. In the injection module, two syringe pumps were used to inject water into the sample and to control system pressure using a dome-type back pressure regulator. Mass flow controllers were used to inject methane gas into the system. A wet test meter and a balance were used for the calculation of gas and water saturation change, respectively. We developed a data acquisition module to control the injection module and acquire the data using LabVIEW in real time, during the whole sequence of experiments. The temperature of the sample was controlled by circulating coolants through the outer space of the tube reactor.

We used artificial particles that mimic the grain-size distribution of hydrate-bearing sandy layers found in the Ulleung Basin, East Sea, Korea. The hydrate-bearing sand column was prepared using the following procedure. First, the dry particles were slowly poured into the vibrated tube reactor, and then the packed sample was fully saturated through water, of which porosity and absolute permeability were measured during this process. Second, the methane hydrate was formed at the state of initial water saturation; this state could be obtained by increasing the rate of methane injection into the sample.

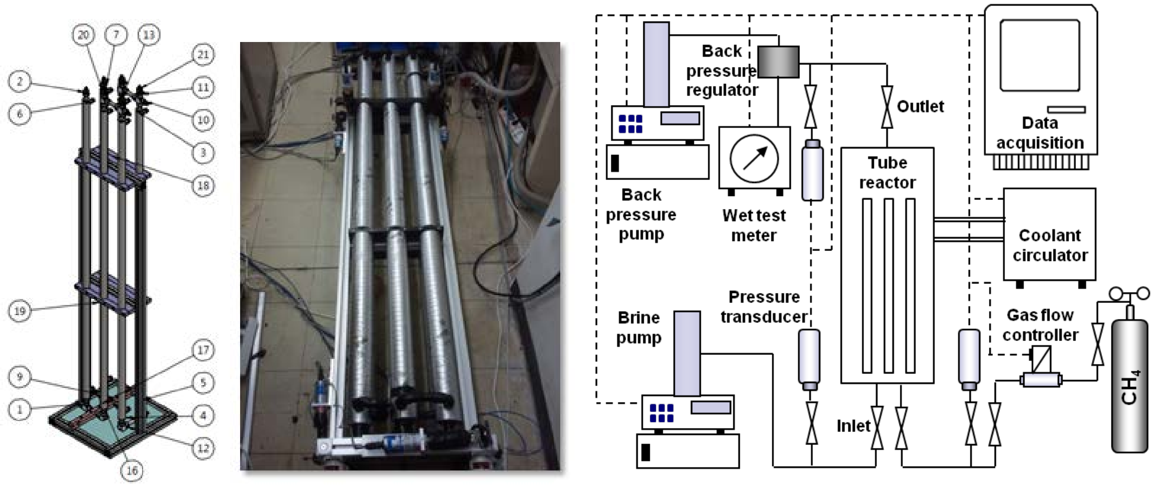


Fig 2.1. Experimental setup for 1D 1-m scale GH production

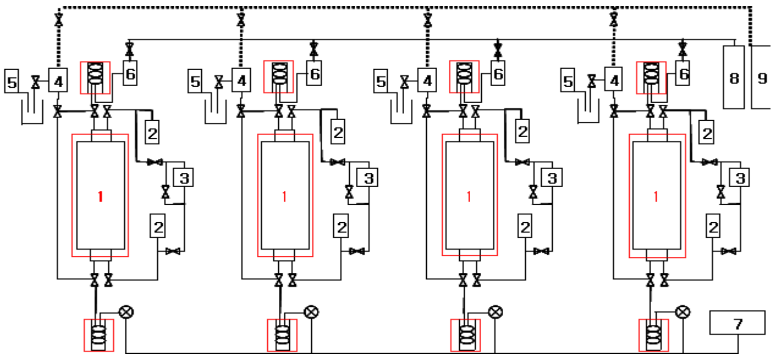
Subtask 2.3 Evaluation of Gas hydrate depressurization experiment of 1.5-m scale system in 3D

Not initiated (future year tasks)

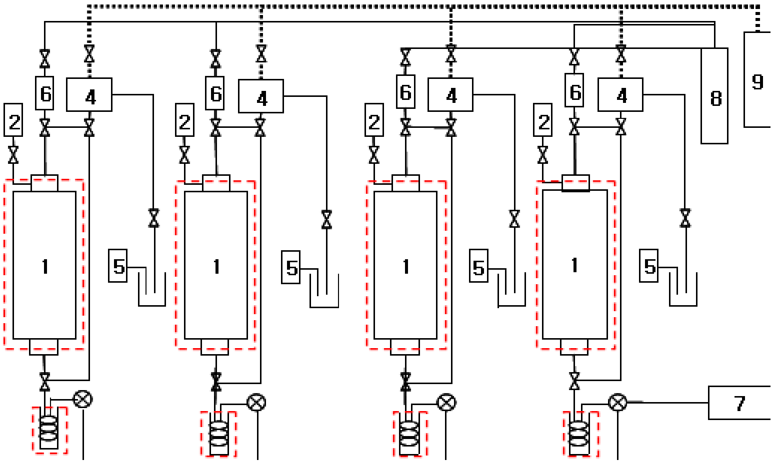
Subtask 2.4 Evaluation of gas hydrate production experiment of the centimeter-scale system

This task is completed. The description of the experimental set-up and some results was shown in the previous quarterly report. The results data of the experiment are stored in the Excel file, which was sent to TAMU.

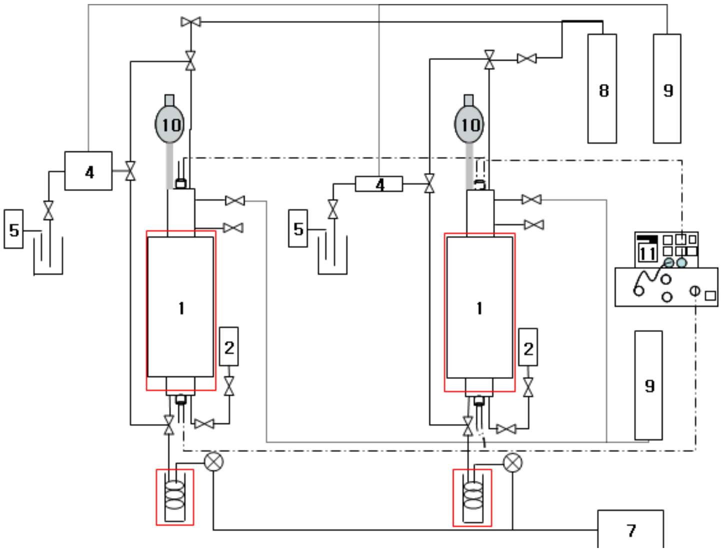
Here, to explain the experiment further, we add the schematics of four units of the experiment: pressure vessels, the data acquisition unit, the flow and pressure control unit, and the temperature control unit (Fig. 2.2).



(a) Permeability measurement system of hydrate-bearing sediments



(b) Resistivity measurement system of hydrate-bearing sediments



(c) P-wave measurement system of hydrate-bearing sediments

Fig. 7. Property measurement systems (1. Sand column 2. Heise Transducer, 3. Differential Pressure Transducer, 4. Back Pressure Regulator, 5. Mass Flow Meter, 6. Mass Flow Controller, 7. Reciprocating Pump, 8. CH4 Cylinder, 9. Syringe Pump, 10. Displacement gauge, Red Rectangles: Temperature controlled unit)

Task 3: Laboratory Experiments for Numerical Model Verification

Subtask 3.1: Geomechanical changes from effective stress changes during dissociation

Subtask Description: In this task, methane hydrate will be formed in the porespace of a porous medium sample in a elastomer sleeve in an X-ray transparent pressure vessel. The sample will be subject to an initial effective stress. We envision that the initial sample will be a fine sand, with subsequent samples containing finer fractions, however will seek feedback from the modelers to design the optimum set of tests. Gas hydrate will be formed in the sand, and the sample resaturated with water. Trying to quantitatively match changes in subsurface effective stress under depressurization conditions, we will increase effective stress while depressurizing the sample, and producing gas from the hydrate. Sample size changes will be indicated using X-ray CT and confining fluid volume changes. Sand production will be prohibited by disallowing sand flow in the tubes.

Update and Progress: We have faced two issues in completing this task. The first is mechanical, in that our cooling jacket would not seal. We planned to perform these tests in our new hydrate pressure vessel allowing larger samples and thus better understanding of the system geomechanics. An ineffective design for the cooling jacket on the new vessel has limited work, resulting in setting up and using an older, smaller vessel while this cooling jacket problem is resolved. Several fixes have been attempted, delaying tests. The second issue has been personnel availability. We have remedied this issue by recently hiring an experienced hydrate researcher to support these tests. He is currently undergoing safety and on-the-job training. We anticipate our first test to begin within 10 days. Significant modifications are **not** needed to shift into subtask 3.2, so we do not expect further delays once in operation.

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

Not initiated (future year tasks)

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

Not initiated (future year tasks)

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

Not initiated (future year tasks)

Subtask 3.5 Identification of Hysteresis in Hydrate Stability

We performed experiments to investigate hysteresis in hydrate stability. Figs. 3.1 and 3.2 show the experiment setup, apparatus, and schematics of the cylinder. We took the following procedure of the experiment:

1. Pressurized the Cell

2. Reduce the temperature
3. Form hydrates
4. Heat the cell to melt hydrates
5. Repeat the procedure

Figs. 3.3-3.6 show the results of different cooling temperatures, summarized in the following table. From the results, we found the followings: (1) When methane hydrates melt at moderate temperatures, the solution retains a structural memory-effect in pore-space. (2) The system with previous hydrate history will lose its memory if the system is heated sufficiently high, in our case up to 40℃. (3) The hydrogen bond strength is dependent on the temperature, thus higher temperature effectively destroys more hydrate cages in the system.

	Initial Temperature	Hydrate Formation Temperature
Initial Hydrate Formation	25°C	2.84°C
2nd Subsequent Experiment	17°C	8.71°C
3rd Subsequent Experiment	25°C	8.32°C
4th Subsequent Experiment	35°C	8.49°C
5th Subsequent Experiment	40°C	3.40°C

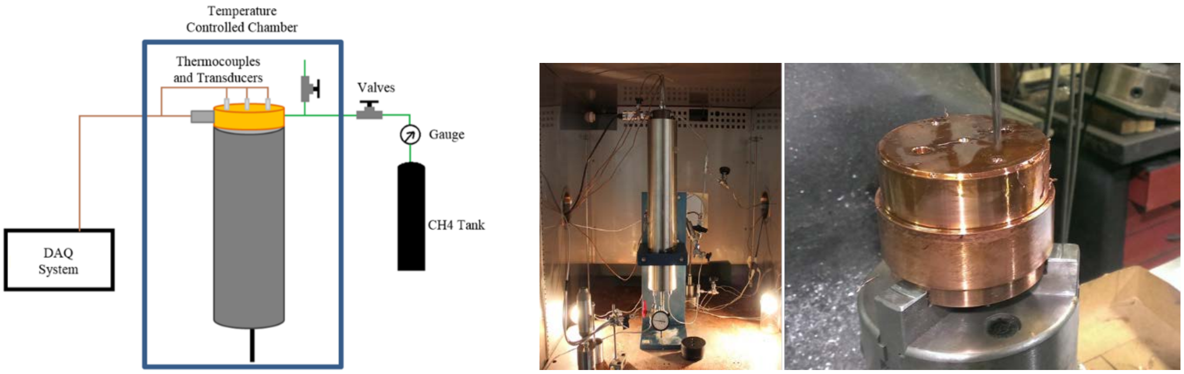
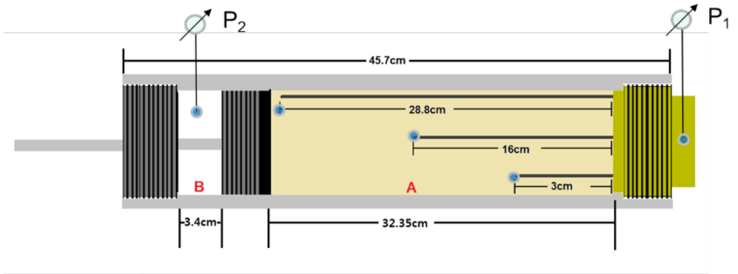


Fig. 3.1 Left: Experiment setup. Right: Apparatus



- 1,200cm^3 of sand
- 36.2% porosity
- 50% water, 50% methane (217.2 cm^3)

- A – Pore Space
- B – Empty Space filled with Water

Fig. 3.2 Schematics of the cylinder

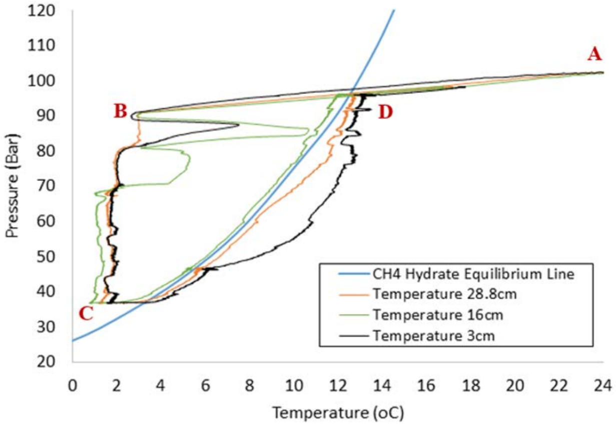


Fig. 3.3 Cooling from 25℃ to 1℃. A: Experiment Start, AB: Cooling, BC : Hydrate formation, CD : Heating. Hydrate formation was observed at 2.84 ℃.

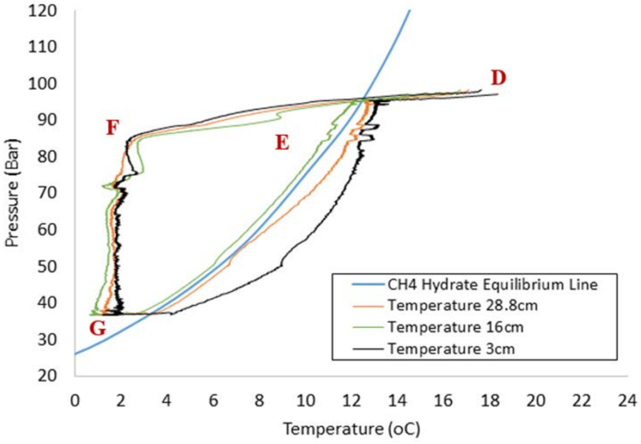


Fig. 3.4 Cooling from 17℃ to 1℃. DF: Cooling, E: Hydrate formation, FG: Onset of hydrate formation, Thermocouple at 16cm closely follows the equilibrium line. Reformation of hydrates was found at 8.71 ℃.

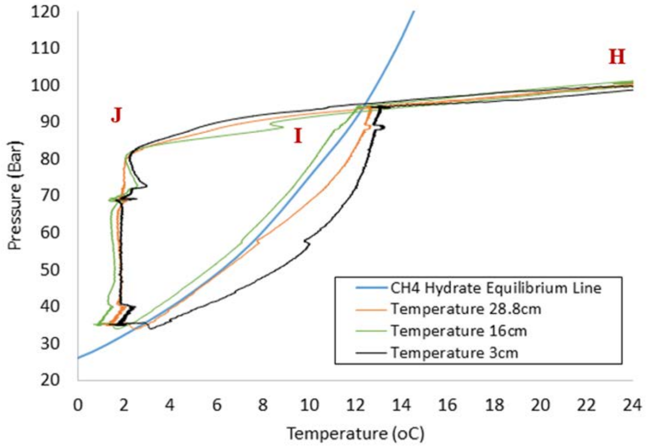


Fig. 3.5 Cooling from 25℃ to 1℃I : Onset of Hydrate Formation. Hydrate formation was found at 8.32 ℃.

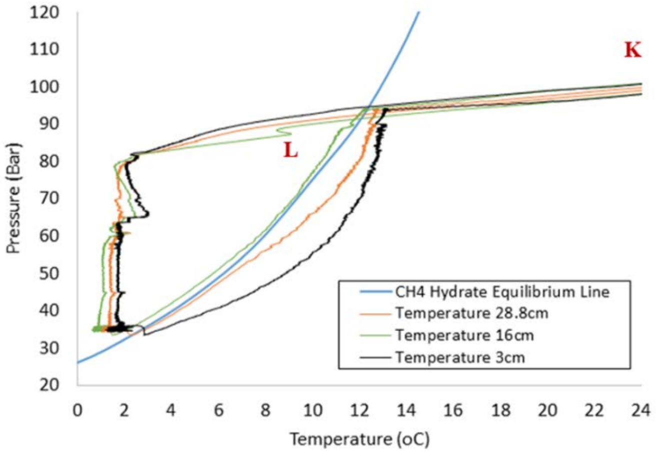


Fig. 3.6 Cooling from 35℃ to 1℃. L : Onset of Hydrate formation at 8.49 ℃

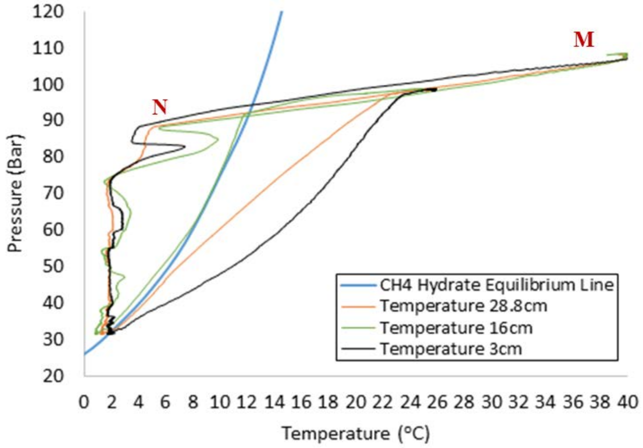


Fig. 3.6 Cooling from 40℃ to 1℃. N : Onset of Hydrate re-formation at 3.40 ℃

Task 4: Incorporation of Laboratory Data into Numerical Simulation Model

Subtask 4.1 Inputs and Preliminary Scoping Calculations

We have initiated post-processing the experimental data of Subtasks 2.1 and 2.4. The processed data will be used for validation of T+M^{AM}, Subtask 5.2. We are also performing processing the data of Subtask 3.5 for numerical simulation.

Subtask 4.2 Determination of New Constitutive Relationships

We keep updating TOUGH+Hydrate, modifying the subroutines of the hysteretic capillarity and relative permeability.

Subtask 4.3 Development of Geological Model

Not initiated (future research work)

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 is completed. We have completed the coupling between largely deformable geomechanics and TOUGH+Hydrate (T+M^{AM}). Specifically, the two codes were made for both regular and cylindrical coordinates. In particular, the code for axisymmetric geometry is used for the following Subtask 5.2.

Subtask 5.2 Validation with experimental tests of depressurization

After verification of the axisymmetric geomechanics-only code, we are verifying and validating the codes of coupled TOUGH+Hydrate and largely deformable geomechanics (T+M^{AM}).

Subtask 5.3 Modeling of sand production and plastic behavior

Not initiated (future task).

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

Currently, we are coupling TOUGH+Hydrate (flow simulator) to this fracture propagation simulator. Specifically, we are using dual meshes (Voronoi grid for flow and triangle grid for geomechanics). This dual grid meshes provide orthogonal flow at a flow interface, reducing convergence issues in flow simulation.

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

Continuing with the previous progress, a new Ph.D student is working on simulations of PBU L106-C unit and Ulleung Basin. Specifically, we have been reviewing the data of the previous simulation and are re-producing the simulation, first using the coupled TOUGH+Hydrate-FLAC3D simulator. Later, we will compare this simulation with the results of T+M^{AM}.

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

After the progress of the previous quarter, no further progress was made during this period of July 1~September 30. Note that this task is the last task on this project.

PRODUCTS

No further products have been made since July 1, 2017.

BUDGETARY INFORMATION

Table 3 shows the information of the budget for this project and the expenditure up to 09/30/2017. The cost share of Tasks and 2.4 related to the experimental data was carried out by KIGAM.

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		
Milestone D	Complete analysis of 1.5m-scale experiment in 3D			
Task 3 Milestones				
Milestone E	Complete geomechanical changes from effective stress changes during dissociation and construction of the relative permeability data	9/30/2017		Delayed. (Activation of the account of BP1 was delayed for one quarter.)
Milestone F	Complete geomechanical changes from effective stress changes during dissociation (sand production) and hysteresis in hydrate stability	9/30/2018		
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		
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		
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	$0	$0
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	$211,153	$292,446
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)	($18,750)	($75,000)
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)	($498,789)	($634,382)

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)								
Federal (LBNL)								
Non-Federal Cost Share								
Total incuured cost								
Variance								
Federal (TAMU)								
Federal (LBNL)								
Non-Federal Cost Share								
Total variance								

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)								
Federal (LBNL)								
Non-Federal Cost Share								
Total incuured cost								
Variance								
Federal (TAMU)								
Federal (LBNL)								
Non-Federal Cost Share								
Total variance								

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