Oil & Natural Gas Technology

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Quarterly Research Performance

Progress Report (Period Ending 6/30/2019)

Dynamic Behavior of Natural Seep Vents: Analysis of Field and Laboratory Observations and Modeling

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

Submitted by:
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U.S. DEPARTMENT OF ENERGY | NATIONAL ENERGY TECHNOLOGY LABORATORY

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1 Accomplishments

1.1 Summary of Progress Toward Project Objectives

The *overarching goal* of this project is to develop a computer model to predict the trajectory and dissolution of hydrate-armored methane bubbles originating from natural seeps. The model is based on the Texas A&M Oilspill (Outfall) Calculator (TAMOC), developed by Dr. Socolofsky, and which has been refined and validated through this project to explain fundamental laboratory and field observation of methane bubbles within the gas hydrate stability zone of the ocean water column. *Our approach* is to synthesize fundamental observations from the National Energy Technology Laboratory's (NETL) High-Pressure Water Tunnel (HPWT) and field observations from the Gulf Integrated Spill Research (GISR) seep cruises (cruises G07 and G08), conducted by the PIs in the Gulf of Mexico, to determine the dissolution pathways and mass transfer rates of natural gas bubbles dissolving in the deep ocean water column. We will achieve these objectives by pursuing the *following specific objectives*:

1. Analyze existing data from the NETL HPWT.
2. Synthesize data from the GISR natural seep cruises.
3. Refine and validate the seep model to predict available data.
4. Demonstrate the capability of the seep model to interpret multibeam data.

Ultimately, the *main outcome and benefit* of this work will be to clarify the processes by which hydrate-coated methane bubbles rise and dissolve into the ocean water column, which is important to predict the fate of methane in the water column, to understand the global carbon cycle, and to understand how gas hydrate deposits are maintained and evolve within geologic and oceanic systems, both at present baselines and under climate-driven warming.

During this reporting period, we focused on Tasks 6 and 7 and continued working on Task 8. For Task 6 (Apply seep model to GISR Multibeam data), we have been analyzing the EM-302 acoustic data and creating figures for a major journal manuscript reporting on the results of our G08 cruise. This work is finalizing the results for Subtask 6.2. For Task 7 (Document model validation), the major effort is to prepare journal manuscripts that summarize the results of our project. During the present reporting period, we have been working on a paper for *Geophysical Research Letters* that will report the results of Task 6 and another paper related to the NETL HPWT data (Tasks 2

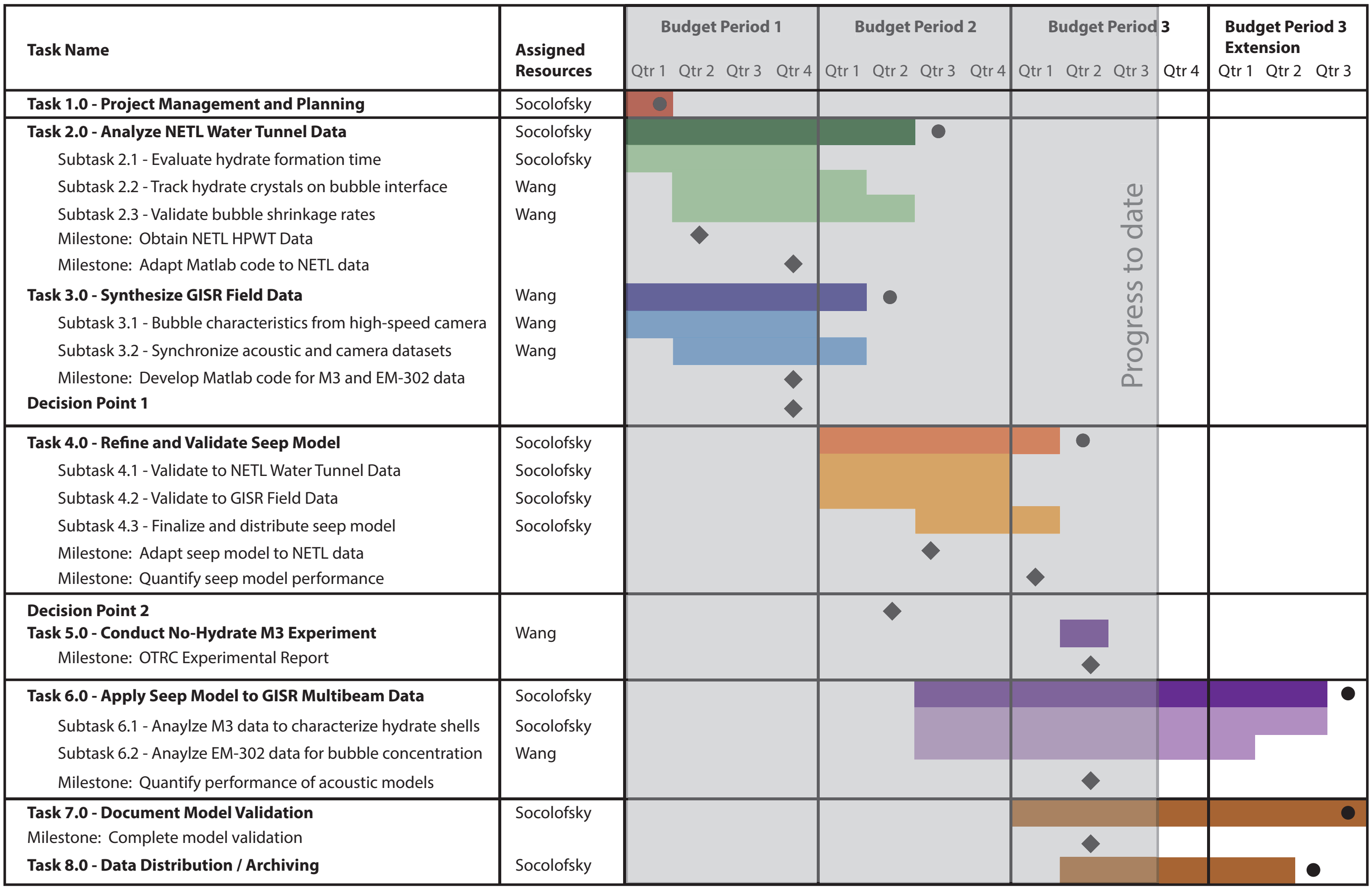

Figure 1: Project Timeline.

and 4) that we plan to submit to *Journal of Geophysical Research–Oceans*. A detailed report of our progress on each of these tasks for the present performance period is reported herein and in the Milestone report for Task 6.

1.2 Progress on Research Tasks

Figure 1 presents the project timeline, showing each of the project tasks, subtasks, and milestones as identified in the Project Management Plan (PMP). During the present reporting period, we were granted a no-cost extension that extends the project until June, 2020. Figure 1 has been updated to reflect the additional three quarters during the extension to Budget Period 3. Project Tasks 6 through 8 will continue into the extension. As of the previous reporting period, each of the Milestones identified in the PMP were completed. The remaining three deliverables are planned for the second (Task 8) and third (Tasks 6 and 7) quarters of the Budget Period 3 Extension. The summary of the completed work together with work conducted on these ongoing tasks during the present reporting period is summarized in the following sections.

1.2.1 Task 1.0: Project Management Planning

The Project Management Plan was completed during the first quarter of Phase 1 and accepted in final form as of October 28, 2016.

1.2.2 Task 2.0: Analyze NETL Water Tunnel Data

In this project, we have analyzed the comprehensive data set of HPWT data collected by NETL. To do this, we have transfered a complete copy of all raw data (primarily image files and time history data of pressure and temperature in the HPWT during each experiment) to Texas A&M University and have installed this data on a secure internal server. Data transfer was completed on March 24, 2017, and achieved Milestone 1 for the project (Obtain NETL HPWT Data). Task 2 was completed as of June 30, 2018. The sections below summarize the key results obtained for each of the Subtasks of this Task.

Subtask 2.1 - Evaluate Hydrate Formation Time

This subtask was completed as of September 30, 2017, and all of the post-processed data has been submitted with the report for Decision Point 1 (see § 1.2.4). In this task, we identified the moment that hydrate skin coverage was completed for each bubble in the experiments as well as for key moments when the hydrate dynamics changed. For a complete description of the data analysis for this subtask and the post-processed results, see the full report for Decision Point 1.

Subtask 2.2 - Track Hydrate Crystals on Bubble Interface

This subtask was completed as of December 31, 2017, and a complete analysis of the results with conclusions was submitted with the first-quarter progress report of FY2018. For this task, we analyzed all of the high-speed camera data for gas bubbles with hydrate shells to track the motion of hydrate plates when the hydrate coverage was not 100%. We found two main types of behavior. First, when hydrate plates are large and their spacing is non-uniform, the plates are observed to translate across the leading edge of the bubbles. The mean speeds of this hydrate shell movement was 10 cm/s, with peak speeds close to the rise velocity of bubbles (20 cm/s). Second, during hydrate dissociation, when many, small hydrate crystals cover the bubble surface in a quasi-uniform distribution, the hydrate particles are not observed to translate over the surface of the bubble. Instead, they remain knitted together, and the boundary condition at the bubble/water interface appears to be no-slip.

Based on these observations, we anticipate that mass transfer rates for the large hydrate shells that move across the leading edge of the bubble will be higher than for dirty bubbles; whereas, we expect the mass transfer rates for hydrate-coated bubbles and cases with small hydrate particles uniformly distributed over the bubble surface to be similar to dirty bubbles or slower. Because the system pressure inside the HPWT was not constant during these events, we will evaluate these mass transfer rates in the context of Task 4 as we compare the model results to these data.

Subtask 2.3 - Validate Bubble Shrinkage Rates

This subtask was completed as of April 30, 2018, and has been reported in several quarterly reports through the project performance period. We adapted our Matlab image analysis program for bubble size evaluation to the NETL HPWT dataset and compared our results for bubble size to those reported by NETL in their report by Levine et al. (2015). Although there were small differences in our computed sizes, these are attributable to different choices in the cut-off and cut-on criteria for identifying the bubble edge and were negligible in comparison to the inherent variability in the data due to bubble motion. This variability is primarily caused by two factors: 1.) rotation of the bubbles when they have non-spherical shape and 2.) changes in the image magnification as the bubbles move toward and away from the camera. Both factors lead to experimental error in the computed bubble sizes. We evaluated this error by analyzing long data sets in sequentially shorter sample periods. Our analysis concluded that bubble shrinkage rates are converged after a minimum of 500 s of sampling, as this is adequate time for the bubble to wander about the whole measurement volume and experience several rotations. These data will be used extensively in Task 4 as we validate the shrinkage rate predictions of the model to those measured in the HPWT.

Progress Toward Milestones

Milestone 1 (Obtain NETL HPWT Data) was completed on March 24, 2017, and Milestone 2 (Adapt Matlab Code to NETL Data) was completed on September 26, 2017. These Milestones conclude the Milestones associated with Task 2.

1.2.3 Task 3.0: Synthesize GISR Field Data

The project PIs conducted two research cruises to natural seeps in the Gulf of Mexico under funding to the GISR consortium. These were the G07 cruise in July 2014 to Mississippi Canyon (MC) block 118 and to Green Canyon (GC) block 600 and the G08 cruise in April 2015 to MC 118. Both cruises were on the *E/V Nautilus* and utilized the remotely operated vehicle (ROV) *Hercules*. This project utilizes two main datasets from these cruises: data from our stereoscopic high-speed camera system mounted on the ROV (Wang et al. 2015) and acoustic data collected by an M3 sonar mounted on the ROV and an EM-302 multibeam sonar mounted on the haul of the ship. The image data from the G07 cruise was analyzed previously and reported in Wang et al. (2016). This project analyzes all of the acoustic data and performs a complete analysis of the image data for the G08 cruise. This task was completed as of December 2017, and the outcomes of each subtask are reported below.

Subtask 3.1 - Bubble Characteristics from High-Speed Camera.

This subtask was completed as of September 30, 2017, and all of the post-processed data were submitted with the report for Decision Point 1 (see § 1.2.4). In this task, we have analyzed images from our high-speed, stereoscopic image system to compute bubble sizes and the rise velocities of individual bubbles. For a complete description of the data analysis for this subtask and the post-processed results, see the full report for Decision Point 1.

Subtask 3.2 - Synchronize Acoustic and Camera Datasets.

This subtask was completed as of March 31, 2018. Data from the cameras and acoustic measurements have been reported separately. The image data include bubble size distributions and rise velocity, and are reported in the report for Decision Point 1. The acoustic data have been analyzed to predict the *in situ* target strength, which is a measure of the acoustic backscatter from the bubbles within each sample volume. This work was reported in the report for Milestone 3. The final output of this subtask was a calibration curve relating the observed bubble characteristics to the target strength measured by the M3 and EM 302 multibeam sonars. The calibration curve for the EM 302 was reported in our report for Milestone 3, and the calibration curve for the M3 was included in our quarterly report for the second quarter of Phase 2. These data along with results of Task 5 (OTRC experiment) will be used in Task 6 to evaluate the seep model at the field scale.

Progress Toward Milestone

Milestone 3 (Develop Matlab Code for EM 302 and M3 Data) was completed on September 29, 2017. This Milestone concludes the Milestones associated with Task 3.

1.2.4 Decision Point 1

The report for Decision Point 1 was completed and submitted as of October 31, 2017. Based on successful completion of the go/no go success criteria for Decision Point 1 outlined in the PMP, we were granted permission to continue into project Phase 2 and begin work on Task 4.

1.2.5 Task 4.0: Refine and Validate Seep Model

Since the Deepwater Horizon accident, the project PIs have been developing a numerical model to predict the fate of petroleum bubbles and droplets in the ocean water column. This model is called the Texas A&M Oil spill Calculator (TAMOC), and is freely available through `https://github.com/socolofs/tamoc`. This model can compute the dissolution of a natural gas bubble in the ocean water column, and prior to this project, had been applied to study the fate of methane released from natural gas seeps along the continental slope of the Gulf of Mexico. In this project, we applied this numerical model to simulate the experiments in the NETL High-Pressure Water Tunnel (HPWT; see Task 2) and the field observations from the GISR expeditions (see Task 3). These simulations are used to validate our model for the formation time of hydrate skins of natural gas bubbles within the hydrate stability zone of the oceans and our equations for mass transfer from bubbles with and without a hydrate skin. This model is important to predict the distribution of methane in the ocean water column from natural seeps, accidental oil well blowouts, hydrate production, or from gas release caused by anthropogenic or changing climate forcing.

Subtask 4.1 - Validate to NETL Water Tunnel Data.

This subtask was completed as of January 31, 2019. In the NETL HPWT experiments, cameras observed the bubbles over time as they dissolved into the surrounding flow, and these experiments were conducted at different pressure and temperature conditions. Because the pressure and temperature in the HPWT is prescribed by the operator and independent of bubble position (the pressure is controlled by a set of piston pumps and the bubble is held at a constant depth in the water tunnel), we adapted the TAMOC model to allow pressure and temperature to be prescribed functions of time so that we model the exact conditions experienced by a bubble during an experiment. For the model validation, we used the mass transfer coefficients β derived through our work on Task 2, given by

$$\beta = 1.6\beta_{emp} \tag{1}$$

where β_{emp} are the empirical mass transfer coefficients reported in the literature (e.g., Clift et al. 1978). Using these values in the TAMOC model, we evaluated the model performance for predictions of bubble size against the equivalent spherical bubble diameters reported by NETL. The model relative percentage error is 2% or less on average (i.e., very low bias) with a standard deviation of 8% error; this latter value is an estimate of the standard error of the TAMOC model simulations.

Subtask 4.2 - Validate to GISR Field Data.

This subtask was completed as of January 31, 2019. In the GISR field experiments, three observation platforms were used: *in situ* imaging from the stereoscopic imaging system at discrete points from the sea floor to about 250 m altitude and acoustic backscatter measurements from the EM 302 haul-mounted multibeam sonar and from the M3 multibeam sonar mounted on the ROV. In this Subtask, we validated the TAMOC model predictions at the seeps surveyed during the G07 and G08 GISR expeditions to these measured data. We post-processed the raw camera images and acoustic backscatter to yield three derived datasets for model calibration and validation. These were the bubble size distribution and flow rate, which served as initial conditions to the model, the lateral spreading of bubbles in the M3 acoustic images, which provided the lateral turbulent diffusivity used in the model, and the observed height of maximum bubble rise in the EM-302 data, which is the predicted variable used in model validation. In our validation exercise, we showed that the model could predict the rise heights of all seeps surveyed and those we extracted from the literature with an r^2 value of 0.98, a bias of 41 m absolute height (out of rise heights between 400 m and 1800 m), and an average mean percentage error of the rise height prediction of 4.7%. This performance is quite good and exceeds that of other models that are used in the literature to predict natural seep flares.

Subtask 4.3 - Finalize and Distribute Seep Model.

This subtask was completed as of January 31, 2019. We provided the source code of the model with the archive of NETL HPWT simulation results. The model is also maintained as publicly available through the Github code sharing website (see Section 2 Products, below). This concludes the major activity under Task 4.

Progress Toward Milestones

Milestone 4 (Adapt TAMOC model to NETL data) was completed on June 19, 2018. Milestone 5 (Quantify seep model performance) was completed with the quarterly report, submitted in January 31, 2019. These Milestones conclude those associated with Task 4.

1.3 Decision Point 2

The report for Decision Point 2 was completed and submitted as of May 31, 2018. Based on successful completion of the go/no go success criteria for Decision Point 2 outlined in the PMP, we were granted permission to continue into Task 5 (OTRC Experiment).

1.3.1 Task 5.0: Conduct No-Hydrate M3 Calibration Experiment in OTRC

The OTRC experiment was completed as of March 21, 2019. In this experiment, we simulated two different natural seep vents at five different flow rates in the 16.8 m deep, central pit of the OTRC's directional wave basin. We measured the bubble size distribution from an *in situ* CCD camera, water velocity in the plume using a Vectrino II acoustic Doppler velocimeter (ADV), and observed the plumes using an M3 multibeam sonar. Using a tungsten carbide ball bearing, we calibrated the M3 acoustic response, and from the measurements of these simulated natural seeps, we further validated our acoustic models for bubble dynamics in the M3 images.

Progress Toward Milestone

Full details of the OTRC experiment set up and results were provided in the report for Milesone 6 (OTRC experiment report, submitted March 21, 2019). The validation of the acoustic models, which relies in part on the data collected in this experiment, were also reported in the report for Milestone 7 (Quantify, performance of acoustic models; associated with Task 6, below). These Milestones conclude those associated with Task 5.

1.3.2 Task 6.0: Apply Seep Model to GISR Multibeam Echosounder Data

In this Task, we use the seep model validated in Task 4 together with the acoustic data analyzed in Task 2 and refined in Task 5 to evaluate the characteristics of the natural seeps at MC 118 and GC 600. This includes an evaluation of the acoustic signature of hydrate shells that may be present in the M3 acoustic cross-sectional data obtained by the ROV and the water column trajectory and flow rate that may be extractable from the haul-mounted EM 302. Together, these activities will explore the role of hydrate shells on the fate of methane from natural seeps and predict the vertical distribution of methane in the water column originating from these seep sources.

Subtask 6.1 - Analyze M3 Data to Characterize Hydrate Shells.

From the OTRC experiments, we obtained a calibration of the multibeam sonar acoustic response. Knowing this calibrated response, we can then relate the target strength of acoustic backscatter emitted by a source to that source's properties. In this project, we want to relate the target strength of a bubble flare to the void fraction or volume flux in the flare. Since we measured both the flow rate and gas bubble size distribution in the laboratory, we can also directly compute the bubble flare flow rate using the measured TS. We plan to apply this approach to the measurements made during the GISR G08 cruise. During the present reporting period, we have been focused on other Tasks and Subtasks.

Subtask 6.2 - Analyze EM-302 Data for Bubble Concentration.

As reported in previous quarterly reports, we use the manufacturer post-processing algorithms to estimate the target strength of water-column backscatter from the seeps measured during the GISR cruises to MC 118. During the present reporting period, we have been running our validated TAMOC model, using the initial conditions measured by the camera at the seafloor, and comparing the model predictions to the EM-302 data.

Using the stereo camera system, we measured the bubble size distribution at the seafloor and the bubble flow rate. We also measured part of the bubble size distribution at several heights above the seafloor, up to 400 m in altitude. During the present reporting period, we have analyzed the bubble size distributions at each of these measurements and compared them to the TAMOC model predictions. Using these validated bubble flow rate and bubble size data from the TAMOC model, we can then predict the target strength using the sonar equations (see previous quarterly reports and Milestone reports for the sonar equation algorithms).

To accurately predict the target strength, we must also estimate void fraction, which is a measure of the spacing between bubbles. We have shown through analysis of our data and experiments like those conducted at the OTRC, that the bubbles spread out following a diffusive process rather than the linear spreading expected for the buoyant plume. During the present reporting period, we have also analyzed the bubble spreading measured by the M3 and EM-302 to estimate the lateral effective diffusivity acting on the bubbles in the ocean water column. We find the best value across all our measurements is 3×10^{-4} m^2/s for the effective lateral diffusivity.

Finally, we have been refining our methods to extract the acoustic response from the EM-302 dataset. The raw dataset includes background noise, harmonic interference, and signals from surrounding seeps. We have worked to isolate the seeps of interest and to extract only the measured, backscatter response of that seep from the overall dataset for each survey pass of the ship. By doing this, we have significantly reduced the noise of the measured data so that a more rigorous model-data comparison can be made.

We are synthesizing each of these results in a journal manuscript (see Task 7) to be submitted to *Geophysical Research Letters*. This paper will conclude the work planned for this Subtask.

Progress Toward Milestone

Milestone 7 (Quantify performance of acoustic models) was completed as of April 30, 2019, and submitted with the quarterly report to that reporting period. That Milestone concluded all Milestones for Task 6.

1.3.3 Task 7.0: Document Model Validation

In this Task, we document the model validation through reporting to NETL, distribution of the model over Github, and reporting of our findings in journal articles in the peer-reviewed literature.

During the present reporting period, we focused our effort on journal manuscripts stemming from the body of work conducted through this project. These in-progress journal papers and the progress achieved during the present reporting period are summarized as follows:

- "Dynamics of gas bubbles from submarine hydrocarbon seeps within the hydrate stability zone," to be submitted to *Geophysical Research Letters*. This manuscript draft is complete, and we are currently polishing the text. This paper will report the results of Tasks 3 and 6. Much of the work during this reporting period focused on Task 6, in which we have carefully compared the TAMOC model predictions to the camera and acoustic data (see discussion above for Task 6). We expect to submit this paper to the journal in August 2019. A confidential draft of the manuscript can be provided upon request.

- "Modeling the behavior of hydrate-affected bubbles rising in the deep ocean," to be submitted to *Geochemistry, Geophysics, Geosystems*. This manuscript draft is also complete, and we are revising the introduction to better synthesize past work and the context of this work. This paper will also report the results of Tasks 3 and 6, and we plan to submit this paper to the journal in August 2019. A confidential draft of the manuscript can be provided upon request.

- "Predicting natural seep flare heights in the deep ocean," to be submitted to *Journal of Geophysical Research–Oceans*. This manuscript is still in prepration, but is largely complete as it stems from the Ph.D. dissertation of Inok Jun, published in December 2019. This chapter will focus on the results of Tasks 4.2 and 6.

- "Mass transfer rates in high pressure water tunnel experiments for methane and natural gas with hydrate armoring." This manuscript will report the data analysis from Task 2 and model validation of Task 4.1. This paper is in preparation. A major focus of our effort during the present reporting period was on refining some of the analysis for this paper. During Subtask 2.3, we determined that a minimum of 300 s is required before a bubble shrinkage rate estimate from the HPWT begins to converge. As we worked on the introduction to this paper, we reviewed other papers in the literature and realized that bubble shape changes may also impact the time required to achieve converged results. In particular, if an initially ellipsoidal bubble transitions to spherical shape, we expect the mass transfer rate (and also the shrinkage rate) to change. Hence, we determined that we must also ensure that shape changes are not occurring during the span of a single bubble shrinkage rate measurement. Equations in Clift et al. (1978) provide the information necessary to deduce the bubble shape, and we are re-checking our shrinkage rate data with this new insight. Finally, we also investigated characteristic time scales in the measured data to look for predictive reasons why 300 s would be a minimum measurement time before statistical convergence begins. With this final analysis completed, we should be able to draft the complete manuscript during the next reporting period. This paper is intended for submission to the *Journal of Geophysical Research–Oceans*, and will be part of the Ph.D. dissertation of Byungjin Kim.

Each of these manuscripts will be a major portion of our project effort continuing into the remainder of project Phase 3 and the Phase 3 Extension.

Progress Toward Milestone

Milestone 8 (Complete model validation) was completed on April 30, 2019 and verified by the quarterly report for that reporting period. While we may continue to analyze the model results and derive new metrics to assess its performance as we draft the journal papers for Task 7.0, the major advances proposed for this project have been concluded, and the model is now in its final form.

1.4 Deliverables

To date, we have completed the following list of deliverables:

1. **Project Management Plan (PMP)**. The PMP was delivered in its accepted and final form on October 28, 2016.

2. **Data Management Plan (DMP)**. No revisions were requested by the Project Officer to the plan submitted with the proposal; hence, the original DMP is the present guiding document. Revisions will be updated as necessary throughout the project as required by the Project Officer.

3. **Task 2 NETL HPWT Analyzed Data**. The recipient shall provide time series of hydrate formation time, periods of crystal motion on the bubble/water interface, and bubble equivalent spherical diameter to NETL in the format of their choice (ASCII, Matlab, NetCDF, etc.) by the end of Task 2. We have provided these data through the reports for Milestone 2, Decision Point 1, and the quarterly reports.

4. **Task 3 GISR Seep Cruise Analyzed Data**. The recipient shall provide all post-processed analyses of the GISR high-speed camera data for the Gulf of Mexico seep cruises along with time series of corresponding M3 and EM-302 datasets. The camera data shall be provided to NETL in the format of their choice; M3 and EM-302 data shall be provided in the manufacturer raw format. The recipient shall submit these data to NETL by the end of Task 3. We have provided these data through the reports for Milestone 3, Decision Point 1, and the quarterly reports.

5. **Task 4 Validated Seep Model**. The recipient shall provide the refined and validated seep model to NETL. The recipient shall submit the model to NETL by the end of Task 4. We have provided the source code to the validated seep model in the data archive submitted for Milestone 5, Quantify seep model performance.

As of the present reporting period, we have concluded the deliverables for Tasks 2, 3, and 4. The next set of deliverables will be generated at the conclusion of Tasks 6, 7, and 8. Progress toward these deliverables is summarized above in the reporting for each Task.

1.5 Milestones Log

Table 1 presents the schedule of milestones with their verification methods for the duration of the project period. The Table reflects the change to the project schedule such that the OTRC experiment (Task 5) was due in March 2019. Presently, all Milestones identified in the Project Management Plan have been completed.

1.6 Plans for the Next Reporting Period

During the next reporting period, we will continue our work to analyze the GISR acoustic data (Task 6) and to draft the journal papers stemming from this project (Task 7). For Task 6, we will finalize our analysis of all of the EM-302 data and begin preparing the data for dissemination to NETL. We will also focus on Subtask 6.1 (M3 data), and begin deriving a quantitative comparison of the TAMOC model results with the M3 data using the calibration achieved in the OTRC. This is the first step toward seeking a signature of the hydrate shells that may be present in the field data. For Task 7, we will submit two manuscripts and continue drafting the other major manuscripts for this project.

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Table 1: Milestones schedule and verification methods.

	Milestone	Comments
Title	Acquisition of NETL HPWT data	
Date Completed	March 24, 2017	
Verification Method	Email verification	
Title	Adapt Matlab code to NETL data	
Date Completed	September 28, 2017	
Verification Method	Report	
Title	Matlab code for M3 and EM-302 data	
Date Completed	September 29, 2017	
Verification Method	Report	
Title	Adapt seep model to NETL data	
Date Completed	June 19, 2018	
Verification Method	Report	
Title	Quantify seep model performance	
Date Completed	January 31, 2019	
Verification Method	Quarterly Reports and Data Archive	
Title	OTRC Experimental Report	
Date Completed	March 21, 2019	
Verification Method	Report	
Title	Quantify performance of acoustic models	
Date Completed	April 30, 2019	
Verification Method	Report	
Title	Complete model validation	Included in Project Timeline but not in Project Management Plan
Date Completed	April 30, 2019	
Verification Method	Quarterly Reports	

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2 Products

2.1 Publications, Conference Papers, and Presentations

- Kim, B., Socolofsky, S. A., and Wang, B., "Comparison between NETL high pressure water tunnel experiment and numerical modeling for analysis of natural gas bubble behavior in the ocean," abstract published in Gulf of Mexico Oil Spill & Ecosystem Science Conference, New Orleans, LA, February 4-7, 2019. Presented as podium presentation by B. Kim.

- Socolofsky, S. A., Kim, B., Kovalchuk, M., Levine, J., and Wang, B., "Mass transfer rates for hydrate-armored bubbles in the NETL High Pressure Water Tunnel," Poster presented at the Gordon Research Conference on Natural Gas Hydrate Systems, Galveston, Texas, February 25 to March 2, 2018.

- Kim, B., Socolofsky, S. A., and Wang, B., "Hydrate formation time analyzed from data for NETL High Pressure Water Tunnel experiments," Poster presented at the Gordon Research Conference on Natural Gas Hydrate Systems, Galveston, Texas, February 25 to March 2, 2018.

2.2 Websites or Other Internet Sites

The natural seep model used for this project, the Texas A&M Oilspill Calculator (TAMOC), is published via an open source code sharing service at:

http://github.com/socolofs/tamoc

2.3 Technologies or Techniques

Nothing to report.

2.4 Inventions, Patent Applications, and/or Licenses

Nothing to report.

2.5 Other Products

Nothing to report.

3 Participants and other collaborating organizations

3.1 Project Personnel

- 1. **Name**: Scott A. Socolofsky
  2. **Project Role**: Principal Investigator
  3. **Nearest person months worked during reporting period**: 1
  4. **Contribution to Project**: Overall project management and direction. Dr. Socolofsky has led the collection of the HPWT data, directed the data analysis methods, and completed all project reporting requirements.
  5. **Collaborated with individual in foreign country**: No
  6. **Travelled to foreign country**: No
- 1. **Name**: Binbin Wang
  2. **Project Role**: Co-Principal Investigator
  3. **Nearest person months worked during reporting period**: 2
  4. **Contribution to Project**: Analyzed the image data for the G08 cruise, created model for acoustic data from M3 sonar and EM-302 multibeam, and compared the measured data to model results from TAMOC. He also trained the Ph.D. student to begin analysis of the NETL HPWT data.
  5. **Collaborated with individual in foreign country**: No
  6. **Travelled to foreign country**: No
- 1. **Name**: Byungjin Kim
  2. **Project Role**: Ph.D. Student
  3. **Nearest person months worked during reporting period**: 3
  4. **Contribution to Project**: Organized the HPWT data, summarized the existing results from the NETL reports, and analyzed HPWT data for bubble size, hydrate formation time, and bubble interface mobility.
  5. **Collaborated with individual in foreign country**: No
  6. **Travelled to foreign country**: No

- 1. **Name**: Soobum Bae
  2. **Project Role**: Ph.D. Student
  3. **Nearest person months worked during reporting period**: 3
  4. **Contribution to Project**: Soobum Bae is working as an unfunded Ph.D. student to help analyze the HPWT data. He has helped to classify the video image data and to evaluate the hydrate equation of state.
  5. **Collaborated with individual in foreign country**: No
  6. **Travelled to foreign country**: No

  1. **Name**: Inok Jun
  2. **Project Role**: Post-doctoral Scholar
  3. **Nearest person months worked during reporting period**: 1
  4. **Contribution to Project**: Dr. Inok Jun has developed the correlation for hydrate formation time and the methods to identify the height of rise of natural seep flares in the oceans. Though funded from other sources, PI Socolofsky has directed her research to also benefit the present project.
  5. **Collaborated with individual in foreign country**: No
  6. **Travelled to foreign country**: No

3.2 Partner Organizations

None to report.

3.3 External Collaborators or Contacts

This project works in close collaboration with researchers in the DOE/NETL funded project "Fate of Methane in the Water Column," led by the U.S. Geological Survey (USGS) in Woods Hole (Carolyn Ruppel), and with a new project led by the University of Rochester (John Kessler) to advance understanding of the environmental implications that methane leaking from dissociating gas hydrates could have on the ocean-atmosphere system. Dr. Socolofsky visits and communicates with researchers in these projects regularly and shares updates on work in progress. Accomplishments associated with these collaborations are detailed in Section 1.

4 Impact

None at this point.

5 Changes / Problems

Schedule. As reported in previously quarterly reports, we had a delayed start to the project and conducted the OTRC experiment later than planned. As a result of these delays, our project has been granted a no-cost extension through June 2020. We have updated the project timeline in Figure 1, above. We will update the spending plan the Budget Reporting Tables below in the quarterly report for the fourth quarter of Budget Phase 3, once we know the exact amount of funds that will be carried forward into the Phase 3 Extension.

6 Special Reporting Requirements

None required.

7 Budgetary Information

Table 2 reports expenditures for Phase 1 of the project, and Table 3 for Phase 2. Table 4 summarizes expenditures for the current phase (Phase 3) of the project.

Table 2: Budget Report for Phase 1

Baseline Reporting Quarter DE-FE0028895	Budget Period 1 Q1 10/1/16 - 12/31/16		Q2 1/1/17 - 3/31/17		Q3 4/1/17 - 6/30/17		Q4 7/1/17 - 9/30/17	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baseline Cost Plan								
Federal Share	$33,752	$33,752	$29,716	$63,468	$27,810	$91,278	$53,034	$144,312
Non-Federal Share	$12,029	$12,029	$12,029	$24,058	$8,019	$32,077	$4,009	$36,086
Total Planned	$45,781	$45,781	$41,745	$87,526	$35,829	$123,355	$57,043	$180,398
Actual Incurred Cost								
Federal Share	$11,037	$11,037	$22,617	$33,654	$25,957	$ 59,610	$ 69,499	$129,110
Non-Federal Share	$12,029	$12,029	$12,029	$24,058	$8,019	$32,077	$4,009	$36,086
Total Incurred Costs	$23,066	$23,066	$34,646	$57,712	$33,976	$91,687	$73,508	$165,196
Variance								
Federal Share	$-22,715	$-22,715	$-7,099	$-29,814	$-1,853	$-31,668	$16,465	$-15,202
Non-Federal Share	$0	$0	$0	$0	$0	$0	$0	$0
Total Variance	$-22,715	$-22,715	$-7,099	$-29,814	$-1,853	$-31,668	$16,465	$-15,202

Table 3: Budget Report for Phase 2

	Budget Period 1							
Baseline Reporting	**Q1**		**Q2**		**Q3**		**Q4**	
Quarter	10/1/16 - 12/31/16		1/1/17 - 3/31/17		4/1/17 - 6/30/17		7/1/17 - 9/30/17	
DE-FE0028895	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baseline Cost Plan								
Federal Share	$18,473	$162,785	$35,552	$198,337	$22,681	$221,018	$44,423	$265,441
Non-Federal Share	$10,125	$46,221	$10,125	$56,336	$6,750	$ 63,086	$ 3,374	$66,460
Total Planned	$28,598	$208,996	$45,677	$254,673	$29,431	$ 284,104	$47,797	$331,901
Actual Incurred Cost								
Federal Share	$29,427	$158,537	$29,427	$187,964	$28,798	$216,762	$16,441	$233,204
Non-Federal Share	$10,125	$46,211	$10,125	$56,336	$6,750	$ 63,086	$3,374	$66,460
Total Incurred Costs	$39,552	$204,748	$39,552	$244,300	$35,548	$279,848	$19,815	$299,664
Variance								
Federal Share	$10,954	$-4,248.13	$-6,125	$-10,373	$6,117	$-4,256	$-27,982	$-32,238
Non-Federal Share	$0	$0	$0	$0	$0	$0	$0	$0
Total Variance	$10,954	$-4,248	$-6,125,64	$-10,373	$6,117	$-4,256	$-27,982	$-32,237

Table 4: Budget Report for Phase 3

Baseline Reporting Quarter DE-FE0028895	Budget Period 1							
	Q1 10/1/16 - 12/31/16		Q2 1/1/17 - 3/31/17		Q3 4/1/17 - 6/30/17		Q4 7/1/17 - 9/30/17	
	Q1	Cumulative Total	Q2	Cumulative Total	Q3	Cumulative Total	Q4	Cumulative Total
Baseline Cost Plan								
Federal Share	$14,625	$280,066	$14,628	$294,694	$23,288	$317,982	$43,553	$361,535
Non-Federal Share	$8,012	$74,472	$8,012	$82,484	$5,342	$87,826	$2,671	$90,497
Total Planned	$22,637	$354,538	$22,640	$377,178	$28,630	$405,808	$46,224	$452,032
Actual Incurred Cost								
Federal Share	$13,668	$246,872	$28,289	$275,161	$12,563	$287,724	$	$
Non-Federal Share	$8,012	$74,472	$8,012	$82,484	$5,342	$87,826	$	$
Total Incurred Costs	$21,680	$321,344	$36,301	$357,645	$17,905	$375,550	$	$
Variance								
Federal Share	$-957	$-33,194	$13,661	$-19,533	$-10,725	$-30,258	$	$
Non-Federal Share	$0	$0	$0	$0	$0	$0	$	$
Total Variance	$-957	$-33,194	$13,661	$-19,533	$-10,725	$-30,258	$	$

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