U.S. Department of Energy
National Energy Technology Laboratory

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Fate of Methane Emitted from Dissociating Marine Hydrates: Modeling, Laboratory, and Field Constraints

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Recipient Organization:
U.S. Department of Energy
National Energy Technology Laboratory

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Ruben Juanes

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1 Executive summary

Work during this period focused on the following tasks:

- Subtask 2.1: Phase-field modeling of a static gas bubble
- Subtask 3.1: Laboratory experiments — flow-loop design, fabrication and construction
- Subtask 4.1: Quantitative analysis of newly-discovered US Atlantic margin methane plumes

2 Accomplishments

2.1 Major goals and objectives of the project

The overall goals of this research are: (1) to determine the physical fate of single and multiple methane bubbles emitted to the water column by dissociating gas hydrates at seep sites deep within the hydrate stability zone or at the updip limit of gas hydrate stability, and (2) to quantitatively link theoretical and laboratory findings on methane transport to the analysis of real-world field-scale methane plume data placed within the context of the degrading methane hydrate province on the US Atlantic margin.

The project is arranged to advance on three interrelated fronts (numerical modeling, laboratory experiments, and analysis of field-based plume data) simultaneously. The fundamental objectives of each component are the following:

1. Numerical modeling: Constraining the conditions under which rising bubbles become armored with hydrate, the impact of hydrate armoring on the eventual fate of a bubbles methane, and the role of multiple bubble interactions in survival of methane plumes to very shallow depths in the water column.
2. Laboratory experiments: Exploring the parameter space (e.g., bubble size, gas saturation in the liquid phase, "proximity" to the stability boundary) for formation of a hydrate shell around a free bubble in water, the rise rate of such bubbles, and the bubbles acoustic characteristics using field-scale frequencies.
3. Field component: Extending the results of numerical modeling and laboratory experiments to the field-scale using brand new, existing, public-domain, state-of-the-art real world data on US Atlantic margin methane seeps, without acquiring new field data in the course of this particular project. This component will quantitatively analyze data on Atlantic margin methane plumes and place those new plumes and their corresponding seeps within the context of gas hydrate degradation processes on this margin.

2.2 Accomplishments in this reporting period

Work during this period focused on the following tasks:

- Subtask 2.1: Phase-field modeling of a static gas bubble
- Subtask 3.1: Laboratory experiments — flow-loop design, fabrication and construction
- Subtask 4.1: Quantitative analysis of newly-discovered US Atlantic margin methane plumes

A detailed Milestones Status Report is included as Appendix 1.

Task 2.0: Theoretical and computational models of coupled bubble rise and hydrate formation and dissociation

Subtask 2.1: Phase-field modeling of a static gas bubble

Introduction. We construct a phase-field model that describes two-component (H_2O-CH_4), two-phase (liquid-gas) miscible system such as a static methane bubble dissolving into water. At this stage, we do not consider momentum effects so that mass transfer is only a result of diffusion and dissolution. We define the phase parameter ϕ as a phenomenological variable that tracks whether we are in liquid or gas phase at any given position and time. The range of ϕ can be arbitrary; here we take $\phi \in [0, 1]$, where $\phi = 0$ indicates liquid phase and $\phi = 1$ indicates gas phase. We define the concentration C as the mass fraction of methane $C = m_{\mathrm{CH}_4}/m_{\mathrm{total}}$.

Free energy description of the system. We adopt the Ginzurg-Landau free energy (F) for a binary system [Provatas and Elder, 2010]:

$$F = \int_V \left\{ \frac{\epsilon_C(|\nabla C|^2 + |\nabla(1-C|)^2|)}{2} + \frac{\epsilon_\phi(|\nabla\phi|^2 + |\nabla(1-\phi|)^2|)}{2} + f(\phi, C) \right\} dV. \tag{1}$$

The first two terms capture the interfacial energies from composition boundaries and phase boundaries, respectively. ϵ_C and ϵ_ϕ are parameters that set the magnitude of the compositional and gas-liquid interfacial energy. The last term in Eq. **??** describes the bulk free energy density of the system and it takes the form:

$$f(\phi, C) = wT\omega(\phi) + g(\phi) f_{\mathrm{gas}}(C) + (1 - g(\phi)) f_{\mathrm{liquid}}(C). \tag{2}$$

The first term in Eq. 2 is the barrier energy associated with the bulk; it depends only on ϕ and is often described using a double-well potential:

$$\omega(\phi) = \frac{1}{4}\phi^2(1-\phi)^2.$$

The rest of Eq. 2 describes the free energy of mixing within each phase, weighted by the blending function $g(\phi)$ such that:

$$g(\phi) = \begin{cases} 1, & \phi = 1 \\ 0, & \phi = 0 \end{cases} \quad \frac{dg}{d\phi} = \begin{cases} 0, & \phi = 1 \\ 0, & \phi = 0 \end{cases} \tag{3}$$

There are many candidates for $g(\phi)$; here we take $g(\phi) = -\phi^2(2\phi - 3)$, as shown in figure 1.

Within each phase, the bulk free energy of mixing (f_{gas} or f_{liquid}) is constructed as a sum of ideal plus excess free energy [Wilson, 1964]:

$$f = f^{\mathrm{ideal}} + f^{\mathrm{excess}} \tag{4}$$

$$\frac{f^{\mathrm{ideal}}}{RT} = C \log C + (1-C)\log(1-C) \tag{5}$$

$$\frac{f^{\mathrm{excess}}}{RT} = -C\log(C + \Lambda_1(1-C)) - (1-C)\log(1 - C + \Lambda_2 C) \tag{6}$$

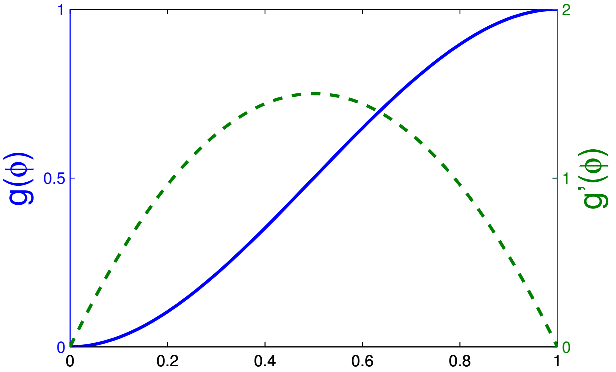


Figure 1: The blending function $g(\phi)$ (in blue) and its derivative $g'(\phi)$ (in green).

We can adjust the parameters Λ_1 and Λ_2 within each phase such that the common tangent construction of the two functions, f_{gas} and f_{liquid}, yield saturation concentrations within each phase that corresponds to experimental measurements. For instance, here we assign $\Lambda_1^{\text{liquid}} = 2.0 \times 10^{-7}$, $\Lambda_2^{\text{liquid}} = 2.0 \times 10^{4}$, $\Lambda_1^{\text{gas}} = 2.0 \times 10^{5}$, $\Lambda_2^{\text{gas}} = 2.0 \times 10^{-8}$. The resulting f_{gas} and f_{liquid} are shown in figure 2. The black line is the common tangent construction for the two free energy functions, showing the solubility of methane in liquid phase ($C_{\text{sat.}}^{liquid} \approx 0.08$) and the dew point of water in the gas phase ($C_{\text{sat.}}^{gas} \approx 0.86$).

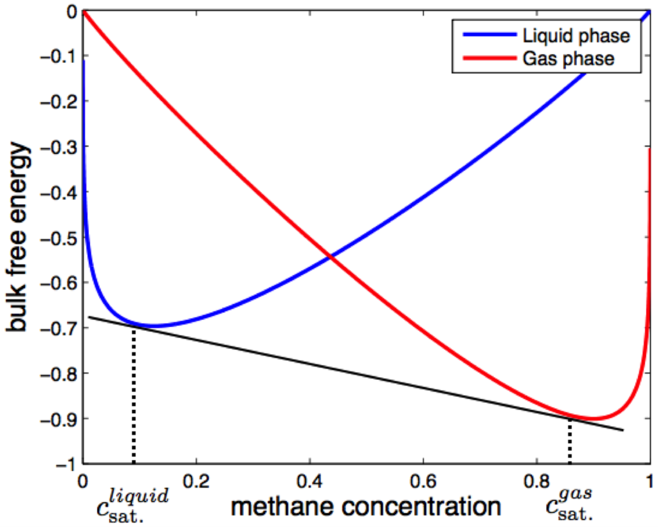


Figure 2: Free energy of mixing within gas and liquid phase and their common tangent construction showing the solubility of methane in liquid phase and the dew point of water in the gas phase.

Figure 3 shows the free energy of mixing (Eq. 2 minus the first term) as a function of ϕ and C; it demonstrates two local minima in this energy landscape at which thermodynamic equilibrium of the system is reached: $\left(C = C_{\text{sat.}}^{liquid}, \phi = 0\right)$ and $\left(C = C_{\text{sat.}}^{gas}, \phi = 1\right)$.

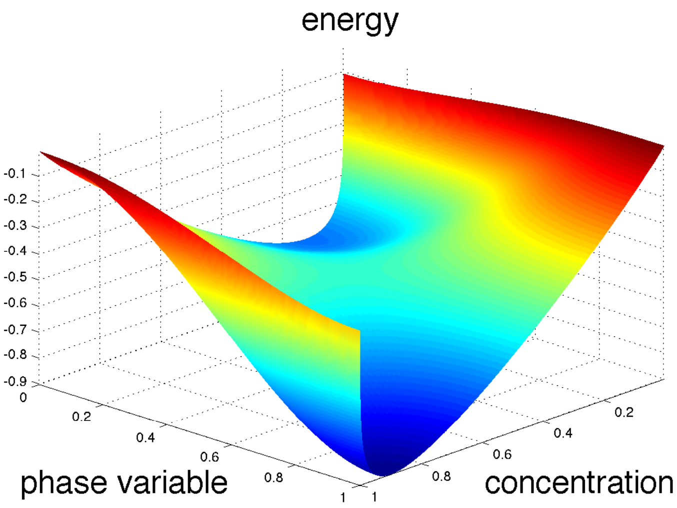


Figure 3: Free energy of mixing as a function of ϕ and C.

Evolution equations. The evolution of this system is driven by two types of potentials. The chemical potential, ψ_{CH_4}, is the rate of change, computed as a variational derivative, of F with respect to C:

$$\psi_{\mathrm{CH}_4} = \frac{\delta F}{\delta C} = \frac{\partial F}{\partial C} - \nabla \cdot \left(\frac{\partial F}{\partial(\nabla C)}\right) \tag{7}$$

Extending the work by van der Waals [van der Waals, 1979], Cahn and Hilliard [1958] proposed that the time evolution of *conserved* phase variable is subject to the interfacial diffusive flux and this flux is proportional to the chemical potential gradient. In a hele-shaw cell without momentum effects, this can be translated into the following evolution equation for C:

$$\frac{\partial[\rho_g \phi C + \rho_l (1-\phi) C]}{\partial t} = \nabla \cdot (\lambda(C) \nabla \psi_{\mathrm{CH}_4}), \tag{8}$$

where ρ_g and ρ_l are the gas and liquid density respectively; $\lambda(C)$ is the chemical mobility that varies with C:

$$\lambda(C) = C(1-C)D,$$

D is the diffusion coefficient of the mixture: $D = D_l + (D_g - D_l)g(\phi)$.

The second potential is the phase potential, ϕ_{gas}, which is the rate of change, computed also as a variational derivative, of F with respect to ϕ:

$$\psi_{\mathrm{gas}} = \frac{\delta F}{\delta \phi} = \frac{\partial F}{\partial \phi} - \nabla \cdot \left(\frac{\partial F}{\partial(\nabla \phi)}\right). \tag{9}$$

The phase variable ϕ defined in this work corresponds to the volume of methane gas in the system, which is a *non-conserved* quantity since it decreases with methane dissolution and vice versa. The simplest evolution dynamics for a non-conserved phase parameter is given by Langevin type equation:

$$\frac{\partial \phi}{\partial t} = -\lambda^{\text{gas}} \frac{\delta F}{\delta \phi}, \tag{10}$$

where the phase mobility, λ^{gas}, is assumed here to be a function of chemical mobility:

$$\lambda^{\text{gas}} = \frac{\lambda(C)}{L^2},$$

where L is the characteristic length of the system.

In the following, we perform numerical simulations of the described system in 1D and 2D. We assume that $\rho_g = \rho_l$ for now; density difference will be incorporated in future simulations. We assume periodic boundary conditions, which allows us to use Fourier methods for spatial discretization. We perform an implicit integration to advance in time.

Simulation results in 1D. We test the model in 1D with an initial condition emulating a saturated methane bubble ($C \approx 0.85, \phi = 1$) submerged in undersaturated water ($C \approx 0.05$, $\phi = 0$), as shown in figure 4. The interface profile of C and ϕ follow a hyperbolic tangent. At early times, we observe rapid and non-smooth transitions at the bubble interface (figure 5b, c). After rapid shrinking during the early time regime, bubble evolution slows down and eventually reaches its thermodynamic steady state where methane concentration increases to its solubility level in water ($C \approx 0.86$ in $\phi = 1$ and $C \approx 0.1$ in $\phi = 0$, as shown in figure 6)

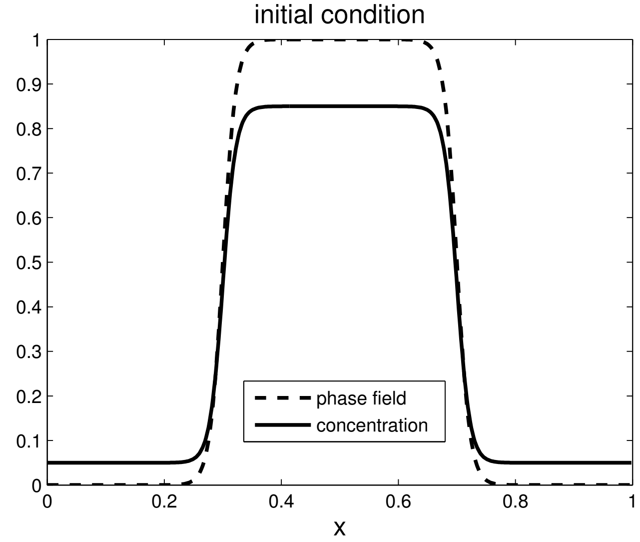


Figure 4: Initial conditions for C and ϕ in 1D emulating a methane bubble about to dissolve partially into surrounding undersaturated water.

Simulation results in 2D. We perform 2D simulations of the model using similar initial conditions in 1D, emulating a methane bubble dissolving into undersaturated water (figure 7). Snapshots of the simulation at an early time point (figure 8) and at steady state (figure 9) demonstrate similar dynamics to what we observe in 1D.

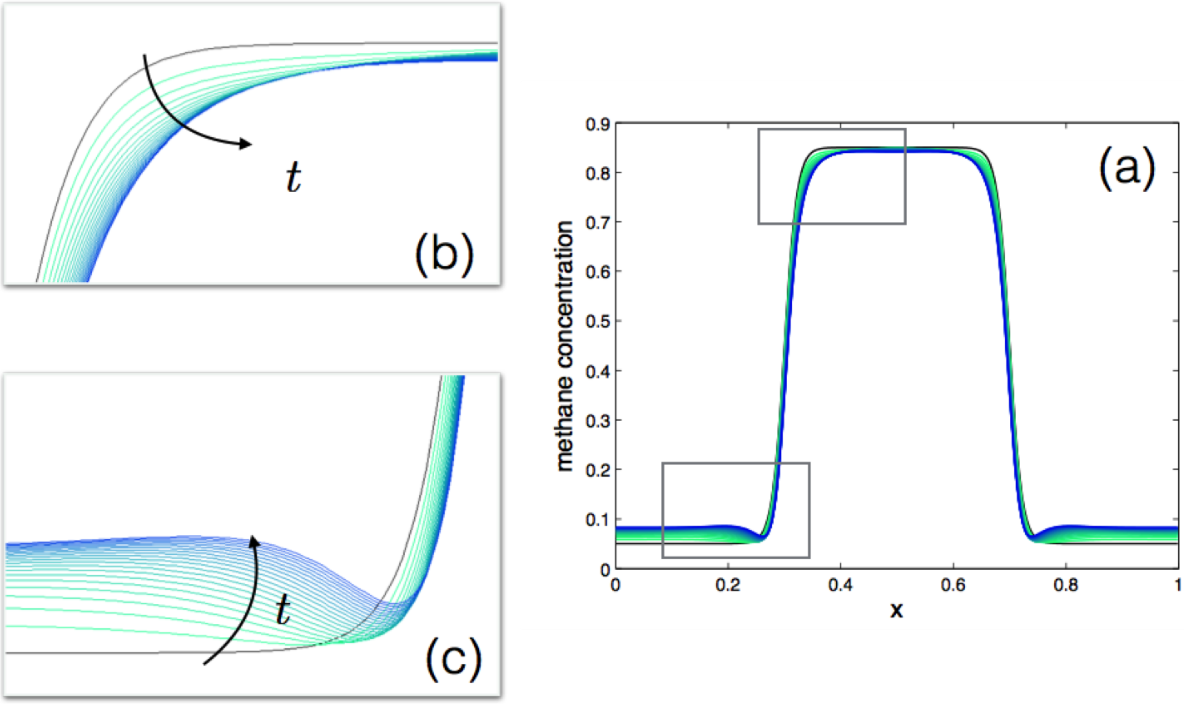


Figure 5: (a) Early time concentration profiles of 1D methane bubble. Black curve is the initial profile; green to blue indicates increasing time; (b) blow up of the concentration profiles at the upper left corner in (a); (c) blow up of the concentration profiles at the lower left corner in (a).

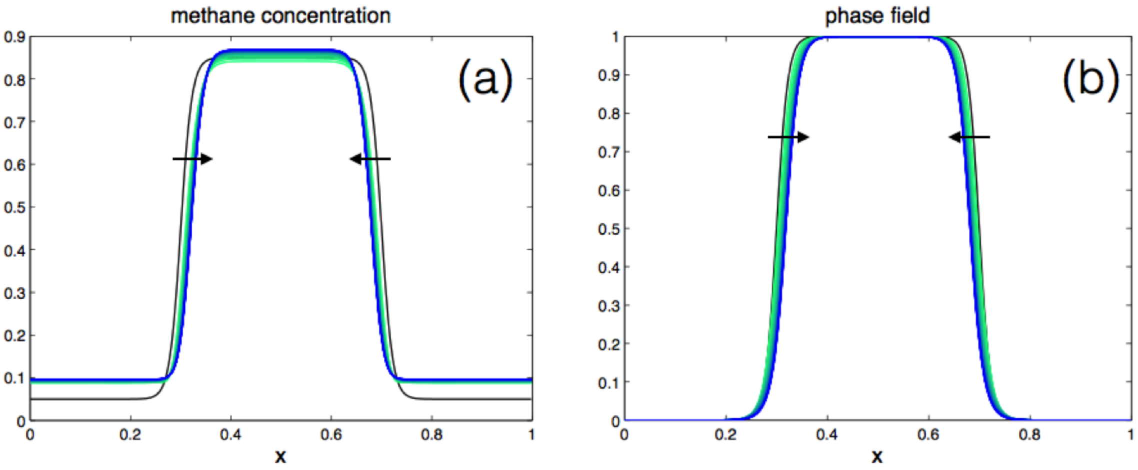
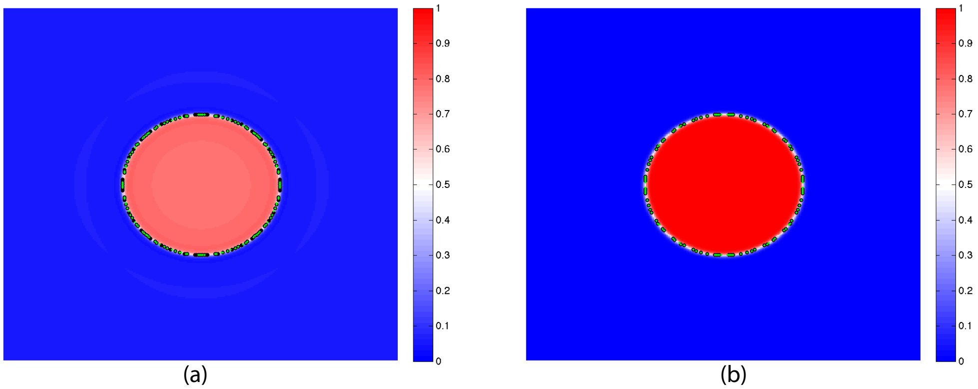
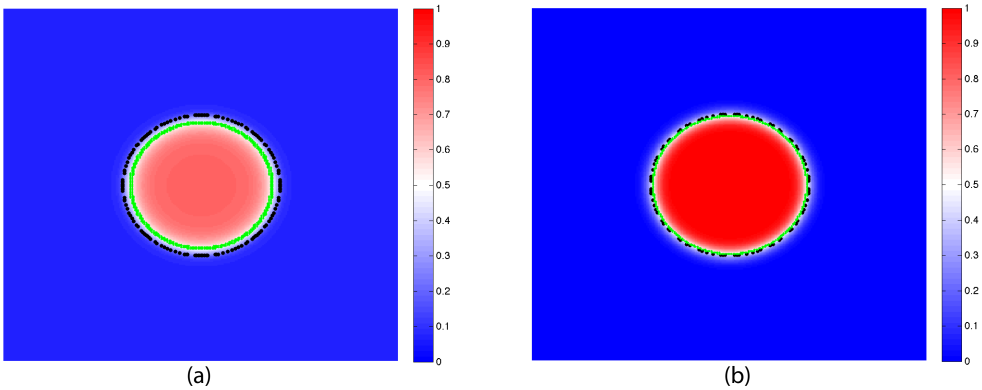


Figure 6: Time series of concentration (a) and phase profiles (b) in 1D, showing shrinking of methane bubble and its reaching thermodynamic equilibrium. Notice that at equilibrium, $C \approx 0.1$ in $\phi = 0$ is much higher than the initial condition, as a result of methane dissolution. There is also a significant reduction in bubble size due to dissolution.



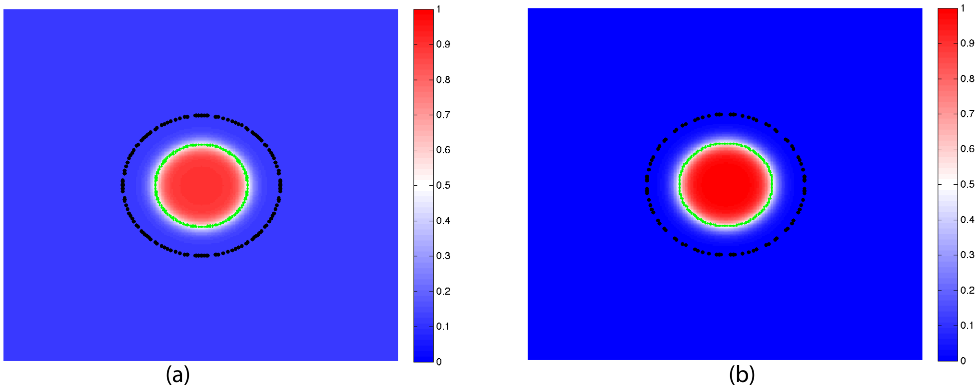
(a) (b)

Figure 7: Initial concentration (a) and phase field (b) for 2D simulation of bubble dissolution. The colormap goes from 0 to 1 in both figures.



(a) (b)

Figure 8: Concentration (a) and phase field (b) profiles at an early time point of $t = 0.5$. The black circles in both figures indicate the initial interface of the bubble. The green circles indicate the current interface of the bubble.



(a) (b)

Figure 9: Concentration (a) and phase field (b) profiles at $t = 49.5$, when the system has already reached steady state.

References

J. W. Cahn and J. E. Hilliard. Free energy of non-uniform systems. I. Interfacial free energy. *J. Chem. Phys.*, 28:258–267, 1958.

N. Provatas and K. Elder. *Phase-field Methods in Materials Science and Engineering*. Wiley, 2010.

J. D. van der Waals. The thermodynamic theory of capillarity flow under the hypothesis of a continuous variation of density (1893). *J. Stat. Phys*, 1(20), 1979. (English translation by J. S. Rowlinson).

G. Wilson. A new expression for the excess free energy of mixing. *J. Amer. Chem. Soc.*, 86 (2):127–130, 1964.

Task 3.0: Laboratory experiments on hydrate armoring, rise rate, and gas loss from ascending bubbles

Subtask 3.1: Flow-loop design, fabrication and construction

Introduction. The USGS is constructing a high-pressure flow loop designed to “capture” gas bubbles for subsequent visual and acoustic imaging studies as well as bubble evolution and rise-rate measurements. The apparatus must be able to operate at pressures high enough for the gas to form hydrate. Xenon was chosen for the hydrate-forming gas, meaning hydrate can be formed at ~1.3 MPa (190 psi) at room temperature (21°C, 70°F), and at lower pressures when the system is cooled [*Ohgaki et al.*, 2000].

Design Summary. A new seal arrangement has been designed to the structure of the flow-loop base.

Fabrication Activities.

Bubble-capture chamber:

- Stainless steel pieces designed to mate with the optically clear chambers and provide pressure seals for the flow loop are being machined.

Fluid pressure and bubble injection:

- A double syringe pump system has been delivered and set up for maintaining fluid pressure in the flow loop.
- Computer control and data logging for the fluid-pressure syringe pump and the bubble-injection syringe pump have been set up.

References.

Ohgaki, K., T. Sugahara, M. Suzuki, and H. Jindai (2000), Phase behavior of xenon hydrate system, Fluid Phase Equilibria, 175(1-2), 1-6.

Task 4.0: Field data analysis to link models and laboratory data to real world gas hydrate dynamics

Subtask 4.1: Quantitative analysis of newly-discovered US Atlantic margin methane plumes

Raw 18 kHz split-beam echo sounder data collected by the Okeanos Explorer have been cataloged and processed to identify and extract acoustic target strength (TS) profiles. These profiles will be analyzed during the coming year to help constrain the evolution of the gas bubbles as they rise through the water column, building upon the techniques used by Weber et al. [2014], as well as the master's thesis work of Kevin Jerram (a recent graduate student at UNH). An overview of the EK60 seep data is shown in Figure 1. There are approximately 70 seeps in total that have been observed with the EK60, including several repeat observations. In particular, note that the southern-most seep observation, which occurred in a water depth of approximately 2200 meters, was observed 31 times during a single cruise (cruise 1205 Leg 1). Additionally, several of the shallower (300-500 m) seep observations were observed several (3-5) times. These repeat observations will allow us the possibility of looking at the variability in the seep acoustic profiles. These 18 kHz split-beam data are being augmented by simultaneous observations made with 30 kHz multibeam echosounder (Figure 2). The profiles of multibeam scattering strength are currently being extracted from the raw data using custom software routines in both the Fledermaus midwater tool and MATLAB. Because gas bubbles act as simple harmonic oscillators with a size- and depth-dependent resonance frequency, having observations at two frequencies is expected to help constrain the dissolution rate of the bubbles as they rise. The multibeam observations are also especially helpful for some of the shallow-water seeps where the split-beam data collection was sub-optimal due to a too-slow ping rate.

Two data sets collected in summer 2014 are now available to augment the Okeanos Explorer data from 2012 and 2013. In July 2013, Weber and Ruppel participated in an NSF-funded cruise in Hudson Canyon led by John Kessler (Univ. of Rochester). Split-beam data were collected over seeps in this area at frequencies near 38 kHz. In August, the R/V Sikuliaq opportunistically collected data over the same region with an EM302 30 kHz multibeam echosounder as well as 18 and 38 kHz split-beam echo sounders. Data collection was focused on seeps found in water depths of approximately 500 m. Although not part of our originally planned work, analysis of these seeps is expected to nicely round out the Okeanos Explorer data (which is of highest quality in the deeper waters).

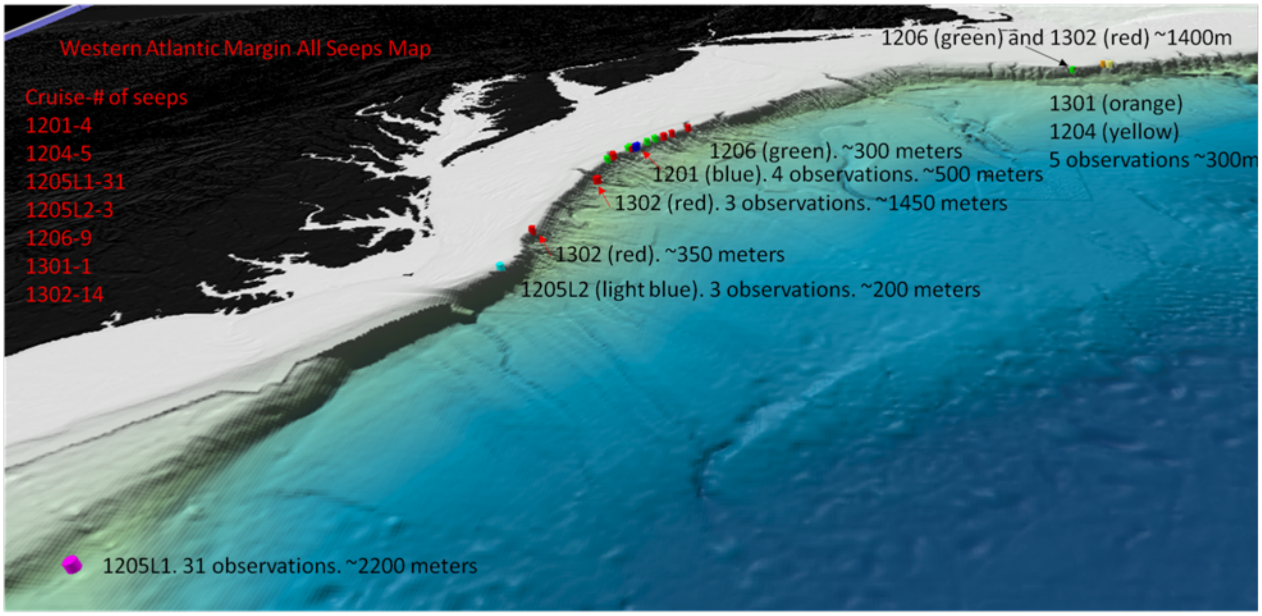


Figure 1. Locations of methane seeps observed in *Okeanos Explorer* SBES data overlaid on bathymetry (ETOP02). Both the cruise number and the number of observations of each seep are shown for each location.

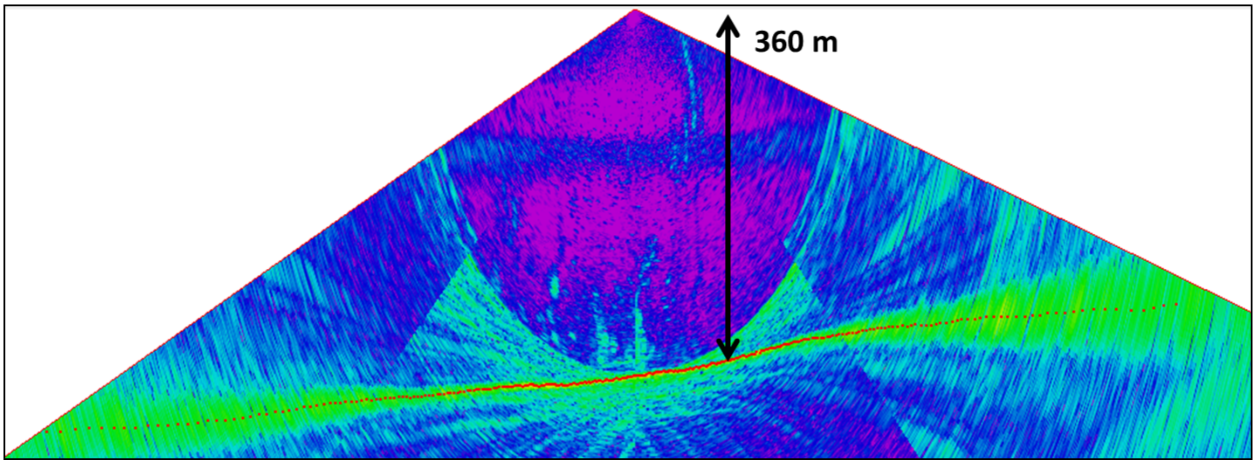


Figure 2. A single ping of EM302 multibeam echo sounder data showing a seep rising toward the surface in 360 m of water.

Weber, T. C., Mayer, L., Jerram, K., Beaudoin, J., Rzhanov, Y., & Lovalvo, D. Acoustic estimates of methane gas flux from the seabed in a 6000 km2 region in the Northern Gulf of Mexico. *Geochemistry, Geophysics, Geosystems*. **15**(5): 1911–1925 (2014).

2.3 Opportunities for training and professional development

The project has offered opportunities for training of our graduate students Amir Pahlavan (MIT), Xiaojing Fu (MIT), and Liam Pillsbury (UNH).

2.4 Dissemination of results to communities of interest

Several PIs and graduate students participated in the Gordon Research Conference on Natural Gas Hydrate Systems, held in March 23-28, 2014, in Galveston, TX. PI Ruppel gave one of the keynote talks, titled "Investigating climate-sensitive marine gas hydrates to evaluate late Pleistocene to contemporary climate change".

Several of the PIs and graduate students have, during this reporting period, submitted abstracts to the upcoming AGU Conference. These include:

- Xiaojing Fu, Luis Cueto-Felgueroso, William F. Waite, Carolyn D. Ruppel, Ruben Juanes. A Phase-Field Approach to Modeling Hydrate Formation on Methane Gas Bubbles in a Water Column.

2.5 Plans for the next reporting period

The project is progressing according to the anticipated plan, with the exception of the construction and validation of the flow loop for hydrate formation using Xenon as hydrate former. We are currently addressing some of the fabrication issues. In the next reporting period we will continue to work on the following tasks:

- Subtask 2.2: Model of buoyant hydrate-coated gas bubble
- Subtask 3.1: Laboratory experiments — flow-loop design, fabrication and construction
- Subtask 3.2: Laboratory experiments — acoustic signature due to hydrate formation
- Subtask 4.2: Estimate of methane flux from Atlantic margin

3 Products

3.1 Journal publications, conference papers, and presentations

3.1.1 Journal publications

- L. Cueto-Felgueroso and R. Juanes. A phase-field model of two-phase Hele-Shaw flow. *J. Fluid Mech.*, 758, 522-552 (2014), doi:10.1017/jfm.2014.512.
- Weber, T., Mayer, L., Jerram, K., Beaudoin, J., Rzhanov, Y. and Lovalvo, D., 2014. Acoustic estimates of methane gas flux from the seabed in a 6000 km2 region in the Northern Gulf of Mexico. *Geochemistry, Geophysics, Geosystems.* 15(5): 1911-1925 (2014), doi:10.1002/2014GC005271.

3.1.2 Conference papers

Nothing to report.

3.1.3 Presentations

Nothing to report.

3.2 Website(s) or other Internet site(s)

Nothing to report.

3.3 Technologies or techniques

Nothing to report.

3.4 Inventions, patent applications, and/or licenses

Nothing to report.

3.5 Other products

(such as data or databases, physical collections, audio or video products, software or NetWare, models, educational aids or curricula, instruments, or equipment)

Nothing to report.

4 Participants and collaborating organizations

4.1 Individuals working on the Project

- Name: Ruben Juanes
  Project Role: Principal Investigator / Project Director
  Nearest person month worked: 1
  Contribution to Project: Ruben Juanes, as project director, is responsible for overall coordination of the effort and for the technology transfer activities, including progress and topical reports, and project review presentations. He takes the lead in the modeling and simulation of hydrate formation and dissociation in rising methane bubbles (Task 2.0), and advises the MIT graduate student responsible for doing the modeling. He also serves as primary advisor to the MIT student who conducts the laboratory experiments of bubble rise and hydrate formation with analogue multiphase fluids (Task 3.0), in collaboration with Waite (USGS).
  Funding Support: MIT academic-year salary / DOE summer salary
  Collaborated with individual in foreign country: No
  Country(ies) of foreign collaborator: Not applicable
  Travelled to foreign country: Not applicable
  Duration of stay in foreign country(ies): Not applicable

- Name: Thomas Weber
  Project Role: Co-Principal Investigator
  Nearest person month worked: 1
  Contribution to Project: Thomas Weber leads the field component of the project (Task 4.0), particularly the quantitative analysis of existing public domain data for northeast Atlantic margin bubble plumes. He also advises a graduate student at UNH. Weber also assists with the acoustics aspects of the laboratory experiments (Task 3.0), both in design of the acoustic component and the interpretation of the resulting data.
  Funding Support: MIT academic-year salary / DOE summer salary
  Collaborated with individual in foreign country: No
  Country(ies) of foreign collaborator: Not applicable
  Travelled to foreign country: Not applicable
  Duration of stay in foreign country(ies): Not applicable

- Name: Carolyn Ruppel
  Project Role: Co-Principal Investigator
  Nearest person month worked: 1
  Contribution to Project: Carolyn Ruppel has responsibility for keeping the project grounded in natural gas hydrates systems and in the issues of greatest relevance for the US gas hydrates research community, particularly the part of the community focused on the environmental impact of methane emissions from gas hydrate deposits. She is also responsible for ensuring that appropriate resources (salary support) are allocated to herself, Waite, and the USGS engineers supporting this project and interacts frequently with Juanes and his students at MIT, where she maintains a second office. She is also responsible for regional analysis and integration of observational data related to

hydrate-derived seeps and plumes on the U.S. Atlantic margin and for linking the newly emerging observational data to other existing data sets (e.g., BOEMs gas hydrates assessment of the Atlantic margin) in this area and in other areas worldwide (Task 4.0).
Funding Support: USGS salary
Collaborated with individual in foreign country: No
Country(ies) of foreign collaborator: Not applicable
Travelled to foreign country: Not applicable
Duration of stay in foreign country(ies): Not applicable

- Name: William Waite
  Project Role: Co-Principal Investigator
  Nearest person month worked: 1
  Contribution to Project: William Waite leads the lab component of the project (Task 3.0) and has primary responsibility for design and construction oversight of the xenon hydrate lab apparatus. He interacts with the USGS engineers, visits UNH to see existing devices at Webers lab, and meets with MIT staff to understand the parameters for the cell installation at MIT. After completion of the testing phase of the laboratory work at the USGS, Waite is responsible for moving the apparatus to MIT. Waite takes on primary responsibility for developing the collaboration among MIT, UNH, and the USGS for the multifaceted lab experiments and working directly with the MIT graduate student on the experiments at MIT.
  Funding Support: USGS salary
  Collaborated with individual in foreign country: No
  Country(ies) of foreign collaborator: Not applicable
  Travelled to foreign country: Not applicable
  Duration of stay in foreign country(ies): Not applicable

- Name: Amir Pahlavan
  Project Role: Graduate Student at MIT
  Nearest person month worked: 3
  Contribution to Project: Amir Pahlavan works on Task 2.0: Theoretical and computational models of coupled bubble rise and hydrate formation and dissociation.
  Funding Support: DOE
  Collaborated with individual in foreign country: No
  Country(ies) of foreign collaborator: Not applicable
  Travelled to foreign country: Not applicable
  Duration of stay in foreign country(ies): Not applicable

- Name: Xiaojing Fu
  Project Role: Graduate Student at MIT
  Nearest person month worked: 0
  Contribution to Project: Xiaojing Fu works on Task 2.0: Theoretical and computational models of coupled bubble rise and hydrate formation and dissociation.
  Funding Support: DOE
  Collaborated with individual in foreign country: No

Country(ies) of foreign collaborator: Not applicable
Travelled to foreign country: Not applicable
Duration of stay in foreign country(ies): Not applicable

- Name: Liam Pillsbury
  Project Role: Graduate Student at UNH
  Nearest person month worked: 0
  Contribution to Project: Liam Pillsbury works on Task 4.0: Field data analysis to link models and laboratory data to real world gas hydrate dynamics.
  Funding Support: DOE
  Collaborated with individual in foreign country: No
  Country(ies) of foreign collaborator: Not applicable
  Travelled to foreign country: Not applicable
  Duration of stay in foreign country(ies): Not applicable

4.2 Other organizations involved as partners

Nothing to report.

4.3 Other collaborators or contacts

We have established a collaboration with Luis Cueto-Felgueroso, formerly a research scientists in Juanes's group and currently a researcher at the Technical University of Madrid, and with Hector Gomez, a professor at the University of La Coruña and who has visited MIT on several occasions and has published joint papers with Juanes. Both researchers are experts in phase-field modeling, and the collaboration will bring new perspectives on the mathematical aspects of multiphase–multicomponent flows.

We have also established contact with Carolyn Koh's group at Colorado School of Mines, where they have built an experimental system that is related to the one proposed in our project. William Waite has already visited their group and we anticipate that this contact will be very beneficial for the experimental aspects of the project.

Ruppel continues to make plans to visit some of the deepwater Nantucket seeps on the R/V Endeavor in July 2014 as part of a NSF cruise funded to J. Kessler (U. Rochester).

5 Impact

5.1 Impact on the principal discipline of the Project

No impact to report yet.

5.2 Impact on other disciplines

No impact to report yet.

5.3 Impact on the development of human resources

The project is supporting the training of graduate students.

5.4 Impact on physical, institutional, and information resources that form infrastructure

Nothing to report yet.

5.5 Impact on technology transfer

Nothing to report yet.

5.6 Impact on society beyond science and technology

No impact to report yet.

5.7 Dollar amount of the awards budget spent in foreign country(ies)

Zero.

6 Changes and problems

Nothing to report.

7 Special reporting requirements

Nothing to report.

8 Budgetary information

The Cost Plan is included as Appendix 2.

MILESTONE STATUS REPORT

Milestone	Task/	Project Milestone	Year 1				Year 2				Year 3				Planned	Planned	Actual	Actual	Comments (notes, explanation
	Subtask	Description	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Start date	End date	Start date	End date	of deviation from plan)
1	1.0	Revise PMP	X												1-Oct-13	31-Dec-13	1-Oct-13	3-Dec-13	Revised PMP sent by email on Dec 3, 2013
2	1.0	Kick-off meeting	X												1-Oct-13	31-Dec-13	1-Oct-13	14-Nov-13	Webex meeting on Nov 14, 2013
3	2.1	Model of static gas bubble in 3D	🟩	🟩	🟩	X									1-Oct-13	30-Sep-14	1-Oct-13	30-Sep-14	
4	3.1	Verify flow-loop	🟩	🟩	🟩	X									1-Oct-13	30-Sep-14	1-Oct-13		slight delay in flow-loop construction
5	4.1	Extract MBES/SBES seep parameters	🟩	🟩	🟩	X									1-Oct-13	30-Sep-14	1-Oct-13	30-Sep-14	
6	3.2	Acoustic signature due to hydrate formation					🟩	🟩	X						1-Oct-14	31-Jul-15			
7	4.2	Estimate of methane flux from Atlantic					🟩	🟩	X						1-Oct-14	31-Jul-15			
8	2.2	Model of buoyant hydrate-coated gas bubble					🟩	🟩	🟩	X					1-Oct-14	30-Sep-15			
9	3.3	Measure gas-loss rate at low initial pressures								X					1-Jul-15	30-Sep-15			
10	4.1	Analyze plume data acquired by NOAA OE					🟩	🟩	🟩	X					1-Oct-14	30-Sep-15			
11	2.3	Model of bubble-bubble interactions							🟩	🟩	🟩	X			1-Apr-15	31-Mar-16			
12	3.3	Measure gas-loss rate at high initial pressures									🟩	X			1-Oct-15	31-Mar-16			
13	4.2	Extend bottom water temperature database								🟩	🟩	X			1-Jun-15	31-Mar-16			
14	2.4	Model formulation and comparison with field observations									🟩	🟩	🟩	X	1-Oct-15	30-Sep-16			
15	all	Manuscripts submitted / Final project synthesis and report					🟩	🟩	🟩	🟩	🟩	🟩	🟩	X	1-Oct-14	30-Sep-16			

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