Oil & Natural Gas Technology

DOE Award No.: DE-FE0010180

Research Performance Progress Report
(January – March 2013)

Gas Hydrate Dynamics on the Alaskan Beaufort Continental Slope: Modeling and Field Characterization
Project Period: October 1, 2012 – September 30, 2015

Submitted by:

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Prepared for:
United States Department of Energy
National Energy Technology Laboratory

May 1st, 2013

Office of Fossil Energy

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ABSTRACT

The second quarter of research associated with the DE-FE0010180 grant included progress on three separate tasks: (1) advancement of 2D heat-flow/hydrate model development by integrating latent heat effects of hydrate formation/dissociation, (2) development of a north slope heat flow map and merging Beaufort ocean temperature analysis with regional on-shore/offshore heat-flow data for 2D/3D hydrate stability assessment, and (3) continuation of research vessel scoping for the up-coming 2014 cruise. We have made significant progress on all tasks. We advanced the numerical model during Quarter #2 by adding the temperature effects of latent heat of hydrate dissociation for both 2D and 3D models. Our analysis suggests that for high concentrations (>20% bulk) of hydrate in the Beaufort, the time for re-equilibration of temperatures to steady state increases significantly. We tested the latent heat model using both analytic solution and experimental data collected for DE-FEAB111 at Oak Ridge National Lab. Preliminary analysis indicates the effects of latent heat of hydrate dissociation is an important factor controlling rates subsurface temperature evolution (and BSR shoaling) in a diffusion-dominated heat flow environment, but is of second-order importance where advective heat flow dominates. We will use the model to place end-member constraints on hydrate stability zone evolution with time in the Beaufort Sea. Additionally, we used offshore BSRs combined with onshore heat flow measurements to generate a new heat flow map for northern Alaska and the Beaufort Sea. We combined this map with Quarter #1 ocean temperature analysis to initiate ongoing analysis of hydrate disequilibrium along the Beaufort Margin. Using this, we anticipate results showing with 2-sigma confidence where hydrates are currently dissociating along the margin. The USGS is also currently writing a manuscript related to their recent MCS data acquisition in the Beaufort, and continues to have discussions with the operators of the *Norseman II* regarding logistics for the 2014 cruise. There were no significant delays or problems during the second quarter of work and we anticipate obtaining additional publishable results and a clearer picture of research vessel options for the 2014 cruise during the next quarter.

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EXECUTIVE SUMMARY

In October 2012, Southern Methodist University in close partnership with The United State Geological Survey at Woods Hole and Oregon State University, began investigating methane hydrate stability in deep water (>100 mbsf) environments below Alaskan Beaufort Sea. This research is part of a three-year study funded by the Department of Energy's (DOE) National Energy Technology Laboratory (NETL). Key goals of this study include integrating and processing marine seismic data collected at the USGS with dynamic 2D/3D/4D heat flow models developed at SMU to determining the depth, location, and dynamics of methane hydrate stability along the Alaskan Beaufort Margin. A key component of this study is to constrain how the methane hydrate stability zone is changing with time. Additional goals of this study include determining areas where concentrated methane hydrate might exist in the subsurface and to understand the role methane hydrate plays in slope stability along the Alaskan Margin.

The second quarter of this project was dedicated primarily to the continued development of 2D submarine heat flow models for assessing hydrate stability in the subsurface. Such Modeling requires robust constraints on both temperature boundary conditions (i.e. regional ocean temperatures with depth), and regional heat flow. During the first quarter of this study, we analyzed long-term (semi-annual to decadal scale) ocean temperatures in the Beaufort Sea to place constraints on the upper boundary condition of the model. During the second quarter of this research, we devoted significant time constraining the bottom boundary condition by estimating regional heat flow using (1) deep water (>1000 mbsl) BSRs combined with (2) previous land-based heat flow data derived from regional wells. Merging these datasets, we developed a new heat flow map for the north slope of Alaska and the Beaufort Sea that we are currently using to constrain BSR depth along the shallow margin. We also devoted approximately one month of quarter #2 towards integrating latent heat effects into 2D/3D diffusive heat flow models for use in predicting hydrate dissociation/evolution with time in the Beaufort. The 2D model for predicting the location and evolution of the hydrate stability zone in the Beaufort now more accurately accounts for temperature changes in the subsurface due to the latent heat of hydrate dissociation. Our preliminary analysis using a diffusive heat flow regime suggests the latent heat effects of hydrate dissociation on temperature re-equilibration is small if there limited amounts of hydrate (<20%) filling pore space but becomes significant at higher concentrations. We tested our latent heat model using both analytic solutions and experimental data acquired from the previous DOE grant DE-FEAB111. Comparison and analysis between the model and the experimental data indicates fluid advection plays a significant role in heat transfer when hydrate dissociates in high permeability sediments. This implies that we need to account for the possibility of advective heat transfer in the Beaufort Margin, particularly if we find high permeability sediments in the cores we recover. The USGS continued to spend much of the quarter analyzing and processing recently collected 2012 seismic data on the Beaufort Slope, and has begun writing a manuscript showing initial results. They also have been in continuing discussion with ship operators to line up Norseman II for 2014 (the ship is currently in drydock in Seattle). In summary, we have completed all tasks as outlined in the project management plan for this quarter. We continue with model development and hope to provide at the end of Quaeter #3 initial results showing at the 95% confidence level where non-steady state methane hydrate conditions exist along the Beaufort Sea Margin.

PROGRESS

Primary project goals for the second quarter of this project, as outlined in figure 1 of the project management plan (PMP) include the following:

TASK 1—continue to develop numerical models for the 1977 USGS data

TASK 2--Scoping of the R/V Noreseman II for 2014 Coring/Heat-flow research.

We continue progressing on Tasks 1 and 2 stated in the PMP and have experienced no significant delays. In february, we completed our ocean temperature analysis in the Beaufort that estimates semi-annual, annual, and decadal scale ocean temperature changes along the margin. We use results from this analysis to constrain the upper boundary condition of the hydrate stability model. During March and April we worked to develop tighter constraints on the bottom boundary condition of the model. This required the creation of a new, more complete heat flow map of the Alaska North Slope. The new map uses both BSR data and on-shore heat flow measurements taken from previous studies of on-shore well sites. The new map is, to our knowledge, the first land/sea heat flow map for this region, and the only one that extends fully into the deep ocean basin. We intend to publish this map in the next year as part of a broader hydrate stability study for our group.

We also significantly improved the numerical model during quarter #2 by incorporating and testing the effects latent heat of hydrate dissociation has on diffusive heat flow. To test this analysis, Hornbach and colleagues integrated model results with experimental hydrate dissociation data. Specifically, we used experimental results from DOE grant DE-FEAB111 collected at Oak Ridge National Lab that involved synthetic hydrate formation and dissociation to test the accuracy of the numerical model and determine the key parameters controlling heat transfer during dissociation. Two finding from this study are (1) relatively small (<20%) amounts of hydrate filling the pore space can significantly increase the relaxation times to steady-state temperature conditions, and (2) accounting for key differences in experimental and numerical results requires advection. The second finding is important because it demonstrates that advection is a key component in heat transport and hydrate dissociation in permeable sediments. Therefore, if we find relatively sandy sediment in the Beaufort, we must adjust our model accordingly, and note that advective processes will likely control the heat flow regime. These results are currently included in a draft manuscript that graduate student John Leeman at Penn State (who worked on Grant DE-FEAB111 as an undergraduate) is writing with Hornbach.

The USGS continues to process seismic data collected last year on the Beaufort as well as scope-out the R/V Norseman II as the likely research platform. The USGS is currently writing a manuscript based on these seismic results. The USGS also had further discussions with the operators of the *Norsman II* to determine if it makes a suitable platform for the 2014 cruise. The Ship is currently in drydock in seattle, and plans are being made for USGS technicians to visit and provide a full assessment by this summer.

Below, we discuss each of the accomplishments as well as additional research results.

RESULTS & DISCUSSION

TASK 1—continue to develop numerical models for the 1977 USGS data (SMU and USGS)

SMU Task 1, Component 1— constraining model boundary conditions.

The accuracy of any methane hydrate stability model critically depends on temperature boundary conditions. During Quarter #1, we constrained the upper boundary condition of the model (ie. the ocean temperature) by conducting detailed analysis of ocean temperature data in the Beaufort with time. The analysis provides detailed ocean temperature profiles with depth and time across the Beaufort. Similarly, during Quarter #2, we constrained the lower boundary condition of the model by devoting our efforts towards a regional heat flow analysis across the North Slope of Alaska and Beaufort Shelf. This involved not only a significant literature review along the North Slope, but also statistical analysis of offshore seismic data and historical conductivity and temperature logs to assess deep water heat flow in the Beaufort. The onshore heat flow regime along the north slope is relatively well constrained [e.g. *Lachenbruch et al., JGR,* 1982; *Demming et al., GSA Bull.,* 1982]. Offshore Alaska along the Beaufort Shelf and Sea, however, heat flow is poorly constrained, with few if any detailed reports of heat flow. Additionally, on a small spattering of thermal conductivity measurements exist in published form for the arctic and Beaufort Sea region. Previous studies by the USGS used BSR depths to place rough constraints on the regional heat flow across the Beaufort Sea [*Pat Hart, Pers. Comm*.]. Such measurements provide a good first-order assessment of the regional heat flow regime. Unfortunately, we cannot use shallow water BSRs to constrain heat flow at our site because of variable intermediate ocean bottom temperatures with time in the Beaufort Sea [i.e. results from Quarter #1 study, as well as *Melling JGR, 1998*]. However, deep water (ie. >800 mbsl) ocean temperatures maintain relatively constant values with time, and generally fluctuate no more than +/- 0.1^{o} C. If good constraints on thermal conductivity exist, we can therefore use deep water BSRs to estimate heat flow in the Beaufort Sea. We therefore use BSRs observed in 1977 USGS data combined with thermal conductivity measurements across the region to calculate heat flow across the continental margin and abyssal plain of the Beaufort Sea. For this analysis, we account both for 3D thermal refraction effects on heat flow via 3D modeling that incorporate bathymetry. We also account for uncertainty in BSR depth estimates from the seismic data by reprocessing (and statistically analyzing) velocity data from the 1977 USGS seismic survey. These data were graciously provided to us by Pat Hart at the USGS. Finally, we account for variability in thermal conductivity across the region using previous studies across the Beaufort and arctic ocean [e.g. *Lachenbruch et al, JGR,* 1982]. With Heat flow constrained using deep water BSRs and on shore well sites, we generate a contour map showing the regional heat flow regime from the North Slope of Alaska to the abyssal plane of the Beaufort Sea. To our knowledge, this map is the first land-sea heat flow map created for the north slope of Alaska, and we intent to integrate the map into a manuscript in the near future. The map indicates significant variability in heat flow across the region with relatively high (> 60 mW/m^2) values on the eastern and western edge of the margin, and cooler values in the middle. The offshore values are surprisingly consistent with land-based heat flow measurements, although in general, heat flow values are consistently higher on land than at sea. With heat flow and ocean temperatures constrained across the region, we know the boundary condition for the methane hydrate model. Therefore, the next step (for Quarter #3), is to integrate these results into the numerical model to predict the expected location of all observable BSRs in the

1977 USGS data assuming steady state temperature conditions. This is the focus of ongoing work.

SMU Task 1, Component 2—incorporating latent heat into the 2D/3D Heat Flow Model

We currently use a steady-state heat flow model to predict the base of hydrate stability (i.e. the depth of the BSR). Comparison of the model-predicted depth of the BSR with the observed BSR depth provides valuable insight into where the methane hydrate system is stable and in steady-state equilibrium versus where dynamic temperature changes exist. The steady-state model therefore provides a useful first-approach for pin-pointing locations where methane hydrate is not in equilibrium, and therefore, unstable. Differences between model predicted BSR depth and observed BSR depth at specific locations along the Beaufort Margin may imply geologically recent (<1000 year) temperature changes at that location. One potential cause of these BSR depth discrepancies is recent changes in ocean temperatures (i.e. changes to the upper boundary condition of the model). Ideally, it would be valuable to determine how dynamic temperature changes impact the hydrate stability zone with time, since hydrate dissociation effects fluid pressures, sediment strength, and ultimately, slope stability. An important goal of this project is to therefore develop a dynamic forward heat-flow models that enable us to better predict how the hydrate stability regime changes when external factors, such as ocean temperature, change in the Beaufort Sea. Specifically, key goal of this research is to improve short term (decadal-scale) predictions for the evolution of the hydrate stability zone in the Beaufort Sea by using ocean temperature changes combined with repeat seismic surveys (1977 and 2010) to test the accuracy of the predictive models.

During Quarter #2, we took the first substantial step towards developing a more accurate predictive hydrate dissociation model for the Beaufort Sea by integrating dynamic changes in the ocean temperature boundary conditions, incorporating latent heat effects of hydrate dissociation, and comparing our results to experimental studies. We know from research conducted during Quarter #1 that ocean temperatures at intermediate water depths (~200-500 mbsf) are steadily rising. We therefore began testing our forward model by driving the 1977 hydrate stability system away from equilibrium using ocean temperature changes observed during the past 30 years in the Beaufort Sea. We then added latent heat effects of hydrate dissociation by incorporating the numerical techniques outlined by *Hu and Argyropoulos* (1996). As a starting point, we first developed a 1D hydrate stability model that includes latent heat. The numerical solution of our 1D model matches benchmark analytical solutions provided by *Jaeger and Carslaw* (1949), and is therefore accurate.

As a secondary test, however, we expanded the model to three dimensions and applied our dynamic heat flow model to experimental hydrate dissociation datasets previously studied by the DOE.Specifically, we used the hydrate dissociation experiments from DE-FEAB111 where hydrate was dissociated in a 5 gallon bucket via four-stage heating using the pressure chamber at Oak Ridge National Laboratory. For the comparison of model results with experimental data, Hornbach worked closely with John Leeman, a graduate student at Penn State University who was involved in the DE-FEAB111 experiment. During the second week of March 2013, Hornbach traveled to Penn State (at no cost to DOE), gave a presentation showing some of our preliminary results, and then spent 4 days working together with Leeman comparing our latent heat model results with Leeman's experimental data acquired at Oak Ridge. We drew two important conclusions from this analysis. The first is that latent heat plays an important role in methane hydrate dynamics, by significantly increasing the time it takes for the system to reach steady state. In particular, we find that hydrate concentrations in excess of ~20% or more in the pore space result in significantly longer steady state temperature relaxation times (for example, 50% or longer relaxation time, depending on hydrate saturation.) The analysis therefore implies that robust constraints on hydrate concentrations in sediment are critical for accurate forward modeling of methane hydrate stability. Since we do not currently know hydrate concentrations in Beaufort Sea deepwater sediments, this result implies we can make end-member predictions only for the effect latent heat has on heat flow equilibration times. For example, we can estimate a maximum time for steady state diffusive heat flow temperature re-equilibration by assuming 100% hydrate filling pore space and a minimum time for temperature re-equilibration assuming no hydrate filling pore space.

The second important finding from the comparison between experimental and numerical modeling results is that we achieved a best fit between model and experimental temperature data if we included advection as a key driver of temperature transfer. This means that model results only closely match the experimental system studied by *Leeman et al.* if advective heat transfer is the dominant driver of hydrate dissociation. This conclusion is arguably not surprising since the experimental data uses high permeability sand. Nonetheless, the study clearly suggests that if hydrates dissociates in high permeability sediments, we must have fluid advection driving heat transfer to best match the model to the data. This observation has potentially significant ramifications for Beaufort Sea hydrate stability modeling: If we recover sandy sediments in 2014 cores, we will need to account for the possibility that advective heat transfer acts as the primary mechanism driving hydrate dissociation. With this in mind, we have begun integration of the "TOUGH2 + Hydrate" program with seismic data to account for potential advective fluid/temperature/chemical transport terms we may need for the forward modeling. Result of the comparison between the forward-model 3D diffusive heat flow study and the Oak Ridge hydrate dissociation experiment are currently being written up and included as a small component of a much larger manuscript to be submitted by Leeman, Hornbach, and several others.

USGS Task #1: numerical modeling support: Processing new USGS MCS seismic data.

With preliminary processing and interpretations complete, The USGS has begun writing a paper using the new USGE MCS Beaufort Sea seismic data. The new seismic data will be released for modeling with SMU once the paper is published. Results associated with this work were presented during the second Quarter in Helsinki at a subsea permafrost meeting, in an hour-long seminar at WHOI, and at the Chukchi drilling meeting at the Byrd Polar Center two weeks ago. Associated with this work, USGS researchers have also spent a significant amount of time editing and commenting on a draft paper from the MITAS group regarding their work in the same area in 2009.

TASK 2--Scoping of the R/V Norseman II for 2014 Coring/Heat-flow research (USGS)
The USGS is taking the lead on investigating the suitability of Alaskan vessels for summer 2014 coring on the upper continental slope. During Quarter #2, the USGS has spent significant time talking with the ship operator, and we are making plans for the leader of the PCMSC (the USGS west coast office) coring operations group to visit Seattle while the *Norseman II* remains in drydock undergoing major modifications (which will benefit us for 2014 for sure). USGS technicians will provide us with ample pictures and specifications after the trip regarding the ship's configuration. We will use this information to write the required DOE report assessing the platform in early summer.

COST STATUS

costs incurred so far at SMU is
--RA support for Hornbach's graduate student, Ben Phrampus. Not including fringe, this cost comes to ~$6,120 for the quarter.
--Research Support for Hornbach (buyout of teaching for research). ~ $26,000.
--Software support: Purchase of TOUGH2 + Hydrate that we will integrate with seismic data for possible advection modeling implementation. $2000.

Total approximate expenditures for SMU in Quarter #2: ~$36,000 (not including overhead).

PROBLEMS OR DELAYS

None.

PRODUCTS

(1) A new, and to our knowledge, first to-date heat flow map for the north slope of Alaska extending into the Beaufort Sea abyssal plain.

(2) 2D/3D diffusive heat flow forward model integrating 1977 seismic data that predicts hydrate stability changes with time accounting for latent heat.

(3) New evidence for advection-dominate heat transfer in hydrate saturated sands.

CONCLUSIONS AND FUTURE DIRECTIONS

In Summary, we continue to make clear and steady progress testing and developing the numerical model and planning for the upcoming 2014 cruise. all tasks were completed for Quarter #2. During the next quarter, we anticipate completion of the following action items: (1) completion of initial model runs using the now well-constrained boundary conditions for the heat flow models, (2) 2D images showing with 2-sigma confidence the locations where methane hydrates are in disequilibrium along the Beaufort Sea, (3) a final report on the Norseman II as a potential research vessel for summer 2014.

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