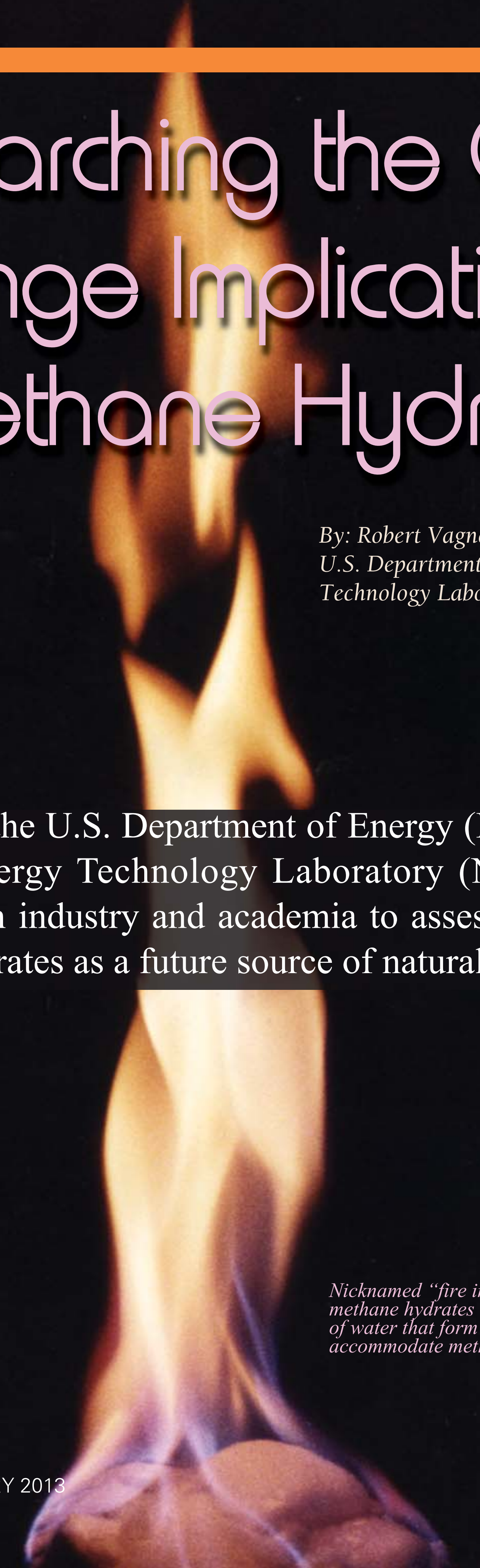
Researching the Climate Change Implications of Methane Hydrates

By: Robert Vagnetti, Ray Boswell, and Skip Pratt
U.S. Department of Energy, National Energy Technology Laboratory

Since 2001, the U.S. Department of Energy (DOE), through its National Energy Technology Laboratory (NETL), has been working with industry and academia to assess the potential of methane hydrates as a future source of natural gas.



Nicknamed "fire in ice" by researchers at NETL, methane hydrates are frozen hydrogen-bonded lattices of water that form polyhedral cavities large enough to accommodate methane molecules, Photo credit: NETL.

While this effort has been the prime focus for NETL, a desire to fully understand all the implications of natural gas hydrates has driven the lab to work with other federal agencies and academia to investigate how Earth's vast stores of gas hydrate might respond to a warming climate, and just what sort of impact large-scale gas hydrate dissociation could have on the world's environment. While it remains widely accepted that gas hydrate breakdown contributes relatively little methane to the environment, there is substantial interest in the possibility that warming climate would substantially increase the release of methane from gas hydrates. In response, NETL and its Federal partners in the U.S. Geological Survey (USGS) and in other agencies have brought together the gas hydrate and global climate change scientific communities—two groups that had had limited previous interaction—in order to focus scientific study.

Nicknamed "fire in ice," methane hydrates are frozen hydrogen-bonded lattices of water that form polyhedral cavities large enough to accommodate methane molecules. This trapped methane represents a potentially large energy resource that could provide the world with additional energy supply options to meet future demands. However, recent observations of numerous seafloor gas vents in the Arctic have raised the issue as to whether warming climates may be initiating a period of increased instability in gas hydrates. While the origin, scale, and causes of these vents (including their links, if any, to methane hydrate) remain unclear, the implications are significant. Given that methane is a very powerful greenhouse gas, such releases (if those releases were to occur at a meaningful scale and to somehow find their way to the atmosphere) could be a significant feedback with the potential to accelerate climate change. Even when that gas does not survive the transit through the water column, it also could have profound impacts on the oceans, including potential acidification.

Typically, methane hydrates are formed by the combination of high pressure and low temperature that occur in the shallow sediments of the deepwater Outer Continental Shelf (OCS). They also exist in areas of permafrost. According to the U.S. Department of the Interior, a key partner to NETL in both gas hydrates energy and climate research, an estimated 500 trillion cubic feet of methane is trapped in U.S. Arctic sediments (reported by the USGS in 1995), while roughly 50,000 trillion cubic feet may occur on the U.S. Lower-48 OCS (reported by the Bureau of Ocean Energy Management in 2012). Outside of a few well-studied areas, these volumes, details of their geographic distribution, the nature of their occurrence in sediments, and the nature of their potential response to changing environmental conditions remains very poorly known. A focus on gas hydrate occurrence and behavior in the most climate-sensitive environments is a key aspect at this time.

While DOE had a fundamental program in gas hydrates in the 1980s, the current program of research began in 2000, when the Methane Hydrate Research and Development Act of 2000 was signed into law. This Act mandates that DOE lead a National Methane Hydrate R&D program and utilize the talents of federal, private, and academic organizations to carry out program goals. Over the past decade, DOE has worked with industry, academia, the DOE national labs, and six Federal partners (USGS, NOAA, BOEM, NSF, BLM, and NRL) to identify, prioritize, and enable laboratory, modeling, and field-based research projects. These projects are designed to assess the nature of methane hydrate resources and develop the science and technology necessary to exploit this unconventional gas resource.

Initial DOE efforts relevant to the role of gas hydrates in the environment focused on the Gulf of Mexico, where abundant shallow and seafloor gas hydrates had been found in association with "cold seeps" (as opposed to seeps associated with hydrothermal vents at the world's mid-ocean ridges) and served as the home for unique, recently discovered assemblages of deepwater organisms.

The interest was in understanding the nature and permanence of these deposits and their sensitivity to subtle changes in environmental conditions. The goal was to advance understanding of the potential local geohazards such hydrates might pose, particularly to deepwater drilling, which was rapidly expanding at this time.

During this period, DOE funded research groups at the Scripps Institution of Oceanography and at Texas A&M University (TAMU). NETL also supported (along with the NOAA and the former MMS) research with the University of Mississippi focused on monitoring hydrates at large seep complexes using remote vehicles and other devices for seafloor observation. These studies have documented the dynamic nature of the deposits near seafloor gas hydrates and their relationship to complex networks of faults that provide methane from below. In addition, to support the understanding of the potential volumes and permanence of gas hydrate in nature, DOE/NETL conducted a range of theoretical studies on the thermal properties of gas hydrate and gas hydrate bearing sediments and enabled scientists from the Idaho National Lab to address the issue of the microbiological origins of the methane typically housed in gas hydrates. This and other fundamental science investigations enabled by DOE are a key foundation to today's current understanding of gas hydrate's implications for climate.

Gas Hydrate and Global Climate Change

At the onset of the 21st century, the view of gas hydrate's role in the global climate change was largely based on the work of Dr. Keith Kvenvolden of the USGS. While among the first to scientifically address the issue, Dr. Kvenvolden determined that gas hydrate was likely to respond significantly to changing climates only in Arctic regions, and that, for a variety of regions, this response was not likely to be a major issue in climate change. Therefore, much research was focused on the broader question of gas hydrate's role in global carbon cycling. In this context, gas hydrates were primarily viewed as that of a long-term "capacitor" for the movement of organic carbon in shallow sediments (a view promoted by Dr. Jerry Dickens at Rice University). This concept recognizes that organic carbon (as methane) can be periodically (over geologic timescales) sequestered or released to the environment in potential large volumes in response to changes in global environmental conditions.

Although the process is complex in detail; overall there would be net uptake of methane when climates are cold and net release when climates are warm. Being a process that acted over geological timescales, much research has focused on attempting to decipher the behavior of methane during major climate events in the past, and then decipher where that methane may have originated (more difficult). For example, the Paleocene-Eocene Thermal Maxima (55 million years ago) was a period of great warmth (the Arctic Ocean was a large duck-weed pond), and data show compelling indications that that warming may have been exacerbated by the massive release of methane from deepwater gas hydrates in response to global warming trigged by as yet unidentified factors.

The issue gained greater urgency based on the work of Dr. James Kennett at U. California-San Diego, who studied high-resolution climate records from the last 400,000 years in the Santa Barbara Basin and noticed that brief warm periods during glacial cycles correlated with the rapid expulsion of methane from seafloor gas hydrate deposits. With DOE support, this "Clathrate Gun" hypothesis was tested by Woods Hole Oceanographic Institution through coring in the southeast Bering Sea. This research confirmed that episodes of intense methane expulsion occurred repeatedly during the last glacial period during discrete climate warming events. Nonetheless, evidence that the observed increases in atmospheric methane during these events could be linked to dissociating gas hydrates has been difficult to pin down. For many researchers, other interpretations—such as the regular expansion and contraction of methane-producing wetlands—appear to better explain the available data than does a series of globally synchronized large-scale gas hydrate dissociation events.

In May 2004, DOE supported NOAA in hosting a workshop to bring together the gas hydrate and global climate communities to assess if further research on hydrate feedbacks to climate was warranted. The workshop noted that global climate models do not incorporate gas hydrate phenomena and recommended that this shortcoming be rectified. Specifically, research should focus on describing the critical processes and rates of formation and degradation of methane hydrate contained in sediments along continental margins to advance knowledge of 1) the pathways and fluxes of methane from ocean sediments to the atmosphere, should those hydrates dissociate; and 2) potential triggers—natural (such as seafloor failures) and anthropogenic—to hydrate dissociation and potential large-scale gas release events. The National Research Council (NRC) echoed these recommendations in 2004.

In recognition that no other Federal agency had the ability to foster the needed research, DOE worked with the USGS (which has hosted several workshops to advance scientific interest in this area), hydrate-bearing settings and define the potential impacts of methane hydrate formation and dissociation on the global carbon cycle and on global climate.

For example, researchers at the University of California at Santa Barbara (UCSB) conducted work in the Santa Monica Basin and elsewhere to determine the strength of the marine biofilter—water column microbial processes that oxidize methane and thereby reduce how much methane emitted at the seafloor actually reaches the atmosphere. Meanwhile, in the Gulf of Mexico, researchers from TAMU, Scripps, and several other universities utilized synthetic aperture radar (SAR) imagery to compile an inventory of active gas and

(Foreground; left to right) researchers Ruo He, Monica Heintz, and Mary Beth Leigh collect water samples from Lake Qalluuraq, located near Atqasuk on the north slope of the Brooks Range in Alaska in May 2009. (Background; left to right) John Pohlman, Matthew Wooller, and Ben Gaglioti prepare coring device for sampling lake sediments, Photo credit: NETL.

NOAA, NRL, BOEM, and BLM to broaden the nation's research portfolio to further address these recommendations. The first projects were awarded by NETL in 2008 and featured a range of experts (from universities and national laboratories) who worked to quantify methane flux from a variety of oil vents and developed a comprehensive approach for quantifying the flux of methane from these seeps. This spurred valuable scientific debate on the conditions under which methane released at such seeps may potentially enter the atmosphere. In addition, DOE supported the UCSB team in conducting additional field work in the Gulf of Mexico, in this case participating (with scientists from Texas A&M and other institutions) in the primarily NSF-funded effort that concluded that very little of the methane or other hydrocarbons released at the site of the 2010 Macondo spill reached the atmosphere. While it is not clear how well this event may relate to natural events, the resiliency of the natural system clearly must be accounted for when assessing hydrate-climate impacts.

Incorporation of the emerging information on gas hydrate behavior into climate models featured two primary studies. In one effort, researchers at the University of Chicago and University of California-Berkeley began developing global models to capture the long-term behavior of gas hydrates in nature, with the goal of replicating current occurrences and providing a platform for modeling future system behavior. In a second effort, the Lawrence Berkeley National Lab (creators of the leading model of gas hydrate behavior in sediments) teamed with scientists at the Los Alamos National Lab (owners of leading ocean-circulation models) to couple projections of future changes in seafloor temperatures to likely responses of gas hydrates. This team then used these results to assess the potential rates of methane release under various future scenarios and the possible implications of those releases on ocean ecology, primarily ocean acidification. These studies have been and will continue to be pivotal in setting research priorities in this area.

A key challenge for linking methane emissions from dissociating gas hydrates directly to increases in atmospheric methane levels is the inability to determine whether a specific gas seep is leaking gas originating from methane hydrates. With partial support from DOE, Dr. Andrew Hunt at the USGS led a team to exploit the unique way that noble gas molecules partition in gas hydrates as a potential fingerprint to distinguish gas streams that feed off disintegrating methane hydrates (as opposed to other gas sources). The initial studies are promising, demonstrating that gas hydrate breakdown may provide a relatively unique fingerprint in the noble gas signatures.

As a necessary complement to the modeling efforts, DOE is supporting the acquisition of data in the field, primarily from the area where the most climate-sensitive hydrates occur—the Arctic. Researchers from the University of Alaska at Fairbanks (UAF) and the USGS collaborated on methane ebullition from some of the thousands of lakes located in permafrost on the Alaskan North Slope. As the Arctic warms and the permafrost thaws, methane flux to the atmosphere is increasing due to a number of processes, including increased microbial production of methane in shallow lake sediments, microbial methane production from newly thawed organic carbon deeper beneath lakes, and possibly from leakage of methane from underlying gas hydrates. As part of the effort led by UAF, scientists reconstructed the first Holocene-scale (last 12,000 year) history of methane emissions from a thermokarst lake, demonstrated that current methane ebullition is

Methane hydrate mound on the Gulf of Mexico sea-floor. Minor amounts of oil stain the hydrate orange, and the mound is covered by a thin drape of sediment. Photo credit: Ian MacDonald.

dominated by shallow (non-hydrate) methane, and have developed an advanced understanding of the microbial processes responsible for the production and consumption of methane in these systems.

Perhaps the major potential for methane release lies offshore. In 2009, NETL, NRL and scientists from the Netherlands, Belgium and Germany completed an initial 12-day expedition designed to determine the state of methane release on the Alaskan Beaufort (Arctic) shelf. This environment, where permafrost-associated hydrates formed during previous periods of lower sea level likely persist, but are actively degrading (due to thermal forces related to ongoing, post-glacial, sea-level rise), has been observed to be releasing potentially massive volumes of methane on the East Siberian Arctic Sea to the west. Observations from this expedition suggest that while methane is present in the water in elevated volumes, such large-scale venting is not ongoing on the Beaufort shelf.

In 2010-2012, DOE supported a research team led by Dr. Carolyn Ruppel of the USGS to work in the Beaufort Sea in an effort to determine the offshore extent of the climate susceptible subsea permafrost (along with any associated methane hydrates) to measure methane oxidation rates (methane sink) in seawater and methane flux across the ocean-atmosphere interface, to image the impact of climate-driven changes on the deepwater gas hydrate system on the Beaufort upper continental slope, and to map potential methane release hotspots. Going forward, the DOE will continue to work with the USGS and colleagues at Southern Methodist University to extend climate-hydrate studies on the Beaufort Sea upper continental slope, where the upper edge of the deepwater gas hydrate system could be dissociating and possibly exacerbating slope failures as Arctic Ocean temperatures and sea-ice conditions change in response to global warming. The behavior of deepwater gas hydrate systems will continue to be a focus of DOE support. In 2013, DOE will also support NRL participation in an international effort to assess gas hydrate dynamics offshore eastern New Zealand.

In order to effectively communicate these broad issues and the breadth of international activity and research directed at resolving them, DOE regularly summarizes its, and other's, research in its Fire in the Ice Newsletter (available at NETL's website) and is participating in a new initiative launched by the United Nations Environment Program titled Global Outlook on Methane Gas Hydrates. The assessment is expected to be released in summer 2013.

Summary

DOE has strived to manage a methane hydrate research program that is well balanced and focused on the knowledge gaps in several key areas: resource characterization, production potential, global environmental impacts, and potential safety hazards. Just as the program is years away from successful production of methane hydrates as an energy resource, we are also just beginning to address the key questions relating to the role of methane hydrates in the global carbon cycle and climate change. By partnering with research groups that can take full advantage of the advances in coupled climate modeling, genomic sequencing, stable isotope probing, and instrumentation for real-time assessment of methane fluxes, as well as with scientists who can lead truly multidisciplinary field programs, DOE is directly contributing to understanding methane dynamics in the seafloor-ocean-atmosphere system and to addressing the critical question of the present and future contribution of dissociating gas hydrates to atmospheric methane levels.

In August 2012, DOE selected several new projects that will undoubtedly move us further down the path of understanding methane hydrates, both as a resource and as a potential contributor to climate change. The selections award over $5.5 million in research funds to 14 universities and their partners to study the distribution and dynamics of natural methane hydrate systems and the potential for resource extraction from gas hydrates.

Information on these new project awards and on the completed projects discussed above can be found at http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/maincontent.htm.