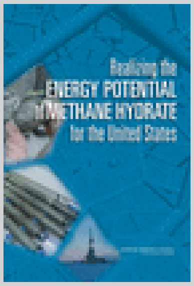

Realizing the Energy Potential of Methane Hydrate for the United States

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Committee on Assessment of the Department of Energy's Methane Hydrate Research and Development Program: Evaluating Methane Hydrate as a Future Energy Resource

Realizing the ENERGY POTENTIAL of METHANE HYDRATE for the United States

Committee on Assessment of the Department of Energy's Methane Hydrate Research and Development Program: Evaluating Methane Hydrate as a Future Energy Resource

Committee on Earth Resources

Board on Earth Sciences and Resources

Division on Earth and Life Studies

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Cover: The backdrop is a three-dimensional rendering of the "structure 1" or s1 methane hydrate in which methane molecules (represented by spheres) are trapped inside hydrogen-bonded water cages. The images embedded within the cages include a hand-held methane hydrate-bearing sediment sample from the Mt. Elbert well at Milne Point, Alaska (*upper left*), prepared drillcores from the Department of Energy/Joint Industry Project Gulf of Mexico methane hydrate cruise (*middle*), and the Doyon 14 drill rig at the Mount Elbert test site, Milne Point, Alaska (*lower middle*). *Images courtesy of: M. R. Walsh, Colorado School of Mines (three-dimensional s1 methane hydrate structure); Mount Elbert Gas Hydrate Research Team (both the Mt. Elbert hand-held core sample and drill rig); Gulf of Mexico Department of Energy/ Joint Industry Project Research Team (prepared drill cores).*
Designed by Michael Dudzik.

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COMMITTEE ON ASSESSMENT OF THE DEPARTMENT OF ENERGY'S METHANE HYDRATE RESEARCH AND DEVELOPMENT PROGRAM: EVALUATING METHANE HYDRATE AS A FUTURE ENERGY RESOURCE

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Preface

The United States is at an important juncture as it considers future, long-term directions for supplying its own energy needs while also reducing the impact on the global environment. Consideration of the greenhouse gas contribution to the atmosphere of each energy source relative to its energy efficiency is a key part of this discussion. Natural gas, and particularly methane, because of its relatively clean environmental footprint—when combusted, natural gas produces less carbon dioxide per energy unit than do other fossil fuels—has emerged as a central piece in planning and implementing the nation's transition to a future with cleaner, more efficient energy use. Whereas the current estimates of the nation's undiscovered, conventional natural gas endowment on- and offshore are fairly substantial, the extent and accessibility of alternative sources of natural gas from "unconventional" (more technically challenging) sources are of increasing interest to policy makers, industry, and the public.

Methane hydrate, a solid form of methane and water that is widespread in Arctic permafrost areas of the Alaska North Slope and along most of the U.S. offshore continental margins, is an unconventional source of a potentially enormous volume of methane. Although the scientific, engineering, and environmental questions associated with exploration and potential commercial production of methane from methane hydrate are challenging, research programs around the world, including the United States, have made recent, substantial progress in understanding the behavior and extent of the resource and in performing drilling and production tests to extract methane from it. The results of these research endeavors provide the input to gauge the next steps toward realizing sustained, economically and environmentally viable production of methane from methane hydrate. The coming decade will prove pivotal as various nations attempt to make the transition from successful basic research and development programs to full-scale production of methane from methane hydrate in commercially supported operations. The United States is one of the international leaders in this field by virtue of the excellence of the research its scientists have conducted and the rich natural endowment of methane hydrate offshore and associated with permafrost in Alaska. Our challenge is to realize this resource in a safe and environmentally sound manner.

In 2005, Congress reauthorized the Methane Hydrate Research and Development Program, initially established in the Methane Hydrate Research and Development Act of 2000 (Appendix A), focused on stimulating advancements in the understanding of methane hydrate. The Program's goals involve generating the needed scientific and technical knowledge to produce methane from methane hydrate as an energy resource in an environmentally sound manner. The Department of Energy, in cooperation with the National Energy Technology Laboratory, has managed this Program through support to about 40 new and continuing projects between fiscal years 2006 and 2009. These projects range in size and scale from large field programs involving multiple institutions focused on drilling into methane hydrate deposits, to single-institution laboratory and modeling studies.

The Act also mandates that a National Research Council (NRC) study be conducted to evaluate the progress that the Program is making toward achieving its goals and to make recommendations about future research and development needs. This report is the product of a committee convened by the NRC for this purpose. The members of this review committee represent a range of expertise including geochemistry, geology, oceanography, geophysics, petroleum engineering, risk assessment, and chemical engineering from industry, academia, government, and nonprofit research foundations (Appendix B). The committee met as a whole four times (twice each in Washington, D.C., and Golden, Colorado) to hear invited presentations and review available materials associated with the Program (Appendix C).

In this report, the committee has tried to provide an overview for the interested nonspecialist on the present state of knowledge in this field, an assessment of the impact the Program has made on the field, and recommendations as to what the technical emphasis of the continuing program ought to be over the next several years. The committee has made these recommendations in the context of a long-term goal for the Program and for many in the U.S. methane hydrate research community: to contribute research appropriate toward demonstration of environmentally and economically sustainable production of methane from methane hydrate by 2025. The committee realizes, however, that other factors, including regulatory issues and market economics, will also affect the ability of and timing for the nation to achieve this production aim. Overall, the committee has been impressed with both the quality of the work the Program has enabled and the progress that has been made toward this long-term goal. The committee's research and development recommendations are thus intentionally high level, but specific with respect to the kind of technical and scientific emphasis we think necessary for the nation to attain this goal.

Charlie Paull
Chair

Acknowledgments

In addition to its own expertise, the committee relied on input from numerous external professionals with extensive experience in various aspects of methane hydrate research. These individuals provided presentations, data, perspectives, and illustrative figures and images which assisted the committee in understanding the scope of domestic and international research in the field and the role played by the Department of Energy Methane Hydrate Research and Development Program and other federal agencies to advance the field. This information was extremely important to the committee in formulating its report, and we would like to express our appreciation to the many highly qualified individuals who provided advice and assistance during the course of the study. In particular, the committee would like to thank the following individuals for their very thorough and helpful responses to our inquiries at all stages of the study: Edith Allison, Ray Boswell, Rick Coffin, Tim Collett, Helen Farrell, Robert Fisk, Matt Frye, Bob Hardage, James Howard, Robert Hunter, Emrys Jones, Tim Kneafsey, Debbie Hutchinson, Yoshihiro Masuda, Ian MacDonald, Kenji Ohno, Brenda Pierce, Kimberly Puglise, Kelly Rose, Carolyn Ruppel, Carlos Santamarina, Dendy Sloan, Bob Swenson, and Scott Wilson.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their participation in the review of this report:

Amos A. Avidan, Bechtel Corporation, Houston, Texas
Nathan L.B. Bangs, University of Texas, Austin
Inez Y. Fung, University of California, Berkeley
Steven H. Hancock, RPS Energy Canada, Calgary, Alberta
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Joel E. Johnson, University of New Hampshire, Durham
Salomon Levy, Levy & Associates, Campbell, California
John R.A. Pearson, Schlumberger Cambridge Research, United Kingdom
Mehran Pooladi-Darvish, University of Calgary, Alberta, Canada
Vladimir E. Romanovsky, University of Alaska, Fairbanks
Terry E. Whitledge, University of Alaska, Fairbanks

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by Charles G. Groat, University of Texas, Austin, who was appointed by the NRC and was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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APPENDIXES

Summary

Methane hydrate is a naturally occurring solid that forms in sediments when methane, in high concentrations, and water combine at low temperatures and high pressures. The incentive for research on methane hydrate[1] is the less than 30-year-old realization that methane hydrate occurs in abundance on the world's continental margins and in permafrost regions, and that it could ultimately provide an additional, potentially significant, unconventional source of methane to augment conventional natural gas supplies. Because methane, the main component of natural gas, releases less carbon dioxide per unit of energy produced during combustion than other fossil fuels, strong interest exists to use natural gas as a key source of energy in the nation's transition to a less carbon-intensive energy portfolio.

In the United States, significant accumulations of methane hydrate occur in the Gulf of Mexico, off the Pacific and Eastern seaboards, and on the Alaska North Slope. The production of methane from methane hydrate accumulations could help to provide greater energy security for the United States and help to address future energy needs globally. However, the environmentally and economically sustainable production of methane from methane hydrate in these locations has not yet been achieved. Complex scientific challenges, which may require the development of new technologies, remain before methane from methane hydrate can be realized as an energy resource. Major research efforts to achieve this production goal are now being pursued seriously in several countries, including the United States.

In addition to its use as an energy resource, methane is an important component of the Earth's carbon cycle on geologic timescales. Methane itself is a potent greenhouse gas and is always present in the Earth's atmo-

[1] Methane hydrate is a term used in this report that is synonymous with "methane clathrate" and "gas hydrate" where the contained gas molecule is mainly methane.

sphere, but at varying concentrations. However, whether methane once stored as methane hydrate has contributed to past climate change or will play a role in the future global climate remains unclear. The potential local environmental impacts associated with either natural or human-caused seepage of methane from methane hydrate are also poorly understood and need to be differentiated from other seepage processes before methane is commercially produced from methane hydrate. Potential impacts include gas leakage to the ocean, land surface, or atmosphere, settling of the seafloor or ground around a well, and effects on biological communities at the seafloor or on the land surface. Although methane hydrate is also commonly perceived as posing geohazard risks to industry, little documentation exists to constrain the extent and magnitude of these potential risks. Present industry practice is to try to avoid methane hydrate–bearing areas during drilling and production for conventional oil and gas resources. The current industry approach of avoidance will be untenable if methane hydrate itself becomes the production target.

Although several U.S. federal agencies conduct significant research on methane hydrate, the Department of Energy's (DOE's) Methane Hydrate Research and Development Program (hereafter "the Program"), established through the Methane Hydrate Research and Development Act of 2000 (P.L. 106-193), and reauthorized in the Energy Policy Act of 2005 (P.L. 109-58), has been tasked specifically to implement and coordinate a national methane hydrate research effort. The Program is directed specifically to understand the

- Physical nature of methane hydrate occurrences;
- Methods to quantify and explore for methane hydrate deposits;
- Stability and behavior of methane hydrate when disturbed by drilling and production;
- Technological requirements to produce methane from methane hydrate; and
- Potential impacts of methane from methane hydrate deposits venting into the environment during methane production or in response to natural changes in the environment.

In response to DOE's request for the National Research Council (NRC) to conduct a review of the Program, as mandated in P.L. 109-58, the NRC established the Committee on Assessment of the Department of Energy's Methane Hydrate Research and Development Program to address several issues including

- Brief review of the research conducted by the Program from 2000 to 2005;
- Detailed review of the research supported by the Program since 2005;
- Evaluation of the Program's review mechanisms and of the processes used by the Program to facilitate collaborations with other agencies, academia, research laboratories, industry, the international community, and the Program's advisory board;
- Evaluation of future methane hydrate research and development needs and programmatic changes necessary to meet these needs; and
- Recommendations regarding (a) the suitability of methane hydrate as a significant contributor to the U.S. natural gas supply by 2025, (b) the effective coordination of the Program's domestic and international collaborations, and (c) graduate education and training in this field of research.

This report constitutes the committee's response to the DOE request and is intended for nonspecialists interested in future, environmentally and economically viable energy options which include national efforts to understand and develop methane gas contained in methane hydrate.

PROGRAM OVERSIGHT

The overarching Program goal is to stimulate the development of knowledge and technology necessary for commercial production of methane from methane hydrate in a safe and environmentally responsible way. The majority of the Program's modest resources are directed toward research through field projects and other cooperative agreements. The remainder of the Program's annual funding allocation is directed toward support for activities at national laboratories, with smaller proportions allocated to program management, selected activities at other federal agencies, graduate research fellowships, and technology transfer.

Project Portfolio

The project portfolio from 2000 to 2005 was reviewed in part by an earlier NRC report from 2004, *Charting the Future of Methane Hydrate Research in the United States*. In addition to serving a coordinating role for interagency methane hydrate research in these initial years, the Program solicited proposals and provided partial support for three large field projects coordinated as cooperative agreements with industry (one in the Gulf of Mexico and two on the Alaska North Slope). Twenty other projects in the laboratory and the field were also supported by the Program, and were performed by researchers at universities, institutes, and national laboratories. Three projects undertaken as part of a federal collaborative effort were managed by and received primary support from the U.S. Geological Survey (USGS). The Program also participated in an international drilling consortium at Mallik in the Canadian Arctic, managed by the Geological Survey of Canada.

The research portfolio of the Program from fiscal year 2006 to present includes two key production-related goals: (1) to provide by 2015 an initial assessment of the scale of the potential commercial development of methane from methane hydrate resources on the Alaska North Slope, and (2) to demonstrate the technical recoverability and assess the economic recoverability of marine methane hydrate–bearing sand reservoirs by 2025. During the past 5 years, the Program has increased the number and scope of its smaller-scale research projects, established two new industry-managed projects on the Alaska North Slope, and supported the continuation of the Gulf of Mexico and one of the Alaska North Slope projects into more intricate phases in their planned research. In total, 38 projects supported since late 2005 include field production and drilling, resource characterization and remote sensing, environmental research, experimental laboratory and theoretical modeling, and geomechanics and geohazard research.

Projects in the Gulf of Mexico and Alaska have been cornerstones of the Program's portfolio since 2001. These projects have been oriented toward improving exploration methods and quantifying methane hydrate resources, as well as evaluating the challenges of methane hydrate production. Important to the research in both regions has been their coordination as cooperative agreements with industry, with significant input from multiple federal agencies, national laboratories, and the academic community. These field projects have received a significant proportion of Program resources (~$52 million has been allocated since 2001), although cost sharing with industry partners is noteworthy. The scientific merits and successes of the research conducted through these field projects have generated new knowledge toward achieving sustained production of methane from methane hydrate. Project priorities include verifying methane hydrate accumulation models and the design, drilling, logging, coring, and continuous monitoring of production wells to test the commercial potential of producing gas. Field trials of a new production methodology that exchanges carbon dioxide molecules for methane molecules within a hydrate structure are also of interest. In the Gulf of Mexico, geohazards associated with the natural occurrence of methane hydrate in areas with conventional petroleum production have not yet been systematically appraised.

The Program has supported several experimental projects since 2005, focused on physical property measurements, computer modeling projects that include reservoir and production modeling, and the development of the U.S. methane hydrate database. The major limitation of the laboratory-based experimental projects has been the nature of the formations being characterized and measured. The samples need to be close analogs to natural methane hydrate samples if the measurement results are to be scaled and extended to the reservoir system, but developing these synthetic analogs in the laboratory has proven difficult.

Six resource characterization and remote-sensing projects to detect and quantify methane hydrate in nature have been conducted in the past 5 years. Focus has been on two areas: (1) seismic and/or acoustic techniques and (2) controlled-source electromagnetic imaging. Useful advances have been provided by some of these research projects to detect and estimate the extent of subsurface methane hydrate accumulations. However, accurate assessment of the temperature and pressure conditions for potential methane hydrate–bearing sediments is still needed to make better predictions of the quantity of the methane hydrate resource, as are seismic surveys dedicated to detecting shallow methane hydrate targets.

Of the 14 projects addressing environmental issues that are supported by the Program, 10 have focused on some aspect of environmental impacts resulting from the natural degassing of methane hydrate. Most projects specifically propose to generate new information regarding the role of methane hydrate and its natural degassing in the global carbon cycle and/or in global climate change. As yet, no major breakthroughs have appeared from this research. To date none of the Program's projects has substantially addressed the environmental impacts expected from the commercial exploitation of methane hydrate, nor has any project considered the mitigation of the environmental impacts of natural methane hydrate degassing and degassing associated with commercial oil and gas development.

Research on methane hydrate to date has not revealed technical challenges that the committee believes are insurmountable in the goal to achieve commercial production of methane from methane hydrate in an economically and environmentally feasible manner. However, many scientific and engineering questions in methane hydrate research remain to be answered before it will be possible to achieve commercial production. When this knowledge is available, informed decisions can be made as to whether or not to proceed with the commercial exploitation of methane hydrate.

Program Coordination

The committee has determined that the overall management of the Program has been consistent and effective. The Program has worked to develop, promote, and improve its scientific directions and management processes since 2005 by (1) increasing the success of the research funded by the Program,

(2) supporting education and training of young researchers, (3) enhancing collaborative engagements with other research entities domestically and internationally, and (4) strengthening management efficiency and the transparency of its activities.

The Program includes project selection and performance evaluation for two primary types of projects: (1) cooperative agreements selected competitively through public announcements and (2) interagency agreements and National Laboratory Field Work Proposals. Once projects have begun, external reviewers are selected to periodically evaluate project quality, relevance, progress, and results. The peer review process established by the Program is reasonably thorough, with considerable effort being made to appraise the progress of funded projects with regularity and in an open forum. Nonetheless, the large, multipartner field projects could benefit from more nuanced and frequent evaluations including open and comprehensive reviews of site survey data; the design of well completion, production, and monitoring approaches; risk assessments; and mitigation strategies.

Peer-reviewed publications based on results of the Program's research projects are increasing, in part because of encouragement from Program management. Continued and enhanced emphasis on peer-reviewed publication is necessary to demonstrate the quality of the results and to establish lasting benchmark contributions. Information about the Program's projects is also being disseminated through the Program Web site, online newsletter, and international conference reports.

Training and educating new researchers in methane hydrate are essential for continued growth of the field. The Program provides the only national funding specifically including education and training of the next generation of methane hydrate scientists. Between 2000 and 2008, the Program provided research opportunities and financial support to over 150 students (mostly master's and doctoral degree students) and 16 postdoctoral researchers from 42 U.S. universities. In 2006, the Program also initiated a Methane Hydrate R&D Fellowship program to provide 2 years of support for particularly deserving graduate or postdoctoral fellows. The Program's large field projects and international collaborations represent valuable additional educational experiences for young researchers, and the

Program should seek to maximize these opportunities for the students and young graduates it supports.

Most of the six federal agencies involved in the interagency collaboration on methane hydrate research and development have their own internally funded methane hydrate research programs. Contributions to the interagency methane hydrate research effort are thus conducted under collaborative agreements with DOE. These agencies include the Bureau of Land Management, Minerals Management Service (MMS), National Oceanographic and Atmospheric Administration, National Science Foundation, Naval Research Laboratory, and the USGS, and each agency has contributed specific, useful research results to the national methane hydrate research and development effort. In the past 2 years, research products from the USGS and MMS, in particular, have notably and significantly advanced the state of understanding of methane hydrate as a potential energy resource. All agencies have indicated satisfaction with the Program's coordination of these interagency efforts.

Although the Program has participated in some international collaborations, active engagement with international partners has been challenging to develop. The Program management has developed formal collaborative ties with international programs investigating methane hydrate (e.g., India, Korea, and Japan), and representatives from the Program are participating in several international field projects. However, the full potential of these endeavors to advance science of value to the U.S. national effort is still to be developed, and the Program has been somewhat reliant on the international research engagement of other agencies, such as the USGS, to provide research results to the Program through the interagency coordination. Enhanced international collaboration under the Program's auspices could serve to expose a broader range of U.S. scientists to these international efforts, to advance education and training, and to encourage lasting working collaborations that are in keeping with the specific goals of the U.S. national effort. Adequate, sustained, and specifically dedicated resources for international collaborations as well as administrative support from high levels within DOE for the Program's efforts in this area are important to strengthening the Program's international research relationships.

RECOMMENDATIONS FOR FUTURE RESEARCH AND DEVELOPMENT

Although methane is a cleaner-burning energy source than other fossil fuels, it is itself a significant greenhouse gas, and understanding the role of methane in the global carbon cycle remains a topic of considerable scientific interest. With respect to considering eventual commercial production of methane from methane hydrate, understanding the potential environmental impacts of methane hydrate degassing[2] and the seafloor hazards ("geohazards") resulting from methane hydrate dissociation as a result of oil and gas drilling and production are of specific importance. Thus, the mandated goals and levels of support that have been available for this Program may require that the Program's future environmental and geohazard research directions be focused on applied and theoretical efforts related to the production of methane from methane hydrate and related oil and gas drilling through methane hydrate occurrences.

In particular, designing production tests, appraising and mitigating environmental and geohazard issues related to production, and quantification of the methane hydrate resource are identified as critical to achieving the Program goals on the Alaska North Slope by 2015 and in marine methane hydrate–bearing sand reservoirs by 2025.

Production tests should be designed to include

- **Development and demonstration of well completions with appropriate production technologies.**
- **Long-term production tests on methane hydrate in a variety of geologic settings,** beginning in the Arctic where technical issues may initially be less challenging than in marine settings. **Demonstrating potential commercial rates for production** is essential for future evaluation of production economics. Study of the factors that affect the production of gas and water should also be

[2]"Degassing" refers to methane from methane hydrate entering the atmosphere.

considered. These factors include, for example, the distribution of methane hydrate, its concentration, the physical properties of the host rock, sediment heterogeneity, and the influence of overlying and underlying sedimentary units.

- **Establishing initial conditions, monitoring changes during production, and determining formation response** after testing by using repeated geophysical surveys; *in situ* formation temperature, pressure, and geomechanical measurements; and other techniques. The field production tests should also be closely integrated with reservoir modeling studies.
- **A staged approach with open and comprehensive reviews of site survey data; completion, production, and monitoring design; risk assessments; and mitigation strategies.**

Appraisal and mitigation of environmental and geohazard issues related to production should include:

- **Compilation of industry experience associated with conventional oil and gas production in areas where methane hydrate occurs.**
- **Organized workshops to solicit input and identify research goals needed to evaluate and mitigate geohazards and environmental issues** specific to the production of methane from methane hydrate and to perturbations of methane hydrate associated with other oil and gas development activities.
- **Studies specifically addressing potential geohazards associated with methane production from methane hydrate** (e.g., laboratory measurements, modeling, and natural perturbation experiments) to provide more confidence in risk assessments and effective mitigation strategies.

Quantification of the resource should include

- **Pilot seismic surveys using existing geophysical methods optimized to map and quantify in-place methane hydrate accumulations.**
- **Improved understanding of *in situ* properties of sediments containing methane hydrate** through comprehensive testing (geophysical, geochemical, microbiological, geomechanical) of undisturbed natural drill cores and synthetic samples.
- **Consideration of the development of new geophysical imaging, processing, and quantification techniques,** particularly with respect to quantifying the in-place resource.

In the future, efforts to collect data that maximize resolution within the zones where methane hydrate occurs and allow the potential resource to be better quantified should be encouraged. New seismic and electromagnetic survey techniques should be developed and preferably used in conjunction with conventional seismic surveys.

Although understanding the role of methane hydrate as a source of global greenhouse gas is of general interest, this research is not uniquely related to realizing methane hydrate as an energy resource. However, quantifying ongoing, natural methane fluxes from methane hydrate on a local scale is needed to provide a baseline to evaluate the effects of any future production and development of the methane hydrate resource. Thus,

- **Studies are required to address the processes involved (a) in the transmission of methane from the subsurface through the methane hydrate stability zone to the surface and (b) in the subsequent fate of the released methane. These studies should focus on degassing processes and potentially enhanced environmental impacts from commercial production of methane from methane hydrate and from methane hydrate associated with other oil and gas developments.**

- **Investigation of the role of methane hydrate in the global carbon cycle is best pursued in collaboration with other agencies.** Resolution of these questions is not central to the Program's goal of resource development.

The committee was impressed with the overall quality of much of the research that is under way through the support and coordination of the Program. The research progress, the positive impact the Program is having on raising the profile of and interest in methane hydrate as a potential energy resource, and the rate at which the Program is moving toward the goal of achieving production of methane from methane hydrate accumulations are all commendable. Achieving the Program goals will require sustained national commitment, because the cost of the necessary pre- and post-drilling assessments, field tests, and the associated laboratory and modeling studies will be substantial.

CHAPTER 1

Methane Hydrate Research in the United States

Ensuring reliable sources of natural gas is of significant strategic interest to the United States. Natural gas is the cleanest of all the fossil fuels, emitting from 25 to 50 percent less carbon dioxide than either oil or coal for each unit of energy produced.[1] In recent years, natural gas has supplied approximately 20-25 percent of all energy consumed in the United States. In 2008, for example, a total of about 23 trillion cubic feet (TCF)[2] of natural gas was used to supply heat and electrical power to various sectors of the economy, with domestic natural gas providing approximately 85 percent of this volume (EIA, 2009a,b). The relatively clean environmental footprint for combustion, the potential for securing significant domestic supplies, and the compatibility with existing infrastructure indicate that natural gas can be a cornerstone of an environmentally and economically sound domestic energy portfolio.

Accumulations of methane hydrate, a solid form of natural gas, may represent an enormous source of methane. Methane hydrate occurs in sediments within and below thick permafrost in Arctic regions and in the subsurface of most continental margins where water depths are greater than

[1] http://www.eia.doe.gov/bookshelf/brochures/greenhouse/Chapter1.htm.

[2] 651 × 109 m^3. The available literature on methane hydrate employs a mix of metric and English units, appropriately reflecting international and domestic contributions to this field of study. This report uses the original measurement unit of the cited reference, whether metric or English, followed by a conversion to the other unit of measure. For the reader's interest, Appendix D contains a comparison of units of measurement of amounts of methane by volume and by weight.

about 1,500 feet (about 500 meters) (Figure 1.1; Box 1.1). Although the estimated total global volume of methane in methane hydrate is still debated, generally acknowledged estimates yield figures between 2 and 10 times greater than those of technically recoverable conventional natural gas resources (see Chapter 2). The existence of such a large and as-yet untapped methane hydrate resource has provided a strong global research incentive to determine how methane from methane hydrate might be produced as a technically safe, environmentally compatible, and economically competitive energy resource (e.g., Council of Canadian Academies, 2008).

Although methane is a cleaner-burning energy source than other fossil fuels, it is itself a significant greenhouse gas, about 25 times more potent per molecule than carbon dioxide on a 100-year basis (International Energy Administration, 2009). Thus, understanding the potential environmental impacts of methane hydrate degassing[3] and the seafloor hazard ("geohazard") potential resulting from methane hydrate dissociation, whether through natural processes or through oil and gas drilling and production, is also important as its potential for commercial production is considered and tested.

NATIONAL APPROACH TO METHANE HYDRATE RESEARCH AND DEVELOPMENT

The Department of Energy (DOE), through congressional authorization in the Methane Hydrate Research and Development Act of 2000 (P.L. 106-193), and as reauthorized in the Energy Policy Act of 2005 (P.L. 109-58) (Appendix A), has led a national research effort to understand (1) the physical nature of methane hydrate occurrences in sedimentary rock layers in offshore and in permafrost areas, (2) methods to quantify and explore for methane hydrate accumulations in nature, (3) the stability and behavior of methane hydrate when disturbed by drilling and production, (4) the technological requirements to produce methane from methane hydrate, and (5) the potential environmental impacts of methane

[3] "Degassing" refers to methane from methane hydrate entering the atmosphere.

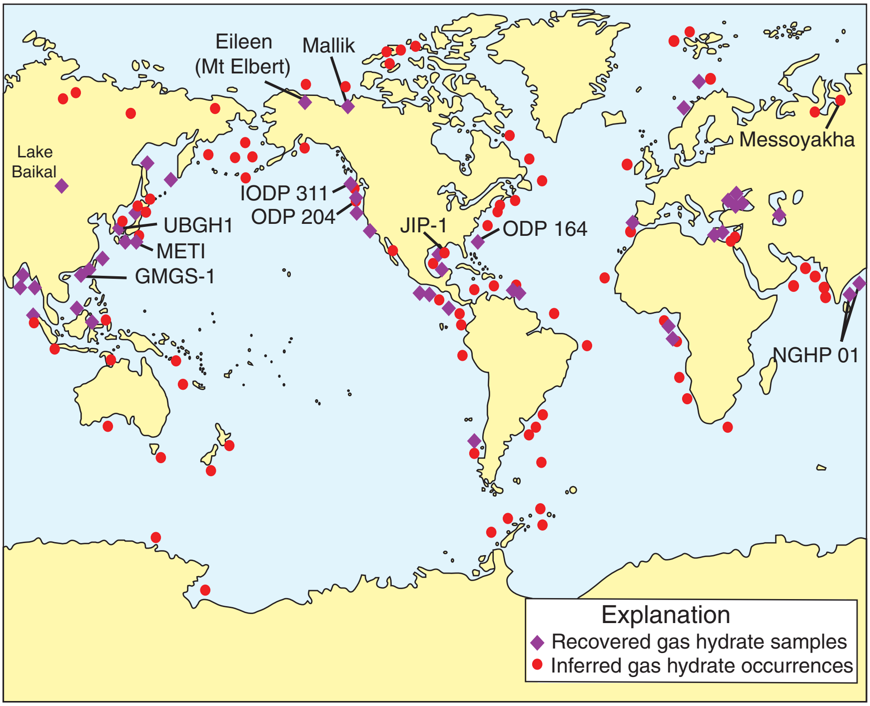


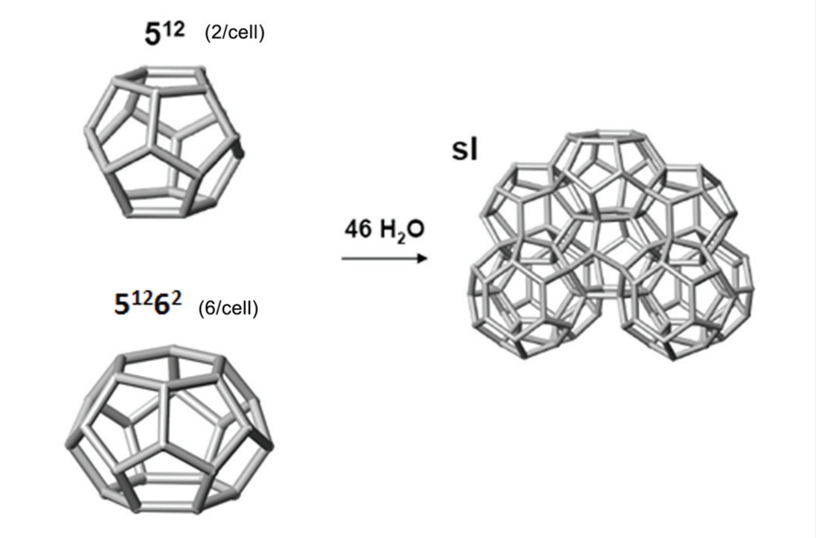
FIGURE 1.1 Worldwide locations of methane hydrate occurrences show the location of sampled and inferred methane hydrate in oceanic sediment of outer continental margins and permafrost regions. Many of the recovered methane hydrate samples have been obtained during deep coring projects or seafloor sampling operations. Most of the inferred methane hydrate occurrences are marine sites at which bottom-simulating reflectors have been observed on available seismic profiles. The methane hydrate occurrences reviewed in this report have also been highlighted on this map. Numbers adjacent to abbreviated site locality names identify project or drilling legs. GMGS = Guangzhou Marine Geological Survey; IODP = Integrated Ocean Drilling Program; JIP = joint industry project (Department of Energy Methane Hydrate Program supported); METI = Ministry of International Trade and Industry of Japan; NGHP = National Gas Hydrate Program of India; ODP = Ocean Drilling Program; UBGH = Ulleung Basin Gas Hydrate. Modified from Keith Kvenvolden and others from the U.S. Geological Survey.

BOX 1.1
The Basics of Gas Hydrate and the Importance of Methane Hydrate

Gas hydrate is an ice-like substance that forms when gas, at high concentrations, and water come into contact at high pressures and low temperatures (e.g., 60 bars, 4°C). Gas hydrate is composed of water molecules that bind together by hydrogen bonds to form a network of cages of various sizes. Small gas molecules such as methane, propane, and carbon dioxide ("guest" molecules) initiate cage formation and may become trapped in these cages (see opposite page). Other cages may remain vacant. Typically, large hydrate cages are more than 95 percent full of guests, while small cages are around 50 percent full of guests.

The most common, naturally occurring gas hydrate structure is known as structure I ("sI"; see opposite page), which contains methane "guest" molecules. Therefore, gas hydrate occurring naturally in permafrost and marine sediments (see images on third page of box) is often referred to as *methane hydrate*.[a] Microbial methanogenesis (the decay of organic matter at shallow depths and low temperatures) is commonly the source of the methane stored in these hydrates. The formation of other gas hydrate structures (e.g., sII and sH, which are not discussed further because these structures are less common in nature than sI) requires additional components of heavier hydrocarbon gases, which are minimally formed during methanogenic gas production. The existence of these heavier components may indicate a thermogenic gas source. Thermogenic processes occur at higher temperatures and greater depths within sedimentary rocks where buried organic material is thermally altered into liquid and gaseous hydrocarbons. Although most of these hydrocarbons may remain at depth as "conventional" oil and natural gas accumulations, some of the gases, including methane, may also migrate to shallow depths and form methane hydrate if appropriate pressure and temperature conditions and sufficient free water exist.

An important difference between methane hydrate deposits and those of "conventional" gas accumulations is the nature of the sedimentary rocks within which the gas is found: conventional natural gas fields trap gas in porous sedimentary beds, surrounded by impermeable rocks; methane hydrate deposits occur in relatively unconsolidated sediments where the ice-like hydrate structure itself serves as the trap for individual gas molecules. These characteristics add challenges to producing methane from methane hydrate—hence the description of methane hydrate as an "unconventional" gas resource.



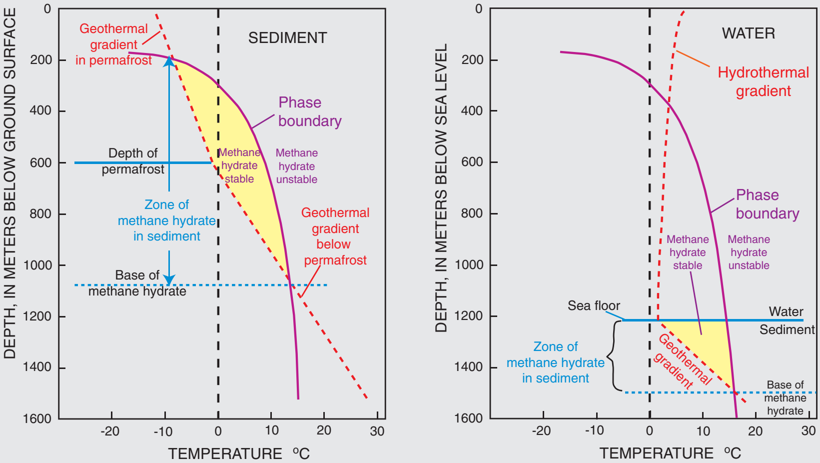
The structure I hydrate unit cell (unit cell = smallest repeating unit of the hydrate crystal) contains 46 water molecules and is composed of two small water cages (5^{12}) and six large water cages ($5^{12}6^2$). The water cages can trap gas molecules (not shown). SOURCE: Koh and Sloan (2008).

Because methane is trapped within the hydrate crystal structure, methane gas in hydrate is greatly compressed. This results in an "energy density" for methane hydrate up to 164 volumes of gas per volume of hydrate (at standard temperature and pressure, or STP) which can be substantially higher than the energy density for conventional gas reservoirs at the same depth. Because the occurrence of methane hydrate is related to specific pressure-temperature conditions, increasing temperature and/or decreasing pressure cause the hydrate to become unstable and "dissociate,"[b] producing methane gas and water (see graphs on next facing page). This dissociation process can take place naturally, because of changing geologic conditions, or may be induced, for example, by drilling through methane hydrate to reach conventional oil and gas or methane hydrate deposits. These dissociation processes may also have environmental and drilling-safety impacts that need to be recognized and understood.

BOX 1.1 Continued

Images showing different types of methane hydrate occurrences: (left) disseminated within pore-space of sand deposits (from Mount Elbert, Alaska North Slope), (right) layered methane hydrate occurrence from drillcore on Southern Hydrate Ridge (ODP Leg 204); sample about 1 centimeter in thickness. SOURCES: (a) Mount Elbert Science Team, photo by E. Rosenbaum (http://energy.usgs.gov/images/gashydrates/MtElbert_coresample2LG.jpg); (b) Tréhu et al. (2003) ODP Leg 204 volume (http://www-odp.tamu.edu/publications/204_IR/chap_02/c2_f11.htm).

Facing page caption: Diagrams showing the depths within and below the permafrost or below sea level at which methane hydrate is stable. The geothermal (or hydrothermal) gradient (red dashed lines) is the change in temperature with depth. Methane hydrate can occur in the yellow envelope where the pressure (related to depth) and temperature are favorable for methane hydrate stability. In permafrost areas (left), the zone (yellow envelope) in which methane hydrate can exist in sediments lies between depths of about 200 and 1,100 meters (about 650-3,600 feet). In continental margins offshore (right), methane hydrate can occur, in this example, to a sediment depth of about 1,500 meters (about 4,900 feet). Although the methane hydrate stability zone extends above the seafloor, methane hydrate generally does not occur in the water column above the seafloor because the methane concentrations



are typically too low to form methane hydrate and methane hydrate is buoyant in seawater. In both permafrost and continental margin cases hydrostatic pressure dominates the pressure regime and accounts for the similar shapes of the phase boundaries. SOURCE: Kvenvolden (1988).

[a] Although "gas hydrate" is the more general term that does not require differentiating whether the "guest" molecules are methane, propane, carbon dioxide, or others, the term "methane hydrate" is adopted universally in the text to conform to the legislative language that authorized the National Methane Hydrate Research and Development Program in the United States (Appendix A).

[b] In this report, "dissociation" of methane hydrate refers to the change in phase that takes place when methane hydrate is outside of its pressure/temperature stability field and converts from a solid to gaseous methane and liquid water.

degassing. Public Law 109-58 specified that DOE establish a National Research Council (NRC) study to assess the progress made by the DOE Methane Hydrate Research and Development Program (hereafter referred to as "the Program") through the year 2009, with focus on the period since the last review of the Program by the NRC (2004). In response to DOE's request, the NRC established the Committee on Assessment of the Department of Energy's Methane Hydrate Research and Development Program to address the issues outlined in the study's statement of task (Box 1.2). The committee consists of nine experts who contributed

BOX 1.2
Statement of Task

The Energy Policy Act of 2005, Section 968, calls for the Secretary of Energy to enter into an agreement with the National Research Council to (1) conduct a study of the progress made under the Methane Hydrate Research and Development (R&D) Program, and (2) make recommendations for future methane hydrate R&D needs.

Specifically, the study will

1. Briefly review previous methane hydrate research conducted by DOE and its federal and nonfederal collaborative partners from 2000 to 2005.
2. Review in detail the methane hydrate R&D conducted by DOE and partners from 2005 to 2007, considering the progress made in identifying and addressing the issues related to resource and reserve estimates, discovery methodology, production technology, and environmental impacts.
3. Review the process by which past and current R&D has been and is being conducted and advised, including domestic interagency coordination (between DOE and the U.S. Geological Survey, National Oceanographic and Atmospheric Administration, Minerals Management Service, Bureau of Land Management, National Science Foundation, and the Office of Naval Research); collaboration with institutes of higher education, oceanographic institutions, and industry; international coop-

their professional expertise in areas of biogeochemistry; organic, environmental, and experimental geochemistry; geomechanics; geophysics; marine geology; oceanography; oil and gas exploration and production, including drilling in methane hydrate–bearing targets on land and at sea; petroleum engineering; and risk analysis (Appendix B).

This report constitutes this committee's response to the study charge. This chapter provides the framework in which the committee examined the Program by reviewing briefly the Program highlights in the period from fiscal years 2000 to 2005 and some of the primary activities the Program has

eration and collaboration; the methane hydrate advisory panel mechanism; and peer review mechanisms.

4. Evaluate future R&D needs, with specific attention to
   a. The use of remote sensing and improved seismic processing for identification of methane hydrate resources;
   b. Developing new technologies to produce natural gas from methane hydrate, including technologies to reduce the risk of drilling through methane hydrate;
   c. Assessing the research conducted to evaluate and mitigate the environmental impact of hydrate degassing, both naturally and in conjunction with commercial exploitation;
   d. The scope and design of exploratory drilling, well testing, pilot and full-scale production well tests on permafrost and non-permafrost gas hydrate necessary to address (a) through (c), above.
5. Make recommendations concerning
   a. Suitability of methane hydrate resources to make a substantial contribution to domestic natural gas supply by 2025;
   b. Changes to the current program of R&D to meet the research needs identified above;
   c. Coordination of interagency, academic, and industrial research and partnerships, domestically and internationally, in carrying out the Program;
   d. Graduate education and training in methane hydrate research and resource production.

undertaken since the 2004 NRC report was issued. Chapter 2 discusses the current state of methane hydrate research domestically and internationally through the description of recent, important experimental, theoretical, and field-based discoveries that have significantly advanced understanding of methane hydrate as well as some of the key remaining research challenges. Importantly, these discoveries and challenges have helped raise the level of research awareness given to methane hydrate from one of general scientific importance with respect to environmental and geohazard concerns to one of focused research interest in methane hydrate as a potentially viable energy resource. Chapter 3 specifically examines the research portfolio of the Program, and Chapter 4 describes the organizational processes the Program employs to coordinate methane hydrate research and development in the United States. Chapter 5 presents the committee's conclusions and recommendations regarding the Program's future research directions.

An important difference between the emphasis of this report relative to that of the last NRC evaluation (NRC, 2004) is the fact that the Program has matured significantly in both the number and progress of its sponsored research projects in the past 5 years. At the time the last review was conducted, only a small number of research projects sponsored by the Program were at advanced enough stages to provide published results that could be used to evaluate and gauge the direction of the Program. The present report thus places significant emphasis on the Program's currently active research areas, progress with active research projects and their results, and impacts of the Program's sponsored research activities to draw meaningful conclusions and recommendations that might further advance the Program. Because this present report is timed to coincide with the final year of the Program's current authorization period, the report results are intended to inform decisions regarding the Program's future directions and resources, particularly with regard to the suitability of methane hydrate to make a contribution to domestic natural gas supply by 2025. The year 2025, as assigned to the committee in its statement of task and also cited in several of the Program's described aims, is viewed by this committee as a convenient longer-term mark against which the Program's achievements can be planned and evaluated, rather than as an absolute determinant of the

Program's overall success. The committee's recommendations thus address research that will assess whether methane from methane hydrate can be technically produced without specific consideration of the years by which specific results will be achieved. The committee acknowledges that commercial production of methane from methane hydrate in the future will depend not only on technical feasibility but also on economic, regulatory, and other issues. The committee did not address these latter factors in the course of this study because they are not part of the Program's current technical research mandate.

THE DOE[4] METHANE HYDRATE RESEARCH AND DEVELOPMENT PROGRAM, 2000-PRESENT

2000 Through 2004

Although DOE has sponsored some research on methane hydrate since at least 1982, the 2000 Methane Hydrate Research and Development Act authorized DOE to establish a focused, 5-year national program, the broad purposes of which were (1) to improve coordination in methane hydrate research among various public and private agencies and science and engineering disciplines in the United States and (2) to support basic and applied research that identified, explored, assessed, and developed methane hydrate as an energy resource. Authorized initially with about \$3 million in 2000, the funding levels for the program were authorized to increase to \$12 million annually by 2004 (NRC, 2004; Appendix E).

In addition to serving a constructive, coordinating role regarding interagency methane hydrate research, the Program used relatively modest resources in these initial years to solicit proposals and provide partial support for three cooperative agreements with industry, one in the Gulf of Mexico (with Chevron in the management role) and two on the Alaska North

[4] The Program is organized and managed by a joint effort between DOE and the National Energy Technology Laboratory (NETL). Because the congressional mandate specifically calls upon DOE to coordinate the Program, we refer to the Program in this report as DOE's without differentiating whether the activities involved DOE, NETL, or, as in the majority of cases, both.

Slope (with BP Exploration Alaska [BPXA] and Maurer/Anadarko in the management roles). Twenty-nine smaller-scale projects were supported by the Program and performed by university, institute, and national laboratory researchers; two additional projects undertaken as part of the federal collaboration effort were managed by and received primary support from the U.S. Geological Survey (Appendix F). The Program also participated in an international drilling consortium managed and coordinated by the Geological Survey of Canada (GSC) and on cruises of the Ocean Drilling Program (ODP) and cruises sponsored by industry. The project coordinated by the GSC focused on drilling and testing a methane hydrate well (the Mallik well) in Arctic Canada (see Chapter 2 for discussion), and the ODP and industry cruises were organized to drill and log methane hydrate core samples.

The three large industry projects in this initial phase of the Program were designed around strong field-based components with an aim to drill exploration- and/or production-test wells in permafrost and offshore regions. Key early, long-term goals included development of exploration and drilling techniques appropriate for methane hydrate, characterization of the physical and chemical properties of methane hydrate from drill cores, and understanding methane hydrate as a potential geohazard. These goals were necessary for both the projects and the Program to generate results that could eventually be applied by industry in a commercial production setting. Two of these cooperative projects with industry (the Chevron- and BPXA-managed projects) continue to the present time (see below, and also Chapters 2 and 3). Exploration drilling was only conducted in one project (the "Hot Ice" well of the Maurer/Anadarko project) at the time of the NRC (2004) report. Unfortunately, no methane hydrate was found in this well. Inadequate site survey planning led to the failure of that endeavor.

The other 26 projects initiated in this period used laboratory experiments, modeling, sample (drill-core) analysis, geophysical research, and technology development to address a number of the Program mandates including understanding the physical and chemical characteristics of methane hydrate in place, the behavior of methane hydrate during changes in pressure and temperature, the development of remote-sensing[5] methods to detect and quantify methane hydrate, and development of new tools to collect and analyze methane hydrate core samples (NRC, 2004). Seventeen of these projects had been completed (by design) as of the time of the present assessment (Appendix F).

The Program employed various mechanisms to oversee its research portfolio during this period. Establishing a Methane Hydrate Advisory Committee (MHAC), an Interagency Coordinating Committee, and selection and evaluation criteria for research proposals and projects were among the more encompassing of these organizational activities. Many of the findings and recommendations of the NRC (2004) report addressed these types of procedural aspects of the Program and indicated areas for improvement, and the report also underscored the critical role played by the Program in providing a national incentive to produce energy from and understand the implications of drilling through methane hydrate. The report went further to indicate that no obvious technical or engineering barriers were apparent that would deter the production of methane from methane hydrate in the future, given sufficient in-place reserves (NRC, 2004). The projects established during this initial period of the Program's existence also established a precedent for collaboration among researchers from academia, federal agencies, research institutions, and industry, with industry and federal agencies in particular participating in cost-sharing agreements (Appendix F). The collaborations with industry are considered integral to enable future commercial-scale applications to be implemented.

2005 Through Present Day

Much of the congressional reauthorization language for the Program in the 2005 Energy Policy Act was similar to the 2000 Program authorization. Consistent themes between the two Acts included a focus on (1) basic and

[5] The committee uses the term "remote sensing" in this report to refer broadly to geophysical techniques employed to "sense" or "detect" subsurface characteristics of methane hydrate occurrences. These techniques may include seismics, electromagnetics, remotely operated vehicle observations, or temperature measurement in boreholes, for example.

applied research to develop methane hydrate as a commercial resource in an efficient and environmentally sound manner, (2) conducting exploratory drilling, (3) technology development to reduce the risk of drilling through methane hydrate, (4) mitigating the environmental impact of natural methane hydrate degassing and degassing associated with development, and (5) education and training. Procedurally, both pieces of legislation also placed importance on interagency coordination and DOE's collaboration with other institutes, effective transfer and communication of knowledge and information, and establishment of an advisory panel of external experts (Appendix A).

Several new additions to the Program focus were also included in the 2005 language: (1) the descriptions of the research and development priorities were more nuanced, with new emphasis on remote-sensing techniques, including acquisition and processing of seismic data, to identify and characterize methane hydrate accumulations; and (2) specific exploratory drilling goals included one or more full-scale production tests in permafrost and nonpermafrost areas. The 2005 language also addressed the Program's management and organization through identification of new graduate fellowships to support education and training, the establishment of external scientific competitive peer review as part of the proposal and grant process, and emphasis on ensuring greater participation by DOE in international cooperative projects. The role of the MHAC was also made more inclusive by indicating that the body would provide scientific oversight for the program, assess progress toward Program goals, and provide recommendations to increase the Program's quality. The authorized appropriations over each of the fiscal years 2006-2010 were also indicated to increase above levels authorized for 2000-2004 (Appendix E).

With modest annual budgets, the DOE Program made specific efforts during 2005-2009 to enact programmatic and procedural changes to improve management and success of its sponsored research projects. These changes were implemented on DOE's own initiative, on the basis of advice from the MHAC, and in response to recommendations in the previous NRC report. Operative visions and rationale for methane hydrate research in the nation and the role of the Program in coordinating this research were also articulated in this period through several public documents (e.g., Boswell et al. [2006]; and MHAC [2007], which included the Interagency Five-Year Plan for Methane Hydrate Research and Development; see Chapter 4 for details). Two key goals articulated by the program include (1) providing by 2015 an initial assessment of the scale of the potentially commercially viable gas hydrate resource on the Alaska North Slope, and (2) demonstrating the technical recoverability and assessing the economic recoverability of marine gas hydrate–bearing sand reservoirs by 2025.[6]

Simultaneously with these programmatic efforts, DOE increased the number and scope of its smaller-scale research projects, established two new cooperative-agreement projects with industry, and supported the continuation of the Gulf of Mexico joint industry project managed by Chevron and the cooperative agreement on the Alaska North Slope with BPXA into more intricate phases in their planned research (Appendix F). Federal agencies and national laboratories also deepened their involvement in various collaborative research endeavors (details in Chapters 2, 3, and 4). Very broadly, then, the Program has taken specific actions in the past 5 years to increase the level and productivity of the national methane hydrate research and development that it helps to support.

COMMITTEE PROCESS

To address the study charge and establish conclusions and recommendations, the committee, in addition to its own expertise, reviewed (a) relevant DOE reports, (b) reports and other public documents from federal agencies involved in interagency methane hydrate research collaborations, (c) peer-reviewed literature on methane hydrate conducted both within and outside the auspices of the DOE program, (d) information from the DOE Web site,[7] and (e) information submitted by and requested from external sources, including three public meetings (Appendix C). Public meetings included

[6] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/rd-program/goals.htm.

[7] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/maincontent.htm.

dialogue with the study sponsors, other federal agencies, university and national laboratory researchers with projects supported by the Program, industry representatives from the large field projects, and importantly also, researchers from the Japanese methane hydrate program. In addition to discussion of research methods and results, information was also provided on the organizational and administrative process employed by the DOE program. Throughout the study process, the committee also received valuable input through informal interviews with various professionals associated with methane hydrate research and/or with various aspects of the Program, such as the MHAC members and participants in the interagency coordinating groups.

CONCLUDING REMARKS

The future U.S. energy portfolio is evolving as energy demand, greenhouse gas emissions, the energy transmission infrastructure, and national energy security issues are considered nationally and locally. Informed planning to develop consistent energy and environmental programs requires consideration of existing and emerging energy sources. With global energy demand projected to increase, unconventional resources such as methane hydrate become important to consider as part of the future U.S. energy portfolio. Methane derived from methane hydrate is an emerging resource candidate that has captured domestic and international research attention but which also presents a number of technical and environmental challenges that require attention before commercial production can be realized. These challenges include developing the technology necessary to produce methane from this unconventional gas occurrence and understanding more about methane hydrate in terms of its potential to behave as a geohazard and how degassing of methane hydrate may affect the environment. Because most of the methane hydrate research presently conducted in the United States is supported by the DOE Program and its federal partners, this report is designed to give DOE, other agencies, and policy makers a framework in which to evaluate the goals of and to determine appropriate support for the Program in the context of the nation's future energy and environmental needs.

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CHAPTER 2

State of the Science: Recent Advances and Current Challenges in Methane Hydrate Research

In recent years, a number of significant advances in methane hydrate research have been enabled by the Department of Energy (DOE) Program. A variety of ambitious field programs have advanced state-of-the-art core sampling, geophysical surveys, and experimental production testing. Substantial scientific knowledge has also been accrued through a number of diverse laboratory investigations and modeling studies. These and several international research initiatives have moved the field forward to the point where concentrated methane hydrate accumulations have been identified, and production concepts have been put forward based on existing oil and gas production methods, modified for the unique properties and reactions of methane hydrate. The state of knowledge of methane hydrate behavior in the environment has also been advanced through consideration of methane hydrate degassing induced by natural geologic processes.

This chapter reviews recent, critical, international, and domestic advances in methane hydrate research and identifies some of the remaining challenges to realizing the goal of commercial methane hydrate production. These challenges form a basis for Chapter 3, which discusses the research projects currently supported by the Program, including their achievements and the remaining knowledge gaps.

METHANE HYDRATE RESOURCE ASSESSMENT

The "goal" in methane hydrate research and development is the identification and quantification of technically and economically recoverable natural gas from methane hydrate occurrences. Because of the paucity of reliable field data, past research focused on the basic documentation of the existence and regional locations of global methane hydrate occurrences. More recently, a number of new quantitative estimates of in-place methane hydrate volumes have been undertaken using petroleum systems concepts developed for conventional oil and natural gas exploration. When combined with field investigations to establish the physical properties of methane hydrate deposits in different geologic settings, a basis has also been established for considering production methods and recoverability.

Global Methane Hydrate Estimates

Over the past 30 years a number of researchers have compiled global inventories of the total potential volumes of natural gas occurring as methane hydrate (Kvenvolden, 1988, 1993; Milkov, 2004). These estimates have garnered much interest and served to stimulate consideration of methane hydrate as a possible global energy resource. However, the utility and application of these estimates are limited because they range over several orders of magnitude and the knowledge and data upon which the predictions have been made remain largely speculative and with correspondingly large uncertainties. For example, early methane hydrate resource determinations in the 1980s and 1990s relied mainly on indirect evidence such as bottom-simulating reflectors (BSRs) identified in marine seismic surveys, or on estimates of the portion of the methane hydrate stability field that might reasonably contain methane hydrate from microbial and thermogenic sources. In the past 15 years a number of dedicated methane hydrate drilling campaigns have been undertaken around the world (see

Figure 1.1), allowing researchers to refine their geologic models and improve their interpretations of geophysical data. Whereas some early global estimates of methane occurring as methane hydrate were as high as 10^{18} m^3 (~35 million trillion cubic feet [TCF] methane at standard pressure and temperature [STP] conditions), estimates by Milkov (2004) decreased the range to 1-5 $\times$ 10^{15} m^3 (~35,000-177,000 TCF). But later estimates by Klauda and Sandler (2005) are much larger (1.2×10^{17} m^3 or 4,200,000 TCF), demonstrating that even recent estimates range over several orders of magnitude. However, even the lowest global resource estimates are 2 to 10 times greater than global estimates of the conventional natural gas endowment of 4.4×10^{14} m^3 (~16,000 TCF) of reserves and technically recoverable undiscovered resources (Ahlbrandt, 2002; IEA, 2006). Recalling that the United States in 2008 consumed 6.5×10^{11} m^3 (23 TCF; see Chapter 1) of natural gas, the global estimates of volumes of methane in methane hydrate are significant.

Although the global methane hydrate resource inventories illustrate the importance of methane hydrate as a component of the global carbon cycle, their utility to address the energy potential of methane hydrate is limited. The majority of the enormous global methane hydrate inventory occurs as dispersed concentrations over large areas and therefore recovery of the methane, for the most part, is unfavorable technically and economically. Conversely, areas with concentrated methane hydrate deposits that may be the appropriate candidates for economic development are more limited in size. Boswell and Collett (2006) reviewed the challenge of appraising the energy potential of the large but uncertain global inventories of methane hydrate and introduced the resource pyramid concept which qualitatively appraises the distribution of the global methane hydrate resource and evaluates which type of deposit holds the greatest economic potential for development (Figure 2.1). They conclude that the deposits that are most concentrated and hold greatest potential for exploitation occur in sandstone reservoirs in the Arctic and deepwater marine environments.

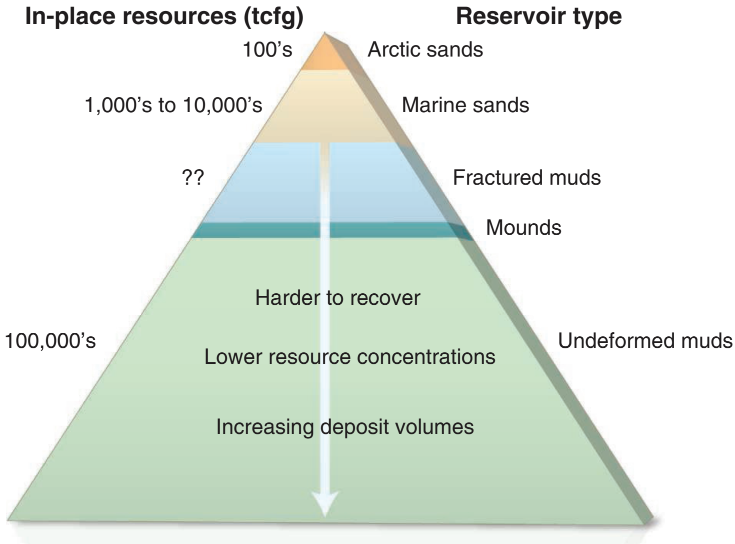


FIGURE 2.1 The methane hydrate resource "pyramid" concept qualitatively appraises the distribution of the global methane hydrate resource by the size and type of the occurrence (deposit) and evaluates which of those hold the greatest economic potential for development. Resources near the top of the pyramid (Arctic and marine sands) are of higher reservoir quality and estimated percentage of recoverable resource, although they represent a smaller in-place resource volume than reservoirs at the bottom of the pyramid that include fine-grained sediments (silts, shales, and muds). Despite their large sedimentary volume, methane hydrate tends to occur in low concentrations in fine-grained sediments, making the recovery of methane from methane hydrate more difficult and a less economic prospect. In comparison, the occurrences of methane hydrate in Arctic sandstones placed at the top of the pyramid are located near existing infrastructure and are more likely candidates for economic development in the near future. SOURCE: After Boswell (2009).

Recent Methane Hydrate Resource Assessments

Considerable effort has been devoted recently to carrying out more focused methane hydrate resource appraisals in specific regions by applying, with some modifications, quantitative methods commonly used for apprais-ing conventional oil and natural gas deposits. This approach is consistent

BOX 2.1
The Methane Hydrate Resource as a "Petroleum System"

Recent field investigations conducted over the past decade in the offshore (i.e., Gulf of Mexico, Cascadia margin, Nankai Trough, India) as well as onshore (Mackenzie Delta of Canada and the Alaska North Slope) have shown that the occurrence of methane hydrate can be interpreted in the context of a "petroleum system," in a manner similar to that used to evaluate conventional hydrocarbon occurrences. The methane hydrate system contains all the elements of a conventional petroleum system with consideration of the source of gas (thermogenic or microbial), possible migration pathways, and nature of the reservoir sediments, traps, and seals. The unique attributes of the methane hydrate petroleum system include the dominant controls of pressure and temperature on its stability and the differences in the manifestation of methane hydrate as a solid rather than gaseous form. This introduces unique considerations of trapping and/or sealing processes and consideration of temporal aspects because the pressure-temperature field may change with time. Typically, marine occurrences of methane hydrate are found at relatively shallow depths ≤ 500 meters below seafloor whereas methane hydrate in permafrost-dominated areas is found ≤ 1,200 meters below the surface (see also Box 1.1).

with the increasing knowledge of the geologic and reservoir controls over methane hydrate occurrences (see also Chapter 3) and the recognition of the applicability of petroleum system approaches that consider the source of gas, migration pathways, reservoir potential, and seals as the basis for establishing regional accumulation models (see Box 2.1).

Recent U.S. Methane Hydrate Resource Assessments

Gulf of Mexico

Using the extensive industry database of exploratory wells and two-dimensional (2D) and three-dimensional (3D) seismic surveys, the

Minerals Management Service (MMS) completed a preliminary methane hydrate resource assessment in the Gulf of Mexico[1] (Frye, 2008). This MMS-funded and -directed work is part of the interagency collaboration on methane hydrate research, and has both contributed to and derived input from the Program's Gulf of Mexico joint industry project (JIP)[2] (see also Chapter 4). The assessment employs a spatial mass balance model and benefits from a long history of industry exploration and production activity in the Gulf of Mexico. Working in collaboration with industry and other research agencies, MMS has developed an extensive drilling database and more than 400,000 km^2 of seismic information (of which about half is 3D data) for the assessment. Although these data were not collected with methane hydrate targets in mind, the data nonetheless provided a substantial basis for model inputs such as geologic setting with respect to the methane hydrate stability field, percentage of sand, as well as considerations of the gas sources, migration pathways, and trapping mechanisms. The assessment also considers possible seafloor indicators such as chemosynthetic communities and carbonates that may be associated with areas of higher probability for methane hydrate occurrences at depth. Using these attributes, the model first calculates gas generation through time, and then reallocates the distribution of gas based on a migration model.

The MMS resource assessment model is based on the geologic characteristics of 200,000 cells that measure 2.32 km^2 each, allowing for an assessed area of approximately 450,000 km^2. The total volume of in-place methane in methane hydrate is calculated to range from about 11,000 TCF to 34,000 TCF with a mean estimate of 21,000 TCF (315 to 975×10^{12} m^3; mean estimate of 607×10^{12} m^3). Anticipating that the production potential may depend on the type of confining sediment in which the methane hydrate occurs, this estimate is further subdivided to a predicted mean of about 6,700 TCF (190×10^{12} m^3) occurring in association with sandstone reservoirs (shown in Figure 2.2) and about 14,700 TCF (417×10^{12} m^3) in association with shale and fractured reservoirs. Significant accumulations

[1] http://www.mms.gov/revaldiv/GasHydrateAssessment.htm.

[2] http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/MethaneHydrate_2007Brochure.pdf; the JIP is managed by Chevron.

are predicted near the margins of minibasins and at the front of the Sigsbee Escarpment at the southern margin of the salt in the Gulf of Mexico (Figure 2.2). Importantly, the estimates represent in-place resources and do not include either technically or economically recoverable resources.

The MMS anticipates using the methods and experiences from the Gulf of Mexico assessment as a framework to evaluate the entire U.S. Outer Continental Shelf including Alaska, Atlantic, and Pacific margins. A phased approach is anticipated. The first effort will assess the in-place methane hydrate resources; subsequently, the gas volumes that could be technically recovered will be evaluated; the last phase will consider economically recoverable resources.

Alaska North Slope

A methane hydrate resource assessment was released in November 2008 by the U.S. Geological Survey (USGS), covering the terrestrial methane hydrate beneath the Alaska North Slope (Collett et al., 2008; Figure 2.3). This work was supported primarily by the USGS with some contributions from DOE as part of the interagency cooperation on methane hydrate research (see Chapter 4 for further discussion). The assessment uses a petroleum systems approach (see Box 2.1). This USGS assessment is the first to estimate the amount of methane in the methane hydrate resource that can be technically recovered using conventional hydrocarbon production techniques. Research supported by the DOE program was central to this assessment as field research enabled through the BPXA-managed Alaska North Slope project[3] provided a well-constrained case history of a North Slope accumulation, and reservoir simulation studies established a basis for predicting recoverability (Figure 2.3). The USGS assessment also carefully considered the results of the Mallik 2002 production research well program in the Mackenzie Delta (see Figure 1.1 for location) and preliminary results from a subsequent program in 2007 and 2008 (e.g., see Box 2.5). Among the various techniques for production, the USGS suggests that

[3] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/projects/DOEProjects/Alaska-41332.html; this cooperative agreement is managed by BP Exploration Alaska, Inc. (BPXA).

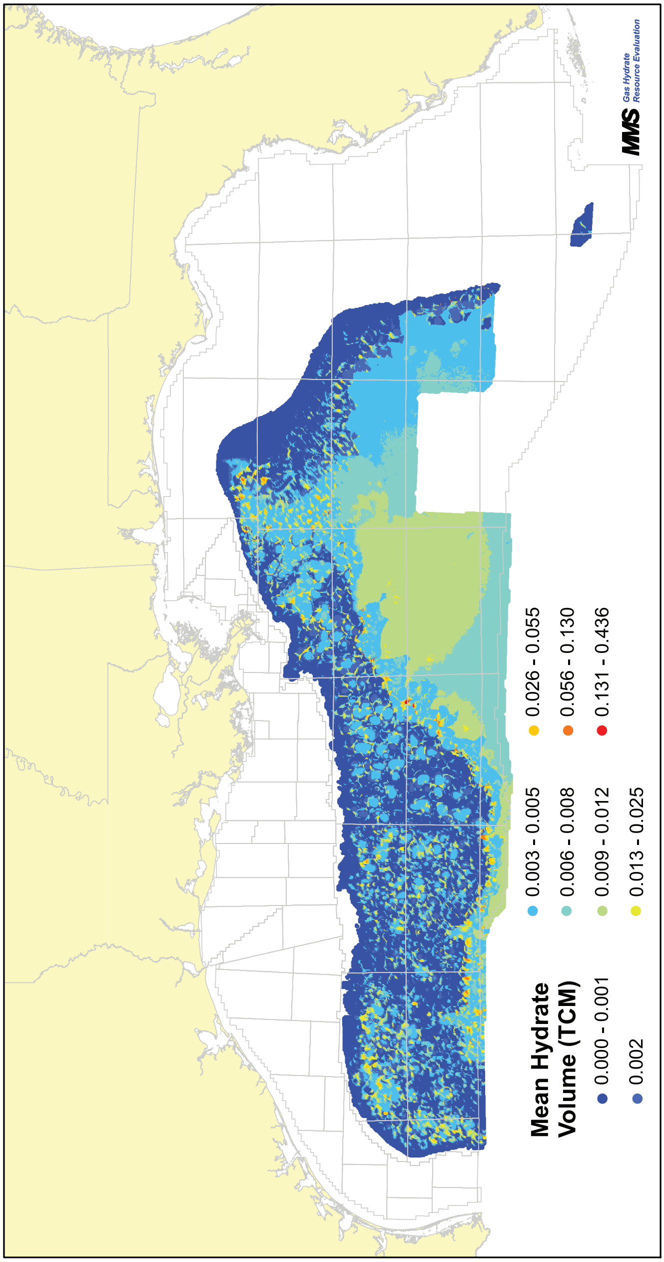

Mean Hydrate Volume (TCM)
0.000 - 0.001
0.002
0.003 - 0.005
0.006 - 0.008
0.009 - 0.012
0.013 - 0.025
0.026 - 0.055
0.056 - 0.130
0.131 - 0.436
MMS
Gas Hydrate Resource Evaluation

FIGURE 2.2 Map view of mean in-place volumes of methane in methane hydrate in the Gulf of Mexico. Color values represent per cell accumulations of methane in methane hydrate (in trillion cubic meters [TCM]), with more than 200,000 cells in the model (although not all of the cells were found to have methane hydrate). 1 TCM or 1×10^9 m^3 = 35.3 TCF. The areal distribution of the in-place volume is heavily influenced by the geometry of the input datasets. Large areas void of any significant methane hydrate accumulation (dark blue) are present across the salt minibasin province that comprises much of the upper continental margin slope. These areas often coincide with very shallow salt features that occupy the bulk of, and sometimes the entire, methane hydrate stability zone. Also, areas that offered a thick sedimentary section, such as the deep minibasins and much of the abyssal plain, provide an abundant supply of microbial methane from the generation model. The sand-rich cone of the Mississippi Fan is evident due to enhanced methanogenesis and methane generation in sandy sedimentary sections. Larger accumulations of methane hydrate (yellow, red) are present along structurally positive areas that often form at the margins of minibasins and along the front of the Sigsbee Escarpment (where the primary southernmost boundary of the dark blue area meets the light blue area). SOURCE: Matt Frye, Minerals Management Service, 2009, http://www.mms.gov/revaldiv/GasHydrateAssessment.htm.

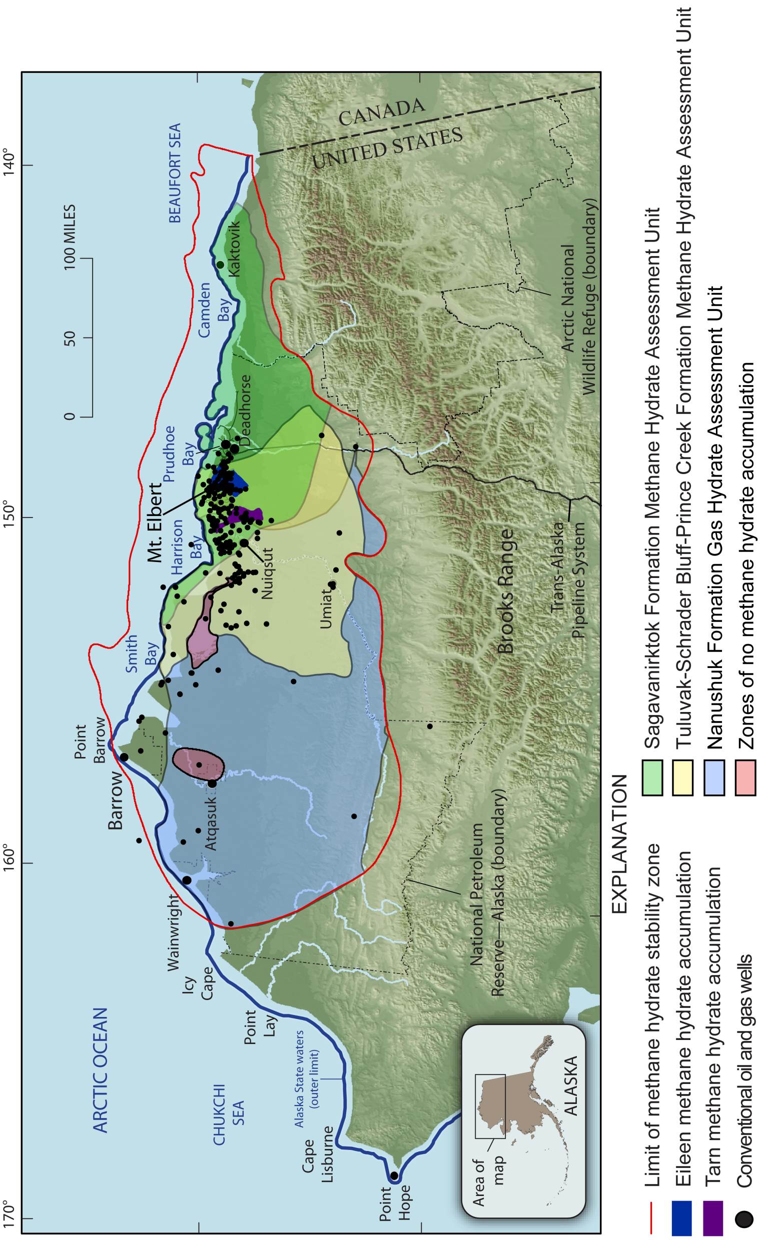

ARCTIC OCEAN
BEAUFORT SEA
CHUKCHI SEA
CANADA
UNITED STATES
0 50 100 MILES
140°
150°
160°
170°
70°
68°
Point Barrow
Barrow
Smith Bay
Harrison Bay
Mt. Elbert
Prudhoe Bay
Deadhorse
Camden Bay
Kaktovik
Nuiqsut
Umiat
Atqasuk
Wainwright
Icy Cape
Point Lay
Cape Lisburne
Point Hope
Alaska State waters (outer limit)
Brooks Range
Trans-Alaska Pipeline System
Arctic National Wildlife Refuge (boundary)
National Petroleum Reserve—Alaska (boundary)
Area of map
ALASKA
EXPLANATION
Limit of methane hydrate stability zone
Eileen methane hydrate accumulation
Tarn methane hydrate accumulation
Conventional oil and gas wells
Sagavanirktok Formation Methane Hydrate Assessment Unit
Tuluvak-Schrader Bluff-Prince Creek Formation Methane Hydrate Assessment Unit
Nanushuk Formation Gas Hydrate Assessment Unit
Zones of no methane hydrate accumulation

FIGURE 2.3 The Northern Alaska Methane Hydrate Total Petroleum System (TPS) shows the limit of the methane hydrate stability zone in northern Alaska (red outline). Within this zone, the U.S. Geological Survey (USGS) assessment predicts the total mean undiscovered technically recoverable methane from methane hydrate to be approximately 85 TCF based on the cumulative mean estimates from three assessment units, the Sagavanirkok Formation, the Tuluvak–Schrader Bluff–Prince Creek Formation, and the Nanushuk Formation. The Mt. Elbert and Barrow localities are identified. Note the concentration of industry well coverage near Prudhoe and Harrison Bay. The Eileen and Tarn methane hydrate accumulation trends were identified in earlier USGS studies. The Mt. Elbert prospect is drilled in the Eileen trend. SOURCE: Adapted after Collett et al. (2008); *http://pubs.usgs.gov/fs/2008/3073/*.

depressurization is the most promising (see also section *Depressurization Technique*).

The total undiscovered technically recoverable methane from the methane hydrate resource for the North Slope of Alaska (Figure 2.3) was estimated by the USGS to range between 25.2 and 157.8 TCF, representing 95 percent and 5 percent probability, respectively, with a mean of 85.4 TCF.[4] This estimate allocates methane in methane hydrate resources to three widespread geologic formations on the North Slope. The assessment screens out occurrences less than 20 billion cubic feet (BCF) and does not consider methane hydrate deposits within ice-bonded permafrost.

The USGS estimate of the technically recoverable methane resource endowment remains uncertain because long-term production has not been demonstrated. However, estimating the recoverability of this resource has been undertaken with the reasonable expectation that conventional oil and gas recovery methods can be employed for sand-dominated methane hydrate reservoirs.

Eastern Nankai Trough, Japan

Japan has been pursuing an ambitious national methane hydrate research and development program to evaluate the energy potential of methane hydrate accumulations in the Nankai Trough (Ohno, 2009). Whereas many other resource assessments around the world have relied primarily on industry exploration data collected during the search for deeper hydrocarbon targets, the Japanese assessment is largely based on field research programs, including drilling and seismic surveys, conducted specifically for methane hydrate exploration (Fujii et al., 2008; Figure 2.4). The Japanese resource assessment applies conventional statistical methodologies using 2D and 3D seismic surveys designed specifically for shallow methane hydrate targets and drilling results from 16 dedicated stratigraphic test wells. This approach allowed researchers to establish a model that predicted high methane concentrations in methane hydrate accumulations within

[4] Technically recoverable range between 0.7 and 4.5 × 1,012 m^3; mean of 2.4 × 1,012 m^3.

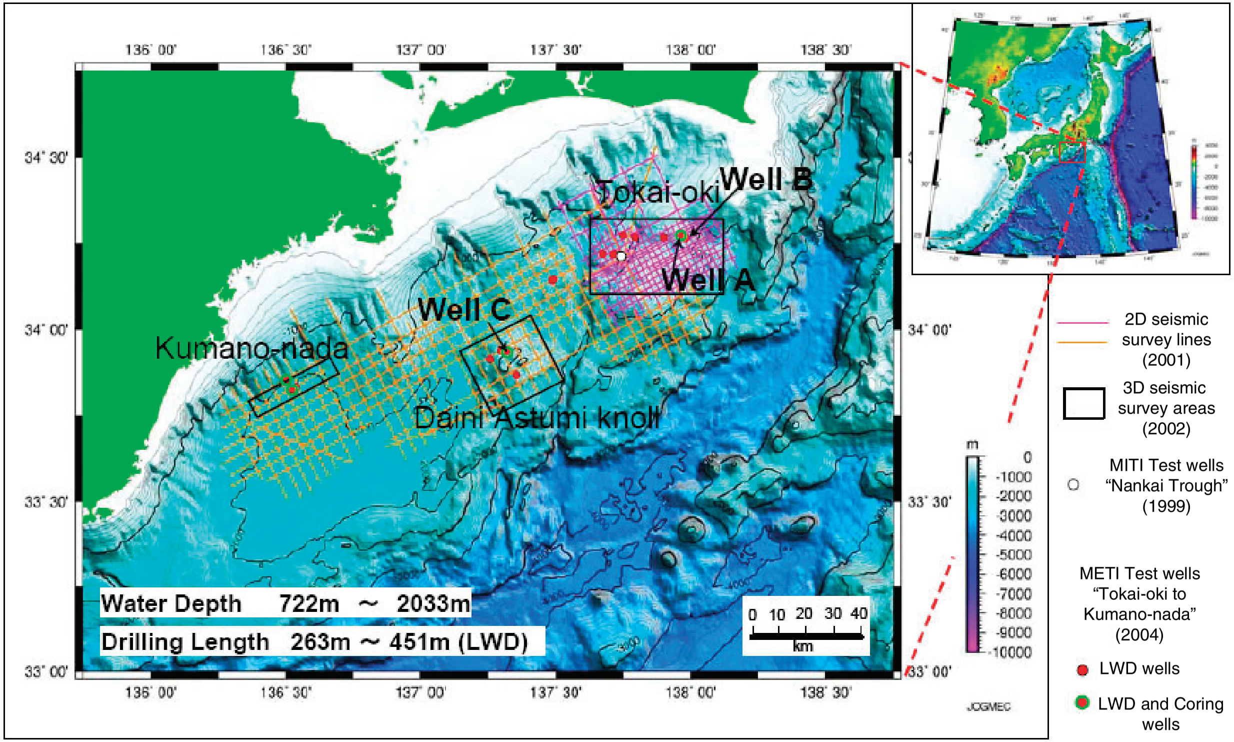


FIGURE 2.4 Map showing the location of 2D/3D seismic surveys and Ministry of International Trade and Industry of Japan exploratory test wells from Tokai-oki to Kumano-nada in the eastern Nankai Trough. SOURCE: Fujii et al. (2008).

turbidite sand sequences. Ten prospective methane hydrate zones were evaluated by considering sedimentary rock volumes that would most likely contain methane hydrate as well as other physical characteristics such as rock porosity and methane hydrate type ("cage occupancy"; see Box 1.1). Calculated resource estimates indicate a methane resource of 1.14×10^{12} m^3 (40 TCF) at STP within the studied region within the Nankai Trough.

THE CHALLENGE OF MAPPING AND QUANTIFYING METHANE HYDRATE

Three unique characteristics control the application of remote-sensing exploration methods for methane hydrate: (1) methane hydrate can only be present under specific formation temperature and pressure regimes, (2) the occurrence of methane hydrate in sediments alters the physical properties of the host material significantly (e.g., porosity, electrical resistivity, seismic velocity, bulk and shear modulus; Santamarina and Ruppel, 2008), and (3) applying petroleum system concepts has been shown to be useful for finding concentrated deposits (e.g., consideration of source, migration, seals, reservoirs, and containment). Although progress has been made to improve methods to map and quantify methane hydrate occurrences, significant technical challenges remain.

Mapping the Methane Hydrate Stability Field (Pressure and Temperature)

Defining the pressure-temperature stability field of methane hydrate (Box 1.1) is an important consideration in undertaking a regional assessment of possible methane hydrate accumulations. Various remote-sensing techniques (see below) can be employed to measure and/or estimate *in situ* pressure or temperature characteristics of the sedimentary column. In marine environments, a first approximation of the temperature regime can be determined by considering the mean annual seabed temperature and regional estimates of the geothermal gradient. Physical measurements can include drill-stem temperature measurements[5] made by industry during drilling of exploration wells and scientific measurements made with probes attached to the drill string (Davis et al., 1997). However, these are only point measurements, and because they are made during the course of drilling, concerns exist that the measurements may be affected by drilling disturbance. More recently, fiber-optic distributed temperature sensors (DTS) have been used with some success to estimate equilibrium temperatures in terrestrial and marine methane hydrate settings (Henninges et al., 2005; Fujii et al., 2008). The substantial advantage of the DTS technique is that it can provide 1-meter vertical resolution to the accuracy of 0.1°C, and with repeat measurements, equilibrium temperatures can be estimated by applying corrections for drilling disturbance.

Occurrences of overpressured zones in association with methane hydrate–bearing sediments can be expected to significantly alter methane hydrate stability (e.g., Bhatnagar et al., 2008). Unfortunately measurements of the *in situ* pressure regime are not routinely undertaken in most methane hydrate field investigations. Typically for marine methane hydrate deposits a hydrostatic pressure gradient is assumed from the seabed. Although this may be reasonable for conditions with uniform geology, areas with complex geology may experience significant overpressure affecting methane hydrate stability.

Finally, the geochemistry of the pore fluids and natural gas species is also important in determining the *in situ* stability of methane hydrate occurrences (e.g., Ruppel et al., 2005). As reviewed in Sloan and Koh (2008) gas composition can affect the methane hydrate structure, and pore fluid salinity can affect methane hydrate stability. The most commonly used approach employed to date is to rely on core measurements where gas and pore fluid samples are collected and analyzed (see section *Geophysical Tools to Detect and Quantify Methane Hydrate Accumulations*). As with the challenge of measuring undisturbed formation temperatures, the challenge of characterizing the *in situ* gas and fluid composition is significant. One

[5] Drill-stem tests are commonly conducted to determine whether a productive horizon has been located in an exploration well.

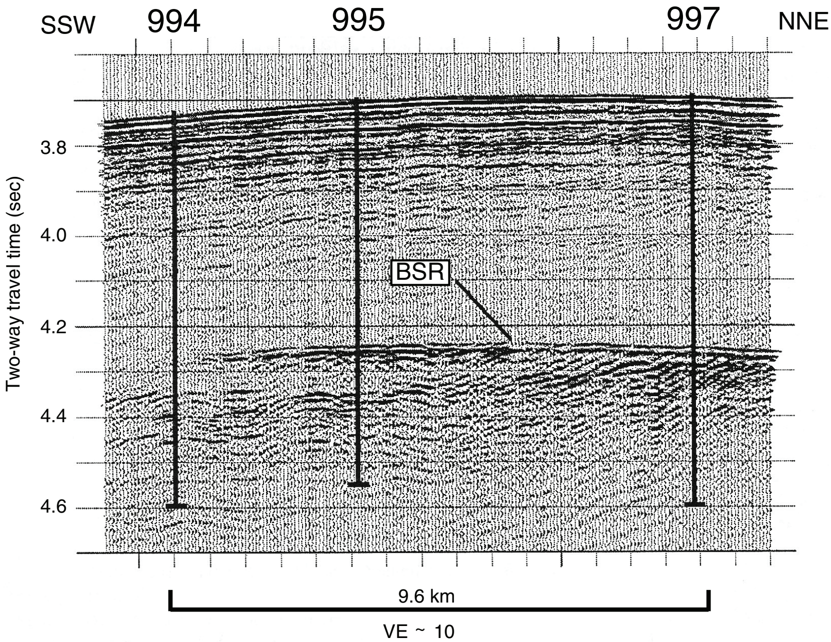


FIGURE 2.5 Seismic reflection profile (CH-06-92 Line 31) across the Blake Ridge along which the Ocean Drilling Program Leg 164 drilled a three-hole transect to identify the origins of the BSR. SOURCE: Charles Paull.

approach that has been used with some success is the Modular Dynamic Formation Tester tool, which can extract *in situ* gas and fluid samples from isolated borehole intervals (Dallimore and Collett, 2005; Hunter et al., 2008).

Use of BSRs as an Estimate of the Base of the Methane Hydrate Stability Zone

Since the 1970s, methane hydrate in the marine environment has traditionally been inferred by mapping of BSRs in seismic reflection profiles (e.g., Shipley et al., 1979). As shown in Figure 2.5, a BSR is a regional seismic response that typically follows the sea-bottom topography. The BSR has been interpreted to indicate a change in physical properties of the sediments across the base of the methane hydrate stability zone (BMHSZ) where primary-wave (P-wave) seismic velocities[6] decrease from high values, due to the presence of methane hydrate above, to low values due to the presence of free gas below the BSR. Because the BSR is conformable with an assumed geothermal boundary rather than a geologic boundary, it has been generally assumed to indicate the BMHSZ.

However, the BSR alone does not provide sufficient information about the amount and exact location of methane hydrate above the BMHSZ, or free gas beneath the BMHSZ. The drilling expeditions on the Blake Ridge (Ocean Drilling Program Leg 164),[7] offshore Cascadia (Integrated Ocean Drilling Program Expedition 311),[8] and offshore India (National Gas Hydrate Program Expedition 01)[9] have all shown an apparent disconnect between the occurrence of methane hydrate and the presence of a BSR. Nonetheless, the presence of a BSR can be an indicator for the presence of some free gas at the BMHSZ, and it can provide a start to focus exploration efforts.

Geophysical Exploration Tools to Detect and Quantify Methane Hydrate Accumulations

Methane hydrate occurs in nature within the host sediment in different macroscopic forms where it replaces pore water: (a) methane hydrate can be disseminated within the sediment pore space or (b) methane hydrate can occur as more massive forms in nodules, veins, or fractures (sizes can vary from millimeter-scale veins to fractures several tens of centimeters thick; see Box 1.1). Independent from the specific macroscopic form of occur-

[6] The P-wave seismic velocity refers to the speed of sound as it passes through materials of different composition. The composition of a rock, including the presence of fluids or gases, will change the rock's overall physical properties so that differences in P-wave velocities can be used to interpret changes in rock composition from one rock layer to the next.

[7] http://www-odp.tamu.edu/publications/citations/cite164.html.

[8] http://iodp.tamu.edu/scienceops/expeditions/exp311.html.

[9] http://energy.usgs.gov/other/gashydrates/india.html.

rence, the bulk physical properties of methane hydrate–bearing sediments are different relative to the corresponding sediments without methane hydrate. The two most important physical properties for detecting and quantifying methane hydrate are electrical resistivity (Box 2.2) and P-wave velocity.

Because solid methane hydrate replaces pore water in sediment, the formation of methane hydrate reduces the porosity of the sediment, which in turn increases the elastic modulus of the sedimentary package. This physical change can lead to differences in the sediment's P-wave velocity, which can be detected with remote-sensing methods. The most common of these methods is a seismic reflection survey (Box 2.2), which uses acoustic waves to image subsurface structures and measure velocity changes between different types of subsurface sediment.

Detection of methane hydrate using seismic reflection data is not free of ambiguity. Natural variation of the physical properties of sediment, for example, from changes in grain size or compaction, or the occurrence of pore-filling materials other than methane hydrate (e.g., carbonates) can also result in the formation of velocity differences. Furthermore, small concentrations of methane hydrate (of about 5 percent or less) can reduce seismic reflection strength. This phenomenon has been reported from marine settings such as the Blake Ridge (Lee and Dillon, 2001). Understanding the natural reflectivity and host sediment characteristics is critical for determining the presence, and estimating the amounts, of methane hydrate based on seismic reflection data. Several approaches use seismic data for methane hydrate *saturation* mapping including impedance inversion and analysis of prestack seismic data; shear-wave or multicomponent seismic data may also be employed to map methane hydrate occurrences (Box 2.2 provides more technical detail regarding these techniques).

Prior to 2002, no strategic geophysical exploration specifically for Arctic methane hydrate had been attempted using seismic techniques. Methane hydrate was encountered in wells as a by-product of conventional hydrocarbon exploration. Definition of the regional methane hydrate stability zone was achieved through the use of the base of permafrost and temperature data from well locations (Majorowicz and Osadetz, 2001).

BOX 2.2
Seismic Reflection Surveys in Exploration for Methane Hydrate

Seismic waves emitted from a controlled source (such as an airgun) reach subsurface discontinuities (geological structures or changes in sediment properties) and reflect the sound waves back to one or more receivers. Recordings of these returning waves allow the calculation of the elastic properties of the subsurface layers through which the seismic waves have passed. Propagation of seismic waves is a function of impedance of the sediments, measured as the product of density and velocity. If methane hydrate is present in sediments, the impedance is typically much higher than for non-methane hydrate–bearing sediments. Impedance inversion can use calibration from well-log data to calculate bulk density, P-wave velocity, porosity, and methane hydrate saturation in sedimentary packages (e.g., Bellefleur et al., 2006). The other type of approach to determine methane hydrate saturation in the subsurface uses prestack seismic data to measure seismic velocity, followed by an inversion step to link methane hydrate concentration to reflection strength (e.g., Dai et al., 2008). This method works without well calibration, but depends heavily on high-quality prestack seismic data and the rock-physics model that links velocity with saturation.

S-wave or multicomponent seismic data may offer an additional approach to help identify methane hydrate occurrences and to distinguish among methane hydrate formation models. However, acquisition of S-wave data is typically more challenging than P-wave data (on land as well in the marine realm). Only a few examples exist in which S-waves were used to image methane hydrate occurrences (e.g., Backus et al., 2006; Hardage and Murray, 2006). Ocean-bottom cables (OBC) may offer a simpler remote-sensing approach over larger regional distances than the use of a higher-seismic-resolution single (or multiple) ocean-bottom seismometer (OBS) station. The high deployment and recovery costs of either OBSs or OBCs are prohibitive for most academic research groups and are thus limited to the conventional oil and gas industry, where these tools are routinely used in areas of active exploration and production.

BOX 2.3
Effects of Methane Hydrate on Electrical Conductivity of the Sediment

As methane hydrate forms, the conductive interstitial pore-water phase is replaced with solid methane hydrate with a significantly lower conductivity. Only pure water can be incorporated in the methane hydrate cage structure, and, if the original pore fluid is saline, methane hydrate formation can cause salt exclusion, referred to as the local salt-inhibition effect (which is only a short-term effect in geological timescales). The result of methane hydrate formation is that the conductive pore water is replaced by methane hydrate. Thus, the bulk resistivity of the methane hydrate–bearing sediment is increased. Also, as the interstitial pore-water volume is replaced with methane hydrate, the porosity is effectively reduced. This increase in electrical resistivity and porosity reduction are described by an empirical relationship referred to as Archie's law (Archie, 1942).

Only recently have dedicated efforts been conducted using 3D seismic data for mapping and quantifying methane hydrate in permafrost settings (Bellefleur et al., 2006; Riedel et al., 2009; Inks et al., 2010).

Remote-sensing techniques such as electromagnetics (EM) or magnetotellurics (MT) can detect higher-resistivity rocks—or rocks that may more likely contain methane hydrate—because of the behavior of methane hydrate as an electrical insulator (see Box 2.3). EM and MT are currently employed mainly in marine environments (e.g., Yuan and Edwards, 2000; Weitemeyer et al., 2006) but are not commonly used in the Arctic because of operational challenges in permafrost regions. However, the typically broad-scale geophysical anomalies detected with these techniques are not optimal for the purpose of methane hydrate resource appraisals.

Methane Hydrate Core and Physical Property Studies

Although progress has been made with the various remote sensing and *in situ* measurement techniques described above, core investigations are essential (a) to determine primary sediment controls on stability and mechanical properties, (b) to validate pore physics models, and (c) to quantify the reaction of methane hydrate deposits to production. The challenges are significant: in addition to heat and fluid contamination that may occur during drilling, changes in the pressure and temperature regime experienced during core retrieval and extraction can cause substantial degradation of methane hydrate and disruption of the sediment properties. To date, two directions have been pursued: (1) improvement of coring techniques to minimize the disruption of the *in situ* pressure and temperature regime and (2) physical property investigations using methane hydrate samples grown under laboratory conditions which attempt to replicate those that might be found in nature.

The development of pressure coring systems, which strive to maintain the *in situ* pressure (and temperature) of a core sample during retrieval in the field, and pressure core testing systems, which allow laboratory tests to be performed on pressure cores (without depressurization) has been a long-standing goal of the methane hydrate research community. The first attempts to apply pressure coring methods for methane hydrate drilling investigations in the 1980s, including later modifications to these systems through the 1990s, identified various technical problems and the significant time required to extract a sample from the core barrel. Subsequent programs successfully developed and applied a coring system that could control both temperature and pressure in research wells in the Nankai Trough (pressure-temperature core sampler [PTCS]; Takahashi and Tsuji, 2005) and an integrated pressure coring and analysis system to allow precise x-ray imaging and gamma densitometry under pressure (Schultheiss et al., 2008). A pressure core testing system has also been developed to enable physical property measurements to be performed on recovered pressure cores of methane hydrate–bearing sediment without depressurization, and/or partial dissociation of the sample (Santamarina, 2008). For example, laboratory measurements of the mechanical properties of hydrate-bearing sediment cores recovered from the Nankai Trough using a PTCS and then subjected to different pressure conditions showed that cores with high hydrate saturations (43 percent) were stronger than cores with either low hydrate saturations (2.7 percent) or dissociated (depressurized) core samples (Hato et al., 2008).

The high cost of field programs, the challenge of retrieving well-preserved core samples, and the need to obtain accurate and reproducible data from close analogs to natural hydrate have also encouraged research efforts to grow methane hydrate under laboratory conditions (Box 2.4). Some of the first researchers to investigate methane hydrate grown in natural sediments used an autoclave to grow methane hydrate in natural and artificial sediment samples by introducing free gas (Ershov and Yakushev, 1992). Modifications of this technique have been used for determining thermal and geophysical properties and salinity effects on methane hydrate stability conditions (Wright and Dallimore, 2010). Another approach described by Stern at al. (2005) has been to form methane hydrate–sediment aggregates by physically mixing sediment and polycrystalline methane hydrate granules together. During the past decade a number of laboratories around the world have strived to build devices styled upon apparatuses used commonly in soil mechanics. These devices hold the potential to apply 3D confining pressure and to introduce methane dissolved in pore water rather then as free gas.

THE CHALLENGE OF PRODUCING METHANE FROM METHANE HYDRATE

Gas recovery from methane hydrate presents significant technical challenges because the gas is in a solid form and deposits occur in remote and hostile Arctic and deep marine environments. As dedicated field studies have been conducted around the world, it has also become apparent that methane hydrate can occur in a variety of different reservoir settings; each may require somewhat different field development strategies. Primary reservoir controls are likely to include (a) concentration and form of the methane hydrate occurrence, (b) physical properties of host rock (e.g., thickness, porosity, permeability, thermal properties, *in situ* stress, and strength), (c) physical properties of overlying and underlying sediments, (d) pressure and temperature environment, (e) nonuniform conditions such as geologic heterogeneity or possible communication with open faults or fractures, and (f) presence of free gas and/or free water zones above, below, or within the methane hydrate occurrence. To ensure safe and efficient drilling, completion, and production, a sound knowledge of the geomechanical properties of methane hydrate–bearing sediments is also necessary, as is the ability to predict changes in these properties during and after methane hydrate dissociation. Finally, environmental concerns associated with production are also keys to consider, including strategies for disposal of produced water, potential effects on the seafloor or subsurface in the case of marine deposits, and interactions with permafrost in the case of Arctic deposits.

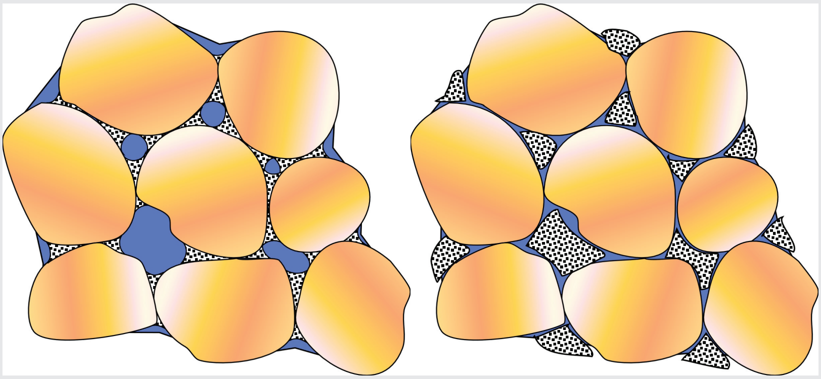
Based mainly on conventional hydrocarbon completion and production methods, three primary methane hydrate production concepts have been proposed: (1) depressurization, (2) thermal stimulation, and (3) chemical stimulation. The goal with each is to manipulate the *in situ* stability conditions of the methane hydrate and induce in-place dissociation to release free gas and associated hydrate-bound pore water. Each of these methods is discussed in more detail below.

Worldwide experience in production testing of methane hydrate is very limited. Makogon (1981) has proposed that the Messoyakha natural gas field in northern Siberia may have been capped by methane hydrate and that the production response of this field can be explained in part by dissociation of methane hydrate as the pressure of the free-gas reservoir declined with time. However, this interpretation has been questioned (Collett and Ginsburg, 1998), and the scarcity of field data to confirm the initial *in situ* conditions or the detailed production response greatly limits any modern engineering evaluation. The only other full-scale methane hydrate production study to be undertaken has been at the Mallik field in the Mackenzie Delta (Box 2.5). At Mallik, a thermal stimulation test was undertaken in 2002 by a five-country consortium, including participation by DOE (Dallimore and Collett, 2005). Full-scale depressurization testing at the site was also undertaken by a Canadian-Japanese research program in 2007

BOX 2.4
Challenges to Laboratory Synthesis of Methane Hydrate–Bearing Sediment Samples

A key challenge in synthesizing repeatable samples that closely represent natural methane hydrate–bearing sediment formations is that natural cores that form within the hydrate stability zone most likely exhibit a methane hydrate pore-filling morphology (formed from an aqueous solution containing dissolved gas), whereas laboratory-synthesized hydrate samples which are typically formed from free gas generally result in methane hydrate cementing the sediment grains (Sloan and Koh, 2008; Waite et al., 2009). Therefore, the synthesis method strongly influences the pore-scale habit (see figure below), thereby potentially affecting the structural and physical properties of the hydrated sample. Methane hydrate–bearing sediment samples synthesized with dissolved gas can exhibit a formation mechanism and morphology more closely replicating nature (particularly hydrate formed within the hydrate stability zone and in coarse-grained sediment; Dallimore et al., 1999; Winters et al., 1999; Waite et al., 2009), but these syntheses involve extremely challenging and time-consuming procedures (Spangenberg et al., 2008; Waite et al., 2009). The use of laboratory-synthesized methane hydrate–bearing sediment samples (prepared using different methods, such as free gas plus partially water-saturated sediment, free gas plus ice grains plus sediment, premixed hydrate grains with sediment, and/or dissolved gas in water plus sediment) can be evaluated by comparing the physical property measurement data obtained using these samples with pressure coring and *in situ* hydrate field measurements. Further studies performed on the pore-scale habit of hydrate-bearing sediment systems could add needed detail to these types of laboratory syntheses.

The need to synthesize methane hydrate–bearing sediment samples that closely resemble natural samples has been recognized by most researchers and has also resulted in the ongoing laboratory synthesis efforts, and a shift away from using the model tetrahydrofuran (THF) hydrate system, which is stable at atmospheric pressure below 4.4°C (and hence is more convenient to prepare and handle in the laboratory than is methane hydrate). Important discrepancies between THF hydrate (sII) and methane hydrate (sI) include the following: (a) THF is miscible in water whereas methane is almost insoluble in water, (b) thermal expansion and heat of dissociation values are different, and (c) effect of pressure on hydrate equilibrium temperature differs. Conversely, similar mechanical properties have been suggested for hydrate-bearing sediment formed from dissolved gas and THF hydrate-bearing sediment (at low hydrate saturations of less than 40 percent). This similarity may result because both of these systems form hydrate in the pore space of the sediment (Yun et al., 2006; Lee et al., 2007).



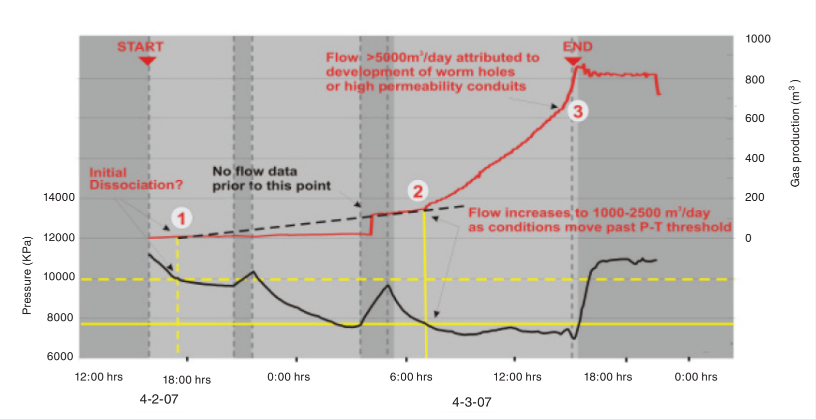
Different pore-scale habits are obtained depending upon the hydrate formation mechanism. In the grain cementing case (left), sediment grains (orange shading) are cemented together by hydrate (gray hatched), with the pore space (blue) mostly free of hydrate. Grain cementing tends to occur when hydrate samples are formed from free gas plus liquid water (sediment grains can be partially or fully water saturated) (Kneafsey, 2009; Waite et al., 2009). In the pore-filling case (right), hydrate (gray hatched) forms in the pore space. Pore filling tends to occur when hydrate is formed from gas dissolved in liquid water (Kneafsey, 2009; Waite et al., 2009). SOURCE: Timothy Kneafsey, Lawrence Berkeley National Laboratory.

BOX 2.5
Response of a Methane Hydrate Reservoir to Pressure Drawdown: The Mallik Well Example

The Mallik site, in Canada's Mackenzie Delta, has had a long history of methane hydrate investigation with international research and development programs undertaken in 1998 (Dallimore et al., 1999) and 2002 (Dallimore and Collett, 2005). Core and well-log studies have confirmed high concentrations of methane hydrate within clastic sands, and the occurrence of methane hydrate as a matrix pore-filling material with an interconnected liquid-water interface with measurable permeability in the 0.001 to 0.01 milliDarcy range. The Japan Oil, Gas and Metals National Corporation, Natural Resources Canada, and Aurora College returned to the site in the winters of 2007 and 2008 to complete the first full-scale pressure drawdown production tests (Dallimore et al., 2008; Yamamoto and Dallimore, 2008). Field activities in the first year included drilling, borehole geophysics, and installation of production and monitoring infrastructure. A 13-meter test interval with high methane hydrate concentrations was selected for pressure drawdown testing. A short production test was undertaken by lowering the formation pressure below the methane hydrate phase equilibrium. The 2007 test results revealed the substantial mobility of methane hydrate–bearing sediments at Mallik when the methane hydrate, which bonds the sandy reservoir sediments, was dissociated. Because of the loss of sediment strength, sand flowed into the well causing operational problems (Dallimore et al., 2008; Kurihara et al., 2008; Numasawa et al., 2008). Although the duration and operation of the test were limited, several flow-rate responses were observed during the latter part of the test to exceed 5,000 m^3/day (see figure on opposite page).

Operational problems encountered with sand inflow in 2007 were overcome in 2008 with the use of sand screens (Yamamoto and Dallimore, 2008), and a simpler operational sequence. A downhole heater was also used to prevent methane hydrate formation within the production tubing. Although detailed production results remain confidential at this time, Yamamoto and Dallimore (2008) and Dallimore et al. (2008) reported continuous gas flow during the 6-day test with rates generally ranging from 2,000 to 4,000 m³/day. Three different drawdown pressures were achieved and water production rates were below 20 m³/day.

The 2007-2008 production testing at Mallik demonstrated sustained methane production from methane hydrate by depressurization from a clastic, sand-dominated methane hydrate reservoir. Continuous and significant gas flow rates were observed and water production rates were judged to be manageable. The program successfully used conventional oil field technologies adapted for the unique physical properties of methane hydrate and can be considered in simple terms as demonstrating a proof of concept for this technique.



Cumulative production (red line) and derived bottom-hole pressure (black line) from pressure drawdown test at Mallik. Operational issues during which the pump did not operate are shown with dark gray vertical shading. A peak flow of more than 5,000 m³/day was achieved near the end of the test. SOURCE: After Dallimore et al. (2008).

(Dallimore et al., 2008; Numasawa et al., 2008) and 2008 (Yamamoto and Dallimore, 2008). Although more limited, additional data are also available from short-term drilling tests conducted by industry in the 1970s (Bily and Dick, 1974) and from small-scale, *in situ* tests of the methane hydrate formations conducted as part of the 2002 Mallik program (Dallimore and Collett, 2005), the 2001 Nankai drilling program (Tsuji et al., 2007), and the 2007 drilling program in northern Alaska as part of the BPXA-managed Alaska North Slope project (Hunter et al., 2008; see also Chapter 3).

Depressurization Technique

The depressurization technique is considered by many researchers to be the most cost-efficient and practical production method (Max et al., 2006). The primary concept is to reduce the *in situ* pressure of the fluids in the porous rocks in contact with the methane hydrate reservoir. This technique can be applied by changing the pressure regime of the methane hydrate reservoir itself, or by reducing the pressure of the overlying or underlying sedimentary rocks in contact with the methane hydrate reservoir and transferring this pressure change to the reservoir. The efficiency of this technique is significantly influenced by the manner in which the methane hydrate occurs (i.e., disseminated within sediment or in massive form) and the abundance and interconnectivity of the liquid pore water which helps to transmit the pressure decrease.

Thermal Stimulation

The primary concept in the thermal stimulation technique is to increase the *in situ* temperature of the methane hydrate reservoir above the pressure-temperature stability threshold. The only full-scale thermal stimulation test was conducted at the Mallik site in 2002. During this test, hot brine was circulated across a 13-meter perforated test interval, relying mainly on heat conduction into the formation to dissociate methane hydrate (see Dallimore and Collett, 2005). Approximately 500 m^3 of gas were recovered during the course of the 124-hour thermal test. This low volume of gas recovery suggests rather limited potential of this technique as a primary production method for methane hydrate. However, the combination of depressurization with modest thermal stimulation may offer the opportunity to both enhance reservoir production and overcome flow assurance issues within the production tubing. A critical challenge in this regard is to understand the endothermic change of the methane hydrate dissociation and the impact this change has on reformation temperatures and the produced water and gas. One category of technique often used to characterize conventional (and even unconventional) hydrocarbon reservoirs is based on pressure testing (or pressure transient testing and analysis). These kinds of techniques are complementary to other characterization techniques because (1) they fill a gap between the small-scale characterization based on cores and logs and large-scale characterization based on geophysical measurement and (2) they provide a measure of flow capacity (e.g., Hancock et al., 2005). Refinement of such techniques for methane hydrate reservoirs could prove advantageous.

Chemical Stimulation

The original production concept for the chemical stimulation of methane hydrate was to modify the *in situ* methane hydrate equilibrium conditions by injecting hydrate inhibitors such as salts and alcohols; these inhibitors act to decrease methane hydrate stability and induce dissociation. This technique has been used for decades to deal with methane hydrate blockages in pipelines, but it has not been seriously considered as an option for long-term production. Prohibitive issues include potential operational challenges to the introduction of the inhibitor into the formation, the significant expense of the method, and environmental issues related to disposing of the used chemicals after production.

Novel Production Methods

Some novel concepts to extract methane from methane hydrate have also been suggested with numerous technical patents being issued around the world. Perhaps the most promising of these is a variation of a chemical stimulation technique which involves injecting another gas species such as carbon dioxide into a methane hydrate reservoir, essentially sequestering carbon dioxide and liberating methane at the same time. This concept is based on laboratory observations and thermodynamic considerations (Graue et al., 2006; McGrail et al., 2007; Stevens et al., 2008), which suggest that when carbon dioxide is brought into contact with methane hydrate it will exchange with methane in the hydrate structure. Although the laboratory and modeling studies are encouraging, the challenge of scaling this technique from the laboratory to field testing has yet to be undertaken.

Other production concepts put forward or patented include techniques to induce *in situ* combustion of the methane hydrate; combustion would heat the formation and stimulate methane hydrate dissociation[10] (Collett, 2002; Max et al., 2006). *In situ* combustion has been pursued to stimulate production from tar sands; however, this concept has not been seriously considered for methane hydrate production. The possibility of seafloor strip mining has also been discussed as a potential approach to recover methane from near-seafloor methane hydrate deposits.[11] With all novel production methods, where practical experience is limited and new techniques are being evaluated, the environmental impacts of development will require careful consideration.

Reservoir Simulation Modeling

Reservoir simulation models are computer models routinely used by engineers to simulate production from a hydrocarbon field over long timescales. They are valuable tools in the petroleum industry to evaluate the effectiveness of various production techniques and methods to stimulate or enhance production, and to consider the environmental consequences of production. Although considerable experience exists worldwide in the use

[10] http://www.patentstorm.us/patents/6973968/description.html.
[11] http://www.freepatentsonline.com/6209965.html.

TABLE 2.1 Reservoir Simulators Under Development

Simulator Model	Research Group
1. TOUGH + HYDRATE	DOE-LBNL (Moridis et al., 2002)
2. CMG Stars	Computer Modeling Group, STARS
3. HydrateResSim	DOE-NETL[a] (Earlier code of TOUGH + HYDRATE)
4. MH21 HYDRES	National Institute of Advanced Industrial Science and Technology, Japan Oil Engineering Co., Ltd., University of Tokyo (Kurihara et al., 2005)
5. STOMP-HYD	Pacific Northwest National Laboratory, University of Alaska, Fairbanks (Phale et al., 2006)

[a] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/rd-program/ToughFX/ToughFx.html#HydrateResSim.

of reservoir simulators for conventional oil and gas deposits, the use of these tools for methane hydrate applications has only been recently considered. Acceptance of a verified methane hydrate simulation model would enable prediction of methane production rates and formation responses from different production strategies (e.g., depressurization, thermal stimulation, chemical inhibitor injection) for either Arctic or marine hydrate reservoirs. The integration of modeling and field studies is essential to effectively evaluate different production strategies and responses. Reservoir models can aid in predictions of both the production rates and responses, as well as in interpreting the experimental observations from the field tests. Reservoir simulators under development in the world are listed in Table 2.1. These numerical models incorporate coupled equations accounting for heat transfer, fluid flow, and kinetic mechanisms that govern methane production from hydrate reservoirs.

Despite the progress made through history matching with the currently available *short-term* field production datasets (Moridis et al., 2009), long-term production field data are lacking for validation of the simulations. However, attempts have been made to compare each model by undertaking a series of simulations using the same reservoir parameters and data from some short-term reservoir studies. As described by Wilder et al. (2008), this code comparison effort determined that all simulators were able to capture basic heat and mass transfer, as well as the overall hydrate dissociation process. They predicted different hydrate front locations when ice formation was expected in some parts of the reservoir. All simulators showed that methane and water production rates increase when free pore water is present. The reliability and accuracy of the reservoir simulation predictions depend upon (a) knowledge of the parameters and relationships that describe quantitatively the physical processes and thermophysical properties of all the components of the system under investigation (these physical properties need to be obtained from laboratory experiments and/or from field tests either by direct measurement or through history matching) and (b) availability of field data for the validation of the numerical models (Moridis et al., 2008). Reservoir simulation models need to be carefully validated and tested with long-term production field data. The geomechanical modeling is still in the early stages of development, and experimental and field data will also be critical to validate the geomechanical predictions.

A recent, additional application of these simulations has been to develop economic models to estimate the commercial viability of methane production from methane hydrate on simulated methane hydrate reservoirs. These models, although very preliminary, are the first economic studies to be performed that estimate the price of natural gas that could lead to economically viable gas production from methane hydrate (Hancock, 2008; Walsh et al., 2009). These economic models result in a range of gas prices for economic production of methane hydrate that is in the range of prices seen historically in North America.

GEOLOGIC PROCESSES AND FEATURES ASSOCIATED WITH METHANE HYDRATE OCCURRENCES

As described previously, methane hydrate in certain marine and permafrost environments is thought to constitute a significant storehouse of natural gas. In addition to the energy potential of methane hydrate, considerable interest exists to understand naturally occurring geologic processes associated with methane hydrate formation and decomposition, as well as the possible role of methane hydrate in global climate change. This section focuses on geologic processes that may be related to methane hydrate degassing, including methane seepage in marine and terrestrial environments, biological processes, submarine landslides, inferred gas venting structures, and methane hydrate as an atmospheric greenhouse gas source.

Methane Seepage

Detailed field studies have demonstrated that methane seepage is ubiquitous in various marine settings where pressure and temperature conditions are appropriate for methane hydrate to be stable at or close to the seafloor. Active methane seepage has been observed to occur in deep waters along essentially all the continental margins of the world including off the U.S. Gulf Coast (e.g., MacDonald et al., 1994), Atlantic (e.g., Van Dover et al., 2003), and Pacific (e.g., Suess et al., 1999). Although these observations seem to confirm that methane can migrate as free gas within the methane hydrate stability field, the detailed processes involved with this migration remain uncertain and the explicit link to methane hydrate is tenuous.

A number of authors have also suggested that methane seepage may occur where natural processes have either warmed formation temperatures or reduced pressure, causing methane hydrate dissociation. Some of the most perturbed methane hydrate deposits in the world occur in the Arctic in terrestrial permafrost environments with very cold mean annual surface temperatures. Here, methane hydrate deposits have in some cases warmed more than 15°C during the past 10,000 years (Kvenvolden, 1988; Taylor, 1991). Paull et al. (2007) suggest that in the transgressed shelf of the southern Beaufort Sea, dissociation of methane hydrate may be responsible for methane seepage and heaving of the seafloor to form large conical hills called pingo-like features. Methane seepage that may be related to degassing of transgressed permafrost methane hydrate accumulations has also been observed in the shallow waters of the East Siberian

Shelf of the Laptev Sea (Semiletov and Gustafsson, 2009). Recent ocean-bottom warming and inferred down-slope retreat of the landward limit of methane hydrate stability conditions is also implicated in the formation of numerous gas vents observed offshore Svalbard (Westbrook et al., 2009). In terrestrial Arctic settings, Holocene warming both from atmospheric temperature changes and the formation of lakes or river channels has also significantly perturbed the geothermal regime in the Arctic. Dissociating methane hydrate has been implicated as a possible source of methane release observed in lakes on the North Slope of Alaska and Siberia (Walter et al., 2006) and as a source for thermogenic gas seeps observed beneath lakes and channels of the Mackenzie Delta (Bowen et al., 2008).

Distinctive Morphological Features Potentially Attributable to Gas Venting and Methane Hydrate Dynamics

Gas venting and methane hydrate occurrences are in some places linked with distinctive seafloor features or processes such as extrusion of sediment onto the seafloor (e.g., mud volcanoes; Kopf, 2002), deformation of the seafloor (e.g., mounds; Hovland and Svensen, 2006), excavation of the seafloor (e.g., pockmarks; Judd and Hovland, 2007), and collapse of the seafloor (e.g., large bathymetric depressions; Dillon et al., 2001). However, detailed physical explanations as to how gas venting and methane hydrate dynamics actually form these features have yet to be developed.

The presence of methane within and at the seafloor in these environments also generates biogeochemical impacts. In subseafloor environments where upward-migrating methane meets sulfate diffusing downward from the overlying seawater, populations of microorganisms anaerobically oxidize methane (Boetius et al., 2000). This process converts the methane carbon into bicarbonate, and the sulfate into hydrogen sulfide which then is used in iron sulfide mineral formation, and thus alters the local environment. The addition of bicarbonate to the pore waters can stimulate the precipitation of carbonate, which can cement the near-seafloor sediment (Ritger et al., 1987). This process can result in a shift from an environment dominated by soft-sediment biological communities to hard-bottom, substrate-dominated communities. In some areas carbonate-cored mounds have been inferred to grow up from the seafloor, creating considerable local topography (Teichert et al., 2005). The availability of either methane or sulfide on the seafloor will stimulate the development of chemosynthetic biological communities. Some seep source estimates have been compiled to indicate the relative importance of various seeps and vents. However, the vast majority of the seeping methane dissolves into the surrounding waters and is consumed by bacteria. Thus, very little of the methane from seafloor seeps in deep water reaches the atmosphere (Reeburgh, 2007).

Submarine Landslides

Many authors have tentatively associated major submarine landslides on continental margins with methane hydrate occurrences (e.g., Paull et al., 2003b). The potential causal link is the changes in mechanical properties and the geopressure regime when methane hydrate decomposes. When methane hydrate decomposes, the solid hydrate transforms into water and dissolved or gaseous methane, causing a consequent decrease in long-term sediment strength, thus making failure more likely. In circumstances in which high methane hydrate concentrations occur and the sediment permeability is restricted, the potential also exists for the buildup of fluid and/or gas pressure which can also substantially reduce the effective sediment strength.

The evidence linking methane hydrate to slope failures is consistently indirect; for example, seismic evidence in headwall sediments suggests that the landslide failure plane is coincident with or at least near a BSR seen in seismic profiles. The potential role of methane hydrate in natural slope stability and sediment dynamics remains largely an academic topic except in cases in which conventional oil and gas seafloor developments are being considered within potential slides and with corresponding tsunami potential (Solheim et al., 2005).

Climate Change

From a climate change perspective the natural dissociation of even a small part of the extremely large global methane hydrate occurrence that exists on Earth (see section *Methane Hydrate Resource Assessment*) could potentially release significant amounts of methane and water into the surrounding environment. However, the scientific evaluation of such releases is complex and involves considerations such as the response time of methane hydrate to change, and the geologic, biologic, and oceanographic processes that ultimately control connection between methane release (associated with methane hydrate decomposition) and methane release to the atmosphere from many other sources. Climate change researchers have generally approached these issues from the perspective of considering climate change in the geologic past, modeling studies, and, only very recently, field investigations.

Dickens (1999) suggests that large excursions in the carbon isotopic records of carbonates in oceanic sediments from the Paleocene-Eocene Thermal Maximum may have been attributed to massive dissociation of methane hydrate. Kennett et al. (2003) developed the clathrate gun hypothesis which proposes that episodic release of large amounts of methane from submarine landslides may have contributed significantly to the distinctive behavior of Late Quaternary climate on orbital and millennial timescales. Although stimulating much discussion in the literature, these theories remain unproven.

More recently, modeling studies have explored the possible past and future interactions between methane hydrate and the global carbon cycle (Archer et al., 2008) and the time lag of methane hydrate deposits to an imposed surface temperature change (Taylor et al., 2002). An example of imposed surface temperature change comes from the Arctic region, where the last major warming began at least 10,000 years ago. These studies indicate that most methane hydrate occurrences can take thousands of years to respond because of the attenuation of the temperature change versus depth, and the endothermic nature of the dissociation process itself.

GEOHAZARDS AND ENVIRONMENTAL ISSUES RELATED TO METHANE HYDRATE PRODUCTION AND FIELD DEVELOPMENT

The challenge to distinguish between methane seepage occurring from natural processes and seepage from active disturbance of methane hydrate during drilling and production is substantial, and many aspects of this field of investigation remain uncertain. In a traditional hydrocarbon context, all methane hydrate deposits occur at relatively shallow burial depths and therefore have the potential to induce either seafloor or surface displacements as long-term field development is undertaken.

Exploratory Drilling

Exploratory wells drilled in permafrost environments in the 1970s and 1980s encountered some uncontrolled gas releases from relatively shallow depths in which methane hydrate was also identified (Bily and Dick, 1974; Yakushev and Collett, 1992; Collett and Dallimore, 2002). The released gas was suggested as being generated either by (1) methane hydrate decomposition while drilling with warm drilling fluids or drilling fluids containing methane hydrate inhibitors such as glycol or (2) encountering preexisting overpressured gas pockets within the methane hydrate stability zone (see Box 1.1). Although drilling with chilled fluids and more carefully selected mud was shown to prevent decomposition of methane hydrate while drilling (Bily and Dick, 1974), the issue of whether overpressured gas pockets were encountered within the methane hydrate stability zone (Weaver and Stewart, 1982) has never been resolved.

In the 1970s, the Arctic was the only area where commercial drilling was conducted in association with potential methane hydrate–bearing sediments, both on- and offshore. Perceived, but unproven, safety issues related to methane hydrate–bearing sediments in commercial drilling projects in the Arctic resulted in a policy of categorically avoiding any drilling operations where methane hydrate was suspected to occur (Paull and Ussler, 2001). In practice this approach meant avoiding areas where BSRs were

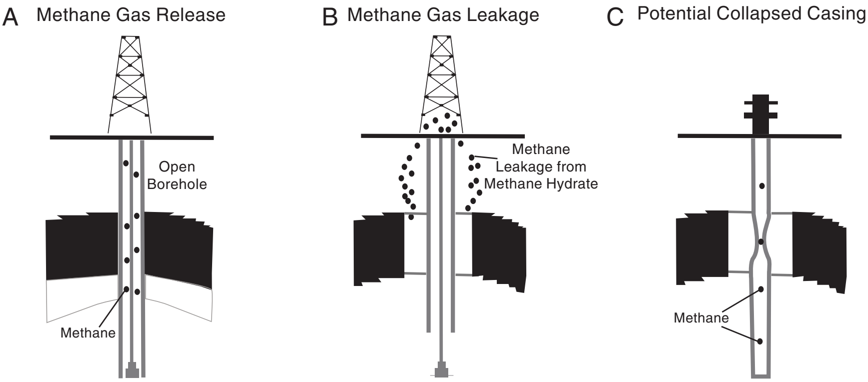


FIGURE 2.6 Conceptual diagram illustrating various conditions that may be encountered either in the active pursuit of (drilling for) methane hydrate or in exploration for and production of conventional oil and gas. Black shading represents methane hydrate–bearing sedimentary rocks. The surface on which the drill rig rests could be either the sea or land surface. The well bore in A-C is drawn at an exaggerated scale in order to demonstrate possible relationships with the methane hydrate and released methane gas. (A) Release of methane into the wellbore from methane hydrate-associated sediment. (B) Release of methane directly into the sediment column surrounding the wellbore. This methane might be associated with decomposition of methane hydrate during the drilling process, over the life of a conventional oil and gas field, and/or through methane production from methane hydrate. Methane is depicted as potentially leaking from the sediment into the bottom water and/or atmosphere. (C) Potential casing collapse associated with pressures generated through methane hydrate decomposition. Despite the concerns about hazards from methane hydrate, addressing the issue with confident scientific and technical approaches remains a challenge because very little data and research exist to support or refute existing theories for understanding of methane hydrate as a geohazard. Current industry practices advocate simply avoiding methane hydrate–bearing occurrences when drilling for conventional oil and gas plays. SOURCE: Collett and Dallimore (2002).

present in the seismic reflection profiles at potential well locations, because BSRs were related to the potential of entering overpressured gas zones beneath the base of methane hydrate stability (Figure 2.6; see also section *The Challenge of Mapping and Quantifying Methane Hydrate*). Despite this practice, a number of unintentional encounters in marine environments with methane hydrate–bearing sediments were made without adverse effects (Paull and Ussler, 2001).

Targeted drilling activities through BSRs where methane hydrate is stable within the surface sediment have also been conducted in numerous global marine settings: drilling projects coordinated by national research programs in China, India, Korea, and Japan; at a research site off Norway; by Deep-Sea Drilling Project, Ocean Drilling Program, and Integrated Ocean Drilling Program expeditions;[12] in the Gulf of Mexico JIP supported by the DOE Program (Ruppel et al., 2008); and through oil industry exploration and production activities. These projects have detected no adverse effects on the drilling operations. The committee is unaware of documented borehole problems that have been attributed to methane hydrate during drilling of exploratory or development holes in deepwater settings where the holes passed through the depths associated with BSRs observed in seismic reflection data over the well site. The combined experiences of these drilling activities have also shown that the amount of interstitial gas needed to generate BSRs and the probable overpressures in marine methane hydrate are modest (e.g., Hornbach et al., 2004).

Considerable experience now exists for drilling operations in non-Arctic marine settings and in the terrestrial Arctic with few operational issues attributed to drilling through methane hydrate (e.g., Yakushev and Collett, 1992; Collett and Dallimore, 2002). Conversely, some evidence suggests that overpressures may occur at shallow depths on the submerged parts of the Arctic shelf where methane hydrate may be undergoing decomposition associated with long-term warming stimulated by the last deglacial transgression (Paull et al., 2007). These overpressures may be significant enough to extrude sediments in the form of gas vents and structures on the Arctic shelf. The identification of these features has occurred in the same areas where Bily and Dick (1974) introduced the concept that methane hydrate may contribute to overpressured conditions in the subsurface. If the link between overpressures and these features is correct, methane hydrate decomposition may, in fact, contribute to the overpressure of sediments,

[12] Legs 11, 143, 146, 164, 204, and 311; http://odp.georef.org/dbtw-wpd/qbeodp.htm.

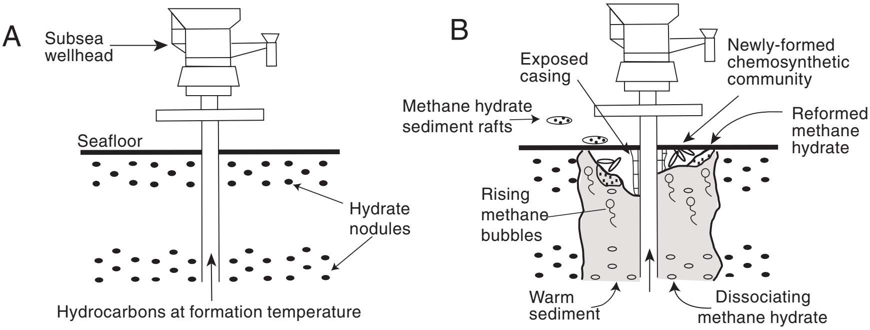


FIGURE 2.7 Potential changes at the wellhead induced by methane venting: (A) initial conditions and (B) the changes induced by methane venting outside the casing. SOURCE: Borowski and Paull (1997).

at least in areas where they already have been undergoing decomposition for hundreds to thousands of years. Again, however, the available data are inadequate to confirm or refute these assertions.

Operational Issues Related to Long-Term Production

A number of issues may be associated with the presence of methane hydrate in the host sediments outside the well casing or the supporting well infrastructure (Figure 2.7). However, most of the scenarios that may suggest methane hydrate is a geohazard to traditional hydrocarbon infrastructure do not manifest themselves at the time the well is being drilled, but rather result as a consequence of the long-term warming of the sediment associated with hydrocarbon production (Figures 2.6C and 2.7; e.g., Borowski and Paull, 1997; Hovland and Tobias, 2001; Nimblett et al., 2005).

These concerns relate to the substantial changes in sediment strength and permeability experienced when methane hydrate deposits are dissociated during production when the production well passes through a hydrate-bearing zone and when the production is from the hydrate-bearing zone. During the life of a potential producing methane hydrate field the dissociated zone may initially affect the near well-bore area, but with time, the affected area could move some distance away from the producing well. Strength and consolidation changes in the near well-bore area and production-induced regional subsidence could induce significant forces on the well casing with the possibility both of building pressure and developing significant casing strain, potentially resulting in casing failure (Figure 2.6C). Because most methane hydrate–bearing sediments are unconsolidated, potential also exists for sediment migration into the producing well, resulting in operational problems (Dallimore et al., 2008). These issues, when combined with permeability changes induced by dissociation, could cause poor sediment contact with the production casing, potentially resulting in failure of the casing cement bond and the creation of vertical migration pathways for gas migration. Although the petroleum industry has considerable experience worldwide in dealing with these types of problems, specific challenges may exist related to methane hydrate, especially if production schemes such as the use of horizontal wells are considered.

Some experience from settings where permafrost overlies deeper conventional hydrocarbon fields may be applicable to address physical property changes that may result when methane hydrate dissociates as a result of drilling and/or production. Permafrost also experiences significant changes in physical properties (strength, porosity, permeability) when the permafrost thaws in the near well-bore area in conventional oil and gas fields. Typical approaches to the predictions of permafrost response have been based on laboratory measurements of the consolidation effects on permafrost core samples and the development of a geomechanical model to predict both the near well-bore and field response to oil and gas extraction at depth. In the situation of a producing methane hydrate field, the case is more complex because the producing and responding interval are the same, and at present, no published laboratory measurements exist of the consolidation response of methane hydrate samples.

Another largely understudied topic is the amount and chemistry of the produced water that may be released when methane hydrate deposits dissociate. Some reservoir simulation models suggest that the pore water liberated when methane hydrate dissociates will be highly mobile and will flow to the producing well. The volume of produced water associated with methane hydrate production will directly impact the design of the well completion (i.e. downhole pump selection) but also be a consideration in terms of ancillary environmental issues related to water disposal.

Secondary Gas Migration

An important environmental consideration in any gas field is the risk of gas migration away from the production well infrastructure interacting with other geologic strata at depth or reaching the surface. In both cases a critical consideration is the seal integrity or the overlying permeability barrier above the production interval in the near well bore and also away from the well bore. For most methane hydrate deposits, the nature of the seals may differ significantly from traditional hydrocarbon reservoirs. In some settings, methane hydrate itself or a permafrost layer may act as a seal and trap free gas below (Grauls, 2001). The relatively shallow depths of methane hydrate occurrences also may mean that secondary sealing by the overlying sediment may only be weakly developed. At present the mobility of the gas and water released from methane hydrate decomposition is unknown, including their potential to migrate to the surface (e.g., Xu and Ruppel, 1999; Judd and Hovland, 2007).

Migrating methane can also reform into methane hydrate within the cold ocean bottom waters and form on top of the bottom-hole well assembly, potentially compromising the blow-out prevention systems. Large pieces of methane hydrate have been observed to raft away from the seafloor because of their low density with respect to seawater (~0.91 g/cm^3; Paull et al., 2003a). Erosion of the seafloor around wellheads could compromise these structures (Figure 2.7).

STATE OF THE RESEARCH FIELD

The level of progress and sophistication in methane hydrate research has been advancing at an exponential rate (Figure 2.8). As outlined in this chapter, observations, data, and analysis acquired from multidisciplinary

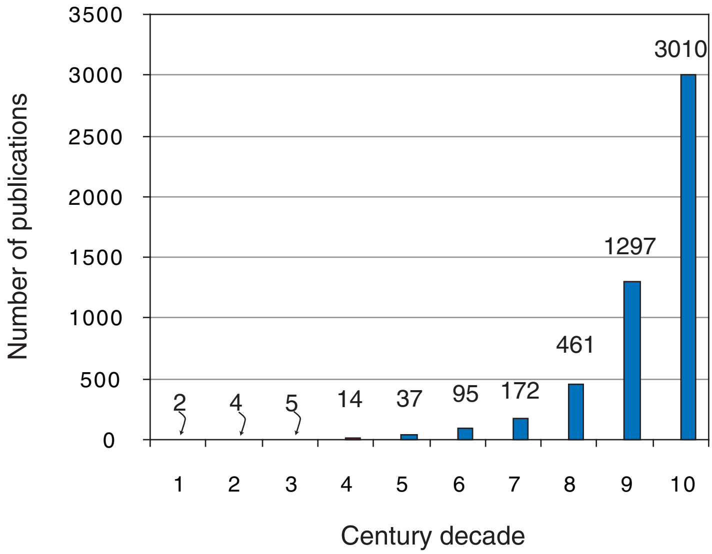


FIGURE 2.8 Level of international publication activity in the field of methane hydrate research over the past century shows a continuous increase in interest and results, with a surge of activity during the past decade. SOURCE: E. Dendy Sloan.

field activities on- and offshore and from laboratory experiments and modeling have advanced the understanding of the behavior and properties of methane hydrate and the potential to produce methane from methane hydrate accumulations. Although these advances in knowledge testify to the great interest in the potential of methane hydrate to serve as a future energy source, they belie the need for considerably more information on methane hydrate including its behavior in nature, during drilling, and in production settings, and the approaches needed to identify and reliably produce methane from this type of occurrence. Chapter 3 reviews the research projects that the Program has supported during the past 5 years in pursuit of some of these outstanding issues.

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CHAPTER 3

Review of Central Research Efforts Within the Methane Hydrate Research and Development Program

Since the start of fiscal year 2006, the Department of Energy (DOE) Methane Hydrate Research and Development Program has supported 27 new research projects and has continued to support an additional 11 projects that had begun between 2000 and the end of fiscal year 2005. Of these new or continuing projects, 25 remain active through the end of fiscal year 2009 or beyond (Appendix F). The projects supported by the Program cover several focus areas and have included discipline-specific research activities proposed by investigators at academic institutions and national laboratories as well as large, multidisciplinary projects conducted jointly with industry and/or other federal agencies, national laboratories, and academic institutions. DOE and some of its federal partners, at the U.S. Geological Survey (USGS), for example, have also participated in internationally organized projects.

This chapter provides a topical review of the Program's scientific projects and major achievements and an assessment of knowledge gaps for research areas that the committee has determined are central to the Program's mission and success (e.g., Appendix A) and follow naturally from the "state of the science" and broad challenges in methane hydrate research outlined in Chapter 2. Thus, field projects with aims toward production tests and drilling, reservoir simulation modeling, geomechanics, remote sensing, and environmental and geohazard-related research are examined here. Although the focus is on research conducted since the last review of the Program (NRC, 2004), background information prior to 2004 is provided where appropriate (Appendix F contains a complete inventory of ongoing and completed projects supported by the Program).[1]

FIELD STUDIES WITH AIMS TOWARD DRILLING AND PRODUCTION TESTS

The Program's field studies[2] have focused in the Gulf of Mexico and on the Alaska North Slope. Research projects in both regions have been important cornerstones of the Program's portfolio since 2001 and have been oriented toward improving exploration methods and quantifying the hydrate resource, and more recently, toward evaluating the challenges of methane hydrate production (Appendix F).[3] Other research specific to the geologic and physical conditions of each region has also been conducted. An important component of the research in both regions has been their coordination with significant input to research coordination, resources, and execution from industry, other federal agencies, national laboratories, and the academic community, in addition to DOE (and the National Energy and Technology Laboratory [NETL]).

[1] Project listings and information, including publications and reports, are catalogued online at http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/projects/DOEProjects/DOE-Project_toc.html.

[2] In this review "field studies" refers to those research projects within the DOE portfolio with active orientation toward production testing (see Appendix F).

[3] In Appendix F, Project Category "Field studies—Production and drilling projects," Report identifiers 1 through 4.

Alaska North Slope Field Projects: Investigating Methane Hydrate Occurrences and Production Response

The undertaking of methane hydrate field studies in northern Alaska has many practical advantages including a long history of scientific investigation in the area, a wealth of conventional hydrocarbon drilling and production experience, and access to logistics infrastructure. Recognizing the efficiencies of working in the Arctic and that the knowledge gained there can have broad applications to other settings, DOE has supported several field programs to date and is working closely with partners in the hydrocarbon industry to develop a number of new initiatives.

The geologic setting of methane hydrate in the Alaska North Slope is well described with a geothermal environment conditioned by thick occurrences of terrestrial permafrost (Osterkamp and Payne, 1981; Lachenbruch et al., 1988; Clow and Lachenbruch, 1998). Regional studies initiated in the 1980s (Collett, 1993, 1995), based mainly on well-log interpretations and data from a coring project carried out in 1972, indicate that evidence for the occurrence of methane hydrate is most commonly found in the vicinity of the Kuparuk River, Milne Point, and Prudhoe Bay oil fields (Figure 3.1; see also Figure 2.3). Occurrences of methane hydrate are thought to be primarily within coarse-grained clastic sediments often overlying deeper conventional oil and gas occurrences.

Alaska North Slope Methane Hydrate Reservoir Characterization

Initiated in 2001, this project, managed by BP Exploration Alaska, Inc. (BPXA) with participation of 16 different research groups has had overarching goals to (1) characterize the in-place methane hydrate resource on the Alaska North Slope and (2) conduct field and laboratory studies to evaluate the commercial potential for its production. The focus of the four-phase study (Phases 1, 2, and 3A) has been BPXA's Milne Point production unit (Figure 3.1). Completion of Phases 1 and 2 (in 2005) resulted in seismic and well-log characterization, structural mapping, and

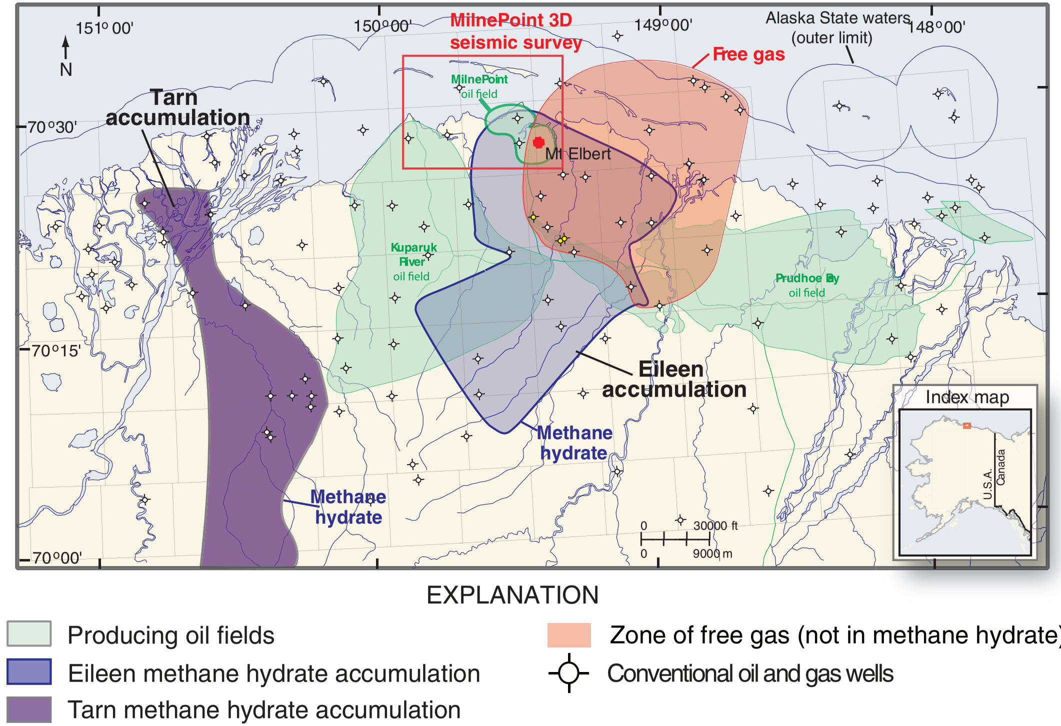

FIGURE 3.1 Map of northern Alaska near the Kuparuk, Milne Point, and Prudhoe Bay oil fields. Location of the Mount Elbert stratigraphic test well is also shown. Analysis of the methane hydrate reservoir and resource characterization relies upon access to subsurface data including industry seismic and well-log information. Data coverage decreases away from the Prudhoe Bay well cluster (see regional well distribution also in Figure 2.3). SOURCE: U.S. Geological Survey.

geophysical and reservoir modeling of the Milne Point area to calculate the regional in-place reservoir potential of a specific structural trend, and to allow economic analysis of field development scenarios.

Phase 3A focused on planning, drilling, and analysis of a stratigraphic test well at the Mount Elbert prospect at Milne Point.[4] Field work was completed in February 2007 with extensive methane hydrate coring, advanced open-hole well logging, *in situ* formation testing, and a comprehensive post-field laboratory and modeling effort (Boswell et al., 2008; Hunter et al., 2008). This program was effectively managed with special attention to site selection and completion of a state-of-the-art research and development program that for the first time documented the *in situ* formation properties of a concentrated methane hydrate deposit on the North Slope. Methane hydrate was recovered from two sandstone intervals, each approximately 43-44 feet thick (Figure 3.2) with about 65 percent methane hydrate saturation. Saturation refers to the percentage of the pore space between sand grains that is occupied by methane hydrate. By integrating detailed core investigations, well-log attributes, and regional three-dimensional (3D) seismic interpretations, the project successfully developed a petroleum system model for the methane hydrate occurrences which established the geothermal setting, gas source, migration and trapping mechanisms, and the *in situ* properties of reservoir sands and enclosing sediments above and below them. These concepts were subsequently extended by the USGS in their assessment of the resource potential of the entire Alaska North Slope (Collett et al., 2008; Lee et al., 2008; USGS, 2008; see also Chapter 2).

The Mount Elbert methane hydrate stratigraphic test well also advanced research pertinent to evaluating the production response of methane hydrate. Small-scale *in situ* formation testing was undertaken using Schlumberger's wireline Modular Dynamic Formation Tester (MDT) tool (Boswell et al., 2008; Hunter et al., 2008; see also Chapter 2). With this tool, a 1-meter formation interval was isolated and the formation pressures

[4] Note throughout this report that Mount Elbert refers to the actual prospect—and test well—within the Milne Point area. Milne Point is a more regional name referring to an oil field in which the Mount Elbert prospect was drilled.

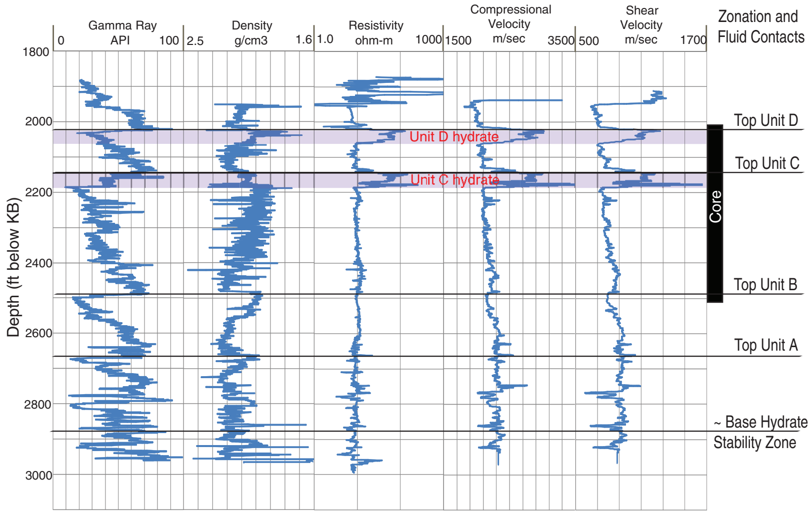

FIGURE 3.2 Geophysical wireline log data with gamma-ray, density, resistivity, compressional, and shear velocity values from the Mount Elbert-01 stratigraphic test well. The well was drilled to 1,987 feet and cored to 2,492 feet below kelly bushing (BKB). Core and logs revealed methane hydrate in two clastic sand intervals within the Sagavanirktok formation "Unit C" and "Unit D." The methane hydrate intervals have distinct geophysical signatures on the well logs, including high resistivity and velocity relative to the surrounding sedimentary units. The base of the methane hydrate stability zone is interpreted at about 2,854 feet BKB. The KB references the elevation of the "kelly bushing" at the rig floor and is 55 feet at this location; log depths are in measured depth, which in this approximately vertical well are about 55 feet deeper than sub-sea depths. SOURCE: http://www.netl.doe.gov/ technologies/oil-gas/publications/Hydrates/2009Reports/NT41332_BPXA-Hunter.pdf.

manipulated. Surface readout of the subsequent pressure response, quantification of the inflowing material (formation water, gas, and sediment), and sampling capability permitted detailed interpretation of the formation response to reducing the pressure regime at the site. This technique had been successfully used in a cased-hole configuration at the Mallik site in 2002 (Dallimore and Collett, 2005; see also Chapter 2) and offshore in the Nankai Trough (Fujii et al., 2008).

At Mount Elbert, the MDT yielded the first tests in the open-hole configuration to enable more accurate formation testing without the influence of casing and cement (Boswell et al., 2008). Although interpretation of the MDT results proved complex (Anderson et al., 2008; Hunter et al., 2008), when combined, the MDT and nuclear magnetic resonance log data from Mount Elbert enabled accurate assessments of the *in situ* and relative permeability of methane hydrate intervals. Methane hydrate dissociation and free-gas production were observed in the later stages of each test when the formation pressure was reduced below methane hydrate equilibrium conditions. Complex pressure buildups were also observed when the methane hydrate dissociated, perhaps indicating more complicated behavior of the methane hydrate or formation of ice (Hunter et al., 2008). Developing a better understanding of the behavior of methane hydrate during pressure drawdown and the efficiency of pressure drawdown in producing methane hydrate remains important for future work at this site.

Within the context of these substantial gains in knowledge, three main challenges and needs remain with regard to understanding the potential to produce methane from methane hydrate reservoirs on the Alaska North Slope. These include

1. Further research to ascertain the detailed ground temperature regime of the *in situ* methane hydrate occurrences;
2. Investigation of the significance and detailed associations of free methane and methane hydrate, especially within the context of identification of geohazards; and
3. Long-term production testing.

New Alaska North Slope Field Studies

Phase 3B of Alaska North Slope project

Building upon the considerable progress made to date in Phases 1, 2, and 3A of the cooperative agreement between DOE and BPXA on the Alaska North Slope, the participant group has expressed interest in continuing the work with increased focus on production testing. In particular, the group agrees that the small-scale MDT testing is not sufficient to assess the production response of a methane hydrate reservoir. The results of this project to date are important, particularly with regard to verification of a proposed geologic model for methane hydrate occurrence. At present, the results of the initial phases of the project are being used to evaluate and rank locations for the development of a long-term production test site in the Prudhoe Bay area. Several sites are under examination by BPXA management for consideration to proceed to Phase 3B. Land ownership and access issues are also part of this process. A decision by BPXA to move to Phase 3B—production testing—is anticipated by the end of March 2010.

North Slope Borough Project

The DOE reached agreement in December 2008 with the North Slope Borough to assess drilling and long-term production testing opportunities to evaluate the methane hydrate resource potential associated with the Barrow Gas Fields (see location in Figure 2.3) where free-gas occurrences have already been developed as an energy source for the community of Barrow. This project is the second-phase follow-on of a 2-year project ("Phase 1") with the North Slope Borough (conducted from 2006 to 2008) to characterize and quantify the methane hydrate resource potential of the Barrow Gas Fields. During Phase 1, methane hydrate stability modeling was conducted to identify the base of the hydrate stability zone in three areas; the aim was to identify areas where a hydrate-stable zone exists in an up-dip position relative to known gas reservoir sands (free gas). Further analysis during Phase 1 defined two locations for potential hydrate test wells.

Research during Phase 2 will include (1) geologic studies to verify this accumulation model of methane hydrate occurrences up-dip and in contact with the free gas and (2) the design, drilling, logging, coring, and continuous monitoring of a production well to test the commercial potential of producing gas through depressurization dissociation from the free-gas zone underlying the hydrate deposits. Although methane hydrate accumulations with lower contacts to free gas have in the past been proposed as a common occurrence, recent field studies around the world have suggested that the free gas may often exist in low concentrations. The Barrow project will provide field verification of this type of accumulation model and allow assessment of the degree of the porous media associations of methane hydrate and free gas. Success with the project will increase industry's understanding of the role of methane hydrate in the recharge of producing conventional gas fields and of how dissociation of methane hydrate may improve field performance.

Methane Hydrate Production Trial Using Carbon Dioxide–Methane Exchange

In fall 2008, ConocoPhillips and DOE agreed to pursue a field research project on the Alaska North Slope with a stated goal to define, plan, and conduct a field trial of a methane hydrate production methodology whereby carbon dioxide molecules can be exchanged *in situ* for the methane molecules within a hydrate structure, thus releasing the methane for production. The purpose of the project is to evaluate the viability of this hydrate production technique and to understand the implications of the process at a field scale (Farrell and Howard, 2009). Conceptually, this novel production scheme has the very desirable attribute that it could reduce the greenhouse gas footprint of methane hydrate production by sequestering carbon dioxide while producing methane. However, achieving this goal presents several significant challenges because the concept is based largely on small-scale laboratory experiments conducted on artificial media (Stevens et al., 2008), and no experiments have been performed to date on fully representative, unconsolidated samples. Scaling these experiments to a full-sized field trial will likely present significant technical challenges including complex well completions and operational procedures.

The project is divided into three phases, with work completed under Phase 1 that included developing a ranked set of possible field sites on the Alaska North Slope. Final field site selection occurred during Phase 2, which began in May 2009. Phase 2 work will include both experimental and well-design components. The third phase of the project, assuming successful completion of Phase 2, aims to validate the laboratory tests in the field. At the time of preparation of this report, the project will initiate Phase 3 in January 2010.

Gulf of Mexico Project Overview

The joint industry project (JIP) in the Gulf of Mexico is a collaborative undertaking led by Chevron Energy Technology Company with a central goal in the initial phases to address critical questions in marine methane hydrate exploration and geohazard assessment. The project has involved 18 industry partners, federal agencies (including DOE, the Minerals Management Service [MMS], and the USGS), national laboratories, and university research groups.[5]

During the first two phases of the project (2001-2007) the JIP made several contributions to the overall understanding of marine methane hydrate, as well as of detailed aspects of local methane hydrate occurrences in the Gulf of Mexico. Phases 1 and 2 culminated in the first successful Gulf of Mexico drilling and coring expedition for methane hydrate in May 2005 at two sites (Atwater Valley and Keathley Canyon; Figure 3.3) during which a substantial quantity of well logs, cores, and borehole seismic data were acquired. Laboratory analyses of the cores included analysis of the physical and mechanical properties of fine-grained hydrate-bearing sediments. New tools specific to the shipboard drilling environment were also tested for acquiring and analyzing field samples.

Among the notable, specific contributions from the project's first two phases were the development of laboratory equipment for making the first physical property measurements on pressure cores under *in situ* pressure conditions and developing a procedure of predrilling site-survey and site-selection efforts. The site-selection process was based on substantial industry 3D seismic datasets, normally unavailable for academic research. The data and results from these phases (summarized in a special volume of *Marine and Petroleum Geology*[6]) were used to develop the third phase of

[5] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/projects/DOEProjects/CharHydGOM-41330.html; members include Chevron Energy Technology Company, Schlumberger Oilfield Services, Halliburton Energy Services, ConocoPhillips, Total, Japan Oil, Gas and Metals National Corporation, Reliance Industries Ltd., StatoilHydro, Korean National Oil Company, MMS, Naval Research Lab, USGS, Rice University, Aumann & Associates Inc., Scripps Institute of Oceanography, Georgia Institute of Technology, AOA Geophysics, and Geotek Ltd.

[6] *Marine and Petroleum Geology*, Volume 25, Issue 9, November 2008.

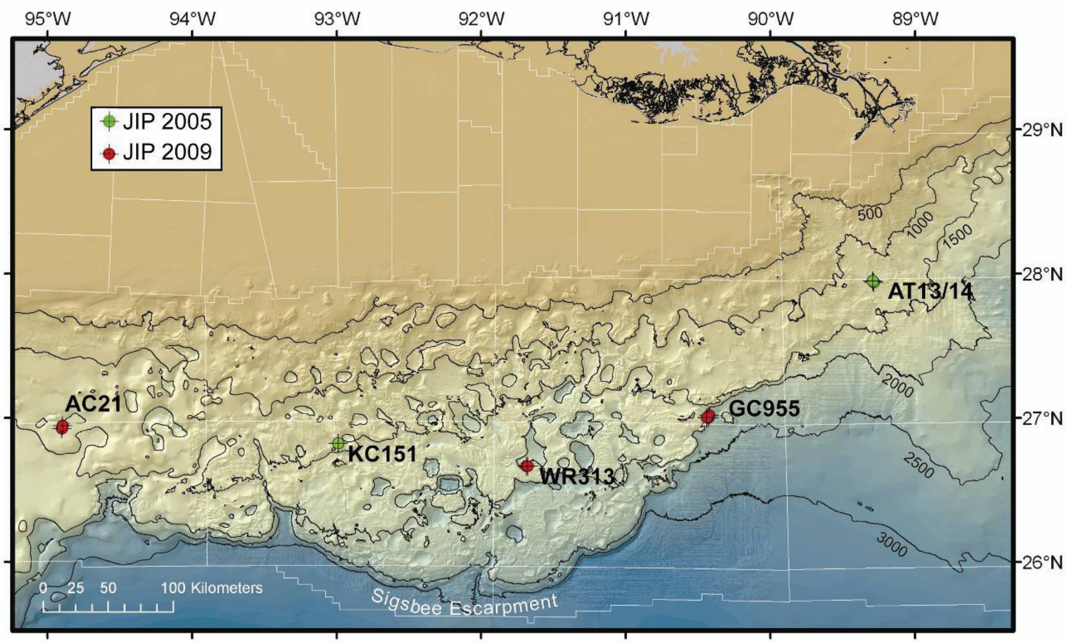

FIGURE 3.3 Bathymetric map of the northern Gulf of Mexico. The outline of the southeastern tip of Louisiana is visible between 89°W and 92°W. Bathymetric contours are in meters below sea level. Sites considered for drilling during Phases 1 and 2 (JIP 2005) and Phase 3A (2009) are indicated. Three sites selected for the logging-while-drilling JIP expedition in spring 2009 (shown in red) were in the Alaminos Canyon (21) (which is also referred to as the "East Breaks" site), Green Canyon (955), and Walker Ridge (313). In water depths of about 1,600 to 2,200 meters (5,250 to 7,218 feet), a semi-submersible rig was used to drill seven wells at these three sites. AC = Alaminos Canyon, KC = Keathley Canyon, WR = Walker Ridge, GC = Green Canyon, AT = Atwater Valley. Isobaths are in meters. SOURCE: Deborah Hutchinson, U.S. Geological Survey.

the JIP which defined a new science plan around selection of new drilling and logging (Phase 3A, begun in 2007) and coring (Phase 3B, slated to begin in the latter half of 2009) sites at Walker Ridge, Alaminos Canyon (East Breaks), and Green Canyon (Figure 3.3). Processing and interpreting the 3D industry datasets before drilling using a methane hydrate petroleum system approach were essential to the success in the latest logging-while-drilling (LWD) expedition (Phase 3A), carried out in March and April 2009.

A significant shift in science strategy in Phase 3 was to identify and sample concentrated methane hydrate occurrences in sand beds as opposed to regional occurrences associated with muds; in keeping with the project's focus on the drilling hazards in the sediments that typify the shallow section in the deepwater Gulf of Mexico, muds had been the targets of Phases 1 and 2. A detailed site-selection process was conducted prior to the 21-day expedition in spring 2009. Seven wells were drilled in Walker Ridge, Alaminos Canyon, and Green Canyon (Figure 3.3). The Phase 3 work aims to refine the use of seismic analysis and geologic information to develop prediction methodologies for hydrate-bearing, coarse-grained sediments, and to develop new pressure-coring tools and core transfer capabilities to enable *in situ* laboratory measurements of hydrate properties. Success with these studies will advance the capability to assess marine hydrate reservoirs and technical recovery of gas from marine hydrate. Assessing and understanding potential safety hazards associated with drilling wells through and running pipelines over sediments containing methane hydrate, and developing wellbore and seafloor stability models pertinent to hydrate-containing sediments remain stated components of the research program.

The main results from the LWD drilling in spring 2009 confirmed predrilling predictions from seismic data (in terms of depth to the methane hydrate target and estimated concentrations), although ground truthing with coring is still required to verify these results (Phase 3B).[7] Four of the

[7] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/2009GOMJIP/index.html.

wells found high concentrations of methane hydrate in porous, permeable sands. Two wells contained low concentrations of methane hydrate in sands and one well intersected good-quality sands with no indications of methane hydrate. The delineation of thick methane hydrate–bearing sand accumulations is a significant result of the LWD drilling. These sands could be producible when a recovery (or production) scenario for marine deposits is developed.

With these substantial gains in knowledge of marine hydrate in the Gulf of Mexico taken into consideration, three main challenges still remain with regard to understanding the potential to produce gas from these marine hydrate resources:

1. Remote-sensing techniques with sufficient resolution to detect methane hydrate occurrences with confidence at a scale that corresponds to the known geologic occurrences need to be developed;
2. Geohazards associated with the natural occurrence of methane hydrate in areas with conventional petroleum production are only beginning to be assessed quantitatively (e.g., Birchwood et al., 2007); and
3. Geohazard and geomechanic issues associated with the production of methane from methane hydrate remain to be addressed quantitatively. Specifically, the response of the shallow formations to removal of gas, and the seafloor response and associated stability issues of the wellbore and pipelines have not been analyzed.

EXPERIMENTAL AND MODELING STUDIES TO ASSESS THE GEOMECHANICS AND FEASIBILITY OF METHANE HYDRATE PRODUCTION

The Program has supported 15 experimental laboratory and modeling projects during the course of this review. An additional five projects were completed prior to the start of this review. A majority of the projects are performed through various national laboratories and universities

(Appendix F).[8] The common goal of these projects has been to provide data on physical properties, formation/dissociation behavior, and kinetics of hydrate-bearing sediments to assess the feasibility of methane hydrate production and geomechanical issues associated with the production of gas from methane hydrate deposits.

In the active project portfolio, the Program includes eight experimental projects focused on physical property measurements and five computer modeling projects, which range from reservoir modeling of the geomechanical behavior of methane hydrate–bearing sediments, to molecular-scale simulations of the growth and dissociation of methane hydrate, to methane hydrate growth at the grain/bed scale. In the latter project the model is used to investigate the hypothesis of whether coupling among geomechanics, dynamics of gas–water interfaces, and phase behavior of gas–brine–hydrate systems result in coexistence of free gas and hydrate in the hydrate stability zone. Results from this type of research may have implications for interpretation of seismic and borehole log data, as well as enabling refinements in the petroleum systems concepts for methane hydrate assessment.

In addition, a reservoir production modeling project has been supported to assess methane gas production using carbon dioxide injection. The project is starting to involve collaborations with the ConocoPhillips field project in which carbon dioxide injection with methane production is integral. One additional project has been focused on the development of the U.S. methane hydrate database for retrieval/submission of thermodynamic, structural, and geophysical property data, which will be linked to international databases through a portal under development from the CODATA hydrate workgroup. Of the eight experimental projects, all involve methane hydrate growth and dissociation kinetics measurements (e.g., evaluation of gas production rates from methane hydrate–bearing sediments) and/or physical property measurements, such as permeability, thermal properties, and geomechanical properties.

[8] In Appendix F: Project Category "Experimental and laboratory modeling studies and NETL projects, Report identifiers 36 through 46 and 52 through 55.

In all the laboratory-based experimental projects, a major limitation is the nature of the sample that is being characterized and measured: The sample needs to be a close analog to naturally occurring methane hydrate formations if measurement results are to be scaled and extended to the reservoir system. In the current studies, samples are largely synthesized from free gas plus water plus sediment, with a limited number of studies employing recovered core samples and even fewer, if any, using pressure-cored samples that have not been depressurized. Given these limitations as well as the need to obtain accurate and reproducible data, synthetic cores are needed, but these need to be analogous to the methane hydrate that occurs naturally within the subsurface formations. Pressure-cored samples provide a closer representation to *in situ* hydrate formations compared to unpressurized cored samples or typical laboratory-synthesized samples. Although the effect of sample disturbance is not completely eliminated by pressure coring, these effects will be significantly reduced compared to unpressurized core samples (also see Chapter 2). Clearly, *in situ* measurements would be the ideal method, but these are not always practical and cannot be performed as extensively and systematically as laboratory measurements. As indicated in Box 2.4, the synthesis method (i.e., using dissolved gas in liquid water, free gas and liquid water, or ice) strongly influences the pore-scale distribution of the methane hydrate, and hence the structural and physical properties of the synthetic core, including stiffness and strength of sediments and bulk conduction properties, which will subsequently determine the level to which these synthetic samples will represent natural formations (Lee et al., 2008; Waite et al., 2009).

The synthesis of samples analogous to natural hydrated sediment systems is a critical step toward being able to scale the laboratory measurement results to the reservoir system, and has been one of the focus areas of some of the currently funded projects. The laboratory measurements of the physical property responses to carefully controlled variables, such as hydrate saturation, grain size and type, pressure, and temperature, for example, can be useful to the field production and resource assessments.

A high-profile initiative in the DOE-supported modeling program has been the DOE/NETL- and USGS-led international code comparison study in which the leading methane hydrate reservoir simulators (CMG STARS, HydrateResSim, MH21, HYDRES, STOMP-HYD, and TOUGH+HYDRATE; see Chapter 2, Table 2.1) were used to predict hydrate production rates and to characterize the natural hydrate-bearing sediments. This code comparison study has been ongoing since late 2004. The DOE-supported reservoir modeling results have produced a number of experience-based techniques, or heuristics, which may be valuable during the field tests/production assessments. Despite the progress made by the modeling projects to assess the production potential of methane hydrate reservoirs, the accuracy of the results is still uncertain because the models have not been validated against ground-truthing field data because of the lack of data from long-term production field tests.

The state-of-the-art advanced simulator from Lawrence Berkeley National Laboratory TOUGH+HYDRATE code (see also Chapter 2) has also been applied to aid in the interpretation of laboratory experimental data, such as in reverse-modeling of computed tomography x-ray data to determine the physical property parameters (e.g., thermal conductivity and relative permeability data for heterogeneous hydrated sediment samples) (Figure 3.4). Recently, the TOUGH+HYDRATE code has been coupled with a commercial geomechanical code, FLAC3D, to assess the yield (failure) distribution during production of hydrate-bearing sediments. Again, experimental data are critical to validate the geomechanical predictions.

REMOTE SENSING

The Program has supported 7 remote-sensing–related projects since 2006, of which four have focused on the Gulf of Mexico (Appendix F).[9] This emphasis is logical given that the JIP project in the Gulf of Mexico requires predrilling site evaluations, including assessing existing industry geophysical data, collecting new geophysical data, and processing these datasets for the specific needs of shallow-drilling and shallow-hazard

[9] In Appendix F: Project Category "Resource characterization and remote sensing," Report identifiers 5 through 10 and 21.

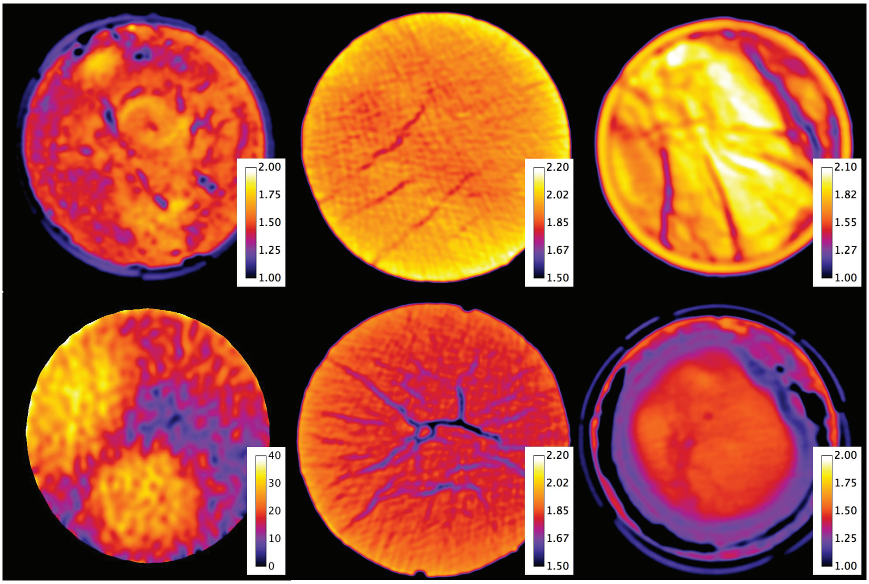

FIGURE 3.4 Computed tomography x-ray core images showing significant heterogeneity in hydrate-bearing sediment cores synthesized in the laboratory (bottom left), and in recovered natural cores from the ocean floor (top left), Mt. Elbert well (middle), and the Indian National Gas Hydrage Program expedition (far right). The color scales for all natural cores represent the bulk density distribution (in grams per cubic centimeter), and for the synthetic hydrate core the color scale represents methane hydrate saturation (%). SOURCE: Kneafsey (2009).

surveys. The result, with the exception of the USGS-related interagency collaboration activities, which include the Alaska North Slope and offshore India, is that remote-sensing–related projects are marine oriented. The research is conducted by various university groups, federal agencies, national laboratories, and industry partners and concentrates on two main types of remote-sensing techniques: (1) seismic and/or acoustic techniques and (2) controlled-source electromagnetic (CSEM) imaging.

Seismic Techniques

A major goal of the Program is to stimulate the development of new geophysical tools and techniques to detect and quantify methane hydrate in nature, primarily using seismic reflection profiling techniques. Some projects attempt to also link this general theme to geomechanical and geohazard issues by coupling with the development of rock physics models to help understand the physical properties (particularly seismic velocities) of the sediments that may contain methane hydrate.

Among the seismic-related projects supported by the Program, one in particular has achieved notable success in combining multicomponent seismic attributes, new rock physics models, and *in situ* data to estimate methane hydrate concentrations in deepwater, near-seafloor strata of the Gulf of Mexico. This project has also advanced the use of other, or nonstandard, seismic techniques such as ocean-bottom cables or ocean-bottom seismometers in understanding methane hydrate in marine sediments[10] (see Chapter 2) (e.g., Hardage et al., 2009; Figure 3.5).

Increasing use in the DOE-supported remote-sensing projects is being made of available industry 3D seismic data, which provide an opportunity to better delineate the prospective methane hydrate deposits within the framework of the petroleum-system concept. One shortcoming of using industry seismic data for methane hydrate detection and quantification is that these data typically were acquired with a deeper target depth in mind, and thus the resulting vertical and horizontal resolution within the methane hydrate stability zone is significantly less than could be obtained if the surveys were optimized for methane hydrate targets. Lack of dedicated seismic surveys for (shallow) methane hydrate targets, particularly those across sites with high-quality LWD data such as those recently acquired during Phase 3A of the Gulf of Mexico JIP (see section *Field Studies with Aims Toward Drilling and Production Tests*), compromises identification and quantification of the methane hydrate resource.

[10] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/projects/DOEProjects/MH_ 42667GOMSeismic.html; see also Appendix X.

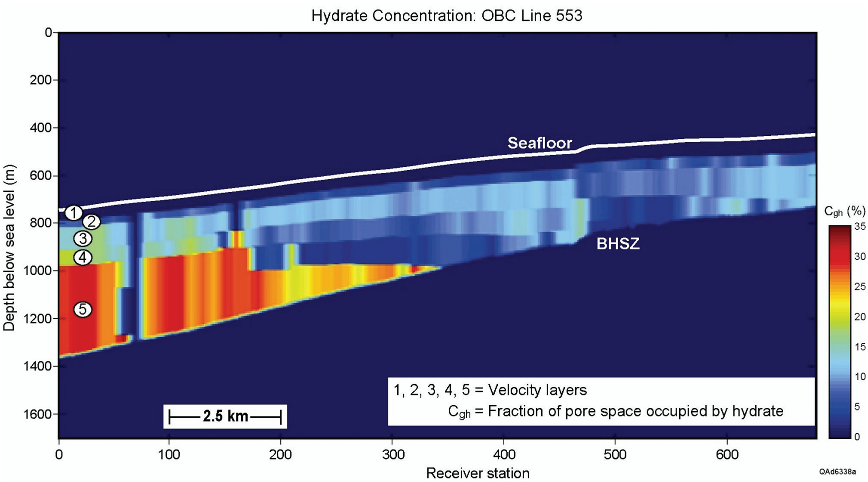

FIGURE 3.5 New technology was developed for imaging near-seafloor geology with four-component ocean-bottom cable (OBC) data. This figure shows hydrate concentrations estimated along one of the study's OBC profiles in the Gulf of Mexico. The units are "percent of pore space occupied by methane hydrate." (Cgh = color scale from 0 to 35 percent on the right-hand side of the figure). Methane hydrate concentrations were estimated for layers identified by the numbers 2 through 5 (left side of the diagram). Concentrations were not estimated for Layer 1 because no log data were available across this shallowest interval immediately below the seafloor. The calculated hydrate concentrations exhibit considerable lateral variation within each velocity layer and considerable vertical variability from layer to layer. The maximum methane hydrate concentration found along this OBC profile was in the left-hand side of the line where methane hydrate occupied a little more than 30 percent of the pore space of the host sediment (red colors). At the south end (left-hand side) of the line, the base of the hydrate stability zone (BHSZ) boundary is defined by a reversal of V_P velocity. At the north end, a published thermal constraint is used to define the BHSZ. The concepts established through this study allowed the researchers to conclude that evaluating deepwater hydrate systems with multicomponent seismic data is highly desirable. SOURCE: Hardage et al. (2009).

CSEM

Two projects in the DOE Program's remote-sensing portfolio have focused on developing new tools, approaches, and equipment to use CSEM techniques as a method for methane hydrate detection. Although CSEM techniques are widely used in exploration for conventional marine hydrocarbons, the technique has not yet attracted significant use in methane hydrate research. However, CSEM techniques hold considerable promise for methane hydrate detection because of the electrical resistivity contrasts between methane hydrate–bearing and water-saturated rocks (Chave et al., 1985; Edwards, 2005; Ruppel, 2009).

Research Challenges

At present, both seismic and CSEM methods as applied specifically to exploration for methane hydrate require additional research and development. Although exploratory drilling and production tests have been conducted in both Alaska and the Gulf of Mexico areas with success (see section *Field Studies with Aims Toward Drilling and Production Tests*), **a critical contribution to advancing the research in these areas involves acquisition of dedicated, new seismic surveys specifically focused on methane hydrate detection.** The combined use of seismic and CSEM in remote sensing for methane hydrate has the potential to minimize ambiguity and resolution limits compared to the use of either technique alone.

As outlined in Chapter 2, exploration for methane hydrate occurrences requires detailed assessment of the temperature and pressure regime within the potential methane hydrate–bearing sediment section to make better predictions of the depth to the base of methane hydrate stability. At this point, the Program's research portfolio does not include temperature (and, if possible, pressure) surveys, either through marine heat-probe deployments or through assessment of existing well data. Results from such studies could narrow the uncertainty in regional methane hydrate assessments and site-specific analyses, for example, through installation of fiber-optic distributed temperature sensors, similar to those used in the Mallik program (Henninges et al., 2005).

ENVIRONMENTAL AND GEOHAZARD RESEARCH RELATED TO METHANE HYDRATE DEGASSING THROUGH GEOLOGIC TIME

The Methane Hydrate Research and Development Act of 2000 (Appendix A) specifically encourages DOE to support basic and applied research "to assess and mitigate the environmental impact of hydrate degassing (including both natural degassing and degassing associated with commercial development)." To this end, the Program has supported a variety of projects from national laboratories, industry, and academic institutions that address many aspects of the environmental consequences of the degassing of methane hydrate. The Program has thus provided an opportunity for investigators to obtain fundamental information concerning the environmental impacts of methane hydrate degassing through geologic time, including impacts caused by current human activities and those predicted for the future.

Of 14 environmental impact projects supported by the Program since 2005, 10 have focused on some aspect of environmental impacts resulting from the natural degassing of methane hydrate (Appendix F).[11] Different approaches have been taken in these 10 projects to obtain relevant information. Some projects deal mainly with methane oxidation, another focuses on the biological origins of methane, some use modeling of methane hydrate geodynamics, and still others consider rates of methane seepage (methane flux) (a) in thermokarst lakes of the Arctic, (b) in the water column of the Gulf of Mexico, (c) inferred in sediment of the Bering Sea, (d) from the stratigraphy of carbonates, and (e) in oceanic sediment based on sulfate profiles. The Gulf of Mexico serves as the field site for five of the 14 projects (Figure 3.6).

[11] In Appendix F: Project Category "Environmental studies," Report identifiers 4, 11 through 19, and 24 through 27.

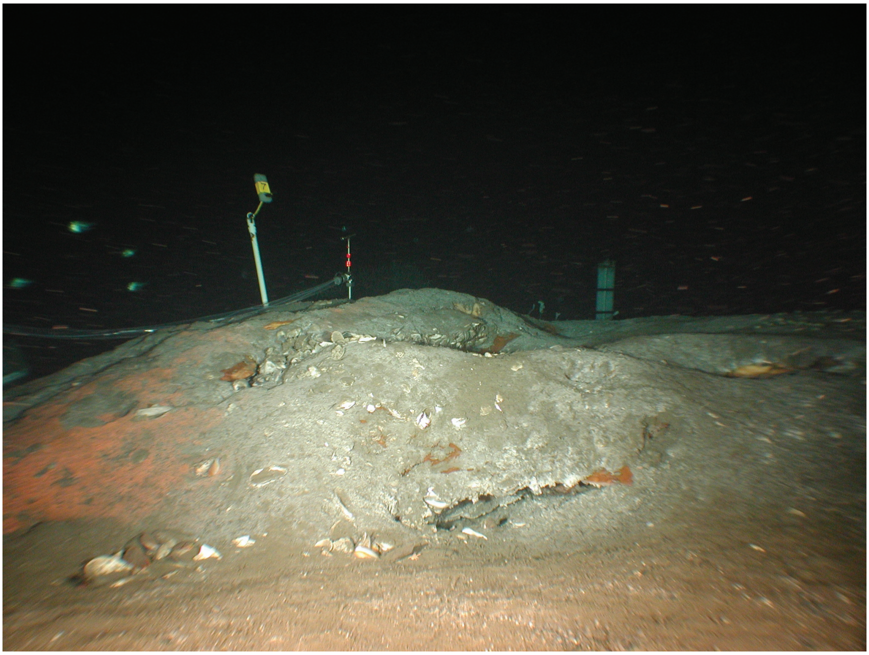

FIGURE 3.6 Gulf of Mexico methane hydrate deposit on the seafloor. A remotely operated vehicle was used to take photographs over a 350-day time series to document methane hydrate occurrences and the drivers for their stability, including bottom water temperatures and the water temperature profile. SOURCE: MacDonald (2009).

Most projects specifically proposed to generate new information regarding the role of methane hydrate in the global carbon cycle and/or in global climate change. Research aimed toward placing methane hydrate degassing into a global context relative to the carbon cycle and climate change is ambitious. As yet no major breakthroughs have appeared from this research in the understanding of possible global roles for methane hydrate resulting from its natural degassing.

To date, **none of the Program's projects have substantially addressed the potentially enhanced impacts expected from the commercial exploitation of methane hydrate** although four of the projects in the environmental portfolio have described some research goals that address geohazards and environmental issues associated with drilling and production. Also, **no project to date has considered the mitigation of the environmental impacts of natural degassing and degassing associated with commercial development as specified in the enabling legislative language.** These latter kinds of studies are critical for the development of strategies to minimize the environmental impacts resulting from any future commercial production of methane from methane hydrate.

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CHAPTER 4

Coordinating Process for the Methane Hydrate Research and Development Program

During the past 5 years, the Program has instituted several programmatic changes and reinforced some existing program directions to refine the Program's overall scientific directions and strengthen its management process. These changes, which are examined in this chapter, were enacted to increase the success of the research funded by the Program, to communicate scientific results, to support education and training of young researchers, to enhance collaborative engagements with other research entities domestically and internationally, and to increase management efficiency and the transparency of its activities.

RESEARCH INFRASTRUCTURE, SCIENCE COMMUNICATION, AND EDUCATION AND TRAINING

The majority of the Program's modest resources are directed toward research through field projects and other cooperative agreements (Appendix F). These types of projects and agreements are conducted primarily by university researchers and their students with added contributions, particularly in the large field projects, from industry. The remainder of the resources is directed toward support for activities at the National Energy

Technology Laboratory (NETL) and other national laboratories, with smaller proportions allocated to program management, selected activities at other federal agencies, graduate research fellowships, and technology transfer (Allison, 2008). The process used by the Program to call for external research proposals and grant support for research projects, to evaluate the progress of individual research projects, and to communicate the scientific results of the projects is examined briefly in the following section.

In its review and assessment of this process, the committee took three issues into consideration: (1) the Department of Energy's (DOE's) authorized role in identifying, facilitating, and coordinating methane hydrate research; (2) the very fundamental nature of much of the research that the Program supports; and (3) the external factors, particularly with field projects, that affect research progress but which may often be beyond DOE's direct control.

Project Selection and Peer Review

The Program includes project selection and performance evaluation for procedures for two primary project types: cooperative agreements selected competitively through publicly announced funding opportunity announcements and those awarded directly through interagency agreements and national laboratory field work proposals (FWPs). Cooperative agreements are openly solicited and competed, and are evaluated on three main criteria: scientific and technical merit, technical approach, and technical and management capabilities. The review panel to examine proposals consists of both internal (Program) reviewers and external reviewers who are considered to be leading scientists within the methane hydrate community. Each reviewer conducts an independent assessment of the proposals, and external reviews are then used by the internal review team in their deliberations. Interagency agreements and FWPs, which typically account for one-fifth of the total program funding, are noncompetitive. They are negotiated directly with the research partner and do not go through an external review process (DOE/NETL, 2008).

Once projects are funded and become part of the Program portfolio, they undergo a merit review process. External reviewers from the methane hydrate community are selected to evaluate project quality, relevance, progress, and results. As in the Program's selection process, the internal review team uses feedback from the external review to create consensus evaluations of each project. Currently, reviews alternate annually, with cooperative agreements assessed in one year and interagency agreements and FWPs in the subsequent year. DOE is considering a plan to consolidate the two reviews into a full program review (of cooperative and interagency agreements, and FWPs) to maximize data exchange between different projects within the portfolio.

Fundamentally new research is being undertaken on a number of fronts by the Program, particularly in the field projects where new types of exploration and drilling of test wells are being evaluated and conducted and which require significant planning, coordination, and resources. Factors such as land permitting and land ownership, and in offshore areas, drill rig availability, are key aspects to conducting successful drilling activities, but are not directly under the Program's or industry partners' influence to control. Delays in any of these aspects of a drilling expedition may delay a project's schedule and acquisition of results.

To address some of these practical challenges, the Program has incorporated some flexibility in its oversight of projects; for example, the Program coordinates its research projects in phases rather than strictly by a fiscal- or calendar-year schedule (see Chapter 3 for examples). At a phase transition, both parties to the agreement (the Program management and the project research partner) may evaluate the progress and relevance of the work and make adjustments to schedules and costs. The decision to move into the next project phase is made by the project research partner by submitting an application to the Program for continuation of the project, with a description of changes, if any, to the research plan (DOE/NETL, 2008).

Although the newly introduced peer reviews and other forms of periodic reporting by the performers to the Program are positive additions to Program management and project oversight, **the committee notes that the large field projects, in particular, may benefit from more**

comprehensive and frequent external peer review to evaluate the scientific goals of these projects, the projects' progress toward achieving these goals, and, if necessary, any modifications in the research plan that may help avoid obstacles to achieving the goals. The greater sophistication of the field tests as the Program moves these large field projects forward toward sustained production of methane from methane hydrate will require greater concentration of resources. More frequent, external peer review assessments may give the Program and project researchers increased confidence in the field tests and in efficient allocation of resources.

Resource Allocation, Coordination, and Partner Contributions

The heaviest investments for the Program continue to be in industry partnerships in the field. Of the Program's allocated and planned support for projects since the Program's inception, approximately 63 percent has been directed toward the four currently active field-based projects (see Chapter 3; Appendixes E and F). The allocation of this proportion of the Program's annual resources to these projects is understood in the context of the high cost of conducting major field expeditions in the Arctic and offshore, including the cost of exploratory and production test drilling. The total cost for field operations in the Alaska North Slope project managed by BP Exploration Alaska is less than that needed to conduct work in the Gulf of Mexico—as of late 2008, the total DOE share contributed to work in the Gulf of Mexico was $24.6 million and to work on the Alaska North Slope project was about $10 million. The cost differences between the two projects are largely due to high daily rates for drill ships in the deepwater Gulf of Mexico which, when combined with logging tool rentals and other costs, reach about $500,000/day (DOE/NETL, 2008). Substantial direct and indirect resource contributions from industry and federal agency partners to these projects are also notable and necessary. By the close of 2008, industry had contributed an additional 29 percent share to the Gulf of Mexico joint industry project (JIP) and about a 37 percent additional share to the Alaska North Slope project; industry contributions in both projects take the form of donated seismic and other data, in addition to sharing a proportion of the labor costs (DOE/NETL, 2008).

A significant contribution to these two field projects has also come in the form of research contributions from other federal agencies. Most of the agencies involved in the interagency collaboration on methane hydrate (see also below) have their own, dedicated methane hydrate research programs which are funded internally and thus are conducted in true partnership with the Program. Any funding support provided by the Program to these agencies for the interagency work is small, if it occurs at all, and is directed toward very specific aspects of the work. In the Gulf of Mexico JIP, involvement by the U.S. Geological Survey (USGS), Minerals Management Service (MMS), and Naval Research Laboratory (NRL) has led to significant advances in the science and success of the project. Similarly, in the Alaska North Slope project, many years of research engagement on the part of the USGS and Bureau of Land Management (BLM) have been fundamental to the achievements of the project thus far (see also Chapters 2 and 3). Specific agency contributions to the interagency methane hydrate collaborations are described later in this chapter. The Program also provided ancillary support to projects associated with the Integrated Ocean Drilling Program Expedition 311 in 2005.[1]

Other research activities that involve experimental laboratory or theoretical modeling or field work not specifically tied to one of the two large field studies comprise the remainder of the Program funding and typically involve one or more institutions as principal investigators, often with explicit student research involvement. Figure 4.1 shows the general resource allocation for the Program appropriation in fiscal year 2008 as an example.

The research supported in this way by the Program is robust, with more than 20 higher education and oceanographic institutions, as well as national laboratories, currently receiving project support (Appendix F). The projects not related to the large field drilling and production research are typically of shorter duration (approximately 2-3 years) and are awarded in

[1] http://publications.iodp.org/proceedings/311/311title.htm.

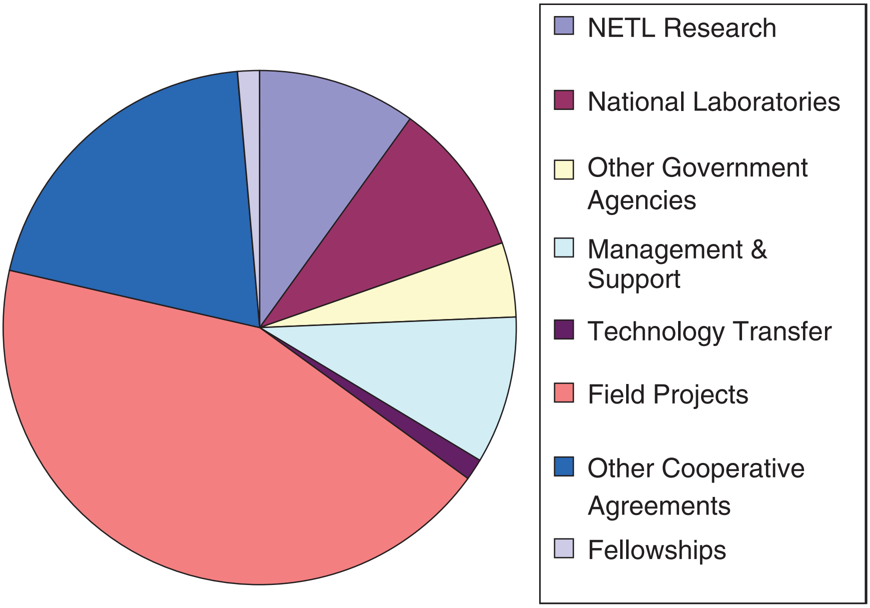

FIGURE 4.1 Funding allocation for the Program's appropriated $14.8 million in fiscal year 2008. Somewhat less than half of the Program's funds were directed toward the field projects. Note that most of the projects also include a cost-sharing arrangement (see Appendix F). SOURCE: Allison (2008).

response to specific proposal requests by the Program. The range of research themes addressed by these projects includes remote sensing, geomechanics, geohazards, and the environment. Modeling, laboratory experiments, and field observations are employed to examine various aspects of each of these themes (Appendix F; see also Chapter 3). Although most of these projects are stand-alone in the sense that each one is proposed by an academic researcher or research team to address one or more specific research topics, a number of the projects are or could be adapted to provide input data, newly developed technologies, or other results to the active field projects in the Gulf of Mexico or on the Alaska North Slope. For example, a laboratory and modeling effort to build a new pressure-core analysis device for use in the Gulf of Mexico JIP is being conducted by the Georgia Institute of

Technology. This project is a separate laboratory and modeling project funded as a Cooperative Agreement through the Program but will feed directly into the JIP in the Gulf of Mexico. The committee is supportive of Program efforts to attempt to integrate research results, where appropriate from individual projects, in order to augment the overall advances of the Program's research, particularly related to the large field projects.

Developing the Next Generation of Researchers

Training and educating new researchers in methane hydrate studies is essential for continued growth of the field, and helps to ensure that the appropriate level of basic and applied knowledge is available to carry work forward to develop safe and environmentally sustainable potential commercial production. The Program has shown a commitment to training the next generation of energy scientists in a diverse range of disciplines including chemical, petroleum, and mechanical engineering; geology, geochemistry, and geophysics; chemistry; biology and microbiology; hydrology; and numerical modeling. During the period between 2000 and 2008, the Program provided research opportunities and financial support to over 150 students (mostly master's and doctoral degree students) and 16 postdoctoral researchers from 42 U.S. universities.[2]

Student and postgraduate research projects are linked directly to various existing research projects coordinated by academic, national laboratory, industry, and government researchers. This linkage gives these students and postgraduates a broader context for their studies as well as umbrella organizations and contacts through which to pursue professional careers. In 2006, partially in response to recommendations in the NRC (2004) report and the reauthorization language of 2005, the Program also initiated a Methane Hydrate R&D Fellowship program to provide 2 years of support for particularly deserving graduate or postdoctoral fellows. Selection of fellows is based on the technical and scientific merit of proposed projects,

[2] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/StudentDirectory.html.

their potential to advance the stated goals of the Program, and the nature of the proposed research environment (including mentors and hosting institutions). As of the end of 2008, about 50 students and 3 postgraduate fellows were actively pursuing methane hydrate research through support from the Program.[3]

Communication of Research Results

The public communication of research results supported by the Program has increased substantially in the past 5 years. This result is partially due to an increase in the number of active research projects and their relative maturity, but has been enhanced by several dedicated efforts on the part of the Program to encourage public awareness of active research in methane hydrate. Primary information outlets for methane hydrate research that have been promoted by the Program include (1) the Program Web site,[4] including release of news and new research results from the international research community in the *Fire in the Ice* quarterly online newsletter;[5] (2) participation in international conferences;[6] (3) mandatory quarterly reporting for its supported research projects by project investigators (available under each project description on the Program Web site;)[7] and (4) publication of peer-reviewed articles (e.g., Ruppel et al., 2008). Federal agency partners are also active in publishing their own research results in professional papers and official reports.[8] The Program Web site, established by DOE within the NETL Web site is a significant source

[3] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/GradFellowship.html.

[4] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/maincontent.htm.

[5] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/newsletter/newsletter.htm.

[6] See http://www.icgh.org/; at the Sixth International Conference on Gas Hydrates in 2008, DOE-NETL researchers contributed 9 separate research presentations.

[7] http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/projects/DOEProjects/DOE-Project_toc.html.

[8] http://energy.cr.usgs.gov/cgi-bin/rooms_pubs.cgi?Gas%20Hydrates&year; http://www.mms.gov/revaldiv/GasHydrateAssessment.htm.

of information about methane hydrate research and the Program, more specifically. Enhancements to the Web site, including a more navigable menu of topics and regular Web site updates have been made during the past several years.

The Web site also has an extensive bibliography of all publications for the Program, peer-reviewed and non-peer-reviewed.[9] An analysis of this bibliography suggests that the use of peer-reviewed publications to communicate research results was emphasized by some project teams and agencies and was notably absent in others. Some of this imbalance in absolute numbers of peer-reviewed publications is related to project duration and size—projects with many organizations and research participants would likely produce a greater number of publications than other projects with single institutions with small numbers of researchers conducting research over shorter time periods. In addition, the committee was not able to assess whether researchers who published results after their Program funding had ended were obliged to provide this information to the Program. These issues notwithstanding, the committee noted a discrepancy between number of projects and their duration, and the low number of peer-reviewed publications by many of the projects; for example, of 13 projects funded in 2006, 4 projects had 5 or more peer-reviewed publications, whereas 8 other projects have not produced any. Although peer-reviewed publications are only one means to report research results, the committee supports greater emphasis on this means of communication as a mechanism to provide community support for and validation of the Program's achievements.

COLLABORATIVE ENGAGEMENTS: INTERAGENCY AND INTERNATIONAL COORDINATION

The Program is dependent upon collaborative engagement and strong cooperation with other federal agencies that have active programs and direct interest in methane hydrate research. Some of these agencies, most

[9] http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/MHBibliography.pdf.

notably USGS, have had active methane hydrate programs for 3 decades. The Program's interest in collaboration extends to the international community, as the number of countries with active methane hydrate research programs continues to grow. Both of these areas of collaboration are explored below.

Interagency Coordination

Seven federal agencies, including DOE with the mandated coordinating role, have taken a constructive approach toward the interagency collaboration specified in the congressional authorization language for the Program in both 2000 and 2005. Specifically, DOE was tasked to collaborate with the Department of Commerce (represented by the National Oceanic and Atmospheric Administration [NOAA]), the Department of Defense (represented by NRL), the Department of the Interior (including BLM, MMS, and the USGS), and the National Science Foundation (NSF) on basic and applied methane hydrate research and technological development. Interagency coordination occurs via four mechanisms: (1) cofunding of projects, (2) building upon agencies' various areas of expertise, (3) direct funding from DOE to other agencies, and (4) using other agencies' technological expertise to develop research and development programs. To facilitate collaboration, an interagency coordination committee and a technical coordination team were established.

A summary of each federal agency's role in the coordination effort follows, with a focus on significant projects and funding sources. Agencies are listed below in alphabetical order without intent to prioritize. The "Interagency Five-Year Plan for Methane Hydrate Research and Development 2007-2011,"[10] "An Interagency Roadmap for Methane Hydrate Research and Development,"[11] the "Interagency Coordination on Methane Hydrates

[10] Appendix C in http://fossil.energy.gov/programs/oilgas/hydrates/MHAC-07-ReportToCongress-final.pdf.

[11] http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/InteragencyRoadmap.pdf.

R&D" brochure,[12] and discussions with partner agency representatives were sources of information for this overview. All of the agency contacts with whom the committee interacted during the course of the study expressed very positive opinions of the value of interagency collaboration regarding methane hydrate research and the efforts of the Program to coordinate these collaborations. The committee notes the importance of revisiting and updating these interagency plans and roadmaps as methane hydrate research efforts proceed.

BLM

Specifically through its established agreements with the USGS and MMS, BLM's engagement in interagency methane hydrate research focuses on examination of the environmental and land impacts of methane hydrate occurrences on the Alaska North Slope and quantification of methane hydrate resources. In anticipation of eventual commercial production of this resource, BLM's efforts are oriented toward understanding the resource for future management purposes. BLM has provided the USGS with interpreted geophysical data, assisted with new interpretations of geophysical data, and provided supplemental funding to USGS for its assessment of the resources in the Alaska North Slope project. As work in the Arctic continues, BLM will also collaborate with USGS on safe drilling practices.

MMS

With responsibility to manage the U.S. mineral resources along the Outer Continental Shelf (OCS), MMS has been a key participant in the Gulf of Mexico JIP. In addition to understanding the size of the in-place resource, MMS uses information gained from methane hydrate research to evaluate the potential environmental impacts from the recovery of the resource offshore including the potential hazards of drilling through methane hydrate. The MMS has worked since 2003-2004 to develop and employ an

[12] http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/MethaneHydrate_2007Brochure.pdf.

extensive new assessment model for the methane hydrate resource in the Gulf of Mexico and has been a participant in the Gulf of Mexico JIP (see also Chapters 2 and 3). An interim report was produced in February 2008 (Frye, 2008)[13] . The ultimate goal of this work is to provide estimates of technically and economically recoverable methane hydrate along the entire U.S. OCS. Together with NOAA and DOE, MMS has also provided support for the Center for Marine Resources and Environmental Technology Sea Floor Observatory in the Gulf of Mexico.

NOAA

NOAA focuses on the role of methane hydrate as it may relate to the global carbon cycle and climate change and its role in the ocean environment as a source of bioproducts. Recent projects include studies of chemosynthetic communities at methane seeps along the U.S. West Coast, East Coast, and Gulf of Mexico[14] (e.g., Van Dover et al., 2003). NOAA is also one of several agencies (with DOE and MMS) that funds the Gulf of Mexico Seafloor Observatory, used to examine interactions between methane hydrate, biological communities, sediment, and the water column. In 2004, a workshop cosponsored by DOE, MMS, USGS, and the Woods Hole Oceanographic Institution was held to study the role of marine hydrate in global climate change, and to integrate climate scientists with the methane hydrate community (NOAA, 2005).

The majority of NOAA's methane hydrate research is funded through NOAA's Office of Exploration and Research (OER; formerly the Undersea Research Program), which has supported methane hydrate research for approximately 15 years. A small amount of additional funding comes through NOAA's Arctic program. NOAA's OER program leverages ship time and assets through a partnership with MMS, which contributes science funding.

[13] http://www.mms.gov/revaldiv/GasHydrateAssessment.htm.

[14] http://oceanexplorer.noaa.gov/explorations/04deepscope/welcome.html; http://oceanexplorer.noaa.gov/explorations/05deepscope/welcome.html; http://oceanexplorer.noaa.gov/explorations/06mexico/welcome.html; http://oceanexplorer.noaa.gov/explorations/07mexico/welcome.html.

NRL

NRL is currently interested in the role of methane flux in climate change with an emphasis on the Arctic. The agency is leading an expedition in collaboration with the USGS and DOE to the Beaufort Sea in September 2009, where the plan is to investigate methane transport from the seafloor to the atmosphere. In the Gulf of Mexico JIP, NRL contributed to drill-site evaluations through seismic surveys, geochemical analyses of piston-core pore water, and deployment of heat-flow probes and interpretation of the measurements they register. Together with the USGS, NRL has also led the development of U.S.-international collaborations in methane hydrate research. In 2001, NRL's methane hydrate research program and the University of Hawaii established an international consortium for methane hydrate research, which presently involves the United States, Canada, Chile, Germany, and Japan. NRL has also hosted three international workshops on methane hydrate research and development (Max et al., 2006). In conjunction with DOE, NRL has also initiated contacts with New Zealand to explore opportunities for collaborative research. To the extent possible, NRL also attempts to facilitate the participation of foreign researchers in U.S.-based methane hydrate research projects.

NSF

NSF supports the study of marine methane hydrate through the competitive grant process. The agency has supported methane hydrate studies off the coasts of Oregon and the Cascadia Margin through the Ocean Drilling Program (Leg 204) and the Integrated Ocean Drilling Program (Leg 311). Leg 311 was funded in conjunction with DOE and included scientific research from the USGS. NSF also funds microbiological and chemical research into methane hydrate through its Life in Extreme Environments project, and has funded research cruises to investigate geophysical indicators of gas hydrate.

USGS

The USGS, the largest and most long-standing agency contributor to methane hydrate development, has had an active research program since

1981. The agency's focus is on methane hydrate as a potential energy source and as a geohazard for conventional oil and gas drilling. USGS scientists contribute to the interagency coordination effort through developing methane hydrate research plans, evaluating research proposals, reviewing ongoing projects supported by the Program, and leading workshops to identify key methane hydrate research topics. The agency has also completed an assessment of technically recoverable methane hydrate in association with BLM (Collett et al., 2008; see also Chapters 2 and 3), has participated in code-comparison studies, and has been involved over many years with methane hydrate resource characterization and production on the Alaska North Slope. Many results produced on the Program's Alaska North Slope project build upon the experience of USGS scientists who had participated in the Mallik well project in Canada (see Chapter 2). The USGS also has a strong engagement with the Gulf of Mexico JIP in (1) support of drilling activities (including identification and evaluation of drill sites) and (2) providing data and interpretation to support the controlled-source electromagnetic survey (CSEM; project lead is Scripps Institution of Oceanography; Pierce, 2008; see also Chapters 2 and 3).[15] In 2006, the USGS also led a large science team, working in collaboration with the government of India, to explore deep-sea methane hydrate resources of the Indian coast through scientific drilling, well logging, coring, and shipboard scientific analyses of recovered samples (National Gas Hydrate Program Expedition 01).[16] The Program contributed support to this endeavor, as well.

International Collaboration

Many nations are currently pursuing methane hydrate research and development. These active interests range from countries such as Norway, with abundant natural energy resources, and not dependent on foreign sources of energy, to countries such as Japan, which is highly dependent upon

[15] Note that some DOE funds were provided to USGS specifically to conduct laboratory analyses on Scripps' CSEM results.
[16] http://energy.usgs.gov/other/gashydrates/india.html.

imports to supply its energy needs (Box 4.1). The Program's participation in international projects has progressed during the last several years from a role primarily as an observer, to one that is more actively engaged in both provision of resources and scientific input to various international endeavors, including signing formal, collaborative agreements with the national program leaders in Japan, Korea, and India. An increasing number of opportunities for the Program to participate more directly in international collaboration have also been facilitated through interagency partners (notably the USGS and NRL; see above).

With specific direction to foster further international collaboration (e.g., P.L. 109-58, Section 968 of the Energy Policy Act of 2005), the Program has pursued collaborations with research groups in India (see above, under USGS), China, and South Korea. Program scientists participated in 2007 expeditions to the South China Sea, led by the Guangzhou Marine Geological Survey (GMGS), China Geological Survey, and the Ministry of Land and Resources of the People's Republic of China, and to the Ulleung Basin, led by the Korea Gas Hydrate R&D Organization and the Korea Institute of Geoscience and Mineral Resources[17] (see Figure 1.1 for locations of these offshore drilling expeditions). Efforts to engage in collaborative research with New Zealand and Chile have also been noted (see discussion on NRL, above).

Although the Program has participated in various international collaborations, including international partnerships established by other agencies such as the USGS and NRL, comprehensive scientific engagement with international partners has been challenging for the Program to develop. Although some aspects of these challenges may lie in the Program's ability to allocate the needed resources to these efforts, the committee encourages high-level administrative support by DOE to the Program to complement inroads already being made by the Program to engage more fully with the international methane hydrate research community.

[17] http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/Newsletter/HMNewsSpring08.pdf#page=6.

BOX 4.1
International Efforts in Methane Hydrate Research

Research in various nations:

Canada

- University-driven research since 1985 is focused mainly on the west coast and Arctic.
- "National" program through the Geological Survey of Canada since 2001 (Council of Canadian Academies, 2008).
- Since 1997, Mallik research site in the Mackenzie Delta—I, II, III and achievements in proof of concept for production. Mallik is considered the best-evaluated methane hydrate deposit in the world.

Chile

- The Foundation for Scientific Development and Technology in Chile funds a national gas hydrate program, Underwater Gas Hydrate: A New Source of Energy for the 21st Century, in existence since 2001.
- Pontifical Catholic University of Valparaíso, in collaboration with researchers from the United States, Europe, Japan, Germany, and Canada, conducts marine methane hydrate field surveys offshore Chile.

China

- Government establishes Guangzhou Center for Gas Hydrate Research in 2004.
- GMGS-1, the first gas hydrate drilling program, was completed in the South China Sea in 2007 for the Guangzhou Marine Geological Survey, the China Geological Survey, and the Ministry of Land and Resources of the People's Republic of China.
- GMGS-1 reveals thick sediment layers rich in gas hydrate just above the base of the methane hydrate stability zone at three of the eight sites drilled (see Figure 1.1 for drill-site location).

France

- Methane hydrate hazards are studied at Institut Français du Pétrole and work on methane hydrate engineering concerns are carried out at École Nationale Supérieure des Mines de St-Etienne.

Germany

- Government launches national program, Gas Hydrates in the Geosystem, in 2000.
- Germany participates in international expeditions to Hydrate Ridge, Gulf of Mexico, Black Sea, Congo Delta, and the Chilean Margin.
- The German Gas Hydrate Organisation is initiated in 2007 by government and research organizations, and includes several private-sector companies as members.
- The SUGAR (Submarine Gas Hydrate Reservoirs; http://www.ifm-geomar.de/index.php?id=3563&L=1) project was launched in 2008 and aims to produce natural gas from marine methane hydrate and to sequester carbon dioxide from power plants and other industrial sources as carbon dioxide hydrate in marine sediments.
- The international Methane on the Move program is coordinated in Germany and includes participation by various German research institutes and universities as well as by the United States (USGS), Norway (Geological Survey of Norway), and Australia (Commonwealth Scientific and Industrial Research Organisation)

India

- Directorate General of Hydrocarbons (DGH) coordinates the Indian National Gas Hydrate Program (NGHP), which is monitored by a Steering Committee chaired by the Secretary of Petroleum & Natural Gas.
- NGHP Expedition 01, April-August 2006, with the collaboration of the DGH, the USGS, and the Consortium for Scientific Methane Hydrate Investigations cored and drilled 39 holes at 21 sites, penetrated more than 9,250 meters of section, found methane hydrate in Krishna-Godavari, Mahanadi and Andaman basins, and recovered 2,850 meters of core for analysis by international experts. A second NGHP drilling expedition is proposed for 2009-2010 to drill and log the most promising sand-dominated methane hydrate prospects

Ireland

- Ireland has not formally quantified its offshore methane hydrate resource, but believes it to be of future significance. An informal assessment was performed in 2003.
- By 2013, Ireland plans to identify and quantify its hydrate resources. It also plans to increase international participation.

box continues

BOX 4.1 Continued

Japan

- Ministry of Economy, Trade, and Industry (METI: then Ministry of International Trade and Industry) establishes the Japan National Gas Hydrate Program in 1995, the first large-scale national gas hydrate program in the world.
- Japan Oil Gas & Metals National Corp. (JOGMEC) develops a highly integrated gas hydrate R&D program of basic research and field studies.
- Seismic surveys confirm extensive bottom seismic reflectors in the Nankai Trough.
- The first 5 years of the Japan National Gas Hydrate Program culminated in 1999/2000 with the drilling of closely spaced core and geophysical logging holes in the Nankai Trough.
- METI launches the Japan Methane Hydrate Exploitation Program in 2001 to evaluate the resource potential of deepwater methane hydrate in the Nankai Trough area. The program carried out multiwell drilling for 16 sites in 2004, cored and analyzed methane hydrate–bearing sands, and plans field testing for 2009 and development of commercial production technologies by 2016.
- JOGMEC plays a leadership role in all three phases of the Mallik research program in Canada's Mackenzie Delta.

Mexico

- Mexican deepwater east coast is geologically similar to the U.S. Gulf of Mexico, with natural oil seeps.
- A 2004 forum on methane hydrate was organized by various industry, government, and academic interests.

New Zealand

- The New Zealand Foundation of Science, Research, and Technology funded small methane hydrate research projects from 1997 to at least 2004.
- New Zealand (NZ) Gas Hydrates Steering Group is currently developing a strategy for the commercial development of NZ's gas hydrate resources, and aims to make the business and science case in 2009-2011 for an offshore gas hydrate technology demonstration site at a sweet spot off the eastern coast of the North Island.

Norway

- Gas hydrate hazard assessment, climate change implications, and CO_2 capture and sequestration are the key drivers for hydrate research led by industry, government agencies, and academia at the Universities of Bergen and Tromsø and the Geotechnical Institute in Oslo.
- Norway is collaborating with ConocoPhillips on CO_2-CH_4 exchange process and Alaska North Slope drilling.

Russia

- Russia claims that 5×10^9 m^3 (0.18 TCF) of gas have been produced from gas hydrate in the Messoyakha gas field since 1969 (see also discussion in Chapter 2).
- The Laboratory for Gas Hydrate Geology at VNIIOkeangeologiya in 1980 published worldwide gas hydrate estimates, consistent with other widely cited estimates.
- VNIIOkeangeologiya published field studies in the North Atlantic, Black Sea, Caspian Sea, and Okhotsk Sea off Sahkalin Island.

South Korea

- Ministry of Commerce, Industry and Energy supports a strong national gas hydrate program, which includes government research organizations and industry partners.
- Program aims to commercially produce gas from gas hydrate by 2015 and provide a 30-year supply of natural gas.
- Korean Gas Hydrate Research and Development project began in 2000 in the East Sea and Ulleung Basin; two phases are now complete with two more planned up to 2014.
- Project carries out first deep-drilling expedition in the Ulleung Basin in 2007.
- New drilling is planned for 2010.

Taiwan

- Since 2004, the Central Geological Survey has led ongoing gas hydrate research efforts and is working on the development of a national program.
- Government launched a 4-year program in 2007 to study offshore gas hydrate occurrences. That year, total estimated reserves of 600×10^9 m^3 of methane in methane hydrate were discovered off the coast of Taiwan.
- Mature Drilling Proposal was presented in 2008 to be forwarded to the Integrated Ocean Drilling Program (IODP).

box continues

BOX 4.1 Continued

United Kingdom

- Gas hydrates in nature are studied at the National Oceanographic Centre in Southampton and the University of Birmingham. Flow assurance problems are studied at Heriot-Watt University and the University of Coventry.
- The European Union–managed HYDRATECH project is established to develop techniques for the quantification of methane hydrate in European continental margins, with a focus on developing seismic techniques that can be used to identify and quantify methane hydrates along the Norwegian margin.

International Program

IODP is an international program that drills research boreholes on the seafloor. IODP is the continuation of the Deep Sea Drilling Project and Ocean Drilling Project. These projects have provided much of the ground-truth information on methane hydrate on the continental margins of the world, both through missions focused specifically at methane hydrate research and by providing a global database on marine sediments and their properties.

SOURCES: Max et al. (2006); Council of Canadian Academies (2008); http://www.marine.ie/NR/rdonlyres/FABFA12E-6338-42B4-BCA0-865170551F57/0/Oil_Gas.pdf.

EXTERNAL PROGRAM OVERSIGHT— THE METHANE HYDRATE ADVISORY COMMITTEE

The Methane Hydrate Advisory Committee (MHAC) was originally established by the Methane Hydrate Research and Development Act of 2000 to assist the Program with development of program priorities. The first MHAC interpreted its main role as a program advocate rather than a provider of scientific oversight (NRC, 2004). Based upon a recommendation from the NRC (2004) and reinforced by language in the reauthorization for the program in 2005 (Appendix A) the role of the MHAC was widened to include scientific oversight for the Program, including assessing progress toward program goals and evaluating program balance. The Program has sought and encouraged a more proactive and independent role for the MHAC to help guide the Program. The MHAC has several meetings a year, organized by the Program management, in which it is briefed on the progress of research projects and other aspects of the Program's activities. The current MHAC members interpret their primary role as one that provides advice to the Program regarding broad program goals over the longer term, rather than to provide detailed evaluations or advice on specific projects. As part of this broadly interpreted advisory role, members have reviewed the Interagency Roadmap for Methane Hydrate Research & Development[18] and in 2007, in accordance with Section 968 of the Energy Policy Act of 2005, submitted a report to Congress that assessed the Program and its 5-Year Research Plan.[19] The current MHAC is composed of 13 members representing academia, oceanographic institutions, state agencies, and industry.

CONCLUDING REMARKS

The Program strengthened its management in several areas during the past 5 years, particularly through initiation of its project peer review process, in balanced allocation of fairly modest resources to numerous research themes relevant to the Program's goals (e.g., Appendix E), through transparent and timely electronic communications, through enhanced support of young researchers, and in efforts to coordinate interagency research endeavors and increase its international project engagement. Although the Program does issue calls for proposals based on research themes identified as critical, the research breadth and depth supported by the Program depend upon the proposals it receives from academic, national laboratory, industry, and interagency research partners and grantees; the Program seems to manage the projects it supports effectively. Recently introduced improvements

[18] http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/pdf/InteragencyRoadmap.pdf.

[19] http://fossil.energy.gov/programs/oilgas/hydrates/MHAC-07-ReportToCongress-final.pdf.

in the proposal assessment and merit review process are the use of both internal and external reviewer panels. However, the procedures are not applied, especially with regard to external review of the major field activities, with as much frequency as might benefit the increasing sophistication and resource investment in these projects. The committee views as very positive the total number of degrees granted and the range of projects completed by students and postgraduates under the Program's auspices; these numbers indicate increasing interest in this growing research field.

The Program adds value from collaborations with other federal agencies on methane hydrate research, and is commended for leading interagency coordination. In addition to interagency work, the Program has expanded its level of activity in international programs with modest resources. These collaborations further national methane hydrate knowledge and provide access to crucial data and samples. A more deliberate approach that includes all levels of DOE management may be needed to better identify the basis for DOE's international participation, including specific objectives and benefits.

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CHAPTER 5

Conclusions and Recommendations

Since the last review of the Program, considerable progress has been made toward the understanding and development of methane hydrate as a possible future energy resource. The U.S. position as one of the leaders in this field can be attributed to the overall high caliber of the research, the breadth of investigations undertaken, the training of new, highly qualified personnel under the Program's auspices, and the successful collaboration between federal agencies conducting research on methane hydrate. Considerable progress has also been made in the overall management of the Program during the past 5 years, including enhanced interagency collaboration and specific efforts to include a peer review process in evaluation of supported research projects. The committee largely endorses the direction that the Program has established.

The accomplishments in the past 5 years of this Program, as well as of current programs in the national and international research community, provide increasing confidence from a technical standpoint that some commercial production of methane from methane hydrate in the United States could be achieved before 2025, contingent upon favorable regulatory conditions and market economics which the current study has not addressed in any detail. Although this production goal remains challenging, the committee believes it can be achieved through the provisions of the Program and the cooperation of the energy industry. The following recommendations aim to guide research priorities for the Program toward achieving an environmentally sound and efficient development pathway to recover methane from methane hydrate on a commercial scale. The mandated goals and levels of support that have been available for this Program may require that programmatic direction in the future be focused specifically on applied and theoretical efforts related to the production of methane from methane hydrate.

TOWARD PRODUCTION

Borehole research studies over the past several years have increased optimism that the long-term production of methane from methane hydrate can be technically achieved. In particular, methane gas flow by the simple depressurization technique has been demonstrated. However, the scale and duration of flow tests have been limited, uncertainty still exists in regard to identifying appropriate production technologies, and challenges remain in predicting the field-scale response.

Designing Future Production Tests

- **Well completions with appropriate production technologies should be developed and demonstrated in the field.**
- **Long-term production tests on methane hydrate are required in a variety of geologic settings,** beginning in the Arctic where technical issues may initially be less challenging than in marine settings. **Demonstrating potential commercial rates for production** is essential for future evaluation of production economics. Study of the factors that affect the production of gas and water should also be considered. These factors include, for example, the distribution of methane hydrate, its concentration, the physical properties of the host rock, sediment heterogeneity, and the influence of overlying and underlying sedimentary units.
- **Production tests should establish initial conditions, monitor changes during production, and determine formation response** after testing by using repeated geophysical surveys; *in situ* formation temperature, pressure, and geomechanical measurements; and

other techniques. The field production tests should also be closely integrated with reservoir modeling studies.

- Because of the complex nature and expense of carrying out a large field program, sound **research management practices should include a staged approach with open and comprehensive reviews of site survey data; completion, production, and monitoring design; risk assessments; and mitigation strategies.**

Research Directions

- **Research that couples carbon dioxide sequestration and the production of methane from methane hydrate should be encouraged.**
- **Increased effort should be devoted to the development of production technology.** These efforts may involve adapting conventional production equipment and procedures or the development of new technologies, such as pressure testing, specific to methane hydrate.

APPRAISAL AND MITIGATION OF ENVIRONMENTAL AND GEOHAZARD ISSUES RELATED TO PRODUCTION

The published literature on environmental and geohazard issues specific to the production of methane from methane hydrate and the response of methane hydrate associated with traditional oil and gas development (exploratory drilling, production, and infrastructure) is surprisingly limited. To date, most studies have only considered these issues as an ancillary focus. Increased emphasis should be placed on better defining what the geohazard issues are, predicting the environmental impacts, and constraining the conditions to be avoided during production.

- **Industry experience associated with conventional oil and gas production in areas of methane hydrate occurrences should be compiled and made available.**

- **Workshops should be organized to solicit input and identify research goals needed to evaluate and mitigate geohazards and environmental issues** specific to the production of methane from methane hydrate and to perturbations of methane hydrate associated with other oil and gas development activities.
- **Studies specifically addressing potential geohazards associated with methane production from methane hydrate** (e.g., laboratory measurements, modeling and natural perturbation experiments) should be stimulated. A goal is to provide more confidence in risk assessments and to engineer mitigation strategies.

QUANTIFICATION OF THE RESOURCE

The establishment of petroleum system models for methane hydrate occurrences has been significantly advanced in the past 5 years. However, substantial challenges remain to quantify the in-place hydrate characteristics and the associated sediment conditions that would be necessary for economic development of methane hydrate accumulations. Further research is required to improve the accuracy, resolution, and reliability of methane hydrate assessments, particularly for those assessments related to economic methane production.

- **Pilot seismic surveys using existing geophysical methods** (acoustic, electromagnetic, geothermal, etc.) **that are optimized to map and quantify in-place methane hydrate accumulations** should be undertaken. The goal is to provide a basis for appraisal of the use and limitations of data acquired by industry and for improvement on the design of future geophysical surveys (resolution) and associated data processing methods.
- **Understanding of *in situ* properties of sediments containing methane hydrate (pore physics models) needs to be improved** through comprehensive testing (geophysical, geochemical, microbiological, geomechanical) of undisturbed natural core (controlled pressure and temperature conditions) and synthetic samples. These

data, when integrated with well-log data, will establish a basis for calibration of the geophysical surveys.

- **Consideration should be given to the development of new geophysical imaging, processing, and quantification techniques,** particularly with respect to quantifying the in-place resource.

METHANE HYDRATE IN NATURE

Although understanding the role of methane hydrate as a source of a global greenhouse gas is of general interest, this research is not uniquely related to realizing methane hydrate as an energy resource. However, quantifying ongoing, natural methane fluxes from methane hydrate on a local scale is needed to provide a baseline to evaluate the effects of any future production and development.

- **Studies are required to address the processes involved (a) in the transmission of methane from the subsurface through the methane hydrate stability zone to the surface and (b) in the subsequent fate of the released methane. These studies should focus on degassing processes and potentially enhanced environmental impacts from commercial production of methane from methane hydrate and from methane hydrate associated with other oil and gas developments.**
- **Investigation of the role of methane hydrate in the global carbon cycle is best pursued in collaboration with other agencies.** Resolution of these questions is not central to the resource development goal.

PROGRAM MANAGEMENT

Participation in International Programs

Methane hydrate is a global field of research, and direct participation in field projects is vital to any program. Although the Program has had some level of activity in several international programs, the specific accomplishments, benefits to the Program, and the basis for participation are not always clear.

- **A strategic plan for international research partnerships,** including estimates of the necessary levels of scientific and financial engagement, should be developed in close collaboration with other U.S. agencies.
- To the degree required to establish international agreements, the **Department of Energy should provide high-level administrative support to the Program.**

Scientific and Expert Review Process of Major Field-Research Activities

The newly introduced peer review process is seen as a positive development of the Program. However, the procedures are not uniformly applied, especially to the major field activities where expert knowledge and close attention to the scientific goals will be required as the projects proceed and evolve. **A more comprehensive and frequent peer and expert review process of major field programs is recommended.**

Appendixes

APPENDIX A

Legislative Authorization Language H.R. 6 – Energy Policy Act of 2005 Section 968. Methane Hydrate Research

PUBLIC LAW 109-58

109th Congress
August 8, 2005
H.R. 6, Energy Policy Act of 2005.
42 USC 15801

SEC. 968. METHANE HYDRATE RESEARCH.

(a) IN GENERAL.—The Methane Hydrate Research and Development Act of 2000 (30 U.S.C. 1902 note; Public Law 106–193) is amended to read as follows:

"SECTION 1. SHORT TITLE.

"This Act may be cited as the 'Methane Hydrate Research and Development Act of 2000'.

"SEC. 2. FINDINGS.

"Congress finds that—

"(1) in order to promote energy independence and meet the increasing demand for energy, the United States will require a diversified portfolio of substantially increased quantities of electricity, natural gas, and transportation fuels;

"(2) according to the report submitted to Congress by the National Research Council entitled 'Charting the Future of Methane Hydrate Research in the United States', the total United States resources of gas hydrates have been estimated to be on the order of 200,000 trillion cubic feet;

"(3) according to the report of the National Commission on Energy Policy entitled 'Ending the Energy Stalemate—A Bipartisan Strategy to Meet America's Energy Challenge', and dated December 2004, the United States may be endowed with over one-fourth of the methane hydrate deposits in the world;

"(4) according to the Energy Information Administration, a shortfall in natural gas supply from conventional and unconventional sources is expected to occur in or about 2020; and

"(5) the National Academy of Sciences states that methane hydrate may have the potential to alleviate the projected shortfall in the natural gas supply.

"SEC. 3. DEFINITIONS.

"In this Act:

"(1) CONTRACT.—The term 'contract' means a procurement contract within the meaning of section 6303 of title 31, United States Code.

"(2) COOPERATIVE AGREEMENT.—The term 'cooperative agreement' means a cooperative agreement within the meaning of section 6305 of title 31, United States Code.

"(3) DIRECTOR.—The term 'Director' means the Director of the National Science Foundation.

"(4) GRANT.—The term 'grant' means a grant awarded under a grant agreement (within the meaning of section 6304 of title 31, United States Code).

"(5) INDUSTRIAL ENTERPRISE.—The term 'industrial enterprise' means a private, nongovernmental enterprise that has an expertise or capability that relates to methane hydrate research and development.

"(6) INSTITUTION OF HIGHER EDUCATION.—The term 'institution of higher education' means an institution of higher education (as defined in section 102 of the Higher Education Act of 1965 (20 U.S.C. 1002)).

"(7) SECRETARY.—The term 'Secretary' means the Secretary of Energy, acting through the Assistant Secretary for Fossil Energy.

"(8) SECRETARY OF COMMERCE.—The term 'Secretary of Commerce' means the Secretary of Commerce, acting through the Administrator of the National Oceanic and Atmospheric Administration.

"(9) SECRETARY OF DEFENSE.—The term 'Secretary of Defense' means the Secretary of Defense, acting through the Secretary of the Navy.

"(10) SECRETARY OF THE INTERIOR.—The term 'Secretary of the Interior' means the Secretary of the Interior, acting through the Director of the United States Geological Survey, the Director of the Bureau of Land Management, and the Director of the Minerals Management Service.

"SEC. 4. METHANE HYDRATE RESEARCH AND DEVELOPMENT PROGRAM.

"(a) IN GENERAL.—

"(1) COMMENCEMENT OF PROGRAM.—Not later than 90 days after the date of enactment of the Energy Research, Development, Demonstration, and Commercial Application Act of 2005, the Secretary, in consultation with the Secretary of Commerce, the Secretary of Defense, the Secretary of the Interior, and the Director, shall commence a program of methane hydrate research and development in accordance with this section.

"(2) DESIGNATIONS.—The Secretary, the Secretary of Commerce, the Secretary of Defense, the Secretary of the Interior, and the Director shall designate individuals to carry out this section.

"(3) COORDINATION.—The individual designated by the Secretary shall coordinate all activities within the Department of Energy relating to methane hydrate research and development.

"(4) MEETINGS.—The individuals designated under paragraph (2) shall meet not later than 180 days after the date of enactment of the Energy Research, Development, Demonstration, and Commercial Application Act of 2005 and not less frequently than every 180 days thereafter to—

"(A) review the progress of the program under paragraph (1); and

"(B) coordinate interagency research and partnership efforts in carrying out the program.

"(b) GRANTS, CONTRACTS, COOPERATIVE AGREEMENTS, INTERAGENCY FUNDS TRANSFER AGREEMENTS, AND FIELD WORK PROPOSALS.—

"(1) ASSISTANCE AND COORDINATION.—In carrying out the program of methane hydrate research and development authorized by this section, the Secretary may award grants to, or enter into contracts or cooperative agreements with, institutions of higher education, oceanographic institutions, and industrial enterprises to—

"(A) conduct basic and applied research to identify, explore, assess, and develop methane hydrate as a commercially viable source of energy;

"(B) identify methane hydrate resources through remote sensing;

"(C) acquire and reprocess seismic data suitable for characterizing methane hydrate accumulations;

"(D) assist in developing technologies required for efficient and environmentally sound development of methane hydrate resources;

"(E) promote education and training in methane hydrate resource research and resource development through fellowships or other means for graduate education and training;

"(F) conduct basic and applied research to assess and mitigate the environmental impact of hydrate degassing (including both natural degassing and degassing associated with commercial development);

"(G) develop technologies to reduce the risks of drilling through methane hydrates; and

"(H) conduct exploratory drilling, well testing, and production testing operations on permafrost and nonpermafrost gas hydrates in support of the activities authorized by this paragraph, including drilling of one or more full-scale production test wells.

"(2) COMPETITIVE PEER REVIEW.—Funds made available under paragraph (1) shall be made available based on a competitive process using external scientific peer review of proposed research.

"(c) METHANE HYDRATES ADVISORY PANEL.—

"(1) IN GENERAL.—The Secretary shall establish an advisory panel (including the hiring of appropriate staff) consisting of representatives of industrial enterprises, institutions of higher education, oceanographic institutions, State agencies, and environmental organizations with knowledge and expertise in the natural gas hydrates field, to—

"(A) assist in developing recommendations and broad programmatic priorities for the methane hydrate research and development program carried out under subsection (a)(1);

"(B) provide scientific oversight for the methane hydrates program, including assessing progress toward program goals, evaluating program balance, and providing recommendations to enhance the quality of the program over time; and

"(C) not later than 2 years after the date of enactment of the Energy Research, Development, Demonstration, and Commercial Application Act of 2005, and at such later dates as the panel considers advisable, submit to Congress—

"(i) an assessment of the methane hydrate research program; and

"(ii) an assessment of the 5-year research plan of the Department of Energy.

"(2) CONFLICTS OF INTEREST.—In appointing each member of the advisory panel established under paragraph (1), the Secretary shall ensure, to the maximum extent practicable, that the appointment of the member does not pose a conflict of interest with respect to the duties of the member under this Act.

"(3) MEETINGS.—The advisory panel shall—

"(A) hold the initial meeting of the advisory panel not later than 180 days after the date of establishment of the advisory panel; and

"(B) meet biennially thereafter.

"(4) COORDINATION.—The advisory panel shall coordinate activities of the advisory panel with program managers of the Department of Energy at appropriate National Laboratories.

"(d) CONSTRUCTION COSTS.—None of the funds made available to carry out this section may be used for the construction of a new building or the acquisition, expansion, remodeling, or alteration of an existing building (including site grading and improvement and architect fees).

"(e) RESPONSIBILITIES OF THE SECRETARY.—In carrying out subsection (b)(1), the Secretary shall—

"(1) facilitate and develop partnerships among government, industrial enterprises, and institutions of higher education to research, identify, assess, and explore methane hydrate resources;

"(2) undertake programs to develop basic information necessary for promoting long-term interest in methane hydrate resources as an energy source;

"(3) ensure that the data and information developed through the program are accessible and widely disseminated as needed and appropriate;

"(4) promote cooperation among agencies that are developing technologies that may hold promise for methane hydrate resource development;

"(5) report annually to Congress on the results of actions taken to carry out this Act; and

"(6) ensure, to the maximum extent practicable, greater participation by the Department of Energy in international cooperative efforts.

"SEC. 5. NATIONAL RESEARCH COUNCIL STUDY.

"(a) AGREEMENT FOR STUDY.—The Secretary shall offer to enter into an agreement with the National Research Council under which the National Research Council shall—

"(1) conduct a study of the progress made under the methane hydrate research and development program implemented under this Act; and

"(2) make recommendations for future methane hydrate research and development needs.

"(b) REPORT.—Not later than September 30, 2009, the Secretary shall submit to Congress a report containing the findings and recommendations of the National Research Council under this section.

"SEC. 6. REPORTS AND STUDIES FOR CONGRESS.

"The Secretary shall provide to the Committee on Science of the House of Representatives and the Committee on Energy and Natural Resources of the Senate copies of any report or study that the Department of Energy prepares at the direction of any committee of Congress relating to the methane hydrate research and development program implemented under this Act.

"SEC. 7. AUTHORIZATION OF APPROPRIATIONS.

"There are authorized to be appropriated to the Secretary to carry out this Act, to remain available until expended—

"(1) $15,000,000 for fiscal year 2006;

"(2) $20,000,000 for fiscal year 2007;

"(3) $30,000,000 for fiscal year 2008;

"(4) $40,000,000 for fiscal year 2009; and

"(5) $50,000,000 for fiscal year 2010.".

(b) RECLASSIFICATION.—The Law Revision Counsel shall reclassify the Methane Hydrate Research and Development Act of 2000 (30 U.S.C. 1902 note; Public Law 106–193) to a new chapter at the end of title 30, United States Code.

APPENDIX B

Committee and Staff Biographical Sketches

Charles K. Paull, *chair*, is a senior scientist and chair of the Research and Development Division at the Monterey Bay Aquarium Research Institute (MBARI) in Moss Landing, California. Dr. Paull also has a courtesy appointment as an adjunct professor at Stanford University. Prior to his work at the MBARI, he served as the Amos L. Hawley Distinguished Professor in the Department of Geology at the University of North Carolina, Chapel Hill. Dr. Paull's research interests include the frequency, distribution, and environmental significance of continental margin pore-water seeps; the establishment of *in situ* characteristics of marine gas hydrates, and the understanding of the diverse processes that initially form and subsequently erode continental margins. He is a member of the American Association of Petroleum Geologists, the American Geophysical Union, and the Society of Economic Paleontologists and Mineralogists. Dr. Paull received his B.A. (Honors) in geology from Harvard University, his M.S. in marine geology and geophysics from the University of Miami, and his Ph.D. in oceanography from the Scripps Institution of Oceanography.

Scott R. Dallimore has served as a research scientist with the Geological Survey of Canada for the past 23 years. His research interests include gas hydrate production and consideration of the climate change implications of natural methane release from warming gas hydrates. Mr. Dallimore has acted as a chief scientist for three multidisciplinary international gas hydrate production research programs at the Mallik site in Canada's Mackenzie Delta. Field programs in 2002 and 2007-2008 included the first full-scale gas hydrate production test studies using the thermal and pressure drawdown stimulation methods. He has contributed significantly to the development of an integrated national gas hydrate research program within Natural Resources Canada and regional gas hydrate studies in the circumpolar Arctic. He earned his M.A.(Sc.) in geotechnical science from Carleton University.

Gonzalo (Gonz) Enciso has a wide range of international and domestic experience as an exploration geologist in the oil and gas industry. He is presently an independent oil and gas consultant, having recently retired from Shell Exploration and Production Company. He spent the first 17 years of his career with Shell working in various roles domestically and internationally. Thereafter, he joined Seagull Energy as director of new ventures in 1998. Following the merger between Seagull and Ocean Energy, he was named vice president of evaluation and chief geologist. When Ocean Energy merged with Devon Energy in 2003, Mr. Enciso was named chief geologist for the corporation, and contributed significantly to their prospect consistency effort. He then joined Spinnaker Exploration as vice president and chief geoscientist with the responsibility to establish a regional geologic perspective and to oversee project evaluation and risking. Following the merger with Norsk Hydro, he continued as an executive of the newly formed Hydro Gulf of Mexico L.L.C. as vice president of exploration portfolio and chief geoscientist. Mr. Enciso then served as a senior associate for Rose & Associates, teaching risk analysis for exploration to oil and gas companies around the world before returning to Shell as a geologic advisor. His expertise includes project risk evaluation, deepwater depositional systems, and seismic stratigraphy, and he applies this knowledge in mentoring roles. Mr. Enciso, who is fluent in Spanish, has presented a number of papers on deepwater sedimentation topics and risk analysis in national and international conferences. He is past chairman of the Diversity Membership Subcommittee of the American Association of Petroleum Geologist and past member of the Board of Advisors for the Energy Geological Institute. Mr. Enciso earned both his B.S. and M.S. degrees in geology from the University of Kansas.

Sidney Green (NAE) is one of the founders and is retired president-chairman-chief executive officer of TerraTek in Salt Lake City, Utah, a geomechanics engineering firm. TerraTek was acquired by Schlumberger, the largest worldwide oil services firm, in 2006, and Mr. Green has been manager of Geomechanics Business Development for the Schlumberger Data and Consulting Services group. Mr. Green has additionally accepted a position of research professor at the University of Utah, where he holds a dual appointment in mechanical engineering and civil and environmental engineering. He has worked in the area of geomechanics for the past 4 decades, and has published numerous papers and reports, holds a number of patents, has given many presentations on geomechanics, and has received a number of rock mechanics/geomechanics recognitions. He is the past chairman of the National Academy of Sciences U.S. National Committee on Rock Mechanics and has recently served on the National Research Council Committee on Destruction of Non-Stockpile Chemical Weapons. Mr. Green has a B.S. from the University of Missouri at Rolla and an M.S. from the University of Pittsburgh, both in mechanical engineering. He attended the University of Pennsylvania, and he received the degree of Engineer from Stanford University in engineering mechanics in 1964.

Carolyn A. Koh is an associate professor in the Chemical Engineering Department at the Colorado School of Mines (CSM) and codirector of the CSM Center for Hydrate Research. Prior to CSM, Dr. Koh was a reader on the chemistry faculty of King's College, London University. Her research focuses on applying a combination of spectroscopic, diffraction, and macroscopic tools, coupled with computer simulations to advance our understanding of the structure and mechanisms of hydrate crystal growth and decomposition. Dr. Koh is a Fellow of the Royal Society of Chemistry and received the Young Scientist Award of the British Association for Crystal Growth in 2001. She received her B.Sc. (Honors) in chemistry and her Ph.D. in surface chemistry and catalysis from the University of West London. Dr. Koh also completed postdoctoral research training in the Department of Chemical Engineering at Cornell University. She has been a visiting professor at Cornell University, Penn State, and London University.

APPENDIX B

Keith A. Kvenvolden is retired from his position as senior scientist after 28 years at the U.S. Geological Survey's Branch of Pacific Marine Geology in Menlo Park, California. Specializing in organic geochemistry, Dr. Kvenvolden studies natural and human-introduced hydrocarbons in the marine environment, including crude oil, hydrocarbon gases, and gas hydrates, and has published more than 300 papers on environmental geochemistry, petroleum (crude oil and natural gas) geochemistry, geochemistry of gas hydrates, geochemistry of recent and ancient sediments, organic cosmochemistry, and biochemical geochronology. He has received international honors and recognition for his investigations of organic geochemistry in settings including seafloor-spreading zones, continental shelves, beaches, and meteorites. An elected fellow of the Geological Society of America, the American Association for the Advancement of Science, the American Geophysical Union, the Explorers' Club, the Geochemical Society, and the European Association for Geochemistry, he is a member of a number of professional societies and has served as editor for several professional journals. He previously served on the National Research Council's Committee on Oil in the Sea. He received his M.S. in geophysical engineering from the Colorado School of Mines and his Ph.D. in geology from Stanford University.

Charles A. Mankin retired at the end of October 2007 from the University of Oklahoma, concluding 48 years of service to the university. During his tenure, he served as director of the Oklahoma Geological Survey, director of the School of Geology and Geophysics, a regents professor at the University of Oklahoma, executive director of the Energy Resources Institute, and director of Sarkeys Energy Center. With basic research and practical industry experience in all fields of geoscience, geophysics, and geology, Dr. Mankin has served on and/or chaired more than 100 boards, committees, and study panels of agencies of the federal executive branch, academic and professional organizations, including the National Petroleum Council and committees of the National Academy of Sciences. He is a member of and/or has served as an officer or board trustee on local and national earth-science organizations including the Association of American State

Geologists, the American Geological Institute, the American Institute of Professional Geologists, the Geological Society of America, the National Institute for Global Environmental Change, and the American Association of Petroleum Geologists. Many of these associations have recognized Dr. Mankin's career contributions through a variety of public service, education, and life membership awards. He received his B.S., M.S., and Ph.D. degrees from the University of Texas at Austin.

William S. Reeburgh is professor emeritus of marine and terrestrial biogeochemistry at the University of California, Irvine (UCI). He joined UCI in 1993 and retired in 2009. Prior to UCI, he was professor of marine science at the University of Alaska, Fairbanks for 25 years. His research interests include methane biogeochemistry, particularly microbially mediated methane oxidation as a flux control and globally important sink in marine and wetland systems; the rate and global extent of anaerobic oxidation of methane; and the role of microbial processes as controls and feedbacks in global climate change. Dr. Reeburgh is a member of a number of professional societies and journal editorial boards, and has served on several national and international committees, including the International Geosphere Biosphere Program, Coordinating Panel on Terrestrial Biosphere-Atmospheric Chemistry Interactions, International Global Atmospheric Chemistry Program, and the U.S. Geological Survey Global Change Research Program. He edited the journal *Global Biogeochemical Cycles* from 1998 to 2004 and was elected fellow of the American Geophysical Union and the American Academy of Microbiology. He received his B.S. degree in chemistry from the University of Oklahoma, and his M.A. and Ph.D. degrees in oceanography from Johns Hopkins University.

Michael Riedel is a research scientist at the Geological Survey of Canada. Prior to joining the Geological Survey in 2009, he was an associate professor at the Department of Earth and Planetary Sciences, McGill University, Montreal, Canada. Dr. Riedel's research interests are in marine geology and geophysics with a specialty in gas hydrates. He has been involved in many marine and terrestrial gas hydrate projects over the past years and has sailed onboard the drilling vessel *JOIDES* (Joint Oceanographic Institutions Deep Earth Sampler) *Resolution* as co-chief scientist for the Integrated Ocean Drilling Program Expedition 311 and the India National Gas Hydrate Program Expedition 01. Dr. Riedel was a member of the expert panel for the Assessment of Gas Hydrates as an Energy Resource, conducted by the Council of Canadian Academies on behalf of Natural Resources Canada. Dr. Riedel received his Ph.D. in geophysics from the University of Victoria in 2001 and his Diplom (M.Sc. equivalent) in geophysics from the Christian Albrechts University in Kiel, Germany, in 1998.

NRC Staff

Elizabeth A. Eide, a senior program officer with the Board on Earth Sciences and Resources, is a geologist with specialization in geochronology applied to crustal processes. Prior to joining the National Research Council, she was a research scientist and team leader at the Geological Survey of Norway for 12 years where she built and managed the Survey's $^{40}Ar/^{39}Ar$ geochronology laboratory. She completed a Ph.D. in geology at Stanford University and a B.A. in geology from Franklin and Marshall College.

Courtney R. Gibbs is a program associate with the Board on Earth Sciences and Resources (BESR). She received her degree in Graphic Design from the Pittsburgh Technical Institute in 2000 and began working for the National Academies in 2004. Prior to her work with BESR, Ms. Gibbs supported the Nuclear and Radiation Studies Board and the former Board on Radiation Effects Research.

Deborah Glickson received her Ph.D. in oceanography from the University of Washington in 2007. She joined the Ocean Studies Board as an associate program officer in 2008, and is involved with studies of future ocean research and technology needs. Her doctoral research focused on magmatic and tectonic contributions to mid-ocean ridge evolution and hydrothermal activity. In 2008, she participated in the Dean John A. Knauss Marine Policy Fellowship and worked on coastal and ocean policy and legislation in the U.S. Senate. Prior to her Ph.D. work, she received an M.S. in geology from Vanderbilt University in 1999 and was a research associate in physical oceanography at Woods Hole Oceanographic Institution.

Nicholas D. Rogers is a financial and research associate with the Board on Earth Sciences and Resources at The National Academies. He received a B.A. in history, with a focus on the history of science and early American history, from Western Connecticut State University in 2004. Mr. Rogers began working for the National Academies in 2006 and has primarily supported the Board on Earth Sciences and Resources on earth resource issues and the board's interdisciplinary projects.

APPENDIX C

Presentations to the Committee

Meeting One—Washington, D.C.

Edith Allison, Department of Energy, *Methane hydrates program at DOE: Program overview and study relevance*

Ray Boswell, Department of Energy, *Review of methane hydrate resource: Volume estimation*

Meeting Two—Golden, Colorado

Timothy Collett, U.S. Geological Survey, *Assessment of Gas Hydrate Resources on the North Slope, Alaska, 2008*

Brenda Pierce, U.S. Geological Survey, *USGS Natural Gas Hydrates Activities*

Matt Frye, Minerals Management Service, *Minerals Management Service Gas Hydrate Resource Evaluation U.S. Outer Continental Shelf*

Dendy Sloan, Colorado School of Mines, *Methane Hydrate Advisory Committee Report to National Research Council Hydrate Committee Review*

Robert Hunter and Scott Wilson, BP/Ryder Scott Co., *Gas Hydrate Research, Stratigraphic Test, and Production Test Plans Alaska North Slope*

Carlos Santamarina, Georgia Institute of Technology, *Hydrate-Bearing Sediments: Physical Properties—Production*

Meeting Three—Washington, D.C.

Emrys Jones, Chevron Corporation, *Chevron/DOE Joint Industry Project for Methane Hydrates in the Gulf of Mexico*

Debbie Hutchinson, U.S. Geological Survey, *USGS Studies and the Gulf of Mexico Gas Hydrates JIP*

Carolyn Ruppel, U.S. Geological Survey, *Prospecting for Hydrates—Evolution of Detection and Evaluation Approaches*

Kenji Ohno, Japan Oil, Gas and Metals National Corporation, *Japan's National Methane Hydrate R&D Program—Overview and Status*

Yoshihiro Masuda, University of Tokyo, *Development of Hydrate Reservoir Simulator (MH21-HYDRES) in Japan's National Methane Hydrate R&D Program*

Helen Farrell and James Howard, ConocoPhillips, *Experimental Basis* CO_2-CH_4 *Exchange for Production from Hydrate Reservoirs: Field-Test Plans*

Ian McDonald, Texas A&M University, Corpus Christi, *Remote Sensing Detection of Active Hydrocarbon Seeps: Implications for Methane in the Sea*

Tim Kneafsey, Lawrence Berkeley National Laboratory, *Hydrologic, Geomechanical, and Geophysical Measurements on Laboratory-Formed Hydrate-Bearing Samples*

APPENDIX D

Comparison of Units of Measurement of Amounts of Methane by Volume and Weight

Amounts of methane can be reported either by volume or by weight. In the petroleum industry, amounts are given by volume, commonly as trillions (10^{12}) of cubic feet (ft^3) or TCF and billions (10^9) of ft^3 (BCF) in the United States. Elsewhere in the world, where the metric system is used, the amounts are usually reported in cubic meters (m^3). A convenient conversion factor is 35.3 ft^3/m^3.

In the oceanographic and atmospheric communities, amounts of methane are often reported by weight, that is, grams (g) or metric tons (10^6 g) usually with an appropriate prefix to simplify the use of exponents. Common expressions are teragrams (Tg = 10^{12} g), petagrams (Pg = 10^{15} g), and gigatons (Gt = $10^9 \times 10^6$ or 10^{15}). The conversions from volume to weight or from weight to volume of methane are based on the relationship that a mol of methane, weighing 16 g, has a volume of 22.4 liters at standard temperature and pressure (STP). Useful conversion factors are 714 g/m^3 and 20.2 g/ft^3.

The following table compares amounts of methane in units of TCF, m^3, and Pg in three categories: (1) assessments of amounts of conventional natural gas (methane); (2) estimates of the amounts of methane in methane hydrate; and (3) amounts of methane in the atmosphere.

TABLE D.1 Comparison of Methane Measurements

	TCF	By Volume, m^3	By Weight, Pg
Conventional natural gas (Methane)[a]			
Global assessment of conventional methane in reserves and technically recoverable resources	16,000	4.4×10^{14}	3.2×10^{2}
U.S. methane consumption in 2008	23	6.5×10^{11}	4.7×10^{-1}
Methane in methane hydrate[b]			
Very early global estimates, based on many erroneous assumptions, of the methane content of gas hydrate	~35,000,000	$\sim 10^{18}$	$\sim 7.1 \times 10^{5}$
Recent range of global estimates of methane in methane hydrate	35,000 to 177,000	1×10^{15} to 5×10^{15}	7.1×10^{2} to 3.6×10^{3}
Mean MMS estimate of methane in hydrate in the Gulf of Mexico	21,000	6×10^{14}	4.3×10^{2}
Mean U.S. Geological Survey estimate of technically recoverable methane from hydrate on the North Slope of Alaska	85.4	2.4×10^{12}	1.7
Estimate of methane in hydrate, eastern Nankai Trough, Japan	40	1.14×10^{12}	8.1×10^{-1}
Atmospheric methane[c]			
Atmospheric abundance of methane	~250	$\sim 7 \times 10^{12}$	~5
Estimate of total global flux of methane from all sources entering the atmosphere per year	30	8.4×10^{11}	0.6
Estimate of total global sink for all methane entering the atmosphere per year	29	8.1×10^{11}	0.58

[a] See Chapter 1.

[b] See Chapter 2.

[c] For discussion, see Kvenvolden, K. A. and B. W. Rogers. 2005. Gaia's breath—global methane exhalations. *Marine and Petroleum Geology* 22:579-590.

APPENDIX E

Program Authorizations and Appropriations FY 2000–2010

TABLE E.1 Comparison of Legislative Authorization to Final Appropriation for the Department of Energy (DOE) Methane Hydrate Research and Development Program, Fiscal Years 2000-2010

Fiscal Year	Appropriation (millions of U.S. dollars)	Authorization in Energy Policy Act of 2005 (millions of U.S. dollars)
2000	2.9	
2001	9.9	5
2002	9.8	7.5
2003	9.4	11
2004	9.4	12
2005	9.4	12
2006	11.8	15
2007	11.8	20
2008	14.8	30
2009	15.0	40
2010	15.0[a]	50

[a]E. Allison, personal communication, January 18, 2010.

SOURCE: Allison, E. 2008. Department of Energy Methane Hydrate Program. Presentation to the Committee on Assessment of the Department of Energy's Methane Hydrate Research and Development Program: Evaluating Methane Hydrates as a Future Energy Resource, Washington, DC, September 11.

APPENDIX F

Project Summary Table

APPENDIX F

Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
Field studies: Production and drilling projects (Identifers 1 through 4)	1	Gas Hydrate Production Trial	DE-NT0006553	**ConocoPhillips Company**	
	2	Alaska North Slope Gas Hydrate Reservoir Characterization	DE-FC26-01NT41332	**BP Exploration Alaska, Inc.** + 15 other performers	
	3	Phase 2—Drilling and Production Testing the Methane Hydrate Resource Potential Associated with the Barrow Gas Fields	DE-FC26-06NT42962	**North Slope Borough**	
	4	Gulf of Mexico Gas Hydrates Joint Industry Project (JIP) Characterizing Natural Gas Hydrates in the Deep Water Gulf of Mexico—Applications for Safe Exploration	DE-FC26-01NT41330	**Chevron Energy Technology Company** + 16 other performers	

Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
10/1/2008 12/31/2010	$11,755,000	$2,934,140	$14,689,140	20	$1,510,000
9/30/2001 3/31/2011	$20,235,336	$6,034,348	$26,269,684	23	$9,819416
10/1/2008 11/30/2009	$1,490,722	$372,680	$1,863,402	20	$1,490,722
9/30/2001 9/30/2010	$40,215,883	$14,752,993	$54,968,876	23	$31,751,045

APPENDIX F

Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
Resource characteriz-ation and remote sensing (Identifiers 5 through 10, with addition of multi-purpose study 21)	5	Gas Hydrate Characterization in the Gulf of Mexico	DE-NT0005668	**University of California at San Diego (Scripps Institution of Oceanography)**	
	6	Heat Flow and Gas Hydrates on the Continental Margin of India	DE-NT0005669	**Oregon State University, College of Oceanic and Atmospheric Science**	
	7	Electrical Resistivity Investigation of Gas Hydrate Distribution in Mississippi Canyon Block 118, Gulf of Mexico	DE-FC26-06NT42959	**Baylor University**	
	8	Seismic Gas Hydrate Quantification by Cumulative Attributes (CATTs)	DE-FC26-06NT42961	**Rock Solid Images**	
	9	Gas Hydrate Research in Deep Sea Sediments - Bottom Source Task	DE-AI26-06NT42878 - Bottom Source Task	**Naval Research Laboratory**	
	10	Combining Multicomponent Seismic Attributes, New Rock Physics Models, and *In Situ* Data to Estimate Gas-Hydrate Concentrations in Deep-Water, Near-Floor Strata of the Gulf of Mexico	DE-FC26-06NT42667	**University of Texas at Austin Bureau of Economic Geology**	

	Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
	10/1/2008 3/31/2012	$861,678	$686,492	$1,548,170	44	$767,869
	10/1/2008 12/31/2010	$149,604	$39,142	$188,746	21	$149,604
	10/1/2006 12/31/2011	$253,849	$68,885	$322,734	21	$253,849
	10/1/2006 10/30/2009	$648,122	$215,430	$863,552	25	$648,122
	6/1/2006 6/30/2010	$150,000	$46,000	$196,000	23	$150,000
	3/1/2006 4/30/2009	$824,338	$215,775	$1,040,113	21	$824,338

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Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
Environmental studies (Identifiers 11 through 19; 4; and completed projects 24-27)	11	Assessing the Efficacy of the Aerobic Methanotropic Biofilter in Methane Hydrate Environments	DE-NT0005667	**University of California at Santa Barbara**	
	12	Remote Sensing and Sea Truth Measurements of Methane Flux to the Atmosphere (HYFLUX Project)	DE-NT0005638	**Texas A&M University at Corpus Christi**	
	13	Characterization of Methane Degradation and Methane-Degrading Microbes in Alaska Coastal Waters	DE-NT0005665	**University of Delaware, College of Marine and Earth Studies**	
	14	Source Characterization and Temporal Variation of Methane Seepage from Thermokarst Lakes on the Alaska North Slope in Response to Arctic Climate Change	DE-NT0005665	**Institute of Northern Engineering, University of Alaska at Fairbanks;** USGS	
	15	Interrelation of Global Climate and the Response of Oceanic Hydrate Accumulations	ESD07-014/08FE-003	**Lawrence Berkeley National Laboratory, Los Alamos National Laboratory**	
	16	Integrating Natural Gas Hydrate in the Global Carbon Cycle	DE-NT0006558	**University of Chicago,** University of California at Berkeley	

	Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
	10/1/2008 9/30/2011	$612,658	$159,972	$772,630	21	$438,995
	10/1/2008 9/30/2010	$1,044,211	$348,614	$1,392,825	25	$1,044,211
	10/1/2008 12/31/2010	$272,293	$85,384	$357,677	24	$272,293
	10/1/2008 9/30/2011	$831,277	$296,839	$1,128,116	26	$733,014
	6/1/2008 5/30/2012	$1,244,900	$0	$1,244,900	0	$894,900
	10/1/2008 9/30/2011	$640,274	$156,397	$796,671	20	$402,350

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Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
	17	Methanogenesis in Hydrate-Bearing Sediments: Integration of Experimental and Theoretical Approaches[a]	FLU5A425	**Idaho National Laboratory,** Oregon State University	
	18	Gulf of Mexico Gas Hydrates Seafloor Observatory Project	DE-FC26-06NT42877 DE-FC26-02NT41628 DE-FC26-00NT40920	**University of Mississippi Center for Marine Resources and Environmental Technology (CMRET)** +4 other performers	
Multi-purpose studies (19-20)	19	Detection and Production of Methane Hydrate	DE-FC26-06NT42960	**Rice University**	
	20	Conducting Scientific Studies of Natural Gas Hydrates to Support the DOE Efforts to Evaluate and Understand Methane Hydrate	DE-AI26-05NT42496	**U.S. Geological Survey**	
Completed field ol study	21	Phase 1—Characterization and Quantification of the Methane Hydrate Resource Potential Associated with the Barrow Gas Fields	DE-FC26-06NT42962	**North Slope Borough,** Arctic Slope Consulting Group, Petrotechnical Resources of Alaska, University of Alaska at Fairbanks	

Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
9/30/2005 9/30/2010	$940,000	$0	$640,000	0	940,000
9/29/2000 7/30/2009	$6,562,830	$1,1,817,703	$8,380,533	22	$6,562,830
10/1/2006 7/16/2011	$1,270,153	$448,099	$1,718,252	26	$1,010,818
4/11/2005 5/31/2010	$2,252,165	$7,962,000[a]	$10,214,165	78	$2,252,165
10/16/2006 3/27/2008	$609,858	$152,465	$762,323	20	$609,858

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Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
Completed production-related and drilling project	22	Methane Hydrate Production from Alaskan Permafrost	DE-FC26-01NT41331	**Anadarko Petroleum Corporation,** + 8 Other performers	
Completed production-related and drilling project	23	*In Situ* Sampling and Characterization of Methane Hydrate	DE-FC26-01NT41329	**Joint Oceanographic Institutions (JOI)**	
Completed environmental study	24	Geochemical Evaluation of Deep Sediment Hydrate Deposits in Alaminos Canyon, Block 818, Texas-Louisiana Shelf	DE-AI26-06NT42878 - Alaminos Canyon Task	**Naval Research Laboratory**	
Completed environmental study	25	Gas Hydrate Research in Deep Sea Sediments—New Zealand Task	DE-AI26-06NT42878 - New Zealand Task	**Naval Research Laboratory**	
Completed environmental study	26	Gas Hydrate Instability in the Southeastern Bering Sea	DE-FC26-05NT42665	**Woods Hole Oceanographic Institute**	
Completed environmental study	27	Support of Gulf of Mexico Hydrate Research Consortium	DE-FC26-02NT41328	**University of California at San Diego (Scripps Institution of Oceanography);** Texas A&M University	
Completed production-related and drilling project	28	The Mallik 2002 Consortium: Drilling and Testing a Gas Hydrate Well	DE-AC26-01NT41007	**Geological Survey of Canada**	

	Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
	9/30/2001 1/31/2005	$7,710,846	$7,018,815	$14,729,661	48	$7,710,846
	9/30/2001 10/31/2006	$1,610,293	$523,214	$2,133,507	25	$1,641,618
	7/1/2007 5/1/2008	$300,000	$330,000	$630,000	52	$300,000
	6/1/2006 11/1/2006	$86,000	$738,000	$824,000	90	$86,000
	10/1/2005 11/30/2007	$233,444	$58,504	$291,948	20	$233,444
	3/4/2002 3/3/2006	$348,041	$93,076	$441,117	21	$348,041
	9/2/1997 8/31/2005	$339,000	$910,486	$1,249,486	73	$339,000

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Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
Completed resource characterization and remote sensing	29	Sampling and Monitoring of Hydrate Mounds in the Gulf of Mexico	DE-AF26-01NT00394	**Texas A&M University at Corpus Christi;** Harbor Branch Oceanographic Institution; University of Nebraska	
Completed resource characterization and remote sensing	30	High Resolution Processing of Seismic Data from GB 424 and 425 and MC 852 and 853, Gulf of Mexico	DE-AF26-01NT00370	**Western Geco**	
Completed resource characterization and remote sensing	31	Three-Dimensional Structure and Physical Properties of Methane Hydrate Deposit at Blake Ridge	DE-FC26-00NT40921	**University of Wyoming**	
Completed resource characterization and remote sensing	32	Characterizing Marine Gas Hydrate Reservoirs Using 3D Seismic Data	DE-FC26-00NT41024	**University of Texas at Austin; Bureau of Economic Geology**	
Completed production-related and drilling projects	33	Characterizing Arctic Hydrates (Canadian Test Well and Alaskan "Wells of Opportunity")	DE-AT26-97FT34342	**U.S. Geological Survey**	
Completed resource characterization and remote sensing	34	Gathering, Processing, and Evaluating Seismic and Physical Data on Gas Hydrates in the Gulf of Mexico	DE-AT26-97FT34343	**U.S. Geological Survey**	

	Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
	5/1/2001 9/30/2002	$94,000	$19,878	$113,878	18	$94,000
	4/7/2001 7/30/2001	$32,000	$0	$32,000	0	$32,000
	9/28/2000 9/30/2005	$228,306	$61,159	$289,465	21	$228,306
	9/29/2000 9/28/2002	$700,418	$178,477	$878,895	20	$700,418
	9/2/1997 4/30/2005	$729,870	$910,486	$1,640,356	56	$729,870
	9/9/1997 4/30/2005	$2,643,469	$0	$2,643,469	0	$2,643,469

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Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
Completed resource characterization and remote sensing	35	High-Resolution Sidescan Sonar and Multibeam Bathymetric Data Collection and Processing, Atwater Canyon, Gulf of Mexico	DE-AT26-97FT34344	**Naval Research Laboratory (Atwater Valley)**	
Experimental laboratory and modeling studies (Identifiers 36-46; 52-55)	36	Mechanism Leading to Coexistence of Gas and Hydrate in Ocean Sediment	DE-FC26-06NT43067	**University of Texas at Austin;** Massachusetts Institute of Technology	
	37	Methane Recovery from Hydrate-Bearing Sediments	DE-FC26-06NT42963	**Georgia Tech Research Corporation,** Oak Ridge National Laboratory	
	38	Gas Hydrate Research Database and Web Dissemination Channel	DE-AI26-06NT42938	**National Institute of Standards and Technology**	
	39	Comparative Assessment of Advanced Gas Hydrate Production Methods	DE-FC26-05NT42666	**Battelle Pacific Northwest Division**	
	40	Laboratory Studies in Support of Characterization of Recoverable Resources from Methane Hydrate Deposits	ESD05-048	**Lawrence Berkeley National Laboratory**	
	41	Characterization of Natural Hydrate-Bearing Sediments and Hydrate Dissociation Kinetics (Phase 2)	FWP-45133	**Pacific Northwest National Laboratory**	

Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
2/8/2005 11/22/2005	$26,000	$24,000	$50,000	48	$26,000
10/1/2006 9/30/2010	$1,272,986	$319,513	$1,592,499	20	$1,272,986
10/1/2006 9/30/2010	$787,586	$244,509	$1,032,095	24	$787,586
9/1/2006 9/30/2009	$750,000	$0	$750,000	0	$750,000
4/15/2006 6/30/2009	$311,291	$78,709	$390,000	20	$311,291
7/1/2003 12/31/10	$1,570,000	$0	$1,570,000	0	$1,570,000
9/1/2004 9/30/2010	$1,962,000	$0	$1,962,000	0	$1,962,000

Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)
	42	Hydrate Formation and Dissociation via Depressurization in Simulated and Field Samples	FEAB111	**Oak Ridge National Laboratory**
	43	Numerical Studies for the Characterization of Recoverable Resources from Methane Hydrate Deposits	FWP-G308 and ESD00-021	**Lawrence Berkeley National Laboratory**
	44	Characterization and Decomposition Kinetic Studies of Methane Hydrate in Host Sediments Under Subsurface Mimic Condition	EST-380-NEDA	**Brookhaven National Laboratory**
	45	Seismic-Scale Rock Physics of Methane Hydrate	DE-FC26-05NT42663	**Stanford University**
	46	Geomechanical Performance of Hydrate-Bearing Sediments in Offshore Environments	DE-FC26-05NT42664 / ESD05-036	**Texas Engineering Experiment Station & Lawrence Berkeley National Laboratory;** University of California at Berkeley; Schlumberger
Completed lab study	47	Petrophysical Characterization and Reservoir Simulator for Gas Hydrate Production and Hazard Avoidance in the Gulf of Mexico	DE-FC26-02NT41327	**Westport Technology Center International,** University of Houston

	Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
	7/1/2002 12/31/2010	$1,771,000	$0	$1,771,000	0	$1,771,000
	6/30/2000 12/31/2010	$2,788,000	$0	$2,788,000	0	$2,788,000
	10/1/2004 12/30/2009	$500,000	$0	$500,000	0	$500,000
	10/1/2005 3/31/2008	$320,577	$80,334	$400,911	20	$320,577
	10/1/2005 4/30/2008	$692,426	$180,000	$872,426	21	$692,426
	6/26/2002 6/30/2006	$817,952	$204,488	$1,022,440	20	$817,952

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Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
Completed lab study	48	Mesoscale Characterization of Natural and Synthetic Gas Hydrates	FEAB105	**Oak Ridge National Laboratory**	
Completed lab study	49	Fundamentals of Natural Gas and Species Flows from Hydrate Dissociation - Applications to Safety Problems	DE-FC26-00NT40916	**Clarkson University**	
Completed lab study	50	Collection and Microbiological Analysis of Gas Hydrate Cores	FWP-4340-60 & FWP-42C1-01	**Idaho National Engineering and Environmental Laboratory**	
Completed lab study	51	Mechanical Testing of Gas Hydrate/ Sediment Samples	DE-AT26-99FT40267	**U.S. Army Corp of Engineers**	

Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
9/1/2001 9/30/2005	$450,000	$0	$450,000	0	$450,000
9/22/2000 9/30/2006	$268,183	$103,795	$371,978	28	$268,183
6/30/2000 12/30/2002	$330,000	$0	$330,000	0	$330,000
7/9/1999 9/30/2003	$110,000	$50,000	$160,000	31	$110,000

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National Energy Technology Laboratory Projects

Project Category	Report Identifier	Project Title	USDOE Project Number	Performer Institution(s) (Lead in **Bold**)	
NETL projects	52	Geoscience Evaluations and Field Studies	NETL-ORD	**NETL Office of Research and Development**	
	53	Methane Hydrate Numerical Simulation Studies	NETL-ORD	**NETL Office of Research and Development**	
	54	Formation and Dissociation of Methane Hydrate	NETL-ORD	**NETL Office of Research and Development**	
	55	Thermal Properties of Hydrate—Tool Development	NETL-ORD	**NETL Office of Research and Development**	

NOTES: The committee attempted to maintain an updated table of projects throughout the study; however, project start and end dates for many studies changed during the course of this study, as new projects or new project phases were approved, and as projects were extended by agreement with project investigators. This table is updated through February 2010.

White fields indicate field or laboratory studies that are ongoing or were completed during the course of this review and specifically those projects that are or were ongoing as of fiscal year 2006 through and beyond the time of writing of this report. Gray fields indicate studies that were completed prior to the start of fiscal year 2006. In the text of the report, much of the discussion focuses on studies listed in the white fields; however, because the study charge includes a review of research and development of the Program, studies completed prior to fiscal year 2006 are also discussed where relevant.

"Project category" (left-hand column) refers to field and laboratory studies in the broadest sense after designations developed by the committee. Field studies include those related to production and drilling; although the project categories, "Resource characterization and remote sensing," "Environmental research" (whether production related or in nature), and "Multipurpose" may also have field-related components but are discussed separately in the report. The category related to laboratory studies includes those that focus on experimental research and those that focus on modeling. These classifications are in keeping with the level of descriptive detail in Chapter 3.

	Project Start/End Date	Planned DOE Cost	Planned Non-DOE Cost	Total Cost	Non DOE Cost Share (%)	DOE Funding to Date
	10/1/2008-present (on going)	$730,000 (through fiscal year 2009)	$0	$730,000	0	$730,000
	9/30/08 (on going)	$334,000 (through fiscal year 2009)	$0	$334,000	0	334,000
	10-1/2008-present (on going)	$1,540,600 (through fiscal year 2009)	$0	$1,540,600	0	$1,540,600
	10/1/2004-present (on going)	$957,400 (through fiscal year 2009)	$0	$957,400	0	$957,400

Some of the studies have many components and overlap with one or more categories. The cross-referenced categories are noted in the left-hand column description for each category and refer to "Report-identifier" numbers. The number of projects described in Chapter 3 under each category corresponds to the categories and number of projects identified in this table (left-hand column identifier numbers). At the start of this review the Program Web site differentiated between "Field studies" and "Laboratory studies"; as of August 2009, the Web site had been changed simply to list studies as either "ongoing" or "completed."

[a]Under project identifier 20, the "Planned Non-DOE Cost" indicates over $7 million dollars contributed on the part of the USGS over the course of this project. This project is the primary cooperative project between the USGS and the Program supporting Gulf of Mexico, North Slope of Alaska, India, and laboratory efforts. This non-DOE contribution was not on the Program Web site, but rather was obtained by the committee for the purpose of this study as an approximation to give some indication of the large contributions to the interagency efforts by agency partners, and also to indicate the difficulty inherent in estimating such dollar amounts. When an agency has ongoing methane hydrate projects or programs of its own, but which are wholly or partially in line with the tasks of the interagency agreements established as part of the DOE Program, the agencies usually will cover their own participants' salaries, and some operating expenses, while the Program may cover major parts of field expenses, for example. However, the agencies will

often continue to develop and test methodologies after a particular year in which the Program may have covered field expenses, and these may augment the overall interagency (national) research effort in methane hydrate, but will not necessarily be tallied as "Planned non-DOE Costs." The committee did not request similar numbers from the other interagency partners because of the effort involved in deriving these estimates. The industry projects have similar issues because of the difficulty industry has in providing accurate tallies of specific dollar contributions (of personnel, equipment, existing data, etc.); the numbers in the table under "Planned Non-DOE Costs" are as accurate as they can be but may not reflect the full extent of the direct and indirect resources being contributed by Program partners to these research efforts.

SOURCE: http://www.netl.doe.gov/technologies/oil-gas/FutureSupply/MethaneHydrates/projects/DOEProjects/DOE-Project_toc.html. The column "DOE funding to date" information was provided by NETL (R. Baker, personal communication, February 8, 2010).