AN INTERAGENCY ROADMAP FOR METHANE HYDRATE RESEARCH AND DEVELOPMENT: 2015-2030

Prepared by

The Technical Coordination Team

of the National Methane Hydrate R&D Program

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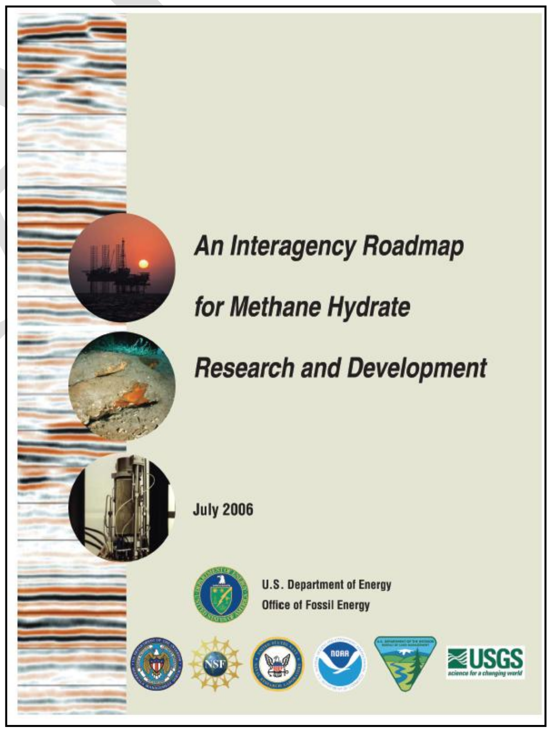
NOTE: This plan is currently in draft form, and will be revised as we continue to solicit input from various stakeholders.

Abbreviations and Acronyms

ANS – Alaska North Slope
BLM – Bureau of Land Management
BOEM – Bureau of Ocean Energy Management
COL – Consortium for Ocean Leadership
CSEM – Controlled Source Electromagnetics
DOE – Department of Energy
DOI – Department of Interior
E&P – Exploration and Production
EM – Electromagnetic
FAC – Federal Advisory Committee
FWP – Field Work Proposal
FY – Fiscal Year
GHSZ – Gas Hydrate Stability Zone
GMGS – Guangzhou Marine Geological Survey
GOM – Gulf of Mexico
HRC – Hyace Rotary Corer
ICC – Interagency Coordination Committee
ICGH – International Conference on Gas Hydrates
IODP – Integrated Ocean Drilling Program
IPTC – Integrated Pressure Temperature Chamber
JIP – Joint Industry Project
LBNL – Lawrence Berkeley National Lab
MHR&D – Methane Hydrate Research and Development
MMS – Minerals Management Service
MPU – Milne Point Unit (Alaska)
NETL – National Energy Technology Laboratory
NGHP – National Gas Hydrate Program (India)
NIST – National Institute of Standards and Technology
NOAA – National Oceanic and Atmospheric Administration
NRL – Naval Research Lab
NSF – National Science Foundation
PTSC – Pressure-Temperature Coring System
PSC – Pressure Coring System
R&D – Research and Development
TCT – Technical Coordination Team
UBGH – Ulleung Basin Gas Hydrate
USGS – United States Geological Survey

1.0 Executive Summary

This *Interagency Roadmap for Methane Hydrate Research and Development* is a joint effort of representatives of the Department of Energy (DOE), the Department of Interior (the U.S. Geological Survey (USGS), the Bureau of Ocean Energy Management (BOEM), and the Bureau of Land Management (BLM)), the Department of Defense (the Naval Research Laboratory (NRL)), the Department of Commerce (the National Oceanic and Atmospheric Administration (NOAA)), and the National Science Foundation (NSF). This roadmap outlines a plan of action to address the science and technology development goals originally articulated in the Methane Hydrate Research and Development Act of 2000 (the MHR&D Act) as amended in Section 968 of Public Law 109-58, 30 USC 1902 (The Energy Policy Act of 2005).



This document is an update to an earlier *Interagency Roadmap* (published in June, 2006), and reviews 1) the progress and findings of the interagency research and development (R&D) program to date, with emphasis on accomplishments over the past six years, 2) the long-term goals and key intermediate milestones for the program, and 3) the program's general structure and management philosophy. This plan, unlike the earlier *Roadmap*, addresses the nature of work that can be done assuming program budgets that are consistent at FY2012/2013 enacted levels. This roadmap retains the MHR&D Act's emphasis on supporting the determination and realization of gas hydrate's energy supply potential and the potential environmental impacts of gas hydrate production, while continuing to address important gas hydrate research questions such as the nature of associated geohazards, and gas hydrate's role in global carbon cycling and climate change.

This roadmap recognizes the profound changes in the U.S. energy industry since 2006, including the decreasing ability of the major private sector companies to support long-range R&D addressing gas supply. These changes only further support the need for federal funding given the long-range, high-risk, high-impact nature of the research.

Gas hydrate R&D continues to advance rapidly, driven by a series of major drilling programs conducted since 2005, both in deepwater (Gulf of Mexico JIP, 2005 and 2009; IODP Leg 311, 2005; India, 2006; China, 2007; Korea, 2007 and 2010) and arctic (Alaska, 2007 and 2011/12; Canada (Mallik), 2007/08) settings. These programs continue to reveal the natural complexity and heterogeneity of gas hydrate geologic systems. Furthermore, there have been numerous studies since 2006 have integrated gas hydrates into climate change hindcasts and forecasts and attempted to quantify the amount of methane emitted by dissociating gas hydrates in the past, present, and future.

While the 2006 *Roadmap's* goal of *demonstrating* commercial viability of marine gas hydrates through field production tests is no longer considered to be within the budgetary realities of the U.S. National Gas Hydrate R&D Program, the agencies will work to further constrain the resource potential of gas hydrates in both the arctic and in the U.S. deepwater through improved understanding of resource volumes and reservoir characteristics. We also will strive to document the impact of natural environmental changes on the stability of gas hydrate as well as any feedbacks hydrate dissociation may have for ongoing climate change.

The Department of Energy, as the lead federal agency in the U.S. National Gas Hydrate R&D Program, will continue to support the integration of methane hydrate R&D ongoing within the various agency efforts. Furthermore, the cooperating agencies will continue to focus their efforts towards aligned public outreach so that all program stakeholders can have timely and accurate information on program results and status. DOE, in its role as primary sponsor of extramural R&D, will repeatedly review its efforts to ensure program quality, transparency, and relevance through external peer review and other means. We will work with all our partners to collaborate with researchers from around the world to leverage the benefits of significant R&D programs in other countries. Finally, we will manage our work to ensure that the nation's best talents, including industry, academia, and government, are brought to bear on the most critical issues in the field of naturally-occurring gas hydrate. This roadmap is designed to maintain the U.S. as a global leader in the science of natural gas hydrate.

2.0 Background

Methane hydrate is a natural form of “clathrate”; unique substances in which molecules of one material (in this case, water) form a rigid lattice that encloses appropriately-sized molecules of another material (in this case, predominantly methane). Research during the past three decades has revealed that gas hydrate exists both as a void-filling material within shallow sediments (both onshore in the arctic and within deep-water continental margins) as well as massive “mounds” (often in association with unique chemosynthetic biota) on deep sea floors. Once thought to be relatively rare in nature, gas hydrate is now widely considered to store immense volumes of organic carbon, and to have had a significant impact on the global environment at many times during the Earth’s history. Nonetheless, despite the recent increase in scientific drilling programs, the vast majority of potential gas hydrate occurrences world-wide remain unexplored.

A major driver for the U.S. National Gas Hydrate R&D Program (hereafter called “the Program”) is the effort to fully understand the geologic controls on the occurrence of gas hydrate in sediments in various settings, and the potential response of those deposits to external perturbations, either natural or induced. With respect to gas hydrate resource issues, this effort will require determination of the necessary conditions for a deposit to be considered a viable production target, confirmation of significant resource volumes within such accumulations, the development of new tools for gas hydrate detection and characterization from remote sensing data, further fundamental advances in the determination of the key physical properties of hydrate-bearing sediments, and the use of numerical simulators to improve prediction of the dynamic behavior of gas hydrate reservoirs and bounding sediments under alternative production scenarios. The Program will closely monitor global R&D, and will seek to test evolving concepts of gas hydrate production potential through future interactions with international and private ventures, as opportunities arise. With respect to environmental implications of gas hydrate, the program will work to better understand the occurrence of gas hydrate in the environments most prone to significant environmental change, as well the potential response of those hydrates to change over various timeframes. The ultimate goal is to provide sound science which will enable more informed policy decisions regarding energy supply, geohazard management, and environmental protection.

2.1 The Nature of Gas Hydrate R&D

As recently as the 1980s, few scientists considered methane hydrate to be a significant part of the natural environment. Consequently, the bulk of prior gas hydrate research was related to the inhibition of spontaneous gas hydrate formation in oil and gas pipelines and other production equipment ("flow assurance"). However, beginning in the late 1960s, observations and interpretations provided primarily by Russian researchers indicated that gas hydrate could be very abundant in nature. A series of deepwater scientific drilling expeditions through the 1970s and 1980s corroborated this view, leading to a scientific consensus that gas hydrate deposits serve as a major global storehouse of organic carbon.

The study of naturally-occurring gas hydrate is highly complex. The ability to create laboratory samples of gas hydrate within natural sediments that mimic those found in nature is improving, but remains a challenge. The most reliable and effective route to understanding the occurrence and nature of gas hydrate is through field studies. However, deepwater marine drilling expeditions are costly, and the inherent instability of gas hydrates upon removal from *in situ* temperature and pressure regimes has required development of specialized equipment to recover, preserve, and analyze natural samples. Such tools are only now becoming tested, reliable, and widely available. In contrast, the development of technologies to maximize data collection through down-hole measurement devices is an increasing priority.

Despite all the progress of the past several years, there is still much to learn about the details of gas hydrate occurrence and behavior in nature. As we expand our knowledge base beyond the very few existing, well-studied sites, new findings are expected that will continue to require studies that are wide-ranging, complex, and multi-disciplinary; incorporating elements engineering, geology, geophysics, geochemistry, hydrology, microbiology, oceanography, physics, and other disciplines.

2.2 The Federal Role in Gas Hydrate R&D

The federal government has a recognized role in addressing key failures of markets to deliver R&D with the potential to significantly promote the public good. Industry has invested greatly in addressing flow assurance issues related to gas hydrates that form spontaneously within production and transmission pipelines; however, private sector spending on gas hydrate resource and environmental issues remains very limited and not well aligned with the potential public benefit. Furthermore, with the recent expansion in unconventional natural gas resource recoverability in the U.S., as well as heightened focus on minimizing operational risks by dedicating personnel and resources to core business activities, industry's ability to facilitate publically-funded R&D through the public-private partnerships that characterized the first decade of the Program has significantly declined. However, increased use of natural gas in all sectors of the U.S. economy, as well as in the increasing potential for the export of U.S. natural gas, suggest that the need for additional supply options may only become more acute. Gas hydrate remains a primary potential option for securing natural gas' promise as a long-term bridge to the sustainable energy supplies of the future. But to be available then, the science and technology development needed to assess both energy resource potential and potential environmental implications, should be conducted now.

While U.S. public investment in gas hydrate research has remained modest over the past five years, international interest continues to grow rapidly. The government of Japan has recently conducted the first marine production test, and has announced plans for further, more expansive tests. South Korea and India continue to plan and conduct deepwater gas hydrate evaluation programs as well. China is currently conducting an extensive marine gas hydrate exploration expedition.

2.3 Recent Advances in Gas Hydrate R&D

Since the publication of the 2006 *Roadmap*, gas hydrates R&D has continued to accelerate, with many significant findings (for recent reviews of research status, see Collett et al., 2009; Paull et al., 2010; Boswell, 2011; Ruppel, 2011 and the references cited therein). The following describes recent key events and R&D findings and their implications for the Program going forward.

2.3.1 Major Field Programs: Progress in gas hydrate R&D is dominated by complex studies conducted in the field. Since 2005, a number of major expeditions have occurred, providing new opportunities to gain fundamental insights on gas hydrate systems through the comparison of gas hydrate occurrence across a wide range of geologic settings.

IODP Expedition 311: Cascadia Margin, Northeast Pacific Ocean (2005): The Integrated Ocean Drilling Program is an international consortium that conducts scientific drilling using a variety of vessels including the *JOIDES Resolution*. Expedition 311 was conducted to build upon the results of several earlier programs (including ODP Leg 204, 2003) that investigated gas hydrate systems within the accretionary wedge sediments off the coast of the North American Pacific Northwest. IODP X311 consisted of a four-hole transect across the continental slope, as well as a fifth location targeting a known cold vent site. The expedition provided further confirmation of an emerging consensus that the nature and distribution of gas hydrate occurrence within the GHSZ is highly heterogeneous and is perhaps most strongly controlled by 1) the nature of the host lithology (with gas hydrate present preferentially within the sand units and largely lacking from the intervening muds) and 2) complex issues related to varying methane solubility in pore water.

Expedition NGHP-01: Indian Ocean (2006): In 2006, the Indian government, with technical leadership provided by the USGS and with the support of scientists from dozens of leading research groups worldwide including the DOE, conducted a 113-day exploratory expedition at more than 20 sites in the Bay of Bengal, Andaman Islands, and Arabian Sea. The expedition, as reported in Collett et al. (2006, 2008a), collected more natural gas hydrate samples than all previous expeditions combined, and generously shared those samples with researchers around the globe. Pressure coring and pressure-core analysis and imaging technologies made major leaps forward in this expedition, achieving unprecedented recovery rates and never-before-seen images of the detailed structure of gas hydrates in marine sediments. Perhaps most notably, the expedition uncovered a major gas hydrate accumulation at "Site 10" within the Krishna-Godovari basin: a 130-meter-thick concentration of gas hydrate in variety of modes (disseminated, large nodules, thin veins and fracture fills, all within a fine-grained matrix). The occurrence of such relatively rich accumulations (perhaps 30% gas hydrate saturation) within fine-grained sediments had not been previously appreciated.

"Mt Elbert" Gas Hydrate Stratigraphic Test Well: Milne Point, Alaska (2007): In February, 2007, the U.S. DOE, BP Alaska Exploration, Inc., the USGS, and numerous other organizations participated in a scientific drilling and data collection program within the Milne Point Unit (MPU) on the Alaska North Slope (ANS). In addition to demonstrating the ability to conduct safe and efficient scientific data collection programs within an area of ongoing industry activity, the drilling confirmed the soundness of the geophysical techniques employed by the USGS in delineating and characterizing fourteen discrete gas hydrate accumulations in the MPU. Analyses of log, core, and downhole pressure response data enabled the international team of researchers to interpret the nature, evolution, petrophysical properties (including in situ permeability in the presence of gas hydrate), and potential production behavior of typical Alaska North Slope gas hydrate reservoirs (see 24 papers compiled in Boswell et al., eds., 2011). These data were key inputs into the 2008 DOI gas hydrate assessment for the ANS (Collett et al., 2008b) discussed below.

Expedition GMGS-01: South China Sea (2007): The Guangzhou Marine Geological Survey (GMGS) of China staged GMGS-01 in the spring of 2007. The expedition drilled, logged, cored, and pressure-cored at nine sites in the South China Sea (Zhang et al., 2008). Among the primary findings reported was the discovery (at three sites) of unexpectedly-high concentrations of gas hydrate (30% or more) at the base of the GHSZ in undeformed and fine-grained sediments. Initial interpretations suggest that this level of gas hydrate concentration may have been enabled by the high abundance of foraminifera in the sediments, a phenomenon previously seen at the Blake Ridge. A second marine expedition is planned for offshore China in early 2013.

Expedition UBGH-01 and 02: East Sea - Korea (2007 and 2010): The Korean Gas Hydrate Development Organization (GHDO) has conducted, with support from the USGS and the DOE, two drilling, logging, and coring expeditions in the Ulleung basin of the East Sea. The 2007 expedition encountered gas hydrate in three wells, with GH occurring in a variety of forms, including both as pore-fill and as thick sequences dominated by grain-displacing, gas-hydrate-filled fractures (Park et al., 2008). One major accumulation (similar in nature to NGHP-01 Site 10) contained over 130 m of fracture-filling gas hydrate in fine-grained sediments. A second expedition in 2010 further confirmed the wide-scale occurrence of gas-hydrate-bearing “chimney structures” in the East Sea, and also established several minor occurrences of gas hydrate in sand reservoirs, which are presently being further evaluated as potential sites for field production testing operations (Lee et al., 2011).

Mallik production well test program: Northwest Territories, Canada (2007 & 2008): The Japanese MH-21 program, in collaboration with Natural Resources Canada (NRCan) and Aurora College, revisited the site of the 1998 and 2002 Mallik efforts (Dallimore and Collett, 2005) to conduct gas hydrate drilling and testing programs in the winters of 2007 and 2008. These programs, as reported in Dallimore et al., (2012) clearly confirmed the technical feasibility of GH production through depressurization. The test suggested that the reservoirs had the potential to exceed the productivity predictions of current numerical models through enhanced permeability related to production-related deformation and natural heterogeneities.

Gulf of Mexico Joint Industry Project Leg II (2009): In April 2009, the DOE-Chevron Gas Hydrates Joint Industry Project (the JIP) conducted logging-while-drilling operations at seven wells at three sites in the deepwater Gulf of Mexico. The program successfully deployed the most advanced LWD tool string used thus far within the deepest and most technically-challenging scientific wells yet attempted in a marine gas hydrate program. The exploration method that guided the selection of the drill sites was unique in the history of gas hydrate investigation in that it was based on a geological and geophysical prospecting approach that integrated direct geophysical evidence of gas hydrate-bearing strata with assessment of the extent of gas hydrate stability conditions, and the existence of gas sources, desired reservoir lithologies (sands), and gas migration pathways linking sources and reservoirs. Six of the seven wells drilled confirmed pre-drill predictions, with four discovering gas hydrates at saturations of 50% to 80% in multiple sand horizons and two others documenting gas hydrates in sand reservoirs at low saturations (see 14 papers compiled in Collett and Boswell, eds., 2012).

"Ignik Sikumi" Field Trial, Prudhoe Bay Unit, Alaska (2011/2012): In 2011, ConocoPhillips, in partnership with DOE, drilled, logged, and conducted wireline pressure tests throughout the gas hydrate sediments below the base of permafrost at site adjacent to the PBU L-pad within the westend Prudhoe Bay Unit (Schoderbek et al., 2012). The logging program confirmed the occurrence of gas hydrate at the site in multiple reservoirs and, when combined with data from prior wells drilled from the L-pad, provided unique confirmation of the structural geometry of multiple gas-hydrate-bearing sands. The data obtained in the logging program was then used to guide planning for a field trial of gas hydrate reservoir response to gas injection. The program successfully injected a mixture of CO_2 and N_2 gas into a 30-foot thick sand with high gas hydrate saturation. Flowback was accomplished via reservoir depressurization in three phases: 1) at pressure draw-downs above that necessary to initiate dissociation of gas hydrate, in which CH_4, CO_2, and N_2 were recovered, 2) at pressures approximating gas hydrate dissociation conditions, in which CH_4 was recovered, and 3) at pressures sufficient to dissociate native hydrate, in which CH_4 was recovered over a period of 19 days at stable and gradually increasing rates. The data from this test were released to the scientific community in March, 2013.

MH-21 Nankai Trough Production Test (2012/2013): In 2012, the MH-21 program conducted drilling and coring programs in the Nankai Trough to establish the geologic conditions and to install monitoring wells and equipment, as well as the top hole for the world's first deepwater gas hydrate production test (Yamamoto et al., 2012). In March, 2013, the drill ship *Chikyu* completed the test well, and achieved six days of production at a reported average rate of 700,000 scf/d (JOGMEC, 2013). MH-21 announced plans to proceed with the offshore testing phase of its program, which will feature a longer-duration deepwater flow test, perhaps in early CY2015.

Additional International Surveys: In addition to the extensive drilling programs listed above, there have been several international programs initiated to collect background data on gas hydrate occurrence in nature via geophysical, heat flow, and shallow geochemical surveys. Taiwan, for example, has conducted extensive studies in preparation for exploratory drilling (Wang et al., 2009). Methane hydrate evaluation has also continued on the Hikurangi Margin, eastern coast of New Zealand (Pecher et al., 2011; Hamdan et al., 2011). Field programs to assess gas-hydrate climate interactions have also been conducted in the Gulf of Mexico and throughout the Arctic, including the East Siberian Arctic Shelf, the Beaufort/Mackenzie Shelf, and the Svalbard margin. These expeditions commonly feature a range of geophysical surveys from ships and AUVs, water and air sampling, and shallow piston coring/geochemical studies to understand the occurrence and dynamics of methane. Plans to further constrain the nature and occurrence of gas hydrates in these environments through drilling programs are in development.

2.3.2 Gas Hydrate Sampling and Analysis Capabilities: The effort to understand the nature of gas-hydrate-bearing sediments through drilling program is central to gas hydrate science, and requires the capacity to effectively recover and analyze natural samples. This effort is challenging, as gas hydrate is not stable at surface conditions, and even the most sophisticated sampling technologies can impart significant disturbances to sediments. However, with each field program, substantial improvements are achieved in both well logging/well log analysis and pressure coring technology/pressure core analysis. In 2012, Japan deployed a new pressure-core system specifically designed to core sand reservoirs with high gas hydrate saturations with success. In early 2013, Georgia Tech and the USGS, worked in tandem with the GOM JIP to successfully deploy an array of analytical devices (Santamarina et al., 2012) to conduct advanced testing on recovered pressure cores during a collaborative program conducted with AIST and JOGMEC in Japan early in 2013. A further generation of the new tool is currently in development by several international R&D programs, including the Gulf of Mexico JIP, with expected delivery by end of CY2013. This tool will then be transferred by the DOE to a group that can make the tool available to support gas hydrate R&D globally.

To supplement the work that can be done with the highly-limited number of natural samples, the 2006 *Roadmap* identified the capability to produce representative synthetic samples of gas-hydrate-bearing sediments for laboratory study, and to conduct laboratory studies that are more relevant to field problems, as a critical research need. Sample creation and characterization is complex, particularly for fine-grained samples, and is also very time-consuming should the preferred method of sample creation utilize gas hydrate formation from methane dissolved in water. Significant improvements in these techniques have occurred, and are currently being further developed (Waite et al., 2010).

2.3.3 Gas Hydrate Geophysical Characterization: A critical goal of gas hydrate science is the ability to collect data via various geophysical methods that can be confidently analyzed to determine the abundance and distribution of gas hydrates over large areas in advance of extensive drilling. Such tools would greatly advance our ability to assess gas hydrate environmental, geohazard, and energy resource, implications. A major effort conducted in Japan (Saeki et al., 2008) indicated that concentrated zones of gas hydrate in marine settings could be delineated with greater certainty where strong amplitudes of appropriate polarity are found coincident with evidence of increased internal acoustic velocities, and geologic evidence of sand-prone lithofacies. Lee et al., 2009 described improved rock physics models for the characterization of gas hydrate accumulations and used these models to correctly predict gas hydrate saturations in advance of drilling at the Mt. Elbert site. Shelander et al. (2012) reviewed the methodology and results used in the successful pre-drill prediction of gas hydrate occurrence from industry-standard 3-D seismic data. Bottom-simulating reflectors (BSRs), which had prior formed the basis for much global gas hydrate exploration, were also seen as a positive, yet not fully reliable, indicator of the presence of concentrated gas hydrate. Shedd et al, (2012) provide an exhaustive review of "BSRs" and similar features in the Gulf of Mexico, their relation to the nature of the local gas hydrate geologic system, and the significance of various manifestations of the BGHS on seismic data in prospecting for concentrated gas hydrate. In early 2013, a collaborative USGS-DOE-BOEM seismic data acquisition program collected a range of geophysical data, including the first advanced, multi-component, ocean-bottom seismic data at a location with comprehensive well log data through the hydrate-bearing sediments. In addition to expanding the use of seismic data, effort has continued to evaluate the potential contribution of controlled-source electromagnetic (EM) surveys for characterization of marine gas hydrate deposits.

2.3.4 Assessment of Global Gas Hydrate Occurrence: After three decades of contemplation of the issue, no clear consensus of the magnitude of potential in-place volumes of methane in hydrate form has emerged. While it appears that a minimum value on the order of 100,000 tcf is likely (Boswell and Collett, 2011), studies continue to appear that are not always easily reconciled with field data. Fortunately, total in-place resource volumes are likely not highly relevant to the first-order research issues facing the gas hydrate community. As a result, assessment is evolving to the more practical issues of understanding resource volumes in specific settings that have direct relevance to local and/or regional energy, climate, or geohazard issues.

The 2006 *Roadmap* used the gas hydrate resource pyramid to illustrate the segregation of global resource volumes into broad categories that relate to potential gas recoverability. This concept has subsequently supported attempts to quantify that portion of gas hydrate global resources that may be amenable to extraction with existing technologies; with recent estimates on the order of 40,000 tcf (Johnson, 2012). An effort to identify potential volumes in areas that are most sensitive to climate change (Ruppel, 2011) similarly suggests that only a small portion (perhaps 5% of total global resources) is directly relevant to that issue. Further, it appears that these two portions of the total gas resource base are mutually-exclusive, providing no justification for linking the separate gas hydrate climate and resource issues beyond the most basic fundamental science issues (Boswell and Collett, 2011). Regionally, three major efforts, two in the U.S., and one in Japan, have provided the first systematic attempts to quantify gas hydrate resource volumes. Similar gas hydrate resource assessment efforts are also underway in Korea, China, and India.

<u>Gas Hydrate Occurrence in the Nankai trough</u>: In 2008, the Japanese MH-21 program released an estimate of 40 tcf gas in-place within a 5,000-sq. mile area of the Nankai trough off the southeastern coast of Japan (Fujii et al., 2008). Of that total, 20 tcf was

assessed to occur within 10 high-concentration accumulations within fine-grained turbiditic sand reservoirs. Fujii et al. (2008) reported that this area represents only 10% of the total area around Japan that is prospective for gas hydrates.

Gas Hydrate Occurrence in the U.S. OCS: As part of its ongoing mission to assess the nation's potential energy resources, the BOEM has been pursuing an assessment of gas hydrate resource throughout the U.S. OCS. The initial report (Frye, 2008) detailed the methodology of a cell-based, probabilistic assessment of in-place gas hydrate resources in the Gulf of Mexico. This assessment took full advantage of BOEM's extensive well and seismic databases, as well as the latest scientific insights on the controls of GH occurrence, ", including particular consideration of issues such as methane generation capacity, lateral distribution of shallow salt bodies, and reservoir lithology." The report indicated a mean estimate of 21,444 tcf gas in-place in hydrate form with one-third of that volume (6,711 tcf mean value) assessed as occurring as pore-filling gas hydrate in high-saturations in sand-dominated reservoirs. In 2012, the BOEM (BOEM, 2012) released the initial findings for gas hydrate gas-in-place volumes throughout the US Lower-48 OCS, including mean estimates for both the Atlantic OCS (21,702 tcfg) and Pacific OCS (8,192 tcfg). When combined with the earlier GOM estimate, the BOEM reports a total U.S. Lower-48 mean estimate of 51,338 tcfg. Given the relative lack of data for the Atlantic and Pacific coasts, these assessments utilize a monte carlo approach that returns a statistical distribution of results, thus incorporating the relatively high degree of modeling uncertainty into the reported results.

Gas Hydrate Occurrence on the Alaska North Slope (ANS): In late 2008, the USGS (Collett et al., 2008a), in collaboration with the BLM, delivered the first estimate of technically-recoverable gas hydrate resources anywhere in the world. The geologically-based assessment followed standard USGS approaches developed to assess conventional oil and gas resources, including prediction of the expected size and number of individual gas hydrate accumulations. The existence of such accumulations, and confirmation of the ability to reliably characterize them through geological and geophysical analyses, had been validated in 2007 by the successful drilling of two gas hydrate accumulations predicted by the USGS to be present at the Mount Elbert site in the Milne Point Unit. In total, the USGS reported that roughly 85 tcf of natural gas exists in gas hydrate across the ANS. Most notably, this resource is determined to be recoverable using existing exploration and production (E&P) technologies. The commercial recoverability of this resource will ultimately depend on the development of methods to achieve commercial production rates, as well as the future expansion of transportation and utilization options for ANS gas.

2.3.5 Gas Hydrate Exploration Technologies: A critical element of the 2006 *Roadmap* was the further application of an integrated approach to gas hydrate characterization that applies conventional concepts of petroleum systems prospecting to the specific case of gas hydrates (Collett et al., 2009). This approach is built on the determination that the most favorable targets for exploration are sand-dominated systems. Therefore, the exploration approach integrates geologic-geophysical evidence for gas sources, gas migration pathways, and suitable reservoir lithologies, with direct geophysical evidence for the occurrence of charged reservoirs. Direct evidence includes well-organized, high-amplitude events of appropriate polarity within sand-prone facies within the gas hydrate stability zone (GHSZ). Such events may be associated with seismic phase reversals where stratigraphic units cross the base of the GHSZ. An initial confirmation of this approach was afforded by the 2007 BP-DOE-USGS “Mt. Elbert” test well which confirmed pre-drill geologic-geophysical predictions (*see* Boswell et al., 2011 *and papers contained therein*). In the marine environment, from 2006-2008 federal and industry scientists collaborating with the Chevron-DOE Gulf of Mexico JIP conducted extensive pre-drill evaluations of existing geophysical data to estimate the lateral extent and degree of saturation of gas hydrate prospects at three Gulf of Mexico sites. Seven wells were drilled at three of these sites in early 2009, with drilling results being in close alignment with pre-drill predictions in four of the five wells drilled (*see* Collett and Boswell, eds., 2012 *and papers contained therein*). The approach used in these programs is now being widely adopted throughout the international gas hydrate R&D community.

2.3.6 Gas Hydrate Production Technologies: Three primary classes of production methods historically have been considered with respect to subsurface gas hydrates: thermal stimulation, depressurization, and chemical injection. Prior to the 2006

Roadmap, a series of successful scientific experiments conducted at the Mallik site in arctic Canada (1998 and 2002) had confirmed that thermal stimulation is likely to be ineffective at commercial scale. However, short duration pressure response tests had indicated that gas hydrate reservoirs likely contain sufficient reservoir permeability and mobile fluids to enable depressurization. As result, the 2006 *Roadmap* identified a long-term production test as one of the critical next steps in advancing gas hydrate research. Critical progress toward such as test was achieved with the 2007 BPXA-DOE-USGS "Mt. Elbert" program, which confirmed reservoir geologic and engineering parameters as well as demonstrated the feasibility of staging a scientific field program within an area of ongoing oil and gas production. A major milestone was achieved the following year (2008) at a Japanese-Canadian research program at the Mallik site with the demonstration of six days of sustained and stable production through reservoir depressurization at the This test has been described as "proof of concept" for the production of gas from naturally-occurring gas hydrates through depressurization. These data from this field program has recently been released to the broader scientific community (see Dallimore et al., 2013, *and papers contained within*).

In 2010, plans for a long-term depressurization test from an established production facility on the Alaska North Slope, including an initial trial of chemical exchange, were developed through collaboration of the DOE, the USGS, and ANS operators (Collett et al., 2012). When those plans were aborted late in FY2010 due to specific legal restrictions on the planned operator, BPXA, the program worked with the Prudhoe Bay partners to secure approvals for ConocoPhillips to conduct a field trail of chemical exchange technology (the "Ignik Sikumi" project) from a temporary ice pad. Operations were conducted over two seasons, with drilling and logging occurring in 2011 (ConocoPhillips-DOE) and testing occurring in 2012 (ConocoPhillips-DOE-JOGMEC) (Schoderbek et al, 2012). These data were provided to the scientific community in early 2013, and, in combination with the 2008 Mallik test data, are expected to enable for a range of scientific learnings that will inform the design of future field tests.

In March 2013, following extensive pre-site characterization work and installation of numerous monitoring devices on the seafloor, in the water column, and in neighboring monitoring wells (Nagakubo et al., 2011), Japan's MH-21 program conducted the initial deepwater gas hydrate field production tests. Initial press releases from METI indicate that ~6 days of depressurization induced flow from turbiditic sands at a total depth of ~1300 meters in ~1000 meters of water depth was achieved, with ~700,000 scf/d of gas production (4.2 mmcf) observed.

Given the relative paucity of field test data and the limited duration of the tests completed to date, very little is conclusively known about the potential commerciality of production. Recent simulations that incorporate full geologic complexity have reported promising maximum production rates (Gaddapati and Anderson, 2012). However, numerous technical challenges exist (Hancock et al., 2008; Boswell, 2011), including potential production hazards associated with the relatively shallow occurrence of producing horizons, and the lack of consolidation of both the reservoirs and the overburden, particularly in deepwater settings. Consideration of these geohazards are expected to focus initial gas hydrate exploration and production to the most geomechanically-stable settings, which include the more technically-viable, deeply buried, sand-rich, accumulations (Boswell and Collett, 2011).

2.3.7 Gas Hydrate Reservoir Numerical Simulation: Modeling of the response of gas-hydrate-bearing sediments to environmental changes and/or simulated production will be critical to the effective planning and interpretation of field investigations. Major developments have been made within many of the leading computer codes, and a public source code (HYDRATE RES-SIM) has been made available via the NETL website. The TOUGH+/HYDRATE code (LBNL), has increasing capability to assess geomechanical phenomena related to production-related destabilization via coupling with the FLAC 3D-code (Rutqvist et al., 2008), has tackled increasingly complex studies using field data (Reagan et al., 2012) and has also been used to model GH response to environmental changes over long-time scales (Reagan and Moridis, 2008). The STOMP-Hydrate code developed at the Pacific Northwest National Lab (PNNL) produced the initial simulations of gas hydrate production via CO_2 injection and CH_4-CO_2 exchange (White et al., 2011). HYDRATE-RES-SM has been utilized to conduct complex simulations of reservoir response to depressurization utilizing detailed geologic characterizations of known Gulf of Mexico gas hydrate reservoirs and their associated "seals" (Myshakin et al., 2012). All codes, including those used in the Japanese MH-21 program, have benefitted greatly from the formation of an international gas hydrate code comparison working group coordinated by NETL. This effort completed and reported on a set of six shared analyses of fundamental modeling problems, resulting in substantial improvements to each of the models that only a controlled and comparative process could provide (Wilder et al., 2008; Anderson et al., 2011).

2.3.8 Gas Hydrates and Industrial Geohazards: Current "industrial" gas hydrate-related geohazards relate primarily to oil and gas production activities and can be categorized as 1) shallow foundational issues related to the installation of infrastructure in areas of shallow sub-seafloor gas hydrates; 2) shallow drilling and well-installation hazards that are encountered by wells targeting deeper horizons ("*drilling through*"), and 3) long-term hazards associated with producing warm hydrocarbons from deeper zones through shallow gas hydrate-bearing intervals ("*producing through*"). The TCT recognizes a significant past contribution from the federal R&D to the issue of drilling though hydrates (see McConnell et al., 2012 for a review) and believes industry is the most appropriate entity to specifically address these issues going forward. However, federal engagement in such studies would clearly advance our collective understanding of the nature and behavior of gas hydrates in nature (and under specific gas-hydrate production scenarios), and should be encouraged and enabled where feasible.

2.3.9 Gas Hydrates and Natural Geohazards: A primary naturally-occurring geohazard associated with gas hydrate is seafloor instability related to gas hydrate dissociation, which releases free gas and excess pore water that results in significant pore fluid volume expansion that can substantially reduce the geomechanical stability of the host sediments. Natural phenomena such as pressure decline due to sea-level drop or temperature rise due to changes in climate or oceanic conditions, can create intervals of potential sediment weakness at the BGHS. The association of large-scale slide events and dissociation of gas hydrates has been investigated over the past decade through field investigations at the Storegga (offshore Norway: Kvalstad et al., 2005) and at Cape Fear (U.S. Atlantic Coast: Hornbach et al., 2007), however, to date, these studies have not confirmed a significant role for gas-hydrate dissociation. While the case for major past episodes of globally-synchronized gas-hydrate-related sea-floor failures remain poorly supported with available data, gas hydrate likely does play a role in certain local seafloor failures (for example, see Lopez et al, 2011). Gas venting may also be a geohazard, and can occur in many marine settings. These events are possibly triggered by free gas accumulations that exceed some critical overpressure at a horizon of reduced sediment permeability, possibly at the base of the gas hydrate stability zone. Perhaps the most compelling evidence reported in the recent literature are the "pingo-like features" observed on the shallow Beaufort Shelf, arctic Canada, that have been interpreted to reflect gas and sediment expulsion associated with ongoing destabilization of permafrost-associated gas hydrate related to post ice-age shelf inundation (see Paull et al., 2007*)*. Many chimney-type structures are found to have a central core of gas hydrate (Ryu et al., 2010*)* suggesting that gas hydrate formation may have a role in mediating the flow of gas through such features, although the processes are not well understood.

2.3.10 Gas Hydrate and Global Climate: Despite limited budgets, the program has worked to initiate study of the linkages between gas hydrate, long-term global carbon cycling and short-term response to global climate change. The program funded (in 2007) an effort with the Lawrence Berkeley and Los Alamos national labs to link the leading gas hydrate and global climate models in assessing the response of marine GH systems to future changes in ocean bottom-water temperature (Reagan and Moridis, 2008). Initial results of the effort confirmed prevailing views (Kvenvolden, 1988) that low-latitude marine systems are likely too well buffered to respond to potential climate change scenarios in the relative near-term, but that high-latitude systems deserved further study. In 2008, four new projects were selected, with an additional five selected in 2012, which include field and modeling studies to better constrain the nature of methane flux in a range of settings, including the deepwater Gulf of Mexico, offshore California, thermokarst lakes on the ANS, and on the shallow-water U.S. Beaufort Shelf. At present, there appears to be minimal risk of significant exacerbation of near-term climate change through gas hydrate dissociation (Ruppel, 2011), although this determination requires further confirmation.

3.0 The U.S. National Gas Hydrate R&D Program

This interagency roadmap for methane hydrate R&D was developed by members of the Technical Coordinating Team (TCT), including representatives of all federal agencies whose missions requires the study of naturally-occurring gas hydrate: the Department of Energy (DOE), the U.S. Geological Survey (USGS), the Bureau of Ocean Energy Management (BOEM), the Bureau of Land Management (BLM), the National Oceanic and Atmospheric Administration (NOAA), the Naval Research Laboratory (NRL), and the National Science Foundation (NSF). Together these agencies, in collaboration with our numerous research partners in academia, industry, state/local governments, and the DOE National Lab system, constitute the broader U.S. National Gas Hydrates R&D Program.

Each federal agency participating in this coordinated effort independently prioritizes and conducts its own efforts as they pursue their individual organizational missions. The purpose of the TCT is to ensure that these efforts are planned and conducted with full communication between the various federal groups to reduce redundancies and maximize synergies. This *Roadmap*, specifically, describes how the U.S. Department of Energy works to achieve the goals of the MHR&D Act by 1) facilitating the integration of activities and scientific finding throughout the U.S. National gas hydrates effort, 2) working to develop this statement of shared long-term goals and R&D priorities, and 3) framing a portfolio of projects in collaboration with industry, academia, national labs, and foreign R&D programs.

3.1 Interagency Collaboration

The Methane Hydrate Research and Development Act specified that an interagency committee, led by DOE, be created to ensure efficient communication and coordination of activities across all entities in the U.S. government that conduct gas hydrate related activities. This group, initially an Interagency Coordination Committee (ICC), and more recently its technical implementation arm, the Technical Coordinating Team (TCT), includes representatives from seven federal agencies (see Appendix A for current memberships). Both groups meet periodically to inform their colleagues of new findings and emerging opportunities for synergistic research and collaboration, and to provide input to the DOE on draft program plans and other matters. Although final implementation of each agency's programs and budgets are the sole responsibilities of those agencies, each partner to this effort recognizes that continued interagency collaboration will be critical to the success of the National R&D effort. The 2006 Roadmap presented four ways in which collaboration occurs and provided numerous specific examples. The following provides additional examples of collaboration that have occurred since 2006.

With regard to *co-funded programs*, NOAA, BOEM, and the DOE continued to co-fund (as directed by Congress in FY2008, 2009, and 2010) the development and deployment of a long-term sea-floor monitoring station within a hydrate-rich location in OCS block MC 118 of the Mississippi Canyon area in the Gulf of Mexico. Interagency review of the project in 2008 resulted in successful initiatives to improve the characterization of the subsurface pathways that deliver gas to the surface mounds. The observatory has recorded information that is enabling observed changes in the occurrence of surficial gas hydrates to be evaluated in the context of changing environmental conditions. The project has also delivered improved techniques for geophysical data processing for the detection and characterization of marine hydrate deposits.

In FY2013, the USGS executed a program of advanced seismic data acquisition over the GC955 and WR313 sites in the deepwater Gulf of Mexico. This program is co-funded by USGS, DOE, and BOEM, and will represent the first instance of dedicated seismic data collection (including multi-component, ocean-bottom data) in an area with comprehensive pre-existing LWD data.

With regard to *expertise and information sharing*, the success of the DOE-funded field program with BP at the Mt. Elbert site (2007) was enabled in large part by the scientific contributions of the USGS, including the delineation of well location options, the selection and pre-drill characterization of the selected well location, and the operational efficiency of the field program. Similarly, the DOI (USGS and BLM) effort to assess the technical recoverability of ANS gas hydrate incorporated the findings of the DOE-funded field program as well as the modeling results developed within the International Code Comparison effort conceived and enabled by the DOE (see Appendix D for a list of participants). In the Gulf of Mexico, the DOE-funded JIP has benefitted greatly from the contributions of the DOI, including both the BOEM and the USGS, as well as the NRL, in the reporting of JIP Leg I results (Ruppel et al., 2008), and in the selection of appropriate sites and operational procedures for JIP Leg II drilling. USGS and DOE personnel served as co-chief scientists for JIP Leg II field program, with BOEM personnel providing on-board geologic expertise in the selection of final drill locations and the real-time interpretation of LWD results. Scientists from all three agencies have contributed substantially to the subsequent data analysis, interpretation, and reporting of JIP Leg II data. These results have also provided insight into the ongoing BOEM effort to assess the volume and recoverability of gas hydrate resources in the GOM (BOEM, 2013).

Third, *agencies provide funds to each other* to conduct work in support of this program when those agencies have unique abilities to provide critical data needs. Recent examples include funding from DOE to the NRL to participate in field expeditions on the Hikurangi Margin (2006), Beaufort Shelf (2009) and Chatham Rise (2013). The DOE has also extended funding to the USGS to enable specific laboratory and field efforts, such as geophysical surveys on the Beaufort shelf and upper continental slope, investigation of noble gas fractionation during hydrate formation/dissociation, and the improvement of laboratory protocols for the formation of synthetic hydrate samples. The BLM has supported the USGS, which in turn has provided funds to the DOE, to conduct an evaluation of the full life-cycle implications of gas hydrate development on the Alaska North Slope. In this program, USGS is contributing geological expertise and is funding DOE to provide numerical modeling expertise.

Fourth, the collaborating agencies have been invaluable in continuing to provide *technical expertise to the development of R&D plans*. The best example is this document, which has been prepared by the interagency TCT. Furthermore, the collaborating agencies have been very responsive to DOE's requests to provide technical comment/review on proposals received under DOE solicitations, to participate as merit reviewers of ongoing DOE research efforts, and to provide the federally-mandated Methane Hydrate Advisory Committee (MHAC) with updates on agency programs.

3.2 International Collaboration

The Program is committed to working with international programs where feasible. Such cooperation provides information on the nature of gas hydrate occurrence in a wide range of geologic settings. International collaboration also provides a framework for gaining additional experience with field sampling and analysis tools. The agencies will also enable, to the extent possible and practical, the opportunities for foreign parties to participate in domestic hydrate field programs. The following reviews international collaboration in the US National gas hydrates R&D Program in recent years.

3.2.1 India: U.S.-India collaborations are managed largely by the USGS, which played a pivotal role in the planning, execution, and reporting for India's NGHP-01 Expedition (2006). DOE also provided substantial direct support to that expedition. USGS in particular, as well as DOE and BOEM, have been supporting India's ongoing effort to assess its national gas hydrate resources, including project planning and site selection for planned NGHP-02 drilling. India's MOPNG maintains an MOU with the DOE, USGS, and BOEM. The U.S. agencies will also support as fully as possible the NGHP's desire to develop numerical modeling capabilities and to establish world-class gas hydrate research centers in India.

3.2.2 Japan: U.S.DOE-Japanese collaboration is enabled by an MOU signed in 2008. Japan's JOGMEC is a long-standing member of the Gulf of Mexico JIP and has supported that program's current effort to develop improved deepwater coring devices through shared information on the design and performance of coring devices within the MH-21 program. U.S. representatives from Chevron and the USGS witnessed initial land-based testing of the Japanese tools in 2011, and USGS and Georgia Tech scientists affiliated with the JIP collaborated with JOGMEC and AIST scientists during the evaluation of pressure-cores at the AIST laboratories in Sapporo in early 2013. This collaboration enabled Japan to obtain a range of technical measurements on pressure-cores that they would not otherwise have obtained, and enabled the U.S. to evaluate the performance of a range of U.S.-built pressure-core analysis devices.   In 2011, JOGMEC partnered with ConocoPhillips to conduct the “Ignik Sikumi” CO_2 exchange field trial in Alaska. JOGMEC provided technical assistance and ~$7.7 million in funding to the total ~$28 million ($15 million DOE, $6 million ConocoPhillips) program.

3.2.3   Korea: In 2007, the Korean National Oil Company joined the Gulf of Mexico JIP, joining existing member companies from the U.S, France, Japan, and India. The USGS and DOE directly participated in Korea’s UBGH-01 (2007) and UBGH-02 (2010) expeditions, including enabling direct contributions from scientists in the field, supporting the analyses of required data, and participating in panels advising Korea on field program plans. A Statement of Intent (SOI) between Korea’s MOTIE (formerly MKE) and the DOE was signed in 2008 and renewed in 2013.

Many international collaborative opportunities have developed over the last decade through the International Methane Hydrate Research and Development Workshop that has been supported by NRL, with support from DOE. This workshop has been held in the U.S., Chile, Canada, Scotland and Norway and attended by approximately 800 scientists from over 25 nations. International collaborations have developed for field work on the mid Chilean Margin, Cascadian Margin, Gulf of Mexico, Blake Ridge, Hikurangi Margin, and the Beaufort Sea. The participating agencies will continue to develop collaborative relationships, both formal and informal, with international groups with interest in gas hydrates R&D.   DOE will also support high-value opportunities for international collaboration that are developed by our collaborating U.S. federal agencies.

3.3 External Scientific Oversight

The DOE and the collaborating agencies in the National Methane Hydrate R&D program recognize the soundness of incorporating external scientific input into major program management decisions. This input is achieved through external peer reviews of ongoing projects, external review of proposals for new projects under DOE solicitations, discussions within interagency groups, open meetings and workshops, ongoing consultation with the Federal Advisory Committee (see Appendix B), and periodic reviews by the National Research Council.

3.3.1 Formal Reviews: In FY2007, DOE commissioned a comprehensive review of the program by the National Research Council. This review was completed and published in January 2010 (Paull et al., 2010) and provided valuable recommendations for the program. DOE conducted a thorough review of all work occurring within Cooperative Agreements in September 2007 on the campus of the Colorado School of Mines. This review featured panels consisting of six subject matter experts each in five separate disciplines. This review resulted in numerous modifications of scope and planned funding for many projects, the termination of several ongoing or planned project activities, and the early discontinuation of one large effort. A similar review of work being conducted through National Lab FWPs and through Interagency Agreements was held in Pittsburgh, PA in July, 2008. In January 2010, DOE conducted a comprehensive 1-week program review in Atlanta, GA focused on information exchange and development of linkages across projects, without formal project review and ratings. A similar meeting is anticipated for early FY2014.

3.3.2 Federal Advisory Committee (FAC): In keeping with the requirements of the MHR&D Act, DOE reports regularly on program activities and plans to its Federal Advisory Committee. The current FAC most recently met in Houston in July, 2012, and in Washington DC in June, 2013.

3.4 Technology Transfer and Outreach

Critical to the ultimate success of this program will be a rigorous scientific vetting of the economic and environmental implications of this program, and the effective communication of those findings to the public. Methane hydrates may represent a new, “unconventional” fossil energy resource, and given 1) the strong links between fossil fuels and potential anthropogenic climate change, and 2) the likely role gas hydrates may have played in global climate events in geologic history, it is important that the program both investigate and report on the environmental implications of potential utilization of gas hydrates as a bridging fuel to the sustainable sources of the future. To be credible, this outreach must include demonstration that the science community has a good understanding of the role that naturally-occurring gas hydrate has in ongoing global environmental processes, as well as how gas hydrates respond to environmental changes, both natural and induced. The TCT continues to recommend that the U.S. science community demonstrate and communicate that it is responsibly addressing these topics and honestly and fully sharing the facts on issues of rightful concern to the public.

3.4.1 Websites and Newsletters: The DOE maintains comprehensive web-sites that provide detailed overviews of both past and ongoing projects, with links to all public-domain, project-related reports and presentations. The website also provides access to various programmatic and outreach documents, such as the Methane Hydrates Primer, past interagency planning documents, and NETL's periodic newsletter, *Fire in the Ice*, which continues to be a leading source of international information for the gas hydrate community. Project related field data, such as the Ignik Sikumi gas hydrate exchange field trial datasets, and initial scientific reports from JIP Leg II are provided through the web-site at the earliest date possible, ensuring data becomes available in timeframes that are much reduced from that associated with peer-reviewed publication. The USGS (http://energy.usgs.gov/OilGas/UnconventionalOilGas/GasHydrates.aspx, as well as http://woodshole.er.usgs.gov/project-pages/hydrates/) maintains comprehensive websites for its gas hydrate programs that include extensive reporting on past project efforts globally. NOAA continues to maintain the highly-popular "Ocean Explorer" website at http://oceanexplorer.noaa.gov/. BOEM has also recently upgraded its website, compiling all information related to the ongoing program of gas hydrate assessment throughout the U.S. OCS, including assessment results and reports, and related information, such as their extensive catalogue of seismically defined seep-sites and "BSRs" within the Gulf of Mexico (see http://www.boem.gov/Oil-and-Gas-Energy-Program/Resource-Evaluation/Gas-Hydrates/GH-RA-Introduction.aspx)

3.4.2 Peer-reviewed Publication: Since FY2006, DOE-supported researchers have published ~XX papers in professional journals and presented more than XXX technical papers at leading conferences. Highlights of include the publication of three Thematic Volumes with the *Journal of Marine and Petroleum Geology* edited by DOE and USGS scientists that served to compile scientific results for the 2005 JIP Leg I program (Ruppel et al., 2008); the 2007 Mt. Elbert Program (Boswell et al., 2011) and the 2009 JIP Leg II program (Collett and Boswell, eds., 2012). DOE will continue to encourage its researchers and research partners to publish their results in peer-reviewed journals and regularly participate in professional conferences.

3.4.3 Focused Workshops: DOE, in collaboration with the USGS and others, will continue to support technical workshops to bring key researchers together to discuss R&D needs and opportunities. Key among these is the ongoing International Methane Hydrate Research and Development workshop (IMHRD, or "Fiery Ice from the Seas"). IMHRD workshops, which are lead by NRL in collaboration with a range of international research groups, is intended to foster international collaboration between scientists from various disciplines to exchange the latest knowledge in gas hydrates research across the full range of first-order science issues. The workshop also provides a platform for national representatives to introduce their gas hydrates programs, share their expertise, and seek opportunities for collaboration. DOE has co-funded all 8 of these workshops, including the 5th IMHRD in Edinburgh Scotland (October 9-12, 2006), the 6th IMHRD in Bergen Norway (May 13-15, 2008), the 7th IMHRD in Wellington New Zealand (May 10-12, 2010), and the 8th IMHRD in Sapporo Japan (May 28 – June 1, 2012). Similarly, the Gulf of Mexico Hydrates Research Consortium (GoMHRC) was organized in 1999 with the goal of advancing gas hydrate science in the Gulf of Mexico. The GoMHRC is managed and coordinated by the Center for Marine Resources and Environmental Technology (CMRET) at the University of Mississippi and focuses primarily on activities at the Mississippi Canyon 118 gas hydrate monitoring site. Membership in the GoMHRC is open to all interested universities, government agencies and private companies. Each year consortium members present the results of their research at annual meetings, which are partially funded by DOE, BOEM, and NOAA, all members of the consortium.

Smaller, focused workshops are also held periodically when appropriate. For example, a USGS-led workshop was held in Cambridge, MA in February 2008 to discuss gas hydrate-global climate linkages. Another workshop was held in Denver in March 2008 to present the results of scientific analysis of data collected at the Mount Elbert well in 2007 and to discuss potential sites and operational plans for future production testing. A third workshop occurred in Atlanta in March 2008 organized by the USGS and Georgia Tech discussed the laboratory protocols for the investigation of the physical properties of gas hydrate-bearing sediments. An open meeting on the status of Alaska field projects was held in Morgantown (WV) in January of 2009. An initial review of Gulf of Mexico JIP Leg II findings was held in Houston in August, 2009 and included extensive participation from industry. A workshop to prioritize climate-hydrates research objectives was organized by the USGS in Boston, MA in February 2011.

In March, 2013, an open review meeting on the results of the Ignik Sikumi test was held at the ConocoPhillips offices in Houston, and included participation of ~50 scientists representing industry, academia and government organizations in seven countries. In June, 2013, a meeting to discuss future options for marine field investigations was held by the Consortium for Ocean Leadership, and included X participants from X countries.

3.4.4 Annual Report to Congress: Each year, DOE prepares an overview of the prior year's activities and findings in its Annual Report to Congress. These reports can be found on the DOE/FE website at http://energy.gov/fe/methane-hydrate-advisory-committee.

3.5 Education and Training

Despite the high-visibility of the industry-led field efforts, universities have played a major role in the program, both as key parts of the industry-led research teams and in conducting their own competitively-awarded R&D projects. In future years, this contribution is expected to increase. At present, the program supports approximately XX students (roughly 50% U.S. citizens) at levels ranging from B.S. to post-doctoral, at approximately XX institutions. Since 2000, the number of students who have contributed to the program exceeds XXX. In addition to the training/educational opportunities provided within the portfolio of NETL cooperative agreements, the DOE established (in 2006) a formal, competitive, merit-based Fellowship program in collaboration with the National Academies of Science. That program has since selected seven "National Methane Hydrate R&D Program Fellows" and hopes to select at least one additional recipient annually.

4.0 R&D Roadmaps: 2014-2025

The following describes the overall nature, scale, and priorities for R&D in gas hydrates as recommended by the interagency TCT given the planning assumptions described below.

4.1 Planning Assumptions

This 2013 *Roadmap* represents a re-evaluation of prior concepts and strategies that have framed the National Program in light of 1) scientific findings in recent years; 2) the recent changes in the natural gas industry and their potential impacts on the ability to expect access to industry capabilities and resources; and 3) recent budget trends, which suggest that assumptions that framed the prior roadmap (including levels of EPACT2005 R&D funding authorizations) are no longer relevant. Therefore, this Roadmap represents the TCT consensus recommendation for appropriate long-range goals for the Program going forward as well as a relevant long-range vision of the nature, duration, and sequence of activities needed to achieve those goals assuming that DOE program budgets are likely to remain flat at no more than $10 million/year. The implications for achievement of program goals under different future budgets are discussed in Section 4.4.

Table 1: DOE Funding for Methane Hydrate R&D: FY1997 – FY2013 ($ millions)

	00	01	02	03	04	05	06	07	08	09	10	11	12	13
Appropriation	2.9	9.9	9.8	9.4	9.4	9.4	11	12	15.8	16.1	15	0	10	4.8
Authorization	-	5.0[1]	7.5[1]	11[1]	12[1]	12[1]	15[2]	20[2]	30[2]	40[2]	50[2]	-	-	-
% of auth.	-	198	131	85	78	78	73	60	53	40	30	-	-	-

[1]*Methane Hydrate Research and Development Act of 2000*
[2]*Energy Policy Act of 2005, Sec. 968*

A critical feature of the Program through the past dozen years has been the effort to build the program around major field-based activities. These field programs have been developed partnership with major oil and gas companies as those are the entities that can most-readily enable access to the leases (relevant to the arctic onshore only), data, personnel, and capabilities that are facilitate drilling and evaluation activities in the Arctic and in deepwater. This approach, which featured the creation of Cooperative Agreements with phased programs, aggressive goals and sufficient flexibility 1) to allow adjustment to changing scientific and market contexts and 2) to accumulate limited budgets over multiple years, has served the Program well. Since 2005, the Program has been able to conduct a series of safe, efficient, and scientifically-successful field programs, including JIP Leg I (2005 with Chevron and members of the GOM JIP); “Mt. Elbert” (2007 with BP Exploration, Alaska); JIP Leg II (2009; again with the GOM JIP); and “Ignik Sikumi” (with ConocoPhillips (2011/2012) and JOGMEC(2012)). However, the TCT has concluded that this strategy can no longer be relied upon as the base strategy for further scientific advance within the program. First, the costs of the needed field operations, particularly long-duration arctic production tests or any production testing in the marine environment, are not consistent with this plan’s $10 million/year budget constraint. Second, in the past five years, expanding recoverability of unconventional resources has changed the outlook for natural gas with the result that many of the Program’s traditional industry partners are decreasingly able to justify deploying company resources to non-core business, or to business with no clear near-term payout. Nonetheless, the TCT agrees that scientific drilling programs are critical to the advancement of gas hydrate science on all fronts. Therefore, it is necessary that the program endeavor to facilitate and participate in field programs through collaboration with a wide range of external groups (industry, service companies, academia, nationally and internationally) and to continue to plan field programs of modest scale that target unique data collection opportunities. Opportunities for collaboration with international programs will continue to be a high focus for the US effort.

Going forward, the Program will focus its effort on core science and technology development activities that advance the understanding of geologic systems capable of gas hydrate accumulations, and the dynamic response of gas-hydrate-bearing sediments to a changing environment. The intent is to be prepared to test and refine these concepts through field-based studies as opportunities arise (either within the program or through collaboration with external efforts). These core science plans will be conducted within a portfolio of projects that tap the best expertise from industry, universities, the National Laboratories, and federal agencies. DOE will also continue to emphasize the development of projects through open and externally-reviewed solicitations. Priorities for these science plans are reflected in this Roadmap, and reflect discussions among the TCT and with the science community through various means, such as the workshops conducted in 2013 in collaboration with ConocoPhillips and COL.

4.2 Goals

Overall, the Program's goals are to create the comprehensive knowledge base and suite of tools/technologies that result in 1) increased confidence in the assessment of gas hydrate volumes within the U.S., and an understanding of their distribution/occurrence in specific settings of relevance to resource and climate issues; 2) the potential response of those deposits to potential pressure/temperature changes, either induced or natural; and 3) to use this information to provide an accurate assessment of the resource, geohazard, and environmental implications of naturally-occurring gas hydrates. Specifically, the goals of the Interagency U.S. program in gas hydrates at the assumed $10 million/year appropriation level are as follows:

10-year Program Goals at planned budget levels: 2015-2025

Ongoing: Monitor opportunities to contribute to the planning and implementation of extended-duration production tests in collaboration with the State of Alaska, ANS industry, and other interested parties

By 2015: through analyses of existing data, determine the optimal production methodologies for potential testing and application on the Alaska North Slope.

By 2017**:** provide an initial estimate of the role of gas hydrate in the flux of methane from sediments to the ocean/atmosphere in key settings across a range of temporal and spatial scales;

By 2022: document the potential for ongoing climate change to affect the stability of coastal gas hydrates, and to evaluate the impact of gas hydrate degassing on atmospheric greenhouse gas concentrations.

By 2025: provide via targeted drilling and/or remote sensing programs, refined models for gas hydrate occurrence within resource-relevant, environmentally sensitive, and/or geohazard prone, accumulations within the U.S. OCS.

The TCT believes that the technical-feasibility of gas production from gas hydrates has been established although the environmental impacts of such long-term production have yet to be definitively determined. Therefore, a key goal of the program during the next five years (2015-2020) is to evaluate the resource potential of methane hydrates for the United States through improved information on the occurrence of gas hydrate at high saturations in sand-rich reservoirs. This evaluation includes both an appraisal of likely volumes as well as numerical modeling efforts to estimate potential production profiles in order to assess relative commerciality. At the planning assumption budget levels, the assessment of volumes would be based on a limited number of reduced-scale field drilling and coring investigations, integrated closely with ongoing assessment activities within the DOI. The assessment of productivity would be based on evaluation of past field data, future field testing data as available, and through extrapolation of laboratory and experimental data. However, no further scientific field production tests could be expected to be funded primarily from the budgets of the U.S. National Program. Consequently, the Program will continue to monitor and pursue opportunities to conduct such tests in collaboration with various international groups.

Field investigations to determine gas hydrate's potential future role in impacting the course of changing climates will be pursued, albeit through field programs of perhaps less comprehensive scale than previously conceived. The following provides descriptions of the nature of high-priority R&D activities going forward.

4.3 Areas of Research Focus

4.3.1 Gas hydrate systems characterization: In order to achieve refined models of gas hydrate accumulations within the U.S. OCS by 2025, detailed characterization is required. A prerequisite to evaluating the varied implications of naturally-occurring gas hydrate is the improved understanding of the controls on the abundance, occurrence, and nature of gas hydrates in sediments. Although it appears likely that gas hydrates do occur in large volumes in the U.S., the extent of accumulations of sufficient extent and richness to be plausible resource targets has thus far only been postulated for the ANS (Collett et al., 2008b) and GOM (Frye, 2008), and both estimates are subject to significant uncertainty. Similarly, current models of gas hydrate role in carbon cycling or potential response to future climate change are based on simplified depictions of gas hydrate occurrence and distribution. Better delineation of those areas most prone to climate-induced destabilization, improved understanding of the distribution of gas hydrate within those regions, and better models for the response of those systems to environmental change, will be pursued. Key to this effort will be the development of remote sensing-based characterization tools integrated with field data-acquisition programs to provide validation of occurrences.

The concentrations and nature of occurrence of gas hydrate varies between the marine and the Arctic settings. Onshore Alaska, the combination of prolific petroleum systems, extensive gas hydrate stability zones, and sand-rich sediment sequences has enabled the interpretation of numerous discrete accumulations of high-concentration gas-hydrate in high-quality reservoirs, particularly within the areas of oil and gas development. Extrapolating these data across the broader ANS introduces greater uncertainty. The Program will make every effort to leverage ongoing industry activity (through participation as feasible in "wells of opportunity"- wells being drilled by industry for deeper targets but which provide opportunities for data collection in the shallow section) to assess gas hydrate occurrence throughout the broader ANS. To fully determine the scale and nature of occurrence of gas hydrates in the ANS, the Program is expected to collaborate with the Alaska Department of Natural Resources (ADNR) and ANS operators as feasible to review existing geologic and geophysical data. In addition, the acquisition of new geophysical data, as well as log and core data from new wells, will be pursued. Further evaluation of gas hydrate occurrence outside the established infrastructure areas will not only provide greater certainty to ANS gas hydrate resource estimates, but would also provide an opportunity to potentially expand the options for field testing programs to locations that could have more readily-manageable operational logistics.

The shallow arctic shelf of Alaska hosts potential "relict" accumulations of gas hydrate. They are called "relict" because they formed in onshore association with permafrost during prior periods of lower sea-level, but are now housed (if they remain) within shallow settings that continue to respond to the dramatically-changed thermal regime. As this thermal pulse works its way through the sediment column, conditions no longer support hydrate stability. These potential relict hydrates are an unconstrained source of methane to the shallow sediments, ocean and atmosphere. Characterizing their occurrence is a prime focus of ongoing DOE-funded efforts by USGS as well as SMU, Scripps Institute of Oceanography, and others.

In deep marine systems, despite numerous recent drilling programs, the nature of marine gas hydrate occurrences in the U.S. continues to be poorly known. Even in relatively data-rich regions such as the Gulf of Mexico, high-quality well and seismic data in the shallow depths where gas hydrate resides is rare. The prioritization of regions to be investigated will likely be highly influenced by the findings of ongoing BOEM assessments of marine gas hydrates on the Atlantic, Pacific, and Alaska OCS, supplemented as appropriate and feasible by new field data collection programs. The TCT also recommends that the full assessment of gas hydrate occurrence should include drilling campaigns that both 1) test specific gas hydrate prospects (and also provide calibration opportunities for the technologies developed to find anomalously-high concentrations that may have resource-relevance) as well as 2) conduct scientific drilling transects designed to reveal the nature and variation of gas hydrate occurrence across a range of geological and geochemical settings.

Therefore a primary near-term goal of the program will be to complete a comprehensive review of existing Gulf of Mexico well data (in partnership with Ohio State University), to further the refinement of interpretation processes for industry-standard seismic data (with Oklahoma State and FugroGeosciences), and to collect (as feasible) advanced remote sensing data utilizing the well-characterized accumulations discovered at sites in GC955 and WR313 during previous Programs (USGS, DOE, and BOEM). In addition, the Program will continue the effort to develop feasible plans for multi-well drilling and logging expeditions within the U.S. OCS. Given the costs and logistical complexities in accessing industry drill-ships, this effort will now focus primarily evaluating opportunities to utilize geotechnical and scientific vessels (Consortium for Ocean Leadership and FugroGeosciences). These field programs plans may include further data collection, most notably acquisition and analysis of pressure cores at one or perhaps two of the established Gulf of Mexico sites (WR313, GC955, or AC21), or gas hydrate exploration and characterization efforts in areas like the Atlantic OCS via new geophysical surveys (as feasible given restrictions on such work inherent in NEPA regulations) or short-duration drilling and logging programs.

4.3.2 Gas hydrate sampling tools/technologies: Given the difficulties in preservation and transfer of natural samples into laboratory equipment, and the complexities of creating synthetic samples that sufficiently mimic natural conditions, strong emphasis will continue to be placed on development of in-situ data collection tools, as well as the improved ability to collect and effectively analyze pressure cores. Therefore, a primary near-term goal for the program will be to complete the development and initial testing of a suite of pressure-core acquisition (Hybrid Pressure Coring System – HPCS) and analysis (IPTC and PCCT: see (Santamarina et al., 2012)) tools through the ongoing partnership with the Chevron-managed Gulf of Mexico JIP. The Program's goal is to provide a coring system that has the flexibility to successfully acquire and analyze cores from a range of drilling platforms and across a range of geologic settings, including gas-hydrate-bearing sands. Once completed DOE will work with the science community to ensure that the devices are available for future scientific research. Opportunities to further the development and improvement of these tools through international collaboration will continue to be monitored and pursued as feasible.

4.3.3 Gas hydrate production technologies: The Program's intent is to conduct the initial tests of gas hydrate reservoir productivity within the most operationally-favorable setting: the well-characterized gas-hydrate-bearing sandstones known to exist under the Greater Prudhoe Bay (including Milne Point, Prudhoe Bay, and Kuparuk River oil fields) infrastructure on the Alaska North Slope. Because the desired production tests are likely to extend to a year or more, test locations need to be permanent production facilities in which R&D operations will not have an undue effect on ongoing industry operations (see

Collett et al., 2012). The program has successfully staged two short-term tests in the area from temporary ice pads (the 2007 "Mt. Elbert" and the 2011/2012 "Ignik Sikumi" programs) and will work closely with industry, the state, and other interested parties to address ongoing logistical barriers to conducting a test from an existing gravel facility. The next test would likely focus on establishing the nature and sustainability of reservoir deliverability from depressurization and feature full environmental-impact monitoring to track the development of the dissociation front, the migration and/or release of any free gas, and land subsidence. Subsequent tests would integrate the accumulated learnings in an effort to lead toward production technologies that appropriately balance productivity with the desire to make the production system as carbon-neutral as possible. The initial test programs have focused focus on obtaining the best possible datasets that will support the further validation/calibration of numerical models of gas hydrate reservoir response to various specific perturbations across a range of geologic settings. These efforts will be closely integrated with experimental work in the lab and through numerical simulation to advance understanding of fundamental processes and properties that will facilitate both better interpretation of test results and improved planning for future tests. Numerical modeling of the geomechanical stability of gas hydrate reservoirs and overburden under a variety of production scenarios will be continued and fully integrated with the field effort. It must be noted that testing programs as described above are not feasible under the base funding assumptions of this Roadmap without significant cost-share and access, neither of which can be assumed to be provided by the companies holding the Prudhoe Bay leases.

4.3.4. Gas Hydrate linkages to global climate change: The program will complete a series of field-based studies in a variety of gas hydrate-bearing areas with the intent to constrain the rates of gas-hydrate-related methane generation and flux from the sediment to the ocean/atmosphere system (by 2017) and fully integrating these data into forward climate models (by 2022) . The effort will focus on data collection in the field and subsequent sample study in the lab, supplemented by the continued incorporation of gas hydrate-relevant data into numerical models of carbon cycling and the response of gas hydrate-bearing systems to environmental change. In parallel, numerical simulation tools will be developed (and calibrated against emerging field data as it emerges) to enable reasonable forecasting of gas hydrate response under different climate change scenarios. The overall goal is to contribute to the development of a general scientific consensus regarding the potential for different modes of natural hydrate degassing to affect the environment. This work will be elucidated by studies of past gas hydrate-climate linkages as appropriate.

4.4 Potential Program Goals under Alternative Budget Assumptions

In 2006, The TCT indicated that the Program would need to conduct a range of field activities to achieve the goals as stated in the 2006 *Roadmap*. At that time, the TCT agreed that long-term funding consistent with that indicated by the Energy Policy Act of 2005 authorization (see Table 1) was a prerequisite for conducting the necessary field projects, including 1) a long-term scientific production test in Alaska, followed by programs that would refine and then demonstrate effective production technologies, 2) a series of multi-well exploration programs in the U.S. OCS to confirm resource volumes, and 3) a production test within the deepwater environment.

Under the assumption of future appropriations of $25 million/year, marine expeditions can be conducted at more appropriate scale and frequency, and be supported by a fuller range of complimentary modeling and experimental efforts, thus yielding results sooner than a $10 million/year program would; and with more confidence in such results. The program might also be in a position to be a major financial contributor to onshore production tests. This funding level, which would enable the evaluation of a greater diversity of sites (more efficiently and in fuller detail), would result in more timely, accurate, and reliable assessment of the energy resource potential of gas hydrates. Marine production testing would remain infeasible even at this alternative budget level.

Program Goals at alternative budget levels: 2015-2025

Ongoing: Monitor opportunities to contribute to the planning and implementation of extended-duration production testing in collaboration with the State of Alaska, Alaska North Slope industry, and other interested parties

By 2015: through analyses of existing data, determine the optimal production methodologies for potential testing and application on the Alaska North Slope.

By 2015**:** provide an initial estimate of the role of gas hydrate in the flux of methane from sediments to the ocean/atmosphere in key settings across a range of temporal and spatial scales;

By 2020: document the potential for ongoing climate change to affect the stability of the gas hydrates, and to evaluate the impact of gas hydrate degassing on atmospheric greenhouse gas concentrations.

By 2022: provide via targeted drilling and/or remote sensing programs, refined models for gas hydrate occurrences within resource-relevant, environmentally sensitive, and/or geohazard prone, accumulations within the U.S. OCS.

5.0 Summary

Despite the recent accomplishments, the challenges facing the U.S .National Gas Hydrate Program remain significant. Since the publication of the 2006 Interagency Roadmap, three successful field programs in the U.S. as well as a series of resource assessment reports from the DOI, we know much more about the extent and potential productivity of gas hydrate reservoirs in the U.S. In addition, successful field programs in Alaska, Canada and offshore Japan have confirmed the technical feasibility of gas recovery utilizing depressurization and provided the first field trials of complementary technologies that could improve the overall carbon footprint of extraction. Ongoing study by the BOEM has identified extensive geophysical evidence for gas hydrate throughout the U.S. OCS that were initially validated by 2009 drilling and logging programs in the Gulf of Mexico. This drilling also validated the overall exploration approach being implemented in the program. Nonetheless, significant additional field validation and calibration opportunities are needed before the U.S. gas hydrate resource potential can be understood with confidence. Marine drilling and coring programs will be pursued, provided the ability to create and fund projects across multiple years. These drilling programs will likely be of shorter duration (testing fewer sites) than would have been envisioned in the prior Roadmap. Marine or arctic production tests of any useful scale are not feasible under current budget assumptions. Therefore, the prior *Roadmap's* goal of demonstrating productivity has been replaced in favor of various analytical efforts to identify the proper engineering design for tests should they occur and to further evaluate production potential through analysis of existing data or data collection within other international programs.

The program has developed a broad portfolio of work to assess the roles gas hydrate plays in global carbon cycling and in global climate. At present, this work suggests that the volumes of gas hydrate susceptible to destabilization under likely future climate scenarios is limited and that the primary impacts are likely to be oceanic, and not atmospheric, chemistry. Field programs and comprehensive numerical models to further confirm this tentative conclusion are needed.

The collaborating agencies recognize that an integrated effort in gas hydrate R&D may lead to enormous public benefits. One outcome will be an improved understanding of our natural environment, providing significant benefits through more informed decision-making on a wide variety of issues ranging from ocean policy to global climate change.

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