The Methane Hydrate Advisory Committee

Advisory Committee to the Secretary of Energy

July 26, 2019

The Honorable Rick Perry
Secretary of Energy
1000 Independence Avenue, SW
Washington, D.C. 20585

Dear Mr. Secretary

Enclosed is the Long-Range Methane Hydrate R&D Roadmap for 2020-2035, which presents the research priorities and strategies for the U.S. Department of Energy's Gas Hydrates Research Program to maintain the U.S. as the unrivaled global leader in natural gas hydrates.

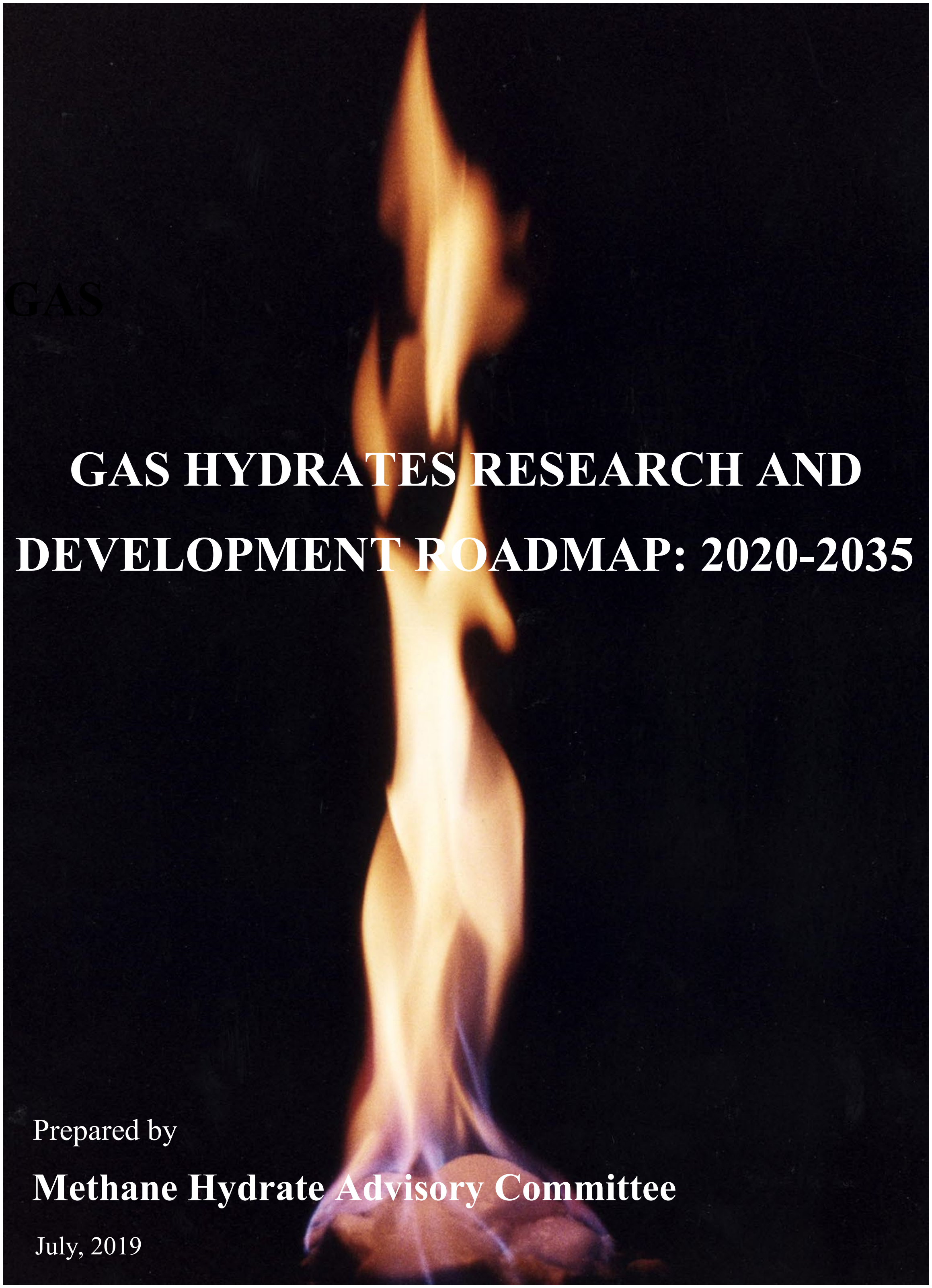
Gas hydrates provide an enormous future U.S. natural gas resource (2,500 TCF of gas), which is larger than the total U.S. technically recoverable gas resources. Critical to the commercialization of gas hydrates, which is important to enhancing long-term national energy security, important scientific questions must be addressed on the long-term production reliability of the massive gas hydrate resources.

The MHAC would appreciate your willingness to meet with representatives of our committee so that we can convey the key strategies presented in the Methane Hydrate R&D Roadmap to realize the enormous U.S. natural gas resource for ultimate commercialization.

Yours truly,

Carolyn A. Koh (Chair)   Miriam Kastner (Vice-Chair)

On behalf of the Methane Hydrate Advisory Committee



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GAS HYDRATES RESEARCH AND DEVELOPMENT ROADMAP: 2020-2035

Prepared by

Methane Hydrate Advisory Committee

July, 2019

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The Methane Hydrate Advisory Committee

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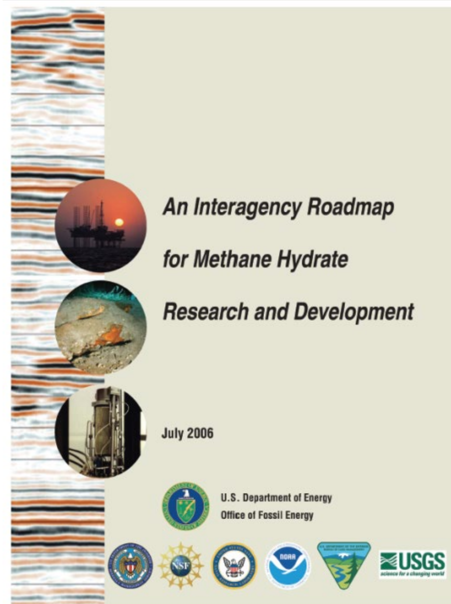
Abbreviations and Acronyms

ANS – Alaska North Slope
AOM – Anaerobic Oxidation of Methane
BLM – Bureau of Land Management
BOEM – Bureau of Ocean Energy Management
CSEM – Controlled Source Electromagnetics
DOE – Department of Energy
DOI – Department of Interior
EEZ – Exclusive Economic Zone
EM – Electromagnetic
FY – Fiscal Year
GHSZ – Gas Hydrate Stability Zone
GOM – Gulf of Mexico
IODP – Integrated Ocean Drilling Program
JIP – Joint Industry Project
LBNL – Lawrence Berkeley National Lab
MHAC – Methane Hydrate Advisory Committee
MHR&D – Methane Hydrate Research and Development
MMS – Minerals Management Service
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 Laboratory
NSF – National Science Foundation
PTSC – Pressure-Temperature Coring System
PSC – Pressure Coring System
QTR – Quadrennial Technology Review
R&D – Research and Development
SMTZ – Sulfate-Methane Transition Zone
TOC – Total Organic Carbon
TCT – Technical Coordination Team
UBGH – Ulleung Basin Gas Hydrate
USGS – United States Geological Survey

1.0 Executive Summary

This *Gas Hydrates Research and Development Roadmap* is an update to the joint effort of a Technical Coordination Team (TCT) comprised 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 draft May, 2013), and reviews the goals of the U.S. National Methane Hydrate R&D Program in the light of the current state of science and technology detailed in the 2015 Quadrennial Technology Review (QTR); Gas Hydrates R&D Technology Assessment. The Technology Assessment for Gas Hydrates R&D is based on extensive collaborative discussions within the Interagency Gas Hydrate Technical Coordination Team (TCT) and extensive review and public discussion via the Methane Hydrate Advisory Committee.



The 2013 Interagency Long-Range Methane Hydrate R&D Roadmap and this Roadmap update, recognizes that recent trends in gas production in the United States have significantly impacted the ability of the private industry to invest time and other resources in long term gas hydrates research. DOE, in its role as primary sponsor of extramural R&D, will continue to review its efforts to ensure program quality, transparency, and relevance through external peer review and other means. This Roadmap outlines research priorities and strategies to address the goals for the U.S. Department of Energy's Gas Hydrates Research Program and is designed to maintain the U.S. as a global leader in the science of natural gas hydrate.

2.0 Background

Gas hydrate is a natural form of "clathrate"; a unique substance 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 – methane hydrate). Research over the past three decades has revealed that gas hydrates exist in nature both as a void-filling material within shallow sediments (both onshore in the arctic and within deep-water continental margins) and as massive "mounds" (often in association with unique "chemosynthetic" communities that are drawing energy not from the sun, but from subsea floor sources of methane gas 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. In response, national R&D efforts (most notably in the U.S., Japan, China, India, and South Korea) have conducted a series of major scientific drilling programs to assess gas hydrate occurrence. Despite the recent increase in scientific drilling programs, the vast majority of potential gas hydrate occurrences world-wide remain unexplored. Industry has also conducted a limited number of studies, both privately and in concert with the government, to assess the implications of gas hydrates for operational (offshore drilling) safety. These studies have resolved the issue of safe drilling through gas hydrate-bearing sediments, but remain inconclusive regarding issues of long-term well integrity over extended periods of conventional oil and gas production. Therefore, despite the recent increase in scientific investigation, the nature, abundance, and behavior of naturally-occurring gas hydrates, and the potential response of those deposits to external perturbations—either natural or induced—remain poorly understood.

The Department of Energy Fossil Energy's Gas Hydrates R&D Program mission is to develop commercially viable technology and methodology for gas hydrates and to advance the potential for gas hydrates to become a dependable future energy resource through collaboration with industry, academia, international research organizations, and other U.S. government agencies. The Department of Energy was designated as the lead R&D agency for gas hydrate research by the Methane Hydrate Research and Development Act of 2000, and reauthorized by the Energy Policy Act of 2005. The QTR 2015 provides an update of the gas hydrate technology assessment domestically and internationally, and can be found at:

https://www.energy.gov/sites/prod/files/2016/03/f30/QTR2015-7C-Gas-Hydrates-Research-and-Development.pdf

3.0 The Department of Energy's Gas Hydrates R&D Program

The goal of the Department of Energy's Gas Hydrates R&D Program is to advance scientific understanding of gas hydrates through early-stage research, to evaluate the occurrence, nature, and behavior of the potentially enormous naturally-occurring gas hydrates resource within the U.S. permafrost and oceanic EEZ. Confirmation of the scale and nature of the potentially recoverable resource through complex drilling and coring programs needs to be carried out. It will be necessary to develop the technologies needed to safely and efficiently find, characterize, and recover methane from hydrates through field testing, numerical simulation, and laboratory experimentation.

Early challenges associated with evaluating the production of methane from hydrates included confirming the existence of reservoir quality occurrences, demonstrating the ability to reliably locate such occurrences, and developing the techniques/technologies required to enable such production. These challenges are being addressed through DOE and internationally supported research efforts.

The commercial viability of gas hydrate reservoirs is not yet known, but will depend on economic conditions in the future. One of the objectives of the Gas Hydrate R&D Program is to encourage the development of technology and methodology to reduce the overall cost of natural gas hydrate development. To date, a very limited number of short production tests have been conducted. A series of controlled scientific field experiments, followed by extended duration production tests are needed to quantify the rates and volumes at which methane can be extracted and to assess any potential environmental impacts.

Tool Development and Experimental Work: Development of new tools to aid in sampling and analyzing gas hydrate properties—including instruments for measuring physical properties of gas hydrate-bearing sediment samples in the field; pressure coring devices for sample collection, retrieval, and transport at controlled pressures; pressure core characterization tools for analyzing acoustic, geomechanical, and hydrological properties of samples in a laboratory setting are needed.

Depressurization is the Base Technology: Several methods of releasing natural gas from subsurface hydrates have been proposed, modeled, and tested under limited conditions. These methods include depressurization, hot fluid injection, anti-freeze fluid injection, electrical heating, and methane-CO_2 exchange. While all the above methods are theoretically feasible, it is scientific consensus that depressurization using production wells is most likely to succeed. This reflects the process' simplicity and ability to directly leverage established hydrocarbon recovery methods for more conventional resources.

Numerical simulations of gas hydrate reservoir response to depressurization has evolved greatly in recent years. Scientific and drilling programs have acquired detailed reservoir data from gas hydrate systems in Canada, Alaska, Japan, India, Korea, China, and the U.S. GOM that enable increasingly realistic reservoir characterizations. Though methane production is technically feasible using depressurization, there has not been a long-term test of methane production from hydrate systems.

4.0 Gas Hydrates R&D Roadmap: 2020-2035

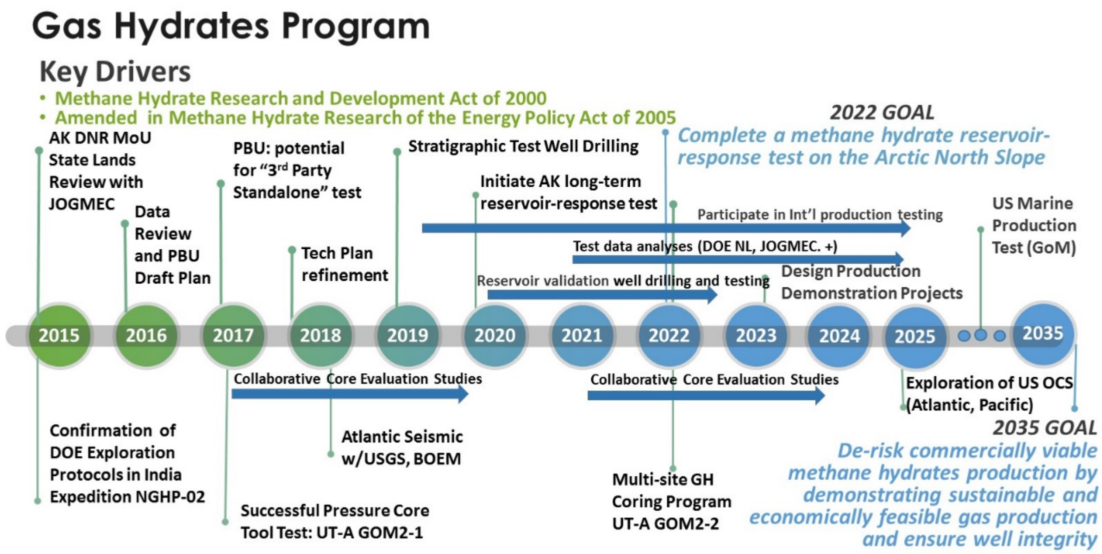
The following describes the overall nature, scale, and priorities for R&D in gas hydrates as recommended by the MHAC. As a technical advisory committee, our priorities are to demonstrate the technical feasibility of sustained natural gas production from methane hydrates through a long-term production test, to gather appropriate production data to support commercial viability modeling, to evaluate the methane hydrate reservoir quality in offshore U.S. resources, and to maintain global leadership in methane hydrate technology. There has been no long-term, sustained production test anywhere in the world. This leaves unanswered critical questions about recovery rates and production reliability over the many years that a commercial well would have to flow.

This 2020 *Gas Hydrates R&D Roadmap* represents a re-evaluation of prior 2013 *Draft TCT Roadmaps* and consensus recommendation for long-term goals for the DOE's Gas Hydrates Program going forward, as well as a relevant long-range vision of the nature, duration, and sequence of activities needed to achieve those goals. Specifically, the goals of the DOE program in gas hydrates are:

15-year Program Overarching Goals: 2020-2035

By 2022: Complete a methane hydrates long-term reservoir response test on the Arctic North Slope.

By 2035: De-risk commercially viable methane production by demonstrating sustainable and economically feasible gas production and ensure well integrity.



Areas of Research Focus

Reservoir Characterization through Drilling & Coring in the Gulf of Mexico: Gas hydrate accumulations (including high gas hydrate saturations) in coarse-grained/sand-rich reservoirs have been identified and investigated in several sites in the Gulf of Mexico since 2005 through extensive geophysical and drilling/pressure coring studies within the DOE' Gas Hydrate Program (in partnership with the US Geological Survey and Private Industry), including the GOM JIP Leg II and UT-GOM2-1 (Boswell et al., 2012a,b; Flemings et al., 2017; Haines et al., 2017; Ruppel et al., 2008). The Gulf of Mexico geophysical investigations have included: three-dimensional (3D) seismic data; logging-while-drilling (LWD) borehole data (Boswell et al., 2012; Collett et al., 2012); and high-resolution two-dimensional (2D) seismic data for information on gas flow and reservoir properties, including gas hydrate saturations, reservoir porosity, etc. (Haines et al., 2017). In addition, pressure coring provided detailed imaging of the hydrate bearing sediments and information on some the geomechanical and chemical properties of these sediments. The hydrate bearing reservoir in the Green Canyon GC 955 Unit that has been investigated in these studies is 232 km south of Port Fourchon, Louisiana, with water depths of 1975 to 2250 m, with the gas hydrate accumulations inferred to be above a salt-cored anticline, seaward of the Sigbee Escarpment (Fleming et al., 2018).

The 2017 UT-GOM2-1 expedition in the GC 955 unit included: pressure core recovery, imaging, and characterization, logging under pressure, and pore water analysis on depressurized cores to evaluate the "engineering capability" and reliability of the DOE pressure coring tool (PCTB). Twenty-one 1 m pressure core sections were successfully recovered, with many showing "minimal disturbance and the fine-scaled geologic structure of the reservoir". GC 955 has "three separate intervals of high gas hydrate saturation, with the Lithofacies comprising high bulk gas hydrate saturations in the range 66-87% (Flemings et al., 2018).

The ultimate objective of the GOM reservoir characterization studies is to have an accurate assessment of the extent and nature of gas hydrate accumulations and the production potential of the GOM hydrate-bearing reservoir. Critical to achieving this objective are the following three goals for the GOM Hydrate Bearing Reservoir Characterization.

GOM Hydrate Bearing Reservoir Characterization Goals (2020-2035)

Goal 1: *Understand heterogeneity, layering, overburden, and gas hydrate distribution with close spaced observation wells and logging & coring data*

Goal 2: *Describe and predict the behavior of the gas hydrate bearing reservoir during production, and validate the numerical reservoir simulators through production testing over an extended time period*

Goal 3: *Establish the fundamental understanding of the relationship between geomechanical behavior and gas hydrate saturation*

Goal 1: *Understand heterogeneity, layering, overburden, and gas hydrate distribution with close spaced observation wells and logging & coring data*

Previous estimates of the amount of gas in the gas hydrate reservoir in the GOM GC955-H are reported to be 6.6 x 10^8 m^3 (Haines et al., 2017) of gas and 5.5 x 10^8 m^3 of gas (Boswell, 2012b). These estimates do not include extensive free gas that could be also present in the reservoir, below the base of the hydrate stability (BGHS), and these estimates have uncertainties associated with them. The extent of in-place gas within the gas hydrate reservoir, along with the reservoir heterogeneity and connectivity will control the development of this gas hydrate resource. A better understanding of these factors is needed in order to obtain improved accuracy in the assessment of the gas hydrate resource potential in the Gulf of Mexico. The reservoir connectivity and other properties are dependent on the interlayering of shale and sand layers, as well as thin mud layers (Haines et al., 2017). Hence, improved understanding of the reservoir properties and controls on gas hydrate accumulations, including fluid flow and gas hydrate and free gas distributions, and structural and stratigraphical heterogeneity, position and thickness of hydrate-bearing layers and hydrate-free interlayers (Moridis et al., 2019) and depth and heterogeneity of the BGHS are critical to assessing the resource potential of the gas hydrate accumulations in the GOM. Hence, collecting high quality logging and high pressure coring data of "minimally disturbed" samples are essential to address these outstanding uncertainties in gas hydrate concentrations and distributions, reservoir quality, heterogeneity, and other reservoir properties. This also requires observation/monitoring wells that are in close proximity to the production wells to facilitate collection of representative lithology and stratigraphy data of the production well within the reservoir, with good well-to-well correlations.

Goal 2: *Describe and predict the behavior of the gas hydrate bearing reservoir during production, and validate the numerical reservoir simulators through production testing over an extended time period*

Numerical reservoir simulators provide a powerful and essential tool for predicting the estimated technical viability of gas production from gas hydrate bearing reservoirs. However, in order to achieve confidence in the accuracy of such a simulator tool, it is important that the models within the simulation tool have the correct physics and physical constraints, and furthermore, the reliability and accuracy of the simulation tool must be validated against actual field production test data. Hence, in addition to the logging and high resolution pressure coring data (outlined in Goal 1), it is critical that a production test is ultimately performed to validate the numerical simulation tool(s). Detailed knowledge of the reservoir properties described in Goal 1, including the gas hydrate saturations, distributions, and reservoir heterogeneity, lithology (and permeability) and stratigraphy data of the reservoir and sediments, and other properties are important inputs to the reservoir simulator model, as are the initial temperature distribution and pressure conditions within the reservoir, and wellbore pressures. These key reservoir property data are critical to developing an accurate "geological model" and hence the reliability of any numerical reservoir simulator model (Moridis et al., 2019). Having established the reliability and validation of the reservoir simulation model, the simulations enable critical parametric and long-term reservoir response and production studies to be performed, including gas and water production of the well(s) throughout time (years), physical property changes and their spatial distributions (*i.e.*, temperature, pressure, gas saturation, gas hydrate saturation, geomechanical stability changes, water-to-gas ratio) within the reservoir during long term production.

A further fundamental research need to assure the accuracy and reliability of assessments of the resource potential of the GOM gas hydrate bearing reservoir and the numerical reservoir simulation tool: is the relative permeability and capillary pressure of the gas hydrate-bearing layers and hydrate-free sediment interlayers within the reservoir, which can influence the gas production rates of the gas hydrate reservoir via heat and mass transfer effects.

Goal 3: *Establish the fundamental understanding of the relationship between geomechanical behavior and gas hydrate saturation*

The geomechanical stability of the gas hydrate bearing reservoir and the possibilities of subsidence or uplift at the seafloor, or at the top of the reservoir are critical environmental and safety considerations, particularly during gas production from gas hydrates (Moridis et al., 2019). Hence, there is a fundamental and critical need to understand the geomechanical response of the gas hydrate bearing reservoir during production and with different gas hydrate saturations. This understanding requires an accurate geological model of the hydrate-bearing reservoir (as detailed in Goal 1), with stratigraphy and lithology details of the gas hydrate layers, hydrate-free interlayers, overburden and underburden, etc. Understanding of the geomechanical properties of gas hydrates can be obtained from pressure cores recovered from the gas hydrate-bearing reservoirs of interest and also well log data, with observation wells enabling in-situ monitoring of geomechanical stability during gas production from the gas hydrate reservoir. This information can be used to correct and validate the reservoir simulation model(s).

Gas hydrate productivity testing and demonstration: The Program's intent is to gather appropriate and sufficient data to substantially de-risk the commerciality of gas production from methane hydrates in sub-permafrost sandstone reservoirs. Known hydrate accumulations are present within the Milne Point, Prudhoe Bay, and Kuparuk River oil fields on the North Slope of Alaska where they are well documented in 3-D seismic surveys and have been penetrated and logged in numerous oil production wells. The world's first long-term production test (*i.e.,* one year or greater) will be performed within the existing infrastructure of the Prudhoe Bay Unit where the testing can occur year-round using an existing gravel pad. The initial stratigraphic test well has been drilled and logged and has confirmed the presence of hydrates with two sandstone intervals near the base of permafrost confirming the viability of the location as suitable for a long-term test. The testing will require the future drilling of a dedicated production well along with an additional monitoring well. To reduce commerciality risk and to understand the reservoir behavior beyond the near wellbore of the producing well, production testing of a year or more is required. The long-term test is being designed in order to be acceptable to the Prudhoe Bay Unit partners and the State of Alaska in order to not impact ongoing production activities.

Previously, 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). These tests provided necessary scientific data and operational experience to enable and justify scale-up to long-term tests.

However, short-term tests do not provide sufficient production data to enable assessment of commercial-scale production with significant confidence. It is envisioned that two additional field tests, a production test followed by a commerciality pilot, will be performed between 2020 and 2035.

The primary goal of the production test (in around 2021-2024) on the Alaska North Slope is to provide sufficient performance and information support for the ultimate commerciality of gas production from hydrates and to convince commercial companies to invest in a larger-scale commerciality pilot. This first production test will not directly demonstrate commerciality — even if fully successful. This is due to the maximum allowable production rates during the test, which will be lacking in gas and water export from the well site, so as not to impact the ongoing conventional oil and gas operations. Rather, the goal of the production test is to indirectly substantiate the potential commerciality by:

- Demonstrating sustainable, safe and stable production for at least a year or more, including sand control, geomechanical reservoir and well integrity, and well shut-in and start-up,
- Reliably and sustainably producing gas at modest rates (about 10x below commercial gas rates),
- Gathering sufficient high-quality downhole pressure, production, and seismic data to enable high confidence in model-based solutions (numerical reservoir simulation and semi-analytical solutions) of commercial-scale production, and
- Obtaining data needed to construct better models for estimation of technical size and economic quality of hydrates resources in sandstone reservoirs.

Gas hydrate productivity testing and demonstration (2020-2035)

Goal 1: *First long-term reservoir response test to help determine if coarse-grained permafrost associated hydrate accumulations can produce at sustainable rates over the long term.*

Goal 2: *Second long-term reservoir response test to substantiate simulation and semi-commercial rates that could support commercial viability.*

Goal 1: *First long-term reservoir response test to help determine if coarse-grained permafrost associated hydrate accumulations can produce at sustainable rates over a long term.*

As previously stated, this will be the first long-term production test for methane hydrates in the world. Industry is unlikely to invest sizably in hydrate development, unless the economic risk can be substantially reduced since the upfront costs of a commercial application in permafrost regions will be large and payback times may be long. Currently, a significant uncertainty exists regarding hydrate reservoir performance during production (*e.g.*, maximum sustainable rates and production decline curves over time). This is because prior pilots were short in duration, which provided critical information about production techniques and initial production behavior, but did not probe large-scale reservoir performance. Short tests largely only dissociate hydrates near the wellbore (*e.g.*, a few 10's of meters), require little heat to transfer from outside the reservoir (*e.g.*, the over and under-burden), and do not strongly probe the impact of geologic and flow heterogeneity on the dissociation front.

This long-term reservoir response test is expected to provide observational data needed to verify and improve predictive capacity of reservoir simulations to model hydrate production rates and recovery. Also, this pilot will determine if existing technologies and completion approaches are adequate for long term problem free production of coarse-grained permafrost associated hydrate accumulations (sand control, geo-mechanical reservoir and well integrity, and well shut-in and startup etc.). The two observation wells (stratigraphic well and monitoring well) will provide a systematic observation of downhole, surface and seismic information to understand reservoir and field dynamics in a coarse-grained permafrost hosted accumulation.

Goal 2: *Second long-term reservoir response test to substantiate simulation and semi-commercial rates that could support commercial viability.*

Assuming the production test is successful, a multi-year large-scale pilot is envisioned for around 2029-2034 to directly demonstrate commerciality of hydrate gas production. To achieve commercial production rates, export capability will be required for produced gas and water, so not to be limited by currently available site facilities. Adding the capacity to export the gas off the test pad will increase the project complexity and cost and hence require the support of the Prudhoe Bay Unit operators. It is envisioned that this pilot would be carried out on the same site as the production test, or near to it. Produced water and gas would be piped, mixed, and processed with conventional gas being produced on the Alaska North Slope.

Assuming the production test produces favorable results, between the end of the production test and start of a commerciality pilot, additional tests may be carried out at the production test site. Such tests may include continued low level production to further explore long-time production behavior and include additional experience gathering on start-up and shut-in production operations. This work would strongly leverage the previous investments, experience, and infrastructure of the site.

Gas Hydrate Potential in U.S. Offshore Waters: In the presence of significant biogenic and/or thermogenic gas, gas hydrate accumulation in marine settings is driven by diffusion and/or advection of gas into appropriate sedimentary facies (*e.g.,* coarse grained sediment gravity flow deposits, contourites, or volcanic ashes). The balance between diffusion- or advection-dominated systems is a direct function of the underlying deformation regime, where deformation (folds, faults, fractures) creates dipping stratigraphic horizons and/or structural conduits for fluid migration to, within, and through the gas hydrate stability zone. Previous Ocean Drilling Program (ODP) drilling on the U.S. Atlantic (Blake Ridge) and U.S. Pacific NW (Hydrate Ridge) and in many other marine sites globally has revealed high saturation gas hydrates are most common in advective environments in the presence of appropriate reservoir facies. The presence and extent of appropriate reservoir facies within the gas hydrate stability zone (GHSZ) is a function of the evolution of continental margin sedimentary environments through time, which is affected by sea levels, climate, and tectonics. Limits to gas hydrate accumulation in the marine environment include a lack of high total organic carbon (TOC) to drive methanogenesis, a limited extent of the GHSZ, gas losses at seafloor seeps, geochemical/microbial consumption of methane via anaerobic oxidation of methane (AOM) at the sulfate-methane transition zone (SMTZ), and inappropriate reservoir lithofacies. The interplay and timescales of each of these factors remains difficult to constrain, yet defines the marine gas hydrate system.

In-order-to assess the extent and reservoir viability of gas hydrates on the U.S. offshore margins a full systems approach is needed to place constraints on the variables in the marine gas hydrate system. This approach has proven successful in previous ODP drilling in gas hydrate systems globally, however, the results to date reveal significant variability in subsea seafloor gas hydrate accumulations, including ideal reservoir conditions that remain gas hydrate-free.

Gas Hydrate Potential in U.S. Offshore Waters (2020-2035)

Goal 1: *Complete the existing, full systems approach, focused studies on the Alaska North Slope and in the Gulf of Mexico*

Goal 2: *Identify significant gas hydrate systems on non-Gulf of Mexico and Alaska North Slope margins through exploratory geophysical surveying/drilling/coring*

Goal 3: *Advance our knowledge of how and at what timescales gas hydrate systems form and evolve through time in different tectonic settings, are they renewable?*

Goal 4: *Constrain mechanisms for methane formation and loss from reservoirs in different tectonic settings (global methane carbon cycling)*

Goal 5: *DOE continues to play a coordinating role in engagement with and development of complementary efforts from other agencies in resource assessments, carbon cycle studies and seafloor mapping efforts both on U.S. margins and abroad*

Goal 1: *Complete the existing, full systems approach, focused studies on the Alaska North Slope and in the Gulf of Mexico*

The existing Alaska North Slope project includes an extended reservoir response experiment followed by a long-term, full-scale production test in the permafrost gas hydrate system on the Alaska North Slope. The existing Gulf of Mexico project (GOM^2) includes reservoir characterization through drilling & pressure coring in preparation for a marine production test by 2030. Results will allow for design and implementation of a full-scale demonstration of gas hydrate reservoir deliverability in a permafrost setting. Scientific drilling and coring are required to assess the extent, quality, and economic viability of U.S. offshore reservoirs in the GOM, to fully characterize and understand a marine gas hydrate system, and to provide foundational data sets to design and implement a marine production test by 2030.

Goal 2: *Identify significant gas hydrate systems on non-Gulf of Mexico and Alaska North Slope margins through exploratory geophysical surveying/drilling/coring*

Reconnaissance geophysical mapping including bathymetry, backscatter, 2-D and 3-D seismic imagery, and controlled source electromagnetic (CSEM) represent well developed tools and technologies for identifying seafloor methane seeps, BSRs, seafloor and sub-seafloor gas hydrate and methane derived authigenic carbonates. This reconnaissance mapping is essential for identifying new, potential economically viable gas hydrate systems. Once identified, these geophysical data should be used to focus on follow-up logging while drilling (LWD) efforts and sediment and gas hydrate sampling through pressure coring to quantify gas hydrate saturations and potential for production. An assessment of existing and planned geophysical data sets on all U.S. margins is a first step toward future exploration. Based on existing data, specific U.S. offshore margin research sites can already be proposed and follow-up geophysical survey(s), LWD logging, and coring expeditions could be supported. Multiple exploration targets on several U.S. offshore margins could be identified by 2030.

Goal 3: *Advance our knowledge of how and at what timescales gas hydrate systems form and evolve through time in different tectonic settings, are they renewable?*

Constraining time in gas hydrate systems remains a fundamental challenge for the community. Gas hydrate systems can exist and evolve through sedimentary sequences during and/or after sedimentation. This means the timing of gas charge and the mechanisms that drive it may not be closely related to the depositional age of the sediments, which is much easier to constrain. Advances in U-Th dating of authigenic carbonates associated with AOM at the SMTZ provide some constraint on the age of AOM and the potential timing of past seafloor venting, but do not reveal much about the timing of gas charge, the duration of the gas hydrate system, or the age, cyclic charge history, or recycling of gas hydrate in a reservoir through time. Recent clumped isotope applications to reconstruct formation temperatures of the methane, hence information on the gas source, local or migrated, are also promising and might be equated to time of formation, however, there can be a significant separation between the timing of gas formation, migration, and the timing of gas hydrate formation and recycling. Effort needs to be focused on advancing laboratory techniques and in integration of data sets from systems approach-driven gas hydrate investigations. These efforts can and should capitalize on existing and ongoing drilling/coring efforts in gas hydrate systems globally and not be restricted to studies in U.S. margin environments. Research efforts towards this goal will continue through 2030.

Goal 4: *Constrain mechanisms for methane formation and loss from reservoirs in different tectonic settings (global methane carbon cycling).*

Gas hydrates in the marine environment represent an ephemeral reservoir of natural gas (mainly methane). The susceptibility of this reservoir to changes in pressure and temperature over sea level cycles has been suggested, but a direct association of past seafloor methane emissions with destabilized gas hydrate remains difficult to demonstrate. Seafloor methane emissions, whether or not associated with gas hydrate, represent a potentially significant flux of methane to the ocean through time. When seafloor methane from seeps are oxidized in the overlying water column, CO_2 concentrations increase, potentially contributing to mostly local ocean acidification. There are currently no global and few regional methane seep assessments in the modern ocean and few reliable proxies for paleo-methane emissions. Continued efforts to map seafloor methane seepage within and outside of the GHSZ should be completed across the U.S. continental margins in an effort to constrain the extent of seafloor methane seepage in the modern ocean. In these regions of active seepage, sediment cores could be collected to determine the seepage history through geologic time. Recent work in sediment cores from gas hydrate systems has resulted in the development of several paleo-SMTZ proxies from barites, sulfides, and authigenic carbonates, which are all well-preserved in the geologic record. Although a shoaling SMTZ does not necessarily implicate methane emission from the seafloor, it is the closest proxy that currently exists. These studies and proxies should be expanded, compared with one another in the same geologic records, equated to time in the stratigraphy, and compared with known mechanisms that might drive seafloor methane emissions. These modern ocean seep mapping and paleo-seepage reconstruction studies should encompass multiple tectonic environments and be a focus area for research through 2030.

Goal 5: *DOE continues to play a coordinating role in engagement with and development of complementary efforts from other agencies/groups (IODP/MeBO Drilling), other agency (USGS/BOEM) resource assessments, NSF/NOAA carbon cycle studies, environmental implications, and seafloor mapping efforts both on U.S. margins and abroad.*

Collaboration and cooperation of scientists working on gas and gas hydrate related studies on both U.S. global margins is essential. Interagency agreements and collaborations that fully engage the government, academic, and private sectors are also essential and will enable us to capitalize on existing data sets and develop future comprehensive studies. These efforts remain at the core of all DOE efforts and will continue as the Gas Hydrate Program grows and evolves through time.

5.0 Summary

In summary, the goals and strategies of this Gas Hydrates R&D Roadmap support the Gas Hydrate Program to maintain the technical U.S. leadership in sustained domestic natural gas production from massive gas hydrate resources that will lead to major commercialization in the U.S. and enhanced long-term national energy security. Also, this Roadmap expands on the priorities from the Committee's November 12, 2018 Recommendation Letter to the Secretary to ensure continued U.S. technical leadership in methane hydrate support for which the following would be essential:

- Extended reservoir response experiment followed by a long-term, full-scale production test on the Alaska North Slope.
- Gulf of Mexico reservoir characterization through drilling & coring, and geophysical investigation.
- Evaluation of hydrate reservoir quality in offshore U.S. waters, other than the Gulf of Mexico and the Alaska North Slope.

The fundamental needs in gas hydrate R&D are the development of science and technology that enable: 1) an accurate assessment of the nature and occurrence of gas hydrates within the U.S.; 2) refinement and demonstration of technologies that can achieve production in an economically-optimal and environmentally responsible manner; and 3) determination and effective public communication of the role of gas hydrate deposits in natural geohazards and in the natural sequestration and cycling of carbon in response to long-term processes.

Recent successful field programs have confirmed the technical feasibility of natural gas recovery utilizing depressurization and provided the first field trials of complementary technologies. However, significant additional field validation and calibration opportunities are needed before the U.S. gas hydrate resource potential can be understood with confidence. Recent trends in unconventional gas production have impacted the ability of private industry to participate in gas hydrate R&D. Until private industry re-engages in this effort, gas hydrate R&D private-public partnerships could be augmented through cross-agency collaboration and engagement with international partners.

Success in these efforts would provide a full scientific evaluation of the potential for gas hydrates to provide an additional option to address potential future energy needs for the U.S. and for key international allies.

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