Paper #1-11

METHANE HYDRATES

Prepared for the
Resource & Supply Task Group

On September 15, 2011, The National Petroleum Council (NPC) in approving its report, *Prudent Development: Realizing the Potential of North America's Abundant Natural Gas and Oil Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Task Groups and/or Subgroups. These Topic and White Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic and White Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 57 such working documents used in the study analyses. Also included is a roster of the Task Group for which this paper was developed or submitted. Appendix C of the final NPC report provides a complete list of the 57 Topic and White Papers and an abstract for each. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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TOPIC PAPER: GAS HYDRATES: RESEARCH STATUS AND POTENTIAL AS FUTURE ENERGY SUPPLY FOR THE UNITED STATES

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I Executive Summary

Gas hydrate is a solid naturally-occurring substance consisting predominantly of methane gas and water that occurs broadly in shallow sediments in Arctic regions and on the outer continental shelves. The scientific consensus is that gas hydrate occurs in large volumes in nature and therefore has potentially significant, but as yet poorly constrained, implications for both long-range energy supply and for a variety of natural environmental processes. This topical paper provides a status report on ongoing research into natural gas hydrate, with a primary focus on U.S. domestic energy supply potential through the year 2050.

Domestic and international gas hydrate research and development has continued to accelerate, with many significant recent scientific findings and technological advancements. Gas hydrate prospecting approaches are rapidly maturing and have been tested by successful drilling of geologically-geophysically delineated prospects in both Alaska and in the Gulf of Mexico, where the thickness and saturation of the gas-hydrate-bearing formations was closely predicted ahead of drilling. Supported by the successful program at the Mount Elbert test site in 2007, the U.S. Geological Survey (USGS) produced the first assessment of technically-recoverable gas volumes (assuming existing technology) from gas hydrate accumulations. The USGS study (*Collett et al., 2008*) estimated a mean value of 85 trillion cubic feet (Tcf) of technically-recoverable gas from gas hydrate accumulations on the Alaska North Slope. In 2009, a government-industry-academia collaborative drilling program confirmed the presence of gas hydrate at high concentrations in reservoir-quality sands at multiple sites in the deepwater Gulf of Mexico (*Boswell et al., 2010*), providing support for earlier federal assessments of more than 6,700 Tcf gas-in-place in the Gulf of Mexico within sand reservoirs (*Frye, 2008*).

Work toward understanding gas hydrate production potential has been highlighted by a 2007–2008 Japanese-Canadian research effort at the Mallik site, onshore northwestern Canada. This program conducted the most extensive production testing experiments yet accomplished, establishing the ability to sustain, over a 6-day period, gas flow at rates that exceeded modeling expectations (*Kurihara et al., 2011*). Based on these results, and prior research findings of substantial resources in the Nankai Trough (offshore southeast Japan) (*Tsuji et al., 2009*), Japan has determined to proceed into the next phase of its R&D program, including two extended-term marine production tests, with the first to be conducted as early as 2012 (*Yamamoto et al., 2011*). In the U.S. Arctic, the Department of Energy (DOE) and the USGS have developed plans to conduct multiple field production test experiments in collaboration with Alaska North Slope operators beginning as early as 2012. In Korea, positive results from a late 2007 marine drilling program resulted in approval to conduct an extensive follow-on program in mid-2010 designed to identify potential production testing sites (*Lee and Ryu, 2011*). The Government of India is similarly planning for a second drilling program to follow up on a landmark 2006 expedition (*Collett et al., 2006*), also with a prime goal of determining optimal production test locations. China also reported success from its early 2007 marine drilling program (*Yang et al., 2008*), and most recently, has announced the discovery of significant potential gas hydrate resources on the Tibetan plateau (*Lu et al., 2010*).

Although the ultimate role of gas hydrate as a commercially-viable resource remains uncertain, results from field programs to date have been consistently positive. Most notably, gas hydrates may now be considered in terms of recoverable volumes from specific prospects, with a developing exploration rationale that holds promise for discovery of significant produceable resources. Work remains to confirm the marine resource volumes within potentially produceable accumulations through exploratory drilling programs; to further refine the tools for gas hydrate detection and characterization from remote sensing data; to determine the details of gas hydrate reservoir production behavior, and to understand the potential environmental impacts of gas hydrate resource development. The results of future production tests will be a key step to determining the prospects of this resource for commercial production.

Several scenarios for gas hydrate development in the U.S. through 2050 are presented, although the limited data make such scenarios highly speculative. In a low-case scenario, the vast majority of marine accumulations will be non-commercial for the foreseeable future and production in the U.S. will be restricted to the highest-quality occurrences on the Alaska North Slope. In such a case, gas hydrate production may peak at ~10s to 100s of billion cubic feet (Bcf) per year. In a high-case scenario, exploration and production efforts confirm initial resource estimates and production modeling, resulting in the addition of ~1000 trillion cubic feet (Tcf) of recoverable resources and annual production approaching 10 Tcf/year by 2050 from both onshore and offshore production. This scenario considers the addition of U.S. marine resources beyond the Gulf of Mexico. A mid-range scenario suggests marine resources develop, but slowly, and that only the largest accumulations are rendered recoverable during the scenario time frame. In such a case, production by 2050 at levels of several Tcf/year is assumed.

II Background

"Methane hydrate" is the common term for a solid formed from the combination of methane gas and water. Hydrates are technically clathrate compounds, unique, non-stoichiometric (no set chemical composition) substances in which molecules of a "host" material form an open solid lattice that enclose, without direct chemical bonding, appropriately-sized molecules of a "guest" material. In nature, the most common host is water and the most common guest is methane, although other guest molecules can also be present. Research during the past three decades, including a series of large-scale drilling programs in the past 5 years, has revealed that gas hydrate exists in a wide variety of forms and geologic settings within sediments both onshore Arctic and within deep-water continental shelves (**Figure 1**). These forms range from void-filling material, to complex networks of grain-displacing gas-hydrate-filled veins, to massive "mounds" (often in association with unique chemosynthetic biota) on deep sea floors.

Gas hydrate was first recognized in Siberian Russian (*Makogon et al., 1972* and others) in the late 1960s; but as recently as the 1980s remained widely considered to be an inconsequential component of the natural environment. However, by the mid 1990's, findings from expeditions of the Deep Sea Drilling Program had persuaded many in the scientific community that gas hydrate serves as one of the largest storehouses of potentially-mobile organic carbon on the planet (*Kvenvolden, 1988a*). As a result, the science of gas hydrate remains relatively new, and despite the recent increase in scientific drilling programs, the vast majority of potential gas hydrate occurrences world-wide remain unexplored.

The study of natural gas hydrate is highly complex. Recent research indicates that the creation of laboratory samples of gas hydrate within natural sediments that mimic those found in nature is exceptionally difficult; therefore, future major advances in scientific understanding will rely heavily on work in the field integrated with focused laboratory analyses and complex numerical modeling. However, arctic and deepwater field ventures are costly. Even in the best-funded international programs, major field programs can only be launched every few years. Furthermore, the inherent dissociation of gas hydrate upon removal from *in situ* temperature and pressure regimes has required the development of specialized equipment to recover, preserve, and analyze natural samples. Such tools are only now becoming tested, reliable, and widely available (*Schultheiss et al., 2009*).

Within the United States, industry gas hydrate R&D is focused on those issues that impact ongoing operations: primarily flow assurance and shallow drilling hazard assessment and mitigation. Domestic research into gas hydrate as a resource and as a constituent of global carbon cycling is primarily conducted by federal agencies and academia, with industry collaboration primarily enabled by a U.S. National R&D Program lead by the DOE in coordination with the USGS, the Bureau of Ocean Energy Management , Regulation, and Enforcement (BOEMRE), the Bureau of Land Management (BLM), the National Oceanic and Atmospheric Administration (NOAA), the Naval Research Laboratory (NRL), and the National Science Foundation (NSF). Although each federal agency participating in this coordinated effort independently prioritizes and conducts its own efforts as they pursue their individual organizational missions, two interagency coordination committees work to ensure that these efforts are planned and

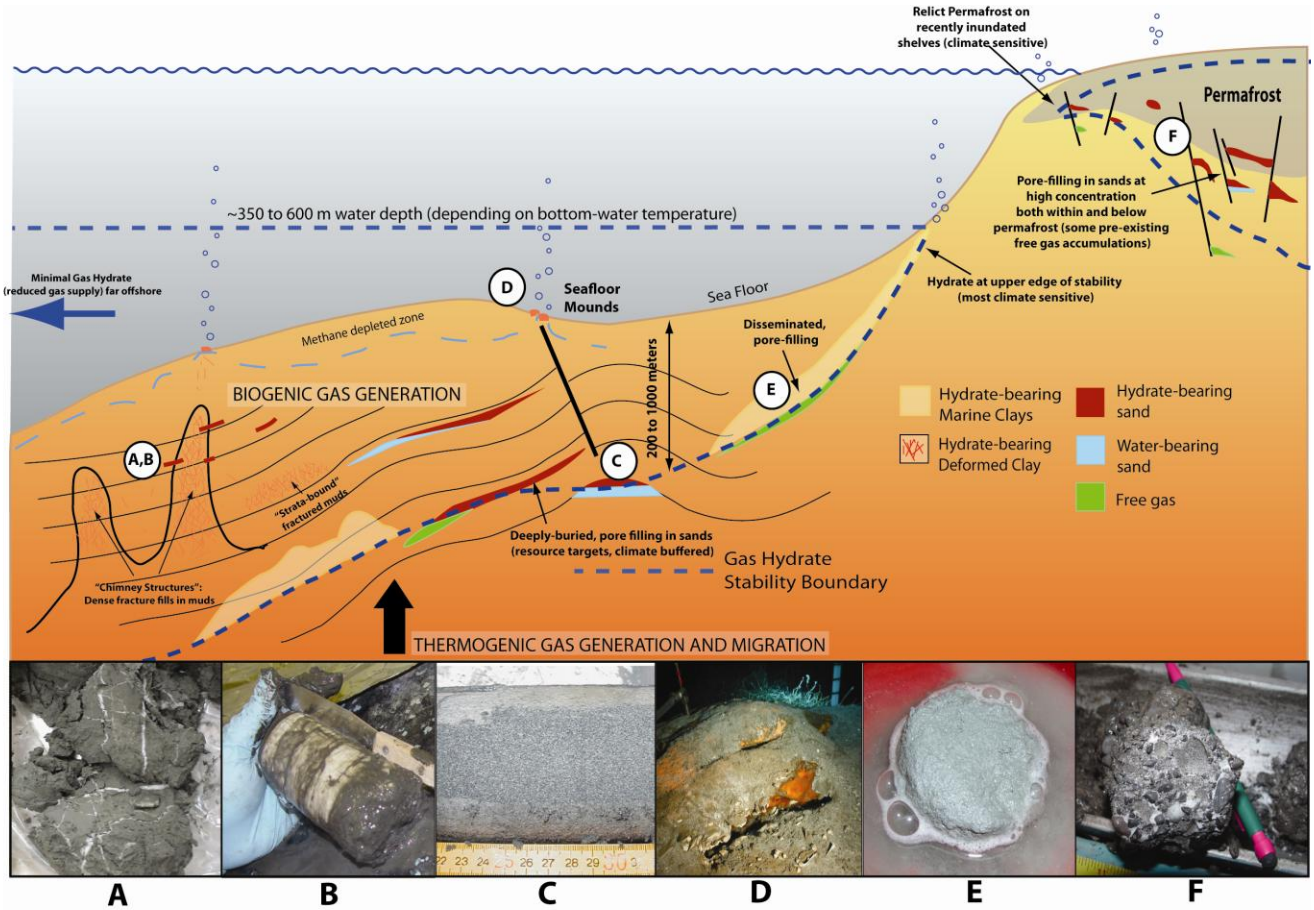

Figure 1: Geologic environments of gas hydrate occurrence. Photos of gas hydrate morphologies observed in nature are shown along bottom courtesy of: A) UBGH-01 Science Party; B) NGHP-01 Science Party; C) JOGMEC; D) Ian MacDonald; E) GMGS-01 Science Party; F) JOGMEC, NRCan, USGS.

conducted in a manner that reduces redundancies and maximizes synergies. The advances in gas hydrates R&D in recent years, particularly the success of field programs in Alaska (in 2007) and in the Gulf of Mexico (in 2005 and in 2009) have thus far kept the U.S. National Program on track to achieve the long-term goals and priorities of the program (*NRC, 2010*).

III State of Gas Hydrate Science and Technology

Gas Hydrate Resource Estimation: The total volume of in-place natural gas housed in gas hydrates continues to be poorly constrained with recent estimates continuing to range over several orders of magnitude (*Boswell and Collett, 2011*). However, there is an increasing awareness that the total in-place resource volume is not fully relevant to the question of gas hydrate energy potential. Instead, there is currently a broad consensus among the major international R&D efforts that the subset of total gas hydrate resources that is housed in sand reservoirs are the most favorable targets for initial evaluation of production potential (*Collett et al., 2009; Boswell, 2009*). This focus is due to accumulated field and laboratory evidence that indicates sand-dominated systems, due primarily to their intrinsic high permeability, are necessary to enable the accumulation of gas hydrate to concentrations that are consistent with extraction (sand-hosted gas hydrates typically occur at saturations ranging from 50 to ~90%). As discussed below, it is also the permeability of the sand matrix that makes well-based production feasible. Since the 2007 NPC Topical Paper on gas hydrate potential (*Kleinberg, 2007*), two efforts in the U.S., and one in Japan, have produced rigorous assessments that provide an initial indication of gas hydrate resource volumes in sand reservoirs in the most well-studied gas hydrate provinces. Based on these recent assessments from three of the best-studied gas hydrate provinces, and the likelihood that gas hydrate bearing sand reservoirs exist within other continental shelf locations worldwide, it seems plausible that global gas hydrate resources within sand reservoirs is substantial. Estimation of this volume is difficult at present, but given the available information, *Johnson (2011)* has provided an initial, probabilistic estimate with a mean value of 43,000 Tcf. The potential recoverability of this resource, both technically and economically, is discussed in a later section.

Gas Hydrate Resources in the northern Gulf of Mexico: In early 2008, the Minerals Management Service (MMS, now BOEMRE) reported on the results and methodology of a cell-based, statistical assessment of in-place gas hydrate resources in the Gulf of Mexico (*Frye, 2008*). This assessment took full advantage of the Department of Interior's (DOI's) extensive well and seismic databases, as well as considerations of various controls on gas hydrate occurrence, including issues such as methane generation capacity, lateral variations in thermal gradients, and most particularly, reservoir lithology. The report indicated 21,444 Tcf gas in-place in hydrate form. More significantly, the mean statistical estimate of gas housed in gas-hydrate-bearing sand reservoirs was slightly more than 6,700 Tcf.

In April 2009, the Gulf of Mexico gas hydrates Joint Industry Project (the JIP) conducted "Leg II" logging-while-drilling (LWD) operations at seven wells in three sites (*Boswell et al., 2010; Collett et al., 2010*). The sites were specifically selected with the intent of discovering gas-hydrate bearing sand reservoirs. Prior to this expedition, only one such occurrence (within the Oligocene Frio Formation – the Alaminos Canyon 818 site; *Boswell et al., 2009*) had been documented in the Gulf of Mexico. Selection of JIP Leg II drill sites were the result of a geological and geophysical prospecting approach that integrated direct geophysical evidence of gas hydrate-bearing strata (*Shelander et al., 2010*) with evidence of gas sourcing, gas migration, and occurrence of sand reservoirs within the gas hydrate stability zone (*Hutchinson et al., 2008*).

Two wells drilled in Walker Ridge block 313 (WR-313) confirmed the pre-drill predictions of gas hydrate at high saturations in multiple sand horizons with reservoir thicknesses up to 50 ft (**Figure 2**) (*Shedd et al., 2010*). In addition, drilling in WR-313 discovered an unpredicted, thick, strata-bound

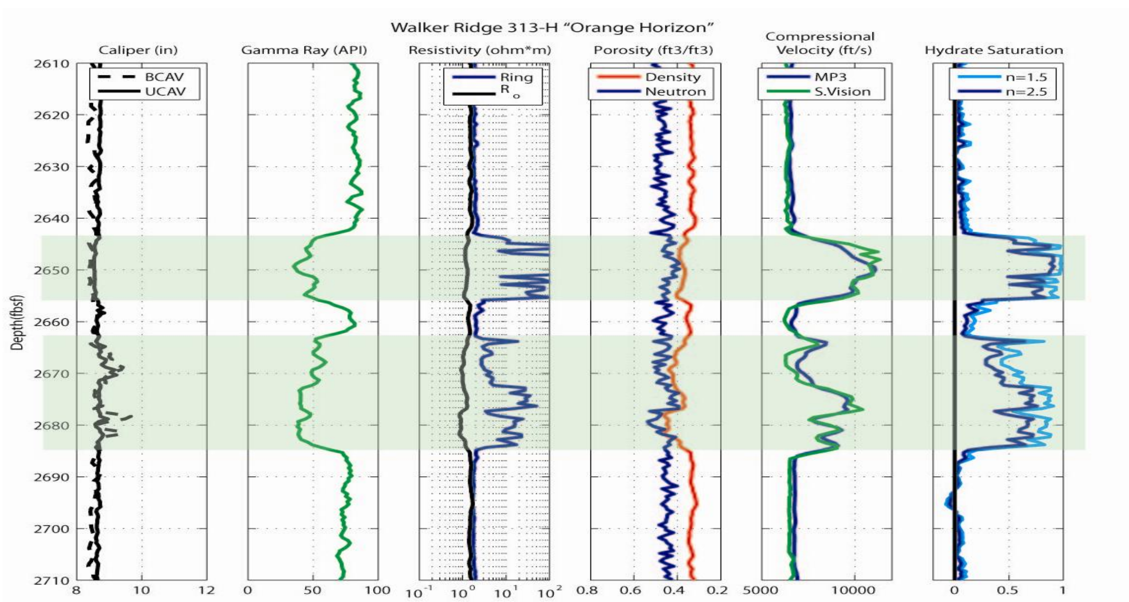

Figure 2: Logging-while-drilling data for gas hydrate-bearing sand in Walker Ridge block 313. Light green interval is the hydrate-bearing section (from *Boswell et al., 2010*, courtesy OTC).

interval of shallow fine-grained sediments with abundant gas hydrate filled fractures. Similarly, two of three wells drilled in Green Canyon block 955 (GC-955) confirmed the pre-drill prediction of extensive sand occurrence with complex gas hydrate fill along the crest of a structure with positive indications of gas source and migration (*McConnell et al., 2010*). Well GC955-H discovered ~100 ft of gas hydrate in sand at high saturations. Two wells drilled in Alaminos Canyon block 21 (AC-21) were consistent with, but not conclusive of, the pre-drill prediction of extensive occurrence of gas hydrate in shallow sand reservoirs at low-to-moderate (20 to 30%) saturations (*Frye et al., 2010*). In addition to providing initial support to the 2008 MMS assessment results, the JIP Leg II program successfully deployed the most advanced LWD tool string within the deepest and most technically challenging wells yet attempted in a marine gas hydrate program (*Collett et al., 2010; Mrozewski et al., 2010*). The JIP plans to expand upon these results with future field operations including recovery and analyses of gas hydrate-bearing sediment cores under pressure.

Gas Hydrate Resources on the Alaska North Slope: In 2008, the USGS, in collaboration with the BLM, delivered the first estimate of technically-recoverable gas hydrate resources anywhere in the world (*Collett et al., 2008*). The geologically-based assessment followed 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 supported in 2007 by the successful drilling of two inferred gas hydrate accumulations at the Mount Elbert site in the Milne Point Unit (*Lee et al., 2011*). In total, USGS reported a mean estimate of 85.4 Tcf of natural gas from gas hydrate as technically recoverable with existing exploration and production (E&P) technologies (**Figure 3**). Though this gas hydrate is considered to be technically recoverable, its commercial viability will ultimately depend on the development of methods to achieve commercial production rates, as well as the expansion of transportation and utilization options for Alaska North Slope gas.

Total Petroleum System *and Assessment Unit*	Field Type	***Total Undiscovered Resources***							
		Gas (BCFG)				***NGL (MMBNGL)***			
		F95	**F50**	**F5**	**Mean**	**F95**	**F50**	**F5**	**Mean**
Northern Alaska Gas Hydrate TPS									
Sagavanirktok Formation Gas Hydrate AU	***Gas***	6,285	19,490	37,791	20,567	0	0	0	0
Tuluvak-Schrader Bluff-Prince Creek Formations Gas Hydrate AU	***Gas***	8,173	26,532	51,814	28,003	0	0	0	0
Nanushuk Formation Gas Hydrate AU	***Gas***	10,775	35,008	68,226	36,857	0	0	0	0
Total Undiscovered Resources		**25,233**	**81,030**	**157,831**	**85,427**	**0**	**0**	**0**	**0**

Figure 3: Summary results of USGS assessment of technically-recoverable gas hydrates on the Alaska North Slope (from Collett et al., 2008a).

Gas Hydrate Resources in the Nankai Trough, Japan: In 2008, the Japanese MH-21 program released an assessment of gas in-place within gas hydrate accumulations within a 5,000-sq. mile area of the eastern Nankai Trough, off the southeastern coast of Japan (*Fujii et al., 2008*). This assessment included rigorous probabilistic analyses of geophysical data calibrated with the results of an extensive drilling and coring program conducted in 2004 (*Tsuji et al., 2009; Fujii et al., 2009*). The study determined a mean total estimate of 40 Tcf of gas in place, with 20 Tcf of that volume assessed to occur within ten discrete high-concentration accumulations within fine-grained turbiditic sand reservoirs. *Fujii et al. (2008)* reported that this area of initial study represents only 10% of the total area around Japan that is currently considered prospective for gas hydrate.

Gas Hydrate Resources in Arctic Canada: To date, gas hydrate resource assessment studies in Canada have focused on permafrost-associated occurrences. Recent studies, based on extensive work at the Mallik research site and review of existing well data, suggest ~150 to 360 Tcf gas-in–place in the Mackenzie Delta/Beaufort Sea region (*Osadetz and Chen, 2010*). A more poorly constrained estimate for the Canadian Arctic Archipelago ranges from 665 to 21,700 Tcf (*Majorowicz and Osadetz, 2001*).

Prospects for Extending Production beyond Sand Reservoirs: In the US, massive gas hydrate occurrences located on the seafloor ("mounds") are not considered resource targets as they host sensitive and unique communities of chemosynthetic biota and are typically of very small size. Gas hydrate as it most commonly occurs, as large but lean (hydrate saturation typically less than 10%) deposits of pore-filling gas hydrate in clay-dominated sediments, will be a significant production challenge. At present, such deposits are considered to be economically unfeasible (*Moridis and Sloan, 2007*) due to low resource density, extremely low intrinsic permeability, and the unconsolidated nature of the host sediments which would greatly complicate efforts to augment permeability via fracturing or other stimulation.

However, a relatively newly discovered, and potentially favorable, class of gas hydrates are those in which structurally-deformed or disrupted sediments contain elevated overall gas hydrate saturations in the form of complex networks of tabular fracture fills, vein fills, and small nodules (*Holland et al., 2008*). A relatively minor accumulation of this type was noted in the 2005 drilling at Keathley Canyon 151 as part of Gulf of Mexico JIP Leg I operations (*Lee and Collett, 2008; Cook et al., 2008*). Similar, but thicker and richer, fractured-mud occurrences were discovered offshore Malaysia in 2005 (*Hadley et al., 2008*). In 2006, a landmark expedition offshore India discovered a 500 ft (130 m) thick and relatively highly concentrated zone of grain-displacing gas hydrate in the Krishna-Godovari basin, in the Indian Ocean (*Collett et al., 2006*). A similar occurrence was encountered in the East Sea during Korea's 2007 expedition (*Park et al., 2008*). In 2009, drilling in the Gulf of Mexico (JIP Leg II) found a less highly concentrated, but areally extensive interval of gas hydrate filled fractures in Walker Ridge block 313 (*Shedd et al., 2010; Cook et al., 2010*). Accurate gas hydrate saturation determinations in such settings is complex (*Lee and Collett, 2009*), but current estimates suggest that values can range from 5% to as much as 30% in such systems (*Hadley et al., 2008; Lee et al., 2009*). Despite potentially housing large volumes of gas (it is not possible at this time to speculate on global resource volumes within this resource category), the production potential from such units is considered low due to lack of conceptual production models or positive numerical simulation results. However, initial theoretical and experimental work is underway (*Santamarina and Jang, 2009*) which is focused on the potential for sediment volume expansion during dissociation to create and maintain potential production pathways.

Gas Hydrate Exploration Technologies: Recent drilling projects have confirmed that the simple co-existence of gas and water within the nominal gas hydrate stability zone is not sufficient to ensure the existence of gas hydrates, particularly in accumulations that are likely to be amenable to production. As it has become clear that gas hydrate production prospects favor high-concentration deposits in sand reservoirs, the application of the "petroleum systems" approach that guides conventional oil and gas exploration has gained favor (*Collett et al., 2009*). This approach features the integration of those features unique to gas hydrates (such as temperature and pressure controls on stability) with geologic-geophysical evidence for gas sources, suitable reservoir lithologies (sand-rich systems), and migration pathways. This approach, which focuses on integrating all available information with geophysical analysis of the specific prospects, has replaced prior exploration models that relied heavily on seafloor features and/or the occurrence of bottom simulating reflectors (BSRs) as indicators of gas hydrate distribution. It is now widely understood that BSRs are a positive indicator of gas presence and a useful check on the extent of the gas hydrate stability zone; but provide very little insight into the nature/extent of gas hydrate occurrence or the existence of specific, concentrated prospects (*Tsuji et al., 2009*).

Underpinning the petroleum systems approach is the ability to directly infer from geophysical data the occurrence of gas hydrate charged sand reservoirs (*Shelander et al., 2010*). Current laboratory and field data support the conclusion that occurrence of pore-filling gas hydrate at relatively high concentrations significantly affects the physical properties of the sediment, including acoustic velocities. Where gas hydrate bearing sediments occur at thicknesses above seismic resolution and at resource-relevant saturations (~50% or more), large impedance contrasts of the same polarity as the sea-floor reflection are expected to occur. The details of the manifestation of gas hydrates in seismic data continues to be investigated, (*Riedel et al., 2008; Bellefleur et al., 2008*, and others); with a major study conducted in Japan (*Saeki et al., 2008*) concluding that concentrated zones of gas hydrate in marine settings could be delineated with greater certainty where strong amplitudes of appropriate polarity are found within the Gas Hydrate Stability Zone coincident with both evidence of increased internal acoustic velocities and supporting geologic evidence of sand-prone lithofacies. This "direct detection" capability may only extend to the most favorable (thick, highly-saturated) reservoirs. Increasingly sophisticated methods will likely be needed to delineate thinner, interbedded, or lower saturation accumulations.

Initial confirmation of the ability to successfully predict the occurrence and degree of saturation of discrete gas hydrate bearing units prior to drilling was provided by the 2007 BP-DOE-USGS "Mount Elbert" test well. The relatively close conformance of the predictions with the drilling results (*Lee et al., 2011*) was encouraging and clearly benefitted from the ability to condition the predictive analysis with nearby well data (*Inks et al., 2009*). An opportunity to similarly test the exploration approach in a marine setting was provided by drilling conducted in 2009 as part of the Chevron-DOE Gulf of Mexico JIP Leg II program. The Leg II site selection process (*Hutchinson et al., 2008*) applied a full petroleum systems approach to select numerous drill locations at three sites in three very different geologic settings. Pre-drill seismic inversion analyses were conducted for two of the sites (**Figure 4**), with subsequent drilling results being in close alignment with pre-drill predictions in four of the five wells drilled (*Shedd et al., 2010; McConnell et al., 2010*). The third site was drilled based on geologic and geophysical data without detailed seismic inversion analyses; results at that site also closely match the pre-drill estimates (*Frye et al., 2010*).

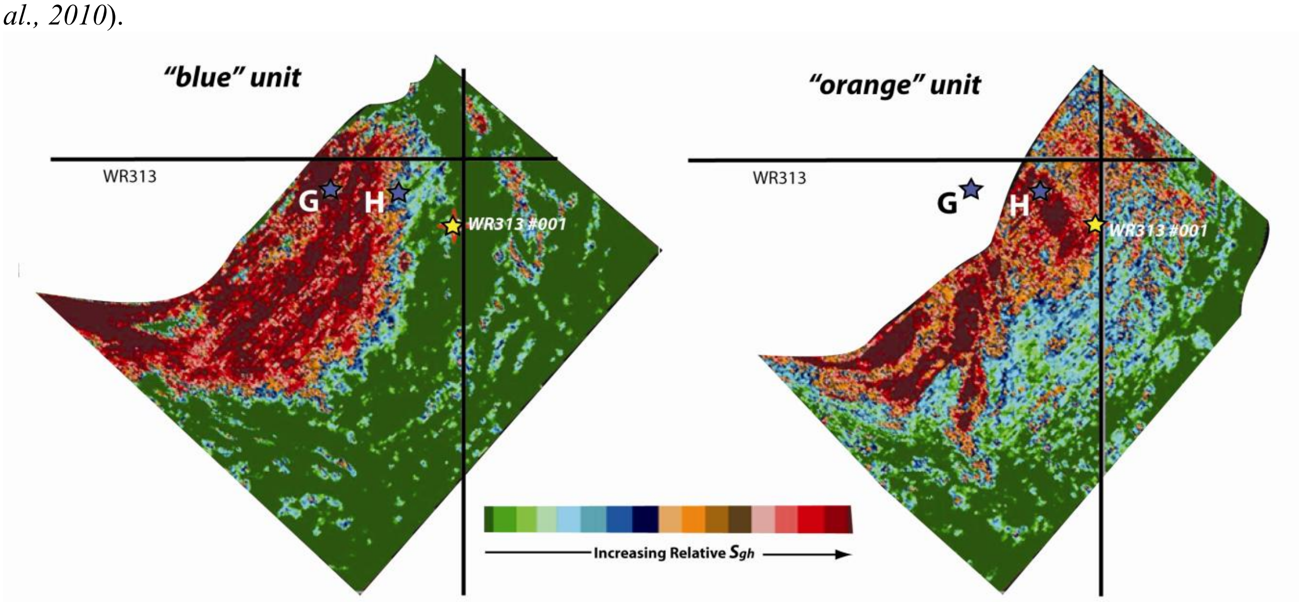

Figure 4: Pre-drill predictions of gas hydrate saturation within reservoir units in Walker Ridge block 313, northern Gulf of Mexico (modified from *Shelander et al., 2010*; also as used by permission of OTC). LWD data for the reservoir shown on the right at the well location "H" shown in Figure 2.

Given the unique electrical resistivity attributes of gas hydrate bearing sediments, electromagnetic (EM) methods have the potential to be a complimentary tool useful in delineating areas of enriched gas hydrate content. Studies conducted at Hydrate Ridge in 2005 were the first focused effort designed to detect and characterize gas hydrate occurrence with EM data and showed promising results (*Schwalenberg et al., 2005*), particularly for vertical, chimney-like features. However, given the somewhat limited vertical resolution of EM data, its utility in delineating specific gas hydrate-bearing sand reservoirs may be limited (*Riedel et al., 2011*). A summer 2008 Scripps Institute of Oceanography expedition (*Weitemeyer et al., 2009)* collected controlled-source electromagnetic (CSEM) data over four sites in the deepwater Gulf of Mexico, including one area of confirmed gas hydrates seafloor mounds (Mississippi Canyon 118), and three sites where drilling results have shown discrete, concentrated gas hydrate deposits in sand reservoirs (Alaminos Canyon 818; Green Canyon 955, and Walker Ridge 313). Results for the Mississippi Canyon 118 location seem encouraging (*Weitemeyer et al., 2010*), but those for the three deeply buried sand accumulations are not yet available.

Gas Hydrate Production Technology: Research on gas hydrate production technologies in the U.S. and Japan is focused on determining the viability of sand-hosted hydrate accumulations. There are no plans within the U.S. or in Japan to treat gas hydrate, whether in the form of mounds or disseminated in near-seafloor sediments, as an "ore" to be gathered by surface dredging or shallow-subsea mining. The environmental impact of such approaches is simply too great, and the energy contained in such deposits are likely too small to be of any real economic value. Rather, production via well bores is the sole focus of these programs. Of the various well-based approaches that have been put forward, including injection of chemical inhibitors and thermal stimulation, reservoir depressurization and chemical exchange are currently the most promising approaches and each is the subject of significant ongoing field and laboratory investigation. All other issues being equal, gas hydrate occurrences those that are the most deeply buried will be favored, due to warmer temperatures, greater mechanical stability, and enhanced isolation from sensitive near-surface environments (*Boswell and Collett, 2011*).

Depressurization: Gas hydrate reservoir depressurization is a relatively simple production concept, and very similar in nature to that used in production of coal bed methane resources. Fluids within a well-bore are pumped to the surface. The pressure gradient developed between the wellbore and reservoir draws mobile fluids ("free water") from the reservoir to the wellbore. The resulting pressure drops within the reservoir is rapidly transmitted through the reservoir, shifting the local region out of gas hydrate stability conditions, leading to the dissociation of gas hydrate into gas and water components. The established pressure gradient then drives the released gas and water to the wellbore, where it is produced to the surface. Early skepticism on the prospects of depressurization assumed that gas hydrate reservoirs were virtually "frozen solid", and therefore lacked any mobile fluid phases that could be withdrawn to enable pressure reduction. However, advanced well logging programs at field sites in Japan, Alaska, and Canada have measured free water phases of 5 to 10% of pore volume (i.e., *Lee and Collett, 2011*). Confirmation of reservoir response to pressure drawdown was provided during pressure transient tests conducted in both Canada (*Hancock et al., 2005*) and in Alaska (*Anderson et al., 2011a*). Most significantly, the 2007 and 2008 field programs at Mallik (*Yamamoto and Dallimore, 2008*) appear to have demonstrated the effectiveness of the depressurization method. Gas hydrate production via depressurization has been rigorously modeled in the U.S., Canada, and Japan using advanced numerical simulation codes (*Anderson et al., 2011b*).

The reservoir response data obtained at both the Mallik and Mount Elbert test sites have provided a foundation for improving modeling codes and developing meaningful production forecasts. Recent modeling indicates that gas hydrate-saturated sand reservoirs are capable of delivering more than 50% (*Kurihara et al., 2011*) and as much as 85% of the in-place resources within a specific reservoir accumulation (*Collett et al., 2008; Moridis et al., 2009*). Furthermore, the wells as modeled are capable of relatively large and sustained flows of gas (Moridis et al., 2009). The most recent studies, which are based on detailed field descriptions of marine gas hydrate occurrences, suggest rates as high as 6 million ft^3/day within a 90-day production test in the Nankai Trough (*Kurihara et al., 2011*) and at least 10 million ft^3/day for gas hydrate-bearing sand reservoirs in the Gulf of Mexico (*Moridis et al., 2010*). They also suggest that earlier modeling work which typically incorporated heterogeneous reservoir descriptions may have significantly underestimated gas hydrate reservoir production potential (**Figure 5**). Yet another positive feature is that gas hydrate production wells will be relatively shallow holes (within 1000 to 3000 feet below the land surface or seafloor), which will make the drilling relatively straightforward and inexpensive. Finally, current production modeling does not incorporate the potential benefits of well stimulations (such as fracturing) that may further improve productivity.

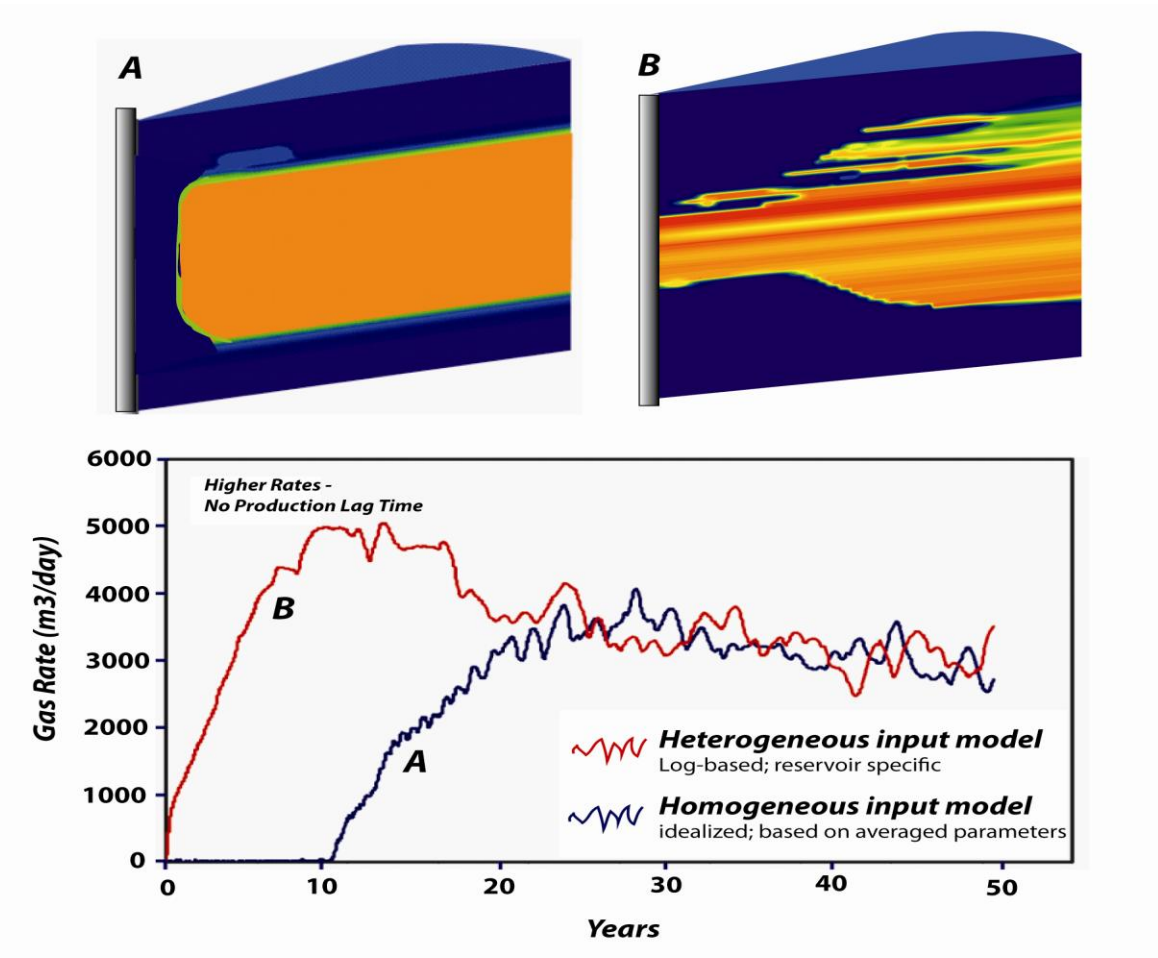

Figure 5: Comparison of modeled production response between homogeneous (A) and heterogeneous (B) reservoir models based on data from the Mount Elbert test well in Alaska. The consideration of vertical heterogeneities results in high production volumes and reduced or eliminated production lag times (modified from *Anderson et al., 2011b*).

Despite the positive initial results from both field and modeling efforts, the issues related to the economics of gas hydrate production remain complex (*Hancock, 2009*). The primary issue is continuing lack of understanding of potential production rates and volumes due to limited field test data. Gas hydrate reservoirs, like coal-bed methane reservoirs, are expected to experience low deliverability at the onset of production. Deliverability would then steadily improve as the radius of gas hydrate dissociation expands and reservoir permeability increases owing to the disassociation of pore-filling gas hydrate. This "slow start" can be a serious economic barrier because the earliest possible return on investment is greatly valued in investment decision-making. Another significant issue is that gas hydrate dissociation is somewhat self-regulating due to its endothermic nature. Production cools the reservoir significantly over time which tends to push it back toward hydrate stability and, more significantly, making formation of pore-clogging ice in the near-well bore environment a serious concern. Careful control of rates and pressures, and the potential intermittent addition of heat energy, are therefore likely requirements.

Well designs to enable commercially-viable gas hydrate production will face numerous challenges (**Figure 6**). Perhaps most challenging is the fact that gas hydrates will be primarily a deepwater resource, which carries significant logistical and operating costs. The wells will be low

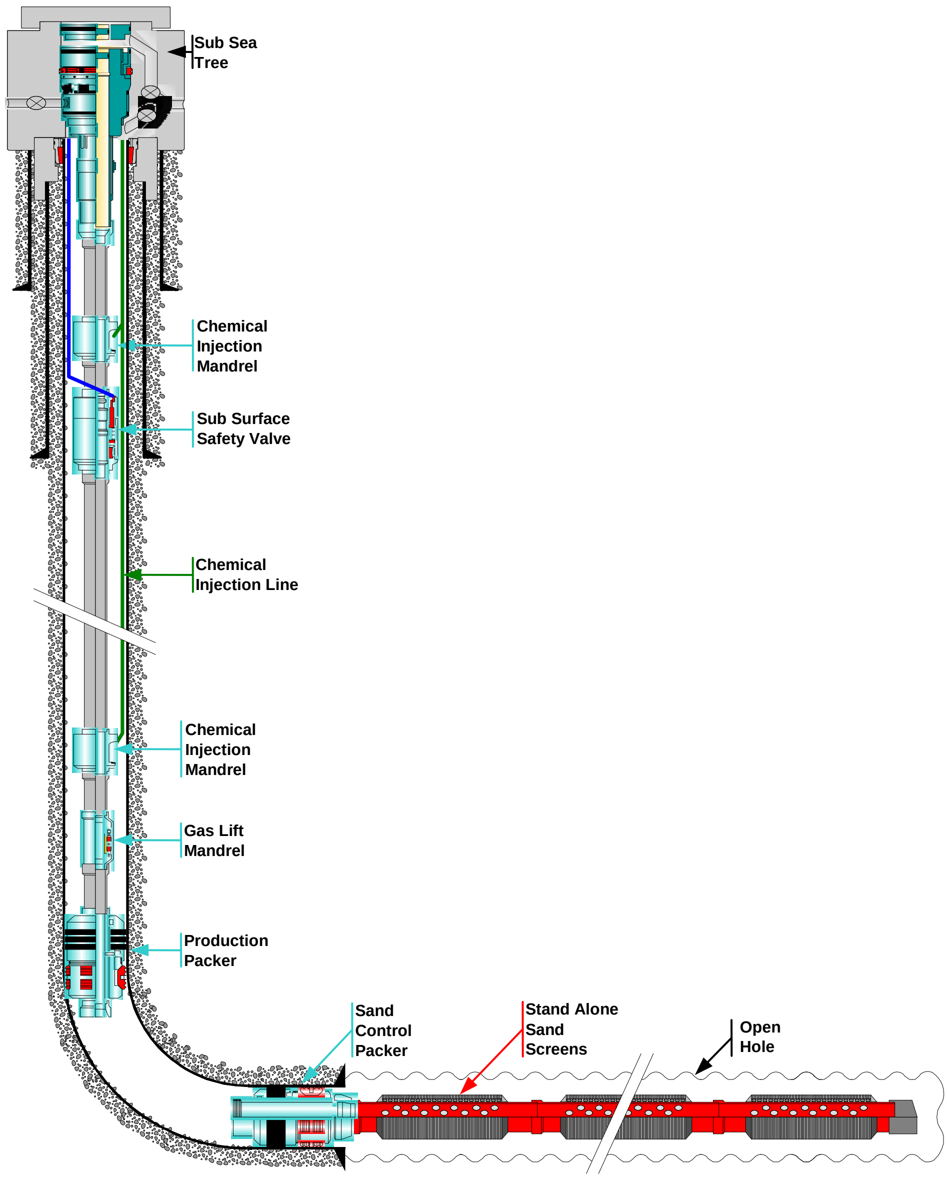

Figure 6: Schematic well design for deepwater marine gas hydrate production (from *Hancock et al., 2010*; ©2011, Offshore Technology Conference).

pressure by design, so artificial lift will be needed. There may need to be arrangements for the collection and disposal of large volumes of co-produced water. While water produced in situ from dissociation is fresh, the produced fluids will be brackish upon production due to mixing with formation brines. Significantly, the induced dissociation and related volume expansion of pore fluids will dramatically reduce the mechanical strength of the reservoir, so rigorous sand control will be needed and compaction and associated ground/seafloor subsidence is possible (*Rutqvist et al., 2010*). Strong pressure gradients in unconsolidated materials will likely lead to fines migration and plugging may occur and require periodic remediation (*Santamarina and Jang, 2009*). The cold temperatures and endothermic nature of the dissociation reaction will necessitate significant flow assurance measures within the well and gathering equipment. Finally, in many settings, obtaining sufficiently high flow rates may require horizontal wells (*Moridis et al., 2009*), which may be a challenge in shallow unconsolidated sediments. While industry has experience overcoming each of these issues through well design, remediation, and stimulation practices, their confluence in one setting creates significant complexities and costs.

Extended-term production testing is clearly needed to achieve a better understanding of gas hydrate production potential. The 2008 Mallik field program (*Yamamoto and Dallimore, 2008*) showed sustained production over a period of six days and suggested that the reservoirs had the potential to exceed the productivity predictions of numerical models through enhanced permeability associated with production-related deformation as well as natural heterogeneities (*Dallimore et al., 2008*). These results ultimately proved sufficient to enable the Japanese government to approve plans to conduct extended term (~ 90-days) production testing in the Nankai Trough in both 2012 and 2014 (**Figure 7**: *Masuda et al., 2010a*). Similarly, the positive results of the 2007 Mount Elbert program and the subsequent modeling studies are now being used to plan future long-term tests of depressurization-based production on the Alaska North Slope (*Collett and Boswell, 2009*).

Initial evaluations of the potential economics of depressurization-based gas hydrate development (*Kurihara, et al., 2008, 2010; Masuda et al., 2010b; Walsh et al., 2009*) remain largely speculative. However, even recognizing the many challenges described above, what is known about the potential productivity of gas hydrate indicates that production with existing technologies could be viable under select future scenarios, assuming production rates as predicted by the leading models from depressurization of high-concentration sand reservoirs (*Hancock, 2009*). With experience and continued technological advancement, it is likely that optimization of production will feature approaches that integrate other techniques (such as periodic thermal, mechanical, and chemical stimulations as well as typical well-bore/reservoir maintenance) with depressurization as appropriate to each specific field setting. Nonetheless, at present, and considering only currently-existing technologies, *Hancock (2009)* reported that fully burdened stand-alone onshore gas hydrate production projects "could be economic at gas prices in the upper range of historical North American gas prices". With respect to offshore projects, Hancock states "while the gas price required to make a gas hydrate discovery economic will be higher than that for conventional gas discovery, the difference in price is measured in terms of dollars, not orders of magnitude." While commerciality will be a strong driver in countries with numerous energy supply options, there are other national motivations, such as increased energy self-sufficiency, that will also play a role in the pace of gas hydrate development.

CO_2-CH_4 Exchange: A recent development in gas hydrate production technology is ongoing work to assess the potential to exchange CO_2 for the CH_4 within the gas hydrate structure as a basis for methane production (see *Stevens et al., 2008*). Although depressurization is thought to be the most effective method for production of gas from gas hydrate reservoirs in terms of potential rates, the exchange approach offers several favorable elements, including the potential to release CH_4 while sequestering CO_2 in hydrate form. This feature may be a prime driver for development of the technology on the Alaska North Slope (ANS), given that up to 12% of currently stranded ANS gas is CO_2, and industry and government may favor technologies that can put that CO_2 to beneficial use.

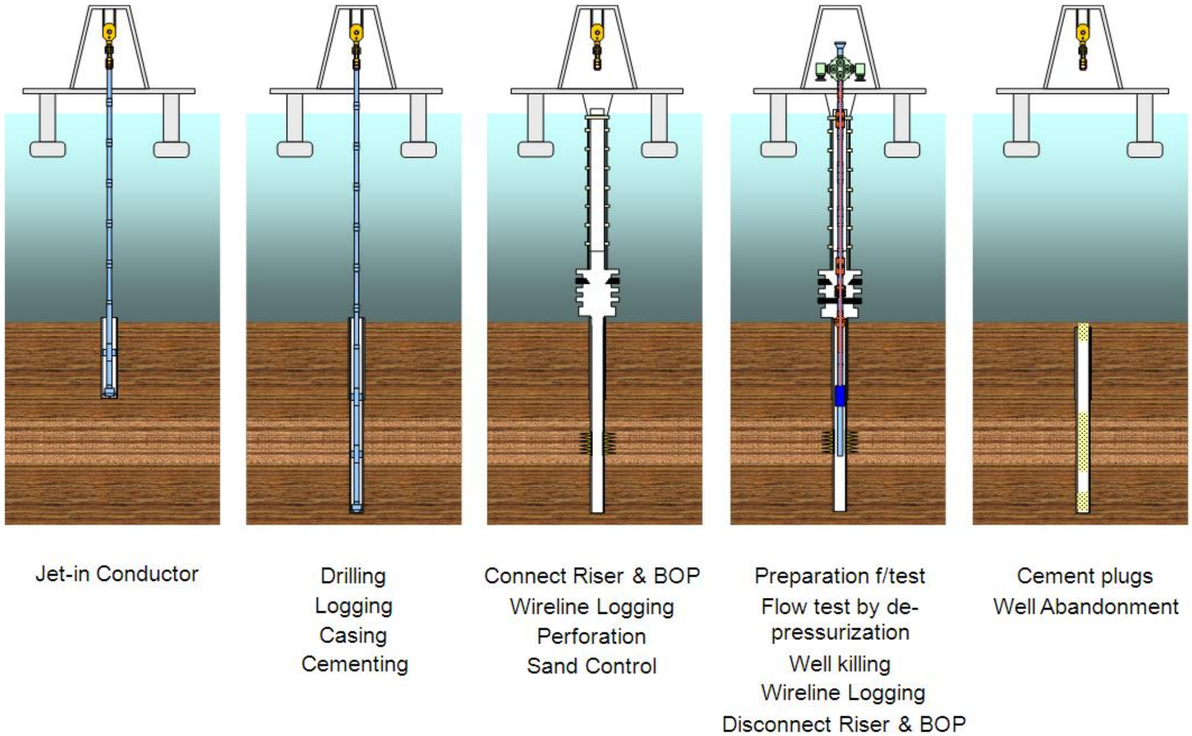

Figure 7: Schematic of proposed marine production test design planned for 2012-2013 in the Nankai Trough (from *Masuda et al., 2010a*).

Recognition of the potential for CO_2-CH_4 exchange was initially based on theoretical and experimental studies using bulk hydrates which confirmed that molecular exchange occurs spontaneously albeit with extremely low exchange kinetics. For many years, these low rates led most to believe that CO_2-CH_4 exchange was impractical for commercial field applications. However, work by a ConocoPhillips-University of Bergen team has shown promising experimental and modeling results for the process in porous media settings at conditions well within both the CO_2-hydrate and CH_4-hydrate stability fields (*Graue et al., 2006*). These results include: 1) relatively rapid CH_4 release; 2) exchange of CH_4 with CO_2 approaching 70%, and 3) exchange occurring with no observable water liberated during the process.

If recent experimental (*Stevens et al., 2008*) and numerical modeling findings (*White and McGrail, 2008; White et al., 2010)* can be validated by initial field trials and subsequent larger-scale multi-well pilot studies, the exchange process could have the potential to not only provide an option for sequestering CO_2, but could also address several key technical hurdles related to depressurization-based gas hydrate production. Such hurdles include reduction or elimination of water production, enhancement of reservoir geomechanical stability, and applicability over a wider range of in situ temperature conditions (*Farrell et al., 2010*). A major challenge facing the exchange concept is the potential for extremely low CO_2 injectivity (and resultant low CH_4 deliverability) related to further reduction of the already low in situ reservoir permeability owing to immediate formation of CO_2-hydrate upon contact with in situ formation water. To further the evaluation of CO_2-CH_4 exchange, the DOE is collaborating with ConocoPhillips to conduct a short duration (90 days or less) field trial on the Alaska North Slope beginning as early as 2012. In April 2011, this project successfully confirmed the occurrence of multiple gas-hydrate bearing sands in the western Prudhoe Bay unit and installed a fully-instrumented well-bore from an ice-pad suitable for future production testing (*Schoderbek and Boswell, 2011*), currently slated for early 2012.

Gas Hydrate Geohazard Evaluation: Gas hydrates, like shallow free gas and overpressured water-bearing sands, are a known subsurface geohazard to offshore oil and gas drilling and production. In general, the gas hydrate-related geohazards can be categorized as 1) shallow drilling and well-installation hazards that are encountered by wells targeting deeper horizons (issues of "drilling through"), 2) long-term hazards associated with producing warm hydrocarbons from deeper zones through shallow gas hydrate-bearing intervals (issues of "producing through"), and 3) geomechanical failure during production of gas hydrate-bearing intervals (issues of "producing from").

Drilling through gas hydrates: Gas hydrate is a common sediment constituent in deep water marine and permafrost-associated settings. The co-location of such shallow deposits over deeper conventional targets in both locales is to be anticipated, as the likelihood of prospective gas hydrate occurrences increases in areas with active petroleum-generating systems. At present, avoidance in the Arctic is not feasible, but the drilling hazards are effectively managed despite the commonality of drilling through thick and highly-saturated sand reservoirs both within and just below the permafrost-bearing section (*Collett and Dallimore, 2002*). The industry approach in the marine environment continues to be avoidance of gas hydrates where feasible, just as it seeks to avoid any potential shallow hazard. With increased drilling in ever-deeper water, however, simple avoidance out of lack of knowledge of the nature of the true hazards is not a sound operational policy. Determination of the real hazards of drilling through gas hydrate-bearing sediments was therefore a key original goal of the Chevron-led Gulf of Mexico gas hydrate Joint Industry Project (*Ruppel et al., 2008*). The JIP conducted an extensive set of laboratory measurements to guide the development of well-bore stability models for drilling through low-saturation gas hydrates within fine-grained sediments, which are the most commonly encountered and less easily detected and avoided. These models were then tested in field drilling programs in 2005 and 2009, and in both cases performed well (*Birchwood et al., 2007; Collett et al., 2010*). A protocol of careful drilling fluid temperature control was deemed sufficient to mitigate those drilling hazards related to gas hydrate dissociation (*Birchwood et al., 2009*). As noted by *Collett et al. (2010),* the gas-hydrate-bearing portions of the wells drilled in the 2009 JIP Leg II program were the most stable portions of these shallow open boreholes, as the solid gas hydrate served to solidify and strengthen the otherwise unconsolidated sediment section.

Producing through Gas Hydrates: Prolonged production of hot fluids f rom deep formations heat well bores, placing thermal stresses on shallow gas hydrate-bearing sediments (*Moridis and Kowalsky, 2007*). Such thermal effects could potentially lead to gas hydrate dissociation, gas leakage, sediment strength loss, and potentially casing collapse. *Rutqvist et al. (2010)* evaluated the potential for induced mass sediment movement (seafloor slides) and determined the risk to be low. For a recent industry development offshore Malaysia in which shallow gas hydrates were extensive, (*Stevens et al. 2008; Hadley et al., 2008*), numerical modeling calibrated with pressure-core and log-derived data, indicated that heat transfer from producing well bores would produce a dissociation front that could advance from 20 to 50 m from a single well, and 60 to 90 m from the center of a six-well cluster, during a 30 year production period. Mitigation measures, such as well-bore insulation, were also modeled, and were determined to slow, but not prevent, the spread of the dissociation front and the associated risk to wellbore integrity. As a result, the operator ultimately determined that the most prudent approach was to develop the field using multiple drill centers to avoid the shallow hazard.

Producing from Gas Hydrate: Gas hydrate reservoirs are typically highly-unconsolidated formations. Pore fluid volume changes during hydrate dissociation will further adversely impact sediment stability. Therefore, gas hydrate production will face significant geomechanical challenges that could increase both costs and potential environmental impacts. The geohazard risks associated with potential gas hydrate production include wellbore collapse from sediment mobilization, surface subsidence, and vertical gas migration due to lack of or loss of seal integrity. Both the Japanese and U.S. national R&D programs have stated that environmental impact monitoring during production testing will be a high priority, but a lack of prolonged field tests to date complicates present evaluation of these geohazards. Work is ongoing to better understand these issues, including preparations for baseline and monitoring studies during planned production tests (*Nagakubo et al., 2011*), as well as experimental efforts and coupling of the leading gas hydrate production simulators with geomechanical codes (e.g. *Moridis et al., 2010b*). Recent modeling studies focused on permafrost-associated settings (*Rutqvist et al., 2009*) have indicated minor reservoir compaction and even less potential land subsidence due to the mechanical strength of the permafrost-bearing overburden (less than 10 cm for a setting like that at the Mount Elbert well), although shear failure of sediments into the well-bore upon complete dissociation is a concern (albeit primarily a well productivity issue). In marine settings, the potential for and magnitude of compaction and subsidence are much greater, perhaps several meters (*Rutqvist and Moridis, 2009*). Similarly, the risks of well-bore complications due to shear failure are, in general, significantly greater in horizontal well settings than in vertical wells (*Rutqvist et al., 2008*).

Gas Hydrate linkages to Global Climate: Gas hydrate is an enormous global storehouse of organic carbon in the form of methane gas. Over long time periods, gas hydrate can be thought of as a global capacitor for organic carbon (*Dickens, 2003*), taking up methane during certain global environmental conditions, and releasing methane during other environmental conditions. Because methane is a highly effective greenhouse gas and rapidly oxidizes to carbon dioxide, which is a less effective but much more persistent greenhouse gas, the release of substantial volumes of methane from gas hydrate accumulations could have significant impacts on global climate (*Archer, 2007*). The actual potential for such release is not yet well known. Early concepts such as gas hydrate release in response to sea-level and consequent coeval hydrostatic pressure declines during Late Quaternary glacial periods have been shown to be unlikely (*Sowers, 2006*), so some significant past climate changes on Earth have probably occurred without any meaningful response/contribution from gas hydrate. Initial attempts to numerically model the response of gas hydrate to changing climate scenarios has indicated that release of methane would be gradual over a long time frame rather than catastrophic (*Archer et al., 2009*). However, some highly significant past climate events, such as that which occurred 55 Ma ago (the Paleocene-Eocene Thermal Maximum) do appear to exhibit geochemical signals consistent with rapid large-scale gas hydrate dissociation. At present, this link is not confirmed (*Dickens, 2011*), but it does appear possible that gas hydrate dissociation may have supplied methane to the atmosphere, and therefore exacerbated, past climate warming events likely initiated by other causes. Gas hydrate dissociation has also been linked to even more severe climatic changes in Earth's ancient past (e.g. *Kennedy et al., 2008*), although the data are inconclusive (*Bristow et al., 2011*).

The findings to date therefore indicate that gas hydrates can conceivably play a significant role in climate events, particularly those that are large, acute, and global in scale. A major scientific question at present is: are we on the cusp of a similar or perhaps even more acute, event (i.e., *Cui et al., 2011*). Recent studies from the East Siberian Arctic Shelf (*Shakhova et al., 2010*) and from offshore Svalbard (*Westbrook et al., 2009*) suggest release of methane from the Arctic. The connection between these releases and gas hydrate remains unclear, and it is not established if these releases are new, or simply newly discovered. Nonetheless, while the magnitude of arctic methane releases appear to be minor in comparison to those from other methane sources, they clearly warrant further study.

Addressing these questions in a scientifically rigorous manner is an important part of understanding the environmental implications of naturally-occurring gas hydrates, and such understanding is a desirable precursor to resource development. Collaboration between those persuing resource and environmental issues is important because a key component of both initiatives is the collection of data on gas hydrate occurrences and their response to controlled perturbations. Initial work to incorporate this information into climate models, which now generally exclude gas hydrate-related phenomena as inconsequential, has been conducted at the Lawrence Berkeley and Los Alamos National Labs. These workers have linked the leading gas hydrate and global ocean circulation models to assess the response of marine gas hydrate systems to potential future changes in ocean bottom-water temperature (*Reagan and Moridis, 2008*). Initial results indicate 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 deserve further study, confirming the earlier view of *Kvenvolden (1988b).*

IV Future Scenarios for Gas Hydrate Production

A common inquiry is: "when can gas hydrate become a contributor to global energy supply?" The answer is not simple. The national gas hydrate programs in Japan and Korea currently envision onset of gas hydrate production in those nations within the next decade. As noted in several reports, there appear to be no major technological hurdles to making this a reality and the issues appear to be largely geologic (confirmation of significant resource volumes) and economic. How the economics of gas hydrate production will be viewed in various regions as respects, for example, potential regulatory/policy incentives, or the relative attractiveness of developing local sources and economic activity, or the perception of environmental risks, are difficult to assess. The question of timing is also a complex, as it tends to presume that gas hydrate will become viable "all at once" at some price threshold, when the reality is that all gas hydrate is not created equal. The very best accumulations may well be theoretically commercial at present, and require only demonstration of commerciality through field testing. However, the vast majority of accumulations is likely not be commercial at present, and will require a range of enabling conditions as local geologic conditions differentially determine the production approaches and production volumes or rates achievable. As with all "new" resources, the acquisition of production experience combined with incremental technological gains will likely result in steady additions to the commercially viable resource base. Regulatory and policy factors may also play a key role, including the clarification of regulatory frameworks under which gas hydrate resources are to be evaluated.

It is worth noting that among the currently-producing suite of natural gas resources, the most promising resource elements (relatively shallow conventional sands) were commercially viable more than a century ago. Subsequently, ever more challenging resources (deep, offshore, tight, self-sourced shales, coalbed methane, etc.) have been periodically added to the commercially viable resource base by technological breakthroughs often separated by periods of decades or more. A similar future path, accommodating the wide natural range of known accumulations, seems plausible for gas hydrates.

Given the limited scientific and engineering data presently available regarding gas hydrate productivity, it remains difficult to constrain the potential future paths for gas hydrate production commercialization. The ultimate utilization of gas hydrate resources will depend on numerous factors, many of which are poorly known or unknown at this time, including 1) resource volumes in the most promising accumulations, 2) obtainable production rates and profiles; 3) operational costs and complexity; 4) assessment and mitigation of environmental impacts; 5) future global energy demand; 6) the comparative local, regional and global economics of gas hydrate projects as compared to the best available alternative for energy investment; 7) development of transportation delivery infrastructure, and likely others. The future production scenarios provided hereafter are therefore inherently speculative, not associated with specific economic conditions, and limited to two presently plausible end-member scenarios and a median scenario (**Figure 8**).

At the low end, it may be the case that gas hydrate recoverability will be limited through 2050 to the most favorable permafrost-associated locations, due to geomechanical and other well maintenance complications that are costly to manage, unacceptable environmental impacts related to poor seal integrity, or lack of supporting regulation in the offshore. The resource associated with the most favorable permafrost-associated locations (both onshore and offshore Alaska) is likely on the scale of several tens of Tcf. Contribution of these resources to meeting demand outside various local Alaska North Slope uses presupposes the development of gas delivery infrastructure to the Lower-48.

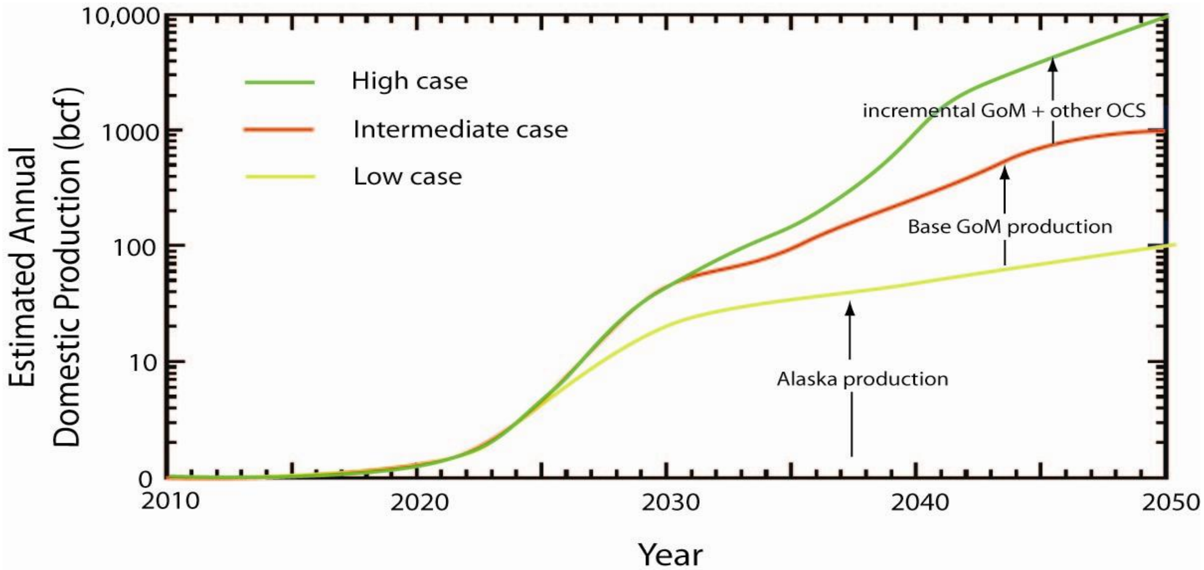

Figure 8: Speculative schematic of three potential annual domestic production scenarios for gas hydrate resources through 2050. Scenarios explained in the text.

A mid-range scenario suggests the realization of significant recoverable marine gas hydrate resources, driven strongly by research activities in Asia as well as the United States, but with yet-to-be-determined commerciality. The scientific data to date suggest that in-place resources within marine sand reservoirs are likely significant (10^4 Tcf or more globally: *Boswell and Collett, 2011*), and that recovery factors will approach that of conventional gas reservoirs (from 50% up to 85%). Therefore, it can be envisioned that a significant share of the assessed resources in the Gulf of Mexico (on the scale of several thousands of Tcf) will be rendered technically viable. However, the share of this resource that will be commercially viable given the high economic hurdle facing any deepwater project is highly speculative. It is most likely that commercialization will begin, not through stand-alone projects, but through production of gas hydrate accumulations that are in close proximity to existing production-gathering facilities, such that the gas hydrate projects need not fully cover the infrastructure cost while serving to extend the life of existing infrastructure. All else being equal, as experience is gained with hydrate production, it is anticipated that an expanding range of deposits will become prospective for development. Given the potential scale of the resource and the productivity potential suggested by the most recent modeling, domestic production of several Tcf per year or more seems plausible.

At the high-end, a more optimistic production potential in the Gulf of Mexico and potential contributions from other U.S. waters can be considered. Evaluation of the potential of such regions, including the Atlantic and Pacific OCS most appropriately will await the results of studies and assessments ongoing within the U.S. Department of Interior. However, assuming that the initial gas hydrate resource assessments turn out to be correct or perhaps conservative and that other emerging energy resources are high-cost or otherwise reduced in favorability, production of up to 10 Tcf/y by 2050 might be possible.

V Conclusions and Summary

Though significant challenges remain in realizing commercial production from gas hydrate-bearing formations, recent gas hydrate research accomplishments have been significant. We know much more about the geophysical response, petrophysical properties, and potential productivity of gas hydrate reservoirs than we did just a few years ago. The 2007/2008 Mallik test results, while not yet public in full detail, clearly indicate technically-viable productivity and were sufficient to enable Japan to move ahead with plans for production testing in the marine environment. In the U.S., there is a strong industry, state, and federal interest in pursuing the needed long-term production tests in Alaska, with separate tests of depressurization and CO_2-CH_4 exchange poised for execution. For the Gulf of Mexico, we have the first estimates of the potentially recoverable portion of the total in-place resource, and drilling conducted in 2009 confirmed the expected existence of high-concentration gas hydrate at two of three sites drilled. The Alaska and Gulf of Mexico drilling results also appear to validate current approaches to gas hydrate exploration, indicating that existing concepts and approaches can be effectively employed. The maturation of numerical simulators, their ability to now more rigorously include natural variation in reservoir properties, and the incorporation of field data into production scenarios has yielded increasingly rigorous and encouraging production predictions. Spurred by international expeditions, there is also a new appreciation of the potential abundance of concentrated gas hydrate in fractured mud occurrences and initial efforts to assess these accumulations are underway. Lastly, the first steps toward integrating gas hydrate science into numerical models of global carbon cycling and the global climate are in progress.

With respect to U.S. gas hydrate resources, it is possible that repercussions of the April 2010 Deepwater Horizon tragedy will impact the presently anticipated pace of research and development due to increased costs and complexity of permitting and conductance of deepwater operations, as well as other factors. Setting those possibilities aside, a near-term focus for domestic marine gas hydrate R&D will be the further characterization of recently confirmed Gulf of Mexico reservoirs and associated seals through pressure-coring operations. These sites will also likely be the focus of expanded geochemical and geophysical investigations to further refine the tools applicable to pre-drill assessment and characterization of gas hydrate prospects. A program of marine production testing will ultimately be required. Marine geophysical programs to identify high potential regions within the US OCS outside the Gulf of Mexico will also be needed. The most promising areas will then require evaluation via multi-well drilling, logging, and coring expeditions.

Additional long-term testing programs, building upon the findings of the initial tests, extending findings to other geologic settings, and/or refining stimulation methods and well design, will likely be needed. A final multi-well pilot test will also likely be needed, and could occur in Alaska before 2020. Assuming success of near-term efforts in Alaska, a production test program could be envisioned for the Gulf of Mexico within the decade, with a second test required shortly after, resulting in improved assessment of the possible scale of marine hydrate technical and commercial recoverability by 2025. Such marine testing programs will require a strong national commitment.

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