

ASSESSMENT OF UNITED STATES GAS HYDRATE RESOURCES

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Keywords: gas hydrates, energy resources, natural gas

I. INTRODUCTION

Gas hydrates are crystalline substances composed of water and gas, in which a solid water-lattice accommodates gas molecules in a cage-like structure, or clathrate. Gas hydrates are widespread in permafrost regions and beneath the sea in sediment of outer continental margins. While methane, propane, and other gases can be included in the clathrate structure, methane hydrates appear to be the most common in nature¹. The amount of methane sequestered in gas hydrates is probably enormous, but World estimates of the amounts are speculative and range over three orders-of-magnitude, from about 100,000 to 270,000,000 trillion cubic feet². The estimated amount of gas in hydrate reservoirs of the world greatly exceeds the volume of known conventional gas reserves. The production history of the Russian Messoyakha gas hydrate field demonstrates that gas hydrates are an immediate source of natural gas that can be produced by conventional methods^{3,4}. Gas hydrates also represent a significant drilling and production hazard. Russian, Canadian, and American researchers have described numerous problems associated with gas hydrates, including blowouts and casing failures^{3,5,6}. As exploration and development activity moves into deeper water (>300 m) and high latitude arctic environments, the frequency of gas hydrate induced problems will likely increase.

One of the fundamental problems that links the gas hydrate resource and hazard issues is the need for accurate assessments of the gas volumes within a gas hydrate occurrence. Most of the published gas hydrate resource estimates have by necessity been made by broad extrapolation of only general knowledge of local geologic conditions². The primary objectives of our gas hydrate research efforts in the U.S. Geological Survey are to document the geologic parameters that control the occurrence of gas hydrates and to assess the volume of natural gas stored within the onshore and offshore gas hydrate accumulations of the United States. This paper begins with a discussion of the geologic parameters that affect the stability and formation of gas hydrates, which is followed by a description of the methodology used to assess gas hydrate resources. This paper ends with a cumulative estimate of the *in-place* gas hydrate resources of the United States onshore and offshore regions.

II. GAS HYDRATE TECHNICAL REVIEW

Under appropriate conditions of temperature and pressure (figs. 1A, 1B, and 1C), gas hydrates usually form one of two basic crystal structures known as Structure I and Structure II. Each unit cell of Structure I gas hydrate consists of 46 water molecules that form two small dodecahedral voids and six large tetradecahedral voids. Structure I gas hydrates can only hold small gas molecules such as methane and ethane, with molecular diameters not exceeding 5.2 angstroms. The unit cell of Structure II gas hydrate consists of 16 small dodecahedral and 8 large hexakaidecahedral voids formed by 136 water molecules. Structure II gas hydrates may contain gases with molecular dimensions in the range of 5.9 to 6.9 angstroms, such as propane and isobutane. At conditions of standard temperature and pressure (STP), one volume of saturated methane hydrate (Structure I) will contain as much as 164 volumes of methane gas -- because of this large gas-storage capacity, gas hydrates are thought to represent an important source of natural gas. For a complete description of the structure and properties of hydrates see the summary by Sloan⁷.

II.A. Permafrost Gas Hydrates

Onshore gas hydrates are known to be present in the West Siberian Basin⁸ and are believed to occur in other permafrost areas of northern Russia, including the Timan-Pechora province, the eastern Siberian Craton, and the northeastern Siberia and Kamchatka areas⁹. Permafrost-associated gas hydrates are also present in the North American Arctic. Direct evidence for gas hydrates on the North Slope of Alaska comes from a core-test, and indirect evidence comes from drilling and open-hole industry well logs which suggest the presence of numerous gas hydrate layers in the area of the Prudhoe Bay and Kuparuk River oil fields^{10,11}. Well-log responses attributed to the presence of gas hydrates have been obtained in about one-fifth of the wells drilled in the Mackenzie Delta, and more than half of the wells in the Arctic Islands are inferred to contain gas hydrates^{12,13}. The combined information from Arctic gas-hydrate studies shows that, in permafrost regions, hydrates may exist at subsurface depths ranging from about 130 to 2,000 m¹.

II.B. Marine Gas Hydrates

The presence of gas hydrates in offshore continental margins has been inferred mainly from anomalous seismic reflectors that coincide with the predicted phase boundary at the base of the gas-hydrate stability zone. This reflector is commonly called a bottom-simulating reflector or BSR. BSRs have been mapped at depths below the sea floor ranging from about 100 to 1,100 m¹. Gas hydrates have been recovered in gravity cores within 10 m of the sea floor in sediment of the Gulf of Mexico¹⁴, the offshore portion of the Eel River Basin of California¹⁵, the Black Sea¹⁶, the Caspian Sea¹⁷, and the Sea of Okhotsk¹⁸. Also, gas hydrates have been recovered at greater sub-bottom depths during research coring along the southeastern coast of the United States on the Blake Outer Ridge¹⁹, in the Gulf of Mexico²⁰, in the Cascadia Basin near Oregon²¹, the Middle America Trench^{22,23}, offshore Peru²⁴, and on both the eastern and western margins of Japan^{25,26}.

Because gas hydrates are widespread in permafrost regions and in offshore marine sediments, they may be a potential energy resource. In-place World estimates for the amount of natural gas in gas hydrate deposits range from 5.0×10^{12} to 1.2×10^{16} trillion cubic feet for permafrost areas and from 1.1×10^5 to 2.7×10^8 trillion cubic feet for oceanic sediments². The published gas hydrate resource estimates show considerable variation, but oceanic sediments seem to be a much greater resource of natural gas than continental sediments. Current estimates of the amount of methane in the world gas hydrate accumulations are in rough accord at about 7×10^5 trillion cubic feet². If these estimates are valid, then the amount of methane in gas hydrates is almost two orders of magnitude larger than the estimated total remaining recoverable conventional methane resources, estimated to be about 9×10^3 trillion cubic feet²⁷.

III. GEOLOGIC CONTROLS ON GAS HYDRATE DISTRIBUTION

Review of previous gas hydrate studies indicates that the formation and occurrence of gas hydrates is controlled by formation temperature, formation pore-pressure, gas chemistry, pore-water salinity, availability of gas and water, gas and water migration pathways, and the presence of reservoir rocks and seals. In the following section, these geologic controls on the stability and formation of gas hydrates will be reviewed and assessed.

III.A. Formation-Temperature, Formation Pore-Pressure, Gas Chemistry

Gas hydrates exist under a limited range of temperature and pressure conditions such that the depth and thickness of the zone of potential gas-hydrate stability can be calculated. Depicted in the temperature/depth plots of figures 1A, 1B, and 1C are a series subsurface temperature profiles from an onshore permafrost area and two laboratory-derived gas-hydrate stability curves for different natural gases²⁸. These gas-hydrate phase-diagrams (figs. 1A, 1B, and 1C) illustrate how variations in formation-temperature, pore-pressure, and gas composition can affect the thickness of the gas-hydrate stability zone. In each phase-diagram, the mean-annual surface temperature is assumed to be -10°C; however, the depth to the base of permafrost (0°C isotherm) is varied for each temperature profile (assumed permafrost depths of 305 m, 610 m, and 914 m). Below permafrost, three different geothermal gradients (4.0°C/100 m, 3.2°C/100 m, and 2.0°C/100 m) are used to project the sub-permafrost temperature profiles. The two gas-hydrate stability curves represent gas hydrates with different gas chemistries. One of the stability curves is for a 100 percent methane hydrate, and the other is for a hydrate that contains 98 percent methane, 1.5 percent ethane, and 0.5 percent propane. The only difference among the three phase-diagrams (figs. 1A, 1B, and 1C) is the assumed pore-pressure gradient. Each phase diagram is constructed assuming different pore-pressure gradient; 9.048 kPa/m [0.400 psi/ft] (fig. 1A), 9.795 kPa/m [0.433 psi/ft] (fig. 1B), and 11.311 kPa/m [0.500 psi/ft] (fig. 1C).

The zone of potential gas-hydrate stability in each phase-diagram (figs. 1A, 1B, and 1C) lies in the area between the intersections of the geothermal gradient and the gas-hydrate stability curve. For example, in figure 1B, which assumes a hydrostatic pore-pressure gradient, the temperature profile projected to an assumed permafrost base of 610 m intersects the 100 percent methane-hydrate stability curve at about 200 m, thus marking the upper boundary of the methane-hydrate stability zone. A geothermal gradient of 4.0°C/100 m projected from the base of permafrost at 610 m intersects the 100 percent methane-hydrate stability curve at about 1,100 m; thus, the zone of potential methane-hydrate stability is approximately 900 m thick. However, if permafrost extended to a depth of 914 m and if the geothermal gradient below permafrost is 2.0°C/100 m, the zone of potential methane-hydrate stability would be approximately 2,100 m thick.

Most gas-hydrate stability studies assume that the pore-pressure gradient is hydrostatic (9.795 kPa/m; 0.433 psi/ft). Pore-pressure gradients greater than hydrostatic will correspond to higher pore-pressures with depth and a thicker gas-hydrate stability zone. A pore-pressure gradient less than hydrostatic will correspond to a thinner gas-hydrate stability zone. The effect of pore-pressure variations on the thickness of the gas-hydrate stability zone can be quantified by comparing each of the phase diagrams in figures 1A, 1B, and 1C. For example, in figure 1A,

which assumes a 9.048 kPa/m (0.400 psi/ft) pore-pressure gradient, the thickness of the 100 percent methane-hydrate stability zone with a 610 m permafrost depth and a sub-permafrost geothermal gradient of 2.0°C/100 m would be about 1,600 m. However, if a pore-pressure gradient of 11.311 kPa/m (0.500 psi/ft) is assumed (fig. 1C) the thickness of the methane-hydrate stability zone would be increased to about 1,850 m.

The gas-hydrate stability curves in figures 1A, 1B, and 1C were obtained from laboratory data published in Holder and others²⁸. The addition of 1.5 percent ethane and 0.5 percent propane to the pure methane gas system shifts the stability curve to the right, thus deepening the zone of potential gas-hydrate stability. For example, assuming a hydrostatic pore-pressure gradient (fig. 1B), a permafrost depth of 610 m, and a sub-permafrost geothermal gradient of 4.0°C/100 m, the zone of potential methane (100 percent methane) hydrate stability would be about 900 m thick; however, the addition of ethane (1.5 percent) and propane (0.5 percent) would thicken the potential gas-hydrate stability zone to 1,100 m.

III.B. Pore-Water Salinity

It is well known that dissolved salt can depress the freezing-point of water. For example, the base of the ice-bearing permafrost on the North Slope of Alaska does not coincide with the 0°C isotherm but with a lower temperature¹⁰. This freezing-point depression has been attributed in part to the presence of salt in the unfrozen pore-waters. Salt, such as NaCl, when added to a gas-hydrate system, also lowers the temperature at which gas hydrates form. Pore-water salts in contact with the gas during gas hydrate formation can reduce the crystallization temperature by about 0.06°C for each part per thousand of salt²⁸. Therefore, a pore-water salinity similar to that of seawater (32 ppt) would shift the gas-hydrate stability curves in figures 1A, 1B, and 1C to the left about 2°C and reduce the thickness of the gas-hydrate stability zone.

III.C. Availability of Gas and Water

Most naturally occurring gas hydrates are characterized by two crystal structures known as Structure I and Structure II⁷. The ideal gas/water ratio of Structure I gas hydrate is 8/46, whereas the ideal gas/water ratio of Structure II gas hydrate is 24/136. These ideal ratios confirm the observation that gas hydrates contain a substantial volume of gas. For example, if all the cages of Structure I gas hydrate are occupied, each volume of gas hydrate will contain 189 volumes of gas at standard temperature and pressure. The ideal hydrate gas/water ratios also indicate that there is a substantial amount of water stored in the gas-hydrate structure. These high gas and water concentrations demonstrate that the formation of gas hydrate requires a large source of both gas and water. Thus, it becomes necessary to quantify the potential sources of gas and water when assessing a potential gas-hydrate accumulation.

III.D. Gas and Water Migration Pathways

Other factors controlling the availability of gas and water are the geologic controls on fluid migration. As previously shown, gas hydrates contain a substantial volume of gas and water that must be supplied to a developing gas-hydrate accumulation. If effective migration pathways are not available, it is unlikely that a significant volume of gas hydrates would accumulate. Therefore, geologic parameters such as rock permeability and the nature of faulting must be evaluated to determine if the required gas and water can be delivered to the potential hydrate reservoir.

III.E. Presence of Reservoir Rocks and Seals

The study of gas-hydrate samples recovered during research coring operations in oceanic sediments suggests that the physical nature of in-situ gas hydrates may be highly variable⁷. Gas hydrates were observed to be (1) occupying pores of coarse-grained rocks; (2) nodules disseminated within fine-grained rocks; (3) a solid, filling fractures; or (4) a massive unit composed mainly of solid gas hydrate with minor amounts of sediment. Because of the limited number of gas-hydrate samples, it is not known if gas hydrates are usually pore-filling material or occur as massive units. A study of well logs from northern Alaska indicate that gas hydrates occur there as pore-filling constituents within coarse-grained reservoir rocks¹⁰. This study suggests that porous rock intervals serve as reservoir rocks in which gas and water can be concentrated in the amounts necessary for gas-hydrate formation. Therefore, the presence of reservoir rocks may play a role in gas-hydrate formation, particularly in well-consolidated rock intervals. It is also speculated that the presence of effective reservoir seals or traps may play a role in gas-hydrate formation. Gas generated at depth moves upward, generally along tilted permeable carrier beds, until it either seeps at the surface or meets an impermeable barrier (trap) that stops or impedes its flow. As migrating gas accumulates below an effective seal, the total gas concentrations may reach the critical amounts necessary for the formation of gas hydrates. Thus, impermeable seals can provide a mechanism by which the required gas can be concentrated within reservoir rocks. Besides conventional reservoirs and trapping mechanisms, it is possible for gas hydrate to form its own reservoir and trap. As gas migrates into the zone of gas-hydrate stability, it may interact with the available pore water to generate gas hydrate. With the appropriate volumes

of gas and water, the pore space within the reservoir rock could be completely filled, thus making the rock impermeable to further hydrocarbon migration. The plugging of gas pipelines and production tubing by gas hydrates is testimony to the sealing potential of gas hydrates⁷. It has also been shown that, in marine environments, gas hydrates can mechanically displace sediments to form their own reservoir. Thus, the availability of reservoir quality rocks may not always be a limiting factor.

IV. GAS HYDRATE RESOURCE ASSESSMENT

The major goal of this resource assessment is to estimate the gas hydrate resources in the United States, both onshore and offshore. Similar to the assessment of the conventional resources in the 1995 U.S. Geological Survey (USGS) Oil and Gas Assessment²⁹, this assessment of gas hydrates is based on a play-analysis scheme, which was conducted on a province-by-province basis. We have defined, described, and assessed all the gas-hydrate plays in the United States regardless of their current economic or technological status. Therefore, this assessment is concerned with the *in-place* gas hydrate resources—that is, the amount of gas that may exist within the gas hydrates without reference to its recoverability. In a play analysis method, prospects (potential hydrocarbon accumulations) are grouped according to their geologic characteristics into plays. The geologic settings of the hydrocarbon occurrences in the play are then modeled. Probabilities are assigned to the geologic attributes of the model necessary for generation and accumulation of hydrocarbons. In this assessment method, geologists make judgments about the geologic factors necessary for the formation of a hydrocarbon accumulation and quantitatively assess the geologic factors that determine its size.

In this assessment, 11 gas-hydrate plays were identified within four offshore and one onshore petroleum provinces (figure 2); for each play, *in-place* gas hydrate resources were estimated. Estimates for each of the 11 plays were aggregated to produce the estimate of total gas-hydrate resources in the United States. The offshore petroleum provinces assessed consist of the U.S. Exclusive Economic Zone (EEZ) adjacent to the lower 48 States and Alaska. The only onshore province assessed was the North Slope of Alaska, which included State water areas and some offshore Federal waters. The provinces shown in figure 2 are geographic in character; however, their formation represents an attempt to group the individual petroleum provinces along broad geologic lines. Maps depicting the geologic data required for this hydrate assessment have been included in the U.S. Geological Survey 1995 National Oil and Gas Assessment CD-ROM²⁹. Maps of bathymetry, sedimentary thickness, total organic carbon (TOC) content of the sediments, seabed temperature, geothermal gradient, and hydrate stability zone thickness have been published for all four offshore provinces assessed in the U.S. Geological Survey 1995 National Oil and Gas Assessment CD-ROM²⁹. Maps depicting the thickness of the onshore gas-hydrate stability zone in northern Alaska are also included in the Assessment CD-ROM²⁹.

The estimates of *in-place* gas-hydrate resources included in this report are presented in the form of complementary cumulative probability distributions (fig. 3). These distributions summarize the range of estimates generated by the FASPU computer program²⁹ as a single probability curve in a "greater than" format (fig. 3). Our estimates are reported at the mean and at the 95th, 75th, 50th, 25th, and 5th fractiles. We consider the 95th and 5th fractiles to be "reasonable" minimum and maximum values, respectively. *In-place* gas resources within the gas hydrates of the United States are estimated to range from 112,765 to 676,110 trillion cubic feet of gas (TCFG) [3,193 to 19,142 trillion cubic meters of gas (TCMG)], at the 0.95 and 0.05 probability levels, respectively (fig. 3). Although these ranges of values show a high degree of uncertainty, they do indicate the potential for enormous quantities of gas stored as gas hydrates. The mean *in-place* value for the entire United States is calculated to be 320,222 trillion cubic feet of gas (TCFG) [9,066 trillion cubic meters of gas (TCMG)]. This assessment of *in-place* gas hydrates represents those deposits that constitute the resource base *without reference to recoverability*.

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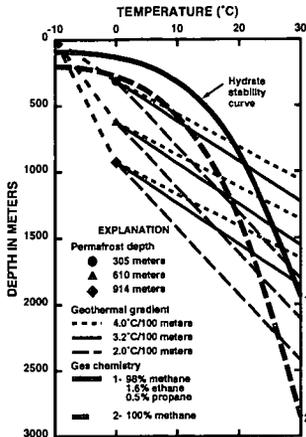


Figure 1A. Graph showing the depth-temperature zone in which gas hydrates are stable in a permafrost region [9.048 kPa/m pore-pressure gradient].²⁸

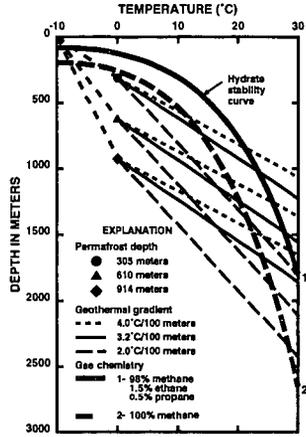


Figure 1B. Graph showing the depth-temperature zone in which gas hydrates are stable in a permafrost region [9.795 kPa/m pore-pressure gradient].²⁸

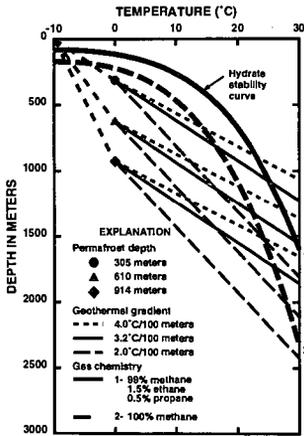


Figure 1C. Graph showing the depth-temperature zone in which gas hydrates are stable in a permafrost region [11.311 kPa/m pore-pressure gradient].²⁸

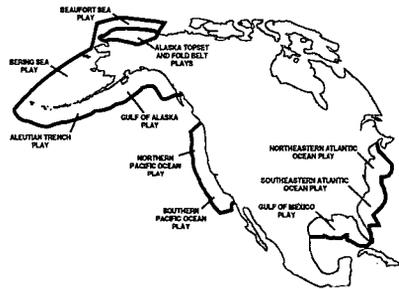


Figure 2. Gas hydrate play map of the United States.²⁹

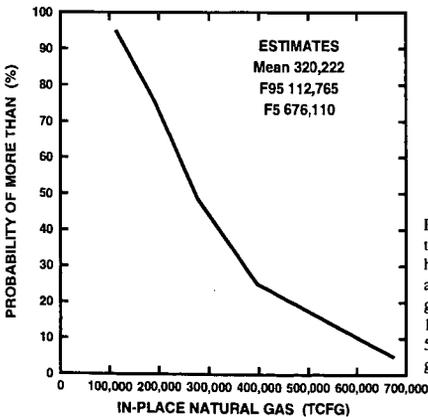


Figure 3. Cumulative probability curve showing the estimated in-place resources within the gas hydrates of the United States. The curve is read as follows: there is a 95 percent chance that the gas hydrate resource potential is greater than 112,765 trillion cubic feet of gas, and there is a 5 percent chance that the gas hydrate resource is greater than 676,110 trillion cubic feet of gas.²⁹