Methane Hydrate, “Fire in the Ice”

Energy Potential and Environmental Implications

First found locked in the Siberian ice, methane hydrate has recently emerged as a naturally occurring energy resource of potentially great significance. It is estimated that resources of methane in natural hydrate reservoirs exceed 10 quadrillion m$^3$, even by the most conservative estimates, indicating that more carbon is contained in methane hydrate than in all other organic carbon reservoirs on earth combined. Aside from their energy potential, hydrates have also been considered as a medium for gas storage, for transport, for water and gas purification, and as a novel method for sequestering carbon dioxide (CO$_2$). A major challenge in utilizing all the benefits of methane hydrate, of course, will be to consider the environmental implications of its occurrence and extraction.

Introduction

Methane hydrate, the most commonly encountered natural hydrate, is a type of clathrate mainly composed of water and methane. Cage-like structures of water molecules bound by either van der Waals or hydrogen-bonding can store gas molecules within the cage under pressure and temperature conditions specific to the gas molecules. When dissociated at standard temperature and pressure, one unit of clathrate hydrates can release 164 units of gas and 0.8 units of water [1].

Hydrate research started at the late 18$^{th}$ century as a purely scientific study. When hydrate was discovered as solid plugs blocking flow in gas and petroleum pipeline systems in the 1930s, the flow assurance became important, particularly in the petroleum industry. Natural gas hydrate was first inferred to exist in nature in 1965 in the Messoyakha Gas Field of western Siberia [2]. Since then, gas hydrates have been identified or inferred at over sixty locations throughout the world (fig. 2). Recently, many countries have launched national research and development programs supported by their unique political, economic, and environmental concerns.

Natural Occurrence
Natural gas hydrate occurs in the Gas Hydrate Stability Zone (GHSZ), a thermodynamic region defined by temperature gradient and phase boundary between hydrate solid and gas [4].

The GHSZ exists typically at depths of less than 1-2 km in permafrost regions and in marine sediments on continental margins lying at water depths greater than 300 meters (fig. 3). Occurrences of hydrate within the GHSZ are affected by numerous additional factors, including availability of gas, water, and geological controls [5].

Methane originates from microbial or thermal degradation of organic matter. The methane produced moves to thermodynamically favorable locations via diffusion, pore water flow, or migration of bubbles to form hydrates. The gas migration mechanisms, along with other controlling factors, can diversify the patterns of hydrate occurrence. Because hydrates mainly consist of water, water availability limits hydrate formation, and pore water salinity significantly shifts the hydrate stability domain. Geologic factors impacting probability of hydrate emplacement include heat flow, gas source and migration, and host sediment characteristics (permeability, porosity, and pore scale). Methane hydrate deposits occur in sedimentary deposits, such as massive deposits encased in fine-grained muds and shales, nodules, vein fills, or permeable sand layers trapped under impermeable sealing layers (fig. 1). Hydrates in the diffuse formations found in Blake Ridge on the eastern U.S. coast may not be economically extractable due to their low resource density and limited permeability. Higher saturation of hydrate deposits in sand-dominated reservoirs, as found on Alaska's North Slope, offshore Japan, or most recently in the Gulf of Mexico will likely be the primary targets for production [6].

**Methane Production**

Concepts for the production of methane from hydrate deposits include
depressurization, in which system pressure is reduced below equilibrium value; thermal stimulations, in which system temperature is raised above the equilibrium values; or injection of inhibitors, such as brine, glycol, surfactants, and alcohol, by which the thermodynamic stability boundary is shifted to lower temperature and higher pressure [7]. A new and intriguing method is the injection of the CO$_2$, which has the potential to liberate the methane while sequestering the CO$_2$.

Methane hydrate deposits have never been subjected to major commercial production, except presumptive contribution to the gas production at the Messoyakha Field [2]. Limited short-term field tests for enhancing scientific understanding and technical viability, rather than achieving economically feasible gas production, were performed at Mallik in 2002 through 2008 and at North Slope of Alaska in 2007 [8]. Numerical reservoir simulation studies currently play a major role in evaluating the potential of reservoir hydrate gas production. Such gas hydrate reservoir simulators as "Tough+Hydrate" and "CMG-Stars" emphasize that large permeabilities and porosities in deeper and warmer highly saturated hydrate reservoir formation constrained by impermeable upper boundaries are essential for economically and technically practical gas production with currently existing technologies [9].

Laboratory tests are underway to help understand the behavior of hydrate and to quantify critical hydrological and thermodynamic properties of hydrate-bearing sediments to validate numerical simulations and support planning and analysis of field programs. Due to limited availability of natural samples, however, laboratory-synthesized samples are mostly utilized for the experimental studies. A major concern is the creation of samples that adequately replicate natural samples. Recent advances on non-destructive observations with X-ray computed tomography enable us to see matrix integrity and fluid flow pattern, as well as evolution of hydrate formation and distribution within sediments (fig. 4).

**Environmental Impacts**

Geologic records show that methane, a powerful greenhouse gas, is alternately released from and sequestered by gas hydrates on a periodic basis [10]. Despite consumption from biogenic oxidation, rapid release of methane could be a positive feedback to ongoing climate change. Also, the link between submarine slides and gas hydrate dissociation continues to be studied. Volume expansion from hydrate dissociation can increase pore pressure in hydrate-bearing sediments, and the elevated pressure can reduce mechanical strength of the sediment, triggering sea floor sliding (fig. 3). Although a few past global warming events are likely
associated with the release of methane from gas hydrates, the nature of that link is not yet well known.

**Conclusion**

The primary challenges of developing gas hydrate reservoirs include creating reliable and effective exploration and production technologies, assessing economically recoverable resources, and understanding the role of gas hydrate in global climate change. Collaborative efforts to overcome these technical challenges should be continued to determine methane hydrate's potential as an environmentally safe and economically viable energy source.

**References**


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