

### 3. Future Supply Potential of Natural Gas Hydrates

Earth's vast deposits of natural gas hydrates hold the promise of meeting the world's natural gas needs far into the 21st century—if they can be tapped. Presently they are at best a sub-economic resource, but realization of even a small part of their potential would provide a very significant new source of natural gas to meet future energy and environmental requirements. Detailed knowledge of natural gas hydrate deposits is scant, and how they might be produced economically and safely has barely been considered. Still:

- Global estimates place the gas volume (primarily methane) resident in oceanic natural gas hydrate deposits in the range of 30,000 to 49,100,000 *trillion* cubic feet (Tcf), and in continental natural gas hydrate deposits in the range of 5,000 to 12,000,000 Tcf. Comparatively, current worldwide natural gas resources are about 13,000 Tcf and natural gas reserves are about 5,000 Tcf.
- The current mean (expected value) estimate of domestic natural gas hydrates in-place is 320,222 Tcf. In comparison, as of 1997 the mean estimate of all untapped technically recoverable U.S. natural gas resources was 1,301 Tcf, U.S. proved natural gas reserves were 167 Tcf, and annual U.S. natural gas consumption was about 22 Tcf.
- Large volumes of natural gas hydrates are known to exist in both onshore and offshore Alaska, offshore the States of Washington, Oregon, California, New Jersey, North Carolina, and South Carolina, and in the deep Gulf of Mexico. Most of the volume is expected to be in Federal jurisdiction offshore waters, although 519 Tcf of hydrated gas-in-place was assessed for onshore Alaska—more than three times the 1997 level of U.S. proved natural gas reserves.

Significant safety and environmental concerns are also associated with the presence of natural gas hydrates, ranging from their possible impact on the safety of conventional drilling operations to the influence on Earth's climate of periodic natural releases into the atmosphere of large volumes of hydrate-sourced methane or derivative carbon dioxide.

Considerable research is needed to characterize more completely and accurately the location, composition, and geology of Earth's natural gas hydrate deposits. This body of research is a necessary precursor to development of means to extract them, as well as to determination of their possible future climatic impacts.

Natural gas is widely expected to be the fastest-growing primary energy source in the world over the next 25 years. In the Energy Information Administration's *International Energy Outlook 1998* reference case,<sup>1</sup> worldwide gas consumption was projected to grow by 3.3 percent annually through 2020, as compared with 2.1-percent annual growth for oil and renewable energy sources and 2.2-percent annual growth for coal. The world's consumption of natural gas was projected to be 172 trillion cubic feet by 2020, more than double the 1995 level. Much of this growth was expected to fuel electricity generation worldwide, but resource availability, cost, and environmental considerations were also expected to contribute to growing use of natural gas in industrial, residential, and commercial sector applications.

Conventional world natural gas resources are estimated to be about 13,000 trillion cubic feet. The ability of this conventional resource base to meet the world's growing gas supply needs is limited by the fact that a substantial portion of it is not located close to major and developing gas markets and would therefore require enormous investments in pipelines and other facilities to move the gas to market. For that reason, much of the current conventional resource is uneconomic to produce.

Natural gas hydrates are a vast potential, though not presently commercial, source of additional natural gas. One of the most appealing aspects of this potential new gas source is that large deposits are located near the expected demand growth areas. Some countries, such as Japan, do

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<sup>1</sup>Energy Information Administration, *International Energy Outlook 1998*, DOE/EIA-0484(98) (Washington, DC, April 1998).

not have indigenous oil or gas resources but do have nearby oceanic natural gas hydrate deposits. Even in those countries that have some conventional gas supplies, additional supplies from hydrate production would allow greater expansion of their use of natural gas. Such prospects, however, hinge on whether or not gas can ever be commercially produced from the world's natural gas hydrate deposits, and if so, to what extent.

Natural gas hydrates are solid, crystalline, ice-like substances composed of water, methane, and usually a small amount of other gases, with the gases being trapped in the interstices of a water-ice lattice. They form under moderately high pressure and at temperatures near the freezing point of water (see box, p. 75). The naturally occurring version is primarily found in permafrost regions onshore and in ocean-bottom sediments at water depths exceeding 450 meters (see box, p. 76 and Figure 25).<sup>2</sup> Although their natural existence has only been known since the mid-1960s, it is firmly established that in sum these deposits are volumetrically immense: their estimated carbon content dwarfs that of all other fossil hydrocarbons combined.

Huge volumes of natural gas hydrates are either known or expected to exist in a relatively concentrated form at numerous locations (Figure 26). Current estimates indicate that the mass of carbon trapped in natural gas hydrates is more than half of the world's total organic carbon and twice as much as all other fossil fuels combined (Table 7). It has been estimated that a maximum of 270 million trillion cubic feet of natural gas could theoretically exist in hydrate deposits. Although the actual maximum volume is probably at least an order of magnitude smaller, it is still a huge volume (see Table 8). The "central consensus" estimate independently obtained by different investigators using varied estimation methods is about 742,000 trillion cubic feet (Tcf), whereas worldwide natural gas resources exclusive of natural gas hydrates are only about 13,000 Tcf and worldwide natural gas reserves are about 5,000 Tcf. In the United States, very large methane hydrate deposits are located both on- and offshore northern Alaska, offshore the

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<sup>2</sup>Most knowledge of naturally occurring natural gas hydrates and their geocontext is of recent vintage. In consequence, a significant portion of the source material for this chapter consists of matter directly published on the Internet rather than in peer-reviewed journals and similar traditional sources. Owing to the extensive list of sources and their fragmented coverage, attribution footnotes appear only for the most important references. A complete bibliography is provided in conjunction with the electronic version of this chapter at the Energy Information Administration's Internet site at URL <http://www.eia.doe.gov>.

States of Washington, Oregon, California, New Jersey, North Carolina, and South Carolina, and in the deep Gulf of Mexico (Figure 27). The U.S. Geological Survey's 1995 mean (expected value) estimate is that in aggregate these deposits contain 320,222 Tcf of methane-in-place.<sup>3</sup> Almost all of it (99.8 percent) is expected to be located in Federal-jurisdiction offshore waters (Figure 27). Nonetheless, 519 Tcf of gas in place—a bit more than three times the 1997 level of U.S. proved dry gas reserves—was assessed for onshore Alaska.

To place these estimates in perspective, consider that the corresponding mean estimate of all untapped technically recoverable U.S. natural gas resources was 1,301 Tcf, proved U.S. natural gas reserves were 167 Tcf at the end of 1997, and in 1997 the United States consumed 22 Tcf, 13 percent of which was imported from Canada.

Irrespective of the large in-place volumes, natural gas hydrates are at present only a potential, as opposed to an assured, future energy source. Methods for intentionally producing gas from them for profit at commercial scale have yet to be developed. How much of the gas-in-place might be technically recoverable is presently unknown, and the economically recoverable volume would be smaller. But even if only a small percentage of the total in-place volume could be commercially produced, the impact would be dramatic. As noted by the Department of Energy's (DOE) Office of Fossil Energy, if 1 percent of the resource could be recovered, that would more than double the domestic gas resource base.<sup>4</sup>

## How To Produce?

Means of economically and safely producing methane from gas hydrate deposits are not yet on the drawing board. Nevertheless, there is one place where commercial production of natural gas hydrate is possibly already happening, although not by design: the Messoyakha Gas

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<sup>3</sup>The U.S. Geological Survey estimated that there is a 95-percent chance that they contain at least 112,765 trillion cubic feet and a 5-percent chance that they contain at least 676,110 trillion cubic feet. The estimates represent the statistical sum (not the arithmetic sum, excepting the mean) of individual estimates for 13 assessed gas hydrate plays.

<sup>4</sup>U.S. Department of Energy, Office of Fossil Energy, Statement of Robert S. Kripowicz, Principal Deputy Assistant Secretary for Fossil Energy, Before the Subcommittee on Energy, Research, Development, Production, and Regulation, Committee on Energy and Natural Resources, U.S. Senate (May 21, 1998).

## What Are Natural Gas Hydrates?

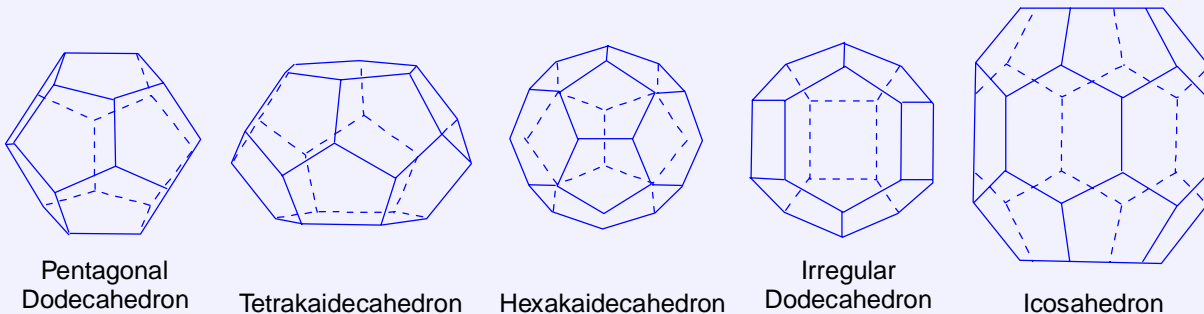
Natural gas hydrates are members of a highly varied class of substances called clathrates. These are solids formed by the inclusion of molecules of one kind (guest molecules) within the intermolecular cavities of a crystal lattice composed of molecules of another kind (host molecules). The guest molecules are necessary to support the cavities, and the association between host and guest molecules is principally physical because such bonding as exists is due to the weak attraction between adjacent molecules, rather than to the stronger chemical bonding responsible for most compounds as well as the hydrate water-ice lattice, which is hydrogen bonded.

Gas hydrates are ice-like substances composed of a host lattice of water molecules ( $\text{H}_2\text{O}$ ) and one or more of a potential suite of guest molecules which at normal temperatures and pressures occur in the gaseous phase and are capable of physically fitting into the interstices of the water-ice lattice. This suite includes the noble gases (the elements helium, neon, krypton, argon, xenon, and radon), the halogens chlorine, bromine, iodine, and astatine, and hydrogen sulfide, sulfur trioxide, sulfur hexafluoride, and carbon dioxide ( $\text{CO}_2$ ). Significantly, it also includes the low molecular-weight hydrocarbons methane ( $\text{CH}_4$ ), ethane ( $\text{C}_2\text{H}_6$ ), propane ( $\text{C}_3\text{H}_8$ ), and the pentanes ( $\text{C}_5\text{H}_{12}$ ). A particular natural gas hydrate can contain from one to all of these.

Depending on the size of the guest molecule, natural gas hydrates can consist of any combination of three crystal structures: Structure I, Structure II, and Structure H. When pure liquid water freezes it crystallizes with hexagonal symmetry, but when it "freezes" as a hydrocarbon hydrate it does so with cubic symmetry for structures I and II, reverting to hexagonal symmetry for Structure H.

- Structure I gas hydrates contain 46 water molecules per unit cell arranged in 2 dodecahedral voids and 6 tetrakaidecahedral voids (the water molecules occupy the apices in the stick diagrams of the void types shown below), which can accommodate at most 8 guest molecules up to 5.8 Angstroms in diameter. Structure I allows the inclusion of both methane and ethane but not propane.
- Structure II gas hydrates contain 136 water molecules per unit cell arranged in 16 dodecahedral voids and 8 hexakaidecahedral voids, which can also accommodate up to 24 guest molecules, but to a larger diameter of 6.9 Angstroms. This allows inclusion of propane and iso-butane in addition to methane and ethane.
- The rare Structure H gas hydrates, which contain 34 water molecules per unit cell arranged in 3 pentagonal dodecahedral voids, 2 irregular dodecahedral voids, and 1 icosahedral void, can accommodate even larger guest molecules such as iso-pentane.

The hydrocarbon hydrates are non-stoichiometric substances, i.e., their compositional proportions are not fixed. A variable number of guest molecules up to the maximums given above can be accommodated in the host lattice since not all of the available lattice positions need be filled. Typically the volume of gas included in a fixed volume of hydrate increases in response to either lower temperature or higher pressure. Thus, given the substantial density difference between water and free gas, one volume of water can accommodate from 70 to over 160 volumes of gas depending on how many of the available voids are filled (the degree of saturation). Natural gas hydrates are often undersaturated, with most samples of the simplest and most common Structure I type falling in the 70- to 90-percent saturated range.



## Where Do Natural Gas Hydrates Occur ... and Why?

The first known natural gas hydrates were man-made, although not intentionally. The early natural gas industry found to its dismay that natural gas hydrate sometimes formed in pipelines as a wax-like, crystalline material which plugged the line. Worse yet, when the pipeline was depressured in order to remove the plug, the gas hydrate often stubbornly remained stable right up to ambient temperature and pressure. This occurred because natural gas hydrates that contain more than one kind of guest molecule are often physically stable over a wider range of temperature and pressure conditions than the range characteristic of pure methane hydrate. Hydrate clogging of pipelines has been simply if not inexpensively avoided ever since by drying the gas stream before injecting it into the pipeline, inasmuch as the removal of water eliminates the possibility of hydrate formation. Its formation is typically chemically inhibited when necessary in production operations.

### Natural Occurrences

Naturally occurring natural gas hydrates were first discovered in 1964 in association with cold subsurface sediments located in Siberian permafrost terrains. The discovery of oceanic gas hydrates within the upper tens to hundreds of meters of continental margin sediments was reported in 1977. Natural gas hydrates also occur in sediments at the bottom of Russia's Lake Baikal, a very deep freshwater lake, but the volumes associated with such occurrences are very small as compared with the other two habitats. These are the only places on Earth in which natural gas hydrates can naturally occur, because they are the only ones where the thermodynamic (primarily temperature and pressure) conditions at which natural gas hydrates are physically stable prevail. Pure methane hydrate can neither form nor persist exposed to atmospheric temperatures and pressures; colder temperatures and higher, though still moderate, pressures are required for its formation and stability. Similarly, natural gas hydrates are stable only below an upper temperature bound and above a lower pressure bound.

### The Hydrate Stability Zone

The range of subsurface or subsea depths within which the prevailing temperature and pressure conditions allow a natural gas hydrate of the particular local gas composition to form and remain stable is called the hydrate stability zone (HSZ) (Figure 25). Because it is much colder at the surface in the Arctic, the top of the HSZ is in most instances much shallower in the onshore permafrost environment than in the oceanic environment. In the ocean, the HSZ starts at around 45 atmospheres of pressure (663 psi), which equates to a depth of 450 meters (1,476 feet). The temperature at that depth is typically in the range of 4 to 6 degrees Centigrade (39 to 43 degrees Fahrenheit). Because the oceanic temperature gradient not only begins at a much higher temperature but also ends at a higher one, a substantially greater hydrostatic pressure and therefore more depth is required for natural gas hydrates to form and remain stable than is the case onshore.

The range of depths over which natural gas hydrates are stable is in most instances much greater in the permafrost terrain environment. Because the Arctic atmosphere has been very cold for a long time, the permafrost, consisting of those sediments in which the resident pore water has remained frozen at zero degrees Centigrade or below for 2 or more consecutive years, extends from the surface (or a few inches below it in mid-summer) to more than 700 meters (2,297 feet) in the coldest areas; its maximum depth along the Alyeska Pipeline is, for example, 2,230 feet—almost a half-mile. Natural gas hydrates are stable anywhere within the permafrost zone and for a variable distance below it depending on the local subsurface heat flow rate. Permafrost terrains occupy about 20 percent of the Earth's surface.

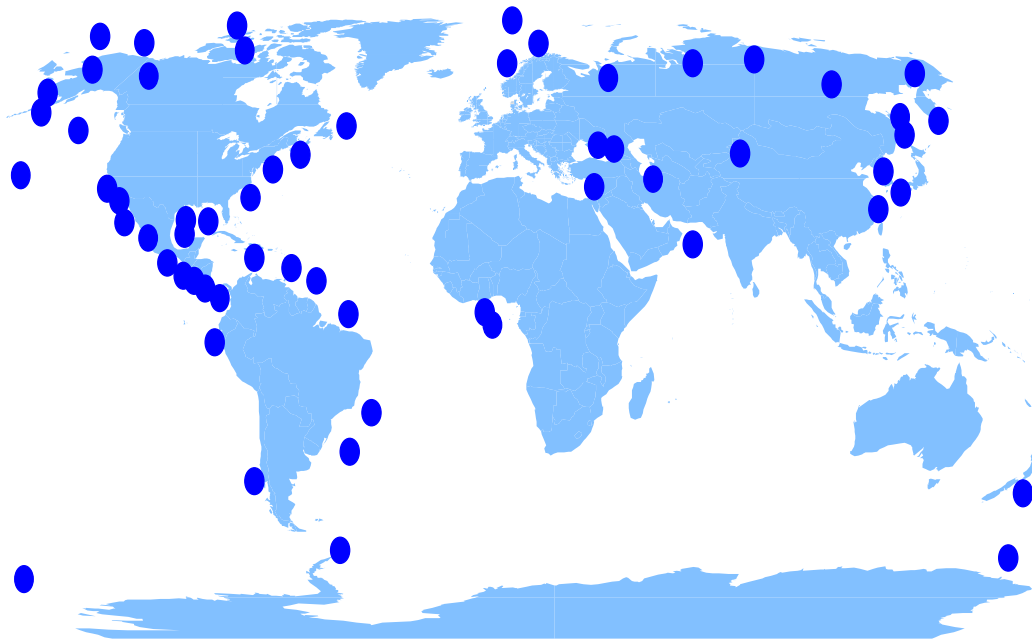
Natural gas hydrates are known to have at least four manifestations within the HSZ: as finely disseminated grains in the sediment (the most commonly observed form), as small nodules in the sediment, as small layers within the sediment, and as massive (blocky) occurrences. They need not and often do not occur throughout the entire HSZ. Beneath the HSZ, in what is called the free-gas zone (Figure 25), the sediment's pore spaces are filled with salty water that contains dissolved gas, or with bubbles of gas if the water is gas-saturated. For gas hydrates to form in sediments: (1) the thermodynamic conditions suited to gas hydrate formation must exist, i.e., there must in fact *be* an HSZ, (2) adequate gas must be generated in the subjacent sediments or by bacteria within the HSZ itself, (3) subjacent generated gas must be able to migrate upward to the HSZ, and (4) water must be present in the HSZ.

**Figure 25. Gas Hydrate Occurrence Zone and Stability Zone**



Source: Energy Information Administration, Office of Oil and Gas, based on W. Xu and C. Ruppel, "Predicting the Occurrence, Distribution, and Evolution of Methane Gas Hydrate in Porous Marine Sediments," draft submitted to *Journal of Geophysical Research* (April 1998).

**Figure 26. Locations of Known and Expected Concentrated Methane Hydrate Deposits**



Source: After U.S. Geological Survey, based on K.A. Kvenvolden, "Methane Hydrate—A Major Reservoir of Carbon in the Shallow Geosphere?" *Chemical Geology*, Vol. 71 (1988).

**Table 7. The Earth's Organic Carbon Endowment by Location (Reservoir)**

Reservoir	Organic Carbon	
	10 <sup>13</sup> Kilograms	Trillion Short Tons
Gas Hydrates (on- and offshore)	10,000	110,230
Fossil Fuels (coal, oil, natural gas)	5,000	55,116
Soil	1,400	15,432
Dissolved Organic Matter in Water	980	10,803
Land Biota	830	9,149
Peat	830	9,149
Detrital Organic Matter	60	661
Atmosphere	3.6	40
Marine Biota	3	33

Note: As a point of reference, the Great Lakes' 5,500 cubic miles of fresh water have a mass of about 25.2 trillion short tons.

Source: K.A. Kvenvolden, "Gas hydrates - geologic perspective and global change," *Review of Geophysics* 31 (1993), pp. 173-187.

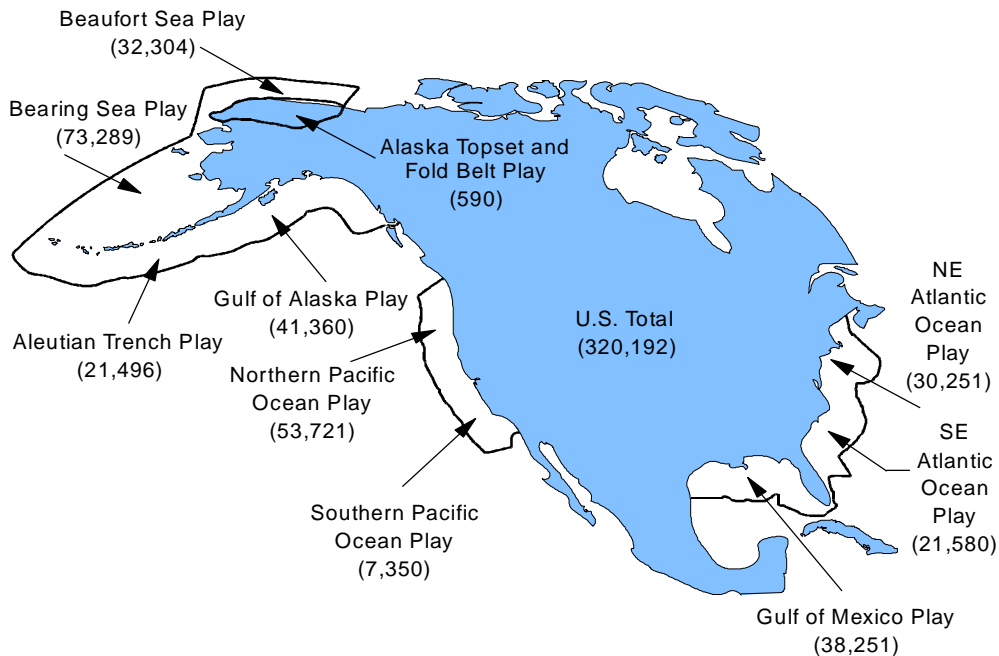
**Table 8. Estimates of Methane in Natural Gas Hydrate Deposits (100,000 Trillion Cubic Feet)**

Date of Estimate/Source	Oceanic Deposits	Continental Deposits	All Deposits
1977/Trofimuk et al	1.8 to 8.8	0.02	--
1981/Mclver	1.1	0.011	--
1981/Meyer	--	0.005	--
1988/Kvenvolden	6.2	--	--
1990/MacDonald	6.9	--	--
1994/Gornitz and Fung	9.3 - 49.1	--	--
1998/Kvenvolden	--	--	0.35 - 16.25
1998/Kvenvolden "Consensus"	--	--	7.42

Notes: The differences in the estimates are due to different assumptions and estimation approaches. Both Mclver and Meyer based their estimates on thermodynamic considerations and assessments of the availability of methane. Gornitz and Fung used estimates of geothermal gradients, porosity, pore fill chemistry, and the two methane generation theories (biogenic and thermogenic) to calculate the potential range of volumes, noting that the actual amount is likely to be near the lower bound. The earlier Kvenvolden estimate represents extrapolation of an estimate of the hydrate present off northern Alaska to all continental margins. The latest Kvenvolden estimate takes into account the most recent work in the field, providing a constrained range and a "consensus" central estimate. Dobrynin, et al. (not tabulated here) estimated theoretical maximum volumes by assuming that methane hydrate would occur at all locations where conditions were favorable and that it would be fully saturated; the result, 2,700,000 trillion cubic feet in oceanic deposits and 12,000,000 trillion cubic feet in continental deposits, is unlikely to be the actual case.

Sources: ●A.A. Trofimuk, N.V. Cherskii, and V.P. Tsaryov, "The Role of Continental Glaciation and Hydrate Formation on Petroleum Occurrence," R.F. Meyer, ed., *The Future Supply of Nature-Made Petroleum and Gas* (New York, 1977), pp. 919-926. ●R.D. Mclver, "Gas Hydrates," *Long-term Energy Resources* (1981), pp. 713-726. ●R.F. Meyer, "Speculations on oil and gas resources in small fields and unconventional deposits," *Long-term Energy Resources* (1981), pp. 49-72. ●K.A. Kvenvolden, "Methane Hydrate—A Major Reservoir of Carbon in the Shallow Geosphere?" *Chemical Geology*, Vol. 71 (1988), pp. 41-51. ●G.J. MacDonald, "The Future of Methane as an Energy Resource," *Annual Review of Energy*, Vol. 15 (1990), pp. 53-83. ●V. Gornitz and I. Fung, *Potential Distribution of Methane Hydrates in the World's Oceans: Global Biogeochemical Cycles*, Vol. 8, No. 3 (1994), pp. 335-347. ●K.A. Kvenvolden, "Estimates of the Methane Content of Worldwide Gas-Hydrate Deposits," *Methane Hydrates: Resources in the Near Future?*, JNOC-TRC (Japan, October 20-22, 1988).

**Figure 27. USGS Assessment of Gas Hydrate Plays and Provinces, 1995**  
(Trillion Cubic Feet)



USGS = U.S. Geological Survey.

Source: **Volumes:** T.S. Collett, *Gas Hydrate Resources of the United States*, Table 2. **Map:** U.S. Geological Survey, *Digital Map Data, Text, and Graphical Images in Support of the 1995 National Assessment of United States Oil and Gas Resources*, Digital Data Series (DDS) 35 (1996), Figure 5.

Field located in permafrost terrain on the eastern margin of Russia's West Siberian Basin. The Messoyakha Field was developed as a conventional gas field and has produced continuously from 1970 through 1978 and thereafter intermittently, primarily in the summer to accommodate regional industrial demand. As is normally the case, reservoir pressure declined as a consequence of production. However, the reservoir pressure remained substantially higher than normally expected. A 100-meter-thick methane hydrate zone is located 700 meters beneath the surface, and the apparent difference between the actual and predicted pressure decline behavior has been attributed to recharging of the reservoir with gas derived from pressure decline-induced decomposition of the natural gas hydrates in this overlying layer. In 1990, the gas evolved from it reportedly comprised nearly half of cumulative field production, although some investigators have expressed doubt that gas hydrate production actually occurred.

## Possible Production Methods

There are at least three means by which commercial production of natural gas hydrates might eventually be achieved, all of which alter the thermodynamic conditions in the hydrate stability zone such that the gas hydrate decomposes.

- The first method is *depressurization*, akin to what may have happened at the Messoyakha Field. Its objective is to lower the pressure in the free-gas zone immediately beneath the hydrate stability zone, causing the hydrate at the base of the hydrate stability zone to decompose and the freed gas to move toward a wellbore.
- The second method is *thermal stimulation*, in which a source of heat provided directly in the form of injected steam or hot water or another heated liquid, or indirectly via electric or sonic means, is applied to the hydrate stability zone to raise its temperature, causing the hydrate to decompose. The direct approach could

be accomplished in either of two modes: a frontal sweep similar to the steam floods that are routinely used to produce heavy oil, or by pumping hot liquid through a vertical fracture between an injection well and a production well.

- The third method is *chemical inhibition*, similar in concept to the chemical means presently used to inhibit the formation of water ice. This method seeks to displace the natural gas hydrate equilibrium condition beyond the hydrate stability zone's thermodynamic conditions through injection of a liquid inhibitor chemical adjacent to the hydrate.

A major disadvantage of the thermal stimulation method is that a considerable portion of the applied energy (up to 75 percent) could be lost to nonhydrate-bearing strata (thief zones). A second major disadvantage is that the producing horizon must have good porosity, on the order of 15 percent or more, for the heat flooding to be effective. These drawbacks make the thermal stimulation method quite expensive. The chemical inhibitor injection method is also expensive, although less so than the thermal stimulation method, owing to the cost of the chemicals and the fact that it also requires good porosity. Finally, the injection of either steam or inhibitor fluid tends to "flood out" the reservoir over time, which makes it ever more difficult for liberated gas to flow to the producing well bore. Depressurization will therefore likely be the first production method tested outside the laboratory. It may prove useful to apply more than one production method in some cases.

## Where Might Production First Be Attempted?

Substantial research will be necessary to determine which, if any, natural gas hydrate deposits are suited to production. In the United States, the onshore Alaskan permafrost deposits are likely to be the first ones tested for producibility, for at least two reasons.

- Site access is physically easier and probably cheaper than for the oceanic deposits.
- The hydrate stability zone occurs in rocks that have petrophysical characteristics similar to those in conventional oil and gas reservoirs, so initial production attempts will not require the degree of technological innovation that will be necessary to produce from oceanic deposits.

As regards the oceanic deposits where most natural gas hydrates are located, those in the Gulf of Mexico are likely to be the first domestic ones tested for production, albeit that they are not very well known at present. The most thoroughly studied domestic oceanic deposits are located on the continental slope and rise off the U.S. Atlantic Coast, proximate to a large and growing natural gas market. But recent sediment studies of the natural gas hydrate deposits at the Blake Ridge, located about 200 miles east of Charleston, South Carolina, have not been encouraging. Blake Ridge is a large hill-like sedimentary feature formed by drift currents in water depths ranging from 900 to 4,000 meters (3 to 13 thousand feet). The studies indicate that about 1,800 trillion cubic feet of hydrated gas plus underlying free methane exists within a 26,000 square kilometer area (10,038 square miles, approximately the combined size of the Commonwealth of Maryland and Chesapeake Bay). Assuming a 50-percent recovery factor, that is equivalent to a 40-year national supply of gas at the 1997 consumption rate.

Unfortunately from the standpoint of production potential, the sediments in the Blake Ridge area are very finely-grained, silty clays. Their bulk porosity, on the order of 55 percent, is not a constraint on producibility but their ability to conduct fluid flow (their *in-situ* permeability)<sup>5</sup> has not been investigated and is probably very limited. Clays characteristically have quite low permeabilities that vary a bit in accord with their water content, which in turn is dependent on pressure. At the depth of the Blake Ridge hydrate stability zone,<sup>6</sup> it is safe to assume that the clays are fully water-saturated and therefore have the lowest possible permeability, which is a potentially serious constraint on methane hydrate producibility. The permeabilities of most conventional reservoir rocks range between 5 and 1,000 millidarcies. A reservoir rock with a permeability of 5 millidarcies or less is considered a "tight formation." While commercial production has been obtained from rocks with laboratory-measured permeabilities as low as 0.1 millidarcy, this may have been due to fractures rather than matrix permeability. Not only do the sediments in the Blake Ridge area fall in the tight formation category, their permeability would also be reduced in proportion to hydrate concentration. The implications for fluid flow and therefore production rates are not encouraging.

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<sup>5</sup>A quantitative measure of the ability of a porous material to conduct fluid flow. That ability is governed by porosity, grain size of the sediment, the pores' interconnections, and physical characteristics of the involved fluid or fluids.

<sup>6</sup>The sea floor in the Blake Ridge area lies about 2,800 meters (9,186 feet) below the surface. The hydrate stability zone (HSZ) begins 190 to 200 meters below the sea floor (mbsf), the bottom of the HSZ is at 450 mbsf, and the underlying free-gas zone extends to at least 700 mbsf.



Other areas along the U.S. Atlantic Coast might be more suitable for production. The Blake Ridge study area comprises only 3.5 percent of the Atlantic Coast's mean estimated in-place hydrated gas volume, and not all sediments on the Atlantic shelf are identical to those at Blake Ridge. Some are coarser-grained and therefore likely more permeable.

The same is true for other oceanic gas hydrate deposits. The limited data available on the clastic sediments associated with natural gas hydrate deposits on the Cascadia margin off Oregon indicate that they have a larger grain size than those at Blake Ridge. Those located in the deep Gulf of Mexico predominantly occur in high-porosity clastic rocks, which is why the Gulf of Mexico, rather than the Atlantic or Pacific oceans, will likely be the site of the first U.S. attempt to produce oceanic gas hydrates.

Irrespective of when and where the first domestic attempts to produce methane commercially from natural gas hydrate deposits ultimately occur, it is clear that considerable research will be required to (1) ascertain the true extent of the United States' and the world's natural gas hydrate deposits, (2) determine what if any portion of these deposits may be suitable for production, and (3) develop means of economically and safely producing natural gas from those that are.

## Possible Transportation Methods

If commercial production from oceanic natural gas hydrates is eventually established, there are at least three ways to transport the gas ashore: (1) by conventional pipeline; (2) by converting the gas hydrates to liquid middle distillates via the newly-improved Fischer-Tropsch process and loading it onto a conventional tanker or barge; or (3) by reconverting the gas into solid hydrate and shipping it ashore in a close-to-conventional ship or barge. The latter option was proposed in 1995 by a research team at the Norwegian Institute of Technology,<sup>7</sup> which determined that use of natural gas hydrate for the transportation and storage of natural gas was a serious alternative to gas liquefaction since the upfront capital costs are 25 percent lower. Yet another positive factor is that it is far safer to create, handle,

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<sup>7</sup>J.S. Gudmundsson, F. Hedvig, A. Børrehaug, Norwegian Institute of Technology, Department of Petroleum Engineering and Applied Geophysics, *Frozen Hydrate Compared to LNG* (Trondheim, Norway, January 1995); and J.S. Gudmundsson, A. Børrehaug, *Natural Gas Hydrate an Alternative to Liquefied Natural Gas*, at <<http://www.ipt.unit.no/~sg/forskning/hydrater/paper1.html>>.

transport, store, and regasify natural gas hydrate than liquefied natural gas.<sup>8</sup>

## Safety and Environmental Concerns

Naturally occurring natural gas hydrates present both mechanical and chemical risks. Normal drilling can generate enough downhole heat to decompose surrounding hydrates, possibly resulting in loss of the well, or in loss of well control and conceivably—should the drilling be from a platform—an ensuing loss of foundation support.

While large volumes of oceanic natural gas hydrate deposits are known to have decomposed in the past absent human influence, information on their role in the global carbon cycle and global climate change is limited. It is clear that the release of large quantities of methane into the atmosphere, for whatever reason, would substantially increase its greenhouse capability since methane is 21 times more potent a greenhouse gas than is carbon dioxide. Very little is presently known about the stability of natural gas hydrate deposits, especially those located on the ocean floor, during a period of “normal” global warming, i.e., gradual and low amplitude.

## Potential Hazard to Drilling Operations

Offshore operators have from time to time reported problems in drilling through gas hydrate zones. Drillers seeking conventional hydrocarbons have whenever possible purposely avoided drilling through natural gas hydrates because the process introduces two foreign sources of heat, friction and circulated drilling muds, that can cause dissociation of hydrates immediately adjacent to the borehole. When not avoidable, the hydrate stability zone is drilled and cased as fast as possible to minimize the risk of wall failure, perhaps leading to loss of the hole. Additionally, the free-gas zone beneath a hydrate cap can be overpressured, such that drilling into it without taking proper precautions can result in a blowout, just as is the case when conventional oil and gas drilling targets are involved. The Minerals Management Service has long maintained maps of the potential offshore natural gas hydrate occurrences to help ensure that this and the next category of risks are avoided or anticipated.

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<sup>8</sup>It has even been suggested that the produced gas be rehydrated at the sea floor and injected into large “bladders” that could then be towed to shore by a submersible “tug.”

## Potential Hazard to Sea Floor Structures

From 200 to 300 miles seaward of the shoreline, the continental shelves, slopes, and rises are replete with many types of man-made structures—drilling platforms, subsea well completions, pipelines, instrument housings, communication cables—and their numbers and distance from shore increase every year. Decomposition of natural gas hydrates, either gradual or rapid and either on-site or nearby, can place those structures located in sufficiently deep water at risk of damage or destruction. One such structural risk results from the fact that hydrate presence inhibits the normal compaction and cementation of sediments. If a hydrate deposit formed in the past has since decomposed, leaving behind poorly consolidated water-filled sediment, significant damage could occur if a heavy structure is placed at that location. If not recognized in a timely manner, compaction of the underlying sediment by the imposed mass, perhaps not uniformly distributed over the base area of the structure, could cause the structure to tilt or topple.

The other source of structural risk is submarine landslides. The sloping continental margins are the principal place of sedimentation and several mechanisms can trigger slope failures on them, such as earthquakes, faunal activity, and undercutting by bottom currents. At least one platform has been lost to a slide triggered by hurricane waves, and it is now known that natural gas hydrate decomposition is yet another cause of minor to major slides. Along the U.S. Atlantic seaboard, there is abundant evidence of such slope failure where, although the sea floor gently dips basinward at an average of less than 6 degrees, the slide locations are concentrated just seaward of the line at which the top of the hydrate stability zone intersects the sea floor (Figure 28). The relationship between hydrate decomposition and mass movement is also evidenced by thinning of the hydrate layer beneath slide scars. The size of these apparently Pleistocene Epoch slides is impressive. The Albermarle-Currituck Slide on the lower slope off North Carolina is 13.7 miles long, 4.3 to 7.5 miles wide, and 980 feet thick.

The Cape Fear Slide, also on the lower slope, is 23 miles long, 6.2 to 7.5 miles wide, and up to 260 feet thick. The Cape Lookout Slide, which cut a shallow trough on the shelf and slope, is 174 miles long and associated with a 22-mile-wide failure on the upper rise. It was apparently triggered by a fairly small upslope failure.

## Potential Hazard to Vessels and Other Floating Structures

Conceptually, the sudden release at the sea floor of large volumes of either methane or crystalline hydrate (which is buoyant in sea water) owing to the mechanical disruption of hydrated sediments (whether or not caused by rapid decomposition of the natural gas hydrate itself) could launch a mass of methane bubbles toward the surface—a methane plume. To the extent that the water column is occupied by bubbles, its bulk density is reduced and it follows that whatever is afloat above such a plume is at risk of quickly sinking.<sup>9</sup>

It is indisputable that massive submarine methane releases do naturally occur, although it is unclear just how sudden they are. The rate of decomposition of natural gas hydrate depends on how fast the ambient pressure and temperature conditions change. In particular, if pressure is reduced very quickly or temperature is increased very rapidly, the gas hydrate can powerfully liberate gas.

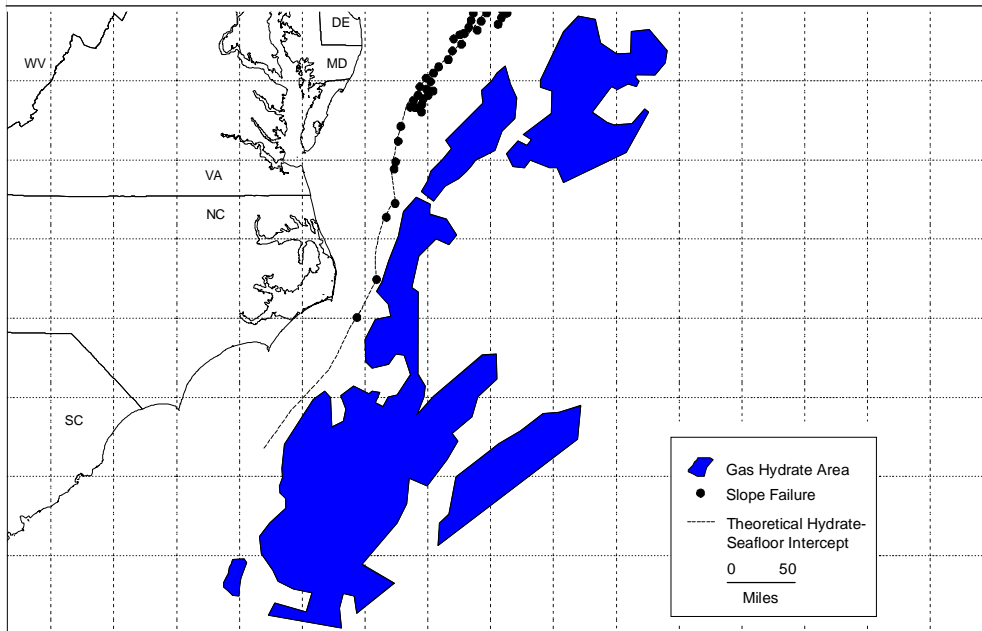
## The Global Carbon Cycle Role of Natural Gas Hydrates

As stated earlier, little is known about the stability of natural gas hydrates during a period of gradual, low amplitude global warming. Various parts of the ocean floor ranging from shallow to deep water are replete with “pockmarks,” roughly conical depressions up to 350 meters (1,148 feet) or more in diameter and 35 meters (115 feet) deep. The area of some pockmark fields exceeds

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<sup>9</sup>For this reason, it has been proposed that hydrate-sourced methane plumes are responsible for what is popularly characterized as a high incidence of “mysterious disappearances without trace” in the so-called Bermuda Triangle. In actuality, such events are no more common in the Bermuda Triangle than anywhere else.

**Figure 28. U.S. East Coast Locations of Marine Slides and Natural Gas Hydrate Deposits**



Note: The mapped areas are those encompassing concentrated hydrates. Dispersed hydrates occur over a much larger area than mapped here.

Source: "Circumstantial evidence of gas hydrates and slope failure associations on the United States Atlantic continental margin," *International Conference on Natural Gas Hydrates*, Vol. 715 (New York: Plenum Press, 1994).

1,000 square kilometers(386 square miles). At Maine’s Belfast Bay, the pockmark density is 160 per square kilometer, the pockmarks are fresh, and methane bubbles up from some of them. In the shallow Barents Sea (average depth a bit more than 1,000 feet) off Murmansk, Russia, the sea floor exhibits many pockmarks believed to have been triggered by the removal of several thousand feet of ice overburden at the end of the last glaciation. Offshore booms and mistpuffers are often heard in areas where pockmarks are common.<sup>10</sup> These physical and auditory signs lead to the prevailing interpretation that the pockmarks are formed by abrupt venting of gas associated with rapid methane hydrate decomposition, although no one has ever “seen” it happen.

More-or-less common and continuous releases of unknown total magnitude originate from ocean floor natural gas hydrate deposits and those associated with mud volcanoes. Gas hydrate can form as a tabular layer on the ocean floor at places where methane escapes from warm-to-hot seeps or vents into water having the necessary pressure and

temperature conditions. Many examples of this occur in the Gulf of Mexico in association with small gas seeps. Since methane normally dissolves or oxidizes in free sea water, and chunks of gas hydrate can also break off into pieces that float away because they are less dense than seawater, this is possible only because the methane is constantly being replenished. In the quiescent state, a mud volcano<sup>11</sup> can emit thousands to tens of thousands of cubic feet of mostly methane gas per day, and in the active state, hundreds of millions of cubic feet per day. Mud diapirs are common in the Caspian and Black Seas and presumably there are many more elsewhere.

Clear indication of the delicacy of at least some natural gas hydrate deposits relative to even minor climate change has recently been provided. In 1987, gas hydrates were found on the ocean floor in 1,700 feet of water at a location in the Eel River Basin off northern California. Peter Brewer of the Monterey Bay Aquarium Research Institute and his colleagues, who in 1997 reinspected the site using a remotely operated vehicle, found no gas hydrates on the

<sup>10</sup>“Boom” and “mistpuffer” are two of the many names given to strange, dull, distant, explosion-like sounds (like sonic booms) that are heard sporadically along the coasts of Europe and Atlantic Canada with no apparent cause.

<sup>11</sup>Mud volcanos are the vents of mud diapirs that occur in places where great thicknesses of sediments were deposited very rapidly leading to large pore fluid overpressures (pressures in excess of normal hydrostatic pressure).

ocean floor although methane gas was actively seeping from the sediments. The disappearance of the ocean bottom hydrates at this location appears to have been caused by a mere 1 degree Centigrade increase of water temperature engendered by the northward encroachment of warm water associated with the recent El Niño event.

Apart from gradual, low amplitude global warming, over the past few years a growing body of evidence has been extracted from the geologic record which supports the hypothesis that very large volumes of methane arising from rapid decomposition of natural gas hydrates have from time to time been released into Earth's atmosphere, either unaltered or following natural oxidation to carbon dioxide. These episodes occurred in response to rare but similarly repeated major-scale geologic events and may have caused or significantly contributed to rapid, significant alterations of Earth's climate with attendant major consequences for the ecosystems and biota then in existence.<sup>12</sup>

That said, it should not be inferred that future commercial production of natural gas from natural gas hydrate deposits will necessarily either cause or contribute to their massive decomposition. The list of possible drilling and production problems is similar to that associated with conventional oil and gas wells, and production done with due care would progressively reduce the environmental risks these deposits pose.

## Natural Gas Hydrate Research

A very modest amount of natural gas hydrate research and development (R&D) has been performed to date. Most of it has been focused on gas industry operations, with the objective of finding better and/or cheaper means of ensuring that natural gas hydrates do not cause problems

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<sup>12</sup>The emerging body of evidence is technically complex and scattered among many journals. The following are suggested starting points. Many other pertinent references are included in the bibliography that is provided in conjunction with the electronic version of this chapter at the Energy Information Administration's Internet site < <http://www.eia.doe.gov>. ● Anon., "Wind of Change," *New Scientist* (May 2, 1998), pp. 35-37; ● R. Monastersky, "Death Swept Earth at End of Permian," *Science News*, 153 (May 16, 1998), p. 308; ● D. Harvey, *Potential Feedback Between Climate and Methane Hydrate*, <<http://www.gcric.org/ASPEN/science/eoc94/EOC2/EOC2-5.html>>; ● E. Nisbet, "Methane Hydrates Could Strongly Amplify Global Warming," in "Climate Change and Methane," *Nature*, 347 (September 1990), p. 23, <<http://www.greenpeace.org/~climate/database/records/zgpz0687.html>>; ● D. Lal, "Global Effects of Meteorite Impacts and Volcanism," *Global Climate Change*, S.F. Singer, ed. (New York: Paragon House, 1989); ● G.R. Dickens et al, "Dissociation of oceanic methane hydrate as a cause of the carbon isotope excursion at the end of the Paleocene," *Paleoceanography*, 10/6 (December 1995), pp. 965-971.

during the production, transportation, and distribution of conventionally-sourced natural gas.<sup>13</sup> The small portion directed to naturally occurring natural gas hydrates, mostly undertaken since 1980 and either U.S.-based or motivated, is summarized in the following section.

## U.S. Efforts to Date

In response to recovery of a 3-foot-long oceanic natural gas hydrate-cemented core by the *R/V Glomar Challenger* in 1981, a 10-year, \$8 million natural gas hydrate research program was established in 1982 by the Department of Energy's (DOE) Federal (formerly Morgantown) Energy Technology Center, with cooperation from the U.S. Geological Survey (USGS), the Naval Research Laboratory (NRL), and universities. This program:

- Established the existence of natural gas hydrates in the Kuparuk Field on the Alaskan North Slope.
- Performed studies of 15 offshore hydrate basins.
- Developed preliminary estimates of gas-in-place.
- Built the Gas Hydrate and Sediment Test Lab Instrument, operated by the USGS at the Woods Hole Oceanographic Institution, which allows generation, dissolution, and measurement of the properties of gas hydrates under controlled conditions.
- Developed production models for the depressurization and thermal modes of production.

The program was canceled in 1992 as government policy shifted to near-term conventional exploration- and production-oriented research and development. Since then, some work has continued on a small scale at the USGS, the NRL, and universities.

In fiscal years 1997 and 1998, the DOE Natural Gas Supply Program provided a small amount of funding to support:

- Participation in the production testing and sample analysis of a 1,200-meter-deep well in the MacKenzie Delta of Canada that was drilled by the Japan National Oil Corporation and the Japan Petroleum Exploration

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<sup>13</sup>It was not until 1946 that the U.S. Bureau of Mines produced the first definitive study.

Company in cooperation with the Canadian Geological Survey and the USGS<sup>14</sup>

- The processing and evaluation of seismic data acquired in the hydrate regions of the Gulf of Mexico
- Design of a global database on natural gas hydrates and related gas deposits
- Participation in the Colorado School of Mines industry/university gas hydrate research consortium.

In conjunction with its pursuit of a wealth of other scientific objectives, the multi-national Ocean Drilling Program (ODP), operating the *R/V JOIDES Resolution*, has drilled into or through and in part pressure-cored and logged the hydrate stability zone at several places around the globe since 1985. Other work, which until very recently consisted of small projects, was also performed during the post-1980 period in Russia, Japan, and Norway.

In late 1997, the Energy Research and Development Panel of the President's Committee of Advisors on Science and Technology recommended "a major initiative for DOE to work with the USGS, the Naval Research Lab, the Mineral [sic] Management Service, and industry to evaluate the production potential of methane hydrates in U.S. coastal waters and world wide." The President's Committee noted that these studies of methane hydrates could also lead to sequestering of carbon dioxide in hydrate form. An initial Department of Energy funding level of \$44 million over 5 years was recommended, thereafter evolving to more or less per year as progress indicated. Subsequently, in May 1998, the Subcommittee on Energy, Research, Development, Production, and Regulation of the U.S. Senate Committee on Energy and Natural Resources reported out S. 1418, "The Methane Hydrate Research and Development Act of 1997." This proposed legislation would authorize DOE, in consultation with USGS and NRL, to conduct methane hydrate research for the identification, assessment, exploration, and development of methane hydrate resources. The measure is in essence just an expression of the intent of Congress; it provides no funds.

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<sup>14</sup>The Mallik 2L-38 well was finished at a cost of \$6 million in April 1998. Natural gas hydrate-cemented fluvial sands and pebble conglomerates were cored from 890 to 920 meters, the first fully confirmed natural gas hydrate retrieved from Arctic permafrost deposits since ARCO and EXXON recovered a hydrate-cemented core in 1972.

## Efforts Elsewhere

Coastal nations that have few conventional oil and gas resources to draw upon are already initiating major natural gas hydrate R&D programs. Japan has mounted a program involving the government, academia, industry, hundreds of researchers, and a planned investment ranging from US\$45 million to as much as \$90 billion through 2005. The program initially aims to demonstrate the feasibility of commercial "harvesting" of natural gas hydrates from deposits in the Nankai Trough east of the main island, Honshu. A test well is scheduled to be drilled there by 2000. Natural gas satisfied 12 percent of Japan's energy requirements with 2.4 trillion cubic feet in 1996. Ninety-seven percent of it was imported as liquefied natural gas (LNG), making Japan the largest LNG importer in the world.

The Oil Industry Development Board of India devoted \$56 million of its \$420 million 1997-1998 budget to a natural gas hydrates exploitation program, the objective of which was to characterize the resource off India's coasts and develop the new technologies needed to produce it. The already approved and funded first phase will collect and interpret seismic data at water depths above 600 meters; the second phase will drill two or more test wells, probably off the west coast on the Arabian Basin margin. Natural gas use in India is primarily industrial: 44 percent for fertilizer manufacture, 40 percent for electric generation, and 5 percent for sponge iron production, with the bulk of the remaining 11 percent scattered among other industries since only a few cities have any residential/commercial gas service.

## Future U.S. Research and Development

Plans for future U.S. natural gas hydrate R&D activities fall into four categories: resource characterization, production research, engineering research into safety and sea floor stability, and climate influence analysis. Many of the proposed R&D activities are itemized in *A Strategy for Methane Hydrates Research & Development*, a 10-year "road map" of R&D activities (Figure 29) published by the Department of Energy's Office of Fossil Energy in August 1998. Quoting from the plan:<sup>15</sup>

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<sup>15</sup>U.S. Department of Energy, Office of Fossil Energy, *A Strategy for Methane Hydrates Research and Development* (Washington, DC, August 1998), p. 10.

“The overall objective of the methane hydrate R&D program is to maximize the potential contribution of the huge methane hydrate resources to reliable supplies of a cleaner fuel with reduced impacts on global climate, while mitigating potential hydrates risks for marine safety and sea floor stability. This will be achieved through a four-pronged approach that will answer the questions:

#### **How Much?**

Determine the location, sedimentary relationships, and physical characteristics of methane hydrate resources to assess their potential as a domestic and global fuel resource.

#### **How to Produce It?**

Develop the knowledge and technology necessary for commercial production of methane from oceanic and permafrost hydrate systems by 2015.

#### **How to Assess Impact?**

Develop an understanding of the dynamics and distribution of oceanic and permafrost methane hydrate systems sufficient to quantify their role in the global carbon cycle and climate change.

#### **How to Ensure Safety?**

Develop an understanding of the hydrate system in near-seafloor sediments and sedimentary processes, including sediment mass movement and methane release so that safe, standardized procedures for hydrocarbon production and ocean engineering can be assured.”

### ***Resource Characterization***

The uncertainty reflected by the wide range in the estimates of the Earth’s total natural gas hydrate endowment underscores both the fact that a standardized assessment method does not exist and the fact that the detailed coverage is geographically spotty. Accurate identification and quantification of the Earth’s natural gas hydrate deposits is a crucial precursor to all other gas hydrate R&D activities.

The principal investigative tool will continue to be seismic (acoustic) surveying, optimized to render the deposits in detail. These data can be augmented with other geophysical data, such as resistivity survey data, and with geochemical

data, such as bottom water or shallow sediment methane concentration surveys (see box, p. 88). However, unlike seismic, these methods cannot alone sufficiently resolve the three-dimensional details of the deposits needed for accurate estimation of the natural gas hydrate equivalent of “gas-in-place,” mapping of the distribution of gas hydrate within the hydrate stability zone, determination of its relationship to structural features, and quantification of the concentration and volume of gas in, or the permeability of, the free-gas zone.

Extensive petrophysical and field research is needed to provide the generalized models that will enable conversion of widespread seismic surveys to sufficiently accurate estimates. This work will also yield a significant body of information about the strength of hydrate-bearing sediments for use in safety and sea floor stability analysis. Efficient means of determining the composition of the hydrated gas will also have to be developed, since that has a major effect on the stability range of the hydrate, knowledge of which is prerequisite to assessment of the response of the world’s gas hydrate deposits to climate change.

### ***Production and Sea Floor Stability Research and Engineering***

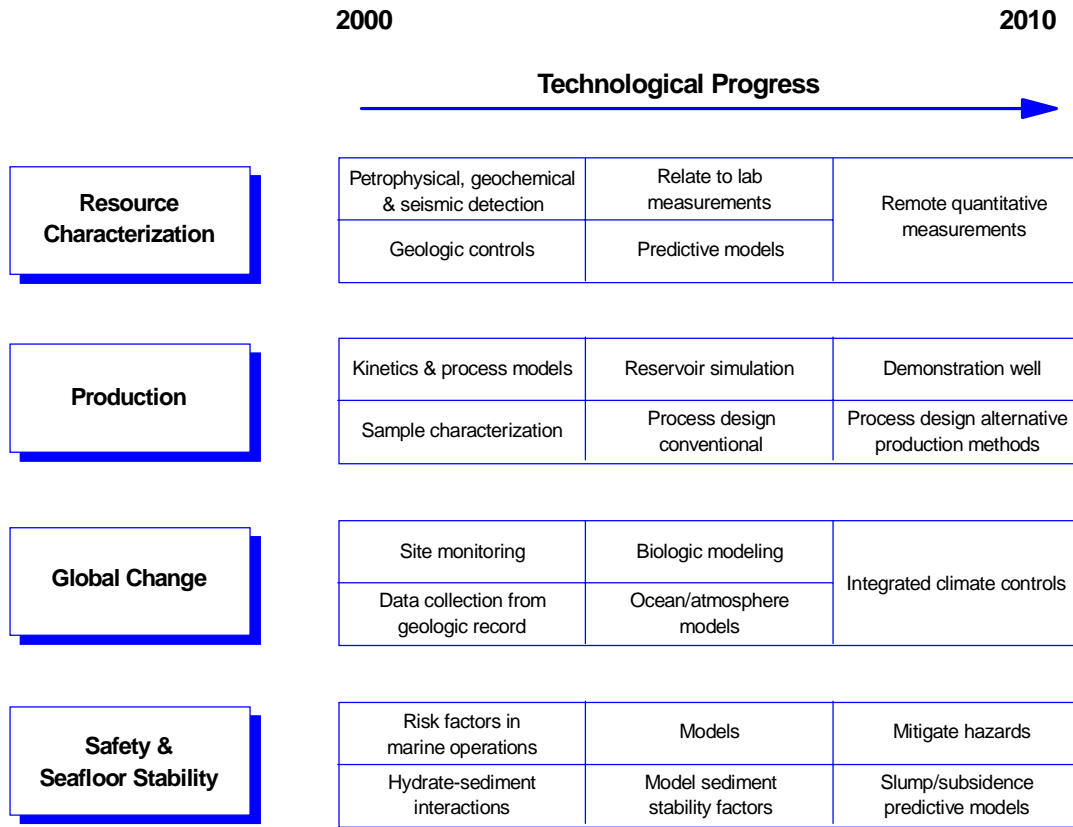
While the bulk of production-oriented research and engineering must await at least the early results of the resource characterization effort, a variety of site-specific geophysical and test borehole studies involving both permafrost and oceanic deposits can be undertaken now. Also, chemical, laboratory, and engineering feasibility studies can be conducted to study potential methods of production from both permafrost deposits and oceanic deposits developed in relatively low-permeability, high-clay content sediments.

As regards safety and sea floor stability, the construction of definitive hazard maps must await detailed mapping of the deposits. In the interim, engineering studies intended to optimize methods of drilling through the hydrate stability zone and to stabilize it in the vicinity of an operating well bore can be worked on. In both cases, investigations must be conducted both in the laboratory and in the field.

### ***Carbon Cycle Influence Analysis***

Analysis of the role of natural gas hydrate deposits in Earth’s carbon cycle involves four main activities:

**Figure 29. The Department of Energy Proposed Technology Roadmap**



Source: U.S. Department of Energy, Office of Fossil Energy, *A Strategy for Methane Hydrates Research and Development* (August 1998), p. 12.

- Assessment of the vulnerability of the deposits to decomposition relative to both gradual and abrupt climate change scenarios
- Assessment of the potential contribution of the evolved methane or derivative carbon dioxide (CO<sub>2</sub>) to climate change
- Additional examination of the geologic record to detect as-yet unrecognized gas hydrate decomposition events and study their causes and consequences
- Integration of the results of the first three activities into improved, high-resolution global climate models.
- Determine what volumes may become unstable in response to various degrees of sea level lowering
- Estimate the thermal effects of changes in water circulation in the vicinity of the deposits that may be induced by global warming and/or alteration of the oceans' thermohaline circulation
- Estimate time lags associated with the resulting explosive (due to gas overpressure) or slower in-situ decomposition process over a range of rates of sea level lowering or bottom water warming
- Investigate the residence time of methane in the water column, its rate of conversion therein to CO<sub>2</sub>, and the rate of transfer of both methane and CO<sub>2</sub> from the ocean surface to the atmosphere over a range of water and air temperatures and surface wind conditions.

In order to assess vulnerability to decomposition and the potential contribution of evolved methane and/or derivative CO<sub>2</sub> to global warming, it is first necessary to map the worldwide distribution of hydrate volume by depth below sea level and by gas composition, and then:

## How Are Natural Gas Hydrates Detected?

Onshore or offshore, seismic surveys are presently the only means of indirectly detecting and mapping natural gas hydrates in sediments. Unfortunately they are not perfect indicators. The vast majority of seismic surveys conducted in the search for conventional oil and gas deposits are shot at sound frequencies which are optimal for finding them, rather than at the higher frequencies needed to map gas-hydrated sediments. Thus, gas hydrate may be present in places where it does not “show” on existing seismic records. Second, most industry seismic surveys are also optimized to produce high-quality images at considerable subsurface depths rather than at the relatively shallow depths where hydrates occur. Third, substantial oceanic gas hydrates have been found in boreholes drilled in areas where no indicators appeared in coincident seismic data, even when appropriate frequencies were utilized. Fourth, the diminished reflection amplitude of the sediment layers located above the bottom simulating reflector that is characteristic of hydrate presence (similar to the ocean bottom reflection but caused by the impedance contrast between hydrated and unhydrated sediments) can result from either hydrate cementation of the sediments or in some cases from lithologic homogeneity, so it may not be entirely diagnostic as regards hydrate presence. Adjunct transient dipole electrical surveys may prove useful in interpreting the oceanic reflection seismic data, in that they can provide a measure of porosity, which correlates with the degree of hydrate cementation, as a function of the resistivity of the sediments.

Another indirect method, bathymetric mapping, can be used to infer the presence of oceanic hydrates on the basis of sea-floor features such as pockmarks and mud diapirs as indicated by the bottom relief, but whether these features reflect current or only past hydrate presence is unknowable from these data alone. Other potential means of indirect detection, such as instruments called “sniffers” towed near the sea floor that can detect the presence and measure the concentration of low molecular-weight hydrocarbons dissolved in the bottom water, have yet to be optimized for and tested in this application.

All of the presently available means of directly detecting gas-hydrated sediments require drilling. The most direct method is to retrieve cores (cylindrical samples that are at most a few inches in diameter) of the suspected gas hydrate zone, using a special drilling tool that can be sealed after coring is completed such that the core sample remains at the pressure at which it was cored during retrieval of the tool, and then retrieving the core barrel quickly enough that the temperature of the sample minimally changes. Examination of the core upon removal from the barrel quickly reveals the presence of gas hydrate based on visual detection of either its physical manifestation or voids in which it was present before it decomposed during retrieval owing to an unavoidable increase of temperature. If still present, the hydrate will immediately begin to decompose, fizzing and bubbling if in visible form or invisibly outgassing if in disseminated form. The core will be noticeably cold to the touch, since hydrate decomposition is an endothermic process. The presence of hydrocarbons as opposed to an alternative gas, such as carbon dioxide, can be ascertained by several means, ranging from lighting a match and touching it to the area of gas evolution to collection of the evolved gas for a variety of definitive chemical analyses.

Another fairly direct but less conclusive method for detection of gas-hydrated sediments involves downhole geophysical logging, which measures physical parameters of the sediments adjacent to the well bore. Resistivity is a measure of the resistance of the sediments to the flow of electric current, which is directly related to the composition of the sediments and their pore contents. Like water ice, natural gas hydrates are electrically insulating. Massive methane hydrate has a resistivity on the order of 150 to 175 ohm-meters, as opposed to methane-saturated water, which has a resistivity in the range of 1 to 3 ohm-meters. Also, one of the consequences of the formation of gas hydrate in the pores of a sediment is the exclusion of dissolved chloride salts from the hydrated volume. The remaining pore water in a hydrated zone is therefore “saltier” than that which is present in nonhydrated sediments, and its resistivity is consequently lower. Resistivity logging of the borehole can therefore be used to infer the presence of a hydrated interval, but whether the hydrate is still present or was only previously present in the interval is unknowable based on the resistivity log alone.



As stated earlier, it appears likely that one to many significant prior global climate change events involved massive decomposition of methane hydrate deposits. Completing the record of such hydrate-associated events would yield greater insight about their frequency, causes, and effects, and that would in turn lead to a more certain projection of the likely base-line climatic future.

Considerable advancement in global climate modeling will be needed to take advantage of the new, evolving body of data on the world's natural gas hydrate deposits and their sensitivity to climate change. Today's global climate models are only capable of modeling regional-scale effects and do not model the effects of coupling between the atmosphere and the mid- and deep ocean layers. They are unable to examine interactions at the scale of concentrated methane hydrate deposits, which range from a kilometer to perhaps as much as 100 kilometers wide, are only a few hundred meters thick, and are located beneath the oceans' surface layer.

Advancements in global climate models are also necessary to improve their treatment of the effects of cloud cover and ocean-atmosphere coupling. The latter problem, which is central to assessment of the likely climate effects of methane hydrate decomposition, has two sources. The first is that knowledge of the oceans is far less than that of the atmosphere, for the most part because of the much more limited body of observations at depth. The second is that oceanic circulation is much slower than atmospheric circulation, with the thermohaline circulation taking several hundred years to a millennium to cover its full route. Coupled atmosphere/ocean climate change models must therefore be run ahead for hundreds of years to capture the oceanic changes, which imposes a tremendous computation burden.

Efforts to develop better global climate models that properly incorporate all of the major influencing factors and feedbacks and have finer geographic resolution are already underway. Some of this work is dependent upon development and proliferation of much larger and faster computers, such as the ones being built under the Department of Energy's Advanced Computing Initiative and their eventual "descendants."

### ***Time, Talent, and Money***

Future gas hydrate R&D efforts will not only vastly improve knowledge of natural gas hydrates, they will also lead to the development of new multiple-application technologies and a greatly improved understanding of the

mid- and deep ocean and of the interaction of the oceans and the atmosphere. The United States proposes to begin its Department of Energy-coordinated efforts at a funding level of \$0.5 million in fiscal year 1999 and \$1.8 million in fiscal year 2000, far less than recommended by the panel of the President's Committee of Advisors on Science and Technology. Several other countries, including Japan, India, Canada, United Kingdom, Germany, Brazil, Norway, and Russia, have active gas hydrate research and development programs and are expected to propose cooperative work as the U.S. program develops.

The large scale of the ultimately necessary R&D effort is dictated by the very widespread occurrence of these deposits, their huge size, and the magnitude and importance of their potential impacts on energy supply and the environment. While some of the required work will be relatively inexpensive, particularly some of the laboratory-based studies, most of the work will involve considerable expense owing to the necessity of extensive field operations in adverse environments and/or the necessity to invent or develop hardware that does not yet exist. The following examples are indicative of the involved cost scale:

- A research vessel suitable for extended high-seas operation charters for anything from \$10,000 to \$50,000 per day depending on how it is equipped. The charter rate does not include the cost of the scientific equipment and staff.
- A single square mile of 3-D marine seismic data presently costs up to \$1 million to acquire, process, and interpret.
- A drilling vessel capable of operating under all conditions in the water depths of the continental slopes and rises costs between \$250 and \$500 million to build depending on the vessel type and its maximum depth capability, and then costs \$130,000 to \$150,000 per day to operate. Such a vessel will be required for some hydrate research studies. But, fortunately, a great deal of valuable natural gas hydrate field research can be done using less expensive vessels equipped with smaller drilling units (since most of the natural gas hydrate in the U.S. economic zone is less than 1.5 kilometers below the surface and periods of very inclement weather could in most cases be avoided).

It is quite clear that the requisite R&D programs are so large, lengthy, and costly that the commercial sector may not be able to undertake them even if the programs' scope were reduced to the matter of gas production alone.

## Outlook

The Earth's natural gas hydrate deposits potentially offer a vast new source of low-polluting, carbon-based energy that could provide a comfortable and very much needed bridge to an eventual carbon-free energy future. Because so little is known about them and their producibility, they are not at present included as a source of methane in estimates of the technically recoverable natural gas resource base, nor are they included as a source of methane in existing energy

models and forecasts. A modicum of increased knowledge of the deposits, coupled with a few breakthroughs regarding their production, could dramatically alter this situation.

These deposits may also be a periodic source of rapid, naturally-caused releases of large volumes of greenhouse gases into Earth's atmosphere. Much more needs to be learned about Earth's natural gas hydrate deposits before their role in the global carbon cycle will be sufficiently understood relative to both slow and abrupt climate change events.