Natural Gas Hydrates Update 2000-2002

by

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Natural gas hydrates research and development (R&D) activity expanded significantly during the 2000-2002 period in response to:

- the impetus provided by the Methane Hydrate Research and Development Act of 2000 (P.L. 106-193) and implementation of the United States' National Methane Hydrates R&D Program by the Department of Energy (DOE);

- instigation or expansion of many cooperative international research projects; and

- evolution of a more-than-academic interest on the part of oil and gas producers.

An important transition is now clearly underway from mostly uncoordinated small-scale laboratory-based investigations to a coordinated suite of larger, more elaborate, inevitably more costly field work-based efforts supported by laboratory research.

U.S. Government Actions

Funding

While Federal funding of natural gas hydrates research in fiscal year 2002 (FY02) reached the authorized level of $7.5 million, more than that was actually committed via supplementation with other research funds available to DOE and several other Federal agencies.[1]

As of late November 2002 the relevant FY03 authorization bills had not yet been passed. The President's FY03 budget mark for DOE Office of Fossil Energy Hydrate R&D funding was $4.5 million, as opposed to the Congressionally authorized level of $11 million. However, the FY03 House mark was $10.8 million and the FY03 Senate mark was $10.5 million. The actual FY03 appropriation could be either of these amounts or any number in between.

Fiscal Year 2002 DOE Gas Hydrate Research Grants

Through the National Energy Technology Laboratory's Strategic Center for Natural Gas, DOE's Office of Fossil Energy partially funded six natural gas hydrate R&D projects, the total value of which was approximately $48 million.

The Scripps Institute of Oceanography at the University of California at San Diego was awarded $550,000 toward a one-year, $612,500 field and laboratory study of the formation and dissociation of exposed hydrates and hydrate-rich sediments located in the northern Gulf of Mexico.

Halliburton Energy Services was awarded $655,750 toward a 3-year, $820,750 project to characterize methane production from a reservoir typical of the Gulf of Mexico, followed by development of a reservoir model and a hydrate reservoir simulator.

Joint Oceanographic Institutions was awarded $959,780 toward a 1.5-year, $4.2 million project to develop and test tools for sampling and characterization of gas hydrates for use aboard the

[1] Details on the participating agencies can be found in "Interagency Coordination on Methane Hydrates R&D," available on request from the Office of Fossil Energy, U.S. Department of Energy, Washington DC.

R/V Joides Resolution in the Gulf of Mexico, about which more appears later.

The three larger DOE-funded projects are also discussed later.

Fourth International Conference on Gas Hydrates

A reportedly "very successful" Fourth International Conference on Gas Hydrates was held in Yokohama, Japan from May 19 to 23, 2002. There were 290 participants, 137 from Japan and 153 from other countries. Authors from 19 nations presented 205 papers which exhibited an evenly distributed categorical breakdown:

Exploration, Resources, and Environment	55
Fundamentals	
Thermodynamic Aspects	28
Kinetics	26
Structural Studies	20
Physical Properties	19
Multiphase Mechanics and Heat/Mass Transfer	18
Hydrate Formation and Prevention in Pipelines	17
Hydrate-based Technologies	22

The proceedings of the conference will be available in print sometime in 2003 and the Fifth International Conference on Gas Hydrates will be held in Trondheim, Norway in 2005.[2]

Other National Programs

Canada

The first gas hydrate resource assessment for Canada was published in July, 2001.[3] The total *in situ* volume of methane resident in Canadian gas hydrates was estimated to be in the range of 1,560 to 28,605 trillion cubic feet (0.44 to 8.1 x 10^{14} cubic meters), as compared to an estimated *in situ* conventional natural gas potential of approximately 953 trillion cubic feet (0.27 x 10^{14} cubic meters). By region, the estimated in-place resource ranges are:

McKenzie Delta-Beaufort Sea:

84.8 to 307.2 trillion cubic feet, or
0.24 to 8.7 x 10^{13} cubic meters

Arctic Archipelago:

671 to 21,895 trillion cubic feet, or
0.19 to 6.2 x 10^{14} cubic meters

Atlantic Margin:

672 to 2,755 trillion cubic feet, or
1.9 to 7.8 x 10^{13} cubic meters

Pacific Margin:

1,130 to 8,476 trillion cubic feet, or
0.32 to 2.4 x 10^{14} cubic meters

The authors of the study consider these estimates to be conservative.[4]

Aside from its participation in several major gas hydrate research efforts as discussed later, Canada pursued an unusual gas hydrate lead during 2001-2002. Fishermen working the Pacific Ocean off the coast of British Columbia had pulled up a chunk of gas hydrate. In August 2002, scientists from the University of Victoria, with the support of Canada's Natural Sciences and Engineering Research Council, the U.S. Naval Reseaarch Laboratory, and the Canadian Scientific Submersible Facility, used the *ROPOS* underwater rover to locate the deposit at the bottom of

[2] Source: <http://hydrate.welcome.to>

[3] J.A. Majorowics and K.G. Osadetz, "Gas hydrate distribution and volume in Canada." AAPG Bulletin, v. 85, n. 7, Tulsa OK, July 2001, p. 1211-1230.

[4] Owing to the nature of the underlying regional resource distributions the end points of these ranges are *not* algebraically additive.

Barkley Canyon, approximately 47 miles (75 kilometers) off the coast and in about 2,789 feet (850 meters) of water. Ross Chapman of the University's Centre for Earth and Ocean Research noted that "There's likely enough methane and natural gas out there to satisfy energy reserves in Canada for about 40 years."[5]

Research Drilling

Permafrost Terrain Deposits

First Intentional Production of Methane from a Gas Hydrate Deposit

The first intentional sustained production of methane from a gas hydrate deposit occurred in March 2002 at the 3,825 foot (1,166 meter) deep Mallik 5L-38 well located in permafrost terrain at the northeastern edge of Canada's McKenzie River Delta at the Beaufort Sea. The well was drilled by an international research consortium consisting of the Japan National Oil Corporation, the Geological Survey of Canada, GeoForschungsZentrum Potsdam, the United States Geological Survey, the United States Department of Energy, and the International Continental Drilling Program. Two slightly deeper observation boreholes were also drilled at an offset of 131 feet (40 meters) from the main well. Approximately 492 feet (150 meters) of hydrate-bearing, mostly coarse-grained sandstone were penetrated in the 722 foot (300 meter) interval from 2,887 feet (880 meters) to 3,609 feet (1,100 meters) deep.

Principal scientific observations involved open hole permafrost logging and continuous wireline coring through both the main gas hydrate intervals and a thin underlying free gas zone, from 2,910 to 3,776 feet (885 meters to 1,151 meters) deep. A comprehensive well log suite was generated using nuclear magnetic resonance, dipole acoustic, and high-resolution electrical conductivity and resistivity tools. The observation wells were used to perform cross-hole tomography experiments, zero-offset and walk-away vertical seismic profiling, and passive acoustic monitoring experiments before and during production. Distributed down-hole fiber-optic temperature sensors provided detailed characterization of the *in situ* formation temperatures and their response to both drilling and production.

Since little free gas exists beneath the hydrate interval at this site, full-scale production via basal depressurization could not be tested. In lieu thereof, small-scale production testing was performed via:

1) Pressure drawdown experiments. These were conducted at 0.5 meter (1.6 foot) thick perforated zones in the free gas interval and in isolated gas-hydrate bearing intervals that had various gas hydrate saturations. The physical behavior, pressure/temperature response, and flows of gas and water were measured during these tests. Geochemical testing was also performed, as were fracture initiation studies and measurements of the effect of fractures on gas flow.

2) Longer duration flow testing. On March 3 casing was perforated for over a 42.7 foot (13 meter) interval that had a high gas hydrate saturation. Production was then thermally stimulated via circulation of warm water (140 degrees Fahrenheit or 60 degrees Centigrade) at a rate of 106 gallons (400 liters) per minute. This resulted in return to the surface of both dissociated gas hydrate and free gas. The produced gas was flared as is common practice during well testing.

The project involved over 100 researchers from more than 30 research centers and cost about $14

[5] Canadian Broadcasting Corporation, "Heated debate over frozen gas off B.C. coast," September 10, 2002, at <http://cbc.ca/storyview/CBC/2002/09/09/methane020909>, and Naomi Lubick, "B.C. methane hydrates," *Geotimes*, American Geological Institute, Washington DC, December 2002, p. 10-11.

million. All of the major equipment reportedly worked well and the energy content of the produced gas exceeded the energy applied downhole to stimulate hydrate dissociation. The detailed results are embargoed until 2004 when a confidentiality agreement signed with the energy companies that partly funded the project expires.

Alaskan North Slope (ANS)

Two important research projects are underway involving gas hydrate resources in the vicinity of Prudhoe Bay Field which, along with several satellite fields, produces crude oil (for sale) and natural gas (currently reinjected for oil reservoir pressure maintenance) from conventional reservoirs. Overlying these reservoirs is a thick layer of permafrost (from the surface to roughly 2,000 feet) and then, in some cases, gas-hydrate bearing strata that were drilled through to reach the more deeply located conventional reservoirs. On the basis of well logs, seismic information and other indicators, gas hydrate zones are believed to be behind-pipe in at least 51 Prudhoe Bay area wells.[6]

BP Exploration (Alaska), Inc., the University of Arizona, the University of Alaska-Fairbanks, and the USGS have kicked off a comprehensive project to determine the technical and economic feasibility of methane hydrate production on BP's ANS holdings. The $21.6 million project (DOE share $13.5 million, BP share $ 8.1 million) is scheduled to run through 2005. It is focused on the already accessible Eileen Trend which is estimated to have up to 44 trillion cubic feet of hydrated gas-in-place plus some underlying free gas, and on the not yet accessible Tarn Trend which is estimated to have up to 60 Tcf of hydrated gas-in-place with no known underlying free gas resource.[7] The first phase of the project seeks to characterize and quantify the hydrate resource-in-place and to verify its prospective commerciality, inclusive of technology development. Among other things this phase will subject $8 million worth of existing well logs and seismic data to examination/interpretation for the presence of gas hydrates, which was not specifically done during the search for oil. Advanced pattern recognition software is being developed for this purpose. The second phase will field test the selected technology, inclusive of test well drilling, to the extent needed to verify its applicability and assess its economics. If Phase 2 is successful, the third phase will extend the work to full pilot scale.[8]

Anadarko Petroleum Corporation, in concert with Noble Corporation, Noble's Maurer Technology subsidiary, and DOE, is mounting a 3-year effort to design and implement a program for safe and economical drilling, coring, and gas hydrate production on the ANS. The project cost is $7.4 million, of which DOE is contributing $4 million. The ultimate goal is to develop an objective technical and economic evaluation of the reservoir potential of North Slope hydrates. Up to three research wells will be drilled on Anadarko's ANS holdings during the FY2003 drilling season. The first of these, scheduled to be spudded in March 2003 in the foothills of the Brooks Range south of the Kuparuk River Field Unit, will be drilled to a depth of 3,000 feet. Hydrated intervals will be cored and an on-site laboratory will be used to determine some of the physical characteristics of the hydrate and the surrounding rock. The well will also be multi-day production tested.[9]

[6] Timothy S. Collett, Energy resource potential of natural gas hydrates, *AAPG Bulletin*, v. 86, n. 11, American Association of Petroleum Geologists, Tulsa OK, November 2002, p. 1978.

[7] BP drilled the NW Eileen #2 well as a gas-hydrate test in the early 1970s. Numerous conventional wells and their supporting infrastructure exist in and to either side of the Eileen Trend. The Tarn Trend, which lies immediately to the west of the conventional production areas, has at present only the Tarn Field discovery well in it.

[8] See "BP Alaska Methane Hydrate Project - DOE - Industry" at http://www.uaf.edu/aetdl/Hunter.pdf and Eric Swedlund, "US to study viability of new natural gas source," *Arizona Daily Star*, December 11, 2001.

[9] "Methane Hydrate Production from Alaskan Permafrost," at http://maureng.com/GasHydrates/alaska.html and "Methane Hydrates" at

Overall, the joint government-industry R&D effort dealing with Arctic permafrost deposits appears likely to pay off much faster than anyone had anticipated even a year or two ago. At this time, commercial development of these deposits seems poised to follow quickly based on production from the free gas zone alone, with consequent production of gas from the overlying gas hydrate stability zone being, in effect, a bonus.[10]

Oceanic Deposits

Oregon Offshore

In June and July of 2000 a consortium of the University of Texas, Oregon State University, and Columbia University shot a high-resolution seismic reflection and refraction survey of Hydrate Ridge, a portion of the Cascadia accretionary complex located 62 miles (100 kilometers) off the southern coast of Oregon, in order to determine why this setting has high concentrations of gas hydrate.[11]

The Ocean Drilling Program's 469 foot (143 meter) research drillship *R/V JOIDES Resolution*, carrying an international crew of 50 scientists, technicians, and engineers hailing from 11 nations, worked above Hydrate Ridge around the clock from July 7 to September 2, 2002. Largely funded by the National Science Foundation, this expedition (officially ODP Leg 204) was dedicated to investigation of the origin and distribution of gas hydrates around the Ridge. DOE contributed $1.9 million to the effort.

A key goal was to obtain core samples of the hydrate-bearing zones and their surrounding sediments, the properties of which could then be compared to a variety of conventional wireline log data and logging-while-drilling-or-coring data that were collected, as well as with seismic surveys that had previously been shot over the site. The development of such correlations is crucial to making the marine hydrate resource eventually locatable, quantifiable, and accessible for production.

During the course of the expedition several holes were drilled at and off the crest of the Ridge, resulting in the recovery of more than 3,068 meters of core, not all of which contained hydrate. Special pressure coring tools were used to sample the hydrate-bearing intervals in order to preserve the core at *in situ* conditions during core retrieval. Two of these tools had recently been developed by a European consortium and one had been developed by DOE and ODP. DOE also provided 34 specially designed pressure vessels that were used to preserve the core for studies beyond those that could be performed aboard ship. An x-ray linear scanner developed at DOE's Lawrence Berkeley National Laboratory barely a month prior to the expedition was used on-board to detect density contrasts that might be indicative of the presence of gas hydrate in the cores.

While the scientific findings from this expedition have not yet been published, there was clear evidence that hydrates form rapidly on the Ridge and important information was reportedly developed on the relationship between hydrate occurrence and/or concentration and sediment composition and grain size.[12] [13] [14] [15] [16] [17]

<http://www.anadarko.com/global/technology/methhyd.shtml>.

[10] Mary H. Yarborough, "DOE advised to retain lead on methane hydrates research," *Inside Energy*, The McGraw-Hill Companies, New York NY, November 18, 2002, p. 12-13.

[11] Nathan Bangs, Mrinal Sen, and Yosio Nakmura, "A Seismic Investigation of Gas Hydrate Accumulation along the Oregon Convergent Margin," University of Texas Institute for Geophysics, at <http://www.ig.utexas.edu/research/projects/hydrate_ridge/hydrate_ridge.pdf>.

[12] Anon., "Ocean Drilling Program Investigates Hydrate Ridge," *EOS*, v. 83, no. 39, American Geophysical Union, Washington DC, September 24 2002, p. 430.

[13] Keir Becker, "Ocean Drilling Program Plans Final Year of Operations," *EOS*, v. 83, no. 14, American Geophysical Union, Washington DC, April 2, 2002, Table 1 at p. 159.

Gulf of Mexico (GOM)

In June and July of 2002 a consortium consisting of the Institute Francais pour la Recherche et al Technologies Polaires, Paul-Émile Victor (IPEV), and the USGS used the 394 foot (120 meter) French research vessel *Marion Dufresne* to obtain 18 large piston cores up to 125 feet (38 meters) long at the widely separated Tunica Mound, Bush Hill, and several Mississippi Canyon sites, all of which are located south and west of the present Mississippi River delta. Much of the cruise focused on finding evidence for the existence of gas hydrate away from obvious sea-floor gas hydrate mounds and at depth in the sea-floor sediments.

The cores are being used to study natural gas hydrate distribution via geochemical analysis of the pore water and gas samples and through physical property measurements. They are also being correlated with existing seismic records to assess the potential for use of the latter in finding gas hydrates in the Gulf. Seventeen deep (33 to 66 feet or 10 to 20 meters) heat-flow profiles were additionally obtained near the piston core sites. These indicated that a widely varying geothermal gradient is present in the northern GOM, and that is important knowledge relative to definition of the sub-bottom extent of the gas hydrate stability zone.

The on-board scientists were associated with the consortium members, the Monterey Bay Research Aquarium Institute, the University of Victoria (BC, Canada), Moscow State University, the University of Tokyo, and Texas A&M University. At-sea help was also provided by some 40 scientists associated with the International Marine Past Global Changes Study (IMAGES) and the Paleoceanography of the Atlantic and Geochemistry (PAGE) program. DOE contributed $750,000 to this effort.[18]

The University of Mississippi's Center for Marine Resources and Technology is establishing a multi-sensor offshore station to monitor deepwater Gulf of Mexico gas hydrates in the 2,625 to 3,281 foot (800 to 1000 meter) deep hydrate stability zone. Hydrophones will measure compression waves. Thermistors will measure temperature. An optical spectrometer will measure pore fluids and hydrocarbon gases. Accelerometers will measure compression and shear waves. Other sensors will handle Doppler current profiling and possibly provide video images. The result will be a baseline database on the physical and chemical aspects of the hydrates, their accumulation and dissociation, and corresponding seafloor stability. This database will be useful in planning of gas hydrate production in the deep Gulf.[19]

ChevronTexaco, Schlumberger Technology Corporation, ConocoPhillips, Halliburton Company, TotalFinaElf, Japan National Oil Corporation, and the Minerals Management Service are jointly conducting a multi-phase, multi-year joint industry project intended to:

- develop and implement a research and

[14] Anon., "Leg 204 (...) Drilling Hydrates on Hydrate Ridge, Offshore Oregon," at <http://www-odp.tamu.edu/publications/tnotes/fy0102/204ab.html>.

[15] Anon., "Ocean Research Vessel Returns with Undersea "Treasure" of Methane Hydrates," U.S. Department of Energy, Washington DC, September 2001, at <http://www.fossil.energy.gov/techline/tl_hydrates_oregon_print.html>.

[16] Anon., "Scientists Explore Large Gas Hydrate Field Off Oregon Coast: Details Emerge of Possible New Energy Source," National Science Foundation, Washington DC, September 2002, via *Science Daily Magazine* at <http://www.sciencedaily.com/releases/2002/09/020911072713.htm>.

[17] Paul Raeburn, "A sedimental journey to find natural gas," in Developments to Watch, *Business Week*, September 23, 2002, p. 67.

[18] Bill Winters and Tom Lorenson, "Gas Hydrate Studied in the Northern Gulf of Mexico," United States Geological Survey, Washington DC, September 2002, at < http://soundwaves.usgs.gov/2002/09/>.

[19] Anon.,"Studies Target Methane Hydrate Behavior," *Hart's E&P*, November 2002, p. 86.

technology plan to assist characterization of sediments containing naturally occurring hydrates in deepwater in the GOM,

- assess and understand potential safety hazards associated with drilling wells and running pipelines through sediments containing gas hydrates,

- develop a database of existing seismic, core, log, thermophysical and biogeochemical data to identify current hydrate containing sites in deepwater GOM,

- use existing knowledge to choose one or more sites in deepwater GOM for field tests,

- plan and execute a drilling and sample collection field testing program to collect data and obtain cores to characterize the hydrate containing sediments in the GOM, and

- use existing data in the database and data collected from the field during the project to develop well bore and seafloor stability models pertinent to hydrate containing sediments in the GOM.

Phase I, involving establishment of an initial database, was completed in 2002. The 2002-2005 Phase II will use this information to plan and execute a drilling, sampling, and data collection field program. Phase II contemplates drilling a research well without well control at the most hydrate-favorable site identified in Phase I, drilling a second well at the same location with well control, and drilling a third well in the least hydrate-favorable location within the same area. Phase III (2005-2006) anticipates drilling of a fourth well in the same area that will be intermediately spaced between the first and third wells and the drilling of a similar suite of wells in two additional prospective areas. The total number of anticipated research wells is therefore 12.[20]

On November 8, 2002, the Minerals Management Service announced that, as soon as it receives the $500,000 budgeted for that purpose in fiscal year 2003, it will begin development of a modeling methodology for the assessment of methane hydrate resources located on the Outer Continental Shelf. The senior MMS official stated that the model should be completed in two years and that [its results] would be included in the next five-year plan for OCS development, covering 2007-2012.[21]

Gas Hydrate Transportation and Storage

BG Group plc (BG), formerly part of British Gas, reported at the 2001 Society of Petroleum Engineers Offshore Europe Conference that it had been working on the development of gas-to-solids technology for application in the production of offshore associated gas (i.e., gas co-produced with crude oil) that is presently stranded because it lacks an economic market, usually owing to its remote location relative to the existing transportation infrastructure and/or to the fact that its too volumetrically small to bear the cost of installing a pipeline.

BG's work involved laboratory testing to validate reactor design and a process model, construction and testing of a thousand gallon per day pilot plant, development of hydrate slurry dewatering techniques, long-term hydrate storage at stable conditions, controlled regeneration of gas from stored hydrate, techno-economic studies, and gas hydrate shipping studies.

One BG-developed process produces a dry

[20] See program plan at <https://qpext.chevrontexaco.com/wwuexpl_gashydrates>.

[21] Mary H. Yarborough, "MMS plans to model methane hydrates' potential ," *Inside Energy*, The McGraw-Hill Companies, New York NY, November 18, 2002, p. 13-14.

storable gas hydrate product by formation of hydrate in a series of continuously stirred reactors. They are designed to maximize the interfacial area between the water and gas. Thereafter, nearly all free water is removed from the hydrate product by use of screens and hydrocyclones, followed by centrifugation. The result is a snow-like dry solid containing more than 150 volumes of gas per volume of hydrate at approximately atmospheric pressure and -40 degrees Fahrenheit (or Celsius). It can be conveyed pneumatically and can be stored and shipped without encountering the problems associated with freezing of free water.

Alternatively, the three-phase gas/hydrate/water mixture produced in a reactor chain operating at a pressure of 870 to 1,305 pounds per square inch (60 to 90 bars) and a temperature between 50 and 59 degrees Fahrenheit (10 and 15 degrees Celsius) can be flashed in a gas/slurry separator to form a 7 weight-percent slurry that floats on the gas/water contact. This can then be thickened via screening and hydrocycloning to a pumpable paste that contains at least 75 volumes of gas per volume of hydrate. The paste can then be transferred to a vessel at a pressure of approximately 145 pounds per square inch (10 bars) and a temperature between 36 and 37 degrees Fahrenheit (2 and 3 degrees Celsius). The hydrate paste could be transported in, for example, insulated and pressurized containers loaded into a converted bulk carrier with a strengthened hull. BG has a program in-place to achieve commercialization of these methods by the 2006/2007 period.[22]

Marathon Oil Corporation has also indicated that it is working on developing proprietary technology for the production and shipping of stable slurries of natural gas hydrate crystals. Marathon expects the new technology to have a significant impact on the handling of remote associated gas, offshore facilities minimization, and gas treating and power plant capacity management applications.[23]

Environmental Implications of Natural Gas Hydrates

The Early Toarcian Extinction Event

On the basis of isotopic carbon analysis of fossil wood fragments from the period, the cause of the mass extinction associated with the Early Toarcian oceanic anoxic event that occurred 183 million years before the present (183 Ma BP) has been hypothesized by researchers at England's Oxford University to have resulted from a large release of methane from natural gas hydrates. They theorize the event occurred over a period of just 5,000 years, during which an amount equal to about 20 percent of the present-day volume of oceanic gas hydrate decomposed.[24]

The Permo-Triassic Boundary Extinction Event

An examination of alternative causal hypotheses for the most severe known biological extinction event, which occurred at the Permo-Triassic boundary 251 Ma BP, was performed using a mass-balance model that calculates atmospheric carbon dioxide (CO_2) concentrations and change in the relative level of the carbon-13 isotope $(\delta^{13}C)$ as a function of time. The tested alternative hypotheses included:

- release of mass amounts of CO_2 from the ocean to the atmosphere;
- release of mass amounts of CO_2 from volcanic degassing;
- release of methane stored in natural gas

[22] Antony Fitzgerald, "Offshore Gas-to-Solids Technology," SPE Paper 71805, summarized in *Journal of Petroleum Technology*, v. 54, no. 4, April 2002, p. 52.

[23] Marathon's Gas Utilization Technologies page at <http://www.marathon.com/Our_Business/Technology/Gas_Utilization/>.

[24] S.P. Hesselbo, et al., "Massive dissociation of gas hydrate during a Jurassic oceanic anoxic event," *Nature*, v. 406, p. 392-395.

hydrates;

- decomposition and oxidation of dead organisms to CO_2 after sudden mass mortality; and

- long-term reorganization of the global carbon cycle.

While long-term reorganization of the global carbon cycle was found to be the most likely cause, it was also noted that decomposition of large amounts of methane hydrate might also have been a significant contributing factor.[25]

The content of this document also appears in *Potential Supply of Natural Gas in the United States, Report of the Potential Gas Committee, December 31, 2002*, Potential Gas Agency, Colorado School of Mines, Golden CO, April 2003.

[25] Robert Berner, "Examination of hypotheses for the Permo-Triassic boundary extinction by carbon cycle modeling," *Proceedings of the National Academy of Sciences*, v. 99, no. 7, National Academy of Sciences, Washington DC, April 2002, p. 4172-4177.