July 2008

Energy From Gas Hydrates: Assessing the Opportunities & Challenges for Canada

Gas hydrates[1] form when water and natural gas combine at low temperatures and high pressures — for example, in regions of permafrost and in marine subseafloor sediments. They exist in abundance worldwide and some estimates suggest that the total amount of natural gas bound in hydrate form may exceed all conventional gas resources, or even the amount of all hydrocarbon energy — coal, oil and natural gas combined. Gas from gas hydrate could therefore provide a potentially vast new source of energy to offset declining supplies of conventional natural gas in North America and to provide greater energy security for countries such as Japan and India that have limited domestic sources.

Complex issues would need to be addressed if gas hydrate were to become a significant part of the energy future of Canada and of the world. These issues arise from unknowns about the resource itself. How much is there? Where is it located, at what concentrations, and in what kinds of geological environments? How could the gas best be produced? The interplay of these physical and engineering issues with future economic considerations, environmental policies and community impact concerns will determine whether, and where, natural gas from gas hydrate might be produced.

Figure 1 — Burning gas hydrate.
Photo supplied by the National Research Council Canada.

To better understand these issues, so as to have a more informed basis on which to develop policy for gas hydrate as one possible future energy option for Canada, Natural Resources Canada asked the Council of Canadian Academies to assemble a panel of experts to address the question:

What are the challenges for an acceptable operational extraction of gas hydrates in Canada?

The panel was asked not to make explicit policy recommendations, but rather to assess the current state of knowledge on matters relevant to possible policy choices.

Overview of Gas Hydrates — The gas held in naturally occurring gas hydrate is generated by microbial or thermal alteration of organic matter under the seafloor or permafrost, producing methane and other gaseous byproducts. (Methane is by far the dominant gas found in gas hydrates, which is why they are often referred to as methane hydrates.) Although chemists have known about gas hydrates for almost 200 years, the oil and gas industry began to take an interest only in the 1930s when gas hydrate formation in pipelines was found to cause troublesome blockages. Russian scientists in the late 1960s were the first to propose that gas hydrate might occur naturally in marine and onshore locations under conditions of pressure and temperature that permit gas hydrate to form and remain stable.

The Expert Panel on Gas Hydrates: Dr. John Grace (Chair) (FRSC, FCAE) University of British Columbia — Professor, Chemical and Biological Engineering and Canada Research Chair in Clean Energy Processes (Vancouver, BC) **Dr. Timothy Collett** U.S. Geological Survey — Research Geologist, Geologic Division (Denver, CO) **Dr. Frederick Colwell** Oregon State University — Professor, College of Oceanic and Atmospheric Sciences (Corvallis, OR) **Dr. Peter Englezos** University of British Columbia — Professor, Department of Chemical and Biological Engineering (Vancouver, BC) **Dr. Emrys Jones** Chevron — Senior Consulting Engineer (Richmond, CA) **Dr. Robert Mansell** University of Calgary — Senior Fellow of ISEEE (Institute for Sustainable Energy, Environment and Economy) and Professor of Economics (Calgary, AB) **Dr. J. Peter Meekison** University of Victoria — Adjunct Professor, Department of Political Science (Victoria, BC) and University of Alberta — University Professor Emeritus, Department of Political Science (Edmonton, AB) **Dr. Rosemary Ommer** University of Victoria — Director, Institute for Coastal and Oceans Research (ICOR) (Victoria, BC) **Dr. Mehran Pooladi-Darvish** University of Calgary — Professor, Chemical and Petroleum Engineering and Senior Technical Advisor, Fekete Associates Inc. (Calgary, AB) **Dr. Michael Riedel** McGill University — Associate Professor, Department of Earth and Planetary Sciences (Montreal, QC) **Dr. John Ripmeester (FRSC)** National Research Council Canada, Principal Research Officer, Materials Structure and Function Group (Ottawa, ON) **Dr. Craig Shipp** Shell International Exploration and Production Inc. — Team Leader, Geohazards Assessment and Pore Pressure Prediction Team (Houston, TX) **Dr. Eleanor Willoughby** University of Toronto — Research Associate, Marine Geophysics Group, Department of Physics (Toronto, ON)

The Full Report will be released in August 2008. Please visit www.scienceadvice.ca for more information.

Global Occurrence and Quantity — Vast portions of the world's continental margins and permafrost regions appear to be underlain by gas hydrates. In recent years, a growing number of deepsea drilling expeditions have been dedicated to assessing marine gas hydrate accumulations, and understanding the geologic controls on their occurrence. Gas hydrate associated with permafrost has been documented in Canada, Alaska and northern Russia. One of the most studied permafrost gas hydrate accumulations is the Mallik site in Canada's Mackenzie Delta.

Recent estimates suggest that the worldwide volume of gas trapped in hydrate accumulations is in the range of 1 to 120 x 10^{15} m^3 (35,000 to 4,200,000 trillion cubic feet, Tcf). With very few drilling and coring data sets available, a reliable estimate of global volume of natural gas hydrate appears to be elusive. Moreover, the various global assessments do not reveal how much gas could be produced from the world's gas hydrate accumulations. Much more work is needed to refine estimates of the total volume of gas hydrate and to quantify producible volumes. For simple comparison purposes (and to give the reader an idea of the magnitudes of other resources), conventional natural gas accumulations, including reserves and technically recoverable global resources, are estimated to be approximately 4.4 x 10^{14} m^3 (15,500 Tcf).

Potential Role in the Energy Future — The commercial viability of gas hydrate as a future source of energy will depend on supply and demand, and therefore price, in the markets for energy, and particularly for natural gas, in the medium to long term. Estimates by the U.S. Department of Energy and the International Energy Agency suggest that global energy demand will grow by between 40 per cent and 70 per cent by 2030. More than 80 per cent of this growth is projected to be met by oil, natural gas and coal. The expectation is that natural gas, given its significantly lower carbon footprint, will displace some growth in the use of both oil and coal.

Canada's potentially large gas hydrate resource could make a key contribution to meeting North American energy demands during this century.

For Canada, natural gas production is projected to begin to decline after 2010 while domestic consumption continues to grow. This projection implies decreasing Canadian gas exports to the United States, where the prospects are for increasing reliance on imports of liquefied natural gas (LNG) as a substitute for conventional U.S. or Canadian supplies. It is in this context, and in view of growing concerns over security of supply, that the possibility of significant production of gas from gas hydrate becomes particularly important. Canada's potentially large gas hydrate resource could make a key contribution to meeting North American energy demands during this century. Given the potential size of the global gas hydrate resource and its relatively wide distribution, many countries such as the United States, Japan, India and South Korea are showing substantial interest in exploiting this resource over the long term.

Global Environmental Considerations — The natural gas that would be produced from gas hydrate would generate carbon dioxide (CO_2) upon combustion, though in lesser amounts, per unit of useful energy generated, than either coal or oil. It is beyond the scope of the report to address the overarching issue of the future role of hydrocarbon fuels in the world's energy supply mix. It should be noted that growing concern over climate change is stimulating a great deal of research and development (R&D) worldwide to develop effective ways to curb and/or sequester CO_2 emissions. The extent to which this effort bears fruit will have a significant impact on the demand for natural gas in the medium to long term. If, as expected, hydrocarbon fuels do continue to be a major component of the global energy supply for at least several more decades, the lower carbon intensity of natural gas (and thus of gas hydrate) will likely make it increasingly attractive relative to coal and oil.

The possibility that global warming may induce widespread gas hydrate dissociation ("melting") causing the release of large amounts of methane (itself a potent greenhouse gas) — and thus accelerating warming due to feedback — is the subject of research explaining historical climate change events and projecting the climatic impact of gas hydrate into the future. Simulation modelling suggests that there is potential for gas hydrate-related release of methane that could far surpass human-caused climate warming on time scales of 1,000 to 100,000 years. It should also be noted that the exploitation of gas hydrate could not remove sufficient quantities from the earth's crust to prevent the possible long-term dissociation of gas hydrate due to climate change. Given existing technology, the emissions of natural gas into the atmosphere as a result of gas production from gas hydrate should be similar to those from conventional natural gas production.

From investigations of continental margins and extensive surveys by offshore energy companies, it is evident that widespread continental margin instability due to dissociation of gas hydrates is not occurring today, nor has it occurred during the past 5,000 years or so. It would appear that seafloor instability will have little impact on the development of gas hydrate as a resource.

Canada's Contribution in a Global Context — Despite having no official national gas hydrate program, Canada has made significant contributions to gas hydrate research. Canadian scientists and engineers have been leaders in elucidating the chemical structure and physical properties of gas hydrates, and Canada is home to two of the world's most intensively studied natural permafrost and marine occurrences: those at Mallik in the Mackenzie Delta and the northern Cascadia margin off the west coast. Canada's main strength has been due to highly-qualified people contributing globally and training researchers from countries where gas hydrates are emerging as a topic of importance. So far, at least, unlike in the United States, there has been very little industrial investment in gas hydrate as a potential energy resource in Canada.

The Quantity and Location of Gas Hydrate in Canada

Canadian Quantity Estimates — Little research exists to assess the regional occurrence, distribution and total volume of gas hydrate in Canada. The total volume of methane locked in hydrate deposits in Canada was estimated in 2001 to be between 10^{12} and 10^{14} m^3 (between 35 and 3,500 Tcf).[2] The reliability of this estimate is limited by the fact that the analysis excludes consideration of local geological and tectonic conditions, and basin characteristics. A later and more refined assessment (2005) for the Mackenzie Delta/Beaufort Sea region alone estimated the volume of gas in gas hydrate in that region to be between 8.8 and 10.2 x 10^{12} m^3 (between 310 and 360 Tcf). There is no equivalent detailed summary estimate for the northern Cascadia margin off Vancouver

Island, the Atlantic coast or the Arctic Archipelago.

Location of Gas Hydrates — Despite extensive research in individual locations, and the high quality of Canadian work in this field, Canada's coastal margins and permafrost areas have not been extensively studied for gas hydrates (see Figure 2). Other mineral resources are commonly estimated without mapping their total occurrence, and attempting to map all Canadian gas hydrate deposits on a basin-by-basin scale is impractical because of the length of Canada's coastline.

Naturally occurring gas hydrates have been studied off Vancouver Island for more than two decades. The Cascadia margin is one of the best-studied gas hydrate environments in continental margin settings worldwide. Studies have included two dedicated deep drilling expeditions by the Ocean Drilling Program (ODP, Leg 146 in 1992) and the Integrated Ocean Drilling Program (IODP, Expedition 311 in 2005). The most significant findings of the recently completed IODP Expedition 311 in Cascadia are as follows:

- Gas hydrate is formed mainly within the sand-rich formations and is virtually absent from the fine-grained sediments. Thus the presence of gas hydrate is mainly driven by lithology (i.e., the type of sediment formation and its physical character in terms of grain size).
- The bottom-simulating reflector (BSR — a seismic signature that can indicate the presence of gas hydrate) is unrelated to the concentration of gas hydrate within the pressure-temperature stability zone, and provides only a first-order indicator of the potential occurrence of gas hydrate.
- All sites showed a high degree of heterogeneity in gas hydrate occurrence (on the 10-metre near-borehole scale to the margin scale on several kilometres). Thus there are potential pitfalls in extrapolating small-scale borehole observations to the regional scale.

To achieve a more reliable estimate of Canadian gas hydrate accumulations and volumes, intensive field studies, combined with spot coring and drilling, are required, especially in yet under-represented areas such as the east coast and Arctic islands.

Gas hydrate research on the east coast of Canada has been very limited. New seismic data analyses have shown few indications of BSRs off Canada's east coast. However, this does not automatically imply that gas hydrates are absent. The existing geophysical data are inconclusive as to the potential gas hydrate resource in this region, and further research, especially direct sampling through deep drilling and coring, is required.

Several attempts have been made to characterize the total gas hydrate potential of the Canadian Arctic, including the Beaufort Sea shelf, the Mackenzie Delta and the Arctic Archipelago. Some of the main findings in permafrost environments are as follows:

- In the Mackenzie Delta/Beaufort Sea (based on more than 200 wells drilled) gas hydrate occurrence was higher offshore, where 45 per cent of wells were interpreted to contain gas hydrate, compared with only 14 per cent onshore.
- In the Arctic Archipelago, gas hydrate was probable in more than half of 168 wells drilled in the Sverdrup Basin.

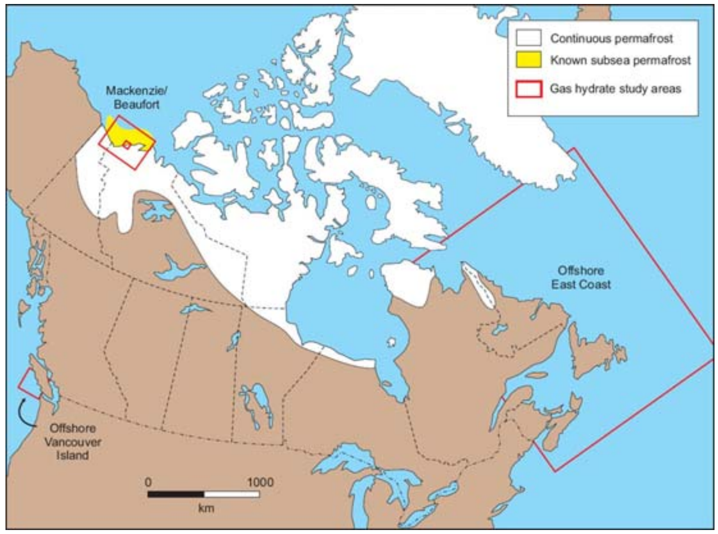

Figure 2 — Regional assessments of gas hydrate in Canada.
Note that while this map shows the three regions on which assessments have been focused to date, gas hydrate may occur on other parts of the margin. (Adapted from Majorowicz, J. A., and K. G. Osadetz. 2001. "Gas hydrate distribution and volume in Canada". *AAPG Bulletin*. American Association of Petroleum Geologists, 85:7, p. 1213. AAPG © 2001 adapted and reprinted with permission of the AAPG whose permission is required for further use.)

- Gas hydrate was found to be more likely to occur in sand layers or coarser-grained sediments.

Although gas hydrate has been reported in many wells across the Arctic, some of the evidence is of doubtful value, and data are inconclusive because of poor knowledge of the vertical extent of the gas hydrate stability zone.

To achieve a more reliable estimate of Canadian gas hydrate accumulations and volumes, intensive field studies, combined with spot coring and drilling, are required, especially in yet under-represented areas such as the east coast and Arctic islands. Because many of the regions of interest have been charted in the past by industry in the course of exploration for conventional hydrocarbons, it may be possible to involve the private sector more closely in the search for gas hydrate deposits in Canada's frontier areas.

The Production of Natural Gas from Gas Hydrate

The current state of knowledge about the producibility of gas hydrate is analogous to the understanding of coalbed methane (CBM) or oil sands about three decades ago. While both CBM and oil sands took several decades to become commercially viable, it is too early to judge whether the development horizon of the gas hydrate resource will be longer or shorter. While it can be expected — by analogy with oil sands and CBM — that gas production from gas hydrate will be facilitated, perhaps significantly, by innovative and "out-of-the-box" ideas, the report limits its attention to technologies currently available for production of hydrocarbons.

Producing Natural Gas from Gas Hydrate — Experience with test wells at Mallik and elsewhere suggests that most problems in drilling and completion of gas hydrate wells can be foreseen and successfully dealt with at the design stage. Long-term experience is nevertheless required to better understand the severity of problems that may be associated with the production of gas from gas hydrate including problems with sand flow. While problems may affect the economy of the operations, they are not expected to be technically insurmountable. Once gas has been dissociated from the hydrate phase and collected from a well, it is like conventional natural gas, the handling and marketing of which are familiar.

Based on current knowledge, the technical assessment of producibility is most readily carried out if the gas hydrate is contained within sand formations at temperatures above the freezing point of water, whether below permafrost or in marine sands. Fine-grained sediments can also contain low concentrations of gas hydrate. While flow may be established in such systems on a local basis, the continuity of the permeable media, which is needed to allow production of a significant amount of gas from the gas hydrate, is not demonstrated and has little analogy with other conventional hydrocarbon production. Massive gas hydrates concentrated in and around seafloor vents are excluded from the report's analysis of producibility in view of the very significant technical, environmental and safety uncertainties related to their potential exploitation.

The hierarchy of feasibility of producing natural gas from gas hydrate can be illustrated schematically as a pyramid (see Figure 3). The vertical distance below the apex indicates, qualitatively, the relative ease of producibility. At the top of the pyramid — which would be the initial focus of experiment and exploration — are gas hydrates in marine and subpermafrost sand formations.

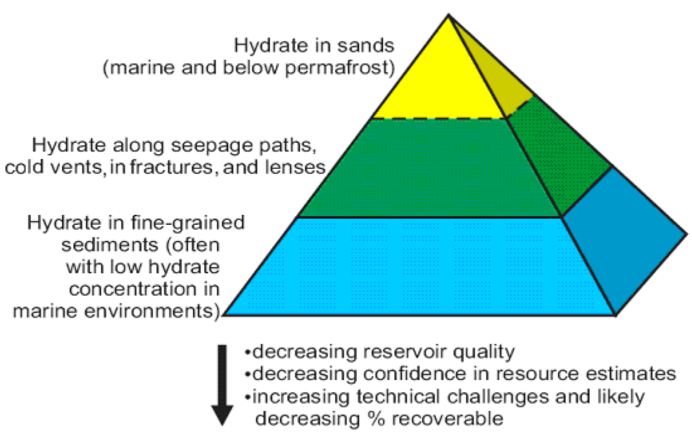

Figure 3 — A schematic representation of technical producibility of the gas hydrate resource, with the easiest on top.
(Adapted from Boswell, R., and T. Collett. 2006. "The gas hydrates resource pyramid". DOE-NETL Newsletter "Fire in the Ice", Fall 2006, p.5).

Recovery begins by dissociating a gas hydrate reservoir into its constituents of natural gas and water, followed by production of the gas via a well. Because gas hydrate is stable only under certain pressure/temperature conditions, the three most commonly proposed techniques are (i) thermal stimulation, in which the gas hydrate is heated beyond its zone of stability; (ii) depressurization, in which pressure in the reservoir is drawn down below the point of hydrate equilibrium at a prevailing temperature; and (iii) "inhibitor" injection to shift the gas hydrate stability conditions. Depressurization is considered the most promising method of production when account is taken of cost and environmental impact.

The availability and type of fluid below the gas hydrate is of significant importance because the volume of hydrate that can be accessed by a production technique such as depressurization — and the rate of heat transfer required for hydrate dissociation — are strongly affected by the presence of an underlying fluid. The most promising type of gas hydrate appears to be that underlain by free gas.

(a) Underlying Free Gas: Under these conditions, production of gas from gas hydrate can proceed in a manner similar to a conventional hydrocarbon reservoir by producing from the underlying free gas. This would initiate pressure reduction and decomposition across the hydrate/free gas interface. Modelling indicates that a significant portion of the gas hydrate would decompose naturally at promising rates. It is possible that production from such "sweet spots" could be accomplished technically within the next 10 years. Nevertheless, the reliability of the models used to predict gas hydrate reservoir performance remains uncertain as they have not been tested against long-term field data.

(b) Underlying Free Water: When the underlying fluid is water, depressurization can be achieved by removing the water. Studies suggest that gas hydrate underlain by free water is technically recoverable, though, as modelling has indicated, less economically attractive than with underlying gas.

(c) No Underlying Fluids: The rate of gas production from gas hydrate reservoirs without underlying free fluids — i.e., bounded by impermeable sediments at top and bottom — remains uncertain. Some studies suggest that in the absence of underlying fluids, a number of other factors (including pressure, temperature and hydrate saturation) need to be favourable for economically attractive flow rates from such gas hydrate accumulations to be possible.

The 2006-08 Mallik Production Research Program successfully demonstrated proof-of-concept for gas production from gas hydrate by depressurization.

Production Testing at Mallik — The focus of gas production testing from gas hydrate in Canada has been at the Mallik site, the only reservoir in Canada that has been studied in enough detail to permit analysis of production rate and volume. The main findings and implications of the three Mallik international scientific programs (1998, 2002 and 2006-08) can be summarized as follows[3]:

- Gas hydrate occurs primarily as pore-filling material within the sands (50 per cent to 90 per cent pore-space saturation). No pore filling is observed in the silt-dominated intervals, suggesting a strong lithologic control on gas hydrate occurrence.
- The presence of gas hydrate appears to contribute substantively to the "strength" of the sediment matrix, with the hydrate providing reinforcement.
- The 2007 production test was deliberately undertaken without sand control measures in order to assess whether the reduction in sediment "strength" caused by gas hydrate dissociation would result in sediment inflow into the well. A substantial inflow of sand did occur, constraining the duration of the test to approximately 24 hours.

- A six-day production test in March 2008 was extremely successful, with excellent equipment performance. (Sand screens were installed to hold back the coarse-grained sediments). While the raw test data and detailed interpretation of results are confidential at this time, sustained gas flows ranging from 2,000 to 4,000 m^3/day (70,000 to 140,000 ft^3/day) were maintained throughout the course of the test, and physical operations proceeded very smoothly during the progression to three target drawdown pressures.
- The 2006-08 Mallik Production Research Program successfully demonstrated proof-of-concept for gas production from gas hydrate by depressurization. The Mallik tests indicate that sustained gas flow can be achieved from a sand-dominated gas hydrate reservoir, through reduction of bottom-hole pressures using conventional oilfield technologies adapted for an arctic gas hydrate system.

Economics of Gas Hydrate Production — Studies of the economics of gas production from onshore and offshore gas hydrate are limited. Those that do exist suggest that a number of factors interact to make production from a gas hydrate accumulation more costly than from comparable conventional gas reservoirs because a gas hydrate reservoir is predicted to:

- produce at a lower rate;
- require compression from the beginning; and
- require more expensive well completion due to:

(i) the production of more water, therefore requiring lift and disposal of the produced water;

(ii) the need for chemical injection equipment and/or local heating to avoid gas hydrate (re)formation and plugging; and

(iii) the application of suitable techniques to avoid production of sand.

Price Scenarios for Natural Gas — A critical determinant of the prospects for commercial gas hydrate exploitation will be the cost of delivered production relative to the likely range of market prices for gas. In 2007, Canada's National Energy Board (NEB) projected natural gas prices associated with several supply and demand scenarios through 2030. The projected prices cover a range from about US$5.70 per gigajoule (GJ) to about US$11.40/GJ based on delivery at Henry Hub, Louisiana (the reference point for North American gas prices). Taking into account (a) the average cost of pipeline transportation from Henry Hub to the Calgary hub (AECO-C), plus (b) an estimate of US$2.85/GJ (or possibly higher) to connect via a potential Mackenzie Valley pipeline, implies that the current NEB gas price forecast range would translate to prices between US$1.90/GJ and US$7.60/GJ at potential supply areas in the Mackenzie Delta. (If one assumes an exchange rate of US$0.90 to C$1.00 over the long run, the foregoing price range would be about C$2.15/GJ to C$8.50/GJ.)[4]

For the Mallik field, preliminary estimates suggest that total capital and operating costs for production could be in the range of about C$4.75/GJ to C$5.70/GJ for gas hydrate over free gas and about C$6.20/GJ to C$9.00/GJ for gas hydrate over free water. When royalties, taxes and returns to capital are included, it would appear that the cost of this gas could be competitive if gas prices were sustained above or near the upper end of the range in the NEB scenarios. Estimates of the production cost of natural gas from gas hydrate must nevertheless be viewed with considerable caution, given the large technical uncertainties.

Further development of Mallik, or other gas hydrate accumulations in the Canadian Arctic, is unlikely unless and until the Mackenzie Valley or other similar pipeline access is in place.

Gas Transport Infrastructure — The prospect of gas hydrate extraction in Canada, even in the medium term of 20 to 30 years, depends on policy decisions of government and commercial decisions of energy companies affecting whether or not infrastructure is put in place in areas where favourable gas hydrate deposits exist in close proximity to conventional gas reservoirs. (The *Unconventional Gas Technology Roadmap* (2006) argues that the lack of transportation systems to bring natural gas from gas hydrate to market is the critical issue facing gas hydrate development in Canada.)[5] Further development of Mallik, or other gas hydrate accumulations in the Canadian Arctic, is therefore unlikely unless and until the Mackenzie Valley or other similar pipeline access is in place.

The cost of developing *offshore* hydrocarbon resources is so large that only a few major energy companies are involved in offshore development, even of conventional hydrocarbons. Development prospects off Canada's Pacific coast are further exacerbated by a general moratorium on all offshore energy exploration and development. On the Atlantic coast, existing production platforms are so few and far between that lack of adjacent infrastructure would likely have a significant effect on the economics of production of gas from gas hydrate.

Security of Supply and Economic Development — While there will be a growing market for Canadian gas exports to the United States, these will have to compete with imported LNG. Once major investments are made to accommodate imported LNG, its competitive advantage could become insurmountable. This suggests that a "security premium," or other such incentive for the development of domestic gas supplies, may be required to bring northern and perhaps other unconventional gas onstream. It is therefore likely that there would have to be government incentives, at least in the early phases, to stimulate development of gas hydrate.

The safety issues associated with producing gas from a gas hydrate reservoir appear to be similar to those encountered in producing from a conventional natural gas field.

Safety Considerations for Drilling and Exploitation of Gas Hydrate — Current gas hydrate-related safety concerns arise primarily when gas hydrate is encountered in the course of *conventional* hydrocarbon exploration and production (offshore and in the Arctic). These concerns come up in the context of targeting deeper hydrocarbons, when trying to *avoid* gas hydrate. Current knowledge of safety issues in offshore and Arctic settings is mostly anecdotal, with only a few published studies that focus on documented drilling problems. Much of the information on gas hydrate-related safety is currently proprietary, residing outside Canada with national energy programs or the commercial energy industry. While taking into account the lack of publicly available documentation, the safety issues associated with producing gas from a gas hydrate reservoir appear to be similar to those encountered in producing from a conventional natural gas field.

Environmental, Jurisdictional and Community Considerations

Environmental Considerations — Extracting natural gas from gas hydrate involves mostly issues common to the recovery of other hydrocarbon resources, especially conventional natural gas. Past experience with resource development in the Far North or in offshore marine settings should serve as models.

The leakage of methane gas from a gas hydrate-bearing formation as a result of production-related activities is not likely to be a problem because, by discontinuing depressurization, any significant wellbore leakage could be controlled. After completing methane production from gas hydrate-bearing strata, these formations would be expected to return to their original state. Inadvertent loss of methane would be detrimental for economic, environmental, and safety reasons. Well operators would be motivated to minimize leakage.

Although significant amounts of water would be produced as gas hydrate is dissociated, the situation is similar to that for other hydrocarbon production processes. As gas hydrates are destabilized, they produce water purified through the freshening effect.

It has been suggested that CO_2 emitted from the burning of fossil fuels could be sequestered in gas hydrate reservoirs by displacing methane hydrate, allowing CO_2 hydrate to form in its place. Although coupling methane extraction with CO_2 sequestration is conceptually attractive, a practical procedure is likely to be decades away. Nevertheless, research into the details and impacts of the idea warrants further support.

Jurisdictional Considerations — The future development of gas hydrate would be affected by a number of jurisdictional issues particular to Canada. The situations differ on the East, West and Arctic coasts. Only the East Coast has a detailed federal-provincial framework for resource development — the Atlantic Accords. These accords may provide a framework for working out a comparable agreement on the West Coast. Gas hydrate development could not take place there until the federal and provincial moratoria on oil and gas exploration off the coast of British Columbia are lifted and a new regulatory regime is put in place. Although the scientific studies and reports conducted by both British Columbia and Canada since 2001 have concluded that there is no scientific evidence to support maintaining the moratoria, the challenges of lifting them are considerable in light of public scepticism and the inevitable complexity of the required regulatory regime. For example, one study estimated that 60 federal statutes and 38 provincial statutes apply to offshore activity.

Arrangements in the Arctic are likely to be influenced by the agreements associated with developing the proposed Mackenzie Valley pipeline, and the debate on devolution of legislative authority to the territorial governments. The federal government is currently placing greater priority on Canada's Arctic regions because they contain much of the country's energy potential. Moreover, Canada could use development and regulation of offshore resources, including gas hydrate, to reinforce its claim over its Arctic territory.

The many lessons that have been learned about resource development in environmentally and culturally fragile areas, and the protocols that have been devised to ensure that local consultation and due process are respected, must apply to any future gas hydrate development in Arctic and offshore areas.

Community Impact Considerations — The social, cultural and economic development considerations related to the exploitation of gas hydrate in northern and offshore areas are similar to those associated with conventional gas production in frontier areas. While the specific circumstances of every proposed project will need to be addressed, the production of natural gas from gas hydrate does not appear to present social and cultural issues unique to *gas hydrate*, as distinct from conventional gas reservoirs of comparable extent. The many lessons that have been learned about resource development in environmentally and culturally fragile areas, and the protocols that have been devised to ensure that local consultation and due process are respected, must apply to any future gas hydrate development in Arctic and offshore areas.

Considerable time is needed to build community collaboration and consensus. For a significant gas hydrate development project, it could take at least 10 years to complete an acceptable and open process of establishing the science and technology, creating the necessary infrastructure, consulting in meaningful ways with local communities, and building local knowledge and consensus. The organizations responsible for planning major gas hydrate projects must be prepared to take these long timelines into consideration.

Prospects for Gas Hydrate Development in Canada

Canada could be well-positioned to be among the world leaders in gas hydrate exploitation if it were to invest sufficiently in exploration, research, development and production. A long-term government commitment would be needed because commercial production of gas from gas hydrate is unlikely in Canada within at least the next two decades.

Three Broad Approaches for the Future — To address the knowledge gaps associated with the gas hydrate opportunity, Canada must choose, explicitly or implicitly, a level of involvement and investment. The support of governments — federal, provincial and territorial — might be based on one of the following three broad approaches:

- ***Research Only:*** Canada could continue to perform scientific research on gas hydrate while leaving, for the foreseeable future at least, gas hydrate development as a resource to other countries with more pressing needs for alternative sources of energy.
- ***Research and Limited Development:*** Canada could devote considerably more funding and effort than at present to research and development of gas hydrate in "sweet spots" to better understand the resource and to develop the expertise needed for extraction and processing, while leaving the major development efforts to other countries. This approach would acknowledge that gas hydrate represents only one of the many

possible future energy sources in Canada that require R&D funding until their relative merits are more clearly delineated.

- *Major Targeted Research and Development:* Canada could make a determined effort to be an international leader in gas hydrate development with hydrate exploitation as a national priority. This effort would require a combination of massive investment, focused strategic R&D, infrastructure facilitation and development of training programs. Such an approach would view gas hydrate as one of the best options for bridging to a future where carbon emissions are greatly reduced and North American energy security is more assured.

The *Research Only* approach would fulfil the need for Canada to better understand its physical territory and resources. This approach would, however, mean that Canada could lose the opportunity to be in the vanguard of what might become a major global development. There is some financial risk associated with the *Research and Limited Development* approach, and more significant financial risk with the *Major Targeted Research and Development* approach. The latter option could be undertaken as a contingent extension of the second because a great deal of preparatory work would be needed before committing to commercial development. If Canada ignores gas hydrates altogether, more damaging ways of meeting energy needs could be adopted, and Canada could lose out competitively to other countries, perhaps even to the point of having others exploit Canadian resources. On the other hand, as climate change escalates, carbon-based energy sources may become unacceptable to Canadians.

Actions Canada Could Take — In view of the great uncertainty and risk associated with the commercial potential of gas hydrate, the federal government would need to provide significant funding and/or assume some risk with respect to many of the following activities, which are offered as examples of what might be done and listed roughly in order from research to commercial development:

- Undertake geological, geophysical and geochemical studies to better delineate the extent, location, quality and potential recoverability of Canada's gas hydrate resources.
- Participate more fully in opportunities for international collaboration in gas hydrate research.
- Undertake a wide range of basic and applied research to gain a better understanding of the environmental issues related to exploitation of gas hydrate.
- Support R&D in all aspects of gas hydrate extraction technology.
- Encourage the private sector to collect and report data about the occurrence and location of gas hydrate in the course of commercial drilling through gas hydrate formations.
- Identify opportunities for developing new technologies for gas hydrate related to instrumentation, drilling and onshore processing, thereby creating technology export opportunities.
- Support educational and training initiatives for developing personnel with skills and expertise relevant to gas hydrate.
- Include gas hydrate on the agenda for ongoing discussions of community development in coastal and northern communities, and with Aboriginal Peoples.
- Undertake one or two major demonstration production/testing projects to extend the engineering and scientific expertise already in place. For example, after reviewing the results of the Mallik 2006-08 project, Canada could proceed, preferably again in collaboration with international partners and industry, with a new Mallik program featuring new objectives to extend the lessons learned in the earlier programs.
- Collaborate with provinces and territories to establish taxation and other measures to ensure that (a) clear rules govern the exploitation of gas hydrate resources, and (b) affected areas receive a return of benefits that assist local communities and help develop renewable energy technology and greenhouse gas sequestration.
- Evaluate the incremental costs, risks and benefits of including gas hydrate extraction, before deciding whether or not to proceed with conventional natural gas extraction projects in the Far North and off the east and west coasts.

Summary Response to the Charge to the Panel

The panel's response to the overarching question may be summarized in terms of the three subquestions, which were part of the charge to the panel:

What share of the total Canadian reserves [of gas hydrate] can be profitably extracted?
It is impossible at this time to provide an accurate assessment of the extent of Canada's exploitable gas hydrate resources. The most that can be stated is that the resource is potentially large, possibly even larger by an order of magnitude or more than conventional hydrocarbon resources. Indications are that gas hydrate underlies coastal areas off the west, north and east coasts of Canada, and that there are also significant amounts beneath the permafrost in the Arctic. The most attractive gas hydrate deposits are those associated with sand below permafrost. It is not known what proportion of the total gas hydrate resource these more favourable deposits comprise.

The exploitation of gas hydrate is most likely to take place when conventional gas extraction is ongoing, or exhausted, in northern drilled sites (e.g., in the Mackenzie Delta) or offshore, by completing wells where gas hydrate was found when drilling initially. The profitability of gas hydrate extraction will depend on further development of efficient means of production, as well as on many of the same unpredictable factors that will govern the future profitability of conventional natural gas. Under some circumstances, and with substantial investment, gas hydrate could be a significant source of energy for Canada in the future. However, it is also possible that other alternatives will become more economically and environmentally attractive, to a point where gas hydrate could not compete in the foreseeable future.

What are the science and technology needs for the safe use of energy from gas hydrates?
Subject to confirmation from long-term production experience, there do not appear to be significant safety issues, unique to the production of gas from gas hydrate, that are not already encountered and addressed in the course of more conventional natural gas production, both onshore and offshore.

What are the environmental considerations related to the use, and the non-use, of this resource? From an environmental perspective, gas, once produced from gas hydrate, is essentially identical to conventional natural gas. Hence, gas hydrate would lead to emission of carbon dioxide (a greenhouse gas) when the gas is used as a fuel. In the medium term, it could displace some oil and coal (fossil fuels with greater greenhouse gas emissions per unit of energy), but there is growing consensus that in the long term, carbon-bearing fuels will need to be curtailed and/or subjected to substantial carbon capture and sequestration.

It is possible that gas hydrates in the earth may warm as a result of climate change to the point where they are unstable and eventually dissociate causing a release of methane that would further accelerate climate change. Although the methane in marine gas hydrate is not expected to dissociate under the influence of global warming in this century, it is possible that gas hydrate under permafrost may be affected by warming in some specific locations. If so, the methane release is expected to be chronic rather than abrupt. The potential exploitation of gas hydrate could not meaningfully mitigate this possibility because it would extract and convert such a tiny fraction of the resource that it would have negligible impact on the overall quantity of gas hydrate and on the possible eventual release of methane from natural destabilization.

KEY MESSAGES AND ISSUES

- Natural gas hydrate is a potentially vast, but yet untapped, global energy source.
- Because Canada appears to have some of the world's most favourable conditions for the occurrence of gas hydrate, and has played a leadership role in geophysical, and laboratory hydrate assessments, as well as field testing and modelling, Canada is well-positioned to be a global leader in exploration, R&D, and exploitation of gas hydrate. At the very least, research is required to fulfill a responsibility to gain a more comprehensive understanding of Canada's physical resources.
- Gas hydrate yields natural gas. Most of the environmental, safety, regulatory and social considerations related to its exploitation appear to be similar to those associated with conventional gas production in frontier areas, whether in the North or offshore.
- No insuperable technical problems are foreseen in producing gas from gas hydrate, though this would be more costly than producing gas from conventional reservoirs in similar environments.
- The most promising method of production appears to be to dissociate gas hydrate via pressure drawdown within a reservoir. The most favourable conditions are when gas hydrate occurs in marine and subpermafrost sand formations.
- Although combustion of gas from gas hydrate would generate less CO_2 per unit energy than either coal or oil, the proportion of gas hydrate, and other hydrocarbons, in the future energy mix will depend on decisions on how best to mitigate the anthropogenic drivers of climate change.
- The volume and location of gas hydrate that might ultimately be profitably produced in Canada cannot be adequately quantified at this time. Ongoing exploration and research will be required to delimit the resource, and to determine the technical and economic factors that would govern gas production.
- Commercial production of gas from gas hydrate in Canada would likely begin in association with (frontier) natural gas fields, developed to exploit conventional resources. Gas hydrate production could share established infrastructure, particularly for gas transport.
- In view of the need for further exploration and appraisal of the gas hydrate resource, the construction of new transport infrastructure, and government approvals for various permits, large-scale, stand-alone commercial production of gas from gas hydrate is not likely to take place in Canada within at least the next two decades.
- The economic, environmental and certain technical uncertainties that affect the commercial prospects of gas hydrate, when considered in the context of current alternative opportunities for energy companies, imply that the private sector on its own is unlikely to undertake development of gas hydrate in Canada at this time. Industry must be effectively engaged if significant progress is to be made. Government-industry partnerships could create the option to include gas hydrate in a diversified energy portfolio for the future.

Endnotes

[1] In this report the panel generally refers to gas hydrate in the singular, but occasionally uses the plural (hydrates) if emphasis is intended on the multiple types of gas hydrate or multiple areas of its occurrence.
[2] For comparison, the National Energy Board (NEB) estimated in 2004 that Canada's ultimate potential of conventional natural gas is 14.2×10^{12} m^3 or about 500 Tcf.
[3] The panel acknowledges the helpful input — on which the listed findings are based — from S. R. Dallimore and J. F. Wright of the Geological Survey of Canada and K.Yamamoto of Japan Oil, Gas, Metals National Corporation.
[4] To the extent that there is some substitutability between oil and gas over longer time periods, some rough correlation between higher (lower) oil prices and higher (lower) gas prices might be expected over the long term. Because the recent world price of oil has substantially exceeded the longer-range prices assumed in the NEB scenarios, it might be thought that the NEB's projected (real) gas prices for 2030 are much too low. While the existence of very substantial forecast uncertainties is acknowledged, it should be noted that (a) supply and demand conditions in domestic gas markets and global oil markets can be very different, and thus the gas-oil price correlation could be very different in the future than in the past; and (b) the current spike in oil prices may or may not reflect the future. In the event that gas prices in the medium to longer term do exceed the NEB scenarios, the viability of gas from gas hydrate would improve, other factors being equal.
[5] Petroleum Technology Alliance Canada. 2006. *Filling the gap: Unconventional gas technology roadmap.* Available at: www.ptac.org/cbm/dl/PTAC.UGTR.pdf. [Accessed June 26, 2008].

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Cover photo of Mallik courtesy of Aurora/JOGMEC/NRCan Mallik 2008 research team.