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SCIENCE AND TECHNOLOGY ISSUES IN METHANE HYDRATE R&D

JAPAN

MARCH 5 - 9, 2006

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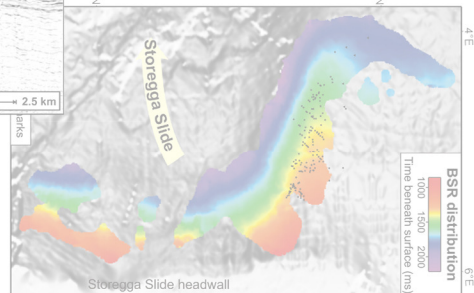
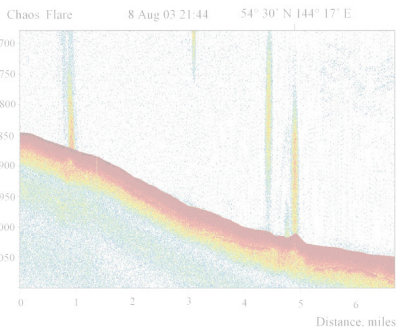
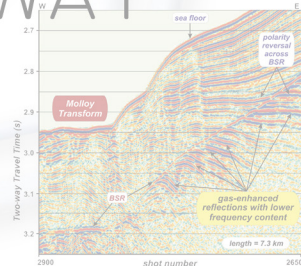
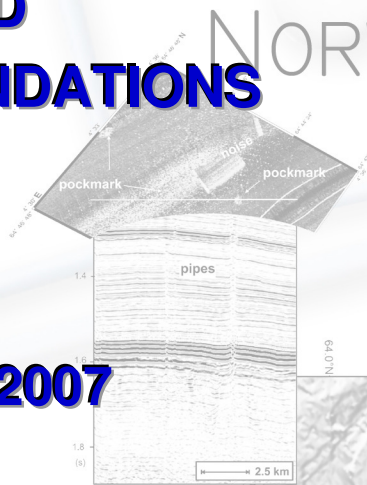
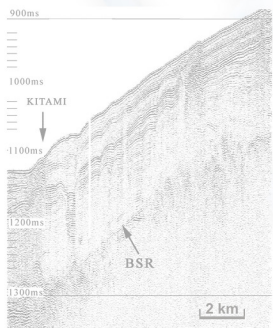
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WORKSHOP SUMMARY AND RECOMMENDATIONS

NORWAY

March 2007



A FOREWORD

Methane hydrates are becoming increasingly recognized as potential resource for natural gas to meet the future global energy needs. It was timely that in March 2006, a workshop entitled “Science & Technology Issues In Methane Hydrate” was convened on the premise of free exchange of ideas in an informal setting in Kauai, Hawaii, USA. The workshop attracted researchers from nine nations of Canada, Chile, Japan, New Zealand, Norway, Russia, The Netherlands, U.K., and U.S.A. The workshop benefited from the generosity of our primary sponsor, Engineering Conferences International (ECI), and other co-sponsors, United States Department of Energy (U.S. DOE), Minerals Management Services, U.S. Department of Interior (MMS-DOI), ConocoPhillips, and Chevron-JIP.

The scientific agenda included invited lectures by noted researchers (Appendix II) who set the stage for lively follow-up discussions by listing thought-provoking questions (pages 11-17). Four thematic Breakout sessions that covered topics such as: Global Hydrate Occurrence and In Situ Measurements, Laboratory Studies and Techniques, Environmental Aspects, and Modeling and Methane Production convened and presented their findings. A special session on International Collaborations brought out elements to foster and expand existing collaborations. The recommendations from these five sessions are summarized under the Executive Summary and in more detail on pages 29-32.

The projects for scoping by drilling for hydrates are being conducted at a rapid pace compared to the past activity. A more aggressive approach comes from countries such as Japan, India and China that are highly dependent on imported energy for their economy. Drilling ships tend to be expensive so it is not surprising that most drilling projects are being conducted as international collaborative efforts. A list of a few recently completed drilling projects is provided in Appendix VIII. The document also summarizes reports from three complementary workshops: 1) 4th International Workshop on Methane Hydrate Research and Development (2005) sponsored by the Office of Naval Research Global (ONR Global) (Appendix V), 2) OCS Resource Management and Sustainable Development Report (1999) sponsored by the MMS-DOI (Appendix VI), and 3) Integration of Modeling and USGS Hydrate Laboratory Research Workshop (2005) sponsored by the United States Geological Survey (USGS) (Appendix VII).

Overall, this report describes a path forward to environmentally compatible methods of methane hydrate development. It is hoped that this document will help funding agencies of the participating nations to consider selecting projects for international collaborations. Such collaborations will avoid data duplication and concentrate financial resources to advance the science of a fascinating resource, namely *Methane Hydrates*.

Devinder Mahajan, Chair
Ponisseril Somasundaran, Co-Chair

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ACKNOWLEDGMENT

The workshop organizers gratefully acknowledge generous financial contributions from the Engineering Conferences International (ECI), the event sponsor and the co-sponsors highlighted on page 6. The Organizing Committee extends their gratitude to two United States agencies: Department of Energy and Department of Interior, for their financial support, participation and input as well. The contribution of Art Johnson, Hydrate Energy International, was crucial to the preparation of this report. A special thanks to Ray Boswell, Manager, Methane Hydrate Program, U.S. DOE for his constructive comments on the document.

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SUMMARY

Large amounts of methane hydrate have been proven to occur in sediments in the Arctic and along continental margins. The existence of these large volumes has implications for global climate, seafloor stability, safety of drilling and other utilities related hardware in those areas, and an energy resource. During the past decade, significant progress has been made in understanding the underlying chemistry of methane hydrates along with their distribution in the world's sediments. Most of this knowledge has been gained through international collaboration involving government agencies, academic institutions, and industrial organizations.

In March 2006, fifty researchers representing organizations from nine nations met to discuss the science and technology needs related to methane hydrate, along with opportunities for additional collaborative efforts. Researchers from all nations and all organizations concurred that international collaboration played a critical role in recent methane hydrate developments and are necessary for maintaining the rapid gains in methane hydrate knowledge. Four breakout sessions and a special session on international collaborations convened to discuss past and future R&D in methane hydrates and submitted their findings. Below we outline specific recommendations under two operational headings: 1) Science and Technology Issues and 2) International Collaboration and Funding Issues.

SCIENCE & TECHNOLOGY ISSUES

Among the critical science and technology needs identified by the conference participants are as follows:

- Better predictive techniques are needed to identify and quantify methane hydrate deposits, either with remote or direct measurements. Proxy measurements are not adequate.
- Better integration of seismic data and wells logs are needed to reduce and quantify uncertainties.
- A thorough and cost effective preliminary survey site protocol needs to be developed to include geochemical, heatflow and EM characterization of deep water sediment hydrate beds. These data will be coupled with seismic surveys to determine deep drilling locations.
- Though major advances have been recently made in the development of a new generation of pressure coring devices and the means to transport and maintain cores under *in situ* pressures and temperatures, work should continue to refine handling of pristine hydrate-bearing sediments,
- Additional drilling sites are needed that are appropriate for resource assessment.

- For hydrate reservoirs, we need to: 1) establish a uniform classification system, 2) better define and model reservoir heterogeneity for different reservoir types, and 3) acquire faster computers for modeling increasingly complex reservoirs
- We need to understand seafloor hazards, and environmental and climate-change impacts of production of gas from hydrates.
- The issue of water disposal related to gas production from hydrates needs to be addressed, including characterization of produced waters, assessment of impact on ecosystems, and effects on other aquifers.
- Preliminary hydrate surveys off the coasts of Chile, New Zealand, Canada and the US show a predictable microbial consortium in hydrate-rich sediments at the sulfate methane interface. Further characterization of the microbial community will assist in biogeochemical evaluation of hydrate beds and assist in understanding microbial cycling of methane.
- A protocol is needed for the laboratory analysis of recovered natural gas hydrates. This will establish an internationally accepted uniform standard of quality control on hydrate data.
- We need to continue to develop international collaborations with the intention of sharing field and laboratory research expertise, ship time cost, and data sets.
- The Messoyakha Field in Russia, the first known site likely to have produced methane derived from hydrate dissociation remains least understood and controversial. Consideration should be given to revisit this active gas field site through a new scientific drilling program, with the ICDP as one of the sources of funding.

INTERNATIONAL COLLABORATION AND FUNDING ISSUES

There was a consensus among researchers from represented nations and organizations that international collaborations played a critical role in recent methane hydrate developments and are necessary for maintaining the rapid gains in methane hydrate knowledge. Though joint drilling projects have been the cornerstone of international collaborations, specific programs at the researchers/institutions level could be put in place between the government bodies to facilitate theme specific collaborations. A way forward to implement the above-identified Science & Technology issues through expanded international effort would consist of the following specific elements:

- Drilling programs. This element is already well established and examples include IODP Expedition 311, Mallik project, and India NGHP Expedition 01. The effort should be expanded to include other sites such as Haakon Mosby Mud Volcano

in the western Barents Sea, the Bering Sea, and the Chilean Exclusive Economic Zone.

- Research personnel exchange programs. The basis for this element is to establish an Exchange Program for researchers- both for established as well as those entering the Methane Hydrate R&D area. The mutual exchange visits could be one to six months duration depending on the project involved and to give researchers schedule flexibility.
- Analysis of previous data. An international committee could be established for analysis of the total 40 years of research results and coordinate research and development work throughout the world.
- Data sharing. The Fire In The Ice (FITI) newsletter and the Methane Hydrate website maintained by the National Energy Technology Laboratory (NETL), U.S. Department of Energy are excellent sources of information for the U.S. effort. The Gas Hydrate CODATA database effort could be a useful tool for global hydrate information dissemination. The CODATA effort should be supported through international funding.
- Funding. Funding increases are deemed necessary to do a coherent job of understanding global occurrence of methane hydrate: first and foremost, its role in climate change and subsequently its potential as a global energy resource.

It is hoped that this document will help funding agencies of the participating nations to consider selecting projects for international collaborations. Such collaborations will avoid data duplication and concentrate financial resources to advance the science of a fascinating resource, namely Methane Hydrates.

WORKSHOP DETAILS

WHAT IS METHANE HYDRATE?

Methane hydrate is a solid crystalline substance composed of water and methane gas in which water molecules form a cage-like structure around the gas molecules. Methane hydrate forms under conditions of moderately high pressure and moderately low temperature (Figure 1). While the most common gas hydrate on earth is methane hydrate, other gases also form hydrates. These include hydrocarbon gases such as ethane, propane and other higher hydrocarbons as well as non-hydrocarbon gases such as CO₂ and H₂S. Methane hydrate occurs naturally in sediments below the permafrost in Arctic environments and is widespread in the uppermost few hundred meters of slope and rise sediments on continental margins where the appropriate conditions of temperature and pressure exist.

Methane hydrate forms at appropriate pressure and temperature conditions and where sufficient gas is present. These conditions are common at water depths greater than 500 meters (1600 feet) at mid to low latitudes and greater than 150-200 meters (500-650 feet) at high latitudes. At these water depths, hydrate can occur within a stability zone that extends into the marine sediments to depths of tens to hundreds of meters beneath the seafloor. The thickness of the hydrate stability zone varies with temperature, pressure, and composition of the hydrate-forming gas, underlying geologic conditions, water depth, and other factors. In deep marine environments, gas hydrate has also been observed as mounds on the seafloor, associated with active vents. If other gases are present, the stability zone can be greatly expanded over that of pure methane hydrate.

An important characteristic of gas hydrate is that the cage structure concentrates natural gas. When hydrate, with totally gas saturated cages, is either warmed or depressurized, it dissociates (decomposes) with a cubic meter of gas hydrate yielding 0.8 cubic meters of water and approximately 164 to 170 cubic meters of gas at standard temperature and pressure. This concentration factor has significant implications for gas hydrates in sediment, whether in regard to geohazards, global climate, or the magnitude of its resource potential. In addition, hydrate accumulates at or near the seafloor host biological communities that are not well understood.

All of these factors have led to dedicated methane hydrate research during the past decade, with some nations (particularly Japan, India, Canada, China, New Zealand and Chile) focused on the resource potential of methane hydrates, while other nations (particularly Norway, Germany and the United Kingdom in Europe) have focused on global climate and geohazards. The United States has funded research on all aspects of methane hydrates. The research conducted worldwide has greatly increased the knowledge base for methane hydrates, and international/interdisciplinary consortia have been a critical factor in the progress in science and technology. The consortia that have produced the most significant results include the Ocean Drilling Program (ODP), the Integrated Ocean Drilling Program (IODP), and the Mallik consortium that drilled at

tested hydrate-bearing sands in the Canadian Arctic. Each of these consortia involved participants from many nations and drew strength from the diverse backgrounds of researchers. In addition, industry-led consortia are making great progress in the Arctic and Gulf of Mexico through collaborative efforts with government agencies and academic institutions. These include the BP-led program on the North Slope of Alaska and the Chevron-led Joint Industry Project (JIP) in the Gulf of Mexico.

SCIENCE AND TECHNOLOGY ISSUES IN METHANE HYDRATE R&D

From March 5 through 9, 2006, a conference was convened in Kauai, Hawaii to review the current state of methane hydrate research and development, and identify fundamental science issues in methane hydrate research that are driven by the technology knowledge base. The conference was chaired by Devinder Mahajan (Brookhaven National Laboratory/SUNY at Stony Brook) and Ponisseril Somasundaran (Columbia University). The initial organizing committee included P. Raj Bishnoi of Canada, Georgy A. Cherkashov of Russia, Richard B. Coffin of the US, Emrys Jones of the US, Bjørn Kvamme of Norway, Juan Diaz Naveas of Chile, Ingo Pecher of New Zealand, Tsutomu Uchida of Japan, and William J. Winters of the USA. The Organizing Committee expanded its membership to add representative from countries present at the workshop. These were: Cor Peters of the Netherlands, P. Mark Rodgers of the UK, and John Ripmeester of Canada.

The conference included fifty methane hydrate researchers from nine nations (Appendix I). The agenda included presentations on recent research results (Appendix II) and the status of research programs (Appendix III). The participants met in four breakout sessions to identify science and technology needs in specific technical areas: Global Hydrate Occurrence and *in situ* Measurements, Laboratory Studies and Techniques, Environmental Aspects, and Modeling and Methane Production. A special session was also convened on “Internal Collaborations”. The results of these sessions are summarized in the sections that follow.

A common theme from all of the breakout sessions is that international collaboration is critical to addressing methane hydrate issues. In addition to the existing consortia among nations, a new consortium was proposed that would conduct drilling and coring operations at the Messoyakha Field in Russia where production data suggests that a portion of the gas produced in the field is derived from hydrate dissociation.

THOUGHT PROVOKING QUESTIONS

All plenary speakers were asked to list at least one “thought provoking” question that relates to their experience in Hydrate R&D. These questions were compiled and laid the basis of discussions during the four Breakout sessions that followed. Both individual as well as general questions for the participants are listed below.

QUESTIONS FOR ALL GROUPS

- What main arguments could be formulated for the governmental/private agencies to support programs of gas hydrate studies?
- Is there a need for a gas hydrate journal?
- How do we improve interdisciplinary collaboration?
- What approach is needed to develop formal international collaborations in methane hydrate research and exploration?
- What are the incentives for more collaboration between academia and industry?
- How do we attract political interest and more funding?
- What more can we learn from additional scientific efforts at Messoyakha?
- What more do we need to know about hydrate dynamics?
- Do we need to establish a committee for analysis of the total 40 years of research results and coordinate research and development work throughout the world?

QUESTIONS SPECIFIC FOR INDIVIDUAL BREAKOUT GROUPS

GROUP 1: GLOBAL OCCURRENCES AND IN SITU MEASUREMENTS

- What is the development needs for seismic analysis, pressure coring, and measuring cores under pressure?
- We need better techniques to identify where hydrate is located – either with remote or direct measurements of properties in the presumed hydrate stability zone (HSZ), rather than with proxies at the top or bottom of the HSZ. (If using proxies, we need to identify and quantify uncertainties). (Note that the HSZ depends on the gases present) This development will provide cost savings for site surveys that provide data for deep drilling. Seismic surveys calibrated with geochemical and heatflow data show the seismics are not always correct in the predictions.
- What is the physical relationship/interaction of gas hydrate and sediment grains and how variable is it?
- How does gas hydrate form in sediments in natural systems, and how does it vary from that created/observed in the laboratory? What is the microbial influence on the hydrate stability and lattice saturation?

- How does the presence of gas hydrate affect seismic properties and sediment strength? How variable is the effect as sediment texture or grain size varies?
- Has the effect of hydrate “frost heaving” been observed in a core? What would it look like? How common is “frost heaving” on a global scale?
- What are the next steps in assessing Chilean gas hydrate potential? How can the international community help?
- Current international programs include India, Canada, New Zealand, Chile, and the US. What other areas can develop for a healthy international collaboration?
- Does it really matter whether the gas in hydrate-bearing sand is biogenic or thermogenic? Does the source have difference in the energy needed for hydrate destabilization? Is there variation in the gas composition that influences the quality of the materials?
- How many Mallik-size fields are there? What are the key regions in the world to start to evaluate the distributions of hydrate fields? Are the Texas-Louisiana Shelf, Cascadia Margin, Nankai Trough, and Bay of Bengal appropriate locations?
- Should we rethink the Blake Ridge model vs. the X311/Nankai/Permafrost model: Hydrate concentrated in coarse units, not at base of HSZ?
- How do we achieve a better understanding of the processes that determine where and when hydrate forms: Gas flux, Heat (energy) flux, Pressure controls, Interactions with local geology (salt? permeability? tectonics?), Biogeochemical influence on the methane concentrations? Scale – multiple scales of spatial & temporal heterogeneity?
- Regarding the renewal of gas hydrate accumulations:
 - What is the rate of gas input to the gas hydrate accumulation?
 - What is the rate of gas hydrate formation?
- Which gas hydrate sites could have multinational status for studies and experiments along the lines of the Lake Vostok drilling program in Antarctica? Could the gas hydrate scientific community establish such a project?
- For resource development, is it enough to be able to locate commercial deposits or do we need to know how emplacement occurred? (flux rate, geochemistry, biogenic vs. thermogenic).
- Hydrates are in a far more rapid dynamic equilibrium with their surroundings than thought. What are the boundary layer data?

- We see large chemical gradients within large masses of hydrate. Are they present in nature?
- After a slump has occurred, how long does it take for the system to re-equilibrate, and how long before hydrates re-form?
- What is the temporal variation in venting activity?
- How universal is the 10 x SMI “rule”?
- What opportunities are there to study gas hydrate in space and cosmos?
- How do we address global warming pertaining to methane hydrates? What are the key areas and how can we mix applied hydrate exploration efforts?

GROUP 2: LAB STUDIES AND TECHNIQUES

- What are the development needs for acquiring and measuring cores under pressure? The current available pressure cores have a low success rate and provide small samples. There is a need for new technology development.
- How does gas hydrate form in sediments in natural systems, and how does it vary from those created/observed in the laboratory? What are the key chemical, physical and biological parameters?
- How does the presence of gas hydrate affect seismic properties and sediment strength?
- How variable is the effect as sediment texture or grain size varies? How do we calibrate the over estimation provide by seismic signatures?
- We need drill sites with multidisciplinary observations, integrated field modeling, and laboratory studies.
- Hydrates are in a far more rapid dynamic equilibrium with their surroundings than thought. What are the boundary layer data?
- We see large chemical gradients within large masses of hydrate. Are they present in nature? And what is the cycling across these gradients on a microscale at the sediment hydrate interface?
- What are the incentives for closer collaboration between experiments and theory?

- How do we develop higher spatial resolution imaging of hydrate formation and dissociation?
- Why is the equilibrium line for gas hydrate dissociation in porous media different than for pure hydrate, and what are the implications of this for commercial production?
- How do we bridge between theory and controlled experiments over to real in situ exploitation situations?
- How does the morphology of hydrate grains affect their growth?
- Why don't the results from bioreactors match the natural world?
- What laboratory measurements do we need to make that we are not able to make now?

GROUP 3: ENVIRONMENTAL ASPECTS

- Has the effect of hydrate “frost heaving” been observed in a core? What would it look like? How common is “frost heaving” on a global scale?
- What is the fate of gas after dissociation?
- Regarding global climate change, are we doing enough to address issues related to gas hydrate production?
- What are the problems with using CO₂ sequestration as a means of methane hydrate production? How do we start to develop a data base to predict the impact of CO₂ on the biogeochemical cycles in the sediment and water column when a key energy source is removed?
- How much gas dissolves into seawater after release from slumps, instead of going into the atmosphere? What parameters control the transport from the atmosphere vs. the water column?
- How much sediment heating is required to release methane that exceeds that anaerobic methane oxidation in the sediment that would result in a continuous flux to the water column. What is the rate of hydrate dissociation that would bypass methane dissolution in the water column and result in a gas transport to the atmosphere?
- After a slump has occurred, how long does it take for the system to re-equilibrate, and how long before hydrates re-form?

- What is the temporal variation in venting activity?
- How will a better understanding of the role of gas hydrate in the global methane cycle address global climate issues?
- How do we address environmental problems related to methane in the atmosphere and tectonic dynamics?
- What is the location and diversity of chemosynthetic communities associated with gas hydrates?

GROUP 4: MODELING AND METHANE PRODUCTION

- Should we rethink the Blake Ridge model vs. the X311/Nankai/Permafrost model: Hydrate concentrated in coarse units, not at base of HSZ?
- What happens to a hydrate-bearing reservoir as hydrate is dissociated over a period of years or decades through commercial production? What is the environmental impact to the sediment and water column?
- Should the focus of production efforts be on mounds associated with vents or with deeper hydrate-bearing sands?
- What things need to come together in organizing a production test?
- Are current timelines for gas production from hydrate realistic? Can they be accelerated?
- Why study Arctic hydrate produceability when the bulk of the potential resource is marine-based?
- What happens within a reservoir when gas hydrate dissociates? Will the presence of clay in a sandstone reservoir form a “mousse” and impair production?
- To what extent can the large in-place resource be transitioned to recoverable reserves?
- What is the fate of gas after dissociation?
- How many Mallik-size fields are there?
- What level of international cooperation is needed for an extended production test at Mallik?

- What is the level of knowledge for the following parameters associated with gas hydrate deposits?
 - Size, Shape
 - Pressure, Temperature, Sub-bottom depth
 - Porosity & Permeability of host sediments
 - GH concentration & distribution pattern within accumulation
 - Potential resources of single accumulation and proposed amount of accumulations in the field (region).
- Regarding the renewal of gas hydrate accumulations, what is the rate of gas input to the gas hydrate accumulation? What is the rate of gas hydrate formation?
- What methods of gas hydrate recovery from deposits associated with vents is more promising: mechanical, hydraulic, and thermo-hydraulic?
- What are the problems with using CO₂ sequestration as a means of methane hydrate production?
- How much heating is optimal for production, and what is the most effective/efficient method of supplying it?
- For heating a gas hydrate reservoir, what are the advantages/disadvantages of using a very hot spot point versus a broader-area heating method?
- How do we connect geological situation with commercial technology for production?
- How do we make the models for gas hydrate development more realistic?
- What is the technology for transporting gas from hydrate deposits?

REPORTS FROM BREAKOUT SESSIONS

BREAKOUT SESSION I: GLOBAL HYDRATE OCCURRENCE AND *IN SITU* MEASUREMENTS

SESSION CHAIRS

**GEORGY CHERKASHOV, VNIIOKEANGEOLGIA
KIMBERLY JUENGER, CONOCOPHILLIPS**

The participants of Breakout Session I focused their discussion on global occurrence, methane hydrate generation processes, methods and instruments, and cooperative efforts.

GLOBAL OCCURRENCE

The participants noted that natural methane hydrate accumulations occur in two principal settings, onshore (permafrost-related) and offshore. The onshore deposits include those in the Mackenzie Delta of Canada, the North Slope of Alaska, and Messoyakha in Russia. Offshore deposits include mounds at or near the seafloor, related to focused fluid venting, and deep-seated accumulations related to fluid filtration. The seismic bottom-simulating reflector (BSR) is normally employed to potentially detect such accumulations. The participants further noted that offshore methane hydrate accumulations may be further subdivided depending on whether the location is on a passive margin such as the Blake Ridge or on an active margin such as the Nankai Trough where sediments are compressed and fluid is expelled. The geologic setting on the Blake Ridge is characterized by low permeability and slow methane flux rate so that the methane hydrates that occur there are relatively old. In contrast, the geologic setting on the Nankai Trough is characterized by high permeability and fast methane flux rate so that the methane hydrates that occur there are relatively young.

Because of the diversity in geologic settings where methane hydrates occur, the breakout session participants recognized the need to select reference sites for various types of studies. The types of studies include the evaluation of resource potential focusing on methane hydrate accumulation, environmental issues, and geohazards/slope stability issues.

METHANE HYDRATE GENERATION AND ACCUMULATION PROCESSES

The participants in Breakout Session I discussed the interaction and physical relationship of methane hydrate and sediment grains. They identified several specific aspects of the hydrate accumulation process that need to be considered; including fluid flux (deemed to be of particular significance), permeability (and the changes in permeability of sediment with time as hydrates form), and the role of surface tension. It was noted that coarse-grained sediments have the potential for high methane hydrate

saturation. Velocity models are inherently different for different grain-size compositions, mineralogies, and hydrate saturations.

The participants discussed the biogenic versus thermogenic origin of the hydrate-forming gas. While the origin of the gas may be of less importance for the production of gas from hydrates, the source of the gas is very important for understanding processes of advection and diffusion. An issue was raised on whether the differences in stability due to variations in composition of the hydrate-forming gas would affect the efficiency of production.

The rate of methane input into a methane hydrate accumulation was discussed as an area of interest. The rates of methane migration through fault zones are not well known, nor are the rates of methane production from microbial sources (although models indicate that microbial sources require on the order of 10^6 years to achieve a steady state). Understanding these rates has commercial significance as the faster migration of methane from thermogenic sources has the potential to renew some accumulations while methane derived from biogenic sources should probably not be viewed as a renewable resource.

METHODS AND INSTRUMENTS (SCIENCE-TECHNOLOGY LINKAGE)

The participants in Breakout Session I noted that improved technology is needed to identify where methane hydrates are located. Their recommendation was for technology for either remote or direct measurements of properties within the HSZ, rather than with proxy measurements at the top or base of the HSZ. If proxies are being used, the uncertainties associated with them need to be identified and quantified. The participants stated the need to correlate well logs with seismic data to reduce and quantify uncertainties. Calibrating seismic data will require drilling and coring in a variety of geologic settings and in locations with varying amounts of methane hydrate.

Among the specific technology needs identified are:

- Improved high-resolution seismic data for detection methane hydrate deposits and their variations in near surface sediments.
- A more thorough calibration of seismic data with geochemical, vertical fluid migration and em surveys.
- Developing a more thorough array of bore hole instrumentation.
- Understanding of nonconservative sulfate profiles that are used to predict deep sediment methane migration.
- A quantitative deep hydrate prediction based on geochemical, vertical fluid migration and surveys that would be followed with deep drilling evaluation.

- A reliable and sensitive methane sensor for in-situ measurements of concentrations in near-bottom water.
- More reliable sampling: new generation pressure core (pressurized coring and transportation system of cores under pressure (development of autoclave system?).
- Porosity and permeability measurements under natural PT conditions.
- Better techniques for remote sensing.
- Better techniques for detection of methane hydrate locations and properties within the HSZ.

During the breakout session discussions, the participants noted the high cost of drilling and observed that improving predictive methods with remote technology should be a high priority. In addition, the participants noted that thorough hydrate studies are needed, not just focused on portions of the larger methane hydrate issues. The participants also recognized a need for categorizing hydrate deposits, a subject also addressed in Breakout Session IV.

COOPERATIVE EFFORTS

In addition to existing collaborations, the participants of Breakout Session I identified several locations such as the Haakon Mosby Mud Volcano in the western Barents Sea, the Bering Sea, and the Chilean Exclusive Economic Zone where methane hydrate research and development could be applied. The participants echoed a common theme of collaboration at all potential global sites.

BREAKOUT SESSION II: LABORATORY STUDIES AND TECHNIQUES

SESSION CHAIRS

WILLIAM WINTERS, USGS
CHARLES TAYLOR, NETL/U.S. DOE

The participants of Breakout session II focused their discussions on three areas: field studies, lab studies, and general needs.

FIELD STUDIES

The participants identified the following issues as areas that need to be addressed regarding field studies:

- More reliable sampling technology is needed for hydrate-bearing sediments, especially a new generation of pressure coring devices and the means to transport and maintain cores and in situ pressures and temperatures.
- Appropriate sites need to be identified for addressing specific methane hydrate science issues, including energy, sediment and water column biological cycles and global warming.
- Improved funding is needed for proper instrumentation.
- A longer financial lead-time is needed for preparing and conducting methane hydrate field expeditions.
- Sediment heterogeneity needs to be more thoroughly incorporated into analyses.

RESULTS FOR LAB STUDIES

The participants of Breakout Session II identified the following issues that need to be addressed regarding laboratory studies:

- Results between labs are difficult to compare because they conduct different analyses and often use different samples. There is a need to establish a matrix of methane hydrate sample characterization so that different labs are working on the same or identical samples. (Set an international protocol.).
- More funding is needed for biological aspects of methane hydrate formation and destabilization. This research needs to focus at a microscale level at the sediment hydrate interface.
- Laboratory studies need to go beyond pure methane hydrate to include a broad range of gas chemistries that could occur in natural hydrate deposits.
- Experiments need to include evaluation of the biogeochemical parameters that control microbial methane oxidation and production.
- Though most hydrate-bearing cores will be analyzed in real time, a protocol should be developed to monitor the long-term storage of hydrate cores.

GENERAL NEEDS

- Laboratory preparation and analysis needs to be standardized.
- Researchers need to have wider access to real cores.
- Triaxial cells are needed for imaging.

- The location of methane hydrate within sediment pores and the nature of the sediment/hydrate interaction require further investigation.
- Biological entities associated with naturally occurring hydrates need to be better understood. .
- There is a need for imaging capabilities at liquid nitrogen temperatures.
- Increased interaction is needed between laboratory researchers and modelers.
- Increased funding is needed to address methane hydrate science and technology issues.

BREAKOUT SESSION III: ENVIRONMENTAL ASPECTS

SESSION CHAIRS

**TSUTOMU UCHIDA, HOKKAIDO UNIVERSITY
KELLY ROSE, NETL/U.S. DOE**

The participants in the breakout session noted that much basic science is still needed regarding the larger issues associated with production of natural gas from hydrates, but additional scientific knowledge is also needed to help understand the significant methane hydrate issues related to the environment.

FUNDAMENTAL RESEARCH NEEDS

The following fundamental research needs were identified that would support both energy-related and environmental science:

- We need to be able to confidently detect where hydrates are and are not. This impacts both the identification and quantification of potential environmental issues along with energy resource potential.
- The potential environmental impacts of methane hydrate production and consumption for energy need to be assessed, along with the impact of CO₂ in former hydrate accumulations.
- A better understanding of the mechanisms, rates, and volumes of natural methane release from hydrates will allow these data to better support global climate modeling and global climate related issues.
- It is important to consider and understand the environmental and safety issues associated with future production/extraction methods this includes seafloor stability issues.

- The parameters that control methane hydrate stability in terms of sediment warming need to be compared at different locations in the world to start to evaluate the impact of global warming on the hydrate stability and fate of the methane.

IMPROVED CHARACTERIZATION AND UNDERSTANDING OF HYDRATE OCCURRENCES IN NATURAL SYSTEMS

The participants of Breakout Session III identified the characterization and understanding of methane hydrate occurrences in natural systems as an important science need related to methane hydrate science. Ten specific issues were described:

- It is important to understand how hydrate exists in sediments and thereby impacts the quantity of methane hydrate and integrity/stability of those sediments.
- Better knowledge is needed regarding the porosity, permeability, pore pressure, and mechanical properties of hydrate bearing sediments, along with the sources and sinks of methane.
- Better knowledge is needed regarding phase change behaviors and equilibrium issues in porous media.
- A better understanding is needed regarding ecological systems associated with methane hydrate, including microbiological influences on methane production or oxidation.
- The fate of methane in the ocean/water column needs to be better understood and that information needs to be integrated with ocean models. Data indicates that methane can drive a significant part of the bacterioplankton cycling in the Gulf of Mexico. Where else does this occur?
- Greater knowledge is needed relative to the transport of methane between the ocean and the atmosphere.
- A better accounting of global inventories of methane hydrate is needed, including both the total volume of methane hydrate and its distribution.
- A global picture of current risks from methane hydrate hazard is needed. Including maps of predicted slope failure risk. At present, slope stability cannot be predicted and the connection between slope stability and methane hydrates is still unanswered.
- Basic research on the microbial consortium through shallow vertical methane flux and how this community controls the methane flux to the atmosphere.

- Critical rates remain unknown including the methane flux through the water column and the methane-oxidizing rate in the ocean system. At present there is insufficient to inform models and we lack a turnover rate.

UNDERSTANDING EXTERNALLY RELATED AND ASSOCIATED PROCESSES

The participants of Breakout Session III noted the need for a better understanding of externally related and associated processes that environmental impacts related to methane hydrate. Eight areas of science were identified:

- The rate of sub-sea sediment movement needs to be better measured. Movement may be catastrophic or creep. The current data available does not allow this issue to be resolved.
- Reliable studies are needed that correlate the presence of methane hydrate accumulations to catastrophic processes, such as seafloor slope failures. Among the specific issues is the need to link and understand tectonic triggers for submarine slides versus slides triggered by hydrate dissociation so we can differentiate between the two. In addition we need to understand what portion of a slope will likely fail if there is a tectonic event and whether hydrate-prone areas are more susceptible to sliding.
- We need to understand which areas of continental slopes are most susceptible to hydrate dissociation, along with the local and regional effects of currents, upwelling of fluids, ocean bottom temperature, and bathymetry variations.
- As CO₂ injection into hydrate-bearing reservoirs has been proposed, a need is there to predict both CO₂ and CH₄ kinetics- both for dissociation and formation. More importantly, the impact of sequestered CO₂ on the microbial and geochemical cycles in the sediment and water column needs to be better understood.
- There is a need for a better understanding of processes resulting in regional variations in the occurrences of hydrate accumulations.
- There is a need for a better understanding of the impact of ocean currents, (past and present) on hydrate distributions and occurrences.
- The possible link between methane hydrates and perturbations in global climate through geologic time is poorly understood.
- There is a need for a more comprehensive understanding of terrestrial methane hydrate dissociation events versus marine hydrate dissociation events and their respective association with global warming.

TOOL AND TECHNOLOGY NEEDS

The participants in Breakout Session III discussed the tools and technology needed to address the science issues identified above. Eleven types of investigations were described:

- Lab studies targeting methane hydrate environmental issues to resolve fundamental questions.
- Observing systems to understand the variations in the flux systems over time.
- Monitoring tools and techniques for global seafloor stability.
- Active perturbation experiments.
- *In situ* seafloor experiments and measurements (including rate experiments).
- Monitoring tools and techniques for global flux rates, occurrences, etc.
- Longer-term experiments and field measurements are needed to better understand the individual and short term measurements made to data.
- 4-D and additional field measurements and maps are needed such as, repeat mapping (multibeam maps resolution to 25cm) and sensors designed and deployed on the seafloor (such as seafloor tiltmeters). As yet we do not know where to place them to gain relevant data, and do not have the technology to address sea floor stability with regard to the impact of methane hydrates.
- Reliable laboratory studies are needed related to gas hydrate environmental issues.
- Models are needed that accurately describe fluxes, composition, occurrences of hydrate, etc. The development of a simple box model tool should be considered.
- Less expensive, more easily deployed shallow (~100 meters) sediment sampling tools are needed, including a reliable pressure coring device.

BREAKOUT SESSION IV: MODELING AND METHANE PRODUCTION

SESSION CHAIRS

ARTHUR JOHNSON, HYDRATE INTERNATIONAL

GEORGE MORIDIS, LBL

The participants in the breakout session focused on two aspects of modeling and methane production, reservoir definition and completion issues.

RESERVOIR DEFINITION

The participants determined that an initial need is the establishment of a uniform classification system for hydrate reservoirs. This will allow aid communication regarding resource estimates by segregating different types of reservoirs. For this report, George Moridis put together a brief summary (Appendix 3) with diagrams on what he has been using to describe hydrate reservoirs. While the use of "Class 1", "Class 2", etc. is currently in use, the participants in the breakout session suggested that "Type 1", "Type 2", etc. nomenclature be used instead to avoid implying that a Class 1 reservoir is always better than a Class 3 reservoir. The participants further suggested that a meeting be convened to develop a formal classification system for gas hydrate reservoirs.

The participants in Breakout Session IV noted that while our knowledge of reservoir parameters is not complete, we do in fact have a significant knowledge base as a result of recent drilling and testing efforts, and modeling. There is no science and technology need that stands in the way of an Arctic production test. There is however a need to better define and model reservoir heterogeneity and different reservoir types. The heterogeneities include mineralogy and texture, salinity, and complex mixtures of hydrate-forming gases such as H₂S and CO₂ that produce significant changes in P/T, heat of dissociation, and dynamic phase equilibria. In addition the effects of biosurfactants and inorganic compounds within a hydrate-bearing reservoir are poorly understood, as with the geomechanical effect of hydrate dissociation during production. Ideally these factors could be incorporated into computer models; however the models take large amounts of time for model runs. The participants identified a need for faster (massively parallel) computers to be utilized in hydrate reservoir modeling.

Despite these needs, the participants noted that existing drilling technology is sufficient for hydrate-bearing sands.

COMPLETION ISSUES

Three completion issues were discussed by the participants of Breakout Session IV. These were:

- Heating the well bore
- Recovery per well
- Water production/disposal.

HEATING THE WELL BORE

There are some differences of opinion on the need to heat, but the models developed and used by George Moridis' indicate that for many methane hydrate reservoirs, the only heating required involves the prevention of gas hydrates from forming in the well bore. This can be accomplished by heating the well bore through the hydrate-bearing intervals plus approximately 10 feet below, and using 200-500 watts per linear meter of well bore. This can be accomplished in a number of ways such as an electric coil or the use of injection tubing with a heated fluid. The critical issue is how much heat needs to be applied, not how to deliver it.

RECOVERY PER WELL (SWEEP)

A fundamental question of recovery is how many wells are required to produce a given reservoir. The breakout session participants observed that this is a future issue that cannot be addressed yet.

WATER PRODUCTION/DISPOSAL

Along with the production of methane from hydrate-bearing reservoirs will likely be the production of water. In most cases the water will have a lower salinity than seawater. As a result, the disposal of produced water will have associated environmental and regulatory issues. Some locations have "zero discharge" rules. If injected into subsurface sands the intermingling due to injection may yield precipitates that would clog injection wells. Fresh water discharge may have negative impact on marine ecosystems. In contrast, in some locations, the production of fresh water can be more of an opportunity than a problem.

The participants recognized three science needs related to produced water and its disposal:

- Characterization of produced waters.
- Assessment of the impact of produced waters on ecosystems.
- Analysis of the effect of injecting produced waters on other aquifers

In reviewing the technology needs related to produced water and its disposal, the participants noted that off the shelf technology might be sufficient. Until the science issues are resolved, the technology needs are unknown.

ADDITIONAL QUESTIONS AND CONCERNS

The participants of Breakout Session IV noted several other issues related to modeling and production:

- There is a need to understand the dynamics of gas hydrates in Type 1, 2 and 3 reservoirs.
- We need extended production tests, but a marine gas hydrate test will be very expensive. Can we learn enough from Arctic results to be able to extrapolate to the marine, and feel comfortable with the spending required for a Gulf of Mexico test?
- There is a need for controlled experiments to reduce uncertainty.
- We need to explore thermal and other methods for dissociation.
- We need to understand seafloor hazards, and environmental and climate-change impacts of production.
- We need to recognize that the technology for producing marine gas hydrates is different than for Arctic gas hydrates, even for the same reservoir type.
- We need a better understanding of the processes that determine where and when hydrate forms (this is also covered in Group I). An effort should be made in modeling spatial and temporal heterogeneity covering the length-scale that span molecular to pan-oceanic.

SPECIAL SESSION: INTERNATIONAL COLLABORATION

SESSION CHAIRS

EDITH ALLISON, U.S. DOE/HQ
ROBERT LABELLE, MMS, U.S. DOI

A special session was convened to discuss the international efforts in the hydrate R&D area to broadly initially discuss the following three aspects:

- International gas hydrate programs.
- Data sharing.
- Research personnel exchange programs.

A fruitful exchange of ideas resulted during discussions between participants representing nine countries. Funding remained the main focus of discussion. Three main recommendations were the outcome of these discussions:

1. This document could be used as a starting point to discuss areas of overlap between represented countries. Areas of expertise would determine collaboration and excessive overlaps could be avoided.
2. If deemed appropriate and with consensus between researchers, this document could be sent to agencies responsible for funding Hydrate R&D in represented countries. The goal is to raise awareness and coherence of the merits of hydrates both as a potential methane source as well as its relation to Climate Change.
3. Funding increases are necessary to do a coherent job of studying Hydrates.
4. The Gas Hydrate CODATA database effort is a useful tool for uniform access to hydrate information dissemination. The CODATA effort should be supported through international collaboration.

GAS HYDRATE COMMITTEE ON DATA FOR SCIENCE AND TECHNOLOGY (CODATA)

Since 2000, the CODATA Gas Hydrate Task Group of fifteen members has been working to establish the database at the international level, in three steps:

1. Establish the need for a connected hydrate databases. This was done in a series of seven international meetings from 2000-2004.
2. Generate a Gas Hydrate Markup Language (GHML) as a common means of hydrate data input. The GHML was written and published in three components (Lab Data, Field Data, and Data for Models) at the CODATA Biennial Meeting in Beijing in October 2006. GHML was posted on the CODATA website (<http://www.codata.org>) on February 1, 2007 for potential user perusal and feedback for six months, ending August 1, 2007.
3. Generate a Gas Hydrate Portal. With the revised GHML in place, a Gas Hydrate Portal will be the final link for connecting individual databases. IT experts in Potsdam, Beijing, and New York, will complete the portal development by January 1, 2008.
4. Meanwhile, countries are generating their individual databases, which will be connected by the CODATA GHML and portal. For example the Chinese national database has been underway at the Chinese Academy of Sciences for two years, and the USA database were funded by DOE for completion at National Institute of Standards and Technology by 2009.

Immediately following the workshop, the Gas Hydrate CODATA group led by Professor E. Dendy Sloan, Jr., Colorado School of Mines and participants from other nations, met on March 9-10 to further discuss establishment of the Gas Hydrate database.

SUMMARY AND RECOMMENDATIONS

Below we summarize the findings of the Breakout Groups in terms of specific recommendations under two operational headings: 1) Science and Technology Issues and 2) International Collaboration and Funding Issues.

SCIENCE & TECHNOLOGY ISSUES

Among the critical science and technology needs identified by the conference participants are as follows:

GLOBAL HYDRATE OCCURRENCE AND *IN SITU* MEASUREMENTS

- A more thorough calibration of seismic data with geochemical, vertical fluid migration and em surveys for detection of methane hydrate deposits and their variations in near surface sediments and within the HSZ.
- Appropriate sites need to be identified for addressing specific methane hydrate science issues, including energy, sediment and water column biological cycles and global warming. Understanding of nonconservative sulfate profiles that are used to predict deep sediment methane migration.
- Sediment characteristics need to be more thoroughly incorporated into analyses.
- More reliable sampling technology is needed to handle hydrate-bearing sediments, especially a new generation of pressure coring devices and the means to transport and maintain cores under in situ pressures and temperatures. Protocols need to be developed for on-board and long-term storage of hydrate cores.

LABORATORY STUDIES AND TECHNIQUES

- Establish a matrix of methane hydrate sample characterization to compare results from laboratories at different locations. Set an international protocol.
- The location of methane hydrate within sediment pores and the nature of the sediment/hydrate interaction require further investigation.
- Establish biological aspects of methane hydrate formation and destabilization. This research needs to focus on the microscale level at the sediment hydrate interface and cover understanding of microbial methane oxidation and production.
- Laboratory studies need to go beyond pure methane hydrate to include a broad range of gas chemistries that could occur in natural hydrate deposits.

ENVIRONMENTAL ASPECTS

IMPROVED UNDERSTANDING OF HYDRATE OCCURRENCES

- A better accounting of global inventories and distribution of methane hydrate is needed. Establish hydrate existence in sediments and quantity and integrity/stability of sediments.
- Better knowledge is needed regarding the porosity, permeability, pore pressure, and mechanical properties of hydrate bearing sediments and phase change behaviors and equilibrium issues in porous media.
- Understand ecological systems associated with methane hydrate, including microbiological influences on methane production or oxidation, the microbial consortium through shallow vertical methane flux and how this community controls the methane flux to the atmosphere.
- The fate of methane in the ocean/water column needs to be better understood for integration with ocean models. Data indicates that methane can drive a significant part of the bacterioplankton cycling in the Gulf of Mexico.
- A global picture of current risks from methane hydrate hazard is needed including maps of predicted slope failure risk.

UNDERSTANDING EXTERNALLY RELATED AND ASSOCIATED PROCESSES

- The rate of sub-sea sediment movement needs to be better measured.
- Reliable studies are needed that correlate the presence of methane hydrate accumulations to catastrophic processes, such as seafloor slope failures. Link and understand tectonic triggers for submarine slides versus slides triggered by hydrate dissociation.
- Studies to understand areas of continental slopes most susceptible to hydrate dissociation, along with the local and regional effects of currents, upwelling of fluids, ocean bottom temperature, and bathymetry variations.
- For CO₂ injection into hydrate-bearing reservoirs, a need to predict both CO₂ and CH₄ kinetics- both for dissociation and formation. Also, establish the impact of sequestered CO₂ on the microbial and geochemical cycles in the sediment and water column.

TOOL AND TECHNOLOGY NEEDS

- Tools for reliable laboratory studies targeting methane hydrate environmental issues to resolve fundamental questions of: 1) variations in the flux systems over time, 2) global flux rates and 3) global seafloor stability.
- Active perturbation including *in situ* seafloor measurements.
- 4-D and additional field measurements and maps are needed such as, repeat mapping (multibeam maps resolution to 25cm) and sensors designed and deployed on the seafloor (such as seafloor tiltmeters).

- Models are needed that accurately describe fluxes, composition, occurrences of hydrate. The development of a simple box model tool should be considered.
- The potential environmental impacts of methane hydrate production including seafloor stability issues and consumption for energy need to be assessed, along with the impact of CO₂ in former hydrate accumulations.
- A better understanding of the mechanisms, rates, volumes of natural methane release and the fate of the released methane (transport of methane between the ocean and the atmosphere) from hydrates will allow these data to better support global climate modeling and related issues.

MODELING AND METHANE PRODUCTION

- There is a need to understand the dynamics of gas hydrates in Type 1, 2 and 3 reservoirs. Also, the technology for producing marine gas hydrates is different than for Arctic gas hydrates, even for the same reservoir type.
- We need to understand seafloor hazards, and environmental and climate-change impacts of production.
- We need a better understanding of the processes that determine where and when hydrate forms. Effort should be made in modeling spatial and temporal heterogeneity covering the length-scale that span molecular to pan-oceanic.
- Three completion issues: 1) Heating the well bore, 2) Recovery per well (Sweep) and 3) Water production/disposal should be addressed by addressing any inconsistencies in existing models. The issue of water management requires characterization of produced waters and the impact of produced waters on ecosystems.

INTERNATIONAL COLLABORATION AND FUNDING ISSUES

There was a consensus among researchers from represented nations and organizations that international collaborations played a critical role in recent methane hydrate developments and are necessary for maintaining the rapid gains in methane hydrate knowledge. Though joint drilling projects have been the cornerstone of international collaborations, specific programs at the researchers/institutions level could be put in place between the government bodies to facilitate theme specific collaborations. A way forward to expand the international effort would consist of the following specific elements:

1. Drilling programs. This element is already well established and examples include IODP Expedition 311, Mallik project, and India NGHP Expedition 01. The effort should be expanded to include Haakon Mosby Mud Volcano in the western Barents Sea, the Bering Sea, and the Chilean Exclusive Economic Zone.
2. Research personnel exchange programs. The basis for this element is to establish an Exchange Program for researchers- both for established as well as those entering the

Methane Hydrate R&D area. The mutual exchange visits could be one to six months duration depending on the project involved and to give researchers schedule flexibility.

3. Analysis of Previous Data. An international committee could be established for analysis of the total 40 years of research results and coordinate research and development work throughout the world.

4. Data sharing. The Fire in The Ice (FITI) newsletter and the Methane Hydrate website maintained by the National Energy Technology Laboratory (NETL), U.S. Department of Energy are excellent sources of information for the U.S. effort. The Gas Hydrate CODATA database effort could be a useful tool for global hydrate information dissemination. The CODATA effort should be supported through international funding.

5. Funding. Funding increases are deemed necessary to do a coherent job of understanding global occurrence of methane hydrate: first and foremost, its role in climate change and subsequently its potential as a global energy resource.

The above outlined R&D recommendations in this document could be used as a starting point to discuss areas of overlap between represented countries. Areas of expertise would determine collaboration and excessive overlaps could be avoided. With consensus among researchers, this document should be sent to agencies responsible for funding Hydrate R&D in represented countries to implement these elements. The goal is to raise awareness and coherence of the merits of hydrates both as a potential methane source as well as its relation to Climate Change.

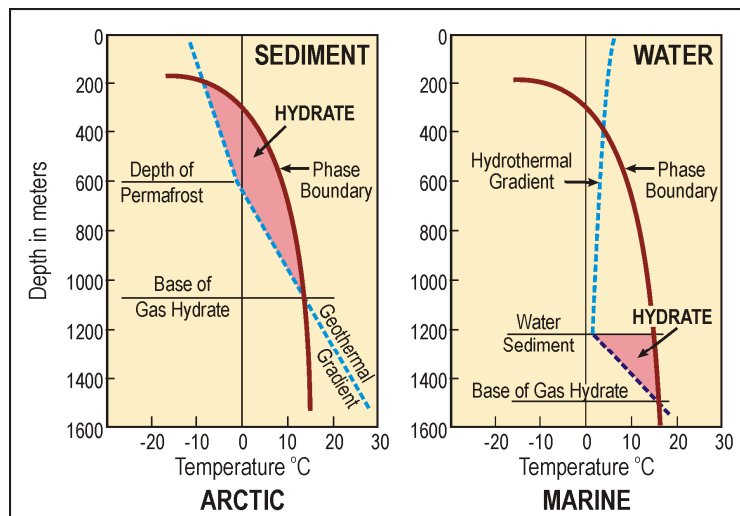


Figure 1. Phase diagrams for methane hydrate in both Arctic permafrost and marine continental margin settings.

APPENDICES

- APPENDIX I. LIST OF CONFERENCE PARTICIPANTS
- APPENDIX II TECHNICAL PROGRAM AGENDA
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- APPENDIX IV HYDRATE CLASSIFICATION
- APPENDIX V 4TH INTERNATIONAL WORKSHOP ON METHANE HYDRATE RESEARCH AND DEVELOPMENT, MAY 9-11, 2005, VICTORIA BC, CANADA
- APPENDIX VI EXECUTIVE SUMMARY OF THE 1999 MMS REPORT: “OCS RESOURCE MANAGEMENT AND SUSTAINABLE DEVELOPMENT”
- APPENDIX VII EXECUTIVE SUMMARY OF THE 2005 USGS REPORT: “INTEGRATION OF MODELING AND USGS HYDRATE LABORATORY RESEARCH: WORKSHOP REPORT”
- APPENDIX VIII LINKS TO ADDITIONAL DOCUMENTS

APPENDIX I

LIST OF CONFERENCE PARTICIPANTS

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APPENDIX II

TECHNICAL PROGRAM AGENDA

FINAL Program (March 5, 2006)

Science and Technology Issues In Methane Hydrate R&D

**March 5 - 9, 2006
Sheraton Kauai Resort Hotel
Kauai, Hawaii**

Devinder Mahajan, Chair
Brookhaven National Laboratory/SUNY at Stony Brook, USA

Ponisseril Somasundaran, Co-Chair
Columbia University, USA

Organizing Committee

P. Raj Bishnoi (Canada); Georgy A. Cherkashov (Russia); Richard B. Coffin (USA); Emrys Jones (USA); Bjørn Kvamme (Norway); Juan Diaz Naveas (Chile); Ingo Pecher (New Zealand); Tsutomu Uchida (Japan); William J. Winters (USA)

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Sunday, March 5, 2006

- 17:00 - 19:00 Registration
- 19:00 – 19:30 Reception
- 19:30 – 21:00 Dinner

Monday, March 6, 2006

- 08:00 – 09:00 Breakfast
- 09:00 – 09:15 Welcome
Devinder Mahajan and P. Somasundaran
- 09:15 – 10:15 **Keynote Lecture**
Edith Allison, Manager, Natural Gas and Petroleum Technology, Office of Fossil Energy, United States Department Of Energy (U.S. DOE), Washington, DC.
“U.S. Department of Energy Methane Hydrate Research: Progress and Potential”
- Plenary Lectures I: Global Gas Hydrate Occurrences**
Session Chair: **Richard Coffin**, Naval Research Lab
- 10:15 – 10:50 **Emrys Jones**, Chevron, USA.
“Overview of GOM JIP Leg 1 Drilling”
- 10:50 – 11:15 Coffee Break
- 11:15 – 11:50 **Ray Boswell**, National Energy Technology Laboratory, U.S. Department of Energy, USA
“Progress and Implications of DOE-BP-USGS Gas Hydrates Research at Milne Point, Alaska North Slope”
- 11:50 – 12:25 **Juan Diaz Naveas**, Universidad Catolica de Valparaiso, Chile.
“Preliminary seismic and bathymetric results of VG06 cruise off Central Chile”
- 12:25 – 13:00 **Ingo Pecher**, Institute of Geological and Nuclear Sciences, Wellington, New Zealand
“Seafloor Erosion and Methane Release Close to the Top of the Gas Hydrate Stability Zone on the Hikurangi Margin”
- 13:00 – 14:00 Lunch
- Plenary Lectures II: Field Data Analysis and Observations**
Session Chair: **R. Boswell**, NETL/DOE
- 14:00 – 14:35 **E. Dendy Sloan, Jr.**, Colorado School of Mines, Golden, USA
“Hydrate knowledge development”
- 14:35 – 15:10 **A. Colvine**, Geological Survey of Canada, Ottawa, Canada
“Reservoir controls on gas hydrate occurrence at the Mallik field, N.W.T., Canada: Implications for exploration and production of terrestrial and marine deposits”

- 15:10 – 15:45 **Debbie Hutchinson**, United States Geological Survey, Woods Hole, *USA*
“Heterogeneity and dynamics in gas hydrate occurrence: lessons learned from the northern Gulf of Mexico”
- 15:45 – 16:20 **Georgy Cherkashov**, Institute for Geology and Mineral Resources of the Ocean (VNIIOkeangeologia), St.Petersburg, *Russia*
“Near Sea-Bottom Gas Hydrate Accumulations as Priority Object for Investigation and Possible Utilization”
- 17:00 – 18:30 **Poster Session I with coffee**
- 18:30 – 20:00 Dinner
- 20:00 – 21:00 Social Hour/Discussion

Tuesday, March 7, 2006

- 08:00 – 09:00 Breakfast
- Plenary Lectures III: Data Collection and Analysis Techniques**
 Session Chair: **John Ripmeester**, National Research Council, Canada
- 09:00 – 09:35 **Peter Brewer**, Monterrey Bay Aquarium Research Institute, Moss Landing, *USA*
“Laser Raman Measurement of Methane Hydrates on the Seafloor”
- 09:35 – 10:10 **Arne Graue**, University of Bergen, *Norway*
“Experimental MRI-Visualization of Methane Production from Hydrates in Porous Rock during CO₂ Storage”
- 10:10 – 10:45 **Yuri Makogon**, Texas A&M University, *USA*
“What We Need to Know Before Production Modeling”
- 10:45 – 11:15 Coffee Break
- Plenary Lectures IV: Modeling and Laboratory Studies**
 Session Chairs: **Evgeny Chuvilin**, Moscow State University, Russia
- 11:15 – 11:50 **Bjørn Kvamme**, University of Bergen, *Norway*
“Kinetic Modeling of Hydrate Phase Transitions by Phase Field Approaches”
- 11:50 – 12:20 **George Moridis**, Lawrence Berkeley National Laboratory, *U.S.A.*
“Depressurization-Induced Gas Production from Class 1 and Class 2 Hydrate Deposits”
- 12:20 – 12:50 **Tsutomu Uchida**, Hokkaido University, *Japan*
“Overview of the Japan Hydrate Program”
- 12:50 – 13:50 Lunch
- Plenary Lectures V: Modeling and Laboratory Studies (Contd.)**
 Session Chairs: **P. Mark Rodger**, University of Warwick, UK
- 13:50 – 14: 25 **Peter Englezos**, University of British Columbia, Vancouver, *Canada*

"Dynamics of Natural Gas Hydrate Crystal Growth"

- 14:25 – 14:50 **Charlie Paull**, Monterey Bay Aquarium Research Institute, Moss Landing, USA
"Does gas escape from gas hydrate deposits?"
- 14:50 – 15:10 **Douglas Bartlett**, Scripps Institute of Oceanography-UC San Diego, USA
"Laboratory Exploration of Microbial Growth on Methane Hydrate"
- 15:10 – 15:30 **C. Aaron Lai**, Los Alamos National Laboratory, U.S.A.
"Effect of Biogeochemistry and Clathrate Hydrates on Ocean Warming"
- 15:50 – 17:00 Free Time
- 17:00 – 19:00 **Poster Session II with coffee**
- 19:00 – 20:30 Dinner
- 20:30 – 21:30 **Special Session: International Collaborations**
Chairs:
Edith Allison, U.S. DOE/HQ
Robert LaBelle, Mineral Management Services, U.S. Department of Interior.
Presentation (20 min.) followed by discussion.
- 21:30 – 22:30 Social Hour/Discussion

Wednesday, March 8, 2006

- 08:00 – 09:00 Breakfast
- 09:30 – 12:30 **Breakout Sessions 1 - 4**
- Session I: Global Hydrate Occurrences and *in situ* Measurements
Chairs:
Georgy Cherkashov, VNIIOkeangeologia
Kimberly Juenger, ConocoPhillips
- Session II: Laboratory Studies and Techniques
Chairs:
William Winters, USGS
Charles Taylor, NETL/U.S. DOE
- Session III: Environmental Aspects
Chairs:
Tutomu Uchida, Hokkaido University
Kelly Rose, NETL/U.S. DOE
- Session IV: Modeling and Methane Production
Chairs:
Arthur Johnson, Hydrate International
George Moridis, LBL
- 10:30 – 11:00 Coffee Break
- 12:30 – 13:30 Lunch

13:30 – 16:00	Free time
16:00 – 19:00	Breakout Sessions (continued)
20:00 -	Conference Banquet

Thursday, March 9, 2006

08:00 – 09:00	Breakfast
09:00 – 12:30	<u>Chairs:</u> D. Mahajan and P. Somasundaran Breakout Session Presentations (Sessions 1-4)
10:30 – 11:00	Coffee Break
12:30 – 12:45	Concluding Remarks and Adjournment
13:00	Lunch

APPENDIX III

LIST OF PRESENTATIONS AND ABSTRACTS FROM PLENARY SESSIONS

Keynote Lecture

Edith Allison, Manager

Natural Gas and Petroleum Technology, Office of Fossil Energy, United States Department Of Energy (U.S. DOE), Washington, DC.

“U.S. Department of Energy Methane Hydrate Research: Progress and Potential”

PLENARY LECTURES

(Listed on the following pages)

Overview of GOM JIP Leg 1 Drilling

Emrys Jones

Abstract

The goals of the JIP are reviewed and precruise predictions are compared to data from the March-April 2005 drilling in the Gulf of Mexico. Precruise predictions are the estimated amount of hydrate in place from a seismic analysis of the two drilling locations.

Data collected during the cruise included mechanical, acoustic, IR, x-ray, and other measurements of the sediments as well as MWD and wire line logs of the holes. Water samples were collected from the core material and analyzed both on the ship as well as on shore. Cores were obtained using both pressure coring and conventional coring equipment. Operational experience was gained with the first ever field application of a vessel for measuring mechanical and other properties of a pressure core maintained under in-situ pressure.

No hydrates were collected and stored in liquid nitrogen. However, all of the precruise analysis, logs, pressure core measurements, and water analysis were in general agreement for hydrate concentrations.

Progress and Implications of DOE-BP-USGS Gas Hydrates Research at Milne Point, Alaska North Slope

Ray Boswell

Abstract

The United States Geological Survey has studied the gas hydrate potential of the Alaska North Slope and currently estimates that up to 40 tcf of natural gas exists within hydrate deposits below existing oil and gas production facilities. However, the technical and economic recoverability of that resource has not been established. In 2000, BP Exploration Alaska, Inc. contributed a state-of-the-art 3-D seismic survey over its Milne Point production unit to a government-industry effort to provide a full evaluation of the feasibility of methane production from Arctic hydrates. The initial phases of the effort produced a comprehensive geophysical, reservoir modeling and geologic characterization of the prospective hydrate-bearing units that resulted in the delineation of numerous drillable hydrate prospects. A location was selected for further field data acquisition, consisting of a vertical stratigraphic test to confirm the prospecting methodology and provide a full suite of core and open-hole log data. Subsequent progression into a phase of extended production testing will be contingent on Phase 3 results and subject to the approval of both DOE and BPXA. The project will be a critical step in the determination of the viability of methane production from Arctic hydrate deposits and will have significant relevance to the appraisal of the recoverability of hydrate-bearing sandstones in the marine environment.

Preliminary seismic and bathymetric results of VG06 cruise off Central Chile

Juan Diaz Naveas

Abstract

The second Chilean FONDEF project on gas hydrates (2006-2009) deals with the exploration of the most promising submarine hydrate reservoirs off Central Chile and of a technical and an economical feasibility study of their exploitation.

The first cruise of this project was carried out between 34° and 37°S, and between the 200m and 3000m isobaths, from February 3 until 22, 2006 on board Chilean Navy AGOR 60 Vidal Gormaz. The University of Aarhus provided a 96 channel 600m long streamer with a 4 sleeve-gun array with a total volume of 160 cubic inches for carrying seismic reflection lines. 58 seismic lines were shot covering an overall length of about 2350km. IfM-GEOMAR provided an ELAC 1050 multibeam echosounder with a maximum swath of 153° and 126 beams and a frequency of 50kHz. The overall area covered with multibeam bathymetry was of 5900km².

Bathymetry reveals a complex structure with ridges, basins, blocky units and submarine canyons. Seismic lines show both complex structural and stratigraphical units. The selected region for semidetalled studies shows a very dense BSR distribution. However, the nature of BSRs differ from line to line. Lines close to 36°S show the most conspicuous BSR. There is a tendency for BSRs to “disappear” when entering non tilted sedimentary basins. Other regions show enhanced reflectivity below the BSR and possible bright spots. Some BSRs appear to reach the seafloor. Line VG02-17_2 shows two mud volcanoes-like features. Also, along this line, which is parallel to the margin, the BSR is more evident than across margin BSRs. Lines VG06-61 and VG06-62 show little mound-like structures with underlying diminished reflectivity. A submarine canyon shows erosion just above the BSR along line VG06- 65. Finally an enigmatic 200Hz reflectivity appears consistently on 4 lines in the water column at a depth of 1500m.

Seafloor Erosion and Methane Release Close to the Top of the Gas Hydrate Stability Zone on the Hikurangi Margin, New Zealand

Ingo A. Pecher

Abstract

Seismic data suggest that seafloor erosion of Rock Garden, an uplifted sub-sea ridge on the Hikurangi Margin, is related to the top of the gas hydrate stability zone (TGHS) in the ocean as marked by pinchouts of bottom simulating reflections. It has been proposed that erosion may be caused by slumping at the base of gas hydrate stability during uplift and/or repeated formation and dissociation of gas hydrate leading to frost-heave-like sediment weakening. We have recently acquired high-resolution bathymetric data that display numerous small slumps at the edge of Rock Garden's plateau-like crest close to the TGHS. The presence of these slumps supports our hypothesis of gas-hydrate-related seafloor erosion. We have also measured methane concentrations in the water column above Rock Garden using towed CTD casts. A sharp increase in methane concentration of up to 10 nM occurs at the upper edge of one of the slump sites in about 680m water depth. At the same location, high backscatter signals were observed in the single-beam echosounder proving the existence of rising bubbles from the seafloor. A subtle but distinctive increase from 2 to 4nM methane was found from north to south during the tows across the crest of Rock Garden. Our observations underline the significance of the TGHS for the role of gas hydrates in seafloor stability and for methane release into the ocean.

Hydrate Knowledge Development

E. Dendy Sloan

Abstract

An overview of hydrate knowledge development will be presented, along with a brief background of hydrate structure and properties. An overview of five applications, which are the major research vehicles, will be related to hydrate structure and properties: 1) safety, 2) flow assurance, 3) energy recovery, 4) climate change and geo-hazard, and 5) gas storage. The development of the CODATA international hydrate database will be discussed, together with the mechanism for accessing and contributing to the database.

Reservoir Controls on Gas Hydrate Occurrence at the Mallik Field, N.W.T. Canada: Implications for Exploration and Production of Terrestrial and Marine Deposits

Scott R. Dallimore
(Presented by A. Colvine)

Abstract

The Mallik gas hydrate field, located at the edge of the Mackenzie Delta and the Beaufort Sea in Canada's Northwest Territories is one of the most concentrated gas hydrate reservoirs in the world. The abundant geologic and engineering data available at this site, similarities to many offshore gas hydrate occurrences and the advantageous logistics presented by its terrestrial location make Mallik a very desirable location for gas hydrate research and development. Two international research programs have been conducted at the site in 1998 and 2002. The most recent was undertaken with a primary goal to undertake the first modern production testing of gas hydrates. Participants the Geological Survey of Canada, Japan National Oil Corporation, GeoForschungsZentrum Potsdam, United States Geological Survey, United States Department of the Energy, India (Ministry of Petroleum and Natural Gas/Gas Authority of India), BP-ChevronTexaco Joint Venture and the International Continental Drilling Program. The scientific results from the Mallik 2002 program were recently published as a compendium volume consisting of 62 peer reviewed papers. Gas hydrate occurs primarily within unconsolidated sands from 890 to 1106 m depth within the crest of a regional anticline feature. Formation temperatures of this terrestrial occurrence are similar to many offshore deposits, however, ~600 m of permafrost control the ground thermal regime rather than the cold sea bottom temperatures. This paper will review reservoir controls and heterogeneity as they affect gas hydrate occurrence (form and concentration), stability and physical properties. Insights will be given on the implications of the Mallik work for exploration and possible development of gas hydrates in other environments.

Heterogeneity and Dynamics in Gas Hydrate Occurrence: Lessons Learned from the Northern Gulf of Mexico

Deborah R. Hutchinson

Abstract

Marine gas hydrates occur in some of the most dynamic environments on Earth: in young, unconsolidated sediments on moderate to steep slopes of continental margins where tectonic, depositional, microbial, and diagenetic processes coincide. These processes influence the pressure, temperature, and chemical conditions controlling hydrate occurrence in ways that are not yet well understood or measured. An extreme example of this complexity occurs in the northern Gulf of Mexico where huge thicknesses of Quaternary sediments have triggered subsidence, halokinesis, faulting, and sediment disturbance. With a leaky world-class petroleum system underlying the margin, and oceanographic patterns affecting water column temperatures and currents, hydrate deposits in the northern Gulf occur in a richly heterogeneous setting where seafloor and shallow subbottom conditions vary at multiple spatial and temporal scales. Many issues from the Gulf of Mexico also face researchers trying to understand hydrates in other marine environments: for example, the relative importance of thermogenic versus biogenic gas in forming hydrates, the roles of advection, diffusion, and seeps in transporting the gas and fluids, the availability of suitable pathways and reservoirs for concentrating hydrate, the role and influence of microbial processes in the sediments, and the pervasive effects of salt tectonism and associated thermal, chemical, and physical modification of the sediments. One of the biggest challenges in understanding natural hydrates in these settings is determining which factors exert primary controls on hydrate occurrence and how these vary in the delicate balance of changing conditions. This presentation will synthesize our knowledge of gas hydrates in the northern Gulf and identify key outstanding challenges facing the research community.

Near Sea-Bottom Gas Hydrate Accumulations as Priority Object for Investigation and Possible Utilization

Georgy Cherkashov

Abstract

Two types of submarine gas hydrate accumulations may be distinguished based on their position beneath the seafloor: shallow-seated (within the upper few meters of the sediment) and deep-seated (the first hundred meters of the sediment). Near sea-bottom gas hydrate accumulations are usually associated with areas of fluid discharge such as mud volcanoes, gas seeps and gas-saturated water seeps. This type of gas hydrate is also characterized by the following features which make them more promising for future investigations and possible production than the deep-seated hydrates: 1. They have well-defined limits, especially at their upper boundary. 2. Gas hydrate formation in fluid-discharge areas is continuing at present with up to 20 000 occurrences worldwide. 3. Gas resources in these hydrates can be considered to be renewable. 4. There is prominent structural control in the fluid-discharge areas. 5. There are elaborated methods and technologies for prospecting and exploration of these accumulations. Estimation of possible gas volume in single accumulations of hydrates and the global budget, as well as possible methods of utilization of the gas from such gas hydrate accumulations are discussed in this paper.

Laser Raman Measurement of Methane Hydrates on the Seafloor

Peter G. Brewer

Abstract

The rapid decomposition of methane hydrates during sample recovery has posed a classical problem for the researcher who wishes to study the solid phase itself, rather than measurement of the gas evolved from the decomposed sample. Recovery of pressurized core samples has been attempted, but is mechanically complex, and only available during major drilling operations. We have developed a novel laser Raman spectrometer for deep-sea science that can be carried by an ROV for rapid non-invasive in situ measurement of methane hydrates exposed on the sea floor. The Raman technique measures the vibrational modes of molecules, which shift in frequency as a function of the molecule's local environment, such as containment within an aqueous cage. The frequency shifts may be used to assign hydrate structure. The instrument is a highly modified holographic commercial instrument (Kaiser Optical) using a 532 nm laser, with real time communication through the vehicle tether. We first made a Structure II hydrate from a methane-ethane gas mixture injected into a glass container so as to create nucleation, and left at 1024m depth for about 40 days. Massive hydrate formation occurred, and this was examined with the Raman system mounted on an accurately controllable tripod positioner for precise laser focusing. The recovered spectrum accurately matched the equivalent laboratory result. We then used this system to probe natural samples released from the sea floor at southern Hydrate Ridge, OR. Hydrates were released from the host sediment by the ROV robotic arm, and trapped in both glass, and mesh, containers. The laser was then focused on these specimens. The recorded spectra showed the specimens to be a Structure I hydrate, but with significant amounts of free gas trapped within the hydrate matrix. Cage occupancy ratios were calculated. This new tool shows great promise for novel hydrate science.

Experimental MRI-Visualization of Methane Production from Hydrates in Porous Rock During CO₂ Storage

Arne Graue

Abstract

Natural gas hydrate accumulations are often associated with technical challenges during drilling operations and stability issues for pipeline operations and sea bed constructions; and historically, of catastrophic dissociation scenarios associated with methane release to the atmosphere and corresponding tsunamis. However, recently natural gas hydrate accumulations are emphasized because of the significant potential for worldwide natural gas supply; combined with a favorable option for CO₂ storage. Storage of CO₂ in hydrate reservoirs offers a natural process driven by the enhanced stability of the CO₂ hydrate to replace the in-situ natural gas hydrate with CO₂ hydrate causing a corresponding release of natural gas. Utilizing Magnetic Resonance Imaging (MRI) hydrate formation in porous sandstone has been dynamically visualized. It has experimentally been determined in-situ that CO₂ sequestration in gas hydrates in porous rock results in spontaneous production of methane, with no associated water production. Exposing methane hydrate to liquid CO₂ caused methane production from the hydrate indicating an exchange of methane molecules with CO₂ molecules within the hydrate; without addition of heat. Theoretical simulations based on Phase Field theory supported this assumption and predicted similar methane production rates as those observed in several reproduced experiments. 3D-visualization was used as an additional tool for the interpretation of the experiments; during the formation of hydrates in the porous rock the high spatial resolution imaging capabilities gave detailed information of the in-situ fluid distribution; revealing where the water was bound in hydrate and where the free fluid saturation was located. Saturation information during the methane production gave quantitative information of the dynamic methane production by in-situ measurements of the CO₂/methane exchange and provided information about instant in-situ production efficiency.

Evaluation of the Efficiency of Bottom Hole Heaters at Gas Hydrate Dissociation

Yuri Makogon

Abstract

Studies presented in [1] show that during gas production from the fields located in the permafrost regions intensive hydrate formation occurs in the bottom hole zone. As a result, well productivity reduces to about 20%. One of the ways of well productivity recovery is the use of different types of heaters. The paper presents the evaluation of the above method efficiency. During the computational experiment the effect of heating intensity, gas well production rate and permeability on dynamics of the formation and dissociation of natural gas hydrates has been studied. The results of calculations for the intensive heating show that regardless of the distance from a well, rate of hydrate saturation growth and its absolute magnitude significantly depend on permeability and production rate and that hydrate formation occurs in a comparatively narrow zone near wells where all pore water transforms into a hydrate. The most unfavorable is the situation when high gas flow rate is forced at low permeability of the reservoir. Heating during 10 days at high temperature difference manifests itself only in a narrow zone near a well. Its size practically does not depend on either permeability, or production rate, but these parameters substantially influence on hydrate saturation distribution in the external zone of a reservoir. Now consider the scenario when the heater temperature only slightly exceeds the equilibrium temperature of hydrate formation. Then, in 10 days gas extraction was resumed. In this case the influence of the heater is more localized than in the first variant and the size of the hydrate-free zone depends both on gas flow rate and bed permeability. Summarizing the results presented, one can say that short time heating causes hydrate dissociation in a narrow zone near a well (about 2 m). But it must be noted that this hydrate-free zone is kept during successive gas extraction for a long time. (References 1. Bondarev E.A., Popov V.V. Dynamics of hydrate formation during natural gas production//Computational technologies, 2002, No. 1. P. 28-33).

Kinetic Modeling of Hydrate Phase Transitions by Phase Field Approaches

Bjørn Kvamme

Abstract

A phase field theory with model parameters evaluated from atomistic simulations/experiments is applied for describing the nucleation and growth and the dissolution of CO₂ hydrate in aqueous solutions under conditions typical to underwater natural gas hydrate reservoirs. It is shown that the size of the critical fluctuations (nuclei) is comparable to the interface thickness, thus the phase field theory predicts a considerably lower nucleation barrier height and higher nucleation rate than the classical approach that relies on a sharp interface. The growth rates of CO₂ hydrate corresponding to different growth geometries (planar, circular, and dendritic) have been determined. The predicted growth rates are consistent with experiments performed under similar conditions. An alternative phase approach based on cellular automata has also been formulated and applied to the same model systems. Time dependence for this approach is derived by relating the diffusivity to the interface thickness. For small times the two approaches appear to give similar results but deviates significantly for larger time scales. Dissolution rates of the hydrate phase have been studied as a function of CO₂ concentration in the aqueous solution. On the basis of a simple model of foreign particles, qualitative simulations were performed to describe hydrate formation in porous media. The Avrami-Kolmogorov exponent evaluated from these simulations varies substantially with the volume fraction occupied by the foreign particles.

Depressurization-Induced Gas Production from Class 1 and Class 2 Hydrate Deposits

George Moridis

Abstract

Class 1 hydrate deposits are characterized by a Hydrate-Bearing Layer (HBL) underlain by a two-phase zone involving mobile gas. In Class 2 deposits, a mobile water zone underlies the hydrate zone. In this study of depressurization-induced gas production from such deposits, we determine that large volumes of gas can be readily produced at high rates for long times using conventional technology. To avoid blockage caused by hydrate formation in the vicinity of the well, wellbore heating is a necessity during production.

Dissociation in Class 1W deposits (involving water and hydrate in the HBL) proceeds in distinct stages, while it is continuous in Class 1G deposits (defined by water and gas in the HBL). These hydrates are shown to contribute significantly to the production rate (up to 65% and 75% for Class 1W and 1G, respectively) and to the cumulative volume of produced gas (up to 45% and 54% for Class 1W and 1G, respectively). Large gas volumes can be produced from Class 2 hydrates, but the continuously increasing gas production attains a substantial rate after a long lead time. Additionally, the permeability of the confining boundaries plays a significant role in Class 2 deposits.

Production from Class 1 (and, to a lesser extent, from Class 2) deposits leads to the emergence of a second dissociation front (in addition to the original ascending hydrate interface) that forms at the top of the hydrate interval and advances downward. Capillary pressure effects lead to hydrate lensing, i.e., the emergence of distinct banded structures of alternating high-low hydrate saturation, which form channels and shells and have a significant effect on production.

Spectroscopic Measurements on Mixed-Gas Molecules in the Clathrate Structures

Tsutomu Uchida

Abstract

Components of natural gas, methane (C1), ethane (C2), propane (C3) and iso-butane (C4) can form gas hydrates when they exist with ice or water. The systematic preparations of mixed-gas hydrate samples (C1-C2, C1-C3, C2-C3, C1-C2-C3, and C1-C2-C3-C4) with powdered ice were carried out to reveal the enclathration process of each guest molecule during the hydrate formation, thus the fractionation of gases. Powder X-ray diffraction analysis in the cryo-system (at about 150K and 0.1 MPa) determined the crystal structure of the prepared sample. Microscopic Raman spectroscopic analysis on these samples measured at about 120K and 0.1 MPa provided the useful information about the guest molecule enclathration into various cages. Gas chromatographic analysis on feed gases and the gases retrieved from hydrate samples supported the spectroscopic measurements. These results revealed the preferential cage occupancies of each molecule, and indicated that it determined the hydrate structure in the system. Collection of Raman spectra of guest molecules in these hydrate samples together with in various phases of pure system also useful for the natural sample analysis via this spectroscopic technique, which provides the characteristics of included guest molecules in the specific cage structure.

Morphology of Natural Gas Hydrate Crystals

Peter Englezos

Abstract

While the determination of the phase boundaries of gas hydrate forming systems can be accomplished experimentally and computationally in a rather straight forward manner the kinetics of the phase transition is still a challenging task. This is because gas hydrate formation is a “poorly” observable multicomponent, multiphase crystallization process at pressures above atmospheric (in majority of systems). Several microscopic and macroscopic techniques are have been employed by various researchers. In this work we will present results based on morphological observations of natural gas hydrate forming systems.

Does Gas Escape from Gas Hydrate Deposits?

Charles K. Paull

Abstract

A lively debate is underway over whether methane release from gas-hydrate reservoirs and Earth's climate are connected. At issue is whether enough methane can be released to the ocean from gas reservoirs at shallow depths within continental margin sediments to alter the composition of the ocean and/or atmosphere. Marine slope failure involving methane-gas-hydrate-bearing sediments is one mechanism for releasing enormous quantities of methane to the ocean and atmosphere. The Storegga Slide, off Norway is the largest continental margin slope failure scar believed to occur in sediments that may have initially contained gas hydrate. To evaluate the fate of gas and gas hydrate originally contained within these sediments, pore water sulfate gradients (a proxy for methane in the subsurface) were measured in cored sediments associated with the Storegga slide events. These measurements suggest that a considerable inventory of methane occurs in sediments adjacent to, and unaffected by, the Storegga slide events, but indicate that methane is notably absent from sediments on the sole of the slide and the distal deposits created by the slide events. Thermal warming is another mechanism to release methane from gas hydrate deposits. The Arctic shelf is currently undergoing dramatic thermal changes caused by the continuing warming associated with the Holocene sea level rise. During this transgression comparatively warm waters flooded over cold permafrost areas of the Arctic Shelf. The resulting thermal pulse is still propagating down into the submerged sediment and should be decomposing gas hydrate as well as permafrost. A search for gas venting from the Arctic seafloor focused on pingo-like-features (PLF) on the shelf of the Beaufort Sea. Cores collected from PLF were systematically elevated in methane concentrations and ROV observations revealed that streams of methane bubbles are coming from the crests of PLF, potentially from decomposing gas hydrate deposits at depth.

Laboratory Exploration of Microbial Growth on Methane Hydrate

Douglas H. Bartlett

Abstract

We are pursuing laboratory-based studies of anaerobic methane oxidation (AMO) using synthetic methane hydrates as the principal carbon and energy source. Bioreactors of approximately 700 cc volume have been inoculated with artificial seawater and AMO sediments from Hydrate Ridge, Cascadia Margin. These samples have been maintained at 4 or 8°C and pressurized with methane to values above the hydrate stability field. In order to enrich for the microbes of interest, a number of cycles of hydrate decomposition, medium replacement and culture re-growth have been performed. Geochemical, microbiological and molecular biological experiments indicate that it has been possible to maintain microbial consortia capable of AMO for more than two years in this system. Geochemical data includes measurements of the build up of sulfide and alkalinity and the loss of sulfate and calcium (due to carbonate precipitation) over time. The apparent sulfate reduction rate in the bioreactors was as high as 3.5 micromoles cc-1 day-1, which is in good agreement with previous Hydrate Ridge measurements. Decreasing the methane pressure to below the hydrate stability field resulted in a large decrease in the rate of sulfide accumulation and alkalinity production. Fluorescence in situ hybridization experiments indicated that after close to two years time the ratio of Bacteria:Archaea was approximately 10:1 in the fluid portion of the bioreactor. 16S rRNA-based phylogenetic analyses of sediment samples indicated that over the course of the bioreactor enrichments a dramatic decrease in the diversity of Bacteria took place with low temperature hydrocarbon-associated clostridia dominating and *Desulfobacterium* also being present. The Archaea at the later time points were mostly relatives of *Thermoplasma* and ANME-1. We are currently examining the phylogenetic distribution of the microbial populations associated with the sediment, medium and hydrate fractions. This research is addressing the interplay between hydrates and microbes and is pursuing the enrichment of more defined microbial communities with which to study the nature of AMO.

Effects of Biogeochemistry and Clathrate Hydrates on Ocean Warming

C. Aaron Lai

Abstract

Through photosynthesis within euphotic layer and other biochemical processes in deeper water, global oceans produce large amount of organic and inorganic materials. Those materials have stored the original light energy from Sun as chemical energy that passes on to species in marine food web. Biogeochemical processes for degradation in deep water eventually produce several small gas molecules like methane, ammonium, carbon dioxide that can be engaged in hydrates in right environments. Clathrate hydrates are crystalline of water molecules forming lattice cages within which there are guest gas molecules. Ocean explorations revealed a huge reserve of marine methane hydrate (MH) worldwide. This writer speculates that there is also a significant amount of other hydrates in seawater. MH floats in seawater. The dissociation of hydrates takes place within a range of ambient temperature and pressure (or depth). Different hydrates dissociate within different layers of seawater. Clathrate hydrates preserve those guest gas molecules from chemical reactions. When gas hydrates dissociate, they release gas bubbles that drift with ocean currents. This provides the time for bacteria to utilize those gas molecules as mass and energy sources. The oceans are getting significantly warmer than ever while the melting of Arctic Ocean sea ice is accelerating. Studies show that the thermal forcing to the oceans due to enhanced atmospheric greenhouse effect alone cannot explain the magnitude of the change of ocean heat content and the broad scale warming of seawater at intermediate depths. The writer analyzed WOCE and GEOSECS ocean geochemistry data. This paper presents a mechanism leading to the ocean internal heat generation that explains the magnitude and the layers of warming in seawater. The two most important concepts raised are: (1) the biogeochemical processes and the formation and dissociation of gas hydrates essentially redistribute the energy absorbed at sea surface to certain layers of seawater, (2) the ocean warming might be the key mechanism leading to global climate change.

APPENDIX IV

HYDRATE CLASSIFICATION

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HYDRATE CLASSIFICATION

In terms of characteristics and behavior (which, in turn, dictate production strategies), hydrate accumulations can be divided into three main classes. Class 1 accumulations (Figure 1) comprise two zones: the hydrate interval (often exhibiting a very low effective permeability because of the presence of large hydrate saturations in the pore space), and an underlying two-phase fluid zone with free (mobile) gas. In this class, the Bottom of the Hydrate Stability Zone (BHSZ) usually coincides with the bottom of the hydrate interval. In terms of gas production, this is the most desirable class for exploitation because of the hydrate thermo-dynamic proximity to the hydration equilibrium (necessitating only small changes in pressure and temperature to induce dissociation).

Class 2 deposits (Figure 2) feature two zones: a hydrate-bearing interval, overlying a mobile water zone with no free gas (e.g., an aquifer). Class 3 accumulations (Figure 3) include a single zone, the hydrate interval, and are characterized by the absence of an underlying zone of mobile fluids. In Classes 2 and 3, the entire hydrate interval may be well within the hydrate stability zone, i.e., the bottom of the hydrate interval does not mark the bottom of the hydrate stability zone. Thus, in Classes 2 and 3, the BHSZ can be as high as the bottom of the hydrate interval (the highest possible BHSZ elevation). However, in general, the BHSZ is below the bottom of the hydrate interval. The desirability of Class 2 and 3 accumulations as gas production targets is less well defined than for Class 1 deposits, and can be a complex function of several issues, including thermodynamic proximity to hydration equilibrium, initial conditions, environmental concerns and economic considerations.

Classes 1 to 3 can be encountered in either permafrost or marine systems. Another possible class of hydrate deposits is Class 4, which involves disperse, low-hydrate-saturation (<10%) sediments in marine systems.

RELATIVE PRODUCTIVITY OF HYDRATE CLASSES

For the same thickness of the hydrate-bearing zone, the following preliminary observations can be made on the subject of relative productivity of the various classes:

- (1) Class 1: Millions of ST m³/day (depressurization).
- (2) Class 2: Hundreds of thousands to millions of ST m³/day if impermeable confining boundaries; Hundreds of thousands of ST m³/day if slightly permeable overburden and impermeable underburden; Hundreds to thousands of ST m³/day if permeable overburden and deep water zone.
- (3) Class 3: Thousands to tens of thousands of ST m³/day if the hydrate saturation is sufficiently low (usually below 50%) to allow depressurization. Hundreds to thousands of ST m³/day if the hydrate saturation is too high (>50%) to allow depressurization, in which case thermal stimulation is the only option.
- (4) Class 4: <10 of ST m³/day using depressurization (thermal stimulation cannot even be considered).

ISSUES THAT NEED TO BE ADDRESSED

- (1) Geological boundary conditions of the various classes, and characteristics of the confining overburden and underburden.
- (2) Possible conditions of hydrates acting as an impermeable gas cap (an issue and a potential problem in marine systems).

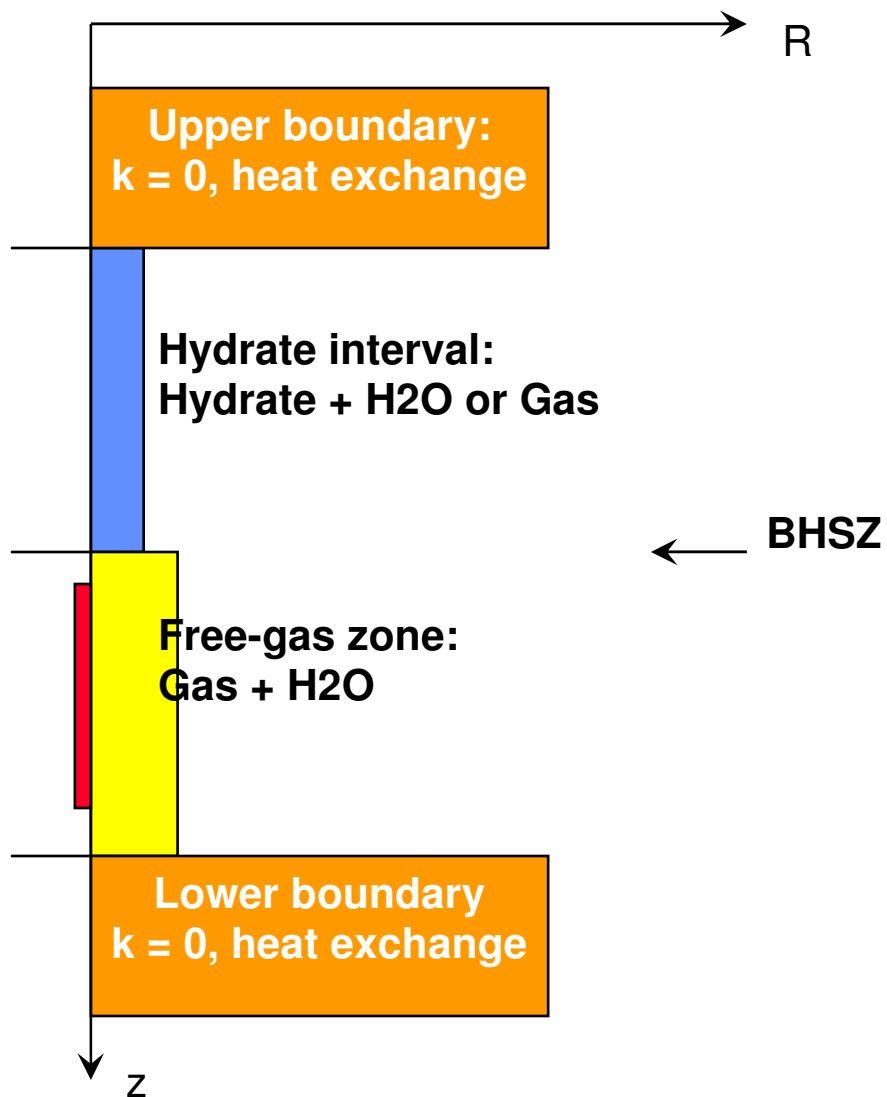


Figure 1. An example of a Class 1 hydrate accumulation.

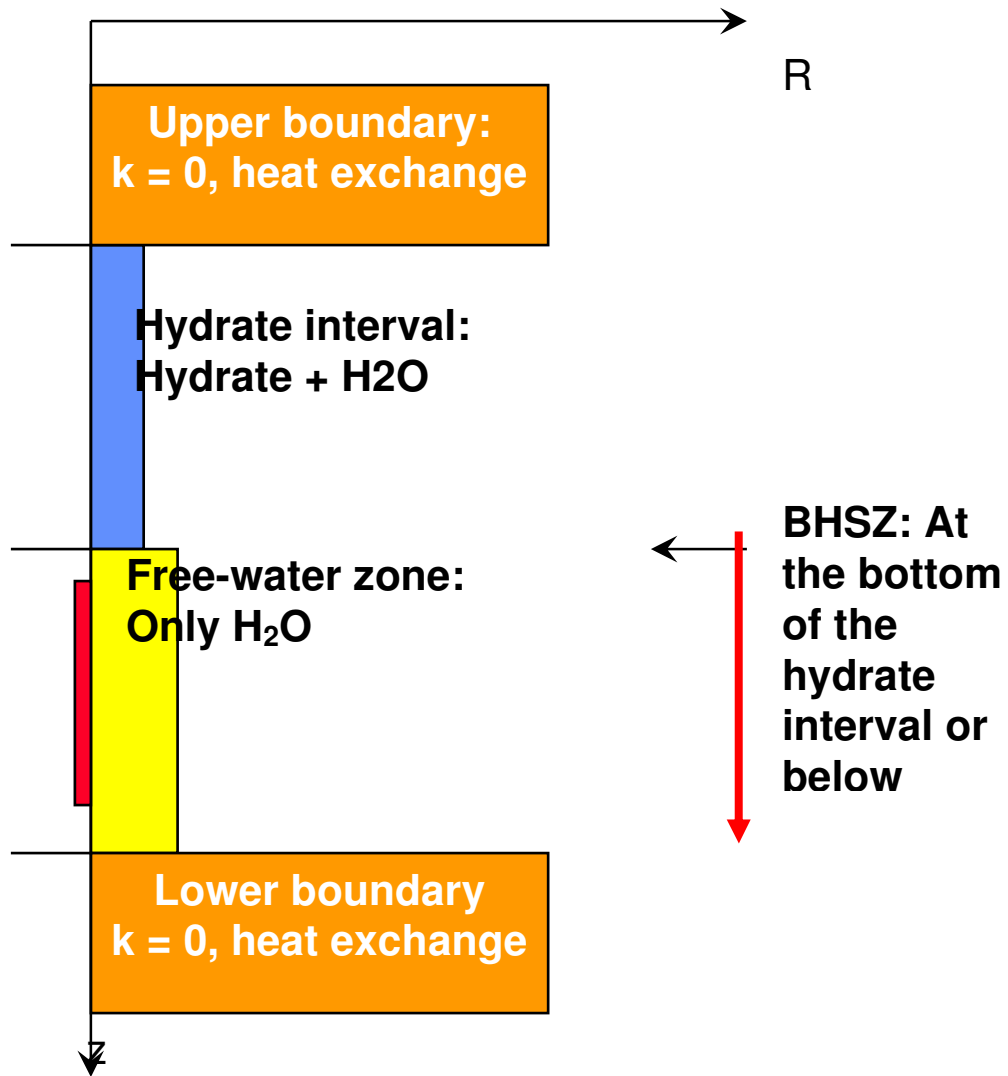


Figure 2. An example of a Class 1 hydrate accumulation.

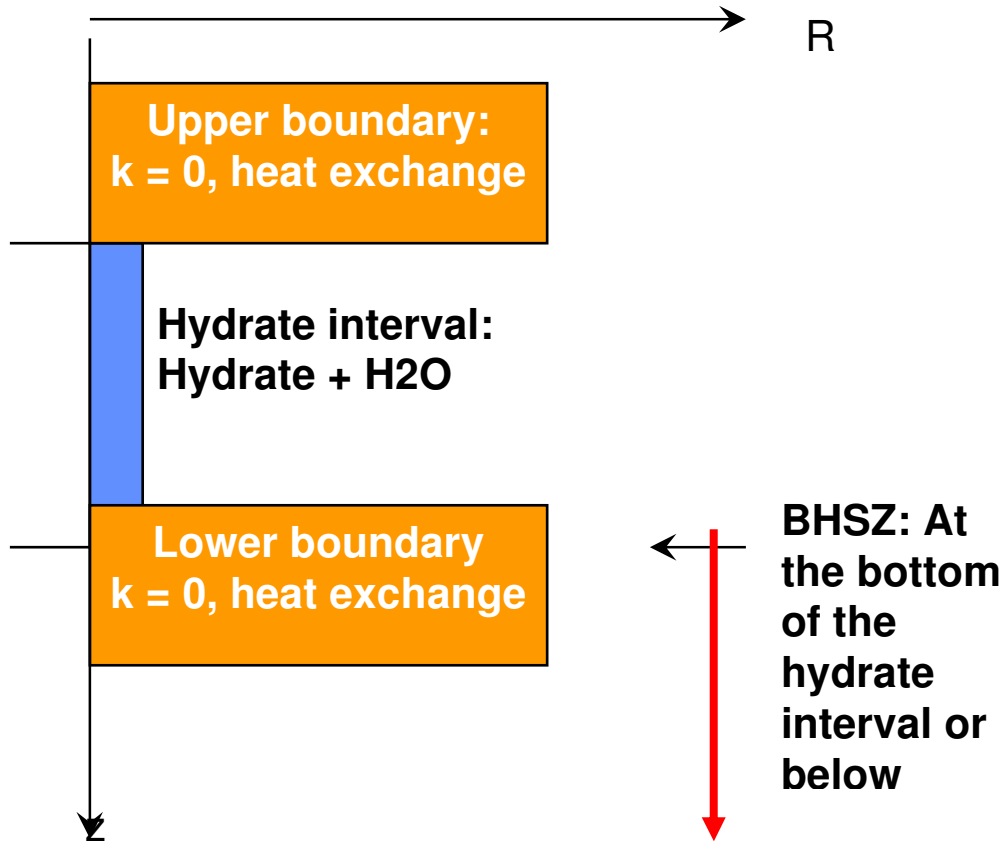
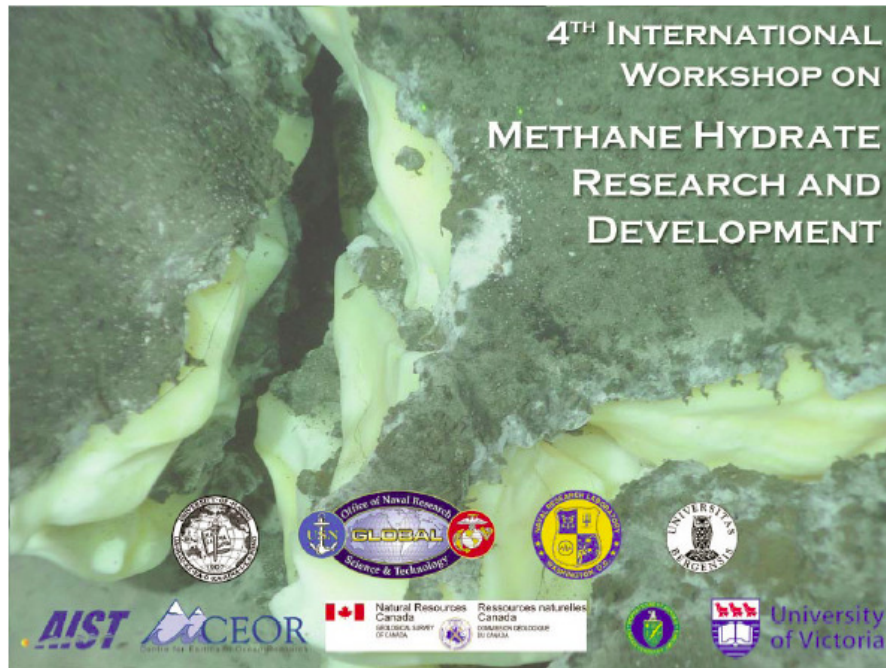


Figure 3. An example of a Class 3 hydrate accumulation.

APPENDIX V

A BRIEF OVERVIEW OF:

4TH INTERNATIONAL WORKSHOP ON METHANE HYDRATE RESEARCH AND DEVELOPMENT VICTORIA, BC, CANADA MAY 9-11, 2005



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Overview

The Fourth Workshop of the International Committee on Gas Hydrates Research and Development was held during 9-11 May 2005 in Victoria, British Columbia, Canada. Invited national agency representatives and international researchers from university, government, and industry convened to assess research priorities and to promote international collaboration on methane hydrate research. The 2.5-day workshop included plenary lectures and panel discussions, conducted as a working event where all participants engaged in open discussions to develop collaborative methane hydrate studies. The workshop was organized by the Centre for Earth and Ocean Research at the University of Victoria, Victoria, British Columbia, Canada; the Marine Biogeochemistry Section at the Naval Research Laboratory, Washington, DC, USA, the Hawaii Natural Energy Institute of the University of Hawaii, Honolulu, Hawaii, USA and in cooperation with the Institute for Energy Utilization, AIST, Hokkaido, Japan; the Department of Physics and Technology at the University of Bergen, Bergen, Norway; the Office of Naval Research - Global; the Geological Survey of Canada and the United States Department of Energy.

This series of annual international methane hydrate research and development workshops was initiated during March 2001 at the University of Hawaii. Subsequent workshops have been held in Washington, DC, USA and Vina del Mar, Chile. At the previous three meetings, the focus was on presentation of research results on selected hydrate themes, and description of national hydrate research programs. The workshops have resulted in international field and laboratory collaborations between US, Canadian, Japanese, Chilean and German scientists working on methane hydrate exploration off the coasts of the US, Canada, Chile and Japan.

At the Victoria workshop, the objective was more ambitious. A primary goal was to begin discussions on developing plans for continuing the collaborative scientific work among the nations. It is our conviction as organizers of the workshop that the national research programs could greatly benefit by combining resources to carry out experiments, and sharing the results of the research. The workshop was organized

around four themes that included: 1) Methane Hydrate Resource Characterization and Distribution, 2) Methane Hydrates Kinetics, Dissociation and Biogeochemistry, 3) Environmental Concerns: Seabed Stability and Ecosystem Health, 4) Methane Hydrate Future Development.

I. INTRODUCTION:

The **4th International Workshop on Methane Hydrate Research and Development** was held in Victoria, BC, Canada from May 9-11, 2005. The Workshop organizers were Dr. Ross Chapman, Center for Earth and Ocean Research (CEOR) at the University of Victoria, Victoria, British Columbia, Canada, Dr. Richard Coffin, Marine Biogeochemistry Section, US Naval Research Laboratory, Washington DC and Sonia Wolff, Assistant Director, Office of Naval Research Global LA.

The Workshop was sponsored by the Center for Earth and Ocean Research at the University of Victoria, British Columbia, Canada; the Marine Biogeochemistry Section at the Naval Research Laboratory, Washington, DC, USA; the Hawaii Natural Energy Institute of the University of Hawaii, Honolulu, Hawaii, USA; and in cooperation with the Energy Technology Research Institute, AIST, Japan; the Department of Physics and Technology at the University of Bergen, Bergen, Norway; the Office of Naval Research-Global; the Geological Survey of Canada and the United States Department of Energy. Building on the success of the three previous international workshops on methane hydrates, this workshop was seen as an excellent opportunity to promote open discussion to identify the most important questions in hydrate research that can be addressed by collaborative international experiments.

The workshop included plenary lectures and open discussions in breakout sessions that were conducted as a working event where all participants had the opportunity to contribute. The objectives at this meeting were to promote open discussion to identify knowledge gaps in hydrate research, and set research priorities that could be addressed by collaborative international experiments. It was our conviction as workshop organizers that the national research programs could greatly benefit by combining resources to carry out experiments, and by sharing the results of the research.

The breakout sessions were organized in four theme topics. The discussions in each group were facilitated by a session leader, who was assisted by a rapporteur to record the discussions that took place. The theme topics included:

1. ***Methane Hydrate Resource Characterization and Distribution***: This session focused on current hydrate exploration in marine and arctic environments. In addition to surveys of the hydrate characterization and distribution, session topics included geophysical, geochemical and biological parameters that are relevant to the field survey.

- Session Chair: Dr. Warren T. Wood, Geophysicist, Marine Geosciences Division, U. S. Naval Research Laboratory

2. ***Methane Hydrates Kinetics, Dissociation and Biogeochemistry***: This session was intended to combine laboratory, field and theoretical

investigations of physical, chemical and biological influence on hydrate stability, molecular content and lattice saturation.

- Session Chair: John Ripmeester, Group Leader, Steacie Institute of Molecular Sciences, National Research Council of Canada

3. ***Environmental Concerns: Seabed Stability and Ecosystem Health:*** Research topics in this session included the influence of coastal hydrates on industrial platform stability, ocean carbon cycling, global warming and coastal inhabitant safety. Research focus between the nations was to be integrated to address this broad range in topics.

- Session Chair: Frederick Colwell, Microbiologist in the Biotechnology Department at the Idaho National Laboratory, operated by Battelle Energy Alliance

4. ***Methane Hydrate Future Development:*** Discussions during the three previous International Workshop on Methane Hydrate R & D have revealed different national focuses in hydrate research. Efficient integration of research between nations requires incorporation of the national goals within the collaborative research plan. This session combined discussion on the participants' research objectives and the intermediate steps to accomplish the goal.

WORKSHOP SUMMARY

A. Summary of the Breakout Topic Discussions.

The 4th Workshop on International Collaboration on Methane Hydrate Research and Development was intended to facilitate the organization of field and laboratory research collaborations among international partners. Workshop presentations and discussions through all sessions were organized to enhance the discussion of knowledge gaps in gas hydrate research, integrate global perspectives on methane hydrate research themes in different nations, and initiate plans to integrate field exploration, laboratory experiments, and theoretical modeling. Discussions and planning were conducted on the basis that new funding will not develop for this program but cost and technology sharing, associated with database development under the different national focuses could enhance each interested researcher's program activity. There were four general topics: 1.) methane hydrate resource characterization and distribution; 2.) methane hydrate kinetics, dissociation and biogeochemistry; 3.) environmental concerns including seabed stability and ecosystem health, and 4.) future development of methane in hydrates as an energy source. Sharing in this effort during the discussions included available data, international expertise, methods and technology, results and models. The workshop format was initial discussion of the four

themes, individual theme breakout discussions, and integration of the themes for concluding remarks.

The open discussions during the breakout sessions introduced detailed information about several current and planned hydrate research programs that was shared with all the participants. This information provides the basis for establishing new collaborations. The concluding plenary session focused on establishing an effective mechanism to sustain the interactions that were developed at the workshop, and provide a means for disseminating new information. The active projects discussed are listed below with lead scientists to contact for further discussion. This summary is not intended to provide an overview of research by all scientists in this field and working in the regions mentioned. Instead, it is intended to provide the potential for researchers that participated in the workshop to expand collaborations, share technology and platform support. Regions discussed for potential collaboration include, the Texas-Louisiana Shelf in the Gulf of Mexico, Cascadia Margin along southwestern Canada, the mid Chilean Margin, several regions off Western Europe and the coast of New Zealand.

The general consensus for future development of international methane hydrate research was that the priorities include resource assessment, environment and platform hazards, industrial processes, climate change, material storage and media transport. The potential for success in this effort is sharing the current activities, knowledge and opportunities in scientific, industrial, political, social and economic contexts. The international plan for the goals of the developing program needs to include integration of the national deliverables, sharing opportunities, sharing the exploration data base, forming stronger linkages between the scientific and industrial communities. An international broadcast of this activity could provide effective lobbying with government and industry in different nations. Success of this international effort would result in the formation of a new gas hydrate exploration paradigm.

With the development of an international program there is a broad base of shared knowledge gaps on scientific, financial, cultural and political topics. In terms of science and exploration technology there is paucity of quality, pertinent field observations. There is a limited database on the spatial and temporal hydrogeology of methane hydrate bearing systems. While seismic surveys for BSR distributions are the primary approach for preliminary hydrate surveys it has been well established that hydrates are present in sediments where the BSR is not detected. There is a strong need for a more thorough survey of the diffusive vs. advective flux in sediments. Surveys need to address the changes in hydrate systems through time dependent thermal regimes. Models for seismic velocity to predict hydrate content in sediments need evaluation for application to fine and coarse grain variation. Further development of electric resistivity coupled with the seismic surveys could enhance the capability to quantify hydrate distributions. Biogeochemical influence on the methane hydrate formation, stability and cage occupancy needs more basic research. Further development also needs to include understanding of the geotechnical behavior of hydrate bearing sediment in terms of sediment strength, dynamics and statics. There is also a need for interaction between field programs and laboratory research, since the

results from laboratory experiments are not always applicable to natural environments. This occurs because simulation of natural gas hydrate in the lab is extremely difficult, and hydrologic measurements are difficult to obtain *in situ*. Standardized laboratory methods will help to compare the experimental database.

A major limitation in the field program for methane hydrate exploration is the sampling techniques for in situ data acquisition. In situ pressure cores would provide samples for thorough physical, chemical and biological parameters. Analytical instruments on the pressure cores would further advance the in situ database. There is a need to test and calibrate new seismic survey tools. This effort could provide better 3-D mapping and initiation of 4-D mapping of hydrate distributions. A need stated during discussions included investigation of shear wave properties of hydrate bearing sediments, as a means to determine anisotropic variation in the sediment permeability. Long term surveys at monitoring stations in dynamic regions with in situ data acquisition will start to access variations in methane fluxes and hydrate bed stability.

Many programs in methane research are undermanned and do not have a critical mass to address multidisciplinary research questions. There are strong “language barriers” between the science and industrial communities. Biases on individual national goals will impede the international development. The international development of this topic needs to combine consensus in the research focus and priorities. An increase in the international collaboration will increase the necessary critical mass. Specific approaches for enhancement of the international collaboration that were presented during the discussions included comparisons of local geology in the gas hydrate formation, an integration of laboratory experiments with models, and a combination of the applied methane hydrate exploration with basic science topics. Experiments and field sampling needs to be designed to obtain data that addresses the temporal aspects of hydrate stability, hydrate physical property parameter changes during formation and destabilization, biological cycling of methane and the result of methane flux into the water column and atmosphere.

B. Current and Future Sites for Methane Hydrate Collaboration.

1. **Cascadia Margin:**
2. **Mid Chilean Margin:**
3. **Coast of New Zealand:**
4. **Texas-Louisiana Shelf:**

Summary of NRL Science Objectives

We seek to understand the mechanisms and habits of methane emplacement at seafloor seeps through detailed seismic, thermal, chemical and biological constraints on numerical simulations of methane flux. Because of the strong affect of gas on acoustic

wave propagation, DTAGS seismic imaging constrains the spatial extent of gas with an accuracy of 1-2m over scales of 100s of meters vertically and laterally. In a methane hydrate system, the gas/no-gas boundary can frequently be used to infer the broad scale (10s to 100s of meters) thermal regime within the sediment. Individual thermometry measurements not only aid the constraint of the thermal regime but also constrain the fluid flux. The thermal gradients over the seep constrain the heat flux that, with knowledge of the fluid temperature and heat capacity, can be used to determine the overall fluid flux. Combining the temperature, pressure, and fluid flux throughout the system with methane solubility yields constraints on methane transport from the sediment to the ocean. The methane flux is also constrained by direct chemical measurements of methane in cores, or more frequently, sulfate gradients that indicate the depth to methane in the system. Measurements of the micro-biota within local reservoirs of methane gas and hydrate will constrain the styles and rates of production and consumption of methane in its various stages of flux and residence in the seep system. The NMR measurements, by detecting the amount of liquid water in a given sample (and how that changes as any hydrate in the sample dissociates) constrain the hydrate concentration within a sample, and where the hydrate is forming within the sediment pores, (important for how the hydrate affects the sediment acoustics).

Although several seep sites have been studied in detail with many techniques, some similar to the ones we have used and plan to use, we know of no sites where measurements of such detail have been brought together comprehensively with the hydrology to quantify the methane emplacement and flux through the seafloor.

NRL Approach: Observations as Constraints on Numerical Models

The development of a completely new model was considered beyond the scope of the current ARI. Therefore, we intend to achieve the modeling objectives by breaking the problem into smaller, tractable problems. Two approaches to modeling are currently being used, a more standard, finite element package, and a more developmental technique based on lattice gas. The finite element code SUTRA, developed by the USGS has been used in preliminary modeling of fluid conduits to determine the extent to which heat transport via fluid advection perturbs the methane hydrate stability zone. In this work the seismic image, due to its acute sensitivity to gas, is used to constrain the extent of gas below the seafloor. In some cases this gas boundary marks the interface between free gas and methane hydrate, and can be used to identify the PT boundary associated with the base of methane hydrate stability. The lattice gas technique generates 3-D simulations of methane-pore water flux through complex, micro-scale media, thus modeling the faults and conduits observed in sediments.

1. Time Dependence – There is a great deal of evidence to suggest that nearly every measurable quantity at seeps is time dependent on one or more time scales. The timing of our measurements is intended to mitigate the time dependence, but time dependence but be considered in the final interpretation. The low thermal diffusivity of saturated sediment works to smooth out the decadal and shorter scale temporal variations in the isotherms affecting the base of gas hydrate stability. Only small (<10s

of meters) perturbations may occur over short (years) time intervals. The highly localized thermal and chemical measurements should be acquired as close in time as possible to mitigate the temporal variability. A series of measurements at a single site would certainly aid our understanding of emplacement mechanisms, but because the ARI was proposed with a single field effort, no attempt has been made to include a series of measurements (requiring multiple mobilizations) at a single site over a period of time.

2. Contribution from High Resolution Seismic (DTAGS) - For almost two decades NRL has maintained a unique deep-tow seismic capability. The Deep-Towed acoustics/Geophysics System (DTAGS) provides high resolution (~2-3 m) images of the seafloor that provide outstanding constraints for modeling. The high vertical resolution results from the 200-1000 Hz source (whose signature remains constant in any water depth) and the high lateral resolution results from towing the system only a few hundred meters off the seafloor, even in water depths of several km.

The value of the seismic data in studying gas hydrate is several fold. Seismic images show faults (identifiable by disjoint layering), where fluid, heat, and methane flux are most likely, as well as free gas accumulations within the sediments, constraining the equilibrium hydrate stability boundary. The image can also shows features in the section such as basement highs or buried relict conduits that may have significant effects on the interpretation (and modeling) of the chemistry and temperatures measured at the seafloor. Further, the image can provide information on the seafloor reflectivity (within the wavelengths used) constraining the extent of such phenomena as carbonate pavements or debris fields. In addition to the image the multichannel nature of the DTAGS data can be used to constrain sediment sound speed velocities, diagnostic indicators of gas and gas hydrate.

3. Geochemical Evaluation - Although seismic surveys are a common approach for evaluation of marine hydrate distribution, the target phase (solid hydrate) is not sensed directly, but is inferred by the presence of a BSR. Complementary analysis of biogeochemical and seismic data is being evaluated to assist in the survey of sediment gas hydrate deposits. Ninety percent of methane generated in anoxic marine sediments is removed through the anaerobic oxidation of methane (AOM) in shallow sediments (3-15 m) by a syntrophic consortium of methanogenic *archaea* and sulfate reducing bacteria (SRB). Evaluation of subsurface gas hydrate based on shallow sediment geochemical gradients of AOM metabolites (i.e., sulphate and methane profiles) is based on the assumption that the gradients are related to migration of gas from a deep seated (200-400m) gas hydrate reservoir. For this approach sulfate profiles from piston core porewater samples are surveyed to determine AOM in shallow sediments. The AOM occurs through the following reaction:



This process occurs in sediments at the SMI where downward diffusing seawater sulfate encounters dissolved methane diffusing or advecting upward. Above this location, sulfate concentrations increase to seawater concentrations at the sediment-

water interface, while below, methane concentrations increase due to on-site methanogenesis or diffusion and advection from deeper microbial or thermogenic sources. The vertical methane diffusion through piston core profiles is calculated with measurements of sulfate gradients. Sulfate is conservative during the core sampling and provides a 1:1 ratio during the oxidation of methane with the reduction of sulfate to sulfide. Diffusive flux calculations from the linear sulfate porewater profiles are applied according to Fick's first law assuming steady state conditions,

$$J = -\phi \cdot D_s \cdot \frac{dc}{dx}$$

where J represents the sulfate flux ($\text{mmol m}^{-2} \text{a}^{-1}$), ϕ is the sediment porosity, D_s is the sediment diffusion coefficient, c is the range in sulfate concentration and x is the range of the linear section of the sulfate profile in the piston core. D_s is calculated assuming a tracer diffusion coefficient for sulfate where,

$$D_s = \frac{D_0}{1 + n(1 - \phi)}$$

as D_0 is assumed to be $8.7 \times 10^{-5} \text{ cm}^2 \text{ s}^{-1}$, n varies between 1 and 3 depending on the sediment composition, and ϕ , the sediment porosity, can be measured through the sediment cores.

4. Biogeochemical Evaluation – Biogeochemical parameters are incorporated in the sediment core and porewater profiles to understand the methane source and biological cycling. Geochemical and molecular biological analysis of piston core porewaters and sediments addresses the hydrate content, lattice saturation and stability; methane source and biological influence on the methane concentrations. Topics addressed in current research projects include:

- Refined geophysical, geochemical and microbiological technologies for prospecting hydrate content and distribution.
- Contribution to definition of high-priority geographical areas of prospective interest.
- Diagnoses of the possible environmental effects and geologic risks at the continental margin associated with the natural resource occurrence and resource exploitation.
- Contribution to understanding the biogeochemical parameters and associated microbial community diversity in shallow sediments that influences the porewater methane and sulfate cycling and resulting sulfate gradient observed through anaerobic methane oxidation.

5. Heatflow - Thermal data collected in the upper few meters of the seafloor using a heatflow instrument has proven to be a reliable provide a proxy for fluid flow and

helps define the limits of active flows around methane seeps and mud volcanoes associated with methane seeps and hydrates. The heat flow instrument used is a 3.5-meter-long “violin bow” or “Lister-type” instrument (Hyndman et al., 1979). Eleven thermistors are arranged 30 centimeters apart in a 1-cm-diameter tube held in tension parallel to a solid steel strength member. There is also a temperature sensor mounted on the top of the weightstand which records the water temperature near the sediment-water interface. The system measures both temperature gradient and thermal conductivity in-situ. Sediment temperatures are calculated from the decay of the frictional heat caused by penetration of the instrument into the sediment. Thermal conductivity is determined from the decay of a calibrated thermal pulse applied after a preset period of time (Villinger and Davis, 1987). Heat flow values were determined at each station by computing thermal resistance values at each thermistor,

$$R = \int (1/\lambda) dz,$$

where λ is the thermal conductivity. In a situation of steady-state conductivity the heat flow is equal to the slope of the line on a Bullard Plot, a plot of temperature vs. thermal resistance. For each station, any non-linear data that might be attributed to bottom water warming or cooling affects, is removed so as not to bias the statistics. A heat flow value is determined from the slope of the best-fitting linear least-squares line through the remaining data. All heat flow values are corrected for instrument tilt.

High resolution transects are done over the seeps and mounds in order to get an accurate sampling of where elevated thermal signatures. Stations are typically stationed no more than 100 meters apart since it has been our experience that the fluid flow associated with seafloor seeps is relatively distinct and confined in lateral extent. Data typically show clear anomalies in sediment temperature and heat flow associated with the mounds and seeps.

5. Electromagnetics - Electrical conductivity of the oceanic crust and overlying sediments is mainly controlled by the presence of conductive fluids. The presence of gas hydrates and free gas within the hydrate stability zone is known to change physical parameters such as electrical conductivity and shear modulus. In hydrated zones the salt water is replaced by insulating gas hydrate or free gas and the bulk resistivity rises. Hydrocarbon vent sites, such as the Bullseye vent on the Cascadia Margin, are associated with significant resistivity anomalies.

Electrical conductivity in the hydrated zone can be measured using a controlled-source electromagnetic (CSEM) system. The system consists of an EM dipole source, and an array of 2-component electrometers. The array aperture controls the depth of penetration of the electromagnetic signal beneath the sea floor. CSEM arrays can examine both the region above the BSR, in the hydrate zone, and the underlying plumping and methane transport, as well as its evolution in time.

6. Laboratory Approaches to Enhance Field Studies - This section is based on the example provided from the Materials Structure and Function Group at the National

Research Council in Ottawa, Canada. For some years now, the Materials Structure and Function Group at NRC has made an effort towards establishing a protocol for the analysis of natural hydrate samples, and to help establish a database on natural gas hydrate properties. Since the science of natural gas hydrates is a complex multidisciplinary area of research, the group establishes connections with field researchers that have recovered natural gas hydrates or plan to do so. The protocol has now developed to a stage where application of the complete suite of techniques now gives a good picture of natural hydrate as a complex mineral, which of course also leads to the possibility of carrying out experiments to model hydrate formation processes in nature. Along with the work on natural samples, the Group does fundamental work on hydrate structures as well as development work to establish new techniques to study hydrate structure, morphology and processes, including methane and hydrogen storage. .

The work is highly collaborative in nature and depends on receiving properly preserved hydrate samples from the field. In the past we have received samples from both Mallik exercises, Gulf of Mexico, Hydrate Ridge, Cascadia (Barkley Canyon and IODP 311). This year we expect to receive samples from offshore India, the South China Sea and the Sea of Japan.

A. Characterization of natural gas hydrates; the idea is to carry out the measurements under controlled conditions to eliminate possible contamination with all measurements taken by subsampling the same recovered material. New techniques are incorporated as necessary to provide new information.

1. Structural determination: using instrumental methods to determine the structure type of natural gas hydrate and the distribution of hydrocarbons over the guest sites in recovered hydrate samples.
2. Measurement of total gas, water and sediment to establish the degrees of saturation and conversion to hydrate.
3. Gas composition measurements: to analyze the compositions of uncontaminated gas of natural gas hydrate with high resolution GC/MS.
4. Isotope analysis – to establish source of hydrocarbons.
5. Sediment characterization – to understand gas hydrate accumulation in nature.
6. Measurement of P,T stability conditions on recovered hydrate.
7. Dissociation of gas hydrate; a variety of issues need to be addressed, preferably on intact recovered samples.
8. To establish the relationship between the physical properties of gas hydrate containing sediments and the amount of gas hydrate. Dissociation properties: to investigate the stability condition and dissociation kinetics of natural gas hydrate in sediments.
9. To determine the kinetics of gas hydrate dissociation under a variety of controlled conditions to simulate natural gas hydrate in reservoirs;
10. To determine connection between thermal input into hydrate formations, hydrate dissociation and the behavior of water and gas released.

11. To examine the presently available methods available to destabilize gas hydrate by evaluating the efficiency of various methods;
12. To develop new methods for the efficient destabilization of gas hydrate.
13. Data Access and Sharing: A major goal for this program is the laboratory and field information sharing. In response to this program goal a proposal, presented by Jan Boon, Natural Resources, Canada, was adopted to establish a dynamic web-based communication mechanism for hydrate researchers within the context of the International Methane Hydrate Research and Development Committee:

Proposal: Gas Hydrate Research and Development Communication System
(presented by Jan Boone – Natural Resources, Canada)

- Vision:
 - Develop an effective, engaged international gas hydrate research community
- Facilitate information exchange of:
 - Current research activities, knowledge and opportunities
 - Key Priorities in research
 - Political, social, and economic context
 - Funding opportunities
 - Communicate successes and the impact of gas hydrate research

APPENDIX VI

OCS RESOURCE MANAGEMENT AND SUSTAINABLE DEVELOPMENT

A REPORT BY:

MMS

U.S. DEPARTMENT OF THE INTERIOR
MINERALS MANAGEMENT SERVICE
OFFSHORE MINERALS MANAGEMENT

SEPTEMBER 24, 1999

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Executive Summary

The United Nations World Commission on Environment and Development (Brundtland Commission) defined sustainable development as “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs.*” In addition, the President’s Council on Sustainable Development maintains that “it is essential to seek *economic prosperity, environmental protection, and social equity* together.” Such an approach entails tradeoffs. On the one hand, economic development inevitably will result in degradation or elimination of environmental resources in some cases. On the other hand, our society already has decided that economic opportunities sometimes have to be forgone or handled very carefully to protect our environmental endowment.

The production and consumption of energy comprise one of the fundamental components of economic development and societal well-being. However, development and use of fossil fuels deplete nonrenewable natural resources. Furthermore, they can entail costs on society, both environmental (e.g., in terms of air and water quality) and social (e.g., in terms of socioeconomic impacts of development on local communities). Therefore, any discussion of sustainable development should consider initiatives in the energy sector. This report is about the efforts of one component of the energy sector, the Offshore Minerals Management Program (OMM Program) of the Minerals Management Service (MMS), to foster a more sustainable future.

While the specific definition of sustainable development used by various groups may differ considerably, two uses of the related term “sustainability” are of special interest. *Environmental sustainability* requires that we leave future generations an environment at least as good as our own. *Economic sustainability* is a broader term that requires leaving future generations no worse off than we are and corresponds to what economists call “non-declining utility.” Either definition can embrace at least some substitution of one set of assets or liabilities for another, so long as the net outcome is better.

Thus, the use of an exhaustible resource is not necessarily inconsistent with the concept of sustainable development. The relevant question becomes not whether something is lost but whether what is gained over a period of generations is worth more than what is lost over the same time period. This paper focuses on what MMS can do, within its mandate and authority, to assure orderly access to resources on the Outer Continental Shelf (OCS), to protect our environment, to improve safety management systems, and to obtain for the public a fair return on OCS resources.

The OMM Program primarily contributes to a sustainable future in two ways. The first way is as a bridge to the future. Until alternative energy sources become viable, obtaining sufficient supplies of fossil fuels at reasonable prices will continue to be crucial to our energy security and the strength of our economy. To the extent society develops

alternative fuel sources and uses the energy and income from fossil fuels to create wealth, rather than for consumption, such use may be considered sustainable.

The second way the OMM Program contributes to a sustainable future is through the creation of wealth. The market value of oil and gas produced, since OCS leasing began in 1953, totals over US\$385 billion. Direct government receipts from that production have totaled over \$126 billion. To that we can add an unknown quantity of profits from the OCS that have added to corporate investment and stockholder wealth. The remainder of the \$385 billion went to pay for labor and goods and services from other industries.

The income generated by oil and gas activities makes it possible for our society to invest in research and development; improve technology and infrastructure; build social programs and public works; finance goods purchases; and, of course, develop, improve, and promote alternative energy including renewable sources.

The OMM has identified several key aspects of sustainable development on which management must continue to focus its efforts to enhance the role of the Program in fostering a more sustainable future. The key aspects are:

- access to resources
- environmental
- safe operations
- conservation of hydrocarbon resources
- economic
- social
- international

Each of these aspects is discussed in some detail in the body of this report.

While the OCS oil and gas program can be an important part of a bridge to a sustainable future, MMS has little influence over energy consumption patterns and the way in which the wealth created by the program is used. Therefore, MMS must focus on those factors within its authority and mandate, which include provision of an orderly process for resource exploration and development, protection of our environmental endowment, and ensuring a fair return to the public for the use of its resources. In the end, the most important contributions MMS can make to the well being of current and future generations are likely to come from its continued efforts to become the best minerals manager possible.

APPENDIX VII

INTEGRATION OF MODELING AND USGS HYDRATE LABORATORY RESEARCH: WORKSHOP REPORT

DENVER, COLORADO
AUGUST 2-3, 2005

PREPARED BY:

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SEPTEMBER, 2005

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Executive Summary

As part of an on-going effort to maintain a research program well integrated and focused on priority problems, the U.S. Geological Survey convened a small workshop on 2-3 August, 2005, to identify how its gas hydrate laboratory studies could be more closely aligned with a growing number of modeling studies. Numerical models dealing with exploration, development, and production of hydrate reservoirs were emphasized because they generally provide understanding of gas hydrates within the context of larger geologic and petroleum (i.e., natural) systems. 29 scientists attended the workshop in Denver, Colorado, representing laboratory experimentalists, numerical modelers, field scientists, and federal managers. Science expertise was multidisciplinary, including geologists, geophysicists, chemists, and petroleum engineers.

The salient recommendations arising from workshop can be grouped into five research directions. Behind these research directions are three assumptions: (a) the focus is on methane hydrate; (b) collaborations among academia, industry, national laboratories, the U.S. federal government and foreign governments (e.g., Japan, India, China, Germany etc.) are essential; and (c) developing shared, distributed databases of hydrate measurements, such as supported by the International Council for Science, Committee on Data for Science and Technology (CODATA) represents an important step forward in making data available to researchers and others interested in hydrate problems.

(1) Measure the dynamics of transport and transient processes in the gas hydrate reservoir system: This research involves understanding time- and space-dependent processes that affect measurements and predictions of parameters such as hydrate saturation, formation permeability, dissociation rates, and thermal properties. Systematic laboratory measurements, iterative modeling studies, and bore-hole field testing/monitoring are essential to advance this research direction.

(2) Better understand how current lab-core-logging measurements represent in-situ natural conditions: Recurring concerns in the workshop were whether cores that have come out of the hydrate stability zone during collection or synthetic laboratory hydrate-sediment mixtures that are made under water-limited conditions are actually representative of natural, in situ systems. This raises the possibility that parameters obtained from these kinds of studies may not be appropriate to use in numerical modeling simulations. There also remains a gap in researchers' ability to scale from confined, well controlled laboratory situations to large, heterogeneous natural conditions.

(3) Continue basic characterization at laboratory and field scales: Among the properties that remain priorities for better parameterization are elastic and thermal properties, especially at in-situ reservoir pressures and temperatures. Measurements on low hydrate saturation systems (especially in fine-grained sediments) are relatively

sparse. Some properties may be important to hydrate dynamics but are not currently measured (e.g., capillary pressure, specific surface).

(4) **Endorse the code-comparison study currently underway at DOE.** This study provides a quantified basis for assessing the relative strengths and weaknesses in currently available hydrate reservoir models. In addition to comparisons based on ideal or simplified situations, the comparisons should also include physical data from well-constrained field and laboratory experiments.

(5) **Encourage more field-based production tests.** Data from the Mallik experiment are the only well-documented, publicly available hydrate-production test well measurements. Expanding this family of measurements to other geological environments is essential to calibrate laboratory and modeling studies for methane extraction and production as well as understanding hydrates in the natural Earth System.

APPENDIX VIII

LINKS TO ADDITIONAL DOCUMENTS

2006 DOE METHANE HYDRATE ROADMAP

A report entitled: “An Interagency Roadmap for Methane Hydrate Research and Development” is prepared by the United States Department of Energy that lays out background and long-term goals of the United States Methane Hydrate R&D program. Please refer to the following web address to access the report.

http://www.fe.doe.gov./programs/oilgas/publications/methane_hydrates/mh_interagency_plan.pdf

RECENT HYDRATE FIELD PROJECTS

- DOE-BP-USGS “Mount Elbert” gas hydrate well test
February, 2007
Rig Doyon 14
Mt. Elbert prospect, Milne Point area, Alaska North Slope
Field reports available at:

www.netl.doe.gov/methanehydrates/answell

- DOE/Chevron Gulf of Mexico (GOM) Gas Hydrate Joint Industry Project (JIP)

Cruise duration: April 17 – May 22, 2005
Drilling Vessel: *Uncle John*
Sites Covered: Atwater Valley Blocks 13/14 and Keathley Canyon Block 151
Report: The cruise report is available at the following website:

<http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/reports/GOMJIPCruise05.pdf>

- Mallik 2002 project

http://gsc.nrcan.gc.ca/gashydrates/mallik2002/bulletin585_e.php.Mallik
2006-2007

A confidential project, participants include JOGMEC and the GSC but not the USGS.

- IODP Expedition 311

<http://iodp.tamu.edu/publications/exp311/311title.htm>.

- India NGHP Expedition 01

Confidential through March 2008 but the following interim news releases are available:

<http://www.usgs.gov/newsroom/article.asp?ID=1579>

<http://energy.usgs.gov/other/gashydrates/india.html>

<http://www.thehindubusinessline.com/2006/05/01/stories/2006050102400100.htm>

<http://pib.nic.in/release/release.asp?relid=18472>