Oil & Natural Gas Technology

DOE Award No.: DE-FC26-06NT42962

Technology Status Assessment
(Phase 2)

DRILLING AND PRODUCTION TESTING THE METHANE HYDRATE RESOURCE POTENTIAL ASSOCIATED WITH THE BARROW GAS FIELDS

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Prepared for:
United States Department of Energy
National Energy Technology Laboratory

February 24, 2009

Office of Fossil Energy

TECHNOLOGY STATUS ASSESSMENT

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This Technical Assessment Report was prepared with support of the United States Department of Energy, under Award No. DE-FC26-06NT42962. Any opinions, findings, conclusions, or recommendations expressed herein are those of the authors and do not necessarily reflect the views of the Department of Energy.

TECHNOLOGY STATUS ASSESSMENT

Introduction

Naturally-occurring gas hydrates are widespread in subsea sediments and in permafrost regions and hold the promise of producing large volumes of methane gas (Collett, 2004). The U.S. Geological Survey (USGS) estimated that permafrost-associated gas hydrates on the Alaska North Slope (ANS) may contain up to 590 trillion cubic feet (TCF) of in-place gas (Collett, 1995), with the volume of gas within known gas hydrates of the Prudhoe Bay-Kuparuk River infrastructure area alone exceeding 100 TCF (Collett, 2004). If this assessment is valid, the amount of natural gas stored as gas hydrates in northern Alaska could be up to seven times larger than the estimated total remaining recoverable conventional natural gas resources in the entire United States (Collett, 1997).

The U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) and industry partners have been studying the hydrate resources overlying the Prudhoe Bay, Milne Point, and Kuparuk oil fields for several years. Although convenient to existing oilfield infrastructure, these accumulations have a number of technical and gas market hurdles to clear before commerciality is proven. On the other hand, there is strong evidence that the Messoyakha field in Siberia, and the East Barrow and Walakpa Gas fields near Barrow have been producing from hydrates at commercial rates for many years.

Occurrence of methane hydrate resources were first postulated in association with the Walakpa Gas Field, south of the village of Barrow, Alaska over 15 years ago (Glenn and Allen, 1991 and Collett, 1992). The North Slope Borough (NSB) has recently completed Phase 1 of a study of the methane hydrate resource potential associated with the Barrow Gas Fields. This study involved analyses of the methane hydrate stability zone in the Barrow area, integrated reservoir characterization of the fields, and reservoir simulation modeling to investigate the potential contribution of methane hydrates to free gas production. The results of Phase 1 support the presence of significant quantities of methane hydrate associated with the East Barrow and Walakpa Gas Fields. Further research is warranted to determine the volume and nature of the hydrate layer and how the hydrate responds to a long term production test.

This project seeks to: 1) unequivocally establish the presence of hydrates in the Barrow Gas Fields by drilling, coring, and logging a well through the hydrate zone, and 2) understand the behavior of hydrates and associated fluids undergoing hydrate disassociation by conducting a long term production test from the underlying free gas leg. Results of recent research into hydrate occurrence, characterization, and producibility in the Alaskan, Canadian and Russian arctic regions have significantly advanced the understanding of methane hydrate resources, and the current study will utilize and attempt to build on this advancing base of knowledge.

Current State of Information.

The required elements necessary for the occurrence of methane hydrate are widespread across the Canadian Arctic and the Alaskan North Slope (Collett, 2004). Significant effort has been undertaken to understand the character of these natural gas hydrate accumulations since their existence was confirmed at the NW Eileen #2 well in 1972 (Kvenvolden and McMenamin, 1980). A very significant milestone in the study of hydrate methane under permafrost occurred in early 2002, when the Mallik wells in the MacKenzie Delta were drilled, cored, and a flow test of hydrates was conducted. A significant milestone in the study of ANS methane occurred in February, 2007, when the first extensive core of hydrate-bearing sediment was recovered from the Mt. Elbert well at Milne Point Field on Alaska's North Slope (BP press release, 2007).

Previous research efforts funded by the US Department of Energy (DOE), suggest that gas hydrates exist in the Barrow area gas fields (Walsh, Stokes, et. al. 2008). The depletion mechanism is primarily gas expansion, with potential contributions from edge water drive, and recharge from gas hydrate dissociation up-dip of the free gas pool. Modeling work completed in Phase 1 of a DOE/NSB funded study (DE-FC26-06NT42962) of the hydrate resource potential of the Barrow Gas Fields showed that volumetric gas expansion alone could not explain pressure response to production of gas from the Barrow Gas Fields, and hydrate dissociation and aquifer influx are both needed to match field production history. The Phase 1 effort represents the first history-matched full field simulation of a producing free gas field interacting with a hydrate accumulation in the world. However, to date there has been no sample of hydrate taken in the Barrow Gas Fields, and no direct measurement of the amount of hydrate dissociation occurring.

Direct evidence for the presence of hydrates in the subsurface is obtained by collecting samples of the hydrate through coring. Indirect methods for detecting hydrates include interpretation of geological, geochemical and geophysical information (Paul and Dillon, 2001). This project, represented as Phase 2 of a DOE/NSB funded study, will collect direct and indirect evidence of the presence of hydrates in one of the Barrow gas fields by gathering core, and by measuring downhole petrophysical properties and temperature change of the hydrate zone.

Since the recovery of a core with hydrate is the only direct way to ascertain the presence of hydrate, it will be a critical aspect of this project. A wellbore will be designed and drilled to capture and preserve a core in a way that proves the presence of hydrates. In addition, experiments will be conducted on the core to study the rock, fluid, and hydrate properties to better understand its characteristics and how it reacts to depressurization.

Because gas hydrates are naturally unstable at surface conditions and have different properties than in-situ, considerable emphasis will be placed on the downhole logging program to gather data in its native state. Indirect evidence in the form of petrophysical, geophysical, geochemical, pressure, and temperature data will be gathered to support the presence of hydrate and measure its properties and behavior.

Geologic evidence of gas hydrate presence is typically accomplished through interpretation of wireline logs, although these techniques are somewhat qualitative, and not yet fully optimized for hydrate analyses. Attention will be paid to not only the geophysics of how the data is gathered, but other factors such as hole rugosity and mud filtrate properties. Fortunately, considerable progress has been made in the last several years at developing a proper suite of logging tools and a keen understanding of how they respond in the presence of hydrates.

To briefly summarize how standard electric line logs respond to the presence of hydrates, the following notes are offered:

- The gamma ray, neutron and density logs generally respond normally and can be interpreted for lithology and porosity. In a gas hydrate zone, there is an increase in neutron-porosity, which contrasts with a reduction in neutron-porosity in a free-gas zone. Within a gas hydrate zone, there is a decrease in density compared to a zone saturated with water. Because the density of ice is similar to that of hydrate, the density log cannot be used by itself to identify hydrates within ice-bearing permafrost.
- With a dual induction log, there is a higher electrical-resistivity deflection in a gas-hydrate zone, compared to that in a free-gas zone.
- The resistivity log sees both water ice and gas hydrate as non-conductive, and estimates of the amount of pore space filled by solid ice or gas hydrate can be attempted. The major source of

error in this approach is knowledge of the formation water salinity, assuming some water remains unfrozen to provide the conductivity seen by the logging tool.

- Gas hydrate and ice permafrost show high acoustic velocities and low transit time compared with unfrozen formations with gas and/or water.
- Combinable Magnetic Resonance Tool (CMR) is used to measure porosity and percentages of free water, capillary bound, and clay bound water. When compared to density log-derived porosities, CMR can be used to estimate the concentration of gas hydrate.

In addition to conventional tools and logs, several advanced tools have been used to measure the unique properties of hydrates. These tools include the Accelerator Porosity Sonde (APS), Elemental Capture Spectroscopy Sonde (ECS), the Magnetic Resonance Scanner, Rt Scanner, and Sonic Scanner. (Fujii, T. et. al. 2008).

Since one of the objectives of this project is to monitor the behavior of a hydrate zone as it is de-pressured, the ability to measure geophysical properties over time is an important consideration. Several cased hole logs including Cased Hole Formation Resistivity (CHFR), cased hole Reservoir Saturation Tool (RST), APS, and Sonic Scanner can be used to gather baseline data prior to production, and periodic time lapse data after production commences.

Geochemical detection involves analysis of formation water and gas composition and isotopic fractionation to determine the presence of hydrate gas, the source of the gas, and the processes leading to the formation and dissociation of the hydrate (Paull and Dillon, 2001). Pore water freshening, coupled with presence of large amounts of methane has been documented as an indicator of hydrate occurrence (Hesse and Harrison, 1981). Gas samples from the Barrow Gas Fields have been collected and analyzed on several occasions, and compositional and isotopic analysis of samples from 9 wells (three from each field) has been completed. Additional samples will be collected and tested as part of this program. Samples will be analyzed and compared to older samples to determine whether geochemical changes are taking place as a result of hydrate dissociation.

Highly Relevant Recent and Ongoing Projects

The current state of information on gas hydrates in permafrost has been greatly advanced by recent projects conducted in Alaska and Canada. As summarized below, these multi-phase projects represent the first efforts to verify theoretical and laboratory-based results using geologic, geophysical and production data collected in areas known to contain gas hydrate accumulations. The results and techniques incorporated in these studies will significantly influence the direction and goals of this study.

The Mallik 2002 Consortium: Drilling and Testing a Gas Hydrate Well project began in 1998, with the first research wells to core hydrate bearing sediment and production testing of the hydrate-bearing reservoir. In 2001 - 2002, a production research well and two observation wells were drilled in the Canadian Mackenzie Delta. Full-scale field experiments monitored the physical behavior of the hydrate deposits in response to depressurization and thermal stimulation. A depressurization test was achieved by a series of MDT tests, and a thermal method was successfully tested using circulation of a heated fluid and measuring the recovery of gas dissociated due to the addition of heat. The results of the Mallik testing were used to develop and calibrate a gas hydrate production simulator, and the simulator was used to make long term production predictions (Collett, et. al. 2005). Simulation results show that cumulative production from hot water injection will be possibly two times higher than simple depressurization, but that depressurization could still recover significant amounts of gas potentially without the capital cost of thermal injection facilities. Validated with data from Mallik, the ToughFX/Hydrate model allows simulation of hydrate dissociation and resultant fluid flows under currently contemplated production scenarios (Boswell, 2005). (GSC Bulletin 585, 2005; Osadetz, 2003; DOE Project Nos. DE-AT26-97FT34342 and DE-AC26-01NT41007 technical and status reports).

The ongoing *Alaska North Slope Gas Hydrate Reservoir Characterization* project was initiated in 2002 to determine reservoir extent, stratigraphy, structure, continuity, quality, variability, and geophysical and petrophysical property distribution in a known gas hydrate area of the ANS. In February 2007 a team of scientists concluded the collection of an exhaustive dataset of core, log, and testing data at the Mt. Elbert gas hydrate stratigraphic test well. (DOE Project Nos. DE-AT26-97FT34342 and DE-FC-01NT41332 topical and status reports. Reports/abstracts from AAPG Hedberg Research Conference, *Natural Gas Hydrates: Energy Resource Potential and Associated Geologic Hazards,* September 12-16, 2004.)

Relevant achievements of the five year program include:

- Regional structural mapping of reservoir units, the mapping of shallow fault offsets, and determination of syndepositional faulting and fault-seal potential was completed.
- CMG STARS, a commercial reservoir modeling package, was adapted to provide reservoir modeling capabilities for hydrate prospects; the model was used to determine production potential of various gas hydrate settings.
- The well was continuously cored from 595 to 760 meters with chilled oil-based drilling fluid, which delivered 85% recovery (154 meters) of gas hydrate and water-bearing sandstone and shale.
- The well was logged with a research-level electric-line logging program including magnetic resonance, dipole acoustic, resistivity scanning, borehole imaging, and advanced geochemistry logging.
- The well was tested with the Schlumberger Modular Dynamic Testing (MDT) over four open-hole intervals. Gas was produced from gas hydrates in each of the tests.
- Gas hydrates were expected and found in two stratigraphic sections, including a 14 meter upper zone and a 16 meter lower zone. Hydrate saturations were found to be in the range of 60 to 75%.

As part of the *Methane Hydrate Production from Alaskan Permafrost* project, the HOT ICE well was drilled in 2003-2004 for the purpose of developing and testing new methods of drilling and recovering methane hydrates. The well was completed at a depth of 2300 feet, which is approximately 300 feet below the gas hydrate stability zone. Gas-bearing sands were encountered in highly porous sandstones that were situated within the hydrate stability zone, but no hydrates were found. The research team also acquired a 3-D Vertical Seismic Profile at the well, which resulted in high resolution images of the subsurface, and possible indications of hydrate updip and east of the well site. Analyses of the core, log, and seismic data from the well indicate that the hydrate in this region occurs in patchy deposits and may require a high methane flux from the subsurface in order to form more continuous drilling prospects. (DOE Project No. DE-FC26-01NT41331, topical and status reports. Reports/abstracts from AAPG Hedberg Research Conference, *Natural Gas Hydrates: Energy Resource Potential and Associated Geologic Hazards,* September 12-16, 2004).

Another project worth noting is the West Siberian Messoyakha Gas Field, which has been suggested to be an example of a hydrate accumulation currently in commercial production using conventional production methods (Collett & Ginsburg, 1998). The production history of this field has been proposed as evidence that the hydrate resource is being depleted by de-pressuring the free gas accumulation beneath a hydrate-bearing zone, thus dissociating the gas hydrates. This is of significance to the Barrow Gas Field Study, in that the proposed production model involves drilling a horizontal development well in the free gas interval in close proximity to the hydrate-free gas interface.

Information that is being reviewed to develop the well and data gathering plans of the Phase 2 drilling program have been categorized into eight topics. Some of the more relevant sources have been summarized as annotated bibliographies in the Appendices, as follows:

- Appendix A – Gas Hydrate Well Planning and Drilling Operations
- Appendix B – Gas Hydrate Coring and Core Analyses
- Appendix C – Logging of Gas Hydrate Wells
- Appendix D – Well Testing and Monitoring of Gas Hydrate Wells
- Appendix E – Seismic and Cross-Well Tomography
- Appendix F – Numerical Models and Simulations
- Appendix G – Economics of Gas Hydrates
- Appendix H – Miscellaneous Topics of Gas Hydrates

In addition to papers on the drilling, coring, logging, and testing of hydrate wells, there are a number of case studies to help design and estimate the costs of a remote well on Alaska's North Slope. Specific to drilling at East Barrow and Walakpa gas fields, daily drilling reports and summaries of past well operations are being reviewed. Analogs for drilling shallow horizontal wells through permafrost are the West Sak and Schrader Bluff wells in the central North Slope (Dunn, et. al. 2005). An excellent analog to better understand the issues surrounding a recent drilling operation in the Barrow area is the Intrepid No. 2 well. This well was drilled by ConocoPhillips and partners in March 2007 at a location just south of the Walakpa Gas Field. Several operational elements including permitting (ADNR 2006) and logistical planning (ConocoPhillips, 2005) are very relevant to Phase 2 of this project.

Development Strategies

While gas hydrate represents a very significant potential resource on the ANS, adequate production testing has not proven the feasibility of commercial production and the recovery factory has not been quantified. Problems being addressed by ongoing and proposed research on the ANS are: 1) can gas hydrate accumulations be identified and delineated; 2) can natural gas be produced from gas hydrate; and if so, 3) in what quantities and at what rate?

Three approaches proposed for the production of gas from gas hydrate are: thermal injection; chemical injection, and depressurization; (Collett, 2004). The Mallik project included a depressurization test, and a thermal method was also successfully tested. The Mt. Elbert project flow tested several hydrate intervals with the use of a dual-packer MDT configuration. Although adequate for confirming the effects of depressurization, this technique does not allow for long term flow to surface. Consequently, the dataset is limited in its ability to predict commercial rates.

Phase 2 of this project will entail drilling a pilot well to core and sample the gas hydrate, and then drilling a second well as a high-angle or horizontal producer, ideally starting in the hydrate zone, and drilling down into the free gas pool. If the first location finds a full column of hydrate and is determined to be a sub-optimal location for monitoring the depressurization affects on hydrates, a better-located observation well will be drilled once the interface has been confirmed with the high angle producer. The proposed hydrate production method represented in the Barrow Gas Fields test would be by depressurization, drilling a test well near the free gas/hydrate interface and drawing down the pressure via production of free gas.

The situation at the Barrow gas fields makes this an ideal place to conduct a long term test of a reservoir containing hydrates. Both the East Barrow and Walakpa gas fields are supplying gas for the city of Barrow on a continuous basis. Consequently, any test of a hydrate well can continue as long as is necessary to collect the required data. In addition to production from a dedicated producer well, the free gas/gas hydrate interface in an observation well will be monitored during production to measure the change in hydrate and establish the contribution to the free gas zone from gas hydrates. Data collected from the observation well and producer well will be used as input to the reservoir model to confirm whether gas hydrates are contributing to gas produced from the free gas zone.

Future Implications

Verifying the presence of a significant gas hydrate accumulation in the gas fields of Barrow will provide an opportunity to test the potential of producing gas hydrates through depressurization. Modeling and history matching results will contribute to the understanding of the gas hydrate stability zone and whether and how much that zone is contributing to production from the Barrow Gas Fields. Ultimately, this study will provide unique insight into the role played by gas hydrate in recharging a producing gas field and will provide a platform for continued development of the tools and technologies developed by previous gas hydrate research. It has been suggested that if hydrates are a factor in the resource potential of the Barrow Gas Fields, the remaining reserves base of the Walakpa Gas Field could be several orders of magnitude greater than current estimates (Collett, 1998).

This project has potential to impact the long-term development of the Barrow Gas Fields, as methane gas hydrate appears to represent a recharge mechanism to the free gas fields currently in production. Understanding the influence, if any, of gas hydrates associated with the Barrow Gas Fields could weigh heavily in decisions on future development drilling, compression requirements, and water handling needs. It will also influence decisions on expansion of energy provision to Barrow and outlying villages in the North Slope Borough.

Applicability

The outcome of this study is broadly applicable to gas hydrate research in the arctic environment, and particularly to accumulations associated with free gas zones. The study will complement and build on current and past gas hydrate studies in Alaska, Canada and Russia, and will utilize and develop tools for exploring and exploiting gas hydrate in arctic environments. While this study is smaller scale than some other industry/government collaborative efforts, it has potential to identify significant opportunities for broadening the research effort in the Barrow Gas Fields, and to act as a catalyst to expand research efforts throughout and beyond the Central North Slope.

The Barrow Gas Fields are unique on the North Slope, in that they represent a commercially viable, in fact critical, gas resource, whereas the natural gas associated with the giant North Slope oil fields has no market without a pipeline. The applicability of this research to meeting the energy needs of remote villages of the North Slope is both direct and immensely important.

Appendix A. Annotated Bibliography on Gas Hydrate Well Planning and Drilling Operations

Takahashi, et. al. (2005)	*Drilling and Operations Overview of the Mallik 2002 Production Research Well Program* • 3L, 4L, 5L-38: 79 days, Dec 25, 2001 – Mar 14, 2002 • Mallik L-38 winter '71-'72. Mallik 2L-38 Feb – Mar 1998 • 2L-38: first core samples from permafrost gas hydrate • Four teams: G&G, Modeling, Production Testing, Drilling • Operations lead: JNOC and JAPEX. JAPEX Canada, operator • Canadian Petroleum Engineering Inc (Ed Fercho), ops supervision • APA – engineering for production testing • Center well, 5L-38, production test well. Adjacent wells (at 40 meters) for temperature and crosswell tomography surveys • 180 km ice road, north of Inuvik. Heavy equipment staged by barge about 25 km from drillsite. Barged between Aug 28 and Sept 30, 2001. • Akita 15 – 2000m, double, telescoping derrick. 60 bed main, 24 bed annex camp. • 2L-38 and 3L-38 took about 15 days to drill and complete. • All three wells used a KCl-polymer mud, with mud weight and temperature held as low as possible. • Observation wells drilled with minimum scientific survey – DTS cables behind casing and tool access for crosswell tomography surveys. No openhole logging or coring conducted on 3L and 4L-38. • 5L-38: cutting samples every 5 m. Continuous coring from THSZ at 885 M to 1151 M. Minimum logging through permafrost. Full suite of open-hole logs in the hydrate layers. • In first well (3L-38) plugging of mud coolers caused mud temperature to rise and melt permafrost, enlarging hole and increasing volume of return solids. Screens were made coarser, overloading centrifuge, and further causing problems at suction of mud coolers. Vicious cycle prompted halt to drilling operations. In second well (4L-38), mud was kept below -2C, requiring 90k ppm KCl, which required heating to dissolve salt, and caused chemical erosion of the hole. • By the 3rd well (5L-38), the targeted mud temp-in in the permafrost was 0 to -3C, targeting mud temp-in in the hydrate was 0 to 6 C. See chart in paper. Lecithin was added to prevent hydrate dissociation. • "it is difficult to prevent dissociation of gas hydrate cuttings returning to surface…while drilling the gas hydrate layers, returning mud just out of the flowline often contained both visible gas hydrate and methane gas releasing due to hydrate dissociation…the only effective way to reduce this gas discharge was to decrease the drilling rate, as it is not effective to increase the mud weight." • Caliper log and actual cement slurry volume indicated a perfect gauge hole across the hydrate interval. Casing was cemented with Arctic set cement to keep heat of hydration as low as possible. • Across the permafrost in the observation wells, cementing volume was about six times the volume of calculated volume of a gauge hole. • DTS cable strapped to outside of casing in the observation wells. DTS provided by GFZ. Running the DTS cable without damaging it was extremely challenging. • Corion Express wireline coring system, by Corion Diamond Products Ltd. Was utilized for coring. 6-1/4" bit, 5-3/4" barrel, 3" core diameter. • Data logger in core barrel recorded temp and pressure. Cold mud temperatures limited dissociation until core was at 200 – 400 m.

	• Samples preserved with liquid nitrogen or re-pressured with methane or nitrogen. Was able to preserve about half of the hydrate with 40 – 60% of pore space hydrate concentrations in many samples. • Mud gas was continuously monitored with a very sophisticated full gas chromatograph, of higher quality than typical O&G mud logger. • Open hole logs across permafrost were compromised due to hole enlargement. Extensive logging across hydrate interval had excellent quality. • Testing conducted with SLB MDT tool. APA designed and supervised test. • Thermal stimulation conducted with 1.66" inside 3-1/2" tubing and a packer. Hot brine was circulated, gas was produced, measured, flared. • It took 2 days of circulating 0C brine to kill the well. • Cased hole formation resistivity (CHFR) and reservoir saturation logs were run after the thermal stimulation test to compare to baseline (pre-test) runs. • Cross well tomography run by TomoSeis Corp. Seismic source in 3L-38 and receiver in 4L-38. VSP run by SLB. • A 480 m X 200 m 3D seismic survey was run with 5L-38 in the middle. One survey before the production test, one survey after the pressure tests, and one during the thermal stimulation test. • All wells were P&A'd with bridge plugs and cement. Fiber optic cables remained intact for future temperature monitoring.
Wiersberg, et. al. 2005	*Real-time Gas Analysis at the Mallik 5L-38 Gas Hydrate Production Research Well* • The main objective was to identify gas-hydrate bearing horizons while drilling, and to distinguish them from other sources, such as free gas below an impermeable seal. • Gas hydrate zones had high methane, low helium concentrations and high Methane:Ethane+Propane ratios.
Ning, Jiang, et. al. 2008	*Analysis on Characteristics of Drilling Fluids Invading into Gas Hydrates-Bearing Formation* • The invasion process is a coupling process of hydrate dissociation, heat conduction, and fluid displacement. They interact and influence formation parameters around the wellbore including intrinsic mechanics, pore pressure, capillary pressure, water and gas saturation, wave velocity, and resistivity. • Good figures of pore space around wellbore, and the various invaded zones.
Kadastar, et. al. 2005	*Methane Hydrate Production from Alaskan Permafrost – Drilling and Coring Operations. Topical Report, Anadarko Hot Ice, February 2005* • Used the Noble Engineering and Development Drill Smart System to allow engineers to monitor and view drilling operations live from Houston • A video of arctic platform transportation construction was provided to DOE • Rolligons and Mattrax equipped pick-up trucks were used first winter, ice road was used second winter for cost savings. • 36 days from spud to TD, including flat time due to 2 season operation • Mud temp targeted for a range of 26 to 32F • Mud temp fluctuated erratically between 21 and 35.5F, with a mud freezing point of 23F. • Root cause of mud temp volatility was traced to a slug of solids that plugged the mud chiller. Foaming problems contributed to freezing of mud lines. • Well used managed pressure drilling procedures and a rotating head. • On-site CT scan by LBNL. • Several core systems were evaluated, including pressure coring systems. • Core diameter was maximized to minimize hydrate dissociation. • Operational problems were rooted in mud and mud chilling. Lessons learned included finer screens, more judicious use of centrifuges, regulation of chiller feed, better mud chemistry, and better mud transfer line insulation.

Hunter, Patil, et. al.	*Resource Characterization and Quantification of Natural Gas-Hydrate and Associated Free-Gas Accumulations in the Prudhoe Bay – Kuparuk River Area on the North Slope of Alaska. Drilling and Data Acquisition Planning Topical Report* • This paper summarizes the seismic work, prospect identification, and prospect ranking that resulting in the picking of the Mt. Elbert location. • Conclusion: Mt. Elbert site would provide a suitable candidate for data acquisition and production testing operations to help narrow the uncertainties regarding gas hydrate bearing reservoir productivity, saturations, absolute, and relative permeabilities.
Boswell, Hunter, et. al. 2008	*Investigation of Gas Hydrate-Bearing Sandstone Reservoirs at the Mount Elbert Stratigraphic Test Well, Milne Point, Alaska* • A good summary of the Mt. Elbert project. • A vertical well from an ice pad was drilled to facilitate acquisition of high quality coring and logging data. • Surface hole drilled with 12-1/4” bit and water based drilling fluid. • 9-5/8” casing set at 1950’ just below base of permafrost. • The 8-1/2” section was cored with a fit-for-purpose oil-based drilling fluid formulated by MI-Swaco. Reasons: it could be chilled to 0C, and promote core, log, and test data. • 430’ of 3 inch diameter core was captured, with an 85% recovery rate. • Initial processing in the pipe shed, where the core liner was cut into a series of 3 foot lengths, and then transferred to an on-site cold-temperature core processing trailer. It is estimated that cores were outside the pressure-temperature stability zone of hydrates for approximately 20 to 45 minutes. • Hydrate was apparent in the core based on 1.) visual inspection of hydrate and ice cementation, 2.) observation of gas release when samples were immersed in water, and 3.) evidence of progressive temperature decrease recorded on temperature probes in the cores. • Logging program consisted of the following: o Run 1 – PEX (GR, Res, Neutron Por, Lithodensity, EPT, and RT scanner logs. o Run 2 – Dipole sonic imager and Oil-based micro imager (OBMI). o Run 3 – Combinable magnetic resonance (CMR), Elemental capture spectroscopy (ECS), and hostile environmental natural gamma ray (HNGS). • Success of the coring and logging is attributed to the mud system and DrillCool mud chillers. • 4 zones were tested with MDT. Each test consisted of multiple stages of varying length, with each stage consisting of a period of fluid withdrawal followed by pump shut-off and monitoring of subsequent pressure build-up.
Williams, Millheim, et. al. 2005	*Methane Hydrate Production from Alaskan Permafrost – Final Report (Anadarko Hot Ice Project)* • Suite of logs included 1) electrical resistivity (dual induction), 2) SP, 3) Caliper, 4) Acoustic travel-time, 5) Neutron-porosity, 6) Density, 7) NMR. • The completion plan mentions plans to use a heater cable (a flat ESP cable that is shorted above the packer) to prevent the freshwater in the tubing across the permafrost from freezing. Modeling results predicted that the heater cable would keep temperature of fluid inside the tubing above 50F. • A detailed completion procedure is included. • Promore gauges and instrument line were to be run. • UAA published a 69 page report on all the issues surrounding water production, water handling, water testing, etc.

Appendix B. Annotated Bibliography on Gas Hydrate Coring

Dallimore, et. al. 2005	*Overview of the Coring Program for the Mallik 5L-38 Gas Hydrate Production Research Well* • The collection of high-quality gas hydrate core samples depends on maintaining in-situ pressure and temperature conditions, or minimizing the time that a core is exposed to P-T conditions unfavorable to hydrate stability. • The use of pressurized core barrels offers significant advantages by maintaining in-situ pressure, and in some cases temperature. Unfortunately they are small and short. • A common operational dilemma is the benefits of limited pressure cores vs. the collection of long conventional cores. • In the 1998 2L-38 well, KCl mud was run at temps of 0 to 3C, with 6 L/m3 of lecithin. Although core retrieval times were over an hour, hydrate bearing cores were recovered with conventional core barrels. Due to dissociation, core was cooler (-10 to -15C), than the mud. • A heat-budget model (core temp vs. depth as it is retrieved) was used to predict when the hydrate exited the HSZ. • Corion Express wireline coring system, by Corion Diamond Products Ltd. Was utilized for coring. 6-1/4” bit, 5-3/4” barrel, 3” core diameter. • Data logger in core barrel recorded temp and pressure. Cold mud temperatures limited dissociation until core was at 200 – 400 m. • A split aluminum liner eliminated the risk of pressure build-up and allowed on-site geologists to inspect the entire length of the core within a few minutes of surface arrival. • Wireline retrieval system requires 5” internal flush drillpipe (drillrod) with 5.75” outer core barrel and 6.25’ core bit. • Cores could be retrieved in about 20 minutes with wireline. • A P-T rabbit (Vemco 8-bit Minilog-TDR) Ltd. was used to monitor pressure and temperature just above the core barrel. For gas-hydrate-free cores, the cooling rates observed were consistent over time during the entire uphole trip. Temp records for gas-hydrate-bearing cores however show distinct inflection in the temp vs. time (depth) cooling curve, noted by a sharper cooling trend of more rapid cooling in the upper part of the hole, about where the core exits the HSZ. Consistent with the endothermic cooling of hydrate dissociation. • The Mallik team placed emphasis on conducting time-sensitive core measurements immediately following core retrieval. • Core recovery averaged 89%, much better than the 50% of 2L-38. • A tracer technique refined for microbiology investigations was used to measure the degree of invasion by the coring fluid. • Gas hydrate bearing samples were observed to contain significant amounts of pore ice as a consequence of endothermic cooling of the core. • An estimate of pressure-temperature stability threshold for each gas-hydrate bearing core reveals that gas hydrate in some cores began to dissociate at p-t conditions corresponding to freshwater MH stability curve, whereas others began to dissociate close to the seawater curve. This variability is considered to be a function of in-situ pore-water salinity in the presence of gas hydrae. • Two core-temperature models were evaluated for their ability to accurate quantify gas hydrate amounts in the core. A model developed during ODP leg 164 considers only sensible cooling induced by endothermic hydrate dissociation, and underestimated the amount of hydrate in the core. A model based on the 2L-38 includes latent heat of freezing, but overestimated gas hydrate amounts in the core. This can be explained by theory that very little pore water froze because it was retrieved much faster than the 2L-38 core.

Schultheiss, et. al. 2008	*Pressure Core Analysis: The Keystone of Gas Hydrate Investigation* • The author argues that the only way to gather reliable, in-situ data about hydrates in sediment is through pressure coring techniques. • Whether it be salinity, resistivity, density, x-ray morphology, modeling of dissociation kinetics, etc., the only reliable data specimen is a core acquired and preserved via pressure coring. • The author states that "only a few borehole pressure coring tools have been developed and used in gas hydrate environments, and only the HYACINTH system currently lends itself to detailed pressure core analysis". • The rest of the paper discusses analyses that can be performed on pressure cores.
Sigal, et. al. 2005	*Methane Hydrate Production from Alaskan Permafrost – Core and Fluid Analysis Topical Report (Anadarko Hot Ice Project)* • This report summarizes the core analyses that was conducted on the cores taken on the Hot Ice well. • Summaries include measurements of P&P, velocity, resistivity, and NMR. • Extensive discussion on the base of the hydrate stability zone and factors that affect the depth, including salinity and temperature at the base of the permafrost, and the thermal gradient below it.
Cohen, et. al. 2002	*Hydrate Core Drilling Tests, Topical Report (Anadarko Hot Ice Project)* • This report discusses the results of simulated coring tests • Conclusions of these simulated coring tests include: o Frozen hydrate core samples can be recovered successfully o A spring finger core catcher works best o Drilling fluid can erode the core and reduce its diameter o Mud must have proper viscosity to lift larger cuttings o Bottom 6 inches of core may need to be cut dry to capture the core • A 10% KCl drilling fluid was used to core with

Appendix C. Annotated Bibliography on Logging of Gas Hydrate Wells

Collett, Lewis, Dallimore 2005	*Mallik 5L-38 Gas Hydrate Production Research Well Downhole Well-Log and Core Montages*
	• This paper describes the tools run and gives a montage of the recorded tracks on the 5L-38 well.
	• Run 1 – to surface casing point at 662m –Platform Express (PEX) with high resolution laterolog (HRLA).
	• Run 2 – across hydrate zone to 1166m. PEX with HRLA, electrical induction tool (AITH), and electromagnetic propagation tool (EPT).
	• Run 3 – Fullbore Formation MicroImager (FMI)
	• Run 4 – Combinable Magnetic Resonance (CMR) with natural gamma-ray spectroscopy (HNGS) and Multi-arm caliper (EMS).
	• Run 5 – Dipole Shear Sonic Imager (DSI) with HNGS and EMS
	• Run 6 – Reservoir Saturation Tool (RST).
	• Run 7 – cased hole. Several time series of RST-GR and a cased hole formation resistivity tool (CHFR).
	• Brief review of the montages reveals the following:
	    • Resistivity-log traces modes 1-5 depict 5 different measurements of formation electrical resistivities by the HRLA, with mode 5 being the deepest reading and mode 5 being the shallowest reading. The high recorded resistivity between 891 and 1107 m have been attributed to the occurrence of in-situ gas hydrate. The overlapping nature of the traces indicate little disturbance or invasion of mud filtrate.
	    • In interval containing hydrates, electromagnetic waves propagate like acoustic waves with faster wave speeds or reduced propagation times relative to water bearing sediments. The attenuation time (EATT) is however mostly controlled by porosity or total water content. A EATT-TPL cross-over plot can be used to identify hydrates.
	    • Per Takayama 2005, total CMR-porosity measurements and density-log-derived porosities can be used to estimate the concentration of gas hydrate in a rock interval.
	    • It is possible to accurately estimate gas hydrate saturations by comparing the apparent porosity from NMR, with actual porosities derived from density-log measurements for example.
	    • CMR can be used to measure how much water is free, capillary bound, and clay bound.
	    • Plona and Kane (2005) have shown that the gas-hydrate bearing sandstone in 5L-38 has low compressional-wave and shear-wave slownesses (higher sound speed) and behaves in a homogenous and isotropic manner. In contrast, the water bearing sandstone exhibits higher compressional-wave and shear-wave slownesses (lower sound speeds), stress-induced anisotropy, and mechanical damage around the wellbore.
	    • Electromagnetic-propagation well log (PEX Run 2) were used for the first time to measure in-situ dielectric properties of natural gas hydrates in the 5L-38 well. Sun and Goldberg (2005) were able to calculate gas hydrate saturations from the derived dielectric constants and density logs.
	    • Comparison of the RLA5 log from the HRLA and the CHFR log clearly shows that changes in formation resistivity have occurred between the time of the HRLA and the cased-hole CHFR log runs.
	• It seems apparent that only SLB is qualified to log these types of wells.

Collett and Lee, 2005	*Electrical –Resistivity Well-log Analysis of Gas Hydrate Saturations in the Mallik 5L-38 Gas Hydrate Production Research Well* • Downhole electrical resistivity and acoustic-transit-time (both compression and shear wave) logs from 5L-38 infer the occurrence of in-situ gas hydrate. • Porosities, derived from density well logs, range from 25 – 40%. • Gas hydrate saturations, derived from downhole resistivity logs, were very high, with peak gas hydrate saturations exceeding 90%. • Matsumoto 2005 document highly variable pore-water salinities that range from 1 ppt to 45 ppt. It is likely that solute exclusion has locally enriched the pore-water salinity within the hydrate zone. • A formation water resistivity (R_w) based on a single assumed pore water salinity would lead to erroneous hydrate saturation estimates.

Takayama, et. al. 2005	*Gas Hydrate Saturation Analysis Using Density and Nuclear Magnetic Resonance Logs from the Mallik 5L-38 Gas Hydrate Production Research Well*
	• The density-magnetic resonance method was used to identify gas hydrate bearing zones in 5L-38. It was determined that the DMR method can calculate gas-corrected porosities and accurate gas saturations.
	• Conventional analysis of gas hydrate saturation falls into 3 categories:
	  • Resistivity method is highly sensitive to presence of gas hydrate and has a relatively deep radius of investigation. However, core samples are required to determine accurate Archie parameters, and saturation calculation is sensitive to salinity of pore water, which is variable with hydrates present.
	  • Acoustic-velocity method is sensitive to hydrate presence, but signal is highly degraded in the presence of free gas.
	  • Statistic inversion method is model based, but requires an extensive log data set.
	• DMR method can provide accurate gas-corrected sediment porosities and gas hydrate saturations. This method shows that the density-log-derived porosities are elevated in gas bearing sediments. ON the other hand, NMR porosity devices yield apparent lower values in gas hydrate intervals. The difference between the two porosities can be used to detect and measure the presence of gas and gas hydrates.

Murray, Fujii, Dallimore 2008	*Developments in Geophysical Well Log Acquisition and Interpretation in Gas Hydrate Saturated Reservoirs* • The paper discusses the utility of nuclear elemental spectroscopy for determining mineralogy, thermal and epithermal neutron porosity measurements, measurement of in-situ permeability, and borehole imaging logs. • At Mallik, nuclear spectroscopy shows that hydrate saturated intervals contain less clay than surrounding zones. • Advantages of using epithermal neutron and Magnetic Resonance (MR) combination is the reduced rugose borehole measurement effects. • Pulsed neutron tools generate neutrons on demand and eliminate the need for an americium-beryllium chemical source. • MR can be used to estimate minimum permeability in the presence of MH, and geochemical nuclear spectroscopy lithology measurement can be used to estimate the rock's maximum permeability for no hydrate. • The borehole sonic response in a hydrate saturated interval in Mallik was previously described by Plona [23]. A complete suite of sonic data was acquired including compressional-wave, Stoneley-wave, and four-component shear-wave with cross-dipole. Plona suggested that the hydrate bearing sandstone had low compressional-wave and shear-wave slownesses (fast

	sound speeds) and behaved in a homogeneous, isotropic manner. And that in contrast, the water-bearing sandstone section exhibited higher compressional-wave and shear-wave slownesses (slow sound speeds), stress-induced anisotropy, and mechanical damage around the borehole.
Fujii, Takayama, et. al. 2008	*Wire-line Logging Analysis of the 2007 JOGMEC/NRCAN/AURORA Mallik Gas Hydrate Production Test Well* • This paper reviews the open hole and case hole logging program used on the re-entry and re-drill of the Mallik 2L-38 well in 2007. • Very good summary of the state of the art for open hole logging of gas hydrates and cased hole monitoring after gas dissociation. • It reviews and discusses all tools run and conclusions from said data. • For precise evaluation of MH bearing formation properties, advanced wire-line logging tools such as APS* (Accelerator Porosity Sonde), ECS* (Elemental Capture Spectroscopy Sonde), and new logging tools such as MR Scanner*, Rt Scanner* and Sonic Scanner* were applied in this logging program in addition to conventional tools.
Lee, Collett (2005)	*Assessments of Gas Hydrate Concentrations Estimated from Sonic Logs in the 5L-38 Gas Hydrate Research Production Well* • Gas hydrate concentrations estimated from acoustic logs compare favorable to estimates from resistivity and NMR logs in sandy intervals; however differ noticeably within shaly intervals. • The NMR porosity log from 5L-38 (Collett, et. al 2005) indicates that gas hydrate prefers to form from the free water that exists in pore space or fractures rather than bound or capillary water. This observation implies that the highest gas hydrate concentration is limited by the amount of free water in the pore space. • When estimating gas hydrate concentration using acoustics, the P-wave velocity is preferred to the S-wave velocity, because errors associated with uncertainties of BGTL parameters of n and G are small for the P-wave velocity.
Anderson, et. al. 2005	*Modeling the Response of the Cased Hole Formation Resistivity Tool in order to Determine the Depth of Has Hydrate Dissociation during the Thermal Test in the Mallik 5L-38 Gas Hydrate Production Research Well* • Modeling of DHFR logs was used to determine the annular radius of gas hydrate dissociation that occurred around the wellbore during the thermal test of 5L-38. • Modeled results based on CHFR measurements indicate that the radius of gas hydrate dissociation exhibited large local variations and was far from uniform. • CHFR measurements of hydrate dissociation compare favorably with the gas volume measured from the test.

Appendix D. Annotated Bibliography on Well Testing and Monitoring of Gas Hydrate Wells

Kurihara, et. al. 2005	*Well-test analysis for Gas Hydrate Reservoirs: Examination of Parameters suggested by Conventional Analysis for the 5L-38 Gas Hydrate Production Research Well* • Conventional PTA and numerical simulation was performed on MDT tests at Mallik 5L-38 to test the applicability of conventional PTA to predict perm, skin, and radius of investigation. Conclusions below: • It is difficult to predict properties with PTA • Permeability predictions were close to average • Permeability of the hydrate interval makes it difficult to predict boundaries, etc. If less than 5md, OK, if more, inaccuracy is high. • It seems to me to not waste time using PTA when fine grid simulation models will be more accurate and account for changing conditions.
Moridis, Collett, et. al 2005	*Analysis and Interpretation of the Thermal Test of Gas Hydrate Dissociation in the Mallik 5L-38 Gas Hydrate Production Research Well* • Similar to Kurihara 2005 work, a model was created to simulate and history match the thermal stimulated well test at 5L-38 • Specific to Mallik. Cool figures. Models an electrically heated horizontal well with perfs only at the heel. Cool idea.
Collett, T. S. 2008	*Geologic and Engineering Controls on the Production of Permafrost-Associated Gas Hydrate Accumulations* • Good summary and resource assessment of Arctic gas hydrates. • Briefly summarizes Mallik and Mt. Elbert projects.
Henninges, et. al. 2005	*Temperature Field of the Mallik Gas Hydrate Occurrence – implications on phase changes and thermal properties* • DTS system – opto-electronic model DTS 800 M10 manufactured by Sensa, United Kingdom has a maximum accuracy of +/- .3C. • Sensor cables located in cement annulus between casing and borehole wall. • The “collars” used to install the fiber optic cables did not work well, and did not prevent damage to the cables. • Temperature profiles were recorded every .25m and every 5 minutes. • Averaging was used to smooth the data. • In a subsequent trip to download the temperature data, the original calibration had “obviously changed”. Calibration is an issue. • The presented evidence implies that at the Mallik site even high gas hydrate saturations of up to 90% of the pore space only have a minor effect on the bulk-rock thermal conductivity as compared to the effect of changes in lithology. • Temperature data indicates that decomposition of gas hydrate had occurred at the base of the gas hydrate bearing zone, probably as a result of a release of heat of hydration after cementing the wells. • For the first time, a step like decrease in temperature was noted at the base of the hydrate layer caused by the consumption of latent heat by the decomposition of gas hydrate during the completion (cementing) of the wells.
Satoh, et. al. 2005	*Production-test Planning for the Mallik 5L-38 Gas Hydrate Production Research Well* • The most obvious test method would be to complete the well in the gas zone at the base of the GHSZ. This would create a pressure sink extending significantly away from the wellbore, resulting in dissociation of GH. Although this represents the most economically recovery method, it was problematic for a number of reasons:

	• The production of gas from hydrates would have to be inferred from the difference between total and theoretical production from free gas • The variation and extent of gas dissociation could not be directly measured. • The free gas zone is thin, and sits on top of free water. • Even small vertical perm barriers would adversely affect the gas hydrate dissociation process. • Conducting tests directly on the gas hydrate interval, where the effects would be limited to the region around the wellbore and number of unknown factors could be limited, was the preferred method to meet data gathering objectives. • Dual packer MDT tests with .5m perforated intervals was used as the test design for the pressure dissociation tests. 6 tests were run, 3 in solid hydrates, 1 in a free water interval, 1 in the free gas on bottom, and 1 in a transition zone with free gas expected. • WELLCAT Prod wellbore thermal and pressure simulation model from Halliburton Landmark was used to plant he thermal stimulation test. • The goal of the thermal stimulation was to raise the temp from 7.5C to 50C by circulating 75C brine. • Surface subsidence was prevented using a refrigerated, insulated conductor. • Thermal stimulation well test was simulated with EOSHYDR2. Assumed properties of 80% S_h, 28% porosity, 20 md perm, 20% S_{wr}, 5% Sg. • Predicted pressure response due to heating in a closed chamber was very high, due to gas releasing and having twice the scf in gas from vs. hydrate form. • The planning effort for these tests took 2 years, and involved extensive investigation and discussion among a team of scientists and engineers.
Fujii, K., et. al. 2008	*Development of a Monitoring System for the JOGMEC/NRCAN/AURORA Mallik Gas Hydrate Test Program* • This paper discusses the measurement of in-situ formation response to long term production, primarily pressure, temperature, and resistivity. • The system was designed to be installed mainly on the outside of the well casing of a production or observation well, enabling continuous monitoring during production testing. • A number of sensor cables were installed on the outside of the casing. Operational difficulties prevented the successful installation of some of the cable strings, resulting in failure or partial failure of some sensors. • A specially designed oriented perforation system was used to avoid damage to monitoring cables. • The system was developed to acquire real-time reservoir parameters such as porosity, permeability, temperature, pressure, and hydrate saturation from downhole measurements throughout the entire production test period. • Pressure and temperature measurements were fundamental parameters so it could be compared to phase equilibrium envelope and support estimation of phase state and thermodynamic stability of the gas hydrate. • By measuring resistivity profiles at the different depths of investigation using electrode arrays, the progression of the dissociation front can be monitored as a resistivity image. • Measuring thermal conductivity will help with future simulation work. • Acoustic parameters such as velocity and attenuation are observed to have different behaviors in hydrate-bearing vs. non hydrate-bearing sediments. Differences in compressional velocity before and after dissociation may make it possible to monitor the progression of the dissociation front using first-break travel time tomography.

Appendix E. Annotated Bibliography on Seismic and Cross-Well Tomography

Bellefleur, et. al. 2008	*An Acoustic Impedance Inversion Approach to Detect and Characterize Gas Hydrate Accumulations with Seismic Methods: An Example from the Mallik Gas Hydrate Field* • A model-based acoustic impedance inversion technique to 3D data was used to characterize the spatial extent of hydrate away from well control. • The inversion method converts reflections into acoustic impedance from which velocity and hydrate saturation can be estimated.
Bauer, et. al. 2005	• Crosshole seismic experiments were conducted using the two observation wells at Mallik. • Following a baseline survey, three time-lapse surveys were run to evaluate seismic capabilities to detect hydrate dissociation. • Modeling studies indicate that the small amount of dissociation at 5L-38 will introduce only very weak changes in the seismic data. Advanced processing would be needed to detect these effects.
Pratt, et. al. 2005	• Time lapse seismic data was gathered at the Mallik field. Waveform tomography was used to form high-resolution quantitative images of the seismic velocity and attenuation from the first repeat survey. • The hydrate bearing sediments are imaged as laterally continuous, high velocity anomalies, and an apparent increase in attenuation.

Appendix F – Annotated Bibliography on Numerical Models and Simulations

Moridis (2002, 2003)	• TOUGH2 -> EOSHYDR2 (mass and heat coupled) • 9 components (hydrate, water, native CH4, dissociated CH4, native and dissociated hydrocarbon, salt, water-soluble inhibitors, heat pseudo-comp) and 4 phases (gas, liquid, ice, hydrate) in 3D • Prediction of the formation and dissociation and hydrocarbon
Moridis, et. al. (2004)	• Depressurization and hot fluid injection through multiple well • Depressurization for free gas underlying hydrate deposit (zone 1) = production ↑ • Depressurization of hydrate underlain by aquifer (zone 2) produce large amount of water • Thermal simulation for hydrate with no gas, no water • S_{hyd} ↑, hydrate initial temperature ↑, circulating water temperature ↑, thermal conductivity of system ↑ at constant pressure = production ↑ • Gas production less sensitive to rock and gas hydrate specific heat and permeability
Hong, Darvish 2005	*Numerical Study of Constant-Rate Gas Production from in-situ Gas Hydrate by Depressurization* • Paper discusses a numerical model for studying depressurization method of gas recovery from GH reservoirs with underlying free gas zone (Type 1). • Results indicated that if reaction rate constants are small, overall rate of gas generation could be affected. Therefore there is a need for better thermal conductivity and kinetic constants. • This paper is a good template for documenting the well level reservoir modeling done for the E. Barrow field in Jan 2009 by PRA.
Moridis, et. al. (2004)	• EOSHYDR2 simulation for Class 1 hydrate accumulation • Modeling site: Mallik, Canada • Depressurization: promising, but low operating pressure results in hydrate cooling and lower gas release rate due to endothermic. • Coupling depressurization with thermal stimulation (for the case of thin hydrate and free gas zone): modest gas production • Hydrate deposits with very thin gas zone underlain by aquifer: standard dissociation approach is not enough. Horizontal well would be better than vertical one
Gerami and Pooladi-Darvish (2005)	• Highlight the invalidity of 'sharp-interface' that divide the reservoir into hydrate zone and dissociated zone → pressure reduction propagates from interface into hydrate zone, leading to decomposition of hydrate throughout hydrate zone • During non-equilibrium stage, heat transfer from cap- and base rocks has small effect on gas production. • Heat of decomposition is mainly by the sensible heat of hydrate and its dissociated rock.
Kurihara, et. al. 2005	*Analysis of the Mallik 5L-38 Gas Hydrate Thermal Production Test through Numerical Simulation* • A 2-d (radial z) simulation model was built of the thermal stimulation test at Mallik. • The model was history matched as postulates that hot water was injected into the reservoir. • Sensitivities and predictions under various temperature and depressurization schemes were modeled.

Appendix G – Annotated Bibliography on Economics of Gas Hydrates

Walsh, et. al. 2008	*Preliminary Report on the Economics of Gas Production from Natural Gas Hydrates* • Simulations with CMG-STARS and TOUGH+HYDRATE were performed to calculate the breakeven gas price for various classes of MH deposits. • However, without long-term production tests to use as a benchmark, it is difficult to assess the accuracy of any hydrate reservoir simulator. Furthermore, because the economic results presented in this report rely directly on the predictions of these relatively untested codes, the results should be seen as preliminary, order-of-magnitude assessments until further production testing and code refinement are performed. • As Hancock, Wilson, and Howe found "hydrate zones associated with free gas (Class 1) would be more likely to be economical at a lower market price than hydrate zones lacking a free gas base.

Appendix H – Annotated Bibliography on Miscellaneous Topics of Gas Hydrates

Jain, and Juanes 2008, MIT	*Pore-Scale Mechanistic Study of the Preferential Mode of Hydrate Formation in Sediments: Coupling of Multiphase Fluid Flow and Sediment Mechanics* • Coarse grain sediments favor capillary invasion, whereas fracturing dominates in fine-grain media. • Our results predict that, in fine sediments, hydrate will likely form in veins that follow a fracture-network pattern, and the hydrate concentration in this type of accumulations will likely be quite low. • In coarse sediments, the buoyant methane gas is likely to invade the pore space more uniformly, in a process akin to invasion percolation, and the overall pore occupancy is likely to be much higher than for a fracture-dominated regime. These implications are consistent with field observations of methane hydrates in natural systems.

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