Methane Hydrate Production from Alaskan Permafrost

Technical Progress Report

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by

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Disclaimer

Abstract

Natural-gas hydrates have been encountered beneath the permafrost and considered a nuisance by the oil and gas industry for years. Engineers working in Russia, Canada and the USA have documented numerous drilling problems, including kicks and uncontrolled gas releases, in arctic regions. Information has been generated in laboratory studies pertaining to the extent, volume, chemistry and phase behavior of gas hydrates. Scientists studying hydrate potential agree that the potential is great – on the North Slope of Alaska alone, it has been estimated at 590 TCF. However, little information has been obtained on physical samples taken from actual rock containing hydrates.

This gas-hydrate project is in the second year of a three-year endeavor being sponsored by Maurer Technology, Noble, and Anadarko Petroleum, in partnership with the DOE. The purpose of the project is to build on previous and ongoing R&D in the area of onshore hydrate deposition. We plan to identify, quantify and predict production potential for hydrates located on the North Slope of Alaska. We also plan to design and implement a program to safely and economically drill, core and produce gas from arctic hydrates.

The current work scope is to drill and core a well on Anadarko leases in FY 2003 and 2004. We are also using an on-site core analysis laboratory to determine some of the physical characteristics of the hydrates and surrounding rock. The well is being drilled from a new Anadarko Arctic Platform that will have minimal footprint and environmental impact. We hope to correlate geology, geophysics, logs, and drilling and production data to allow reservoir models to be calibrated. Ultimately, our goal is to form an objective technical and economic evaluation of reservoir potential in Alaska.

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1. Introduction

The purpose of this project is to plan, design and implement a program that will safely and economically drill/core and produce natural gas from arctic hydrates. A significant amount of research has been conducted on naturally occurring gas hydrates, and our team (Maurer, Anadarko and Noble) will adapt and apply laboratory R&D and technology in the field.

This is an aggressive project that will identify, quantify and predict production potential of hydrates by drilling the first dedicated hydrate well on the North Slope of Alaska in an area with hydrate potential. This project will use an Anadarko special purpose on-site laboratory to help analyze hydrate cores. Additionally, the well will be drilled from a special purpose-built arctic platform. Data generated in this project will also assist research organizations and technical teams as we begin to make an objective technical and economic assessment of this promising natural gas reservoir potential.

2. Executive Summary

Objectives and Scope of Work

The objectives of this gas-hydrate project are to analyze existing geological and geophysical data and obtain new field data required to predict hydrate occurrences; to test the best methods and tools for drilling and recovering hydrates; and to plan, design, and implement a program to safely and economically drill and produce gas from hydrates in Alaska.

The overall Scope of Work is to:

1. Evaluate geological and geophysical data that aid in delineation of hydrate prospects
2. Evaluate existing best technology to drill, complete and produce gas hydrates
3. Develop a plan to drill, core, test and instrument gas-hydrate wells in Northern Alaska
4. Characterize the resource through geophysics, logging, engineering and geological core and fluids analysis
5. Test and then monitor gas production from hydrate wells for one year
6. Quantify models/simulators with data for estimating ultimate recovery potential
7. Learn how to identify favorable stratigraphic intervals that enhance methane production
8. Assess commercial viability of developing this resource and ultimately develop a long-term production plan
9. Provide real hydrate core samples for laboratory testing
10. Develop and test physical and chemical methods to stabilize hydrate wellbores and improve core recovery
11. Step outside the well-known Prudhoe Bay/Kuparuk River area to further delineate hydrate deposits in Alaska
12. Report results to the DOE and transfer technology to the Industry

Phase I has been completed, which included well planning, site selection and equipment construction.

Phase II Participants:

Maurer Technology Inc. – Performs project coordination, project management and DRC testing.

Anadarko Petroleum Corporation – Overall project management for the design, construction, and operation of the Arctic Drilling Platform, mobile core lab, and field coring operations.

Noble Engineering and Development – Provides personnel and real-time data collection and transmitted digital data and video to project participants located offsite and wellsite drilling personnel.

University of Alaska – Supports studies on geology, tundra, and produced water disposal.

Lawrence Berkley National Lab (LBNL) – Performs reservoir modeling used for well test planning and onsite portable X-ray scanner with wellsite operator.

Sandia National Lab – Provides downhole mud pressure and temperature recording tool.

Pacific National Lab (PNL) – Provides portable infrared scanner.

United States Geological Survey (USGS) – Provides synthetic core for drilling tests, phase behavior model for hydrates, pressure vessels for hydrate core storage and technical advice. Models hydrate preservation and dissociation. Provides personnel for coal core and analysis.

Schlumberger Oilfield Services – Provides CMR equipment used in mobile core lab and two onsite analysts; and well-logging services.

Paulsson Geophysical Services – Performs vertical seismic profiling.

Advisory Board – Craig Woolard, University of Alaska, Anchorage; Steve Bartz, Schlumberger; Steve Kirby, USGS; Tim Collette, USGS; Theresa Imm, Arctic Slope Regional Commission; C. Sondergeld, University of Oklahoma; Richard Miller, University of Kansas; and David Young, Baker Hughes Inteq.

Accomplishments

- Design and construction of Anadarko's Mobile Core Laboratory completed in August 2002. This lab permits cores to be maintained and analyzed at a reduced temperature and in close proximity to the drill site.

- Operational and logistics planning, geology and geophysics analysis, and site selection completed and environmental and operations permits obtained by the end of December 2002.

- Anadarko's Arctic Platform was installed on site in February 2003. Technology being tested here could help to achieve three goals independent of this project:

    - allow operators to work outside the present operations season

    - provide access to remote areas where water to build ice roads is scarce and steep grades make it difficult to set or supply a drilling rig

    - reduce the environmental impact of a well location on the tundra

- Arctic Platform topside facilities were set during March 2003.

- Hot Ice #1 Well was spudded March 31, 2003.

- Well cored, logged and cased to the base of the permafrost during April 2003.

The Hot Ice No. 1 well is located approximately 20 miles south of the Kuparuk River oil field center and about 40 miles southwest of Prudhoe Bay. Based on evidence from nearby offsets in the Cirque and Tarn gas hydrate accumulations, hydrates are expected to be found in sands near the base of the permafrost. The well was spudded on March 31, 2003, and was continuously cored from a depth of 107 feet to 1400 feet (RKB) with core recovery of 93%. The base of the permafrost was crossed at about 1250 ft. Open-hole logs were acquired and 7-inch casing set in a shale zone between the Ugnu and West Sak formations.

Current Status and Remaining Tasks

Operations on the Hot Ice well were suspended pending the return of cold weather (**Figure 1**). Drilling operations will start on or about January 7, 2004 at the opening of the conventional operations season. An ice road will be constructed from an existing road to the west of the well location (**Figure 2**).

Figure 1. Arctic Platform during Summer

Casing was set directly above the West Sak formation. A sand accumulation at the top of the West Sak should provide a good chance to encounter hydrates. After operations recommence, the hydrate stability interval will be cored, approximately to 2200-2400 feet (670-732 meters) deep. After total depth is reached and the well ID logged, VSP will be run and depending on the amount of hydrates encountered, a final completion program will be formulated.

The complete set of core, well log, production and downhole pressure and temperature data will be made available for use in evaluating the hydrate reservoir's quality and to determine potential for production from arctic hydrate intervals. The data will be incorporated into hydrate reservoir models to test possible scenarios for producing methane from hydrates in similar settings.

A number of other officials from the State of Alaska, the U.S. Department of Interior and the Department of Energy visited the site. DOE NETL has also established a special web page for references to their support of gas-hydrate development. At their site (http://www.netl.doe.gov/scng/hydrate/) are posted updates describing the Hot Ice project as well as the latest version of "Fire in the Ice," the National Energy Technology Laboratory Methane Hydrate Newsletter.

Drilling the Hot Ice No. 1 well marked the first test of Anadarko's Arctic Platform. The primary platform consists of 16 lightweight aluminum modules fitted together and mounted on steel legs 12 feet above ground. The platform is large enough to contain a coring rig, auxiliary equipment, mud tanks, and the mobile core analysis laboratory. Another five modules form an adjacent platform with living quarters for 40 people.

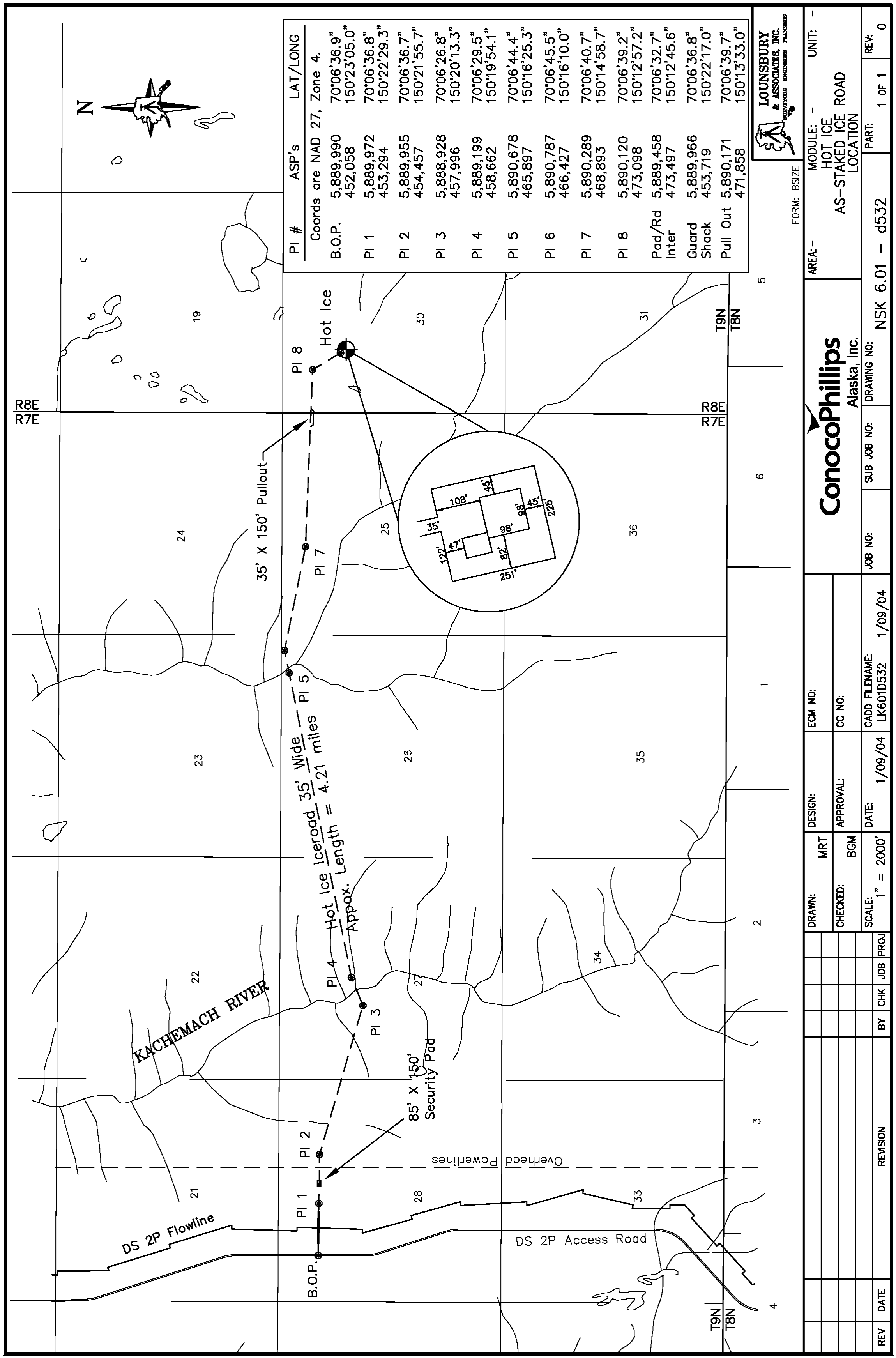

Figure 2. Map of Ice Road to Site

The Hot Ice No. 1 well was cored with a wireline retrievable coring system using drilling mud that had been chilled to 23°F (-5°C) to preserve the 3.3-inch (8.5-cm) core and to prevent any hydrate from dissociating during core recovery. The mobile core laboratory was employed to immediately perform measurements on both whole core and 1-inch plugs taken from the whole core, while maintaining that temperature. Whole core measurements included: core gamma log, infrared temperature, velocity measurement, geologic description and white light photographs, high resolution CT scan (equipment from LBNL), and a nuclear magnetic resonance measurement (with CMR tool from Schlumberger) on a portion of each section of core. Plug measurements included: bulk volume, grain density, helium porosity and permeability at confining stress, P and S wave velocity, resistivity, and thermal conductivity. For hydrate samples, the NMR system (Schlumberger CMR Tool) is used to determine the fluid volume in the sample at various steps in the dissociation process, while released gas volumes and composition are also recorded.

The well was suspended on April 21, 2003 due to unseasonably warm conditions that prevented transport of heavy loads over the tundra. The mobile core lab and collected core were moved to Deadhorse, Alaska, to permit continuation of core analysis. The lab was shipped to Tulsa, Oklahoma where repairs and upgrades have been ongoing by the University of Oklahoma. Well operations are scheduled to resume January 7, 2004.

3. Experimental

3.1 BACKGROUND

Natural-gas hydrates (**Figure 3**) beneath the permafrost have been encountered by the oil and gas industry for years. Numerous drilling problems, including gas kicks and uncontrolled gas releases, have been well documented in the arctic regions by Russian, USA and Canadian engineers. There has been a significant volume of scientific information generated in laboratory studies over the past decade as to the extent, volume, chemistry and phase behavior of gas hydrates. However, virtually all of this information was obtained on hydrate samples created in the laboratory, not samples from the field.

Figure 3.
Methane Hydrate

Discovery of large accumulations around the world (**Figure 4**) has confirmed that gas hydrates may represent a significant energy source. Publications (Makogon and others) on the Messoyakhi gas-hydrate production in Siberia (which has produced since 1965), document that the potential for gas-hydrate production exists. Several studies have also addressed the potential for gas hydrates in the permafrost regions of North America. The results from the Mallik Hydrate, Mackenzie Delta Northwest Territories, Canada wells (hereafter, the "Mallik wells") drilled by JAPEX, JNOC and GSC, provide a significant amount of useful background information. The USGS made sizeable contributions to the Mallik project, as well as many other investigations on gas hydrates in the USA (especially Alaska), and has a tremendous amount of basic information on the presence and behavior of hydrates.

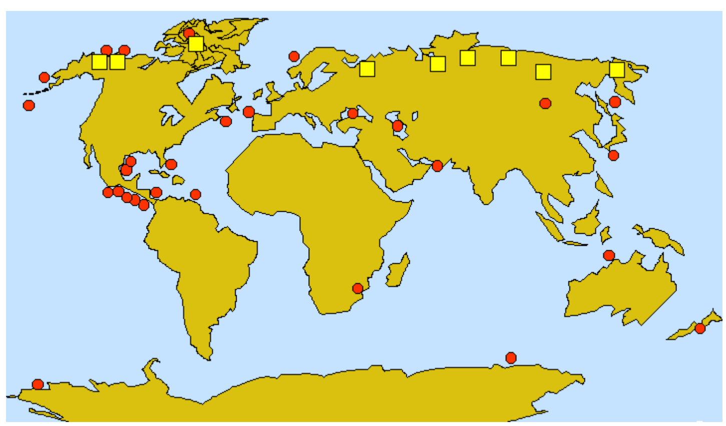

Figure 4. Methane Hydrate Deposits (USGS)

The project team now believes it is time to apply this knowledge to environmentally sound development of this resource. The first critical step is to drill and monitor wells in regions in the USA with the greatest likelihood of commercial quantities of methane hydrates. In fact, the project work represents the first attempt to drill, core and monitor hydrate wells in the USA. The specific objective of this effort is to obtain the field data required to verify geological, geophysical and geochemical models of hydrates and to plan, design and implement a program to safely and economically drill and produce gas from arctic hydrates. These "ground truth" data did not previously exist.

North America's emphasis on utilizing clean-burning natural gas for power generation has increased demand for gas and resulted in higher gas prices. A number of forecasts, including the NPC Study on Natural Gas (2000), indicate higher demand with prices in the range of $4 to $8/mcf. This is sufficiently high to allow investments in sources previously deemed uneconomic. The projected US demand for natural gas may grow to nearly 30 TCF by the end of the decade. This demand, particularly on the West Coast of the US, strongly suggests that a proposed Alaska Natural Gas Pipeline may now be economically feasible. This pending pipeline should provide a commercial market for natural gas, thereby allowing the necessary investments in new technology to develop and market the hydrate resource.

Anadarko is the one of the largest independent oil and gas exploration and production companies in the world, with 6.1 TCF of gas reserves and 1046 MMBO of oil reserves (more than 2 BBOE). Domestically, it has operations in Texas, Louisiana, the Mid-Continent and Rocky Mountains, Alaska and the Gulf of Mexico. Anadarko, one of the most active drillers in North America, is balancing its current exploration and production programs by investing in developing new gas resources in North America, including areas where the risks and potential rewards are high with the application of advanced technology. It is now one of the largest leaseholders in Alaska, with an ambitious program of exploratory drilling and seismic studies. Anadarko holds nearly 500,000 undeveloped acres under lease, many with the potential for commercial production from hydrates. Anadarko also has extensive holdings in the Mackenzie Delta region of the Northwest Territories of Canada, which also hold potential for hydrates. Thus, Anadarko is very interested in developing this resource.

With the amount of information on hydrates now available and the potential of developing this huge resource, this project makes good economic sense at this time. The best resources and ideas from around the world will be used to implement the technology in the field. Thorough planning of the test wells should allow avoiding some of the problems encountered in previous gas-hydrate wells.

This project will provide valuable information to the DOE, industry, and research community to identify key barriers and problems related to gas-hydrate exploration and production. This information will be highly useful in developing innovative, cost-effective methods to overcome these barriers. Close interaction will be maintained with an Advisory Board that includes Teresa Imm, Arctic Slope Regional Corp., Craig Woolard, University of Alaska Anchorage, Steve Kirby, USGS, Steve Bartz, Schlumberger, Timothy Colette, USGS, David Young, Baker Hughes Inteq, Rick Miller, Kansas Geological Survey, and Carl Sondergeld, University of Oklahoma.

3.2 OBJECTIVES

The objectives of this gas-hydrate project are to:

1. Analyze existing geological and geophysical data and obtain new field data required to predict hydrate occurrences

2. Test the best methods and tools for drilling and recovering hydrates

3. Plan, design, and implement a program to safely and economically drill and produce gas from hydrates.

3.3 SCOPE OF WORK

The overall scope of the work for this Alaskan Hydrates project is to:

1. Evaluate geological and geophysical data that aid in delineation of hydrate prospects

2. Evaluate existing best technology to drill, complete and produce gas hydrates

3. Develop a plan to drill, core, test and instrument a gas-hydrate well in Northern Alaska

4. Characterize the resource through geophysics, logging, engineering and geological core and fluids analysis

5. Test and then monitor gas production from the hydrate wells for an extended period of time.

6. Quantify models/simulators with data for estimating ultimate recovery potential

7. Learn how to identify favorable stratigraphic intervals that enhance methane production

8. Assess commercial viability of developing this resource and ultimately develop a long-term production plan

9. Provide real hydrate core samples for laboratory testing

10. Develop and test physical and chemical methods to stabilize hydrate wellbores and improve core recovery

11. Step outside the well-known Prudhoe Bay/Kuparuk River area to further delineate hydrate deposits in Alaska

12. Report results to the DOE and transfer technology to the Industry

4. Results and Discussion

4.1 DELIVERABLES

During **Phase I**, an effective plan was developed for drilling new hydrate wells in Alaska. This included geological and geophysical assessment, site selection, and developing well plans.

In separate reports the project team provided DOE with the following Phase I Deliverables:

- Digital map of well locations
- Well log correlation sections
- Seismic maps and sections showing stratigraphic and lithologic units within gas hydrate stability zone
- Reservoir modeling report
- Well data for control wells used for site selection
- Site selection plan
- Testing and analytical procedures (Topical Report)
- Well plan
- Permit application
- NEPA requirements

Additional Phase I achievements beyond the original contract obligations were also delivered. These include:

- Topical reports from University of Oklahoma and the Drilling Research Center on hydrate core apparatus and testing
- Support of other DOE hydrate projects including the Westport Core Handling Manual

- Three reports from the University of Alaska Anchorage:

    1. Geological Research of Well Records

    2. Water Generated during Production of Gas Hydrates

    3. Permafrost Foundations/Suitability of Tundra Platform Legs

- USGS report on dissociation of hydrates at elevated pressures

- LBNL report on hydrate preservation in cores

- Arctic platform video

- National Press Release and Conference in Washington, DC

- First-ever North Slope coal cores provided to the USGS for coalbed methane study

- New equipment for measuring hydrates

Phase II encompasses drilling/coring a new hydrate well. After drilling, the well will be thoroughly logged and tested. Core will be analyzed on site using an innovative mobile laboratory. After completion, shallow seismic will be shot. The wells will then be monitored for an extended period and assessed for production potential. An advanced hydrates simulator will be calibrated with field data and used in the development of economic and production models for these and other hydrate accumulations.

4.2 TEAM ORGANIZATION

Team organization is shown in **Figure 5**.

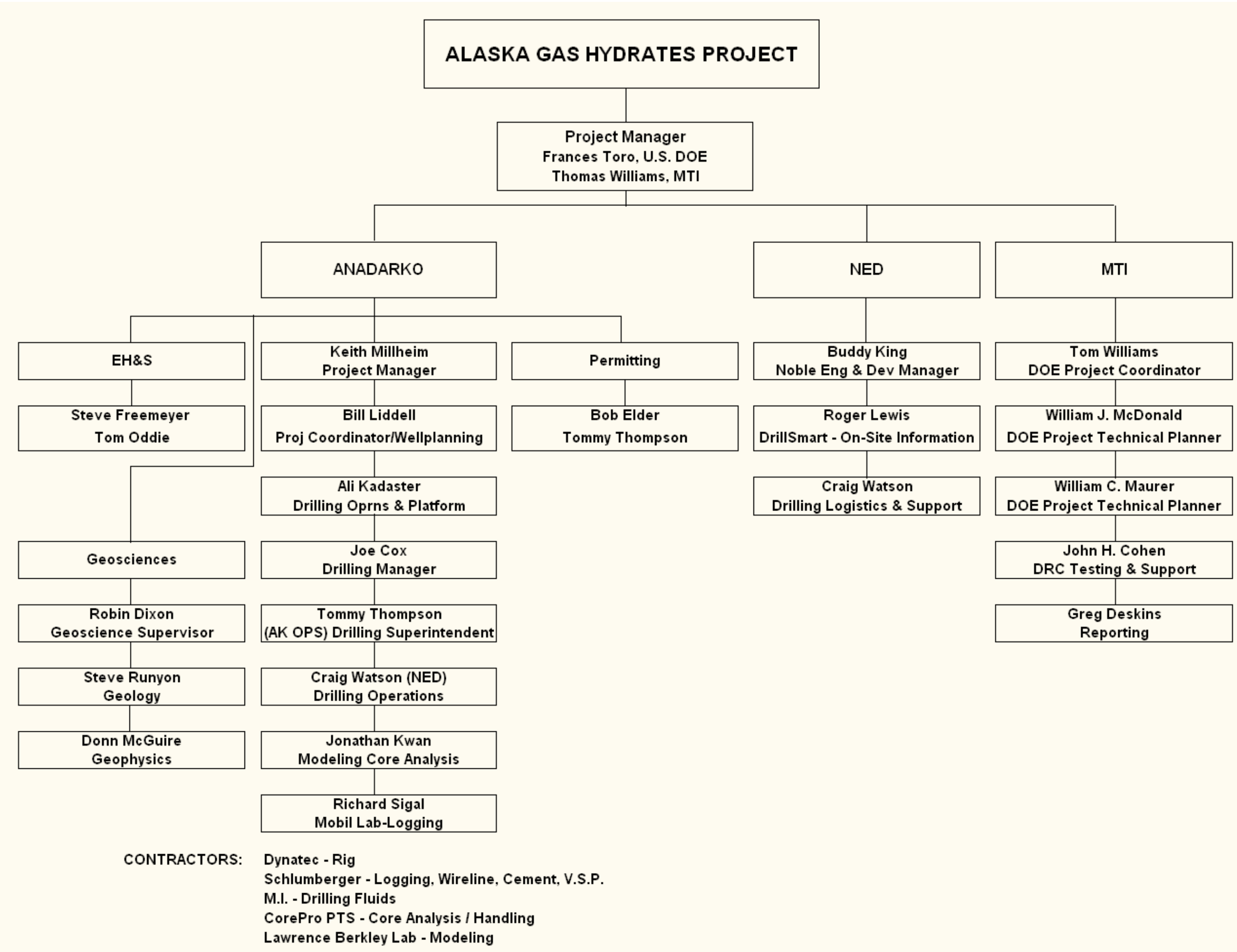

Figure 5. Project Team Structure

4.3 ACCOMPLISHMENTS

PHASE I

Phase I is now complete. Tasks 1-7 were completed.

Phase I Task Activities that Continue into Phase II

A "lessons learned" workshop was held at Anadarko's office in the Woodlands on June 12–17, 2003. Each activity and task were reviewed and a budget revision was completed. The cost of the unanticipated demobilization and stand-by fees have significantly increased the cost of the project.

Subtask 4.2 – Permitting

Permitting was completed; however revisions for re-mobilization prior to the normal drilling season (due to freezing of the permafrost) are on-going. Permitting the VSP is currently an issue. The platform has not moved due to thawing this summer and It is anticipated Anadarko will be allowed on the well early. Three wells were initially permitted, named Hot Ice #1, #2 and #3 (HOT ICE = High Output Technology Innovatively Chasing Energy). Following the Anadarko Geological and Geophysical assessment and the Site Selection task, the best location was selected in November and final permitting activity has focused on this location for HOT ICE #1. With the addition of the Arctic Platform, new permitting activities and costs have been required. Meetings with and inspections by State and Federal regulators have continued. A number of positive reports complimentary of the operation have resulted.

The permit application was provided to the DOE.

A recent map showing the location of the site is presented in **Figure 6**.

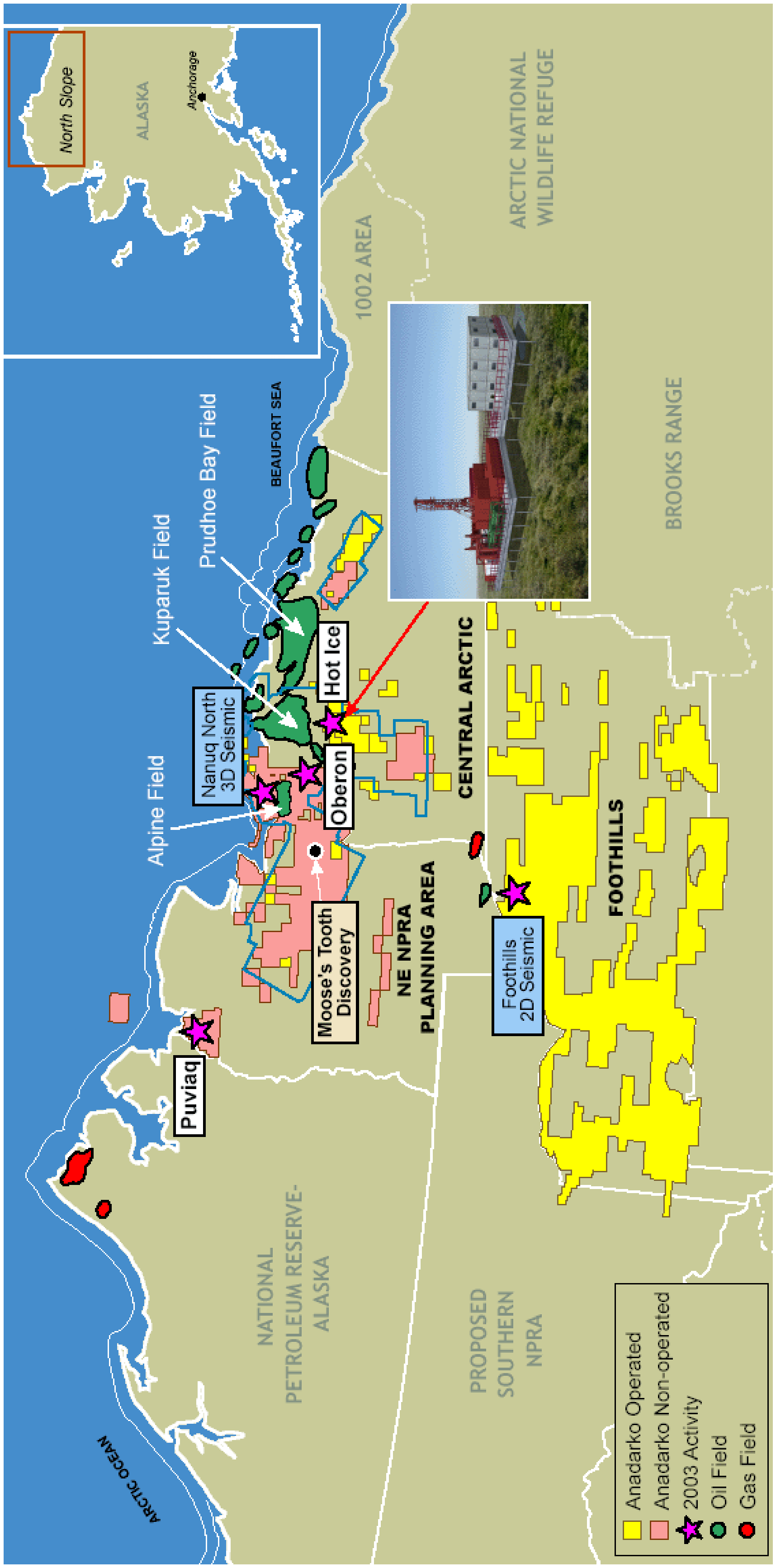

Figure 6. Map of North Slope Showing Location of Hot Ice #1

Task 7.0 – Posting Data on Existing Web Sites

Maurer constructed an Internet web site (http://www.maurertechnology.com/index-hydrates.html) for hydrate project updates. It is linked to the NETL hydrate web site and displays presentations, progress highlights and photos. This site will continue to be updated to make results available to the R&D community. Special information is available to the project team (including DOE) through a password-protected page. Information about our project is being exchanged with other hydrate research organizations and meetings. Press releases have been issued, and the energy press has contacted Maurer and Anadarko for progress updates and information about the project. A number articles have appeared in Pe*troleum New Alaska, Hart's E&P, World Oil,* and others. These articles and publications are shown in the attached project bibliography.

PHASE II

The overall objective of Phase II is to test exploitation techniques developed in Phase I by drilling/coring and completing one or more wells, and then performing a comprehensive battery of well tests and logs. Next, the well will be monitored to develop long-term production options. Tasks to accomplish these objectives are described below.

The current schedule for Phase II is shown in **Figure 7**.

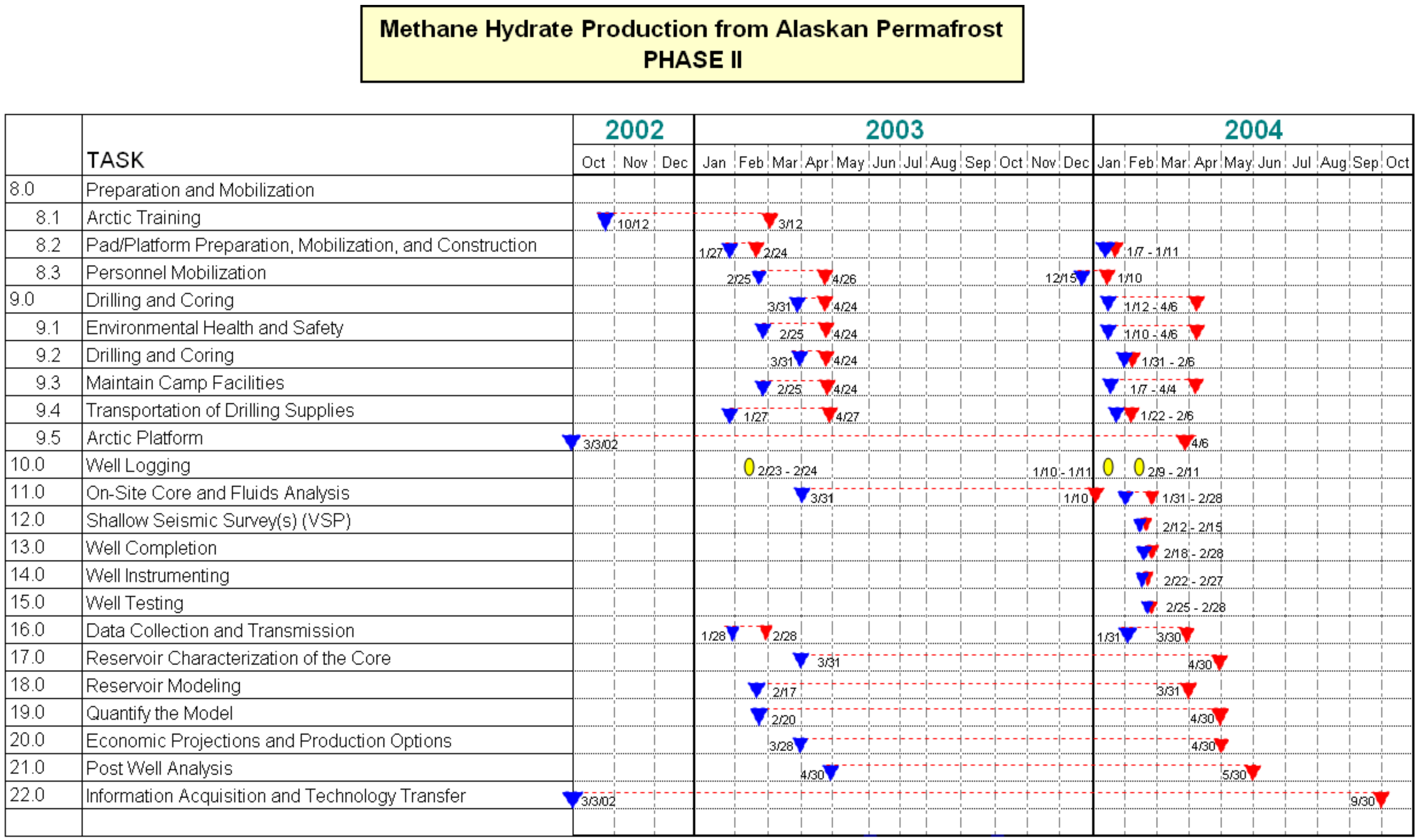

Figure 7. Phase II Project Schedule

Task 8.0 – Preparation and Mobilization

Subtask 8.1 Arctic Training

The required training will be conducted for personnel who will be working on the North Slope overnight in support of this project. Training courses included: First Aid, Respiratory, FIT Test, H_2S Training, NSTC Training, Hazcom/Hazwoper, PPE, Alaska Safety Handbook, Arctic Survival, Bear Awareness, NPRA Training, and Fire Extinguisher Training.

Subtask 8.2 Pad/Platform Preparation, Mobilization, and Construction

Permits have been issued, and the arctic platform was installed at the well location in February. The recipient has mobilized the drill platform equipment to the well location, using an existing gravel road and a staging area at the end of the road. The permits allowed the platform to remain during the summer months. An ice road has been permitted for access during operations in 2004.

Phase 2 of the drilling operation will incorporate an ice road (**Table 1 and Figure 2**) instead of making use of Rolligons.

Table 1. Hot Ice Location Winter Access Alignment

Point Name	Lat (WGS 84)	Long (WGS 84)	Comments
001	70.10992	150.38774	Road Alignment
002	70.11032	150.38779	Road Alignment
003	70.10943	150.38774	Road Alignment
HI Start	70.10991	150.38741	Beginning of Ice Road Alignment off road
PL-X-1	70.10997	150.38255	Pipeline crossing
004	70.10959	150.37146	
005	70.11026	150.37123	Power line alignment
HI PI-03-1	70.10712	150.34009	Point of Intercept
HI X-03-1	70.10763	150.33920	Steam Crossing 1
HI X-03-2	70.11195	150.27660	Stream Crossing 2
HI-1	70.10836	150.21756	Hot Ice #1 Platform location (West Side)

The three pipelines at the single pipeline crossing are protected by casings and 7 ft of coarse gravel. The gravel ramp on each side is shown in **Figure 8**.

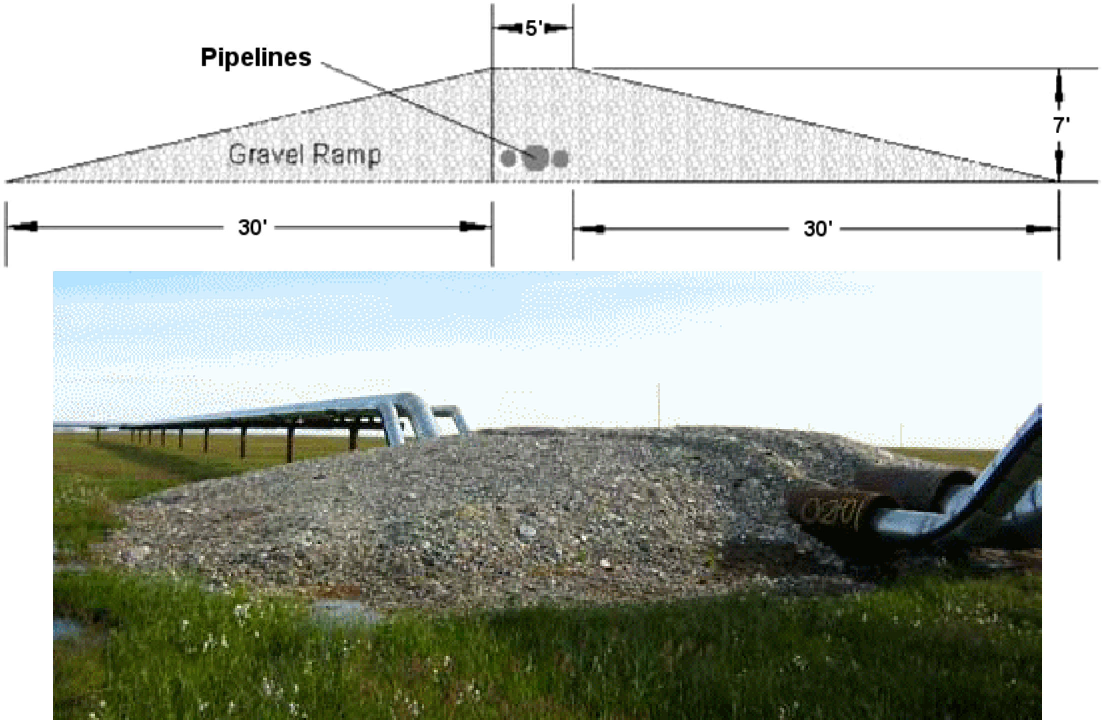

Figure 8. Gravel Ramp for Pipeline Crossing

The sites for Stream Crossings 1 and 2 are shown in **Figure 9**.

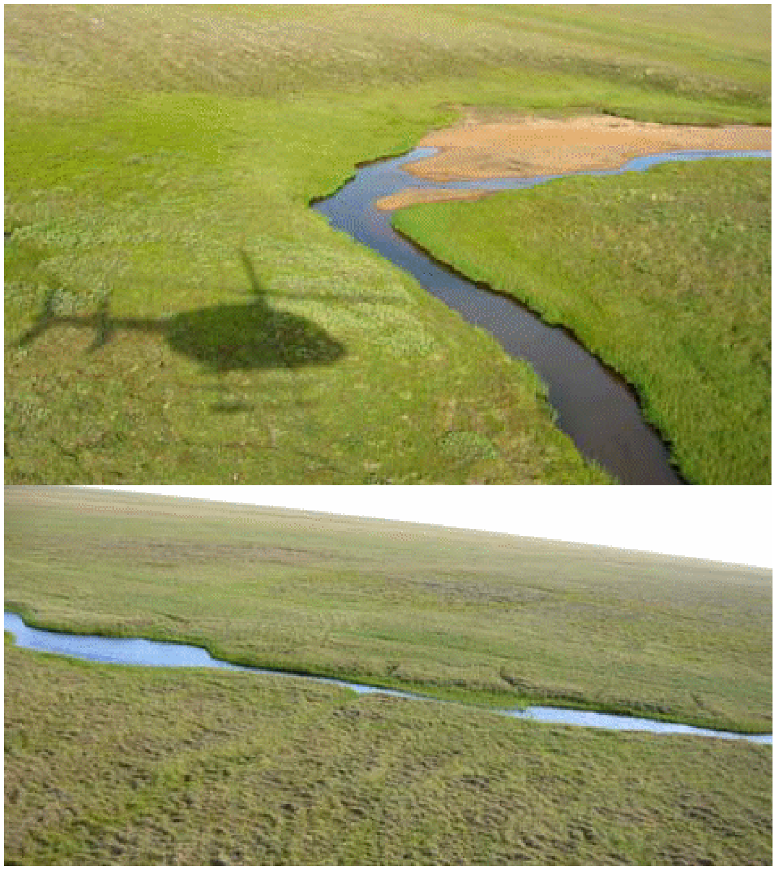

Figure 9. Stream Crossing 1 (upper) and 2 (lower) for Ice Road

Subtask 8.3 Personnel Mobilization

The recipient shall transport all project personnel to and from the well site. This task shall include transport of camp crew, catering staff, maintenance crew, rig crew, lab crew, logging crew, cementing crew, mud crew, and supervisory personnel.

Table 2. Hot Ice No. 1 – Time Line

(January 7, 2004 Start Date - Operations Commence with Ice Road - WELL TESTED Case)

ID	Task Name	Duration	Start	Finish	Predecessors
1	Tundra Opening (Forecast)	0 days	1/7/2004	1/7/2004	
2	Mob Ice Road Crews & APC Supervisors	4 days	1/7/2004	1/11/2004	
3	Hot Ice Project Resumption	85 days	1/12/2004	4/6/2004	
4	**Mobilization**	**9 days**	**1/12/2004**	**1/21/2004**	
5	Build 4-mile Ice Road From Meltwater	6 days	1/12/2004	1/18/2004	
6	Open Deadhorse Facility	3 days	1/15/2004	1/18/2004	
7	Prep Hot Ice Camp	3 days	1/18/2004	1/21/2004	5
8	MOB Crews	1 day	1/20/2004	1/21/2004	
9	**Rig Up & Preparation for Spud**	**8 days**	**1/21/2004**	**1/29/2004**	
10	RU Electrical	2 days	1/21/2004	1/23/2004	8
12	RU Plumbing	2 days	1/21/2004	1/23/2004	8
13	Haul Fuel & Fluids	1 day	1/22/2004	1/23/2004	
14	RU Rig & Support Equipment	2 days	1/23/2004	1/25/2004	
11	RU Communications	1 day	1/23/2004	1/24/2004	10
15	Set & RU Lab	1 day	1/25/2004	1/26/2004	14
16	RU Instrumentation	2 days	1/26/2004	1/28/2004	15
17	Test BOP	1 day	1/28/2004	1/29/2004	16
18	**Drilling & Coring Operations**	**20 days**	**1/29/2004**	**2/18/2004**	
19	RIH w/BHA, DO Ice Plugs & Displace Hole	1 day	1/29/2004	1/30/2004	17
20	Test Casing, DO Shoe & 20', FIT/LOT	1 day	1/30/2004	1/31/2004	19
21	Core 11,425' to 2,300'	6 days	1/31/2004	2/6/2004	20
22	TOH, Test BOP, TIH, C&C	2 days	2/6/2004	2/8/2004	21
23	C&C, TOH & RU Loggers	1 day	2/8/2004	2/9/2004	22
24	OH Log	2 days	2/9/2004	2/11/2004	23
25	Wiper Trip	1 day	2/11/2004	2/12/2004	24
26	RIH w/Paulsson VSP - Rum 3D VSP	3 days	2/12/2004	2/15/2004	25
27	Wiper Trip & POOH	1 day	2/15/2004	2/16/2004	26
28	Run 4-1/2" Csg. & Cmt.	1 day	2/16/2004	2/17/2004	27
29	WOC	1 day	2/17/2004	2/18/2004	28
30	**Completion & Testing**	**10 days**	**2/18/2004**	**2/28/2004**	**29**
31	NU Tbg. Spool/BOP & Test	2 days	2/18/2004	2/20/2004	28
32	PU & RIH w/tbg. & Csg. Scraper	1 day	2/20/2004	2/21/2004	31
33	WL set TCP Guns	1 day	2/21/2004	2/22/2004	32
34	RIH w/Completion Assembly	2 days	2/22/2004	2/24/2004	33
35	RU Surface Test Equipment	5 days	2/20/2004	2/25/2004	31
36	Flow Test	2 days	2/25/2004	2/27/2004	35
37	SI Buildup Test	1 day	2/27/2004	2/28/2004	36
38	**Abandonment & Demobilization**	**38 days**	**2/28/2004**	**4/6/2004**	
39	P&A/ L/D CHD 134 & Set Packer & Plugs	1 day	2/28/2004	2/29/2004	37
40	Rig Down & Demob. Rig Topside	15 days	2/29/2004	3/15/2004	39
41	Rig Down & Demob. Rig Platform	3 days	3/15/2004	3/18/2004	40
42	Remove Rig Platform Legs	7 days	3/18/2004	3/25/2004	41
43	Rig Down Camp	3 days	3/25/2004	3/28/2004	42
44	Remove Camp Platform & Legs	7 days	3/28/2004	4/4/2004	43
45	Remediate Site	2 days	4/4/1940	4/6/2004	44

Task 9.0 – Drilling and Coring

The recipient has winterized the drill rig and mobilized it to Deadhorse and then to the well location. The recipient shall drill and core one or more wells from the arctic platform.

Subtask 9.1 Environmental Health and Safety

The recipient shall monitor and respond to environmental health and safety concerns, including monitoring and manifesting waste, in order to ensure compliance with regulations specified in permits.

Subtask 9.2 Drilling and Coring

The recipient shall drill and core one or more wells from the arctic platform constructed in Subtask 8.2. The recipient shall use chilled drilling fluids and monitor the downhole temperature and inclination using a tool provided by Sandia National Lab. The recipient shall use the Noble Engineering and Development Drill Smart System to allow engineers to monitor and view drilling operations live from Houston. Owing to unseasonably warm weather, the recipient was unable to complete the drilling program as originally scheduled during the Spring of 2003. The recipient shall resume drilling operations during the Winter 2004 drilling season.

Subtask 9.3 Maintain Camp Facilities

The recipient shall provide camp facilities to house and feed the crews rotating on a 12/12 shift schedule.

Subtask 9.4 Transportation of Drilling Supplies

The recipient shall transport by trucks and Rolligons personnel, equipment, and supplies used in the drilling operations, including drilling fluids and drilling mud. The recipient shall construct a new ice road during the Winter 2004 season, to facilitate the mobilization of equipment, supplies, and personnel to the Hot Ice #1 Site to complete the drilling and coring operations.

Subtask 9.5 Arctic Platform

The Anadarko Arctic Platform was constructed and tested in Houston, Texas. The structure is made of lightweight aluminum. It was mobilized to the base camp in January 2003, and inspected prior to mobilization to the well location in February (**Figure 10**). The legs were tested and put on location as soon as the freeze period began in January. A video of the transportation and construction was provided to the DOE. Legs were installed into the tundra permafrost and frozen into place. The platform can be mobilized by either helicopter and/or Rolligon from the base camp and assembled at the well location. Environmental monitoring equipment was also installed.

Figure 10. Arctic Platform at Hot Ice #1

The platform drilling area is 100 x 100 ft, and the base camp is 62.5 x 50 ft on an adjacent platform. The rig, equipment and base camp were installed on the platform by Rolligon and two cranes. After completion of drilling and completion operations, some of the equipment will be demobilized, with the remainder staying until well testing has been completed. The entire platform will be demobilized to Dead Horse. The platform will be thoroughly inspected by a third party and a post-analysis study conducted with recommendations on future operations. A thorough report will be provided after completion of this subtask.

Task 10.0 – Well Logging

The recipient shall run a suite of logs in the well(s) to characterize gas hydrate-bearing intervals, including the following: 1) electrical resistivity (dual induction), 2) spontaneous potential, 3) caliper, 4) acoustic transit-time, 5) neutron porosity, 6) density, and 7) nuclear magnetic resonance. Core data will be used to calibrate and quantify log information. A report on NMR log measurements of core taken during the 2003 drilling season is presented in **Appendix E**.

Task 11.0 – On-Site Core and Fluids Analysis

The recipient shall analyze core and fluids using a specially constructed mobile core laboratory, staffed by trained laboratory technicians. Core will be received in the cold module, where it will be photographed and assessed for the presence of hydrate. One-inch plugs will be removed from the core, and these plugs will be measured for porosity, permeability, compressional and shear wave velocity, resistivity, thermal conductivity, and NMR with specialized equipment specifically designed for making these hydrate core measurements, including a Schlumberger CMR tool. All of these measurements will be made under controlled pressure and temperature. Hydrate dissociation shall be monitored. Laboratory technicians will assist in preparing core for additional testing at other locations. Laboratory equipment is shown in **Figure 11**. Results of core and fluids handling procedures will be incorporated into the DOE-funded Westport Hydrate Core Handling Manual. The results of the analysis will be incorporated in Tasks 17, 18, 19 and 20.

Subtask 11.1 Mobile Lab Repair and Upgrade

The recipient shall repair and upgrade the mobile core lab, specifically to: 1) redesign the pressure and cooling system for the NMR spectrometer, in order to achieve significantly lower temperature capability required for analysis of hydrate samples; 2) improve insulation for the velocity-thermal conductivity-resistivity measurement system; 3) configure the NMR and VCR systems with capability to allow positive pore pressures of methane for hydrate stability; and 4) develop a central database for managing and storing all data measured in the mobile core lab.

Figure 11. Example Equipment in the Core Laboratory

Regarding the use of the LBNL CT on site:

1. We partitioned one end of a 20-ft Conex with a separate door to the outside for the X-ray room

2. There is a heater located in the room or an electrical outlet to add a portable heater

3. The x-ray room is adjacent to the station where the core will be cut to 3-ft lengths

4. Core sections were taken outside and then into the x-ray room

5. The x-ray machine can be started in a temperature-controlled environment

6. During shipment, the machine will be subjected to ambient temperatures as low as -40°F, (unless special measures are taken)

The x-ray scanner is certified to be "cabinet safe." This means that any personnel can be near it for normal operation, and the user does not need to be fitted with a dosimeter. Only a certified "system maintainer" can use tools to perform maintenance and has the ability to modify or override interlock safety features. This authority is granted from our EH&S department, and Victor will be the system maintainer. He will bring his own badge.

Regarding operation – the machine will need to be "tuned" to the samples that are collected. This means that adjustments must be made to both x-ray voltage and current depending on the density and composition of the samples. There could also be adjustments to the camera behind the image intensifier. It is hard to predict how often and when this task will need to be performed. Since we will be performing dual-energy scanning, both our hard and soft x-ray energies will need to be periodically readjusted depending on the collected core density and composition.

LBNL modified the machine so that it will hold a 3-ft piece of core. Four-ft long core holders were constructed since the extra space at the top of the core holder will be empty, preventing concern about core length. The quick scan will be performed in about two to three minutes from the time the sample in the sample holder is placed in the x-ray unit, to when it can be removed from the x-ray unit. A more detailed full 3-D CT characterization will take about 12 minutes for the entire 3-ft length. A shorter interval (i.e., 4 inches) can be scanned in full 3-D mode in about 2 minutes. We will have three to five core holders so that one can be loaded, while another one is being cleaned or prepped and a third can be in the scanner.

Task 12.0 – Shallow Seismic Survey(s)

After the well has been logged, a 3D vertical seismic profile (VSP) will be acquired to calibrate the shallow geologic section with seismic data and to investigate techniques to better resolve lateral subsurface variations of hydrate-bearing strata. Paulsson Geophysical Services, Inc. will deploy their 80 level 3C clamped borehole seismic receiver array in the wellbore to record samples every 25 ft. The surface vibrators will successively occupy 800 different offset positions arranged around the wellbore. This technique will generate a 3D image of the subsurface. Correlations of these seismic data with cores, logging, and other well data will be generated. This task shall include additional fabrication of receiver cables, rental of field vibrators and recording equipment and associated personnel.

Task 13.0 – Well Completion

After the seismic data have been collected, the recipient shall complete the well(s). The completion method will be determined based on the results of drilling, coring, and logging.

Task 14.0 – Well Instrumenting

The recipient shall core the well with a pressure and temperature gauge and a surface sensor to provide monitoring capabilities.

Task 15.0 – Well Testing

Well testing will be determined after the completion of the well by the recipient. If sufficient hydrates are encountered, the well will be shut in and the bottom hole pressure recorded. Water and gas samples shall be collected to determine their composition. The well may be monitored for pressure and temperature response for an extended period of time. After testing, the well will be plugged and abandoned.

Task 16.0 – Data Collection and Transmission

The recipient shall perform lab work and collect data on fluids captured during the well testing. The recipient shall also collect and transmit on-site monitoring information.

Task 17.0 – Reservoir Characterization of the Core

The recipient shall characterize the hydrate reservoir, based on analyses of fluids, geology, engineering, logs, geophysics, and rock physics. All these data will be included in a well simulator. The recipient shall determine the percentage of gas contained in the hydrate zone that can be recovered from the reservoir, and the potential production rates. Core studies will be conducted to accurately predict reservoir producibility potential.

Task 18.0 – Reservoir Modeling

The recipient shall use information developed in reservoir characterization efforts to quantify Lawrence Berkeley National Laboratory's hydrate simulator. LBL's advanced simulator system is based on EOSHYDR2, a new module for the TOUGH2 general-purpose simulator for multi-component, multiphase fluid and heat flow and transport in the subsurface environment. Reservoir simulation during this phase of the project will focus on considering production schemes, both short and long term, for hydrate production on the North Slope based on all the reservoir characterization data obtained. Depressurization, injection and thermal methods are some of the production processes to be considered with the simulation.

Task 19.0 – Quantify the Model

This task will parallel Tasks 17 and 18. The reservoir model used will need to be continuously refined as well test data are acquired. This effort is an ongoing task required for making projections. Models will be enhanced iteratively to incorporate dynamic production data during the well test period.

Task 20.0 – Economic Projections and Production Options

After all model results are received, the recipient shall assess economic projections and production options. The recipient shall present the results of the program to the Advisory Board and DOE. Information from other gas-hydrate projects shall be reviewed and included in our recommendations. Model-based estimates and production options will then be developed. If it is determined that a significant volume of gas production from hydrates is technically possible, an economic analysis will be conducted.

Task 21.0 – Post Well Analysis

This task is designed for planning to conduct operations including an extended well production test in 2004 on another area of the North Slope of Alaska. A report and budget for an additional well and an extended well test will be produced based on the information generated from the Phase II activities (including lessons learned). It will be determined if an additional well and/or extended production test is warranted, and recommendations will be presented to the DOE in sufficient time for FY 2004 budget planning. We anticipate the additional well will be drilled in another lease area/region of Alaska. The production test plan will help determine the producibility of hydrate deposits. These plans will be valuable for future hydrate operations, even if this project is not extended into Phase III.

Task 22.0 – Information Acquisition and Technology Transfer

The recipient shall communicate and exchange information with experts in the field of hydrate well drilling, coring, and testing, including Advisory Board members, to stay abreast of the latest technology and preferred methodologies. The recipient shall also document results of the field tests and transfer this technology to the industry.

Subtask 22.1 Information Acquisition

The recipient shall identify and network with other experts in the field of hydrate well drilling, coring, testing, and analysis to gain insights into the latest methodologies and technologies. The recipient shall follow the latest developments related to hydrate wells by meeting with experts in the scientific and drilling communities.

Subtask 22.2 Technology Transfer

The recipient shall document project results and transfer the new information and technology to the industry, via web site postings, meetings, workshops, and at least one technical paper. The recipient shall also use the NED Smart Drill system to allow well activities to be viewed by scientists, engineers, and DOE project managers who are not present at the well site.

DELIVERABLES

The periodic, topical, and final reports shall be submitted in accordance with the attached Reporting Requirements Checklist and the instructions accompanying the checklist. In addition, the Recipient shall submit the following:

Phase I

1. Digital Map of all well locations in and adjacent to project area (Task 2.1)
2. Well log correlation sections showing lithologic and stratigraphic units that fall within the gas hydrate stability zone in and adjacent to the project area (Task 2.1)
3. Seismic maps and sections showing extent of stratigraphic and lithologic units that fall within the gas hydrate stability zone in and adjacent to the project lease area (Task 2.2)
4. Reservoir modeling report for proposed site (Task 3.0)
5. Well Data for individual control wells used for site selection (Tasks 2.1 & 4.1)
6. Site Selection Plan (Task 4.1)
7. Testing and analytical procedures report (Task 5.0)
8. Well plan(s) (Task 6.0)

Phase II

1. Drilling and Coring Report (Task 9.2)
2. Well Logging Report (Task 10.0)
3. Core and Fluid Analysis Report (Task 11.0)
4. Bibliography of Publications by Project Personnel (see Section 6)
5. Seismic Survey Report (Task 12.0)
6. Well Completion Report (Task 13.0)
7. Well Testing Report (Task 15.0)
8. Hydrate Reservoir Characterization and Modeling Report (Tasks 17, 18, &19)
9. Economic Projections (if production volumes dictate) and a Production Options Report (Task 20.0)

10. Plan for Future Hydrate Well on the North Slope (Task 21.0)

11. Technical Publications Summarizing Project Findings (All Tasks)

12. Final Report Summarizing Project Findings (All Tasks)

In addition to the required reports, the recipient shall submit informal status reports directly to the COR. These are preferred monthly with short descriptions of successes, problems, advances or other general project status information. The report should not exceed one page in length and shall be submitted via e-mail.

The Contractor shall also provide the following to DOE: a copy of all non-proprietary data, models, protocols, maps and other information generated under the cooperative agreement, when requested by DOE, in a format mutually agreed upon by DOE and the participant.

5. Conclusions

Operations on the Hot Ice #1 Hydrate Well are currently suspended pending the return of cold weather. Anadarko is committed to resume coring operations in the first quarter of 2004, prior to the opening of the conventional operations season. Casing was set just above the West Sak formation and a sand accumulation at the top of the West Sak should provide a good chance to encounter hydrates. After operations commence, the hydrate stability interval will be cored to approximately 2200-2400 feet (670-732 meters) deep. After total depth is reached and the well ID logged, depending on the amount of hydrates encountered, a final completion program will be formulated.

The complete set of core, well log, production and downhole pressure and temperature data will be made available for use in evaluating the hydrate reservoir's quality and to determine the potential for production from arctic hydrate intervals. The data will be incorporated into hydrate reservoir models to test possible scenarios for producing methane from hydrates in similar settings.

DOE NETL has also established a special web page for references to their support of gas-hydrate development. At their site (http://www.netl.doe.gov/scng/hydrate/) are posted updates describing the Hot Ice project as well as the latest version of "Fire in the Ice," the National Energy Technology Laboratory Methane Hydrate Newsletter.

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Appendix A: Hot Ice #1 Site/Rig Photos

Figure A-1. Hot Ice Well #2 Site

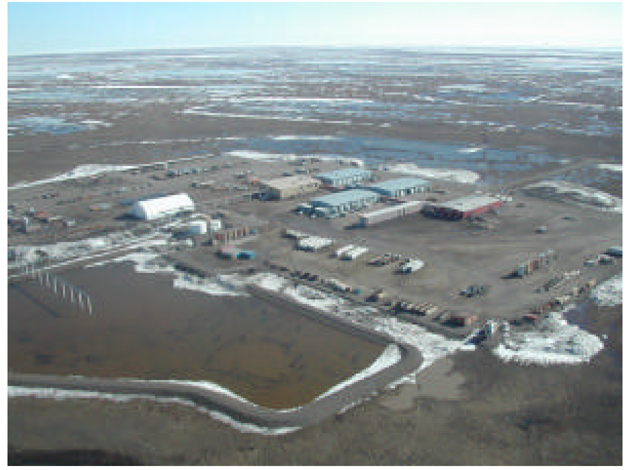


Figure A-2. Base Camp

Figure A-3. Setting the First Platform Module

Figure A-4. Assembling the Platform

Figure A-5. Complete Camp Ready for Drilling

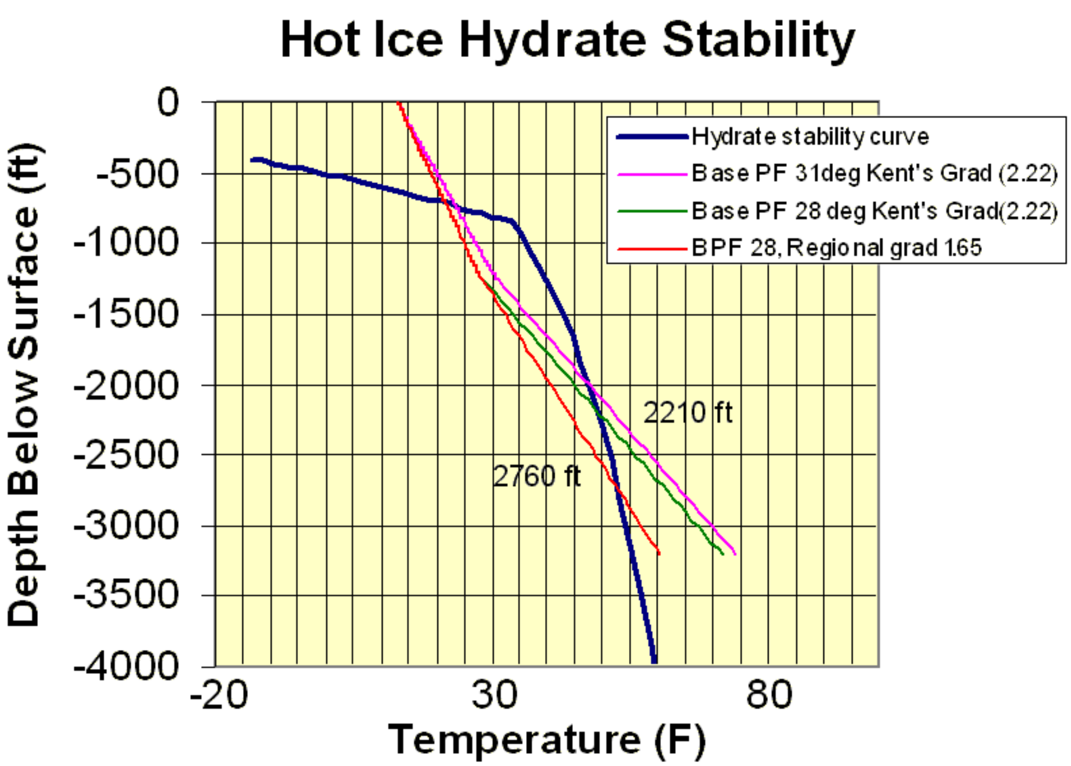
Figure A-6. Team Members on the Rig Floor

Appendix B. Recalculation of Base of Hydrate Stability Zone

Information from the Hot Ice well and an analysis of the local geothermal gradient provided a new estimate for the base of the hydrate stability zone (BHSZ). This re-analysis places the BHSZ at **2210 ft** below the surface at the Hot Ice location. This is 400 ft shallower than the estimate based on regional maps from Collett et al. (1988).

Both core and log data show the well entering into unfrozen material at 1240 ft below the surface at the Hot Ice location. The base of frozen material occurs in a thick sand interval. Because of this, 1240 ft is the base of permafrost. The BHSZ then depends on temperature at this depth, thermal gradient, and the methane hydrate stability curve. Collett et al. find the average temperature at base of permafrost to be 28°F. The BHSZ only weakly depends on the exact temperature chosen within the possible range of values. The most important variable is the thermal gradient.

Newsham (Internal Anadarko Report) examined logs from West Sak 20 Cirque 2 and Ruby State 1. Using the log-identified base of permafrost, corrected bottom hole temperatures, and a temperature at base of permafrost of 28°F, he finds a local thermal gradient of 2.22°F per 100 ft. The most critical part of this calculation is the correction to the log-recorded bottom hole temperature. Newsham corrected the bottom hole temperature data using the diffusion model documented by Lachenbruch et. al. (1982). This local gradient is somewhat larger than the regional gradient of 1.65°F per 100 ft given in Collett et al. (1988). The figure below shows the BHSZ determination using both gradients and two possible temperatures at the base of permafrost.



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Appendix C. Notice of Opening of Tundra for 2003-2004 Winter Season

STATE OF ALASKA

FRANK H. MURKOWSKI, GOVERNOR

DEPARTMENT OF NATURAL RESOURCES

DIVISION OF MINING, LAND AND WATER

NORTHERN REGION
3700 AIRPORT WAY
FAIRBANKS, ALASKA 99709-4699
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January 8, 2004

NORTH SLOPE WINTER OFF-ROAD (Tundra) TRAVEL

NOTICE OF OPENING
Western Coastal Area

Department of Natural Resources staff has documented differential ranges of ground hardness and snow cover within the various tundra opening areas. The Western Coastal area has reached the same hardness as the East Coastal Area, which was opened on December 23, 2003. However, the Lower Foothills and Upper Foothills areas are still much softer than the coastal areas. Therefore, the Department of Natural Resources going to open the Western Coastal Area.

The tundra is open to all vehicles in the Western Coastal Area for the 2003-2004 winter season effective at 8:00 AM January 9, 2004.

This opening applies only to those operators who have *valid off-road vehicle travel permits* to operate on state-owned lands on the North Slope.

Note that the ground may be relatively soft in areas with heavily drifted snow. Special attention should be given to the Division of Mining, Land and Water's stipulation regarding winter off-road vehicle travel, which requires adequate frost and snow cover. Site inspections will be conducted periodically by state personnel to ensure compliance.

Note also that DNR staff will continue to travel to the North Slope to determine when the Lower Foothills and Upper Foothills areas can be opened. Until these areas are open, projects in these areas (especially those using low ground pressure vehicles) will be approved on a case-by-case basis.

If you have any questions concerning this opening, direct them to Leon Lynch at 659-2830 or Chris Milles at 451-2711. Please note that this and subsequent notifications will be distributed only by e-mail; faxes will no longer be sent out.

Harry Bader
Regional Manager

Appendix D. Geological Exhibits – HOT ICE #1

The following will be developed during and following the completion of the well:

Base Map with Structural Contours:

This exhibit will be the primary reference map for Anadarko Petroleum Corporation's geological investigation for gas hydrates on the North Slope of Alaska with the following information:

- Anadarko's acreage position with the prospective Hot Ice locations spotted.
- Well control displayed on the map are those with available shallow log data that could be utilized for this study.
- Color coding on well control depicts the presence of free gas as red, gas hydrates in green or the presence of neither as blue based on data presented in USGS open file reports or from our own investigations. The text indicates the presence of free gas, gas hydrates or both by Z-zonation and alphabetically designated units based on USGS cross-section presented in this report as cross-section A-A' and USGS open file reports.
- Cross-section lines A-A' (USGS cross-section), B-B', C-C' and D-D' and NW – SW lithologic section annotated.
- Revised structure map on Top of the West Sak sequence (basal Ugnu shale) at a contour interval of 200'. Structural strike is generally north and south with monoclinal east dip. Structural contours and faults are a digitized and slightly edited version of maps for the Milne Point and West Sak units that are exhibits of public record available from the AOGCC. The maps will probably include both seismic and subsurface controlled and generated by the operator Conoco/Phillips. The horizon mapped by the operator to match picks for the Top of the West Sak interval.

Gas Hydrate Potential Map:

A transparency designed to overlay the base map to illustrate the potential areal extent of gas hydrates and concomitant free gas accumulations that may exist as delineated by investigations conducted by the USGS and Anadarko Petroleum in this general area. The western and eastern boundaries of the potential gas hydrate accumulation in the Tarn/Cirque/Meltwater roughly defined as the entry and exit point of the West Sak and Ugnu interval in the HSZ. The southern boundary established by the absence of any indications of free gas or gas hydrates in wells of that area. To the north, the potential undefined. The USGS has documented the presence of gas hydrates in some of the wells situated to the north of the dashed line that indicates a loosely defined border in that direction.

A Post drill assessment will reduce the areal extent of the Probable Gas Hydrate realm.

Appendix E. NMR Measurements of Permafrost: Unfrozen Water Assay, Growth Habit of Ice, and Hydraulic Permeability of Sediments

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12 January 2004

Abstract

Nuclear magnetic resonance (NMR) measurements have been made on permafrost recovered from a well on the North Slope of Alaska. These measurements show that unfrozen water is correlated with the clay content of the sediments, and inversely correlated to ash content of the coals. NMR is sensitive to the pore-scale distribution of liquid water, so the growth habit of ice within the pore space of the sediment can be determined. Hydraulic permeability can be rapidly estimated, and has been found to depend strongly on the unfrozen water content. The ratio of the permeability of ice-affected sediment to the permeability of the same sediment saturated with liquid water appears to be surprisingly independent of lithology. Comparison between core measurements and wireline logs demonstrates that the unfrozen water content of permafrost can be predicted from borehole NMR measurements of thawed formations.

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1. Introduction

Anadarko Petroleum Corporation, Maurer Technology Inc., and Noble Drilling Corporation collaborated to drill the Hot Ice #1 well on the North Slope of Alaska. During the 2002-2003 drilling season an innovative drilling rig was constructed and a well drilled to the base of permafrost. A mobile arctic core laboratory was installed on the drilling rig to process core cut continuously from surface to total depth. Schlumberger-Doll Research provided personnel and a nuclear magnetic resonance (NMR) instrument to this laboratory *gratis*. After completion of drilling, Schlumberger Oilfield Services logged the well; magnetic resonance was included among the borehole measurements.

The objective of the project was to assess the potential gas hydrate reservoir and initiate production tests. No gas hydrate was detected in the permafrost zone, and time constraints prohibited drilling to hydrate deposits expected at greater depths. Therefore all scientific results from the first drilling season at Hot Ice #1 pertain to permafrost. The permafrost results are of interest in themselves. Moreover, although permafrost and gas hydrate deposits differ in many respects, similarities between ice and gas hydrate suggest that insight into one may be gained by study of the other.

Permafrost has been studied for many years, but fresh perspectives can be derived from the use of magnetic resonance well logging tools that have been developed over the last decade [*Kleinberg*, 1996]. One of these instruments [*Kleinberg et al.*, 1992] has the unusual capability of making measurements on compact samples external to the antenna and magnets of the apparatus. Because this instrument is designed to withstand the rigors of oilfield deployment, it can be used on an arctic drilling rig under conditions that would challenge the survivability of conventional laboratory equipment.

Nuclear magnetic resonance is commonly thought of as either a spectroscopic probe for organic chemistry or a medical imaging modality. The petrophysical applications of NMR are quite different from either of these [*Kleinberg and Flaum,* 1998; *Kleinberg*, 1999]. As used to characterize sedimentary rock, NMR quantitatively determines oil and water content, oil viscosity, and the pore size distribution of water-saturated rock. Knowledge of pore size distribution is used to estimate hydraulic permeability.

Recently these capabilities have been applied to the study of methane hydrate synthetically produced in rock and sediment under conditions thought to mimic earth processes [*Kleinberg et al.*, 2003a, 2003b], and to the well log evaluation of natural gas hydrate deposits [*Kleinberg et al.*, 2004]. These techniques are directly applicable to the study of permafrost, both in recovered core and *in situ* in the earth.

2. Location, Apparatus, and Methods

Measurements were made on the Anadarko Hot Ice 1 drilling rig, located approximately 35 km (22 miles) south of the Arctic coast of Alaska, 67 km (42 miles) east of Deadhorse AK, latitude N 70°06.535', longitude W 150°12.508' (NAD 83). Ground level elevation was 57 meters (188 feet) above mean sea level, and the kelly bushing of the drilling rig was 65 meters (214 feet) above mean seal level. Unless otherwise stated, all reported depths are relative to the kelly bushing. Continuous 7.6-cm (3.0-inch) diameter core was taken from surface to 428 meters (1403 feet) during March and April 2003. Lithologies in the drilled interval are unconsolidated fine sands ("sandstone"), clays ("mudstone"), ice lenses typically thinner than 1 cm, and coals.

Average temperature a few meters below the surface is -9°C [*Shiklomanov and Nelson*, 1999]. Observed base of permafrost is at a depth of 384 meters (1260 feet) (376 meters (1234 feet) below ground level). The base of permafrost does not, in general, correspond to the 0°C isotherm, which can be considerably deeper [*Lachenbruch et al.*, 1982; *Collett et al.*, 1993]. The cored interval overlaps several hundred meters of the gas hydrate stability zone [*Collett et al.*, 1993], but no evidence of free gas or gas hydrate was found.

Special core handling techniques were used to preserve the integrity of the permafrost core. After drilling a 3-m interval, a wireline-retrieved core barrel was recovered from the well, the core extracted, and then cut into 1-m lengths. The core was immediately delivered to a core analysis trailer adjacent to the rig floor for petrographic description and NMR measurement. The wellbore was maintained near -3°C, the rig floor and cutting shack were typically -14°C, and temperature of the core-analysis trailer was maintained between -5°C and -2°C. Generally speaking, approximately 60 minutes elapsed from the time core was recovered at the wellhead to the start of NMR measurements, which took approximately 5 minutes per sample.

The nuclear magnetic resonance instrument used in this investigation was the Schlumberger Combinable Magnetic Resonance Tool (CMR). The CMR is an oilfield wireline logging tool rated to survive and operate in arctic, tropical, desert, and marine environments. Deployment of this tool to drilling rigs on the North Slope of Alaska is routine. For the purpose of measuring whole core as it was retrieved from the well, the CMR was installed in the chilled core analysis trailer adjacent to the rig floor.

The CMR volume of investigation is approximately 15 cm long and 2x2 cm in cross-section, centered about 2.5 cm inside the sample. The primary calibration was a water-filled Plexiglas tube whose dimensions were identical to the recovered core. The calibration sample had the same concentration of potassium chloride as the drilling fluid, [KCl] = 1.4 moles/liter, and was doped with iron sulfate for measurement convenience. The calibration sample was remeasured about once a day to detect instrument drift; none was detected.

Typically, each 1-m long piece of core was measured at one location; hence coverage was 15 cm per meter of core length. Some attempt was made to minimize selection bias. Grossly washed-out sections and conglomerates were both undersampled, on the basis that measurements of these intervals would be meaningless in any event. Visible ice lenses, which comprised a very small fraction of the recovered core, were generally excluded from the measured volumes, as the goal of the investigation was to understand how permafrost interacts with pore space of the sediment.

The CMR is sensitive to electromagnetic interference at 2.2 MHz, and to broadband noise sources in general. To minimize measurement noise in the core analysis trailer, a 38-cm diameter x 85-cm long open-ended wood-frame copper screen shield was installed around the tool antenna and core sample. It was found that when core protruded from the end of the shield it could conduct significant interference to the antenna. Thus, cores were broken when necessary so that the measured piece would fit entirely within the shield enclosure. Similarly, noise could be conducted to the antenna by salty debris on the conveyer belt used to position the cores at the CMR antenna. Occasional cleaning of the belt was required.

3. NMR Fundamentals

3.1 NMR Relaxation of Water in Sediments

Measurements of transverse nuclear magnetic relaxation times, T_2, have proven to be useful in porous media studies. The Carr-Purcell-Meiboom-Gill (CPMG) [*Carr and Purcell*, 1954; *Meiboom and Gill*, 1958] pulse sequence is used. When irradiated with this sequence, a nuclear spin system will radiate back a series of equally spaced magnetic field pulses, called spin echoes. Echo spacing, T_E, is typically on the order of 10^{-4} s. Measuring the decay of echo amplitudes during the sequence monitors the transverse magnetization relaxation. Zero-time amplitude of the proton NMR signal is proportional to the hydrogen content of the sample.

For most liquids in bulk, including water, transverse magnetization decay is exponential, so the amplitude of the n^{th} spin echo, occurring at time $t = n \cdot T_E$, is

$$M(t) = M_0 \, exp\left[-\frac{t}{T_{2B}}\right] \tag{1}$$

Amplitude M_0 is proportional to the number of hydrogen nuclei in fluids in the volume of investigation. Characteristic decay time of the echo amplitudes, T_{2B}, is called the bulk transverse relaxation time. Bulk relaxation times, which are independent of the concentration of salt at ocean salinities, are $T_{1B} = T_{2B} =$ 1.762 s at 0°C [*Simpson and Carr,* 1958].

NMR relaxation rate of fluids in porous media is largely controlled by relaxation at the pore/grain interface [*Bloch,* 1951]. Molecules in a fluid diffuse, eventually reaching a grain surface where their nuclear spins can be relaxed. For water in sediments and sandstones, the rate limiting step is the relaxation process at the surface, not the transport of unrelaxed spins to the surface [*Kleinberg et al.*, 1994]. Magnetization decay, M(t), in an individual pore is exponential:

$$M(t) = M_o \, exp\left[-\frac{t}{T_{2S}}\right]. \tag{2}$$

Decay rate does not depend on pore shape but only on the surface-to-volume ratio, S/V, of the pore:

$$\frac{1}{T_{2S}} = \rho_2 \left(\frac{S}{V}\right)_{pore} . \tag{3}$$

Thus, water in small pores relaxes rapidly, while water in large pores relaxes more slowly. The surface relaxivity coefficient ρ_2 is a characteristic of magnetic interactions at the fluid/solid interface [*Kleinberg et al.*, 1994; *Foley et al.*, 1996]. In sandstones and analogous materials it is dominated by paramagnetic ions residing at grain surfaces. It is independent of temperature [*Latour et al.*, 1992] and hydrostatic pressure [*Chen et al.,* 1994] over broad ranges. Its value is typically ρ_2 = 5 μm/s for sandstones [*Kleinberg*, 1999], which is expected to hold, at least approximately, for sediments encountered here.

Bulk and surface relaxation processes operate in parallel, so the observed magnetization decay is written as

$$M(t) = M_o \, exp\left[-\frac{t}{T_2}\right] \tag{4}$$

where

$$\frac{1}{T_2} = \frac{1}{T_{2B}} + \frac{1}{T_{2S}} \tag{5}$$

Rocks and sediments generally have very broad distributions of pore sizes, and therefore magnetization decays can be expressed as a sum of exponential decays [*Gallegos and Smith,* 1988]:

$$M(t) = \sum_i m_i \, exp\left[-\frac{t}{T_{2i}}\right] \tag{6}$$

where m_i is proportional to the volume of fluid relaxing at the rate $1/T_{2i}$. The sum of the volumes is proportional to the fraction of the material occupied by liquid, the porosity ϕ_{NMR}:

$$M_o = \sum_i m_i \sim \phi_{NMR} \tag{7}$$

Thus there is a direct mapping from the distribution of pore sizes, or more precisely the distribution of surface-to-volume ratios, to the distribution of relaxation times.

To analyze measurements reported here, monotonic but non-exponential magnetization decays were fit to Eqn (6), where M(t) typically represented the amplitudes of 5000 spin echoes with T_E = 200 μs, and the T_{2i} were typically 50 preselected time constants, equally spaced on a logarithmic scale between 0.3 ms and 5000 ms. The number of terms in the summation is somewhat arbitrary since the exponentially decaying basis functions are not linearly independent. In fact, there are far less than 50 independent pieces of information in a typically noisy decay. Therefore, the set of 50 $m(T_{2i})$ was found using a regularized nonlinear least-squares technique that renders the results smooth and stable in the presence of random noise [*Butler et al.*, 1981]. The function $m(T_2)$, conventionally called a T_2 distribution, maps linearly to a volumetrically weighted distribution of pore sizes [*Gallegos and Smith,* 1988; *Kleinberg*, 1999].

3.2 The Effect of Ice

Ice contains abundant hydrogen, but this hydrogen is invisible because the CMR is not sensitive to nuclei in solids. Therefore the presence of ice, like methane hydrate, reduces apparent NMR porosity [*Kleinberg et al.*, 2003a]. It also diminishes the integrated amplitude and changes the shape of the apparent (i.e. water-filled) pore size distribution. These changes depend on where the ice resides within the pore space, and on the magnetic coupling between pore water and ice.

If ice coats grain surfaces, its relaxivity to liquid water, ρ_2(water-ice), replaces ρ_2(water-rock) in Eqn (3). In principle, pore size information will be retained, but the transformation between T_2 and pore diameter is changed. On the other hand, if ice grows in the interior of pores, its surfaces add to the silica grain surfaces, and Eqn (3) must be generalized to account for the simultaneous influence of two different surfaces.

Relaxivity of the ice/water surface is unknown, but the following end-member scenarios can be identified:

1. Ice coats grain surfaces and ρ_2 (water-ice) << ρ_2(water-rock): In all but the smallest pores, the bulk relaxation process will dominate, and the relaxation time distribution $m(T_2)$ will tend to pile up at T_{2B} ~ 1.7 s.

2. Ice coats grain surfaces and ρ_2(water-ice) >> ρ_2(water-rock): Shapes of the relaxation time distributions are approximately preserved, but are reduced in amplitude and displaced toward shorter relaxation times relative to the same sediment fully saturated with liquid water.

3. Ice fills the largest pore spaces and ρ_2(water-ice) << ρ_2(water-rock): Water relaxes at grain surfaces while being excluded from large pore bodies. Signal disappears first at the longest

values of T_2. Paradoxically, there will be a concomitant increase of signal at short values of T_2, which occurs due to rapid relaxation of remnant liquid water coating mineral grains in large pores mostly filled with ice.

4. Ice fills the largest pore spaces and ρ_2(water-ice) >> ρ_2(water-rock): Water relaxes at both grain and ice surfaces, so the relaxation time distribution is concentrated at short values of T_2.

In reality, the NMR response might be composed of a combination of these effects, for example if the grains are partially coated with ice. In general, as the pore space fills with ice, the amplitude will decrease, with likely distortion of the T_2 distribution.

4. Recovered Core Results

4.1 Unfrozen Water Assay

As expected, apparent permafrost NMR porosity (liquid-water-filled pore space as a fraction of total sediment volume) was generally less than 0.1, considerably lower than would be expected for shallow unfrozen liquid-water-saturated sediments. In contrast, coals were characterized by unfrozen water contents of about 0.20-0.25 of total volume. At the base of permafrost, which occurred within a reasonably massive sand body, NMR determined porosity increased rapidly over an interval of 4 m. A sudden systematic increase in NMR-determined unfrozen water content was an earlier indication of the base of permafrost than petrographic examination. These results are discussed further in connection with borehole log data in Section 5.

4.2 Growth Habit of Ice: Observations While Thawing

Two typical 30-cm lengths of core, one sand (from depth 211 m (692 feet)) and one mud (from depth 202 m (662 ft)), were removed from storage at -14°C and allowed to thaw in an 18°C room. NMR measurements were made on the cores approximately once an hour for nine hours. The unfrozen water porosities are plotted as a function of time in Figure 1. The sand started with significantly lower unfrozen water porosity than the mud. The mud completely thawed in 4.5 hours, and the sand in 6 hours. The data reflect conditions in a volume centered 2.5 cm from the surface of the 7.6-cm diameter cores, as described in Section 2.

In both cases, the unfrozen water at -14°C was significantly lower than the unfrozen water found when the core was first removed from the well, at a temperature of approximately -3°C. Wellhead values of apparent NMR porosity are denoted by horizontal lines in **Figure 1**.

Relaxation time distributions are shown in **Figure 2** for the mud and **Figure 3** for the sand. A pore space model is required to convert relaxation time to pore diameter. A convenient model is a network of interconnected cylindrical tubes; this is the model used (often implicitly) to analyze mercury porosimetry data for natural earth materials. In this model, surface-to-volume ratio of a pore is S/V = 4/D, where D is pore diameter. Then NMR-determined pore diameter is related to relaxation time T_2 by

$$D = 4\rho_2 T_2 = (20\,\mu m/s) \cdot T_2 \tag{8}$$

For both sand and mud, the frozen cores are characterized by low amplitude distributions centered on short relaxation times. As the cores thawed, amplitude increased, especially at the longest relaxation times. In both **Figures 2** and **3** the topmost curves represent thawed fully liquid-water-saturated pore size distributions.

In **Figure 3**, growth of the porosity component around 2 ms (0.04 μm pore diameter) is not monotonic. This effect is widely observed in NMR well logs of natural gas reservoirs, and is easily explained. When a nonwetting phase occupies large pores, water generally continues to coat pore walls. Surface-to-volume ratio (S/V) of this pore-lining water is much greater than S/V of water when it completely filled the same pore. Thus the remnant water relaxes at a faster rate, thereby appearing to add to the smaller-pore population [*Kleinberg and Boyd*, 1997].

Comparing these results to the four possibilities listed in Section 3.2, the mudstone results are consistent with (2), (3) or (4). Sandstone results are consistent only with (3).

4.3 Growth Habit of Ice: Transition Zone Sands

Fortuitously, the base of permafrost (at a depth of 384.0 m (1260 ft)) lay within a reasonably massive and homogeneous sand body. This sand body thus constituted a natural laboratory for exploring the development of frozen sediment. The transition from fully liquid water-saturated sediment to permafrost occurs over a depth interval of 4 m.

Relaxation time distributions through the transition zone are shown in **Figure 4**. Distributions at 384.7 m (1262 ft) and 386.8 m (1269 ft) appear to be trimodal while the others are bimodal. The trimodal curves are unlikely to represent three distinct populations in the liquid-water-filled pore size distribution, but instead represent a limitation of the nonlinear signal processing. A reasonable interpretation of the 384.7 m and 386.8 m curves is that they are essentially flat-topped.

Above the base of permafrost, the water signal is small and concentrated at short relaxation times. Following the same reasoning used in the discussion of the thawed samples, these observations indicate that unfrozen water is localized in small pore spaces, where it is in contact with grain surfaces that are not coated with ice. As depth increases, unfrozen water occupies more of the pore space. In the transition zone, water occupies small, mid-sized and large pore spaces of this sand, as reflected by the low NMR signal amplitude. At a depth of 387.7 m (1272 feet), water is completely unfrozen and the relaxation time distribution reflects the pore size distribution of the sediment.

As for the samples discussed earlier, excess signal at short relaxation time in the frozen samples reflects the presence of water coating the grain surfaces of large pores, the interiors of which are filled with ice. Results are consistent only with possibility (3) listed in Section 3.2: ice preferentially fills the largest pore spaces, and it is not an effective relaxing surface for liquid water.

4.4 Hydraulic Permeability

Hydraulic permeability of a porous medium depends generally on the square of the cross-sectional dimension of the flow channels [*Scheidegger*, 1960]. Sensitivity of NMR measurements to pore size makes it a good permeability indicator for sandstones [*Straley et al.*, 1994]. The NMR estimate of permeability has been tested on thousands of sandstones over the years; order-of-magnitude agreement with laboratory measured values is expected. However, the technique has not been systematically tested in unconsolidated sediments, nor in sediments consolidated by ice. Therefore we must proceed with some caution.

The empirical correlation that connects hydraulic permeability k_0 to porosity and a one-parameter measure of relaxation time, T_{2LM}, is

$$k_0 = C \cdot \phi_{NMR}^4 \cdot T_{2LM}^2 \qquad (9)$$

where T_{2LM} is the logarithmic mean value of the T_2 distribution.

$$T_{2LM} = 10^{\left[(1/\phi)\sum_i m(T_{2i}) \cdot \log_{10}(T_{2i})\right]} \qquad (10)$$

C is a coefficient which depends on mineralogy and on the magnetic impurity content of the grain material. A large number of measurements on water-saturated clean and clay-rich sandstones showed that typically $C = 4000\ D/s^2$ [*Straley et al.*, 1994] (1 Darcy $\approx 0.987 \times 10^{-12}\ m^2$).

4.5 Relative Permeability

Relative permeability is the permeability of sediment to a single fluid when two or more constituents occupy the pore space. In a rock or sediment containing oil, water, and/or or gas, each of these fluids will have different relative permeability, which depends on the saturations. Here we use the term to describe hydraulic permeability when part of the pore space is partially filled with ice:

$$k_{rw} = \frac{k(S_W)}{k_0} \tag{11}$$

where k_0 is permeability of the fully liquid-water-saturated sediment, and $k(S_W)$ is permeability at water saturation S_W, with the remaining pore space filled with ice at saturation $S_i = 1 - S_W$.

Relative permeability may be found when permeability measurements of both fully water-saturated sediment and the same sediment partially saturated with ice are available. This is the case in the thawing studies, where NMR properties of a sample are followed over a range of water saturations. It is also the case at the base of permafrost, to the extent that sediment properties are uniform over the transition zone. Water saturation is found from

$$S_w = \frac{\phi_{NMR}(S_w)}{\phi_{NMR}(S_w = 1)} \tag{12}$$

where $\phi_{NMR}(S_W)$ and $\phi_{NMR}(S_W{=}1)$ are apparent NMR porosities in the partially and fully water saturated sediment, respectively. Using this and Eqn (9), NMR estimated relative permeability is

$$k_{rw} = \frac{k(S_W)}{k_0} = S_W{}^4 \cdot \left(\frac{T_{2LM}(S_W)}{T_{2LM}(1.0)} \right)^2 \tag{13}$$

The mineralogy-dependent coefficient C does not appear in this ratio.

As noted above, this approach has some important limitations: the permeability estimate is based on an empirical correlation, not a flow measurement, and it assumes that the correlation is as valid for ice-affected sediment as it is for water-filled rock. A subsidiary assumption is that NMR relaxation of liquid water at an ice surface is no stronger than at a mineral grain surface, i.e., ρ_2(water-ice) << ρ_2(water-rock), as concluded in Sections 4.2 and 4.3. It also assumes that differences of the microgeometrical distribution of water in unfrozen and partially frozen rock do not invalidate the correlation.

Relative permeability estimates for the thawed samples, and for sands at the base of permafrost are shown in **Figure 5**. All data follow a common trend as a function of liquid water saturation. This is surprising since k_0 differs widely among these three samples, as noted above. However, the proportionate impact of the presence of ice appears to be the same.

The data can be compared to simple models for relative permeability derived elsewhere [*Kleinberg et al.*, 2003b]. Results for various models are:

ice coating the walls of capillary tubes:

$$k_{rw} = S_w{}^2 \tag{14}$$

ice growing in the centers of capillary tubes:

$$k_{rw} = 1 - (1 - S_w)^2 + \frac{2 S_w{}^2}{\log(1 - S_w)} \tag{15}$$

ice coating the surfaces of a grain pack:

$$k_{rw} = S_w{}^{n+1} \tag{16}$$

For this model, the saturation exponent n equals 1.5 for $0<S_i<0.8$ ($1>S_w>0.2$) [*Spangenberg*, 2001]. For $S_i>0.8$ ($S_w<0.2$), the saturation exponent diverges, but in this regime relative permeability to water is already small, and the increase of the saturation exponent has only a minor effect.

ice growing in the centers of a grain pack pore space:

$$k_{rw} = \frac{S_w{}^{n+2}}{\left(1 + (1 - S_w)^{0.5}\right)^2} \tag{17}$$

Neglecting the effects of capillary pressure, the saturation exponent increases from n = 0.4 at $S_i = 0.1$ ($S_w = 0.9$) to unity at $S_i = 1$ ($S_w = 0$), [*Spangenberg*, 2001].

NMR estimates of relative permeability agree better with the models that assume ice fills the centers of pores than with those that assume ice coats pore walls. The same conclusion is independently drawn from the relaxation time distributions discussed above.

5. Core/Log Comparison

In addition to measurements made on recovered core, magnetic resonance well log measurements were made in the borehole after the completion of coring. The NMR instrument used for well logging was a nearly identical copy of the instrument used in the core lab to measure retrieved core samples. The pulse sequence was the same as that used for the core measurements. Pulse sequence parameters were somewhat different, but the differences are not expected to affect the results.

During the 15 days of coring operations the 428 m (1403 feet) deep wellbore was substantially thawed by the 1.4M KCl drilling fluid. Unconsolidated sediment sloughed into the wellbore with the result that it was enlarged beyond the 216-mm (8½-inch) diameter of the drill bit (**Figure 6**). The wireline tool was pressed against the borehole wall with a bow spring, but in the irregular borehole the sensor can intermittently lose contact with the surface. The wireline magnetic resonance measurement, like the NMR measurement on core, is made in a volume centered 25 mm from the face of the apparatus. If there is borehole fluid in this volume, the NMR amplitude will be erroneously high.

As **Figure 7** reveals, well log porosities frequently exceeded the maximum porosity expected in shallow terrestrial sediments, about 0.4. Except for a few minor intervals at the top of the well, there is no agreement between core measurements of unfrozen water porosity and well log porosity measurements, even where the borehole was not enlarged beyond bit size. This suggests that not only was the wellbore enlarged but also thawed, at least to the radial depth of the NMR measurement volume, prior to well logging. Even if near-wellbore sediments were below the freezing point of fresh water, KCl migration from the borehole into the pore space lowered the freezing point of the pore fluid.

In conventional interpretation of petrophysical measurements, the NMR signal is partitioned into bound water (small pore) and free water (large pore) porosity [*Kleinberg*, 1999]. In sandstone formations, this partition is conventionally made at T_{cutoff} = 33 ms. Water in pore spaces relaxing faster than 33 ms, corresponding to a pore diameter of about 0.7 μm, is not movable at a pressure difference of less than 0.7 MPa (100 psi). Taking into account the details of how water is trapped in porous media by capillary forces, a tapered function is applied to the fully-water-saturated pore size distribution to determine the amount of porosity included in the small-pore fraction [*Kleinberg and Boyd*, 1997]. For T_2 components below $T_{2cutoff}/4$ all measured porosity is included in the small-pore estimate. For $T_2 > T_{2cutoff}/4$

$$m(T_2)_{taper} = m(T_2)\left[\frac{T_{cutoff}}{2T_2} - \left(\frac{T_{cutoff}}{4T_2}\right)^2\right] \tag{18}$$

The small pore analysis is illustrated at 365.8 m (1200 ft) in **Figure 8**. The topmost curve is the well log relaxation time distribution of the thawed formation; the corresponding porosity is 0.317. Within it is plotted the small pore relaxation curve computed using Eqn (18), with a porosity of 0.047. The lowest curve (inverted for clarity) is the relaxation time distribution measured on the core taken from the same depth, with a porosity of 0.039. The small-pore-porosity from the well log and the unfrozen-water-porosity from the core agree to within the ±0.01 error bars of the measurement.

This analysis was repeated for the entire borehole, a representative section of which is shown in **Figure 9**. Below the base of permafrost (horizontal line at 384 m (1260 feet)), core unfrozen water includes both small-pore-porosity and large-pore-porosity, and therefore the core points fall above the log-derived small-pore-porosity. Above the base of permafrost the data are in excellent agreement.

Agreement persists even where the borehole is grossly washed out and NMR values spike to values well above 0.4, indicating that substantial amounts of borehole fluid must be included in the well log measurement, see e.g. 250–300 m. Log small-pore-porosity agrees with core unfrozen-water-porosity in washed out intervals because the borehole water contributes only to the free fluid (large pore) signal with $T_2 > 33$ ms. Although conventional oilfield drilling muds usually have T_{2B} around 20 ms, the drilling fluid used here had a relaxation time of 50 ms.

Since permafrost unfrozen water correlates with small-pore-porosity, it should be in greatest abundance in fine-grained sediments. During data taking it was noted that higher values of unfrozen water porosity were found in mudstone than in sandstone (see e.g. **Figure 1**). **Figure 10** shows a cross plot between log small-pore-porosity and log gamma ray amplitude. The latter is predominantly a clay indicator [*Hearst et al.*, 2000]. A correlation between high clay content and high small-pore-porosity is common in sandstones and sediments. The anomalous jet extending to the upper left is isolated in **Figure 11**. All the points in the jet originate in coals, identified petrographically in the recovered core. Natural gamma radioactivity correlates with ash content [*Reeves*, 1971]. **Figure 11** suggests that small pore porosity in coal is inversely correlated with ash content, and that therefore it is primarily associated with the organic component.

6. Conclusions

Nuclear magnetic resonance methods used in evaluation of oil- and gas-bearing formations are also useful in understanding pore-scale interactions between sediments and ice in permafrost. The quantitative assay of unfrozen water content is model independent and does not depend on any adjustable parameters.

NMR-derived pore size distribution is subject to interpretation. However, the preponderance of experimental results shows that the silt and clay sediments investigated here remain liquid-water-wet in the presence of ice, which tends to accumulate in the largest pore spaces.

Permafrost retrieved from the wellbore was well-consolidated and robust. The cohesiveness came from ice which, when melted, left loose silt and clay. Data presented in this work suggest that ice does not preferentially cement grain contacts, but perhaps it stiffens the sediment by bridging large pores. This hypothesis is supported by the NMR and sonic well logs of the Mallik 5L-38 gas hydrate test well. There the dependence of sound speed on NMR-derived hydrate saturation was found to be consistent with hydrate partially supporting the granular matrix without coating the grains or cementing the grain contacts [*Kleinberg et al.*, 2004].

Although permeabilities of the various sediments, as estimated by NMR, vary widely, their relative permeabilities to water as a function of ice saturation are remarkably uniform. However, use of NMR to estimate permeability in permafrost is unproven. It would be very desirable to make laboratory permeability measurements of samples that are also characterized by NMR.

Although the borehole was thawed and washed out during the drilling process, and therefore no permafrost remained in the NMR volume of investigation during well logging, there is a strong correlation between well log NMR small-pore-porosity and core measurements of unfrozen water in intact permafrost.

Coals in permafrost formations have large unfrozen water contents that correlate inversely with ash content.

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Appendix: Notation

C: coefficient of NMR permeability correlation
k_{rw}: relative permeability to water of ice-affected sediment
k_0: permeability to water of water-saturated sediment
m_i: i^{th} coefficient of relaxation time distribution
$m(T_2)$: relaxation time distribution
$m(T_{2i})$: i^{th} coefficient of relaxation time distribution
M_0: initial amplitude of magnetization decay
$M(t)$: magnetization decay as function of time
S_i: fraction of pore volume filled with ice
S_W: fraction of pore volume filled with water
S/V: surface to volume ratio of pore space
T_{cutoff}: T_2 value separating small-pore and large-pore water
T_E: spin echo spacing in CPMG sequence
T_{1B}: longitudinal relaxation time of bulk liquid

T_2: NMR transverse relaxation time

T_{2B}: transverse relaxation time of bulk liquid

T_{2i}: transverse relaxation time of i^{th} component

T_{2LM}: logarithmic mean of the relaxation time distribution

T_{2S}: relaxation time due to surface relaxivity

ϕ_{NMR}: apparent porosity measured by NMR

ρ_2: relaxivity of a solid surface to water protons

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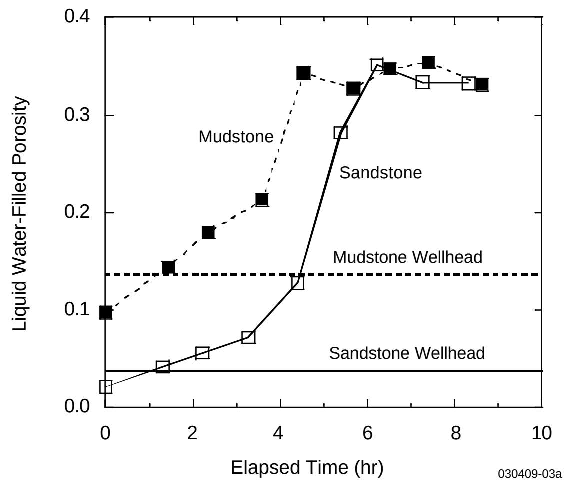

Figure 1. Thawing of mudstone and sandstone cores monitored by NMR porosity measurements. Cores were precooled to -14°C, then warmed in an 18°C room. The horizontal lines indicate porosity measurements immediately after retrieval of the core from the borehole, which was approximately -3°C.

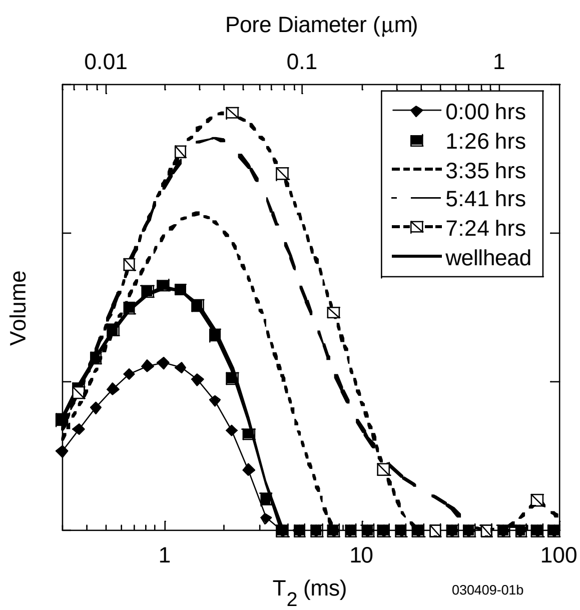

Figure 2. Relaxation time distributions of mudstone during thawing from -14°C to 18°C. Frozen samples are characterized by low NMR amplitudes and short relaxation times. After 1.5 hours of warming, the core returned to the state in which it was removed from the wellbore (solid squares, heavy solid line). During the melting process the amount of NMR-visible (liquid) water increased, and successively larger pore spaces thawed. By 7.5 hours (outermost line) the permafrost had completely melted, revealing the pore size distribution of the water-saturated sediment.

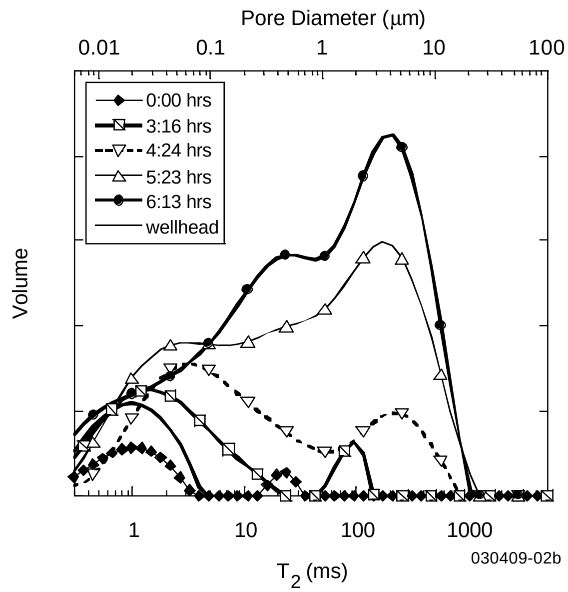

Figure 3. Relaxation time distributions of sandstone during thawing from -14°C to 18°C. Frozen samples are characterized by low NMR amplitudes and short relaxation times. During the melting process the amount of NMR-visible (liquid) water increased, and successively larger pore spaces thawed. By 6.25 hours (outermost line) the permafrost had completely melted, revealing the pore size distribution of the water-saturated sediment.

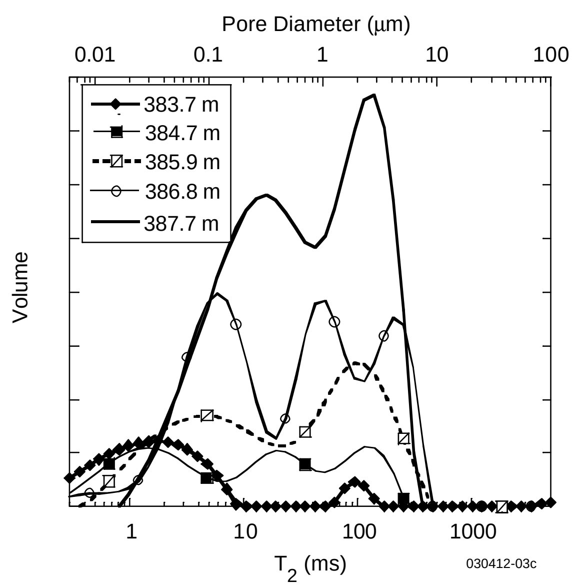

Figure 4. NMR relaxation time distributions near the base of permafrost (384 m, 1260 ft). Above the base of permafrost, cores are characterized by low NMR amplitudes and short relaxation times (solid diamond curve). As depth increased, successively more of the pore space was occupied by liquid water. The rock was fully liquid-water saturated 4 m below the base of permafrost, revealing the pore size distribution of the liquid-water-saturated sediment (topmost curve). The apparently trimodal curves are discussed in the text.

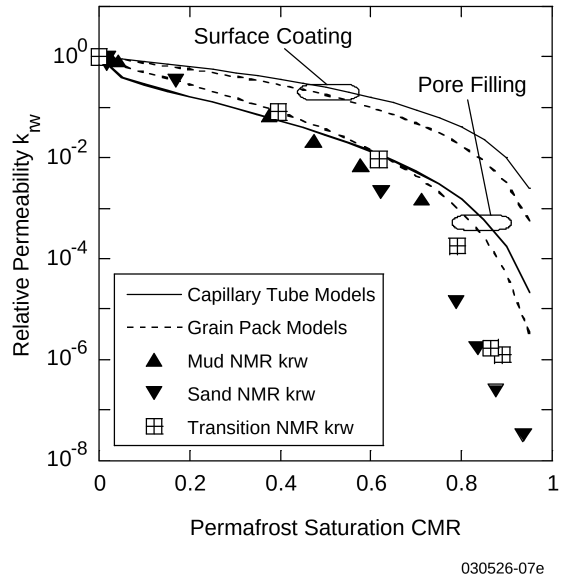

Figure 5. Relative permeability to water computed using Eqn (13) for three groups of samples: thawing mudstone (▲), thawing sandstone (▼), and cores from the base of permafrost (crossed squares). Curves are predictions of grain coating and pore filling models, as described in the text.

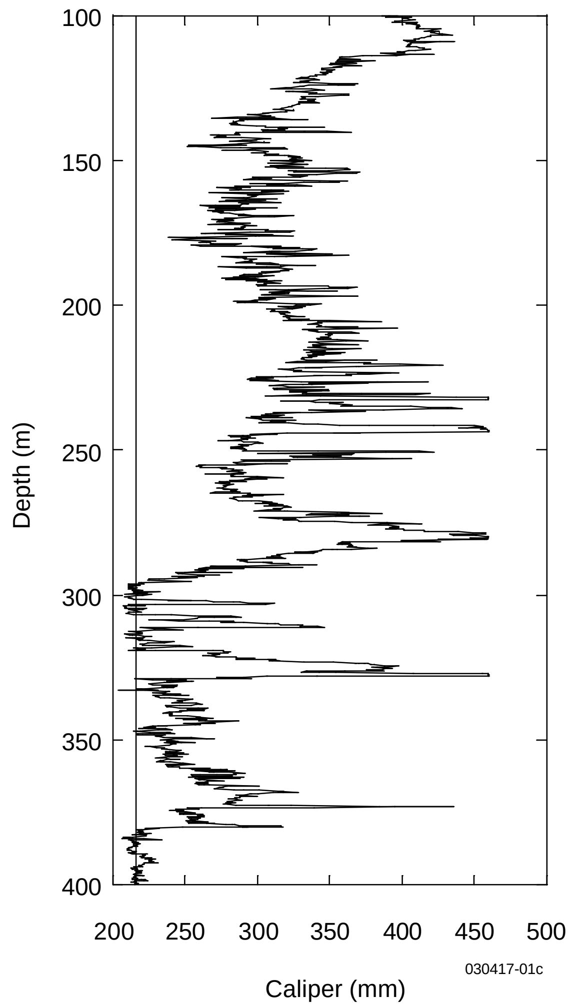

Figure 6. Wireline caliper log of borehole diameter. Vertical line is the 216-mm (8½-inch) bit size. The borehole was significantly washed out during coring operations.

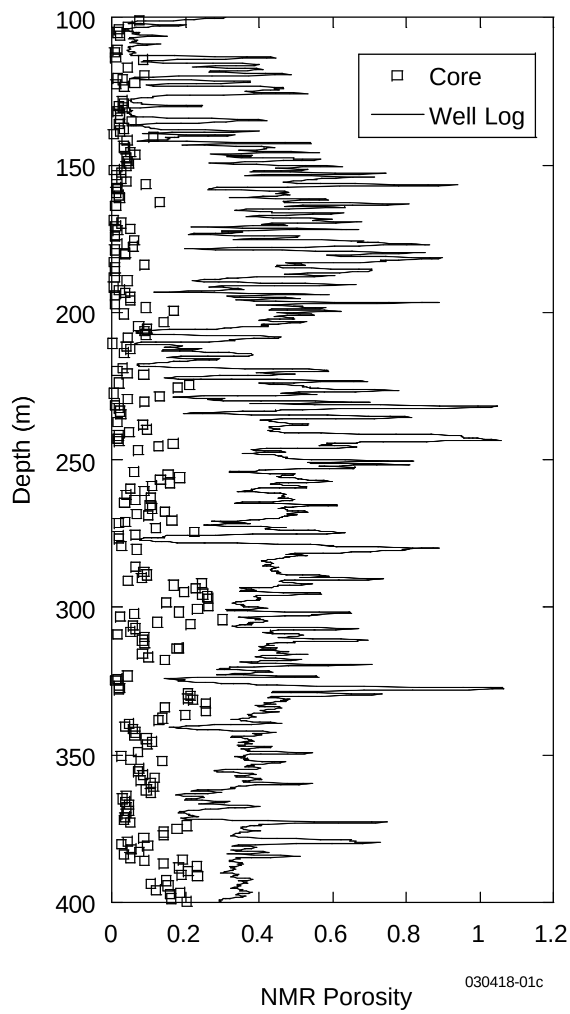

Figure 7. Wireline NMR log total porosity (solid curve) and laboratory NMR core unfrozen water porosity (squares). Anomalously high values of log porosity (>0.4) occurred at edges of washouts (see previous figure), where the sensitive volume of the logging tool included borehole water.

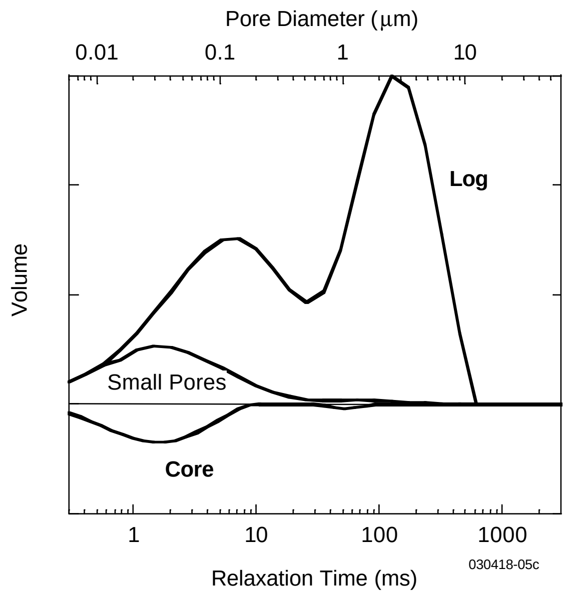

Figure 8. *Above horizontal line:* Relaxation time distribution from log at 365.8 m (1200 ft) (upper curve) and its small pore porosity computed from Eqn. (18) (lower curve). *Below horizontal line:* Relaxation time distribution of unfrozen water from permafrost core sample at the same depth (inverted for display purposes). Note similarities in the T_2 distributions of log small pore water and core unfrozen water.

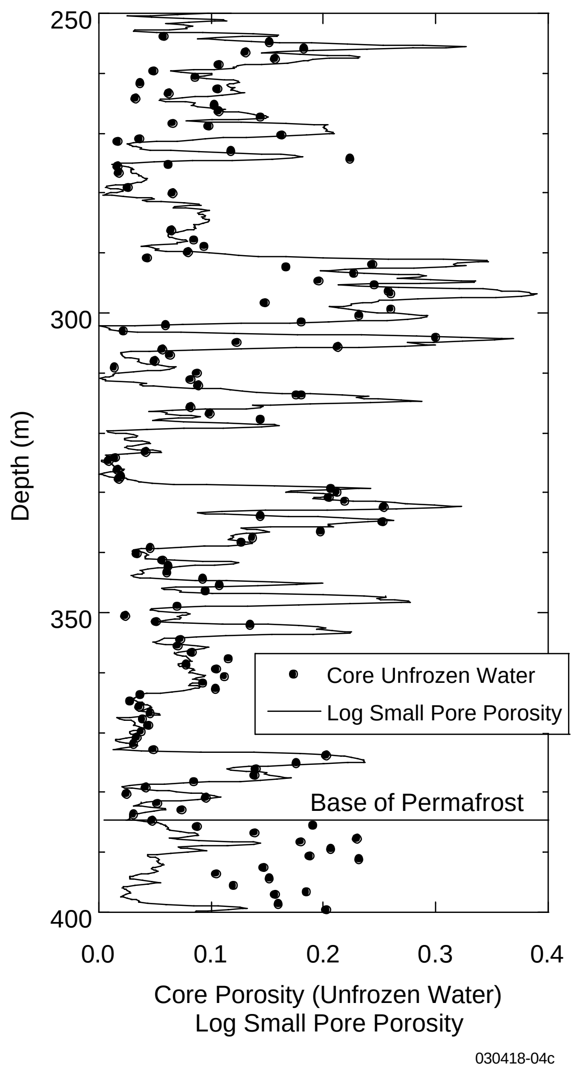

Figure 9. Log small-pore-porosity (solid curve) and core porosity (unfrozen water content) (symbols). Above the base of permafrost (horizontal line at 384 m, 1260 ft) the data are in excellent agreement. Below the base of permafrost, core unfrozen water includes both small pore porosity and large pore porosity, and therefore the core points fall above the log small-pore-porosity.

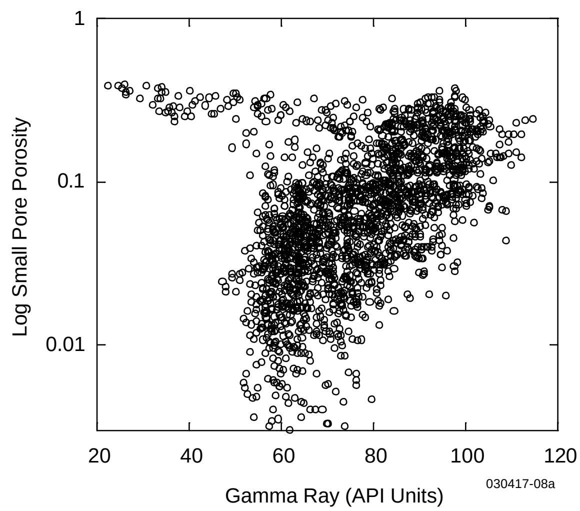

Figure 10. Cross plot of log small-pore-porosity and natural gamma-ray log. The latter is predominantly a clay indicator. A correlation between high clay content and high small-pore-porosity is common in sandstones and sand sediments. The anomalous jet extending to the upper left is explained in the text and the next figure.

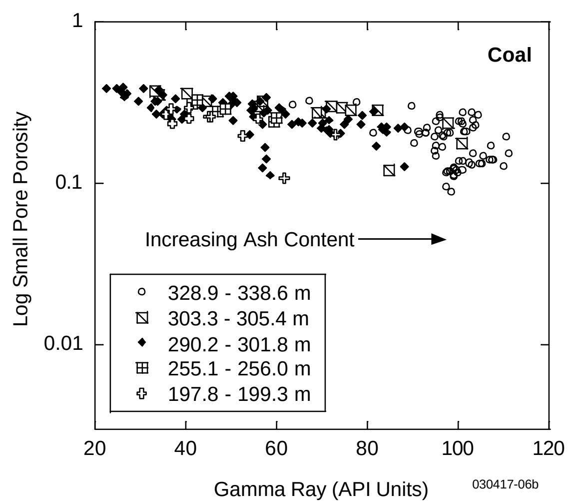

Figure 11. Points comprising the anomalous jet of Figure 10 are all from coals. The depth intervals indicated in the plot legend were identified as coal-bearing by visual examination of the cores. In coal, natural gamma radioactivity is associated with ash [Reeves, 1971]. Therefore, small-pore-porosity is proportional to organic matter content.

Appendix F. 2004 Core Analysis Personnel Schedule

Hot Ice Project 2004 Core Analysis Personnel Schedule

Case II - Drill, Log, VSP and P&A				**Prep to Spud**							**Drill/Core/OH Log/VSP**																	**P&A**	
				January, 2004										**February, 2004**															
				22	23	24	25	26	27	28	29	30	31	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Personnel	**Position**	**Company**	**Confirmation Code**																										
Jeff Van Eerde	Lab Tech Manager	Corpro	**GRTMAY**				**T**	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	**T**	
Guy McCardle	Lab Tech	Corpro	**CWWZLC**				**T**	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	**T**	
Nathan Emery	Lab Tech	Corpro	**FNINOU**							**T**	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	**T**	
Rick Schweizer	Lab Tech	Corpro	**JCHPGE**							**T**	X	X	X	X	X	X	X	X	X	X	**T**								
Bill Zogg	Lab Geologist	Corpro	**EFZEHB**							**T**	X	X	X	X	X	X	X	X	X	X	**T**								
Jim Ebanks	Lab Geologist	Corpro	**EFZEHB**							**T**	X	X	X	X	X	X	X	X	X	X	**T**								
Barry Freifeld	X-Ray Tech	LBL	**DPDLVN**			**T**	X	X	X	X	X	X	X	X	X	X	X	X	**T**										
Richard Sigal	Lab Operations Manager	Anadarko	**EMDNMD**					**T**	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	**T**	
Steve Runyon	Project Geologist	Anadarko	**BQODKB**															**T**	X	X	X	X	X	**T**					
Charles Barker	Coal Specialist	USGS	**DPIMEG**								**T**	X	X	X	X	X	**T**												
A - denotes Anchorage																													
X - denotes North Slope																													
T - Denotes Travel from Anchorage to Deadhorse																													
T - Denotes Booked Travel Arrangements																													