

# Oil & Natural Gas Technology

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## Final Technical Report (Phase 1A)

### Characterization and Quantification of the Methane Hydrate Resource Potential Associated with the Barrow Gas Fields

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Prepared for:  
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May 2007



Office of Fossil Energy

**Phase 1A Final Technical Report**

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**CHARACTERIZATION AND QUANTIFICATION  
OF THE METHANE HYDRATE RESOURCE POTENTIAL ASSOCIATED WITH THE  
BARROW GAS FIELDS**

**DOE Project Number: DE-FC26-06NT42962**

*Awarded to*

**North Slope Borough, Alaska**

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# 1. Project Overview

## 1.1. Statement of the Problem

The North Slope Borough relies on gas production from the Barrow Gas Fields (East Barrow, South Barrow and Walakpa Fields) for heating and electricity for Barrow, a community of approximately 3400 residents which also includes businesses and government services in this western North Slope city. Based on current estimates of remaining reserves and consumption rates, the borough's gas supply should last for over 150 years. However, demand for energy is expected to grow in Barrow, and the prospect of distributing gas to outlying villages in the borough will create increasing pressure on the public utility to grow gas supply to meet demand.

The North Slope Borough Department of Public Works Energy Management Group commissioned a study<sup>1</sup> of the remaining reserves in the Walakpa Gas Field in 2005, and is considering future studies to:

- Develop a depletion plan for the Barrow Gas Fields,
- Identify possible infrastructure and operations upgrades to expand gas production,
- Increase surveillance activities at the Walakpa, East Barrow, and North Barrow Fields,
- Update the geologic model for the Barrow Gas Fields to support the planning and drilling of additional development wells,
- Characterize, quantify and evaluate the impact of a postulated gas hydrate accumulation associated with the Barrow Gas Fields.

The depletion mechanism for the Barrow Gas Fields is primarily gas expansion, with potential contributions from edge water drive, and recharge from gas hydrate up dip of the free gas pool. Understanding the details of the drive mechanism is critical to field management, and will impact future development plans, particularly selection of new development well locations and future compression requirements.

The need to characterize and quantify a postulated methane hydrate accumulation in the Barrow area is closely aligned with the USDOE objectives. If the presence of a significant methane hydrate accumulation is verified, the producing gas fields in Barrow provide an excellent opportunity to test the potential of production of methane hydrates through depressurization of the free gas zone at the free gas/hydrate interface. If Phase 1, definition of prospective hydrates in contact with one of the Barrow Area gas fields, is successful, the North Slope Borough intends to drill a dedicated gas hydrate well in Phase II to obtain methane hydrate samples and to test hydrate production technologies.

The phased study builds on the results and recommendations of a prior research effort (Glenn and Allen, 1991)<sup>2</sup>, and will determine if gas hydrates exist in association with the Barrow Gas Fields, and if so, to determine if hydrates contribute to the pressure support of one or more of the fields. The study builds on past and current methane hydrate studies, and will involve creation of a static reservoir model to characterize the reservoir

extent, pore fluid properties, and pressure and temperature regime to determine the likelihood of gas hydrates. If the probability of methane gas hydrate presence is high, the next phase will involve detailed geologic mapping to choose an optimum location for a dedicated gas hydrate well to intersect the gas hydrate/free gas surface. The objective of such a well would be to sample the hydrates, produce gas hydrates indirectly through production of free gas beneath the interface, and to monitor the hydrate/free gas interface and both zones as production occurs.

## 1.2 Current State of the Art

### Physical conditions for formation of hydrates

The pressure and temperature conditions under which gas hydrates exist are shown in Figure 1 for methane hydrates and also for gas with heavier components. North Slope hydrates are believed to contain mainly methane (Walakpa Field produced gas is 98% methane) but any heavier components would extend the pressure, temperature and hence depth range of hydrate stability. The salinity of the water in which hydrates form may also affect the range of hydrate stability as shown in Figure 2, with increasing salinity reducing the range. Since formation water salinities at shallow depths in this region of the North Slope are low this effect should be small.

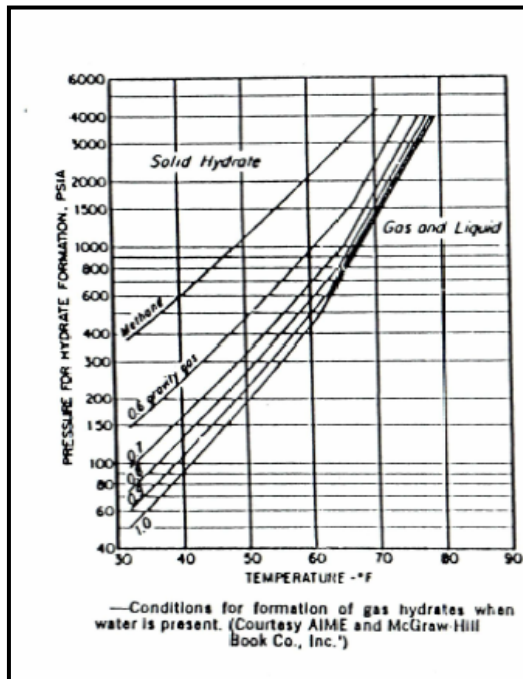


Figure 1. Conditions for gas hydrate formation<sup>3</sup>.

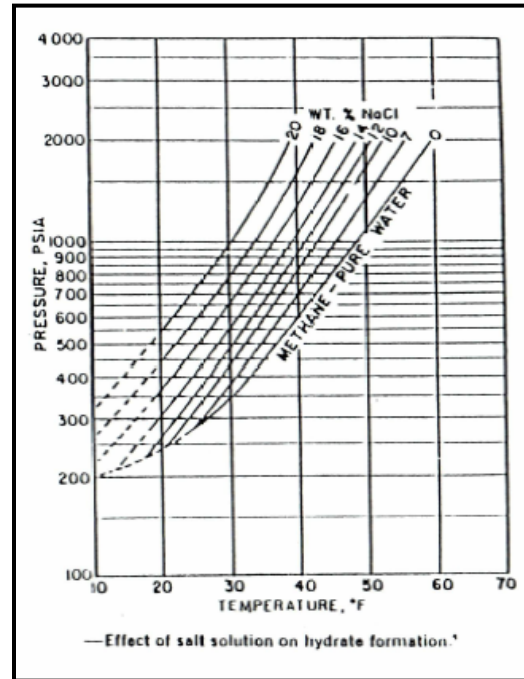


Figure 2. Effect of salinity on hydrate formation<sup>3</sup>.

The pressure and temperature conditions for methane gas hydrate stability in the Eileen trend of Greater Prudhoe Bay have been converted to a sub-sea depth reference in Figure 3. A normally pressured formation gradient has been assumed (0.433 psi/ft) to construct a depth-temperature trend for methane gas hydrate. Any heavier components in the gas would push the trend line to higher temperatures at a given depth. The base of the ice



bearing permafrost is approximately 1700 ft subsea in this location, where the formation temperature from stabilized temperature surveys is 32°F. Above base permafrost the temperature trends to a mean surface temperature of 15°F and below base permafrost the temperature increases by 2.3°F/100ft. These trends are plotted on figure 3 as the formation temperature gradient line.

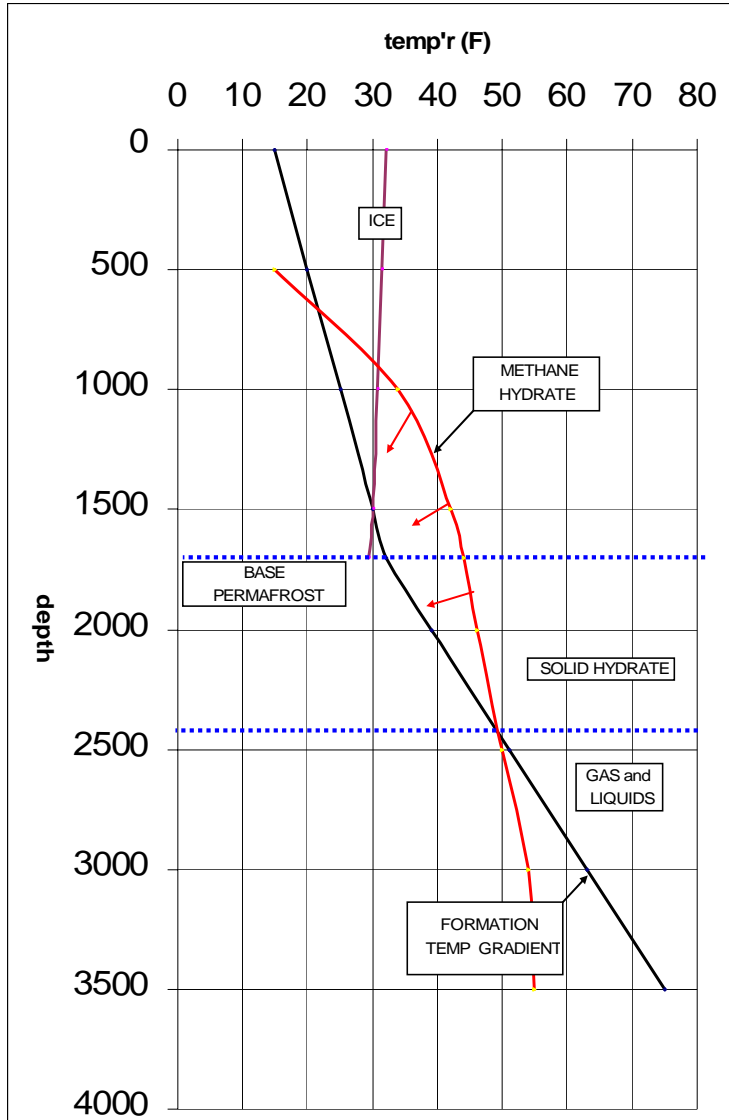


Figure 3. Methane hydrate stability zone for Eileen hydrate accumulation

Modeling of the hydrate stability zone to incorporate detailed gas and formation water composition, and hydrate structure can be accomplished using tools such as the Colorado School of Mines' CSMHyd, and the HWHydrate tool developed at Heriot-Watt University. Modeling hydrate stability based on known compositional characteristics and geothermal and pressure gradients provides a valuable means of indicating the probable presence or absence of hydrates in the subsurface. This type of modeling is very applicable to the question of whether or not hydrates exist in the Barrow area, and would be a first step in this study.

## Log Response to Methane Hydrates

Much of the published work on North Slope gas hydrates has been by Dr. Timothy Collett of the USGS. One of the more recent papers, Collett, 1998<sup>4</sup>, reviews the evaluation of gas hydrate saturations from logs and the following discussion of log responses and the interpretation of well NWEILEEN-2 are similar in general to those outlined in his paper.

The major issue in detecting hydrates from well logs is that gas hydrates and water ice permafrost have the same responses for the standard suite of logs. Hole conditions for logging can also be poor due to thawing by the drilling mud and subsequent enlargement of the hole in the unconsolidated formations. The gamma ray, neutron and density logs respond normally and can be interpreted for lithology and porosity.

The resistivity log sees both water-ice permafrost and gas hydrate as non-conductive and estimates of the amount of pore space filled by solid ice or hydrate can be attempted. The major source of error in this estimate is knowledge of the formation water salinity, assuming some remains unfrozen to provide the conductivity seen by the logging tool. Salinities are known to be low in this area at shallow depths and in the region of 2000 to 6000ppm. Figure 4 shows the corresponding resistivity ( $R_w$ ) for these salinities at the formation temperatures shown in Figure 3.

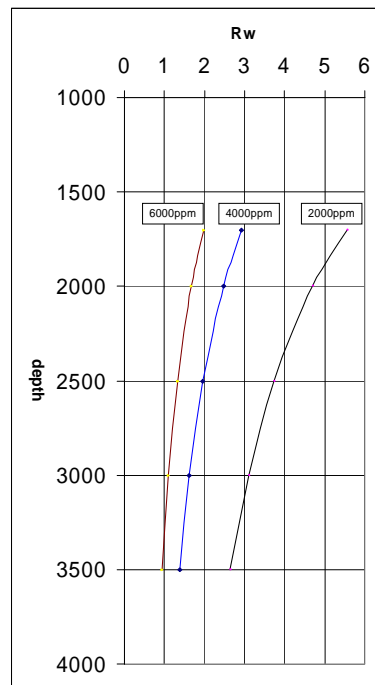


Figure 4.  $R_w$  with salinity and temperature.

At 2000 feet the possible error in calculated water saturations due to uncertainties in salinity and temperature could easily be a factor of two. There is a lack of core laboratory studies to quantify the range of hydrate saturations or the parameters suitable for use in log saturation calculations.

Gas hydrates and ice permafrost on the North Slope show high acoustic velocities, low transit time, compared with unfrozen formations. Base permafrost is usually picked where the resistivity reduces to a consistent value less than about 50ohmm and the sonic transit time at that point increases in the sands from around 100 $\mu$ s/ft to 140-150 $\mu$ s/ft. Figure 5 shows an example well, Walakpa 1, with the base permafrost picked at 896 ft ss.

Hydrates below the base of the continuous permafrost can be identified by these high acoustic velocity and high resistivity log readings and saturation calculations attempted. Hydrates within the permafrost are very difficult to distinguish from water ice. Mud logs may give some indications and carbon/oxygen or nuclear-magnetic-resonance type logs might work if hole conditions are suitable.

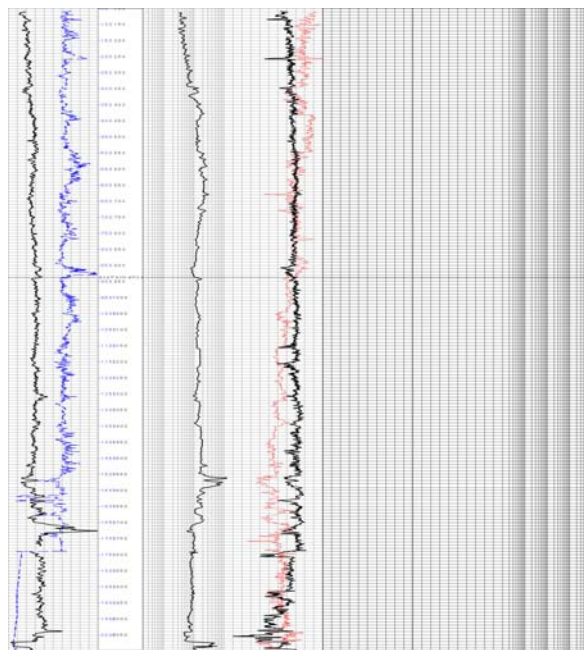


Figure 5. Base permafrost in the Walakpa 1 well.

### Production of gas hydrates

While gas hydrates are estimated to represent a very significant resource on the North Slope (a 1995 USGS study<sup>5</sup> estimated that gas hydrate in-place volumes approach 590 TCF across the North Slope), adequate production testing has not proven the feasibility of commercial production of this resource, and recovery factor has not been quantified.

The three approaches proposed for the production of gas hydrates are: depressurization; thermal injection; and chemical injection, as shown in Figure 6.

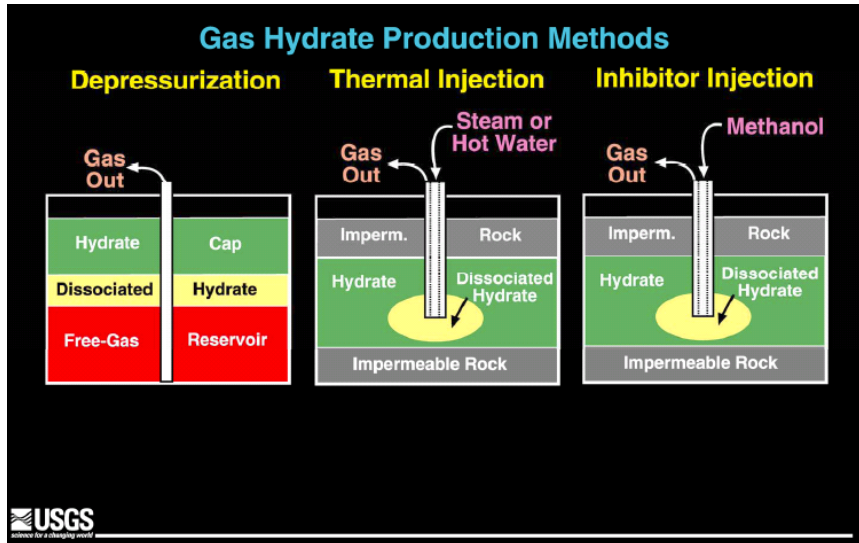
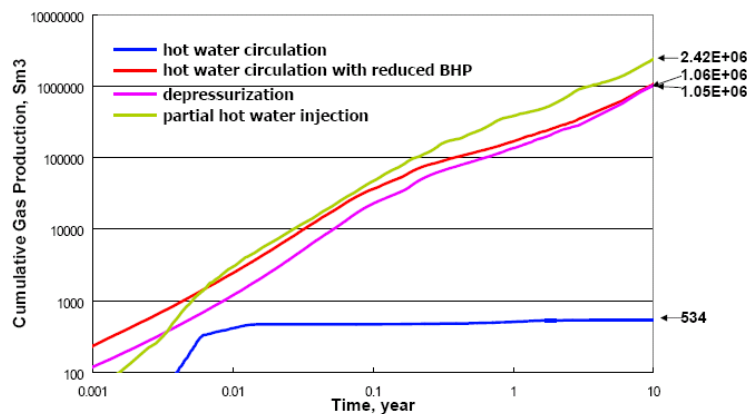


Figure 6. Proposed Gas Hydrate Production Methods (T. Collett<sup>6</sup>)

At Mallik<sup>7</sup>, a depressurization test was achieved by a series of MDT tests and a thermal method was successfully tested using circulation of a heated fluid and measuring the recovery of gas dissociated due to the addition of heat.

The results of the Mallik testing were used to develop and calibrate a methane hydrates production simulator. The simulator was used to make long term production predictions as shown in Figure 7.

### Cumulative Gas Production - 10 Years



Japan Oil Engineering Co., Ltd.

Figure 7 Modeled gas production based on Mallik well tests<sup>8</sup>

Simulation results show that hot water injection will be possibly 2X higher than dissociation, but that dissociation could still recover significant amounts of gas potentially without the capital cost of thermal injection facilities.

The proposed production method in a Barrow Area gas fields test would be by depressurization, drilling horizontally through the up-dip methane hydrates zone and then

horizontally down dip into the free gas zone. This plan is based on the current understanding of the Barrow Area gas fields geology and will be confirmed by geologic models of the reservoir and the methane hydrate stability zone.

A dedicated methane hydrate well drilled in Phase 2 could allow for initial testing in the hydrates zone and then later production from the free gas zone in the toe of the horizontal completion.

### **1.3 Proposed Solution**

It has been suggested that a methane hydrate accumulation exists in the up dip extent of the Walakpa Gas Field (Glenn and Allen, 1991<sup>1</sup>), and the interval was tested with the Walakpa #1 well. However, modeling of hydrate stability using Walakpa gas and formation water compositions, and accurate geothermal and pressure gradients needs to be completed to verify hydrate stability. This modeling effort should indicate whether or not hydrates are possible at the depths and temperatures of the reservoir with a fairly high degree of confidence.

Another issue which must be addressed is the presence of sufficient thickness and quality of reservoir up dip of the free gas accumulations. This will require an expansion of the geoscience work done prior to and since the development of the Walakpa Field, with particular emphasis on the characterization of the pinchout of the reservoir sands. This review will utilize the available 2-D seismic data and the 10 Walakpa wells, integrated with analysis of the production testing completed by PRA in 2005 to model the up dip terminus of the Walakpa sands. The South and East Fields have not been the focus of recent geoscience and reservoir analysis, and the study will include as detailed a review of those fields as the data will support.

Assuming the results of the hydrate stability modeling and reservoir limits review are positive, a detailed reservoir characterization to support simulation of hydrate production methodologies and planning of a dedicated hydrate well would be undertaken. Very sophisticated reservoir simulation tools and techniques have been developed to model the Mallik production tests, as well as to predict production rates and mechanisms in association with the BP-USDOE dedicated hydrate well that was planned and drilled at Milne Point.

Of particular interest in the reservoir simulation modeling will be to quantify the impact of hydrate dissociation on recharge of the producing gas fields. This work will aid in the understanding of secondary production effectiveness through depressurization of an associated free gas interval, and will potentially impact future field operations and development plans.

Based on the static and dynamic reservoir modeling, an optimum location to drill a dedicated hydrate well to sample and production test would be determined for drilling in Phase 2. The well would be designed to fit the geologic, reservoir, and operational specifics required in the Barrow Gas Fields, but would leverage and expand on the learnings of the Hot Ice, Mallik and Milne Point wells.

## **1.4 Study Objectives and Approach**

The objectives of this study are to characterize and quantify the postulated methane hydrate resource in the Barrow area, and to sample and production test this resource to determine its impact on future free gas production and its viability as an energy source.

The objective of Phase I is to integrate prior research efforts with the current knowledge base to determine if methane hydrates exist in association with the BGF and if so, to characterize the hydrate accumulation in an integrated reservoir model. Phase I has been divided into two sequential elements (i.e., Phase IA and Phase IB) to allow for timely evaluation of new data and reassessment of methods and objectives as the project proceeds. The work objectives for Phase I are to:

- Develop a research management plan for the study,
- Perform a Technology Status Assessment,
- Determine that the methane hydrate stability zone exists up-dip of one or more of the Barrow Gas Fields,
- Determine probability that the reservoir is continuous up-dip into the methane hydrate stability zone through integrated geological/geophysical interpretation and mapping,
- Identify an optimum location for a dedicated methane hydrate well, based on geologic, infrastructure, and logistical considerations,
- Model the expected production (gas and liquids) from the optimized well.

The approach to completing this project is based on integrating prior research results with current knowledge to determine if methane hydrates exist in association with one or more of the BGF. Phase I represents the first step in better defining the local potential for methane hydrates. A brief rationale for the proposed approach follows.

Phase I includes information gathering; gas sampling and geochemical analysis; methane hydrate stability modeling; seismic and well log analysis, including computer modeling; and documentation and dissemination of information to the DOE and other interested and affected entities. Phase I is comprised of a series of eight tasks, the first three tasks were completed as part of Phase IA and are described in the following section of this report which represents Task 4 of Phase 1A. Tasks 5 through 8 will be completed as Phase 1B, if justified by the results of Phase IA.

## **2 Phase 1A Technical Work Description**

### **2.1 Task 1 — Research Management Plan**

The Research Management Plan was developed to define the project objectives, management structure, tasks for each phase, milestones and decision points, technology transfer plan, work breakdown structure and schedule. This RMP was submitted on December 14, 2006, including input from DOE-NETL COR.

## 2.2 Task 2 — Technology Status Assessment

A Technology Status Assessment was prepared to characterize the current state of research, in order to create a global and local context for the current study. The TSA focused on results of research involving hydrate accumulations in arctic environments, and specifically on the areas of detection, characterization and quantification of hydrates, and potential production technologies applicable to hydrate development on Alaska's North Slope. The TSA identified several arctic hydrate research projects whose objectives, approach and results should have significant influence on the Barrow Gas Fields study. These key studies include: Mallik, in the Canadian Arctic, Messoyakha Gas Field in the Russian arctic, BP and partners' Mt. Elbert study, and Anadarko's Hot Ice project, both on Alaska's North Slope. These studies in composite have addressed the questions associated with this study, as well as many others which are outside the scope of our rather modest project.

Key learnings were captured from the wealth of valuable research of the Mallik Consortium<sup>9</sup>, which began in 1998, and continues to produce significant results of high relevance to this project.

The Messoyakha Gas Field in West Siberia<sup>10</sup> is an important analog to the Barrow Gas Fields study, in that gas production from a free gas leg at Messoyakha has been attributed to dissociation of a hydrate accumulation above the free gas pool. This depletion model may be a factor in production from the Barrow Gas Fields as well, a question that will hopefully be answered by this study.

The Methane Hydrate Production from Alaskan Permafrost project<sup>11</sup> ("Hot Ice") was highlighted in the TSA as an important reminder of the challenges associated with the Barrow Gas Fields study, and the importance of establishing the presence of a hydrate stability zone as a critical first step.

The ongoing Alaska North Slope Gas Hydrate Reservoir Characterization<sup>12</sup> project has made great strides in detecting, characterizing, quantifying, and sampling in-situ methane hydrates in the Milne Point Field in Alaska's Central North Slope, and this study shares many common themes with the Barrow study. The Mt. Elbert well was successfully drilled, cored and tested in February of 2007. The well recovered 430 feet of hydrate core, as well as extensive wireline and MWD well logs over the target interval. The well was production tested using the Modular Dynamic Testing tool (MDT) to acquire information on the flow potential of the reservoir, and to collect fluid samples. The results of this effort have added greatly to the understanding of hydrate-bearing formations on the Alaska North Slope.

This Project will build on previous work by the USGS and the North Slope Borough focused on the geology, petroleum systems, and hydrate potential of the Barrow Gas Fields.

The final TSA, including DOE-NETL input was submitted on March 19, 2007, and the TSA can be viewed or downloaded on the NETL website:

[http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/reports/MH42962\\_TechStatAssess.pdf](http://www.netl.doe.gov/technologies/oil-gas/publications/Hydrates/reports/MH42962_TechStatAssess.pdf)

## **2.3 Task 3 — Develop a methane hydrate stability model and analyze gas sample chemistry**

### **2.3.1 Gas Sampling and Collection of Previous Gas Sample Data**

#### Historical Gas Sample Data

Well files and field records were researched to inventory and organize all historical gas and water analyses for the three North Slope Borough gas fields being studied.

#### New Gas Sample Collection

New samples were collected from the fields for current compositional analysis and isotope characterization this winter. The samples were shipped to Isotech Labs and the compositional and isotopic analyses have been completed and incorporated in hydrate stability modeling.

Wells in the South Barrow Field that were sampled were:

- South Barrow # 11 - Structurally high in the Middle Barrow Gas Sand
- South Barrow # 10 - Mid-structure in the Middle Barrow Gas Sand
- South Barrow # 9 - Structurally low in the Middle Barrow Gas Sand

Wells in the East Barrow Field that were sampled were:

- East Barrow # 21 - Structurally high in the Middle Barrow Gas Sand
- East Barrow # 14 - Mid-structure in the Middle Barrow Gas Sand
- East Barrow # 15 - Structurally low in the Middle Barrow Gas Sand

Wells in the Walakpa Field that were sampled were:

- Walakpa # 5 - Structurally high in the Walakpa Gas Sand
- Walakpa # 10 - Mid-structure in the Walakpa Gas Sand
- Walakpa # 8 - Structurally low in the Walakpa Gas Sand

The new gas samples have been analyzed and used in the methane hydrate stability determination, as well as for comparison to historical gas analyses to see if changes in composition would suggest possible indication of methane hydrate dissociation.

#### Gas Sampling Procedure

The following procedure was used for the collection of samples of produced gas from the Walakpa Field and the East and South Pools of the Barrow Field.

1. Flow well to be sampled for minimum of 12 hours.
2. Using procedure in Figure 8, connect the sampling tool to the flowing (annulus) side of tubing, purge IsoTube container and collect 2 samples per well.
3. Label each sample using adhesive backed labels provided, including well name, and date of collected sample.



4. Remove yellow copy of label and send to PRA.
5. Pack IsoTube gas-filled-containers with the white copy of the labels attached to the IsoTubes in the UN certified box, and ship via Evert's Air Freight to PRA in Anchorage.

### Collecting Wellhead Samples in Single-Use IsoTubes®

1. Locate a suitable valve or gauge port for collecting the sample. The sampling port must have a control valve that can be used to turn the gas on and off and should provide a dry, liquid free gas sample. The sampling equipment provided has a 1/4" NPT thread and if the wellhead does not have this same female fitting, an adapter will be necessary. **CAUTION: the equipment provided has a pressure regulator that is rated for use up to a MAXIMUM of 3000 p.s.i. (200 bars). If pressures higher than this may be encountered, additional pressure control will be required.**
2. Make sure that the threads on the sampling device are clean and then apply 2 or 3 layers of Teflon tape to the male threads on the filter, wrapping the tape clockwise as you look at the end of the fitting.
3. Screw the sampling device into the sampling port using a wrench on the lower hex of the filter, and then slowly open the control valve on the sampling port (not shown).
4. Remove the plastic bag and end caps from an unused IsoTube and insert the bottom IsoTube valve (observe arrow on IsoTube) into the chuck by simply pushing it in firmly. There are cogs in the chuck which grip the threads on the IsoTube valve and hold it in place.
5. Turn the handle on the 3-way valve to the "fill" position (handle pointing up). If the IsoTube valve does not seem to be making a seal in the chuck (that is, if you can hear gas escaping or the outlet pressure does not build up to about 50-60 psi), lightly rotate the IsoTube with your fingers to screw it into the chuck until a seal is made.
6. The sampling valve and the IsoTube can be purged by taking one of the valve caps that was removed from the IsoTube and use the button on the end of the cap to depress the spring valve in the tip of the top IsoTube valve (like letting the air out of a tire). Holding the spring valve open for a few seconds will purge the IsoTube (3-way valve still in "fill" position). This shortcut should be minimized if you are sampling very wet gases or under very cold conditions as it can result in condensing liquids in the IsoTube.
7. Final purging and filling of the IsoTube is accomplished by rotating the handle on the 3-way valve 90° back and forth to alternately pressurize and vent the IsoTube. If the gas you are sampling contains hydrogen sulfide or other toxic components, a length of tubing can be attached to the vent port to direct the gas safely away from you.
8. The IsoTube should be filled to the output pressure of the regulator and then vented to atmospheric pressure by watching the outlet pressure gauge and listening to the flow of gas out the vent. The more times this process is repeated, the less the chance of atmospheric contamination of the sample. A minimum of 6 cycles is recommended. If the IsoTube was not purged as described in step 6, a minimum of 10 cycles are recommended.
9. After the IsoTube is filled for the last time, leave the 3-way valve in the fill position.
10. The IsoTube may now be removed from the chuck by sliding the knurled sleeve on the outside of the chuck down, away from the IsoTube, which will retract the cogs holding the IsoTube valve in place. This process should be done quickly so as to minimize the amount of gas lost. If the IsoTube is held very lightly, it will generally pop up out of the chuck from the spring action of the valve and the gas pressure. Be ready to catch it. Slightly pulling up on the IsoTube as the sleeve on the chuck is being pulled down can also facilitate removing the IsoTube quickly, provided the upward force is not so great as to impede retracting the cogs in the chuck.
11. Replace the end caps on the IsoTube valves and fill out one of the adhesive-backed labels with the sample identification information using the ball point pen provided (press hard as three copies are made). Attach the label to the IsoTube in the location marked and return the IsoTube to the shipping carton. When an entire sheet of sample tags has been used, one of the copies should be placed in the box with the IsoTubes and the other can be retained for your records.
12. Seal the box with tape, attach the appropriate hazardous material labels, and ship the samples as described on the enclosed shipping instructions.

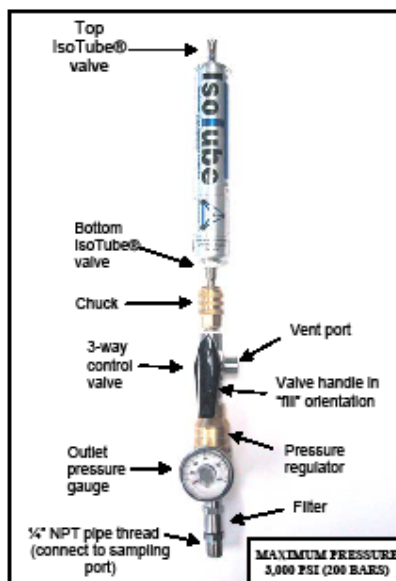


Figure 8. Collection Procedure with Iso-Tube sampler (Courtesy of Isotech Laboratories, Inc.)

### 2.3.2 Gas Compositional and Isotope Analysis

#### *South Barrow Field*

#### Comparison of Isotech results of current samples Top, Middle and Low on Structure

Table 1 shows samples taken in March 2007 from the South Barrow Field, which were analyzed by Isotech Laboratories for gas composition and isotopic characterization.

**Table 1: South Barrow Field Gas Samples – Present Day from different structural depths**

Well Name	S Barrow 11		S Barrow 10		S Barrow 9	
Structural Location	High		Middle		Low	
Sample ID	Isotech 110656		Isotech 110655		Isotech 110654	
Sample Depth	2250'SS		2290'SS		2390'SS	
Component	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only
He, %	0.0101		0.0220		0.0218	
H <sub>2</sub> , %	0.0101		0		0	
CO <sub>2</sub> , %	0.17		0.26		0.16	
N <sub>2</sub> , %	0.65		0.85		0.82	
C <sub>1</sub> , %	97.76	98.59	97.79	98.91	97.98	98.97
C <sub>2</sub> , %	1.30	1.31	0.983	0.99	0.934	0.94
C <sub>3</sub> , %	0.0339	0.0342	0.0289	0.0292	0.0243	0.0245
iC <sub>4</sub> , %	0.0245	0.0247	0.0249	0.0252	0.0248	0.0251
nC <sub>4</sub> , %	0.0113	0.0114	0.0103	0.0104	0.0094	0.0095
iC <sub>5</sub> , %	0.0071	0.0072	0.0075	0.0076	0.0069	0.0070
nC <sub>5</sub> , %	0.0034	0.0034	0.0035	0.0035	0.0033	0.0033
C <sub>6+</sub> , %	0.0152	0.0153	0.0153	0.0155	0.0176	0.0178
Isotope						
δ <sup>13</sup> C <sub>1</sub> , ‰	-39.85		-40.05		-40.23	
δDC <sub>1</sub> , ‰	-170.1		-170.1		-169.2	
δ <sup>13</sup> C <sub>2</sub> , ‰	-36.55		-36.03		-35.55	
δ <sup>13</sup> C <sub>3</sub> , ‰	<b>-27.7</b>		<b>-26.1</b>		<b>-25.9</b>	
Specific Gravity	0.566		0.566		0.565	
BTU, SCF	1018		1012		1013	

**\* carbon isotopes to one decimal obtained online via GC-C-IRMS**

In general, while the C<sub>1</sub> compositions are the same for the three different locations, the high structural well has higher amounts of C<sub>2</sub> and C<sub>3</sub> than the middle structural (C<sub>2</sub>: +32%, C<sub>3</sub>: +17%) and low structural (C<sub>2</sub>: +39%, C<sub>3</sub>: +39%) wells. There is little difference in the iC<sub>4</sub> compositions between the different wells.

There is little difference in the δ<sup>13</sup>C<sub>1</sub>, δDC<sub>1</sub> and δ<sup>13</sup>C<sub>2</sub> isotopes. The δ<sup>13</sup>C<sub>3</sub> isotope decreases going from the high structural to the low structural well.

Comparison of Same Well Gas Composition over Time

Table 2 shows the comparison of current day gas compositions to compositions of previously analyzed gas samples from the same wells in South Barrow Field.

**Table 2: South Barrow Field gas compositions over time from individual wells**

Well Name	S Barrow 9				S Barrow 11			
Structural Location	Structurally Low				Structurally High			
Sample ID	1/79 Gruy Report		Isotech 110654		1/79 Gruy Report		Isotech 110656	
Sample Date	1978		3/01/2007		1978		3/01/2007	
Component	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only
He, %			0.0218				0.0101	
H <sub>2</sub> , %			0				0.0101	
CO <sub>2</sub> , %			0.16				0.17	
N <sub>2</sub> , %	3.72		0.82		3.72		0.65	
C <sub>1</sub> , %	94.51	98.16	97.98	98.97	94.22	97.86	97.76	98.59
C <sub>2</sub> , %	1.47	1.53	0.934	0.94	1.79	1.86	1.30	1.31
C <sub>3</sub> , %	0.1	0.1	0.0243	0.0245	0.1	0.1	0.0339	0.0342
iC <sub>4</sub> , %	0.05	0.05	0.0248	0.0251	0.03	0.03	0.0245	0.0247
nC <sub>4</sub> , %	0.05	0.05	0.0094	0.0095	0.03	0.03	0.0113	0.0114
iC <sub>5</sub> , %	0.03	0.03	0.0069	0.0070	0.02	0.02	0.0071	0.0072
nC <sub>5</sub> , %	0.04	0.04	0.0033	0.0033	0.02	0.02	0.0034	0.0034
C <sub>6+</sub> , %	0.03	0.03	0.0176	0.0178	0.07	0.07	0.0152	0.0153

In the well S Barrow 9, the structurally low well, the following composition changes over time:

- a decrease in C<sub>2</sub> (-38%)
- a decrease in C<sub>3</sub> (-76%)
- a decrease in iC<sub>4</sub> (-52%)
- a decrease in nC<sub>4</sub> (-82%)

In the well S Barrow 11, the structurally high well, the following composition changes over time:

- a decrease in C<sub>2</sub> (-29%)
- a decrease in C<sub>3</sub> (-67%)
- a decrease in iC<sub>4</sub> (-21%)
- a decrease in nC<sub>4</sub> (-63%)

***East Barrow Field***

Comparison of Isotech results of current samples Top, Middle and Low on Structure

Table 3 shows samples taken in March 2007 from the East Barrow Field, which were analyzed by Isotech Laboratories for gas composition and isotopic characterization.

**Table 3: East Barrow Field Gas Samples – Present Day from different structural depths**

Well Name	E Barrow 21		E Barrow 14		E Barrow 15	
Structural Location	High		Middle		Low	
Sample ID	Isotech 110659		Isotech 110657		Isotech 110658	
Sample Depth	2012'SS		2037'SS		2150'SS	
Component	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only
He, %	0.0608		0.0249		0.0216	
H <sub>2</sub> , %	0.0058		0		0	
CO <sub>2</sub> , %	0.17		0.16		0.081	
N <sub>2</sub> , %	3.25		1.35		0.81	
C <sub>1</sub> , %	95.88	99.36	97.54	99.06	97.92	98.82
C <sub>2</sub> , %	0.38	0.39	0.568	0.58	1.02	1.03
C <sub>3</sub> , %	0.0337	0.0349	0.0264	0.0268	0.0526	0.0531
iC <sub>4</sub> , %	0.0066	0.0068	0.0062	0.0063	0.0293	0.0296
nC <sub>4</sub> , %	0.105	0.1088	0.132	0.1341	0.0158	0.0159
iC <sub>5</sub> , %	0.0542	0.0562	0.0786	0.0798	0.0117	0.0118
nC <sub>5</sub> , %	0.0186	0.0193	0.0447	0.0454	0.0043	0.0043
C <sub>6+</sub> , %	0.0215	0.0223	0.0649	0.0659	0.0308	0.0311
Isotope						
$\delta^{13}\text{C}_1, \text{‰}$	-41.35		-41.91		-40.22	
$\delta\text{DC}_1, \text{‰}$	-171.6		-170.3		-172.1	
$\delta^{13}\text{C}_2, \text{‰}$	-33.7		-32.29		-35.99	
$\delta^{13}\text{C}_3, \text{‰}$	<b>-32.3</b>		<b>-32.7</b>		<b>-30.3</b>	
Specific Gravity	0.591		0.57		0.565	
BTU, SCF	940		1012		1016	

\* carbon isotopes to one decimal obtained online via GC-C-IRMS

In general, the C<sub>1</sub> compositions decrease slightly going from high on structure to low. The high structural well has lower amounts of C<sub>2</sub>, higher amounts of C<sub>3</sub> and iC<sub>4</sub> than the middle structural well (C<sub>2</sub>: -32%, C<sub>3</sub>: +30%, iC<sub>4</sub>: +9%) and lower amounts of C<sub>2</sub>, C<sub>3</sub> and iC<sub>4</sub> than the lower structural (C<sub>2</sub>: -62%, C<sub>3</sub>: -34%, iC<sub>4</sub>: -77%) well.

There is little differences in the  $\delta^{13}\text{C}_1$ ,  $\delta\text{DC}_1$ ,  $\delta^{13}\text{C}_2$  and  $\delta^{13}\text{C}_3$  isotopes.

#### Comparison of Same Well Gas Composition over Time

Table 4 shows the comparison of current day gas compositions to compositions of previously analyzed gas samples from the same wells in East Barrow Field.

**Table 4: East Barrow Field gas compositions over time from individual wells**

Well Name	E Barrow 15				E Barrow 14			
Structural Location	Structurally Low				Structurally Middle			
Sample ID	Chem Lab 5108-2		Isotech 110658		Chem Lab 5434		Isotech 110657	
Sample Date	9/24/1980		3/01/2007		2/14/1977		3/01/2007	
Component	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only
He, %			0.0216		0.0300		0.0249	
H <sub>2</sub> , %			0				0	
CO <sub>2</sub> , %	0.001		0.081		0.05		0.16	
N <sub>2</sub> , %	1.66		0.81		1.84		1.35	
C <sub>1</sub> , %	98.25	99.91	97.92	98.82	97.11	99.01	97.54	99.06
C <sub>2</sub> , %	0.08	0.08	1.02	1.03	0.57	0.58	0.57	0.58
C <sub>3</sub> , %	0.01	0.0	0.0526	0.0531	0.03	0.0	0.0264	0.0268
iC <sub>4</sub> , %	0.001	0.00	0.0293	0.0296	0.01	0.01	0.0062	0.0063
nC <sub>4</sub> , %		0.00	0.0158	0.0159	0.14	0.14	0.132	0.1341
iC <sub>5</sub> , %		0.00	0.0117	0.0118	0.09	0.09	0.0786	0.0798
nC <sub>5</sub> , %		0.00	0.0043	0.0043	0.06	0.06	0.0447	0.0454
C <sub>6+</sub> , %		0.00	0.0308	0.0311	0.07	0.07	0.0649	0.0659

In the well E Barrow 15, the structurally low well, the following composition changes over time:

- an increase in C<sub>2</sub>
- an increase in C<sub>3</sub>
- an increase in iC<sub>4</sub>
- an increase in nC<sub>4</sub>

In the well E Barrow X, the structurally middle well, the following composition changes over time:

- a slight decrease in C<sub>2</sub> (-1%)
- a decrease in C<sub>3</sub> (-12%)
- a decrease in iC<sub>4</sub> (-38%)
- a decrease in nC<sub>4</sub> (-6%)

### ***Walakpa Field***

#### Comparison of Isotech results of current samples Top, Middle and Low on Structure

Table 3 shows samples taken in March 2007 which were analyzed by Isotech Laboratories for gas composition and isotopic characterization.

**Table 5: Walakpa Field Gas Samples – Present Day from different structural depths**

Well Name	Walakpa 5		Walakpa 10		Walakpa 8	
Structural Location	High		Middle		Low	
Sample ID	Isotech 110660		Isotech 110662		Isotech 110661	
Sample Depth	2120'SS		2230'SS		2400'SS	
Component	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only
He, %	0.0095		0.0109		0.0121	
H <sub>2</sub> , %	0		0		0	
CO <sub>2</sub> , %	0.11		0.1		0.086	
N <sub>2</sub> , %	0.094		0.1		0.11	
C <sub>1</sub> , %	97.76	97.97	97.45	97.65	97.22	97.42
C <sub>2</sub> , %	1.62	1.62	1.79	1.79	1.91	1.91
C <sub>3</sub> , %	0.278	0.2786	0.383	0.3838	0.446	0.4469
iC <sub>4</sub> , %	0.0346	0.0347	0.051	0.0511	0.062	0.0621
nC <sub>4</sub> , %	0.047	0.0471	0.0592	0.0593	0.0749	0.0751
iC <sub>5</sub> , %	0.0138	0.0138	0.0165	0.0165	0.0223	0.0223
nC <sub>5</sub> , %	0.0099	0.0099	0.0091	0.0091	0.013	0.0130
C <sub>6+</sub> , %	0.0256	0.0257	0.0329	0.0330	0.0441	0.0442
Isotope						
$\delta^{13}\text{C}_1, \text{‰}$	-38.15		-38.01		-37.64	
$\delta\text{DC}_1, \text{‰}$	-161.5		-152.4		-155.5	
$\delta^{13}\text{C}_2, \text{‰}$	-32.23		-32.6		-32.93	
$\delta^{13}\text{C}_3, \text{‰}$	<b>-30.5</b>		<b>-30.7</b>		<b>-30.9</b>	
Specific Gravity	0.568		0.571		0.572	
BTU, SCF	1032		1036		1039	

\* carbon isotopes to one decimal obtained online via GC-C-IRMS

In general, while the C<sub>1</sub> compositions are the same for the three different locations, the high structural well has lower amounts of C<sub>2</sub>, C<sub>3</sub> and iC<sub>4</sub> than the middle structural well (C<sub>2</sub>: -10%, C<sub>3</sub>: -27%, iC<sub>4</sub>: -32%) and has lower amounts of C<sub>2</sub>, C<sub>3</sub> and iC<sub>4</sub> than the lower structural well (C<sub>2</sub>: -15%, C<sub>3</sub>: -38%, iC<sub>4</sub>: -44%) wells.

There is little differences in the  $\delta^{13}\text{C}_1$ ,  $\delta\text{DC}_1$ ,  $\delta^{13}\text{C}_2$  and  $\delta^{13}\text{C}_3$  isotopes.

#### Comparison of Same Well Gas Composition over Time

Table 6 shows the comparison of current day gas compositions to compositions of previously analyzed gas samples from the same wells in Walakpa Field.

**Table 6: Walakpa Field gas compositions over time from individual wells**

Well Name	Walakpa 5				Walakpa 10				Walakpa 8			
Structural Location	Structurally High				Structurally Middle				Structurally Low			
Sample ID	Arco 94G0004		Isotech 110660		Arco 94G0002		Isotech 110662		Arco 94G0008		Isotech 110661	
Sample Date	Jan-1994		3/01/2007		Jan-1994		3/02/2007		Jan-1994		3/02/2007	
Component	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only	Composition by Mole %	Normalized Hydrocarbons Only
He, %	0.01		0.0095		0.0130		0.0109		0.0120		0.0121	
H <sub>2</sub> , %	0		0		0		0		0		0	
CO <sub>2</sub> , %	0.12		0.11		0.095		0.1		0.093		0.086	
N <sub>2</sub> , %	0.48		0.094		0.33		0.1		0.56		0.11	
C <sub>1</sub> , %	95.30	97.87	97.76	97.97	96.60	97.55	97.45	97.65	96.80	97.57	97.22	97.42
C <sub>2</sub> , %	1.71	1.76	1.62	1.62	1.96	1.98	1.79	1.79	2.03	2.05	1.91	1.91
C <sub>3</sub> , %	0.26	0.3	0.278	0.2786	0.34	0.3	0.383	0.3838	0.28	0.3	0.446	0.4469
iC <sub>4</sub> , %	0.031	0.03	0.0346	0.0347	0.045	0.05	0.051	0.0511	0.037	0.04	0.062	0.0621
nC <sub>4</sub> , %	0.044	0.05	0.047	0.0471	0.052	0.05	0.0592	0.0593	0.043	0.04	0.0749	0.0751
iC <sub>5</sub> , %	0.014	0.01	0.0138	0.0138	0.016	0.02	0.0165	0.0165	0.013	0.01	0.0223	0.0223
nC <sub>5</sub> , %	0.011	0.01	0.0099	0.0099	0.009	0.01	0.0091	0.0091	0.008	0.01	0.013	0.0130
C <sub>6+</sub> , %		0.00	0.0256	0.0257		0.00	0.0329	0.0330		0.00	0.0441	0.0442
Isotope												
δ <sup>13</sup> C <sub>1</sub> , ‰	-38.36		-38.15		-36.99		-38.01		-35.67		-37.64	
δDC <sub>1</sub> , ‰	-156		-161.5		-157		-152.4		-159		-155.5	
δ <sup>13</sup> C <sub>2</sub> , ‰	-32.24		-32.23		-32.34		-32.6		-31.97		-32.93	
δ <sup>13</sup> C <sub>3</sub> , ‰	-30.63		-30.46		-30.44		-30.66		-29.34		-30.91	

- In each of the Walakpa wells, in general, there is a decrease in C<sub>2</sub> over time and an increase in C<sub>3</sub> and iC<sub>4</sub>. The increases in C<sub>3</sub> and iC<sub>4</sub> are more pronounced the further down dip the well is located.
- There does not appear to be significant differences in the δ<sup>13</sup>C<sub>1</sub>, δDC<sub>1</sub>, δ<sup>13</sup>C<sub>2</sub> and δ<sup>13</sup>C<sub>3</sub> isotopes.

Summary of Gas Compositional Analysis

Review of the compositional and isotope data was done with consultation of Tim Collett and Tom Lorenson of the USGS. A summary of their observations<sup>13</sup> are shown below:

- Using the CSM model, the Walakpa data and most of the Barrow data shows a structure II hydrate, or just on the edge between SI and SII.
- The gas isotope composition also suggests that the gas is thermogenic type I-II kerogen from late mature (Barrow Pool) to over mature (Walakpa sand) which also could account for the relatively high proportion of methane in the gas composition relative to a more typical GOM gas.
- No consistent or convincing trends regarding methane hydrate dissociation (possible gas hydrate indicators are flagged with an \*):

South Barrow  
 C2 depleted with time  
 C3 depleted with time  
 iC4 depleted with time  
 nC4 depleted with time

iC4/nC4 going from 1 to 2.6\*

East Barrow

C2 enriched or the same with time\*

C3 enriched with time\*

iC4 enriched with time (questionable analysis)

nC4 enriched with time (questionable analysis)

iC4/nC4 mixed trends

Walakpa

C2 depleted with time

C3 mixed response with time

iC4 enriched with time\*

nC4 mixed trends

iC4/nC4 mixed trend (Walakpa 5 from 0.6 to 0.737; Walakpa 10, 1.0 to 0.862; Walakpa 8, 1.0 to 0.827)

### **2.3.3 Temperature and Pressure Gradient**

#### Pressure Gradients

Original reservoir pressures were used to determine hydrostatic gradients at each field to convert pressure to depth for hydrate stability zone determination. For East and South Barrow Fields, the gradient of 0.5 psi/ft was used based on original reservoir pressures. For Walakpa, the gradient of 0.45 psi/ft was used based on original reservoir pressure.

#### Temperature Gradients

To determine static reservoir temperature gradients, all of the temperature gradients were plotted and the outliers were excluded in the cases of surveys influence by production.

### **2.3.4 Hydrate Stability Modeling**

The methane hydrate stability models for the three BGF are based on the analysis of gas composition, formation water composition, and local pressure and temperature gradient of the individual fields. These parameters, along with the known phase behavior of methane gas hydrate, determine the existence and extent of the hydrate stability zone, postulated by previous researchers. The results of gas composition analysis and gas hydrate stability modeling are to be used to decide whether or not to proceed with Phase IB. Detailed results of this modeling are included as Appendix A.

Historical temperature gradient surveys were collected from well files and field records. These were summarized to use for definition of the methane hydrate stability zone (HSZ).



## East Barrow Field HSZ Results

Static temperature gradient surveys were made in wells E Barrow #15 and #21, which had been shut-in for 7+ months and the temperature data from these wells represents the best static reservoir temperature information available.

University of Alaska Fairbanks Petroleum Engineering began using gas and water compositions in the Colorado School of Mines (CSM) methane hydrate stability model. The modeling results are sensitive to formation water salinity, and the best information available for the East pool indicates salinities in the range of 2.1-2.4% NaCl, based on analysis of samples from the Barrow Sand interval in the SB #15 and SB #17 wells.

Model results indicate that the East Barrow Field is in communication with a methane hydrate zone, as the base of the hydrate stability zone intersects the shallowest known free gas reservoir (Figure 9). This may explain why there appears to be pressure support in the reservoir, but no appreciable water production or watering out of wells, as would be expected if a water drive was providing support to the reservoir. The East Barrow Field was suspected to be a reservoir with strong aquifer support from initial material balance work, based on P/Z response (Figure 10) and the field was expected to water-out by now, having produced over 8 BSCF of gas from an original reserve estimate of 6 BSCF. Pressure support from hydrate dissociation could possibly explain the pressure response and production characteristics of this field. The other indicator that may support hydrate dissociation occurring in the East Barrow Field is the cooler temperature gradient at equivalent depths compared to the South Barrow Field. Figure 3 shows the temperature gradients for East Barrow and South Barrow Fields at equivalent subsea depths. The cooler temperatures in the East Barrow Field may be due to the endothermic cooling from the dissociation of methane hydrates. In any case, the lower geothermal gradient at East Barrow promotes a deeper base to the methane hydrate stability zone than that in the South Barrow pool.

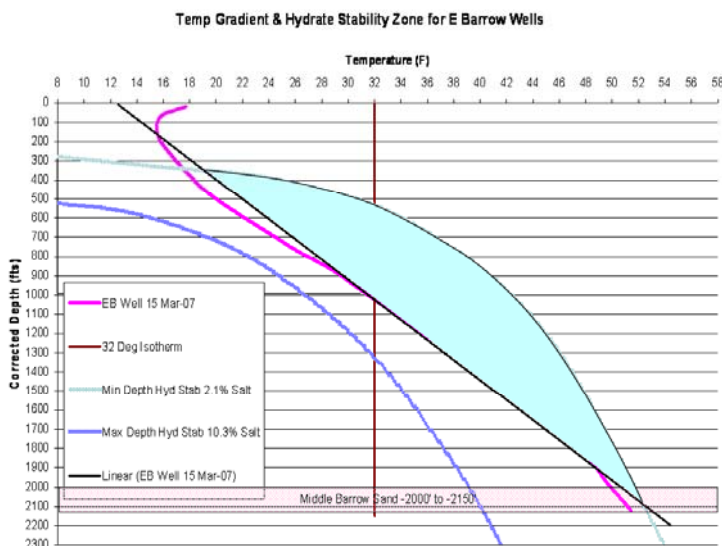


Figure 9. East Barrow Gas Field HSZ Model

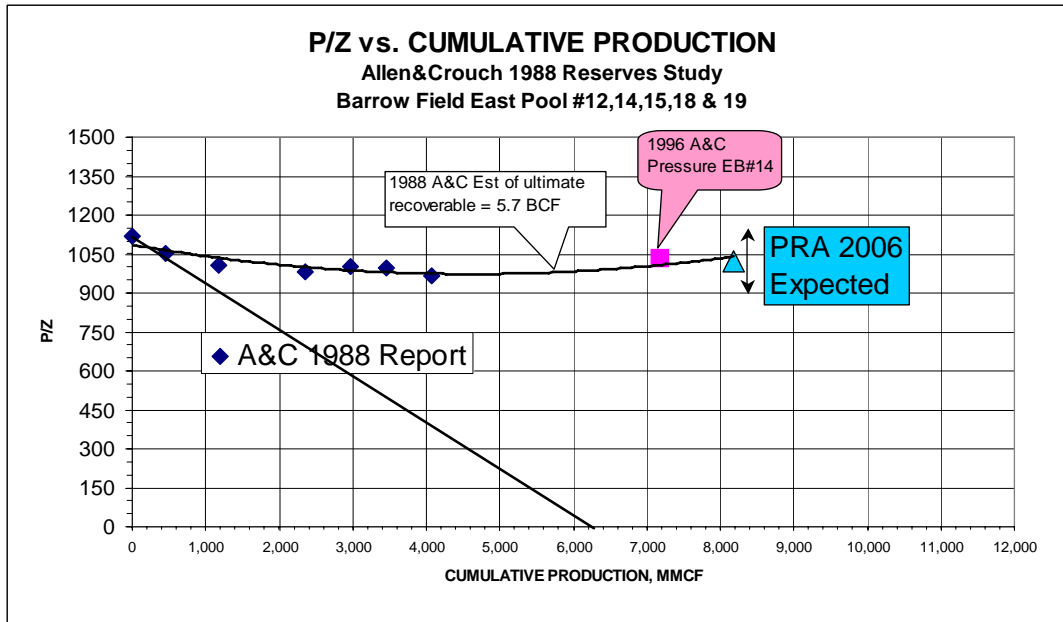


Figure 10. East Barrow Field Material Balance

The model results for the East Barrow pool support progression to Phase 1B, do to the fact that the hydrate stability model indicates intersection between the know free gas reservoir and the base of the hydrate stability zone, and the material balance modeling indicates a strong pressure support mechanism beyond the expected volumetric gas expansion mechanism.

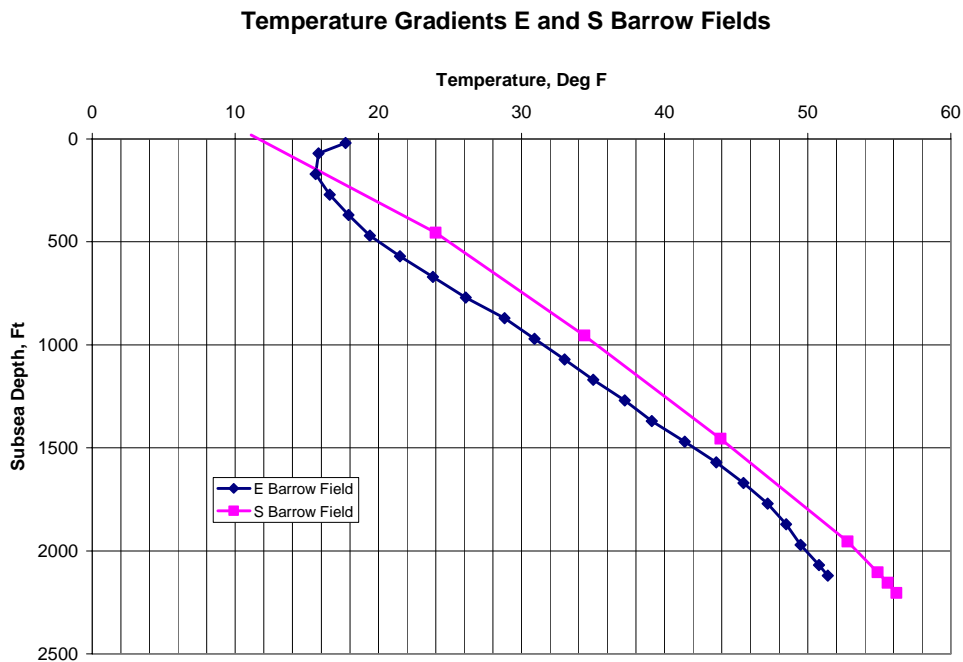


Figure 11 - Temperature Gradients for East and South Barrow Fields

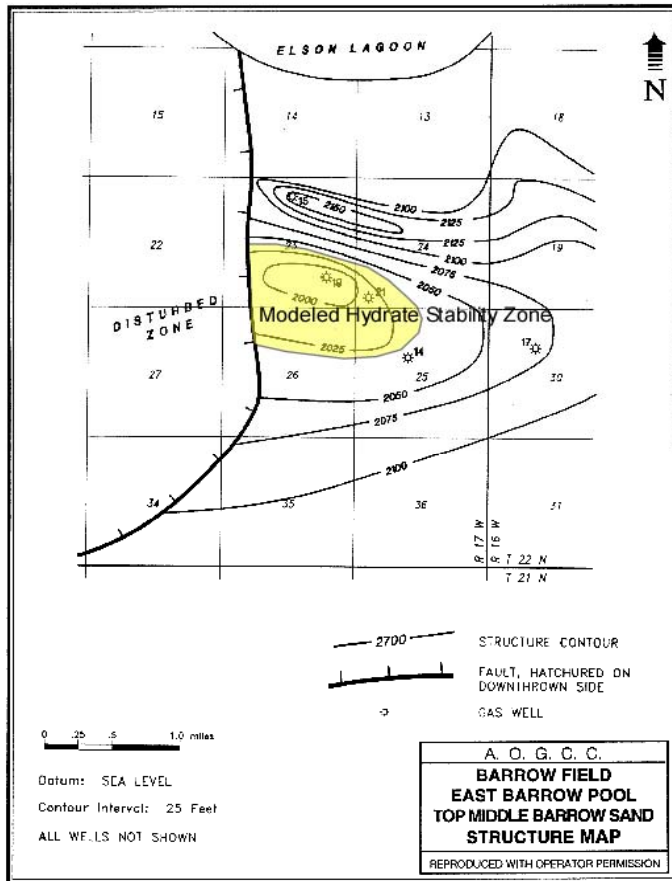


Figure 12 - Modeled most likely hydrate stability zone depth in East Barrow Field

### Walakpa Field HSZ Results

Analysis of the pressure, temperature, gas and fluid data for the Walakpa Field similarly support the presence of a hydrate stability zone which is potentially in communication with the free gas reservoir in this field. The base of the modeled hydrate stability zone at Walakpa (Figure 13) coincides with the shallowest well penetration of the free-gas sand, and Phase 1B emphasis in the Walakpa area will be on extension of the reservoir sands up dip into the hydrate stability zone.

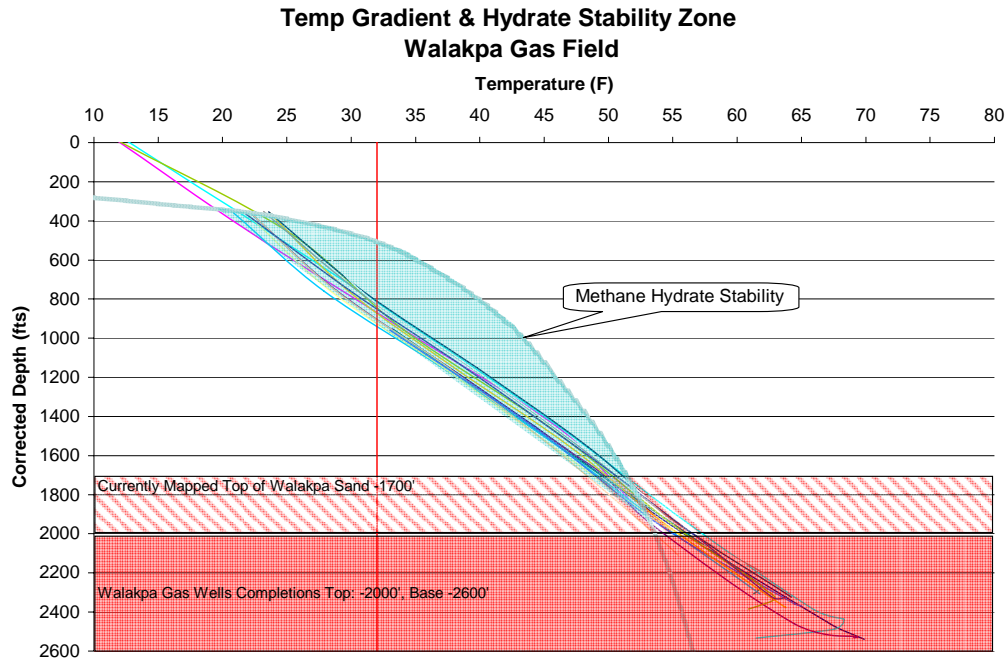
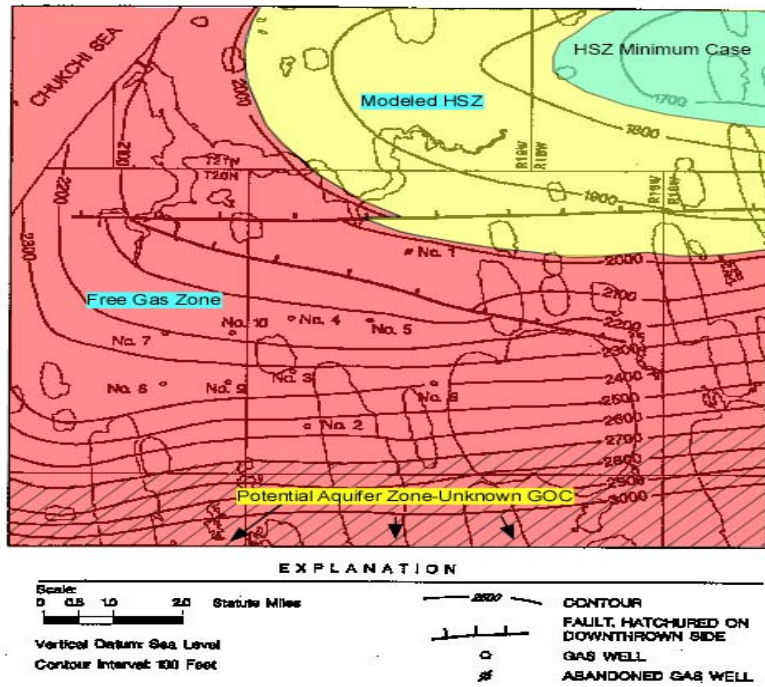


Figure 13 - Walakpa Field Modeled Hydrate Stability Zone



Modified from Glenn and Allen, 1989

Figure 14 - Modeled most likely hydrate stability zone depth in Walakpa Field

## South Barrow Field HSZ Results

Results of the hydrate stability modeling for the South pool indicate that the HSZ is significantly above the known gas sand shallowest penetration, and it is not clear that the reservoir sands extend up dip enough to intersect the HSZ. This question will be addressed in Phase 1B by mapping the reservoir sands in more detail.

### **3 Conclusions and Recommendations**

#### **3.1 Conclusions**

Extensive effort went into the search for existing data on the gas and formation water composition, and pressure and temperature gradient for the three Barrow Gas Fields. This data was supplemented by newly acquired information gathered specifically for this study. Considerable variability was revealed in the temperature gradient data between different fields, wells, and over time in a single well, and some decisions had to be made regarding data credibility. Where possible, temperature gradient information from wells which had not yet flowed, or which had been shut in for long (multi-year) periods before measurement were favored in the analysis to avoid effects of transient temperature behavior. The resulting dataset was supportive of the hydrate stability zone modeling.

Formation water sample information is sparse for the three fields, although the available samples indicate average salinities of 2-2.5%, with some samples as high as 4% salinity. Hydrate stability modeling incorporated several salinity values to measure sensitivity of the hydrate stability zone depth ranges to variation in salinity. Collection and analysis of produced water samples from the three fields would be a proposed scope addition to Phase 1B.

Gas sample data and analysis was available for the Barrow Gas Fields from prior studies, and this data was supplemented with newly collected samples from three wells from each of the three fields. The analysis indicates that the gas is thermogenic in origin, Type I-II kerogen, and late mature to over mature, accounting for the very high proportion of methane in all gas samples. Using the CSM model, the Walakpa data and most of the Barrow data shows a structure II hydrate, or just on the edge between SI and SII. No consistent or convincing trends regarding methane hydrate dissociation are apparent in the compositional or isotope analysis, although there are a few indicators consistent with possible hydrate dissociation.

Material balance modeling for the Walakpa and E. Barrow pools indicates a secondary depletion mechanism is in play in the two fields, beyond simple volumetric gas expansion. E. Barrow, in particular, has a very flat, even negative decline curve, and the field was originally considered to be characteristic of a strong edge water drive. However, the wells have not watered-out as expected, and it is possible that hydrate dissociation is playing a role in pressure support in this field, which has exceeded original estimates of ultimate recovery by approximately 30%. Walakpa, which is a far

larger field shows signs of additional pressure support, but it is too early to characterize this effect with any confidence.

The methane hydrate stability modeling carried out at the University of Alaska, Fairbanks strongly supports the presence of hydrate stability zones above all three gas fields; however, only the East Barrow pool appears to demonstrate clear overlap between the base of the hydrate stability zone and the free gas reservoir. The hydrate stability zone over the Walakpa field appears to be slightly overlapping with the shallowest penetrated free gas reservoir, but slightly up dip of the Walakpa #1 well we would expect there to be a free gas-hydrate interface. It has been suggested that the Walakpa #1 well is actually within the hydrate stability zone, based on the results of production testing when the well was drilled. Based on the results of a four-point production test, the calculated absolute open flow rate for this well was 370MSCF/D, but the well shut in due to hydrate or ice formation in the wellbore. The South Barrow pool is somewhat more challenged, in that the modeled hydrate stability zone is significantly shallower than the known free gas reservoir.

The objectives of Phase 1A have been met, with significant new data and previously recorded information integrated in a study indicating high probability of methane hydrate stability zones associated with the Barrow Gas Fields.

### **3.2 Recommendations**

Based on the findings of Phase 1A, it is the recommendation of the study team to continue to Phase 1B of the study, in order to characterize the reservoir, quantify the hydrate resource potential, and model the potential production from the hydrate resource.

Revision of the research management plan based on the results of Phase 1A is warranted in order to make scope and schedule adjustments, although the modifications are expected to be minimal.

## 4 References

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- <sup>1</sup> 2005 Walakpa Field Reserves Study by
  - <sup>2</sup> Glenn and Allen 1991
  - <sup>3</sup> Pressure-Temperature Hydrate Chart (McGraw-Hill Book Co, Inc)
  - <sup>4</sup> Collett,1998
  - <sup>5</sup> 1995 USGS study
  - <sup>6</sup> Figure 6. Proposed Gas Hydrate Production Methods (T. Collett)
  - <sup>7</sup> At Mallik, a depressurization test was achieved by a series of MDT tests
  - <sup>8</sup> Figure 7 Modeled gas production based on Mallik well tests
  - <sup>9</sup> valuable research of the Mallik Consortium
  - <sup>10</sup> Messoyakha Gas Field in West Siberia
  - <sup>11</sup> Alaskan Permafrost project (“Hot Ice”)
  - <sup>12</sup> Alaska North Slope Gas Hydrate Reservoir Characterization project
  - <sup>13</sup> Review of the compositional and isotope data was done with consultation of Tim Collett and Tom Lorenson of the USGS

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