Presentation Outline

- Introduction / Collaboration
  - Gas Hydrate Resource
  - Resource Characterization
  - Production Technology
  - Reservoir/Development Models
- Conclusions
Collaborative Research Team

U.S. Department of Energy

GOVERNMENT

USGS

science for a changing world

National Labs

bp

Unconventional Resource Determination

INDUSTRY

ASRC Energy Services

APA Petroleum Engineering

UNIVERSITIES

Research Innovation

3D Seismic & Well Data, Infrastructure
### Project Timing & Phases

**Phase/Year**
- 2001
- 2002
- 2003
- 2004
- 2005
- 2006
- 2007

**Project Proposal**
- DOE-Industry Alignment

**Wells of Opportunity – Acquire Data**
- Characterize Reservoir/Fluid
- Calculate In-Place Resource

**Drilling/Production RE/PE Studies**
- Wells of Opportunity – Acquire Data
- Characterize Reservoir/Fluid
- Calculate In-Place Resource

**Reservoir and Development Modeling**
- Validate Regional Prize, Determine Alignment, Plan/Acquire Data
- Characterize & Calculate Resource

**Possible Pilot Development Testing?**
Presentation Outline

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Gas Hydrate in U.S.

- Alaska
- Onshore
- Gulf of Mexico
- Infrastructure
- Technology

GAS HYDRATE PLAY MAP
Alaska North Slope Operators

- Alpine
  - ConocoPhillips (O) 78%
  - Anadarko 22%

- Milne Point
  - BPXA (O) 100%

- Northstar
  - BPXA (O) 98%
  - Murphy 2%

- Endicott
  - BPXA (O) 68%
  - Exxon Mobil 21%
  - Unocal 11%

- Greater Kuparuk
  - ConocoPhillips (O) 55%
  - BPXA 39%
  - Unocal 5%

- Greater Prudhoe Bay
  - Exxon Mobil 37%
  - ConocoPhillips 37%
  - BPXA (O) 26%

- Pt. Thomson

- North Slope Gas **Resource** ➔ 35 TCF
- PBU Production = 8 BCF/Day ➔ Reinjected ➔ Reservoir Energy
Gas Hydrate **In-Place**, ANS Basin (USGS) ➔ 590 TCF

Gas Hydrate **In-Place**, ANS Infrastructure area (USGS) ➔ 100 TCF

Gas Hydrate **In-Place**, Eileen Trend ➔ 33-44 TCF

Gas Hydrate/Gas **In-Place** Milne Point ➔ ~ 617/90 BCF (mean)
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Phase-I. Assess existing geologic, geophysical, and engineering data to characterize the resource potential of the Eileen and Tarn gas-hydrate/free-gas accumulations (FY 03-05).

BPXA – USDOE project synergy.

Phase-II. Assess existing geologic, geophysical, and engineering data to characterize the resource potential of the undiscovered gas hydrate accumulations in NPRA, ANWR, and the State lands between the Canning and Colville Rivers (FY 05-06).

Phase-III. Assess the economically recoverable resource potential of gas hydrates and associated free-gas accumulations in northern Alaska (FY 07).
Gas Hydrate Stability Zone
Alaska North Slope

Petroleum System also Required:
Gas Source, Migration, Reservoir, Trap, Seal
Gas Hydrate Core
Gas hydrate stability zone
Ice-bearing permafrost
Free-gas, oil, or water-bearing
Composite of A-F Hydrates

Collett et al. 1-2004

Milne Pt 3D Survey

Free Gas-prone

Milne Point Gas Hydrate Accumulation

TARN

EILEEN

GAS HYDRATE

GAS HYDRATE

PRUDHOE BAY OIL FIELD

KUPARUK RIVER OIL FIELD

MILNE POINT OIL FIELD

Collett et al. 1-2004
Structural Complexity
AOI located along major rift margin discontinuity

Northern tip of major transcurrent FZ that segments foreland basin and fold-thrust belt to south (Casavant, 2001)

Basement blocks at variety of scales are differentially uplifted, rotated, translated indicating that arch is faulted rather than just a jog

Long-lived depocenter
Seismic structure (mkr 34)
- ~USGS “C” pay unit
Idealized pull-apart basin attributes from analog modeling

1. Inactive borderland structures
2. Oblique-reverse fault
3. Terraced sidewall fault zone
4. Cross-basin fault zone
5. Negative flower structure
6. Relay ramp
7. PDZ in-line graben/push-ups

“East Basin”

MPU (schematic)
Transtensional basin => fault complexity

Hagbo, 2003
WSAK 25
~ projection of WSAK-25

Sidewall Shear zone - multiple reactivation

Net/gross increases

En echelon grabens
Seismic Modeling and Velocities

Dipping Layer Model

- 10 Ft Gas Hydrate
- 20 Ft Gas Hydrate
- 10 Ft Gas Hydrate over 10 Ft Gas
- 20 Ft Gas over 10 Ft Water
- 20 Ft Water

Time in Milliseconds

Velocity Pull-up  Velocity Push-down

Gas Hydrate  Gas  Water

Base of GHSZ

USGS
Science for a changing world
Seismic Amplitude Assessment

Free Gas trapped beneath Gas Hydrate?
Mt. Elbert Gas Hydrate Prospect
Seismic Amplitude

3-way Fault-bounded Trap, Gas Hydrate-bearing Reservoir
Gas Hydrate Prospect, Seismic Amplitude

Top Staines Tongue Contact against Base Gas Hydrate

GAS HYDRATE?
FREE GAS?
Gas Hydrate Prospect Uncertainty Analyses

**BULK ROCK VOLUME**
Assumption: Elbert C

Normal distribution with parameters:
- Mean: 3,000,403,160.32
- Standard Dev.: 300,040,316.03

Selected range is from 2,550,342,686.27 to 3,450,463,634.37

**SATURATION**
Assumption: G5

Triangular distribution with parameters:
- Minimum: 40.0%
- Likeliest: 59.7%
- Maximum: 90.0%

Selected range is from 40.0% to 90.0%

**POROSITY**
Assumption: G3

Triangular distribution with parameters:
- Minimum: 34%
- Likeliest: 38%
- Maximum: 40%

Selected range is from 34% to 40%

**NET-TO-GROSS**
Assumption: G4

Triangular distribution with parameters:
- Minimum: 70%
- Likeliest: 80%
- Maximum: 95%

Selected range is from 70% to 95%
<table>
<thead>
<tr>
<th></th>
<th>Antero C</th>
<th>Bierstadt D</th>
<th>Bierstadt E</th>
<th>Blanca C</th>
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<th>Elbert D</th>
<th>Grays Peak B</th>
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<td>80%</td>
<td>80%</td>
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<td>Gas Saturation</td>
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<td>49.8%</td>
<td>66.9%</td>
<td>55.1%</td>
<td>49.8%</td>
<td>59.7%</td>
<td>52.6%</td>
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<td>Volume in Place (cu ft)</td>
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<td>27.8</td>
<td>41.1</td>
<td>20.4</td>
<td>157.6</td>
<td>89.3</td>
<td>46.2</td>
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<th>Maroon Peak A</th>
<th>Mt Princeton D</th>
<th>Pikes Peak B</th>
<th>Red Cloud B</th>
<th>Snffels D</th>
<th>Uncompaghre Peak D</th>
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<td>13.6</td>
<td>17.0</td>
<td>43.6</td>
<td>9.6</td>
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14 “Intra-Hydrate” Prospects

620 BCF Median Estimated Gas in Place
### MPU Associated Free Gas VOLUMETRICS

<table>
<thead>
<tr>
<th>Area (acres)</th>
<th>Long's Peak Middle</th>
<th>Mt Yale Upper</th>
<th>Kit Carson Upper</th>
<th>Maroon Peak Middle</th>
<th>Mt Shavano Middle</th>
<th>Mt Holy Cross Middle</th>
<th>Mt Holy Cross Upper</th>
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<tr>
<td>Gross Thickness (ft)</td>
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<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
<td>25</td>
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<td>Porosity</td>
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<td>36%</td>
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<tr>
<td>Net-to-Gross</td>
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<td>80%</td>
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<td>Gas Saturation</td>
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<td>70.0%</td>
<td>70.0%</td>
<td>70.0%</td>
<td>70.0%</td>
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<tr>
<td>1/Bg</td>
<td>108</td>
<td>108</td>
<td>108</td>
<td>108</td>
<td>108</td>
<td>108</td>
<td>108</td>
</tr>
<tr>
<td>Volume in Place Gas (billion cu ft)</td>
<td>18.9</td>
<td>9.5</td>
<td>13.7</td>
<td>9.0</td>
<td>6.0</td>
<td>24.0</td>
<td>9.3</td>
</tr>
</tbody>
</table>

**Median Estimated Gas In Place**

7 Prospects Totaling 90.3 BCF

- Based on these prospect analyses and proximity to infrastructure, locations to acquire data would be chosen in collaboration with the resource owner.
- We have developed a workflow that can be used for gas hydrate prospecting in other areas of the North Slope.
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Productivity/Development Challenges
Gas Hydrate Production Methods

**PRESSURE**
- Gas Out
- Water Out?

**TEMPERATURE**
- Gas Out
- Hot Brine or Gas

**CHEMICAL**
- Gas Out
- Methanol, Brine, or CO₂

- Endothermic Heat of Gas Dissociation
- Temperature Recovery Lag Time
- Hydrate Self-Preservation

- Large energy in
- Heat Host Rock
- In-situ combustion?
- In-situ Electromag?

- Methanol High cost
- PNNL Lab Tests CO₂
- Not Field-Tested
- Potassium Formate?

Modified
After Collett, 2000
Proof-of-Principle

CH4 → CO2

Theory: Inject CO₂ to Recover CH₄ from Gas Hydrate

- Thermodynamically Favorable
- Offsetting Dissociation Enthalpy: CO₂ Hydrate Formation Heat ~20% > CH₄ hydrate dissociation
- Sediment Mechanical Stabilization

Results: CH₄ from Gas Hydrate by Injecting CO₂

- Liquid- CO₂ Emulsion Best Method
- Temperature Reading Immediately Spiked from -2.5°C to 8°C
- Only Methane Gas Output
- Lab bench "--->" vs... Field Trial
Productivity/Development Challenges
Gas Hydrate Production Methods

Shale Barrier

HZ wellbore

gas and water flow

Hydrate Saturated Formation
Presentation Outline

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Reservoir Modeling Historical Perspective

Positive By-Product of a Normal Practice

Build Lab Model to Test Concept

Field Test With Specific Objectives

Tune Computer Models With Field Results

Identify Targets for Implementation

Build Initial Computer Models
Reservoir Modeling

- Adapted Industry-Standard Reservoir Models to Gas Hydrate Phase-behavior
  - Used CMG-STARS and special inputs
  - Enabled Well/Field-scale modeling
- Developed Type-Well Cases/Ranges
  - Studied Pressure Response Variables
  - Evaluated Coalbed Methane Analog
  - Expanded to Full-Field Development
CMG STARS Reservoir Model Results
Gas Production & Gas Hydrate Dissociation

2nd Refined Milne Point grid: 6/9/2004
Hydrate Saturation 2005-01-02

175 Meter Horizontal Well
3 ½” Tubing

5 miles
3 miles

~ Free Gas

Gas Hydrate
CMG STARS Reservoir Model Results
Gas Hydrate Dissociation after 15 years

201 x 340 x 2 cells = 136,680 total cells
82.5 foot grid spacing

2nd Refined Milne Point grid: 6/9/2004
Hydrate Saturation 2019-04-18

5 miles
3 miles

~ Free Gas

Gas Hydrate

File: MP+10d69res
User: swilson
Date: 2004-08-20
Z/X: 8.00:1
Reservoir Model: Depressurization

Significant Production Increase (~2X) due to Free Gas Dissociation from Gas Hydrate

Significant Uncertainties Remain
• 40% initial $S_w$
• Well Placement in Hydrate zone
• Initial $S_w > S_{w_{irr}}$
Intra-Hydrate Production Scenarios

2nd Refined Milne Point grid: 6/9/2004
HydProd 001-MPbase40pctSWNoFreeGas30mdNoSl.irf

- 60% $S_{hyd}$, 40 % $S_w$ includes 20 % $S_{wirr}$

< Gas Hydrate, > Water
> Productivity

2nd Refined Milne Point grid: 6/9/2004
HydProd 001-MPbase20pctSWNoFreeGas150mdNoSl.irf

- 80% $S_{hyd}$, 20 % $S_{wirr}$

> Gas Hydrate, No Mobile Water
< Productivity
<table>
<thead>
<tr>
<th>Zone</th>
<th>GIP (TCF)</th>
<th>Risked GIP (TCF)</th>
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</thead>
<tbody>
<tr>
<td>A</td>
<td>18</td>
<td>6</td>
</tr>
<tr>
<td>B</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>C</td>
<td>11</td>
<td>8</td>
</tr>
<tr>
<td>D</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>E</td>
<td>6</td>
<td>4</td>
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<tr>
<td>Total</td>
<td>50</td>
<td>33</td>
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North Slope Hydrate Forecasts

Type Well Gas Production Forecasts

Reference Case

- 160 Acre High Sw
- 640 Acre High Sw
- 640 Acre Low Sw

High Upside Case

- 160 Acre High Sw
- 640 Acre High Sw
- 640 Acre Low Sw
- Upside 640 Acre Low Sw
- Upside 640 Acre High Sw

North Slope Hydrate Forecasts

Type Well Cumulative Production Forecasts

Reference Case

- 160 Acre High Sw
- 640 Acre High Sw
- 640 Acre Low Sw

High Upside Case

- 160 Acre High Sw
- 640 Acre High Sw
- 640 Acre Low Sw
- Upside 640 Acre Low Sw
- Upside 640 Acre High Sw

North Slope Hydrate Forecasts

Type Well Water Production Forecasts

Reference Case

- 160 Acre High Sw
- 640 Acre High Sw
- 640 Acre Low Sw

High Upside Case

- 160 Acre High Sw
- 640 Acre High Sw
- 640 Acre Low Sw
- Upside 640 Acre Low Sw
- Upside 640 Acre High Sw
Coal Bed Methane Analog?
Development Modeling

- Predicted to follow historical patterns
- Initial positive results expanded to full-field

Stage 1: Initial Pilot Testing and Data Acquisition

Stage 2: Multi-well Pilot Testing and Calibration

Stage 3: Limited Initial Development

Stage 4: Full-Field Development

Stage 5: Resource Harvesting and Optimization

Stage 6: Manage and Expand Resource

Stage 7: New Technology / Infill Drilling
Stage 1: Single Well Pilot Testing

2nd Refined Milne Point grid: 6/9/2004
Ternary 2018-10-20

File: 001-MPbasehighCp
User: swilson
Date: 2004-08-17
Z/X: 3.00:1
Stage 2: Multi-well testing/calibration

- Well locations schematic-only
- Multi-well 160 Acre Pilot
Stage 3: Limited Initial Development

- Well locations schematic-only
- Fully Dependent upon successful Stage 1-2
- Conceptually Similar to WSak 1J pilot in KRU viscous oil
- Additional area tests
- First Major Capex
- First Reserve Booking
Stage 4: Full-field development

- Well locations schematic-only
- Latter stage development
- Major Capex Required
- Filters applied to reduce well count to ~148 at 640 Ac. in C/D sands > 0’
- Infilling as-needed
Stage 5: Resource Harvesting

- Well locations schematic-only
- Latter stage development
- 640 to 320 Acre Spacing
- Infilling to tighter spacing
- Major Capex Required
- Optimization
- Possible new pad extensions
Stage 6: Manage/Expand Resource

- Well locations schematic-only
- Very Late-stage development
- 640 to 320 Acre Spacing
- Infilling to tighter spacing and extension
- Major Capex Required
- Optimization
- Possible multi-laterals
- Possible new pad extensions
- Resource on-decline
- New Technology?
Stage 7: New Technology/Infilling

- Well locations schematic-only
- Latest stage conceptual full-field development
- 160 Acre spacing
- Major Capex Required
- Optimization
- Improved technology?
Fieldwide Production Forecasts

Production trends predicted using the type wells and development timing. Four cases:

1. **Downside case:** Poor Pilot test, additional testing and ultimate project economic failure, technical resource evaluation success.  
   **1-4 wells, 0 TCF Recovered**

2. **Reference case:** Encouraging pilot results and Stage 2 (18 well) pilot development transition into large scale development.  
   **172 wells, 2.5-9.6 TCF**

3. **Upside case:** Good pilot and Stage 2 results transition into 320 acre development with heat or chemical assisted production.  
   **283 wells, 3.6-11.8 TCF**

4. **Extreme upside case:** Outstanding pilot/Stage 2 confirms resource; development moves forward rapidly on 640 acre spacing.  
   **141 wells, 8.8-9.3 TCF**
Potential case analog in the lower-48 Coal Bed Methane (CBM)
Extreme Upside Case

Gas and Water Production Forecast

Cumulative gas & water

MCF Gas

Bbls Water
Production Uncertainties

- Dissociation & gas production character/rate
- Associated water production rate
- Endothermic effects of production
- Initial and dissociating permeabilities
- Gas hydrate saturations
- Production technologies

Uncertainty Mitigations

- Prospect delineation of seismic-prospects
- Production testing (short & long-term)
- Thermal enhancement understanding
- Sand control, Artificial Lift, In-situ combustion?
Interim Conclusions

- **ANS – Gas Hydrate Petroleum System**
  - Complex Shallow Structure & Stratigraphy
  - Multiple High-graded MPU Prospects Revealed: 620 BCF
  - Regional Development Scenarios Under Evaluation

- **Significant uncertainties remain**
  - Regional Resource In-Place may be >33 TCF Eileen Trend
  - Resource Potential Remains Uncertain – 0-12 TCF possible
  - Direct Detection Geophysical Methods Require Delineation
  - Additional Data Acquisition Could Calibrate Resource Potential
  - Type Well Production Rates Modeled at 0.4-2 MMSCF/d
  - Peak Field-wide Forecast Models up to >350 MMSCF/d
  - Modeled Production Character Long with Flat Declines
  - Potentially High Associated Water Volumes

- **Technical Project Results Helping to Solve Issues**
  - Industry & Government to make more Informed Decisions