Unconventional Gas Production

Commercialization of Hydrated Gas

James Mansingh
Jeffrey Melland
Objective Statement

- Methane hydrates hold a massive potential for production of natural gas, so we set out to find an economical way to produce hydrated gas and deliver it to market
Intro to Hydrates

- Methane & water have the ability to form hydrates.
Clathrates

- Methane trapped in a cubic water crystals
- Unstable at standard temperature and pressure
- Estimated to produce 150 units of gas
Overview

- Operations
  - Locating
  - Drilling
  - Production
  - Piping
  - Liquefaction
  - Shipping
  - Regasification
  - Sales
Locating
Locating

- Seismic Surveying
  - Acoustic

- Seismic Analysis
  - 2 month project, 3 man team
  - Block = 3 square miles
  - Usually shoot 30-60 blocks at a time
  - Project a 2000 square km area with a depth of 1200ft to 3300ft
Locating cont’

- Seismic Survey Costs
  - $30,000 for shooting a block
  - $12,000,000 for the 2000 km² area with a depth of 400m-1000m
  - $3,000,000 for reprocessing cost and time for the seismic survey
  - Total Cost = $15,000,000
Drilling
Drilling

- Drilling and Measurements
  - Directional drilling and basic logs to locate promising zones
Drilling

- Reservoir Evaluation
  - In depth logs of promising areas
  - Perforations into methane hydrated areas
Drilling

- Well Stimulation
  - Pressurized solution addition into the formation to stimulate backflow of desired product
Drilling cont’

- Drilling and Measurements
  - 17 day projects
  - 90fph thru basic formation
  - 10fph thru hydrate formation

- Reservoir Evaluation
  - 2 separate day projects
  - Log 1200ft to 3300ft
  - HILT with FMI and Sonic
  - Two 3ft perforations at 2100ft & 2200ft

- Well Stimulation
  - 3 separate fracturing day projects, 1 casing job, 1 cementing job
  - 70 miles each way to get to location
Drilling Cont’

- Basis for a well
  - 25 day project

- Initial investment
  - $20.5 million

- Yearly operating cost
  - $8.2 million

- Drilling and Measurements
  - $895,500

- Reservoir Evaluation
  - $14,700

- Well Stimulation
  - $5,840,000

- Well Completions
  - $68,300
Production

- Assumptions
  - 165 scm gas per cubic meter of hydrate
  - Formation behaves as a tank
  - Formation is homogenous and isotropic
  - No intermediate phases
  - Isothermal process
  - Rock expansion is negligible
  - 300 m vertical fractures in 2 directions, 180° separation
  - Negligible pressure gradient along fractures
  - Hydrate formation is on average 70 m deep
Production – hydrate stability

\[ \ln(P_{\text{dissociation}}) = -7657.3 \left( \frac{1}{T} \right) + 33.877 \]

281 K
5.2 MPa
Free gas
Permafrost
Hydrated gas
Gas flow

\[ P = 1600 \text{ kPa} \]

70 m

Permafrost
Fracture gradient
Moving hydrate boundary

300 m

Hydrated gas

\[ P = 5200 \text{ kPa} \]

Free gas

300 m
Production cont’

- Kinetics
  - Dissociation is faster than diffusion under down hole conditions
  - Flow through the formation is much slower
  - Focus on flow through formation
  - Linear Pressure gradient

\[
\frac{dx}{dt} = K_0 e^{-\frac{E}{RT_s}} \left( f_{eH} - f_\infty \right)
\]
$G_f = \frac{V_f}{ZXT} \left( \frac{P_{eH} + P_{wf}}{2} \right)$

$\frac{Q_g}{A} = k \nabla P$

$G_{eH} = 165V_{eH}$

$G_{fg} + G_P = G_{eH}$

$P = 5200 \text{ kPa}$

$P = 1600 \text{ kPa}$

$\nabla P = \frac{dP}{dx} = C$

$C = \frac{P_{eH} - P_{wf}}{x}$

$P(x) = \frac{x(P_{eH} - P_{wf})}{X} + P_{wf}$

Hydrated gas
Production

Rates may seem high, but an analysis of the velocity of the hydrate boundary shows that a max velocity of 3mm/min at the beginning of dissociation, slows to 0.24 mm/min at the end of a year.
Production cont’

Graph showing the relationship between Qg (scm/day) and t (months) with logarithmic scales.

- Qg ranges from 1.00E+05 to 1.00E+07
- t ranges from 0.1 to 100

The graph indicates a declining trend for Qg as t increases.
Production cont’
Production

\[ y = 1 \times 10^8 x^{-0.4895} \]

\[ R^2 = 0.9586 \]

Power law model
Production

Drill 22 wells
Production - conclusions

- Control gas production initially at 10.5 MM scm/day
- Rate drops off to about 2.25 MM scm/day after the first month
- Expected production for the first month is 1,770,000 scm per foot of formation
- Expect to continue significant gas production for entire project.
Production - conclusions

- 22% of gas from hydrates is left down hole
- Exposing as much hydrate surface as possible is best way to produce gas
- Wells produce significant gas over an extended period
- The monthly rate is fairly accurately modeled by a power regression, this was used after the first 70 months
Piping

- **Challenges**
  - Provide a force to push the gas through the pipe
  - Preventing methane and water from reforming into a hydrate in the pipe
  - Excess water causing erosion damage to pipeline

- **Solutions**
  - Use Bernoulli's formula to solve for minimal compressor power required to move gas, simulated in ProII
  - Remove water from gas via a dehydration station
  - Maintain gas above 4C to prevent refreezing
Piping

Mountain Piping

Wellsite

Gas Pipeline

Compressor Station

Compressor/TEG Station

Liquefaction Plant
Piping cont’

- **Local Mountain Pipeline Assumptions for Calculations**
  - 4 miles of pipe required to reach bottom of mountain
  - 8” pipe from well site
  - 12” pipe header into compressor station

- **Compressor/TEG Assumptions for Calculations**
  - Producing an average 10.5 million cubic feet of gas per day
  - Use Centrifugal pumps rated 6000kw and 75kW for commercial industry

- **Pipeline Assumptions for Calculations**
  - Roughly 50 miles from the first compressor station to LNG Plant
  - Temperature above 4C and pressure above 1000kPa
  - 36” main pipeline to the LNG Plant
Piping cont’
- **TEG Dehydration Station**
  - $450,000

- **Compressor Costs**
  - $3.6 million for a 6000kW compressor (9 total)
  - $0.3 million for a 560kW compressor (6 total)
  - Total compressor cost = $11.5 million

- **Piping Costs**
  - $60 million for 36” pipe going 50 miles
Piping cont’

- Equipment Costs
  - $94 million
- Initial investment
  - $270 million
- Yearly operating cost
  - $87 million
Liquefaction cascade

- Natural gas
- Methane
- Ethylene
- Propane
- LNG
Liquefaction

- Heat exchangers
  - 266 at 200 m² each (52,200 m² required)
  - $14.8 million

- 4 compressors –
  - 53 at 6000 kW each (309 MW required)
  - $68.4 million

- Flash drum – $250,000

- Storage tank – $12,200
Liquefaction

- 1.25 billion kg/year capacity
- $500 million investment
- $270 million yearly operating costs
  - $140 million per year for electricity
  - $60 million for depreciation
  - Taxes, insurance, repairs personnel, etc…
Shipping

- LNG will be transported from Kamchatka to Japan via one LNG ship

- Assumptions
  - 8 day sea voyage one way trip
  - 6 days for loading, unloading and in port maintenance operations
  - 22 day round trip voyage
  - 15 nm average speed of LNG ship
Shipping cont’

- Costs
  - Round trip - $1.5 million
  - Daily operational cost is a function of building costs, financing and operating the ship
  - One LNG ships in operation will cost $65,000 per day
Shipping cont’

- 3 Ships Costs
  - $150 million each
- Initial investment
  - $58.1 million
- Yearly Operating Costs
  - $71.2 million
Regasification

- **Challenges**
  - Phase change of LNG to gas methane
  - Achieve regasification with minimal power requirements

- **Solutions**
  - Use seawater as heat source
  - Use propane as a medium b/w seawater and LNG to harness expansion power of a gas and generate power
Regasification

LNG → Methane Gas

Seawater
Regasification cont’

Expander (propane, gas)

\[ Q = -3155.863 \text{ HP} \]
\[ h = 58.4 \text{ ft} \]
\[ P = 14,700,036.41 \text{ psi} \]
\[ \text{volumetric flowrate } \times \text{discharge pressure} = 353.5716666 \text{ kPa-m}^3/\text{s} \]
\[ \text{Power in kW} = -2353.327039 \text{ kW} \]
\[ \text{cost of expander (max value at 1000 kW)} = -157,862 \]
\[ \text{Number of Expanders needed} = 1 \text{ approximately } 3 \]
\[ \text{cost (horizontal pump @ 174 kPa-m}^3/\text{s)} = 473,586.00 \]
\[ \text{Selling price of Expanders energy in kW} = -188.27 \text{ per hour} \]
\[ -4,518.39 \text{ per day} \]
\[ -1,649,211.59 \text{ per year} \]
Regasification cont’

- **Equipment Costs**
  - $14 million

- **Initial Investment**
  - $84 million

- **Yearly Operating Costs**
  - $17 million
Decisions

- 1 LNG Ship
  - 3.5 scm/day
  - TCI $690 million
  - Expected ROI 7% per year
  - Final Cash Position of $1.74 billion

- 2 LNG Ship
  - 7.0 scm/day
  - TCI $1.25 billion
  - Expected ROI 12% per year
  - Final Cash Position of $5.8 billion

- 3 LNG Ship
  - 10.5 scm/day
  - TCI $1.9 billion
  - Expected ROI 12% per year
  - Final Cash Position of $4.17 billion
Regret

- Regret analysis is the analysis of unrealized profit associated with production choices
<table>
<thead>
<tr>
<th></th>
<th>lowest</th>
<th>low</th>
<th>expected</th>
<th>high</th>
<th>highest</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Ship</td>
<td>$ (1,189.42)</td>
<td>$ (479.07)</td>
<td>$ 732.96</td>
<td>$ 2,597.31</td>
<td>$ 3,220.50</td>
<td>$ 976.46</td>
</tr>
<tr>
<td>2 Ship</td>
<td>$ (1,605.89)</td>
<td>$ (186.40)</td>
<td>$ 2,237.76</td>
<td>$ 5,952.30</td>
<td>$ 6,704.74</td>
<td>$ 2,620.50</td>
</tr>
<tr>
<td>3 Ship</td>
<td>$ (2,311.69)</td>
<td>$ (193.75)</td>
<td>$ 3,401.06</td>
<td>$ 9,113.69</td>
<td>$ 11,154.77</td>
<td>$ 4,232.82</td>
</tr>
<tr>
<td>highest</td>
<td>$ (1,189.42)</td>
<td>$ (186.40)</td>
<td>$ 3,401.06</td>
<td>$ 9,113.69</td>
<td>$ 11,154.77</td>
<td>$ 4,232.82</td>
</tr>
</tbody>
</table>
# Regret

<table>
<thead>
<tr>
<th>Ship</th>
<th>lowest</th>
<th>low</th>
<th>expected</th>
<th>high</th>
<th>highest</th>
<th>Maximum regret</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>$1,122.27</td>
<td>$292.67</td>
<td>$2,668.10</td>
<td>$6,516.38</td>
<td>$7,934.27</td>
<td>$7,934.27</td>
</tr>
<tr>
<td>2</td>
<td>$416.47</td>
<td>$1,163.30</td>
<td>$3,161.39</td>
<td>$4,450.02</td>
<td>$4,450.02</td>
<td>$4,450.02</td>
</tr>
<tr>
<td>3</td>
<td>$1,122.27</td>
<td>$7.35</td>
<td>$-</td>
<td>$-</td>
<td>$-</td>
<td>$1,122.27</td>
</tr>
</tbody>
</table>

minimax regret $1,122.27

3 ship
Pipeline to China vs. LNG Conversion

- **LNG Costs**
  - (Using 3 ships)
  - FCI $1.3 billion
  - WC $318 million
  - TCI $1.7 billion

- **Gas Costs**
  - (Using 32” pipe)
  - FCI $1.8 billion
  - WC $798 million
  - TCI $2.6 billion

- **Difference in Gas vs. LNG**
  - FCI $404 million
  - WC $480 million
  - TCI $883 million
  - TPC $260 million
Pipeline to China vs. LNG Conversion

![Bar chart showing costs for FCI, WC, TCI, TPC for LNG, Gas Pipeline, Difference]
## Total Capital Investment ($Million)

<table>
<thead>
<tr>
<th>Description</th>
<th>Cost</th>
<th>% of TCI</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCI</td>
<td>$1,700</td>
<td></td>
</tr>
<tr>
<td>Locating</td>
<td>$15</td>
<td>0.88%</td>
</tr>
<tr>
<td>Drilling</td>
<td>$21</td>
<td>1.80%</td>
</tr>
<tr>
<td>Piping</td>
<td>$270</td>
<td>19.11%</td>
</tr>
<tr>
<td>Liquefaction</td>
<td>$1,252</td>
<td>59.59%</td>
</tr>
<tr>
<td>Delivery</td>
<td>$58</td>
<td>15.70%</td>
</tr>
<tr>
<td>Regasification</td>
<td>$84</td>
<td>3.79%</td>
</tr>
</tbody>
</table>
Total Capital Investment ($Million)

- Locate
- Drill
- Pipe
- Lique
- Ship
- Regas

$0.00 to $1,400,000,000.00
# Total Production Cost ($Million)

<table>
<thead>
<tr>
<th></th>
<th>TPC</th>
<th>$453</th>
<th>% of TPC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drilling</td>
<td>$8.2</td>
<td>1.80%</td>
<td></td>
</tr>
<tr>
<td>Piping</td>
<td>$87</td>
<td>19.11%</td>
<td></td>
</tr>
<tr>
<td>Liquefaction</td>
<td>$270</td>
<td>59.59%</td>
<td></td>
</tr>
<tr>
<td>Delivery</td>
<td>$71</td>
<td>15.70%</td>
<td></td>
</tr>
<tr>
<td>Regasification</td>
<td>$17</td>
<td>3.79%</td>
<td></td>
</tr>
</tbody>
</table>
Total Production Cost ($Million)

- Locate
- Drill
- Pipe
- Lique
- Ship
- Regas

Costs:
- $0.00
- $200,000,000.00
- $400,000,000.00
- $600,000,000.00
- $800,000,000.00
- $1,000,000,000.00
- $1,200,000,000.00
- $1,400,000,000.00

Legend: TCI
Value Chain

Piping

$0.06/MMBtu

Market

$0.13/MMBtu

$3.36/MMBtu

($7.00/MMBtu)

$0.53/MMBtu

$2.00/MMBtu

$0.7/MMBtu
Value Chain

Profit

($3.64/MMBtu)
Cumulative Cash Position $9 gas

$9.9 billion after 15 years

MM$

$12,000.00
$10,000.00
$8,000.00
$6,000.00
$4,000.00
$2,000.00
$-
$(2,000.00)
$(4,000.00)

time (years)
Cumulative Cash Position $8 gas

$7.9 billion after 15 years
Cumulative Cash Position $7 gas

- $7,000.00
- $6,000.00
- $5,000.00
- $4,000.00
- $3,000.00
- $2,000.00
- $1,000.00
- $-  
- $(1,000.00)
- $(2,000.00)
- $(3,000.00)

$5.8 billion after 15 years

$MM$

time (years)
Net Present Worth

- **$7 gas**
  - Expected NPW of $3.4 billion
  - 12% ROI per year
  - 180% ROI over all

- **$8 gas**
  - Expected NPW of $4.5 billion
  - 16% ROI per year
  - 240% ROI over all

- **$9 gas**
  - Expected NPW of $3.4 billion
  - 20% ROI per year
  - 300% ROI over all
Questions?
References

- Sloan, E. Dendy Jr., *Clathrate Hydrates of Natural Gases*, 1998
- Foss, Michelle Michot, *Introduction to LNG*, 2003