INDUSTRIAL APPLICATIONS OF CLATHRATE HYDRATES

A BRIDGE TO COMMERCIAL GAS HYDRATE PRODUCTION
First named and characterized by Michael Faraday in 1823. He first encountered clathrates during his fundamental work on chlorine. It remained a laboratory curiosity for more than 100 years.

Gas field operators in the 1930’s experienced hydrate blockages in pipelines during winter. Additives like methanol were developed to solve the problem making it a gas field and laboratory curiosity.

Natural methane hydrates were first observed by Soviet geologists in Siberian permafrost during exploratory drilling in 1960’s. Geologists have since shown that natural hydrates dwarf traditional fossil fuel reserves.

Still mysterious = Opportunity
Phase Change Can Be Controlled
By Both Temperature and Pressure

Thermodynamic Reversibility

Isothermal Compression

Both are Moderate

Thermal Energy Storage

What Else Can Do All of This?

High Latent Heat and Higher Formation Temperature than Ice

Ability to Separate Gases and Purify Water
WHY HASN’T THIS BEEN DONE BEFORE?

Wrong Model Applied to the Right Technology

LNG Worked for Largest Gas Fields

Classic Valley of Death Scenario
Discovery by Rudy Rogers research group at MSU that surfactants enable rapid hydrate formation in an unstirred reactor in 1997.

NETL funded 1000 liter demonstration reactor that was run only 6 times.

Shortcuts were made and poor heat transfer prevented demonstration living up to its potential.

HEAT TRANSFER IS THE CRITICAL FACTOR
OUR SOLUTION

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<th>Displacement</th>
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<tr>
<td>Number of Tanks</td>
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<td>Gas Storage</td>
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<td>Potential Power</td>
<td>~3700 MWh</td>
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Tank Volume | 50,000 liters
Storage Capacity | 250 MMBtu
Formation Energy | ~1800 kWh
Potential Power | ~30 MWh

INCREASE FLEXIBILITY & REDUCE FIXED CAPEX
THE GAS SUPPLY CHAIN REPRESENTS THE LARGEST AND MOST EXPENSIVE ENGINEERING PROJECTS ON EARTH
HOW DOES GAS GET TO MARKET TODAY?

**COMPRESS**
- Pipelines
  - Geographically and politically constrained.

**LIQUIFY**
- Land Based
  - Expense limits applications to only the largest gas fields.
- Floating
  - Cost of $5.00-7.00/Mmbtu and $7-15 Billion CAPEX

HOW WILL HYDRATES GET TO MARKET?
The energy supply chain explains why oil is worth more than gas.

Oil is the benchmark because it is a liquid. Low CAPEX storage and high energy density make it worth $20/mmbtu.

Gases are much more challenging. High CAPEX storage and volatility make it feasible for only the largest fields and customers.

Flowchart:
- Energy Resource
- Transport
- Unload/Store
- Distribute & Store
- Customer
DEMAND FOR LNG HAS TRIPLED CAPEX OVER THE LAST DECADE

LOW HANGING FRUIT HAS BEEN PICKED
HYDRATES OFFER AN UNCONVENTIONAL ALTERNATIVE

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<th>Hydrates store simple gases in a three dimensional water crystal cage network similar to ice. Upon crystallization 150 cubic feet of gas can be stored in 1 cubic foot of water.</th>
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<td>Safe</td>
<td>Hydrates are inherently safe. Like ice, hydrates require significant amounts of energy to dissociate and will not release gas fast enough to trigger an explosion</td>
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<td>Scalable</td>
<td>Hydrate formation requires only pressure and chilling. Standardized modules can be scaled to applications ranging from thousands to billions of cubic feet. Modules can be reallocated</td>
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<td>Efficient</td>
<td>Hydrates represent nature's way of storing gases. The hydrate formation process isothermally compresses natural gas to the equivalent of 150 bar using only water at near ambient conditions.</td>
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<td>Selective</td>
<td>As the hydrate crystal grows it excludes virtually everything from the lattice, including dissolved salts. Process parameters can be further tuned to selectively separate hydrate forming gases.</td>
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HYDRASTOR MODULAR PLATFORM

- Displacement: 10,000 Tons
- Number of Tanks: 124
- Gas Storage: 31,000 MMbtu
- Potential Power: ~3700 MWh

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SIMPLICITY OF HYDRATES
TRANSFORMS SHIPPING COSTS

LNG Supply Chain 500 Nautical Miles
- Exploration and drilling: $3.00-4.00
- Liquefaction: $1.00-1.40
- Shipping: $0.80-1.50
- Regasification: $0.75-$1.00
- Pipeline Delivery: $5.55-8.00
- Total Cost to Power Plant or Industrial User

HDX Supply Chain 500 Nautical Miles
- Exploration and drilling: $2.50-4.00
- Barge or Ship Based Hydrastor Platform Delivered Directly to Dockside or Floating Power Plant: $2.50-4.00
- Total Cost to Power Plant or Industrial User

SIMPLICITY OF HYDRATES
TRANSFORMS SHIPPING COSTS
10,000MW OF FUEL OIL READY FOR LOW COST US GAS
DELIVERED COST COMPARISON OF HYDRATES VS LNG

Cuba 250 Miles

Haiti 750 Miles

ALASKA?
ALASKA NATURAL GAS?

WHAT WILL SEA ROUTES LOOK LIKE IN 2035?
Gas flaring in the Texas Permian Basin is nearly **2X higher** than what companies report

- **Total Flared Gas**: 104 billion cubic feet
- **Reported Flared Gas**: 55 billion cubic feet

Flaring volumes in billion cubic feet

Source: NOAA Satellite, RRC flaring data

**This is for 2017...situation is clearly getting worse.**
US JUST PASSED NIGERIA IN TERMS OF GAS FLARING
GAS STORAGE IS CHANGING

HOURLY DEMAND VS SEASONAL
GAS PIPELINES ARE AMERICA’S ACHILLES HEEL.
ALISO CANYON

THE HEART OF SOUTHERN CALIFORNIA’S GAS SYSTEM
REAL CONSEQUENCES

AND NO READILY AVAILABLE SOLUTION
REAL CONSEQUENCES

Figure 10: Daily Cost of Real-time Imbalance Energy Offset

Source: CAISO

TOTAL COST >$45 MILLION IN 4 DAYS
HYDRATE LINEPACK?

HYDRATES CAN BALANCE PRESSURE WITH MINIMAL INTERVENTION
HOW TO USE MULTIPLE ATTRIBUTES OF GAS HYDRATES

CONFIDENTIAL

Ambient Air

Air Cooling Coils

Cold Air

GAS AND THERMAL ENERGY STORAGE

VARIABLE BURN RATE

INTRADAY INJECTION AND WITHDRAWAL

Fixed Rate Pipeline Gas

CHILLER

Cooling Tower

C4 DISTRIBUTED ABOVE GROUND SOLID GAS STORAGE

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THE PROBLEM WITH BIOGAS

BASELOAD AND ONLY HALF THE ENERGY CONTENT OF NG
THE VALUE OF RENEWABLE NATURAL GAS

Assumptions: Commodity - $2.50/MMBtu; $0.04/kWh; RINs: D3 - $1.85/RIN; D5 - $0.90/RIN; LCFS: $100/credit; Carbon Intensities: LCFS Standard - 90g/MJ; Landfill Gas - 50g/MJ; Food Waste -20g/MJ; Animal Waste -100 g/MJ; RECs: $50/MWh RNG to Electricity efficiency: 40%
Gas Separation

- \( \text{H}_2\text{S}/\text{CO}_2 \)
- \( \text{CH}_4/\text{CO}_2 \)
- Ethane/Ethylene
- \( \text{H}_2/\text{CO}_2 \)
- \( \text{CO}_2/\text{N}_2 \)

LCFS VALUES RNG @ >$30/MMBTU
DESALINATION

- PRODUCED WATER
- BORON
- SEAWATER
- BACTERIA
- VIRUSES?

CAN BE COMBINED WITH GAS AND THERMAL ENERGY STORAGE
THERMAL ENERGY STORAGE

- Cheapest form of energy storage
- Formation Temperatures Higher than Ice is a Big Deal
- Higher Latent Heat than Ice and Faster Formation
- Can Be Combined with Desalination or Storage
THE ORIGINAL VISION

OFFSHORE STRANDED GAS TO FLOATING OXYFUEL PLANT WITH INTEGRATED GAS SEPARATION AND TRANSPORT

FIG. 9