GTI Small Scale Liquefier Technology

LNG 17 – Houston, TX
April 18, 2013
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Gas Technology Institute
What We Do

GTI takes on tough energy challenges, turning raw technology into practical solutions that create exceptional value for our customers in the global marketplace

Energy Solutions… Delivered
Company Overview

Natural Gas Research and Development Focus

> Staff of 250
> 350 active projects
> 1,200 patents; 500 products
> Partnering at every phase of the technology development cycle, from concept to commercialization.
GTI Offerings

> **Technology Development and Commercialization**
  - GTI-owned inventions
  - Joint RD&D with commercialization partner

> **Proprietary Contract R&D**
  - Partner’s IP, products, services + our people and hardware

> **Program Management**
  - Partner’s IP, products, services + our people managing

> **Testing Services**
  - Customer need or problem + our people and hardware, no IP

> **Consulting**
  - Aggregating, transforming, and presenting information for others, including, techno-economic screening for investors and inventors, and expert testimony

> **Education**
  - Technician through senior management courses
Sources of LNG in North America

> Plant Types
  > “Merchant” plants (firm availability)
  > “Peaker” plants (interruptible)
  > Imports and/or Exports

> Plant Sizes
  > Merchant > 1MM gpd
  > Small 250,000 – 1MM gpd
  > Micro 50,000 – 250,000 gpd
  > Mini? Nano? 5,000 – 50,000 gpd
US Has Long LNG History – Mainly For Utility Peakshaving

Current capacity to produce 4.9 million LNG gallons/day

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
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<tbody>
<tr>
<td>Peakshaving Total Capacity (Gallons/Day)</td>
<td>4,924,788</td>
</tr>
<tr>
<td>Peakshaving Total Capacity (MMSCF/Day)</td>
<td>410</td>
</tr>
<tr>
<td>Average Capacity (Gallons/Day)</td>
<td>87,943</td>
</tr>
<tr>
<td>Number of Facilities</td>
<td>56</td>
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</tbody>
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Photo courtesy of AGL Resources

US Natural Gas Peakshaving and Proposed Liquefiers
Domestic LNG Used for Transportation, Other Applications

> Using 10% of peakshaving and new export liquefaction facilities for domestic use could help accelerate NGV market growth

— Nearly 100 bcf/year (835 million gasoline gallon equivalent)

<table>
<thead>
<tr>
<th>Total Annual Capacity</th>
<th>Total Annual LNG Production Capacity</th>
<th>@10% Used for US Transportation</th>
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<tbody>
<tr>
<td></td>
<td>BCF/Year</td>
<td>LNG Gallons/Year</td>
</tr>
<tr>
<td>US Peakshaving (90% capacity factor)</td>
<td>135</td>
<td>1,617,792,899</td>
</tr>
<tr>
<td>Sabine Pass (90% capacity factor)</td>
<td>821</td>
<td>9,875,913,700</td>
</tr>
<tr>
<td>Totals:</td>
<td>956</td>
<td>11,493,706,598</td>
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Small Liquefaction & LNG Markets

**Sources**

- Pipeline Natural Gas
- Gas Resource Deployment
  - Stranded natural gas reserves
  - Opportunity Fuels (landfill gas, wastewater gas, digester gas)

**Uses**

- LNG for Utilities and Industry
  - Peakshaving/Standby
  - Remote community natural gas service
- LNG for Vehicles
  - Medium and heavy-duty trucks and buses
  - Off-road (Rail, Marine, Mining, E&P Operations)
GTI Small Scale Liquefier

> Mixed Refrigerant Liquefier

- Sponsored by U.S. Department of Energy & Brookhaven National Lab
- Uses specially designed, patented multi-component refrigerant
- Proven HVAC screw compressor technology for reliability and low cost, well suited for rapid & frequent start/stop cycles
- Electric motor or gas engine drive
- System design for simplicity, energy efficiency, and low cost
- Pre-Commercial 1,500 gal/day unit built & tested (using natural gas engine drive)
- Design scale-up to 5,000 to 30,000 gallons/day
- Licensed to commercial partner in 2005
Small-Scale Liquefaction

Capital Cost ($/LNG gallon/day)

Target Small-Scale Liquefaction Plants

Conventional Liquefaction Plants

Conventional Negative Scaling Effect?
# Natural Gas Liquefaction Options

<table>
<thead>
<tr>
<th>LIQUEFIER TYPE</th>
<th>OPERATING PRINCIPLE</th>
<th>REMARKS AND TRADEOFFS</th>
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<tbody>
<tr>
<td>Precooled Joule-Thomson (JT) Cycle</td>
<td>A closed-cycle refrigerator (e.g. using Freon or propane) pre-cools compressed natural gas, which is then partially liquefied during expansion through a JT valve</td>
<td>Relatively simple and robust cycle, but efficiency is not high. Used in Anker Gram onsite liquefier for LNG truck fueling (which is no longer operating).</td>
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<tr>
<td>Cascade Cycle</td>
<td>A number of closed-cycle refrigerators (e.g. using propane, ethylene, methane) operating in series sequentially cool and liquefy natural gas. More complex cascades use more stages to minimize heat transfer irreversibility.</td>
<td>High-efficiency cycle, especially with many cascade steps. Relatively expensive liquefier due to need for multiple compressors and heat exchangers. Cascade cycles of various designs are used in many large-capacity peakshaving and LNG export plants.</td>
</tr>
<tr>
<td>Mixed-Refrigerant Cycle (MRC)</td>
<td>Closed cycle refrigerator with multiple stages of expansion valves, phase separators, and heat exchanger. One working fluid, which is a mixture of refrigerants, provides a variable boiling temperature. Cools and liquefies natural gas with minimum heat transfer irreversibilities, similar to cascade cycle.</td>
<td>High-efficiency cycle that can provide lower cost than conventional cascade because only one compressor is needed. Many variations on MRC are used for medium and large liquefaction plants. ALT-Ei Paso Topock LNG plant uses MRC. GTI is developing simplified MRC for small plants (under 10,000 gpd).</td>
</tr>
<tr>
<td>Open Cycles with Turboexpander, Claude Cycle</td>
<td>Classic open Claude cycle employs near-isentropic turboexpander to cool compressed natural gas stream, followed by near-isenthalpic expansion through JT valve to partially liquefy gas stream.</td>
<td>Open cycle uses no refrigerants other than natural gas. Many variations, including Haylandt cycle used for air liquefaction. Efficiency increases for more complex cycle variations.</td>
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<tr>
<td>Turboexpander at Gas Pressure Drop</td>
<td>Special application of turboexpander at locations (e.g. pipeline city gate), where high-pressure natural gas is received and low-pressure gas is sent out (e.g., to distribution lines). By expanding the gas through a turboexpander, a fraction can be liquefied with little or no compression power investment.</td>
<td>This design has been applied for peakshaving liquefiers, and it is currently being developed by INEEL in cooperation with PG&amp;E and SoCalGas to produce LNG transportation fuel. Very high or “infinite” efficiency, but special circumstances must exist to employ this design.</td>
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<td>Stirling Cycle (Phillips Refrigerator)</td>
<td>Cold gas (usually helium closed cycle using regenerative heat exchangers and gas displacer to provide refrigeration to cryogenic temperatures. Can be used in conjunction with heat exchanger to liquefy methane.</td>
<td>Very small-capacity Stirling refrigerators are catalog items manufactured by Phillips. These units have been considered for small-scale LNG transportation fuel production.</td>
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<tr>
<td>TADOPTR</td>
<td>TADOPTR = thermoacoustic driver orifice pulse tube refrigerator. Device applies heat to maintain standing wave, which drives working fluid through Stirling-like cycle. No moving parts.</td>
<td>Currently being developed by Praxair and LANL for liquefaction applications including LNG transportation fuel production. Progressing from small-scale to field-scale demonstration stage.</td>
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<tr>
<td>Liquid Nitrogen Open-Cycle Evaporation</td>
<td>Liquid nitrogen stored in dewar is boiled and superheated in heat exchanger, and warmed nitrogen is discharged to atmosphere. Counterflowing natural gas is cooled and liquefied in heat exchanger.</td>
<td>Extremely simple device has been used to liquefy small quantities of natural gas. More than one pound of liquid nitrogen is required to liquefy one pound of natural gas. Nitrogen is harmless to atmosphere. Economics depends on price paid for liquid nitrogen.</td>
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Adapted from USA Pro/California Energy Commission with modifications
GTI Mixed Refrigerant System
Simplified Process Schematic

Prime Mover (engine or motor drive)
Screw Compressor
Oil Cooler
Oil Separator/Filter
Mixed Refrigerant Loop
Evaporative Cooler

Natural Gas (inlet)
Heat Exchanger
LNG
Expansion Valve

US Patent #6530240 (Gas Technology Institute)
GTI Small-Scale Liquefier
1500 gpd (Pre-Commercial)
First Commercial Small-Scale Liquefier ~10,000 gpd

> Gasrec’s Albury Landfill near Surrey, UK
> Started June 2008
> Landfill Gas Recovery and Clean-up to Vehicle Fuel
Linde – Waste Management
Altamont, CA Landfill Gas to LNG

> World’s largest landfill gas to LNG facility @ 13,000 gallons per day
> Serves over 300 refuse trucks at various stations
> A renewable fuel with substantial carbon reduction compared to diesel
Third Commercial Installation
~ 32,000 gpd

- Remote gas recovery and use for LNG trucks in Tasmania, Australia
- Opened early 2011
- Serves six refueling stations across the region
- Includes GTI-licensed liquefaction technology
Summary

> GTI has a long history of energy RD&D activities with a focus on more energy efficient and cost effective natural gas technologies

> Economics from fuel savings are drawing users and equipment suppliers together to find small-scale LNG solutions

> LNG fuel supply constraints are being addressed in a variety of ways, may need to be augmented

> Interest in license/commercialization partners
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