Hydrogen Delivery
Liquefaction & Compression

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Strategic Initiatives for Hydrogen Delivery Workshop -
May 7, 2003
Agenda

- Introduction to Praxair
- Hydrogen Liquefaction
- Hydrogen Compression
Praxair at a Glance

- The largest industrial gas company in North and South America
- Only U.S. Hydrogen Supplier in All Sizes (Cylinders to Liquid to Pipelines)
- Operations in 40 countries
- Over 23,000 employees
- 3,000 active patents
- One million customers worldwide
Merchant Hydrogen Plants

- Praxair Liquid Hydrogen Plant
- Praxair Tube Trailer Hydrogen Plant
- Praxair HGS Plant
- Praxair Cylinder Hydrogen Plant
Gulf Coast Pipeline System

245 miles of pipeline serving 50 major customers
Hydrogen Liquefaction

- There are 10 hydrogen liquefaction plants in North America
  - Train size ranges from 6 to 35 TPD (5,400 to 32,000 kg/day)

- In the 1960’s, liquid hydrogen plants were built to support the Apollo program. Today, liquid hydrogen is used to reduce the cost of hydrogen distribution.
  - Delivering a full tube trailer of hydrogen to a customer results in a delivery of less than 300 kg
  - A modern liquid hydrogen trailer carries 4000 kg of liquid hydrogen
Hydrogen Liquefaction

H₂ Source  H₂ Purification  H₂ Liquefaction

SMR  PSA  Cryogenic
Byproduct  Cryogenic
Gasification  Membrane  (-423°F)
Renewable
The plants are very capital intensive

- Praxair has started capacity expansions approximately once every 5 years since 1980. The infrequent builds means it’s very difficult to reproduce designs.
- While larger plants are more capital efficient, it’s hard to take the capital risk of building the plant too large.

The process is very energy intensive

- Typical unit powers are on the order of 12.5 to 15 kWh/kg

The cost stack looks like:
Hydrogen Liquefaction
Process Review

- \( H_2 \) Flash Compressor
- \( H_2 \) Recycle Compressor
- External Refrigeration
- \( GN_2 \) to \( N_2 \) Liquefier
- LN\(_2\) Add.
- To Storage/Fill
Forms of Liquid Hydrogen

- Normal Hydrogen is 75% Ortho, 25% Para
- Liquid Hydrogen is 0.2% Ortho, 99.8% Para

- Heat of Conversion from Normal to Para is 0.146 kWh$_{th}$/kg
- Heat of Liquefaction is 0.123 kWh$_{th}$/kg
- Conversion can cause Vaporization
Hydrogen Liquefaction
Issues for Consideration

- Methods to decrease capital cost:
  - Larger scale plants (850 tpd)
  - Plant repeatability

- Methods to decrease energy requirement:
  - New compression and expansion technology
    - High speed centrifugal compressors and possibly expanders
    - Materials development required

- Something completely different?
  - New approaches to low temperature refrigeration
    - Magnetic refrigerators
    - Acoustic refrigerators
Challenges:

- More cost effective LH2 production systems
  - System modularization for traditional sized units
  - Larger scale equipment
  - Higher efficiency compressors and expanders
  - More efficient refrigeration
  - Lower cost high-efficiency insulation

- Cost effective small scale hydrogen generation
  - Low cost high pressure compressors and expanders
  - Novel low-temperature refrigeration
  - Low heat leak liquid storage units
Hydrogen Compression

H₂ Production
- SMR
- Byproduct
- Gasification
- Renewable

H₂ Purification
- PSA
- Cryogenic
- Membrane

H₂ Compression
- Small
- Large
Hydrogen Compression

- Hydrogen is difficult to compress
  - Very small molecule
  - Positive displacement compressors are used

- Hydrogen compressors are expensive
  - Materials
  - Size
  - Redundancy required for reliability

- The process is energy intensive
  - Typical unit powers are:

<table>
<thead>
<tr>
<th>Inlet-Outlet (psig)</th>
<th>Adiabatic Efficiency</th>
<th>Compression Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>300 - 1,000</td>
<td>70-80%</td>
<td>0.6 - 0.7 kWh&lt;sub&gt;e&lt;/sub&gt;/kg</td>
</tr>
<tr>
<td>100 - 7,000</td>
<td>50-70%</td>
<td>2.6 - 3.6 kWh&lt;sub&gt;e&lt;/sub&gt;/kg</td>
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**Issues Unique to Hydrogen Compression**

- **Compressor Seal and Clearance Tolerance**
  - Hydrogen is the lightest of all the gases and has lower viscosity than NG. Hence, it is easier to migrate through small spaces.
  - Special seals and/or tolerance standards need to be established to achieve high pressures.

- **Hydrogen Embrittlement of Metals**
  - At elevated pressure and temperature, hydrogen can permeate carbon steel resulting in decarburization.
  - Conventional Mild Steel has been used in Germany and France since 1938 as pipeline material.
  - Alloy steels containing Chromium and Molybdenum have been suggested for compressor materials.
Hydrogen Compression for Large Scale Pipeline Delivery (Present)

- **State of the Art**
  - Multi-Stage Reciprocating Machines - typical to install redundant units in order to keep on-line time between 98-99%.
  - 700 - 1000 psig delivery pressures
  - Adiabatic efficiencies of 78-80%
  - High maintenance costs due to wearing components (e.g. valves, rider bands, piston rings)

- **Typical Manufacturers**
  - Dresser-Rand
  - Sulzer Burckhardt
  - Ariel
  - Neuman-Esser
Hydrogen Compression for Small Scale Fueling Stations (Present)

- **State of the Art**
  - V-Belt driven multi-stage reciprocating
  - Hydraulically driven multi-stage reciprocating
  - V-Belt driven diaphragm
  - 5,000 - 10,000 psig delivery pressures

- **Typical Manufacturers**
  - Neuman-Esser
  - Fluitron
  - PDC
  - Greenfield
  - Rix
  - Hydro-Pac
  - CompAir
Hydrogen Compression for Small Scale Fueling Stations (Present)

Compressor Cost Comparison (6000 psig)
Hydrogen Compression
Issues for Consideration

- Issue of numbers - what happens if we build 100 times the units we build today:
  - Cost impact on current technology
  - Potential for new technology
- Reliability improvements
- Maintenance cost reduction
- Methods to decrease energy requirement:
  - New mechanical concepts
  - Non-traditional approaches to compression
Hydrogen Compression (Future)

- Newer Approaches
  - Mechanical
    - Guided Rotor Compressor (GRC)
    - Linear Compressor
  - Non-Traditional
    - Electrically Driven Membranes
    - Hydride Compressors