PRAXAIR

Hydrogen Delivery
Liquefaction & Compression

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Strategic Initiatives for Hydrogen Delivery Workshop - May 7, 2003

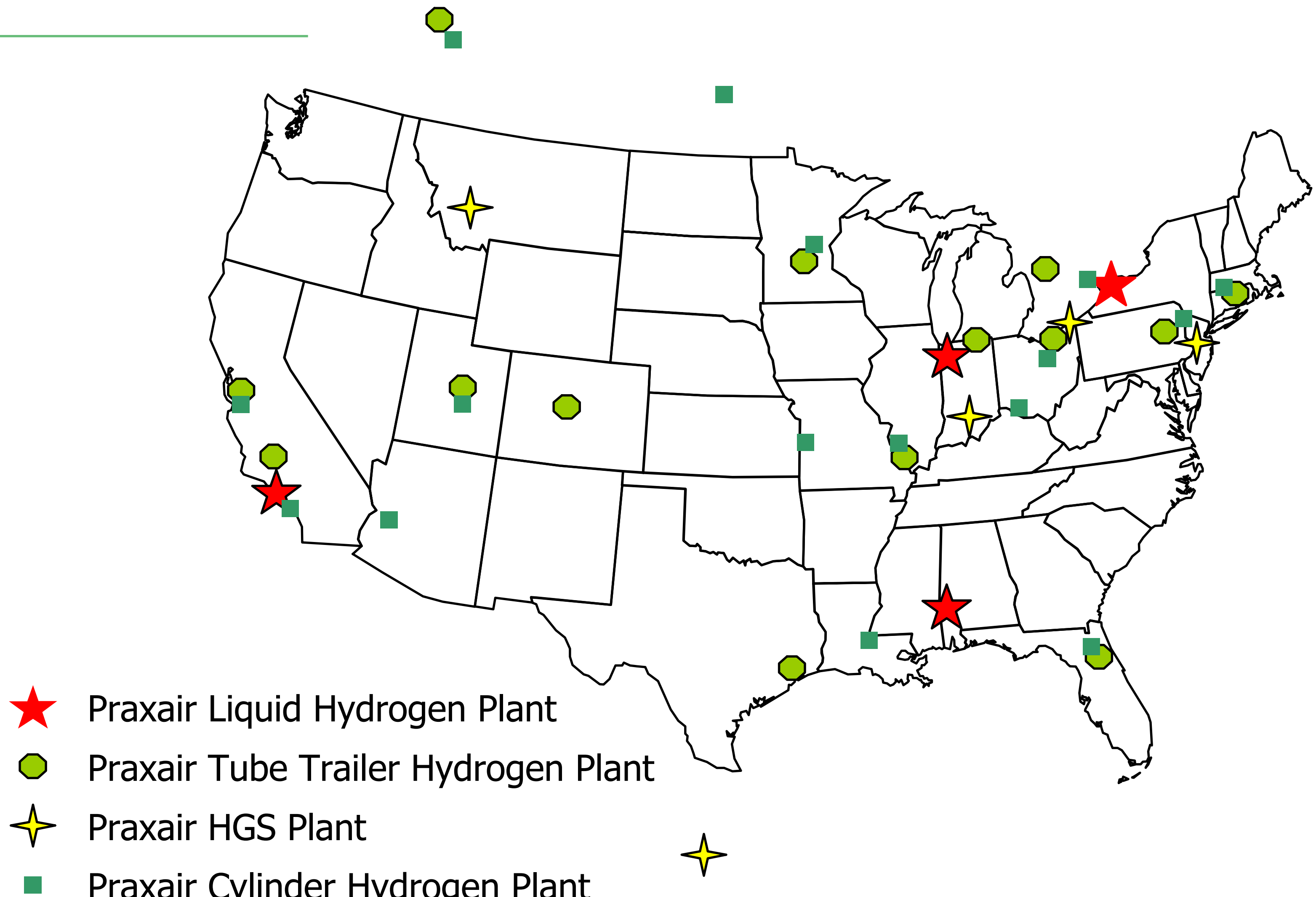
Agenda

- Introduction to Praxair
- Hydrogen Liquefaction
- Hydrogen Compression

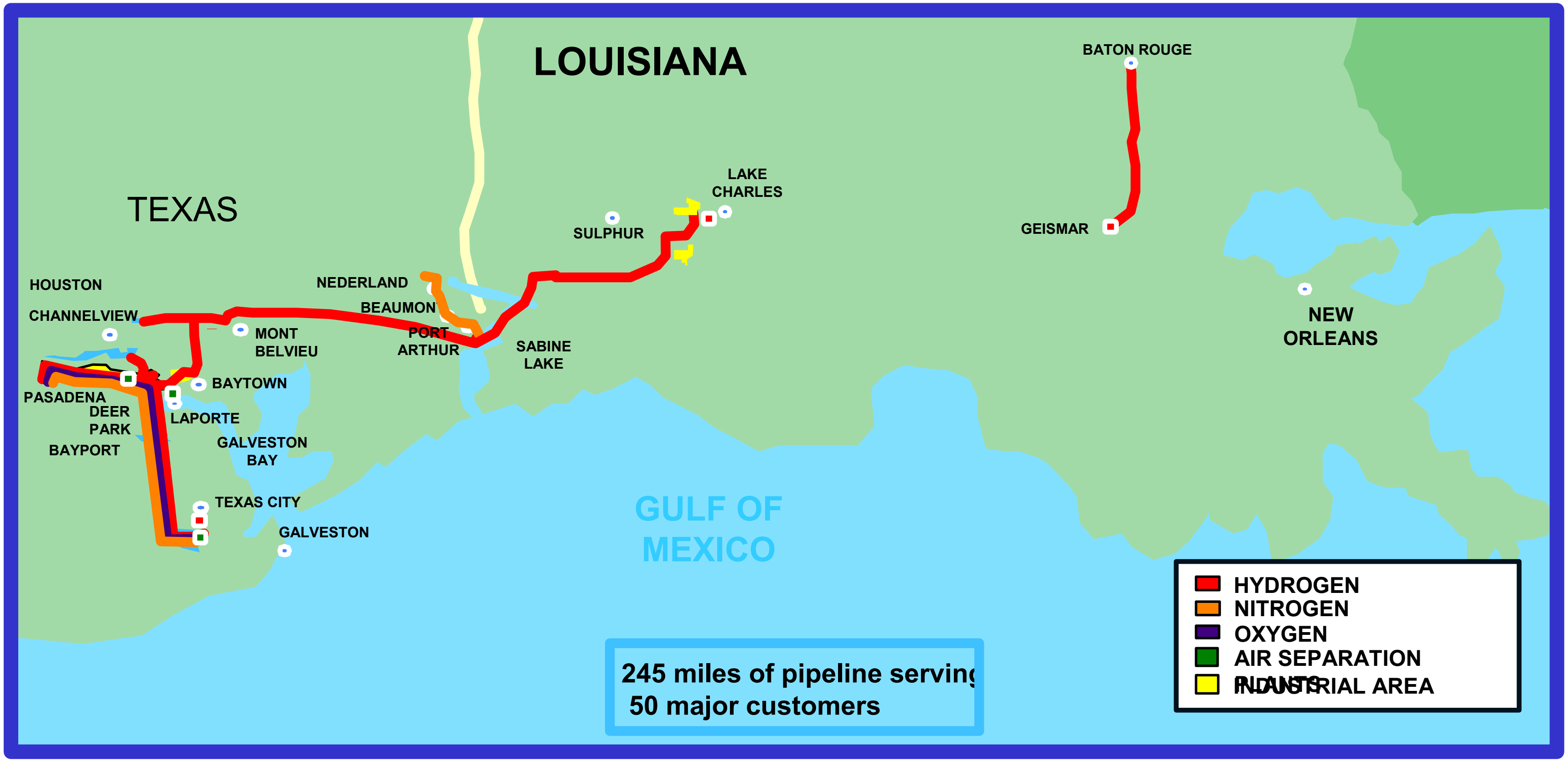
Praxair at a Glance

- 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

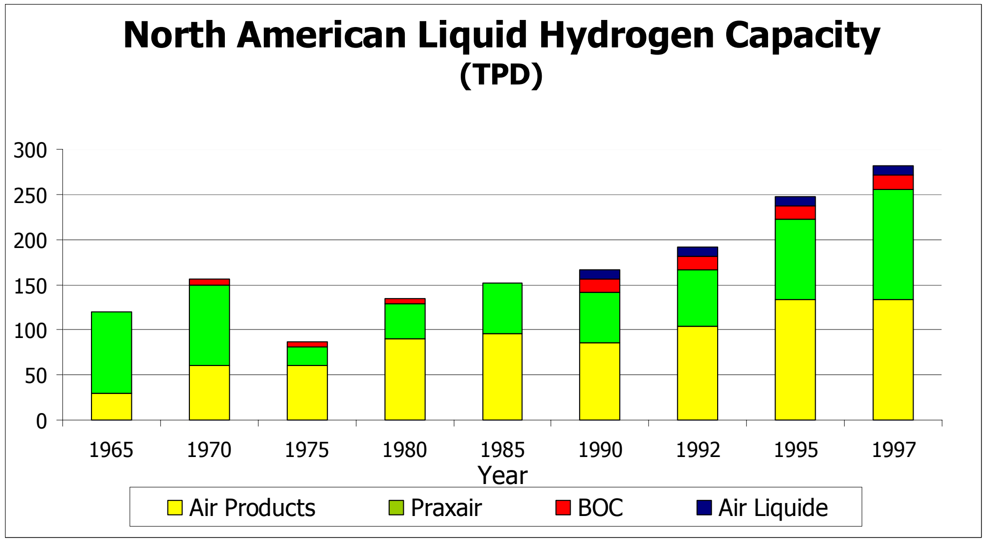


Gulf Coast Pipeline System



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

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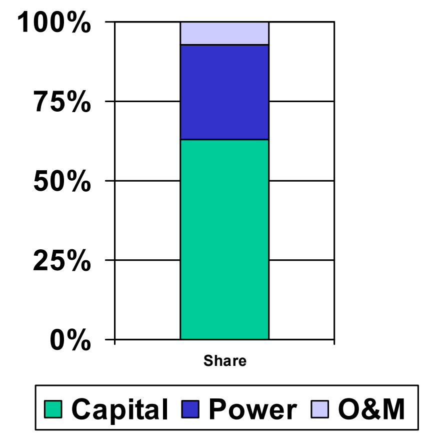
H_2 Source		H_2 Purification		H_2 Liquefaction
SMR Byproduct Gasification Renewable	→	PSA Cryogenic Membrane	→	Cryogenic (-423ºF)

Hydrogen Liquefaction

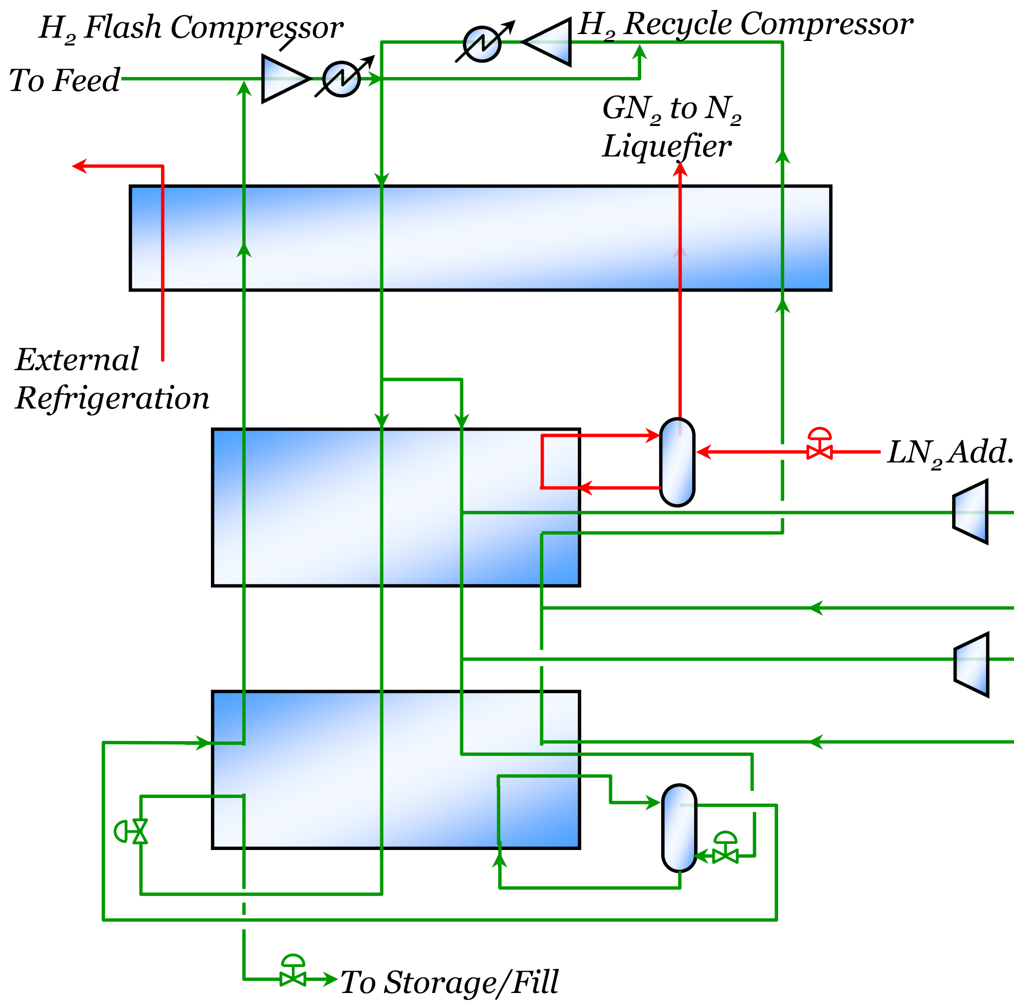
- **The plants are very capital intensive**
  - Praxair has started capacity expansions approximately once every 5 years since 1980. The infrequent builds means it's very difficult to reproduce designs.
  - While larger plants are more capital efficient, it's hard to take the capital risk of building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

- **The process is very energy intensive**
  - Typical unit powers are on the order of 12.5 to 15 kWh_e/kg

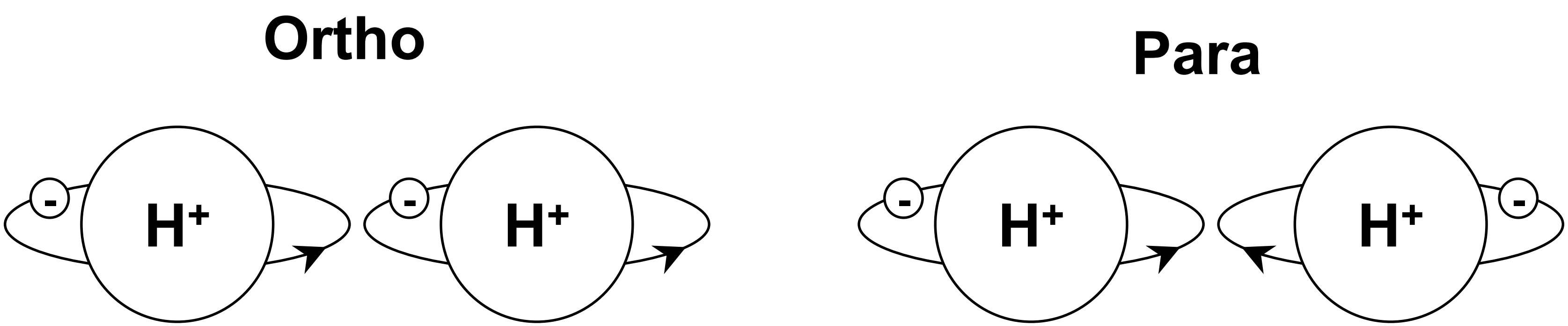
- **The cost stack looks like:**



Hydrogen Liquefaction
Process Review



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

H_2 Production

- SMR
- Byproduct
- Gasification
- Renewable

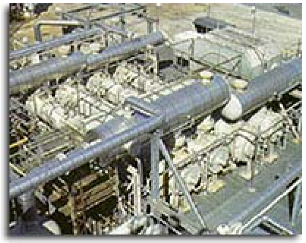
H_2 Purification

- PSA
- Cryogenic
- Membrane

H_2 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:

Inlet-Outlet(psig)	Adiabatic Efficiency	Compression Energy
300 - 1,000	70-80%	0.6 - 0.7 kWh_e/kg
100 - 7,000	50-70%	2.6 - 3.6 kWh_e/kg

Issues Unique to Hydrogen Compression

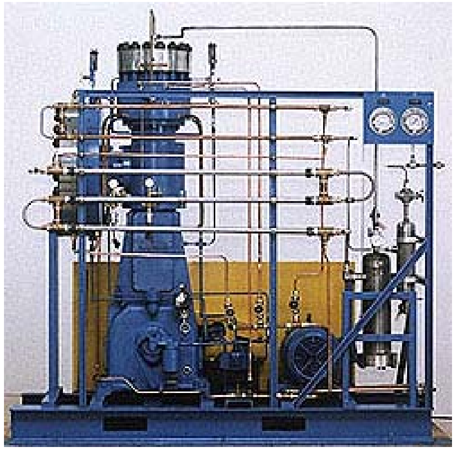
- **Compressor Seal and Clearance Tolerance**
  - Hydrogen is the lightest of all the gases and has lower viscosity than NG. Hence, it is easier to migrate through small spaces
  - Special seals and/or tolerance standards need to be established to achieve high pressures
- **Hydrogen Embrittlement of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

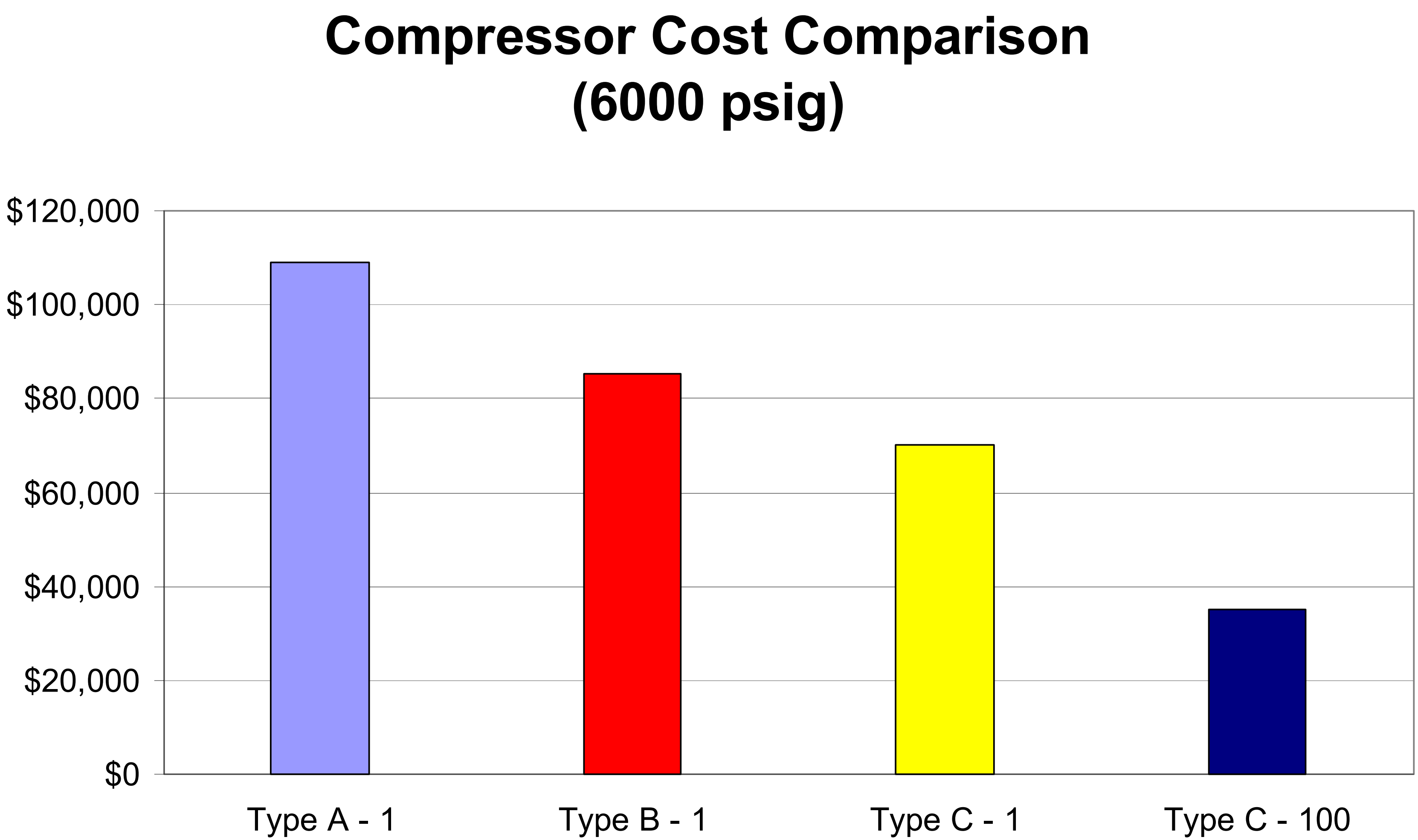
Hydrogen Compression for Small Scale Fueling Stations (Present)

- **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)



Hydrogen Compression
Issues for Consideration

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- **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

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Hydrogen Compression (Future)

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