Novel Compression and Fueling Apparatus to Meet Hydrogen Vehicle Range Requirements

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This presentation does not contain any proprietary or confidential information
FY 04 Objectives

- **Primary**
  - Develop a process design for a novel compressor
  - Identify potential hydraulic fluids
  - Complete technical/economic evaluation of system

- **Secondary**
  - Investigate other fueling components to support 700 barg (10,000 psig) hydrogen fueling
## Budget

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<td>Labor</td>
<td>$290,141</td>
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- 50% Cost Share
- Special Program through Pennsylvania Department of Environmental Protection
Technical Barriers and Targets

- **Technical Barriers**
  - High Cost of Hydrogen Compression
  - High Cost of Storage and Dispensing
  - Cost of Hydrogen

- **FY 05 Targets**
  - $0.29/kg cost of compression
  - $0.19/kg cost of storage and dispensing
  - 85% efficient compression
  - $3/kg hydrogen fuel
Approach

- Conceptual Design
- Process Design
- Thermodynamic Data
- Fluid Selection and Testing
  - Measure hydrogen solubility in various fluids
  - Test permeation of pressure transducer diaphragms at various pressures
- Dynamic Modeling
  - Evaluate compressor using a custom model
  - Optimize design, operation and control
  - Evaluate heat transfer issues and check isothermal assumptions
  - Evaluate sensitivity of unit to various design parameter upsets and operating conditions
- Component Design, Fabrication, and Testing
- Prototype
- Long Term Testing
Approach

Design Issues

- Compressor
  - Isothermal
  - High pressure
  - Single stage
  - Low cost

- Fueling Station
  - Lower the delivered cost of hydrogen
  - Composite vessels
  - Breakaway and fuel nozzle
  - Fueling codes
Safety

- **Air Products Hydrogen Experience**
  - Over 10,000 fills (60/week)
  - 13 fuelers installed last year (>20 total, 6 in construction)
  - Industrial hydrogen (30+ years, 55% merchant market share, 1000 gaseous/500 liquid customers, pipelines, reformers, electrolysis)

- **Internal Hazard and Operability Review**
  - Divide system into nodes
  - Review deviations and effects

- Our fueling systems have undergone rigorous third party independent safety reviews
  - ABS Consulting – Singapore
  - NASA - White Sands, NM
  - KHK/JHPGSL – Kagoshima, Japan

- **Management of Change, Near Miss Reporting, Quantified Risk Assessment, and other project management systems.**
# Timeline

| Task Name                                           | 2002 Qtr 3 | 2002 Qtr 4 | 2003 Qtr 1 | 2003 Qtr 2 | 2003 Qtr 3 | 2003 Qtr 4 | 2004 Qtr 1 | 2004 Qtr 2 | 2004 Qtr 3 | 2004 Qtr 4 | 2005 Qtr 1 | 2005 Qtr 2 | 2005 Qtr 3 | 2005 Qtr 4 | 2006 Qtr 1 | 2006 Qtr 2 | 2006 Qtr 3 |
|-----------------------------------------------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|------------|
| Start Date                                          |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| Contract Approval                                   |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 1.0 Feasibility/System Design                       |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 1.1 System Pressure Analysis                        |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 1.2 Isothermal Compressor Analysis                  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 1.3 Packless Valve Analysis                         |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| Program Review                                      |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 2.0 System Design                                   |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 2.1 Flow Lab Design                                 |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 2.2 Dispenser Design                                |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 2.3 Isothermal Compressor Design                    |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 2.4 Packless Valve Design                           |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| Program Review                                      |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 3.0 Lab Installation and Testing                    |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 3.1 Compressor and Valves                           |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 3.2 Connectors and Flow Controls                    |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 3.3 Composite Vessels                               |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 3.4 Installation                                    |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 3.5 Testing                                         |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| Program Review                                      |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 4.0 Field Installation and Operation                |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 4.1 Penn State Review and Plan                      |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 4.2 Installation                                    |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 4.3 Operational Field Tests                         |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| Program Management                                  |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 5.0 Program Management                              |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
| 5.1 Final Report                                    |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |            |
Technical Accomplishments

Novel Compressor – Basic Concept

- **No Mechanical Piston:** Gas compressed by liquid piston
- **Isothermal:** Gas cooled during compression
- **Single Stage:** Liquid piston permits high pressure ratio by elimination of piston to cylinder clearance concerns
- **Liquid Pump:** Inherently lubricates all dynamic seals
- **Dynamic Gas Seals Eliminated:** No gas seals to atmosphere
- **Issues:**
  - 14,000 psig hydraulic pump
  - Fluid selection
  - Level control
  - Inefficient pump
  - Fluid carryover

Patents Pending
Technical Accomplishments
Hydraulic Fluid Selection

Criteria:
- Low viscosity for good flowing characteristics
- Low volatility to avoid contamination of downstream equipment and fluid loss
- Low H₂ solubility to minimize H₂ recycle
- Lubricating properties at high pressure to minimize pump wear

Problem:
- Hydrogen solubility data not available for fluid at high pressure
Technical Accomplishments

Fluid Solubility Test

- H₂ fills test chamber under pressure
- Fluid introduced, pumped in
- Pressure measured vs. time

H₂ Solubility & Pressure Transmitters Test Unit

Cylinder diameter & surface area simulates actual hardware
Technical Accomplishments

Pressure Decay

H2 Solubility Test with Test Fluid @ 12,600 psig

Current Design Basis:
Total Cycle Time = 30 seconds
Assumed Degas Volume Loss = 2% per cycle
Observed Pressure Loss < 0.2% in 30 seconds

solubility well below acceptable limits
Technical Accomplishments
Cylinder Pressure and Temperature

Cylinder Pressure (psia) vs Time (sec)

Cylinder Temperature (°C) vs Time (sec)

~ 3-4 °C temperature rise for 140:1 compression ratio
Technical Accomplishments
Dyanaic Simulation Results

- Identified key operational issues and design parameters:
  - Surface area requirements in heat exchanger and heat transfer coefficients for near isothermal operation
  - Liquid inventory management needs (pressure/flow regulation)

- Quantitative results on potential sources of inefficiency:
  - Hydraulic intensifier friction
  - Circuit DPs
  - Hydrogen solubility in compression fluid
  - Heat transfer limits and design of heat exchanger

- Process sensitivities to the following parameters studied:
  - Initial accumulator gas volume
  - Pump flow
  - Hydraulic intensifier flow
  - Valve flow coefficients

*novel H₂ compressor unit is feasible*
Technical Accomplishments

Pressure Analysis

- All automotive OEM’s are pursuing 700 barg fueling to achieve US norm of 300 mile range.
- Fast fill (~ 3 minutes) is the only method that has commercial potential.
- Cascade fueling is the most promising method of achieving a low cost, fast fill.
- Cascade filling requires a minimum of 25% overpressure to counter vehicle tank heating.
- Fast fill to 700 barg will require cooling of the hydrogen on most days.
- ASME and Air Products requirements for relief valves (set at vessel MAWP) impose a maximum operating pressure of 90% of MAWP.

\[
(700 \text{ Barg} \times 125%) / 90\% = 972 \text{ Barg MAWP (14100 psig)}
\]

System pressure requirement is 14100 psig MAWP
Technical Accomplishments
Fueling Apparatus

- Air Products has developed hydrogen fueling systems up to 700 barg (10,000 psig).
  - Valves
    - Manual
    - Actuated
    - Pressure Control
  - Flexible Hose
  - Tubing
  - Fittings and Adapters
  - Controller
  - Packaging

Most components available today for 700 barg fueling
FY 05 Next Steps

- Safety Review of Process / Hazard Review.
- Complete detailed design / drawings.
- Obtain quotes for all parts & purchase.
- Assemble and Test.
- Determine overall costs.
- Determine feasibility of future use.
- Long term prototype testing, if warranted.
- Scale-up unit, if warranted.
Interactions/Collaborations

- Air Products and Chemicals, Inc.
  - Future Energy Solutions
  - Advanced Systems Machinery
  - Advanced Controls
  - Dynamic Modeling
  - Corporate Safety
Questions?
Thank you
tell me more
www.airproducts.com