

# Novel Compression and Fueling Apparatus to Meet Hydrogen Vehicle Range Requirements

Todd Carlson  
Future Energy Solutions  
Air Products and Chemicals, Inc.  
May 24, 2004

## Contributors:

Bharat Bhatt (Process Design)  
Bob Byerley (Process Controls)  
David Chalk (Machinery Design)  
Simone Kothare (Dynamic Modeling)  
William Kottke (Process Design/Machinery)  
Jorge Mandler (Advanced Controls)  
Nick Pugliese (Fabrication)

**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

	To Date	Remaining	Total
Labor	\$290,141	\$ 155,833	\$ 445,974
Materials	\$19,481	\$ 225,420	\$ 244,901
Total	\$309,622	\$ 381,253	\$ 690,875

- **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

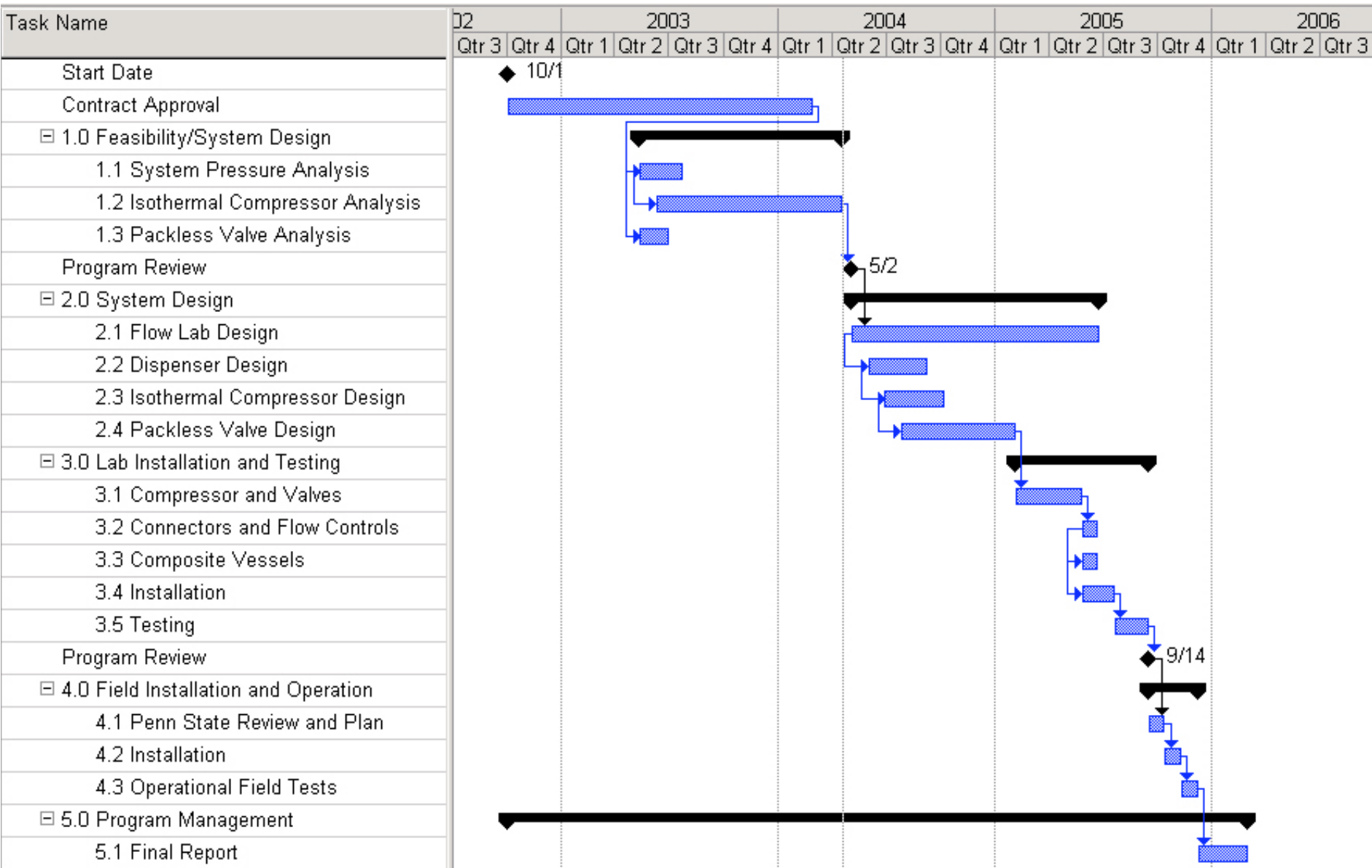
## Design Issues

- **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





# 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

*many typical machinery issues eliminated by liquid piston*

# Technical Accomplishments

## Hydraulic Fluid Selection

### Criteria:

- Low viscosity for good flowing characteristics
- Low volatility to avoid contamination of downstream equipment and fluid loss
- Low H<sub>2</sub> solubility to minimize H<sub>2</sub> recycle
- Lubricating properties at high pressure to minimize pump wear

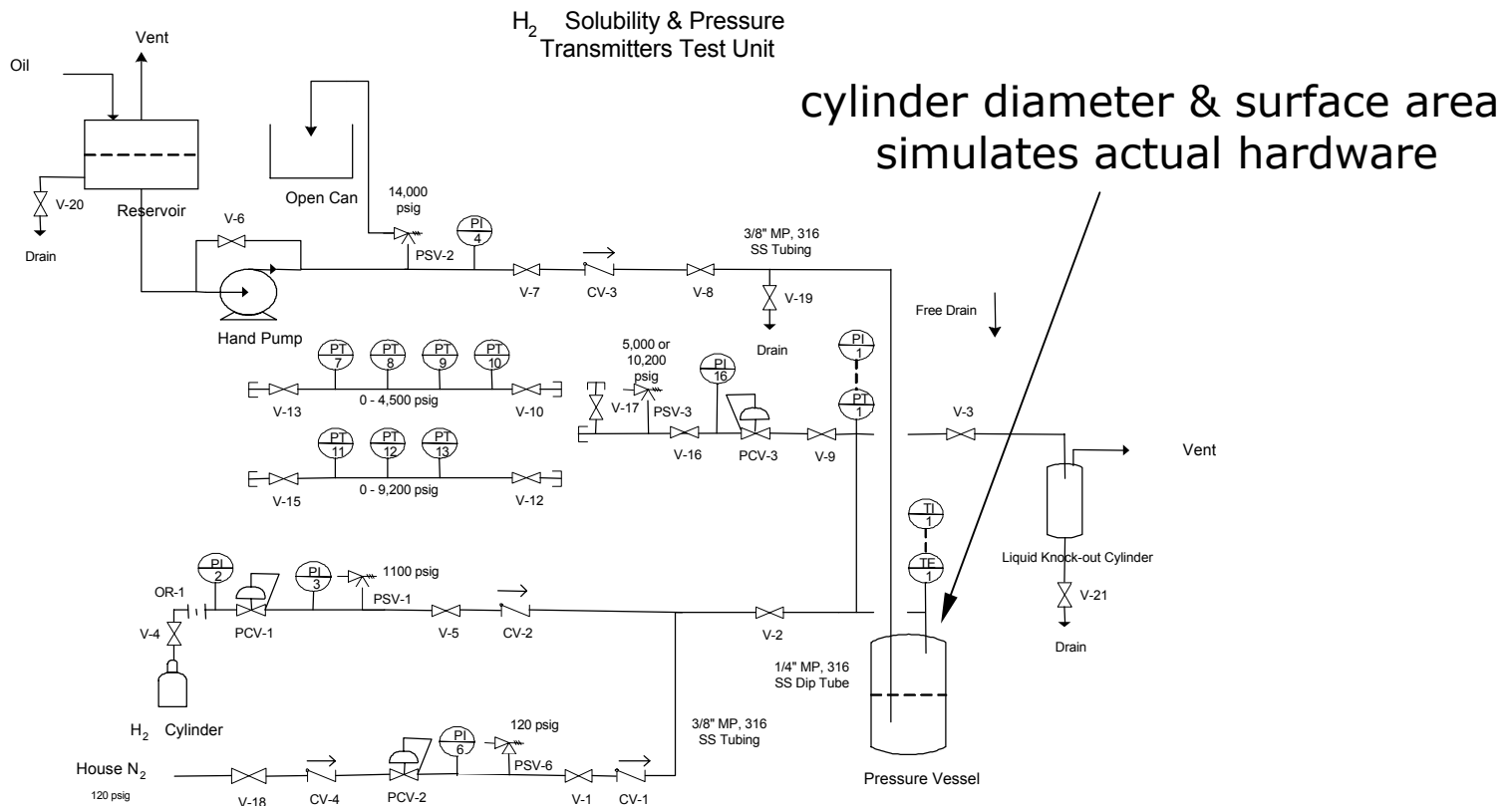
### Problem:

- Hydrogen solubility data not available for fluid at high pressure

# Technical Accomplishments

## Fluid Solubility Test

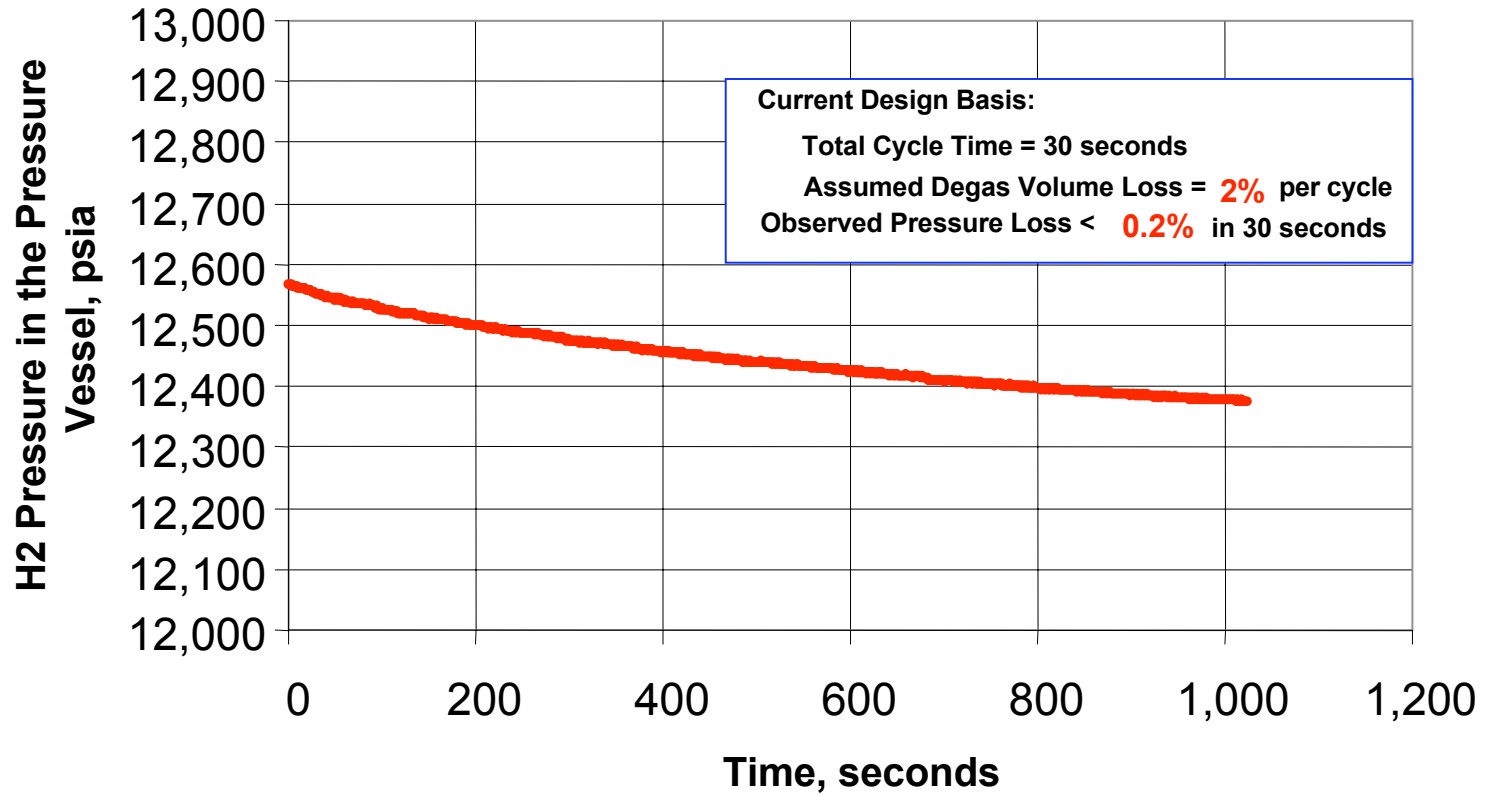
- H<sub>2</sub> fills test chamber under pressure
- Fluid introduced, pumped in
- Pressure measured vs. time



# Technical Accomplishments

## Pressure Decay

### H2 Solubility Test with Test Fluid @ 12,600 psig

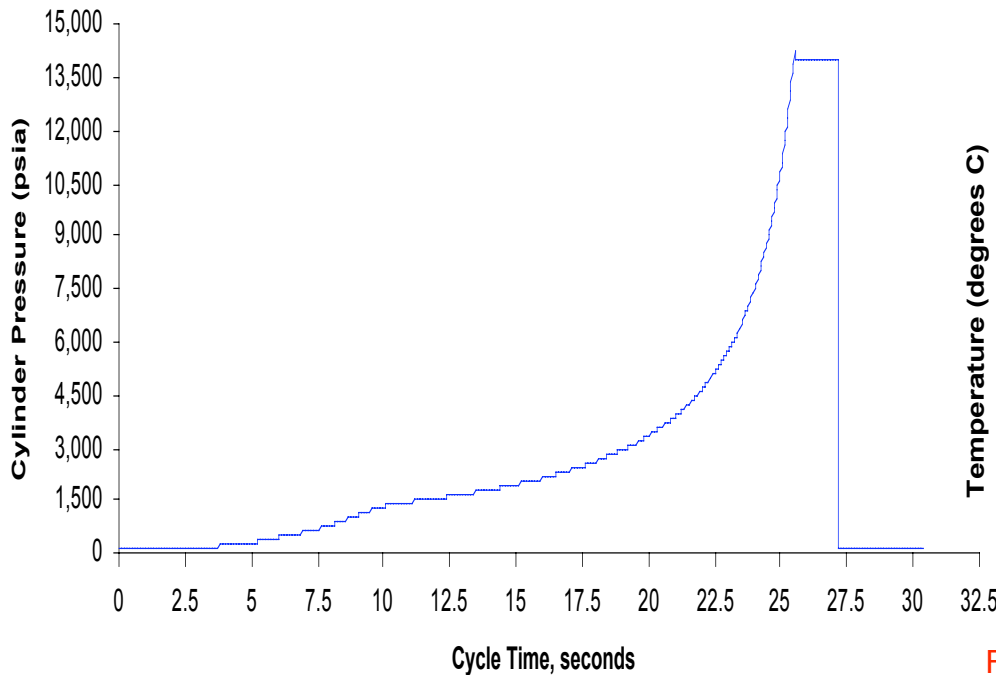


*solubility well below acceptable limits*

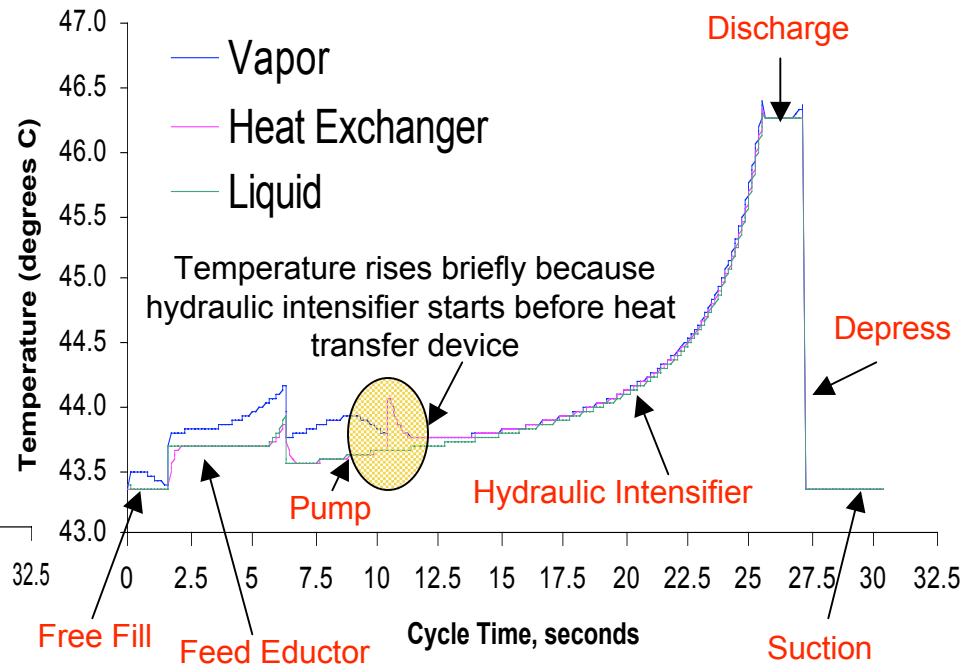
# Technical Accomplishments

## 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

## Dyanamic 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 H<sub>2</sub> 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.

$$(700 \text{ Barg} * 125\%) / 90\% = 972 \text{ Barg MAWP (14100 psig)}$$

*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](http://www.airproducts.com)