# Development of a Natural Gas-to-Hydrogen Fueling System

DOE Hydrogen & Fuel Cell Merit Review

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# Overview

- Timeline
  - Start: 2/2002
  - Completion: 7/2006
  - % Complete: 95%
- Budget
  - Total: $4.72MM
    - DOE: $2.98M
    - C/S: $1.75MM++
- Barriers
  - Distributed H2 Cost: $2.50 by 2010
  - H2 Production Eff'y 70% by 2010
- Partners
  - GreenField Compression, QuestAir, APCI, SeQual, Pall, Lincoln Composites, Dynetek, PDC, ANGI International, Emerson Process Controls, OPW, others

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# Objectives

- Develop and validate onsite, integrated natural gas-to-hydrogen fueling stations
  - Develop or test state-of-the-art subsystems
  - Address integration, operation, maintenance, reliability, and safety
  - Pre-packaged system designs with simple installation requirements
- Leverage compact & efficient hydrogen generation technology
- 40 to 60 kg/day system with nominal 350 bar (5075 psig) dispensing

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# Plan & Approach

- Task 1: Fuel Reforming (90% Complete)
  - Increase efficiency
  - Improve turndown
  - Controls
- Task 2: Fast-Fill Testing (100% Complete)
  - Build SOA Test Facility
  - Refine CHARGE thermodynamic model
  - Conduct testing
- Task 3: H2 Dispenser (100% Complete)
  - Validate filling algorithm
  - Component availability & cost
  - Metering and fill accuracy
  - Codes & safety
- Task 4: H2 Compressor (100% Complete)
  - Analytical design
  - Tribology & materials
  - Empirical testing
  - Reformer/purifier interface
- Task 5: H2 Purification (95% Complete)
  - Adsorbent, membrane strategies
  - Reformer/compressor interface
- Task 6: Design & Economics (90% Complete)
  - System design, model, and safety
  - System controls
  - Economic model

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# Accomplishments*

## Hydrogen Production/Fuel Processing

- **Five Fuel Processors Built and Tested**
  - 1st Gen 20 kg/day fuel processor built, tested (low pressure)
  - 2nd Gen 50 kg/day fuel processor built, tested (low pressure)
  - 3rd Gen 50 kg/day fuel processor built, in test (pressurized unit)
  - 1st Gen 10 kg/day fuel processor built, tested (low pressure)
  - 2nd Gen 10 kg/day fuel processor built, in test (pressurized unit)
  - US Patent issued in 2005 on GTI's fuel processor technology
- **System Features Tested**
  - Steam reforming, water gas shift catalysts
  - Burner design, safety and temperature monitoring features
  - Internal radiation materials
  - Methods for internal steam generation and heat recovery
  - Various desulfurization adsorbents for $H_2S$ & odorant removal

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* Includes cost share and in-kind parallel efforts by GTI

# GTI Fuel Processing Systems

- Fully integrated fuel processors with low cost construction
- Internal steam generation and heat recovery
- Single stage shift
- Automated start-stop controls
- Low pressure (below 20 psig) & high pressure (up to 200 psig)

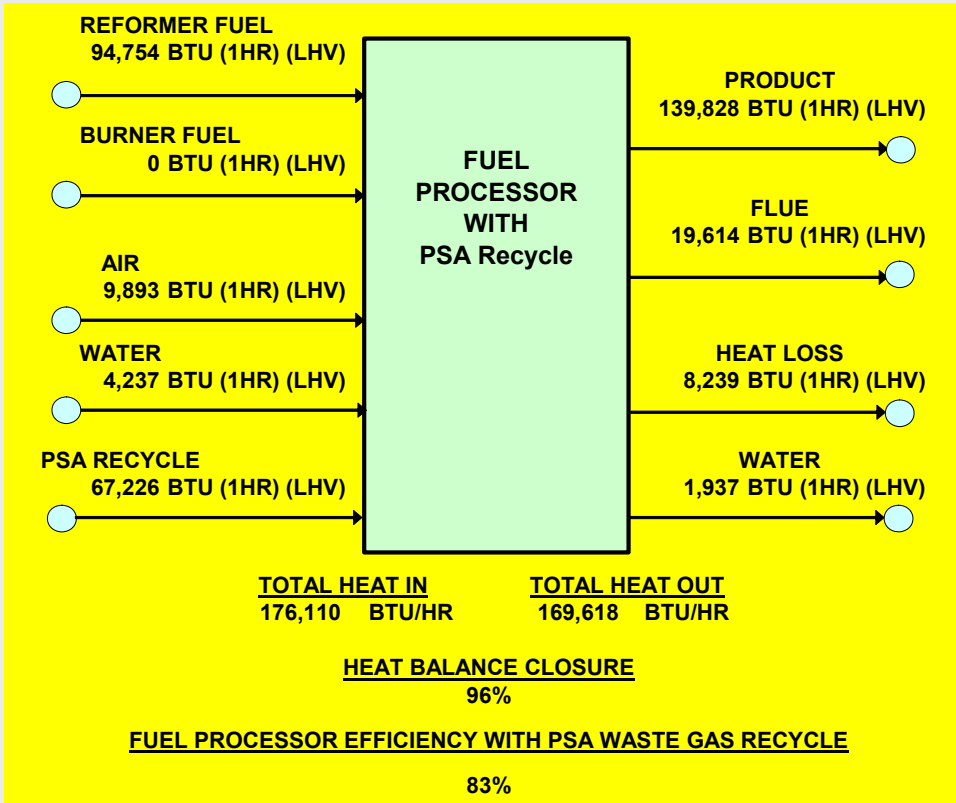

5-8 kg/day
$H_2$ Generator

8-15 kg/day
$H_2$ Generator

50-80 kg/day
$H_2$ Generator

# 50 kg/day $H_2$ Fuel Processor Heat and Thermal Efficiency Balance

**On track to achieving USDOE 2015 goal for 80% H2 Production Energy Efficiency**



# Accomplishments

## Fuel Purification

- Developed PSA testing cells
- Designed multi-adsorbent, multi-functional PSA
  - Deferred development with FuelMaker
- Tested ultra-compact SeQual PSA system
- Tested Air Products PSA system
- Tested QuestAir's new H-3300 PSA
- Tested Hy9 Corp. ultra-thin Pd-Cu membrane
- Tested Pall Corporation/LANL PBI on metal membrane
- Planned: QuestAir H-3200 unit
- Incorporated PSA tail-gas recycle to fuel processor burner for efficient operation

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# Fuel Purification Systems



Tested several “large” and “small” Pressure Swing Adsorption products

Can meet technical PEMFC fuel purity requirements

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# Accomplishments

## Fuel Dispensing

- Developed thermodynamic hydrogen cylinder filling model (CHARGEH2)
  - First principle thermodynamic model using multiple differential equations to characterize fuel station storage, dispensing, and vehicle container filling
  - Ran hundreds of cases using wide matrix of starting conditions, end conditions, flow rates, cylinder types, etc
- Constructed full-scale high-pressure hydrogen test facility
  - Three-bank storage cascade (pressure to 7500 psig)
  - Full temperature control over wide range
- Developed lab-based hydrogen dispenser with full instrumentation
- Performed high-pressure hydrogen mass flow meter tests using high-precision gravimetric scale

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# Accomplishments

## Fuel Dispensing (cont)

- Conducted comprehensive hydrogen fast-fill tests
  - Three different cylinder types (Type 1, Type 3, Type 4)
  - Eleven different thermocouples mounted inside (in gas) and surface mounted outside to fully quantify heating effects
  - Over 100 controlled H2 fill tests from -20°F to 120°F
- HydroFill™ H2 dispenser fill control algorithm developed
  - Patent applications award notice received
  - Continuation-in-part with expanded claims
  - Detailed PLC-based HydroFill program developed
  - Implemented on low-cost controller
  - Licensing underway; one license in place

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# Accomplishments

## Fuel Dispensing (cont)

- Commercial hydrogen dispenser built, tested, and first commercial sale completed
  - Working with GreenField Compression
- Tests run to examine isentropic cooling of vehicle cylinders from drive cycle (two cylinder types) and impact on filling
  - That is, what is effect if dispenser cannot directly measure starting cylinder temperature when refilling
  - Type 3 and Type 4 cylinders
- Performed post-test modeling to characterize dynamic heat transfer and temperature profiles throughout cylinder structure
  - Type 3 (aluminum lined, composite wrapped) and Type 4 (plastic lined, composite wrapped)

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# Hydrogen Dispenser & Cylinder Filling

- Validation testing from -20 to 115 °F

| Group | Avg. Fill % | s | n |
|---|---|---|---|
| Type 3 > -10°F | 100.6* | 1.45 | 22 |
| Type 4 > -10°F | 97.5 | 1.89 | 9 |

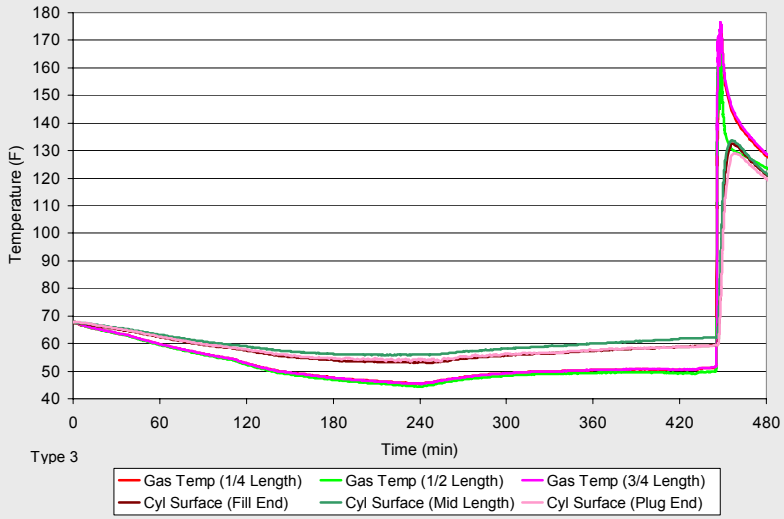
- Units being sold on commercial basis by GreenField Compression

GTI/GreenField H2 dispenser Production in Richardson, Texas

GTI/GreenField H2 dispenser at Victoria, Vancouver Island, BC

# Vehicle Cylinder "Heavy Drive Cycle" Refill Test Results

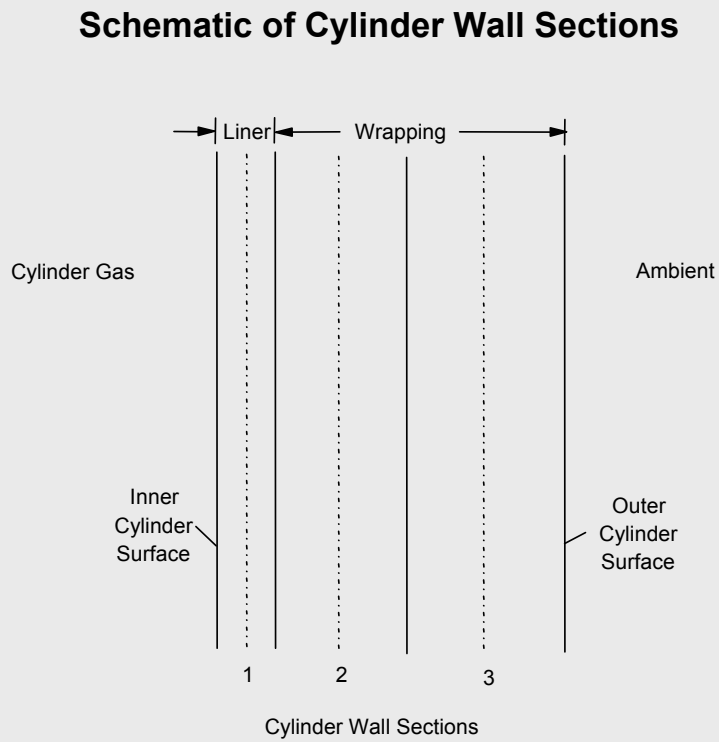
| | Full to 500 psig to Full (7.5 hours) | |
|---|---|---|
| | Gas Temp. Change* | % Fill |
| Type 3 | 76 F to 51 F | 99.3 |
| Type 4 | 76 F to 41 F | 96.5 |

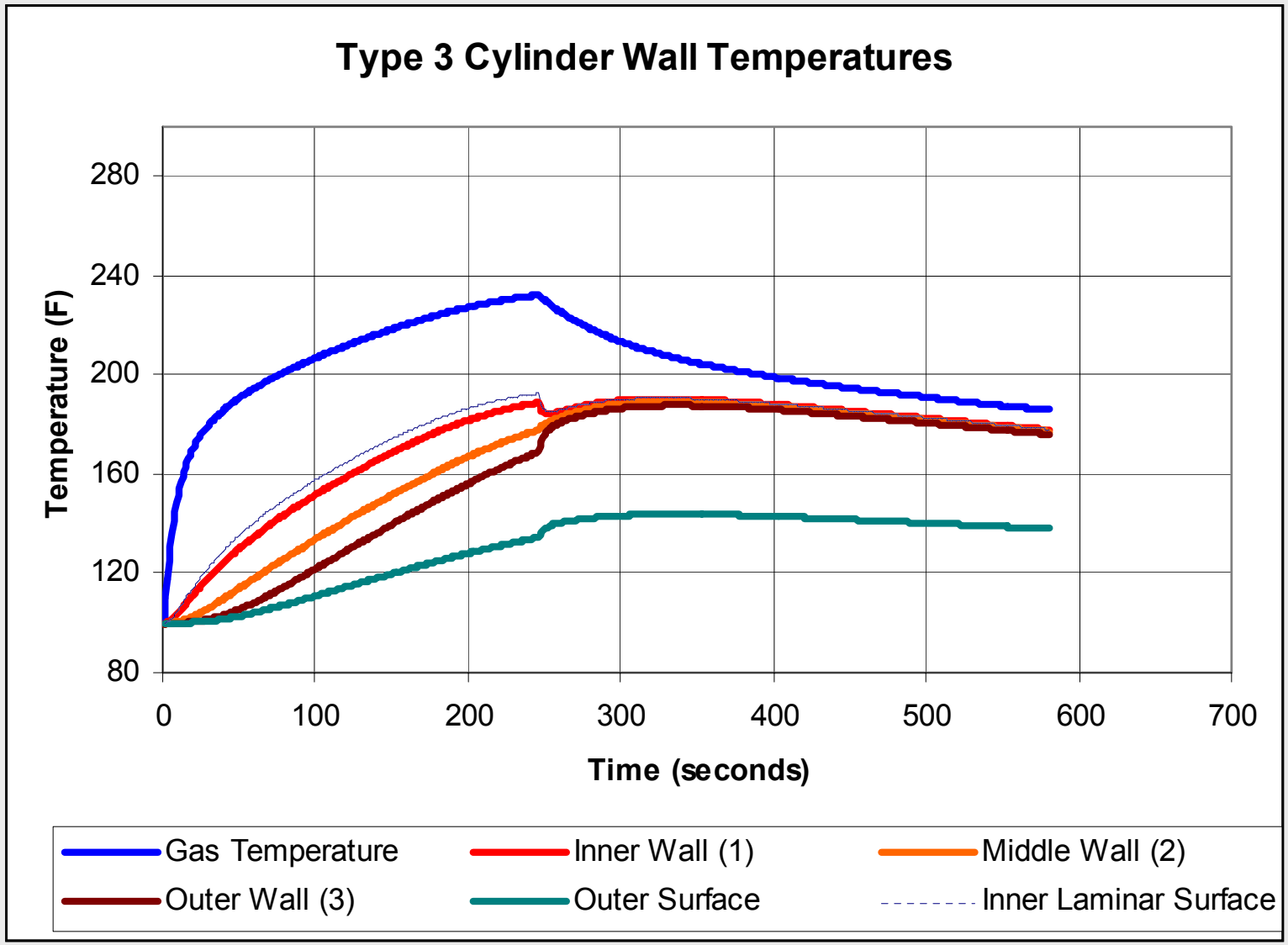



* Gas temperature change shows the starting vehicle cylinder gas temperature and the gas temperature after depressurization (just before filling)

# Cylinder Material Dynamic Temperature Modeling

- Used GTI H2 CHARGE model to assess actual material temperatures
- Examined Type 3 & Type 4 containers
- Segmented wall to see detailed effects




Type 3 Cylinder Wall Temperatures
Temperature (F)
280
240
200
160
120
80
0
100
200
300
400
500
600
700
Time (seconds)
Gas Temperature
Inner Wall (1)
Middle Wall (2)
Outer Wall (3)
Outer Surface
Inner Laminar Surface

# Accomplishments

## Hydrogen Compression

- Due to timing/risk, terminated subcontractor who was developing two different hydrogen compressors (low pressure and high pressure)
- Shifted to available two-stage diaphragm compressor (PDC)
- Working also with GreenField Compression on oil-free reciprocating compressor

## Hydrogen Storage

- Three-bank cascade storage built (7500 psig) using conventional ASME storage containers
- Designed three-bank canopy storage system using composite pressure vessels
- Built two different three-bank hydrogen cascade using lightweight composite containers rated at 7000 psig
  - One stationary and other mobile

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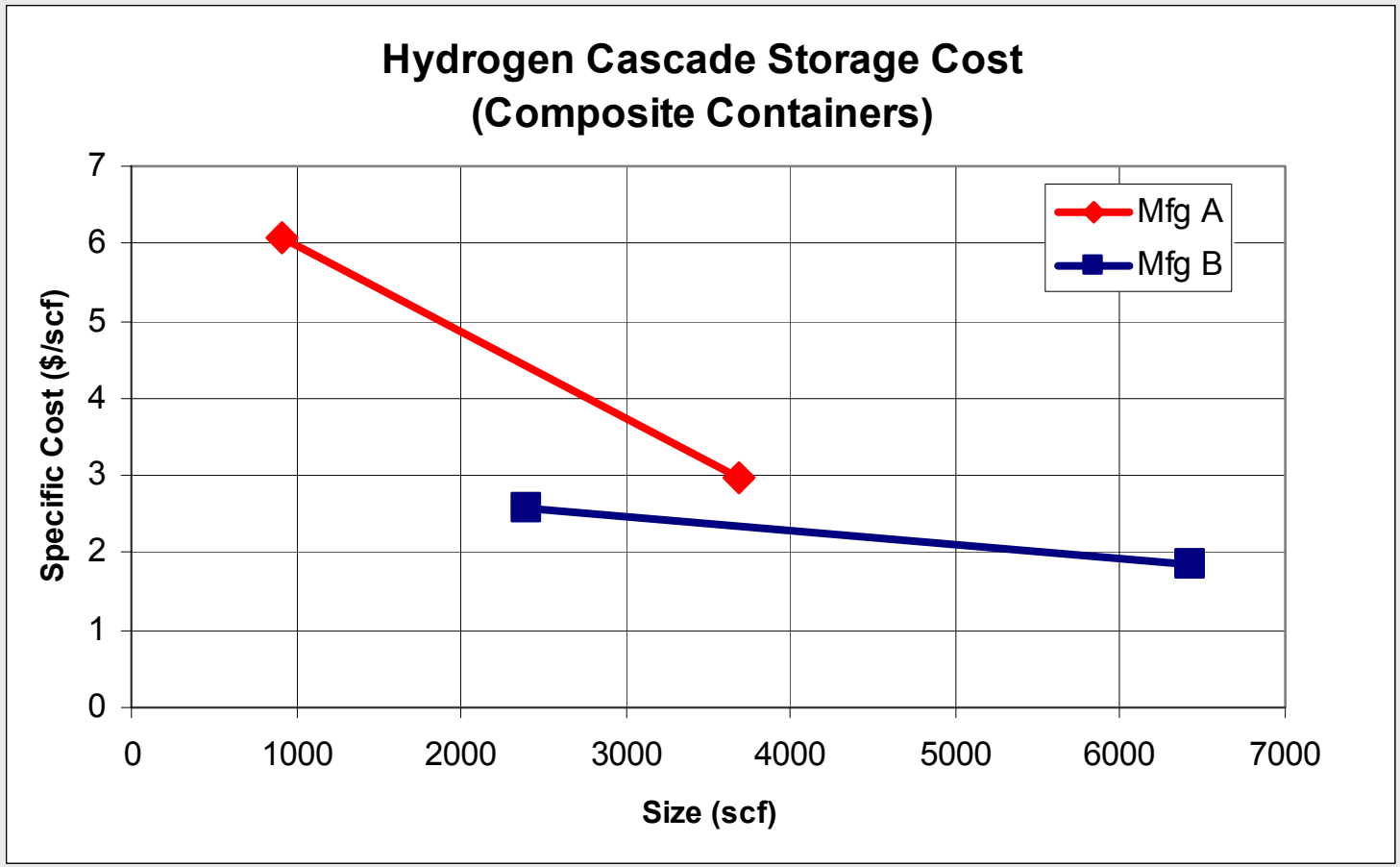
# H2 Cascade Storage Cost




Circa 2004 prices

# Compressed Gas Storage Cascades

Conventional CNG Cascade Using Steel Alloy (~22,000 lbs)

Hydrogen Cascade Using Lightweight Composites (~2800 lbs)

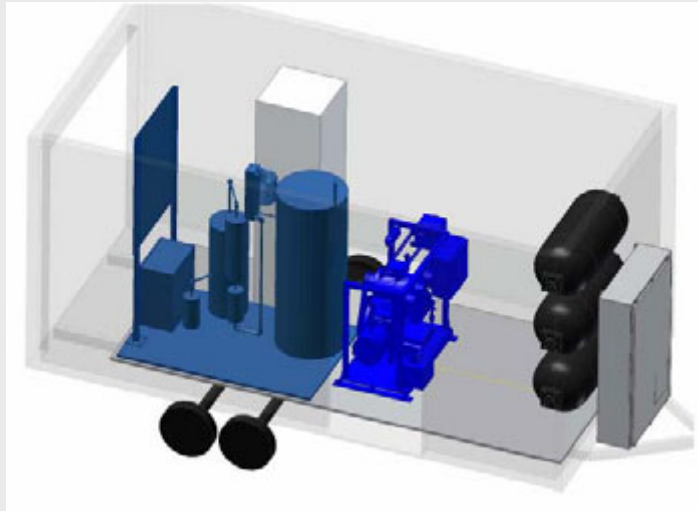
Lightweight hydrogen cascade in GTI Mobile Fueling Station

Capacity: 2,766 scf @ 7000 psig

Container Weight:
3 * 250 lbs = 750 lbs

# Mobile Hydrogen Fueling System

- Complete trailer-mounted H2 fueling station
  - On-board fuel processor, clean-up, compression, storage & dispenser
  - Produce 10-15 kg/day for about 3-5 light duty vehicles per day



# Next Steps

- Complete final testing on 50 kg/day system
  - Including 1000 hour test
  - Operate as keycard access station at GTI
- Use Mobile Hydrogen System for demo programs
- Continue tech transfer, licensing, and commercialization
  - Work with partners and stakeholders on various hydrogen station efforts

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# GTI/GreenField Compression

- Working with State of Texas on next generation packaged H2 stations
- Look to demo & deployment projects in 2007 and beyond
- GreenField Compression
  - Leader in compressed gas systems

# Summary and Conclusions

- Efficient, compact fuel processing feasible
  - 75 to 80% efficiency (and higher) is possible
  - On target with USDOE 2015 goal
- Complete fill hydrogen dispenser developed and validated
  - Simple approach that avoids added cost, complexity
- Fuel clean-up systems
  - Improved PSA solutions coming online
  - Continue looking at membrane technology advances
- Onsite natural gas-to-hydrogen stations technically feasible
  - Cost improvements will continue over time

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