# IV.A.4 Development of a Natural Gas to Hydrogen Fuel Station

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## Objectives

- Overall objective is development of cost-competitive technology for distributed production of high-pressure hydrogen from natural gas to fuel hydrogen-powered vehicles.
- Design and testing of a fast-fill natural gas-to-hydrogen fueling system with 40-60 kg/day delivery capacities.
- Reduce costs of distributed production, high-pressure hydrogen to $3.00/kg.
- Demonstrate innovative, compact natural gas steam reforming system.
- Develop a hydrogen dispenser that can accurately, safely, and cost effectively fill hydrogen vehicle containers.

## Technical Barriers

This project addresses the following technical barriers from the Hydrogen Production section of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

- A. Fuel Processor Capital Costs
- C. Operation and Maintenance (O&M)
- D. Feedstock Issues
- E. Control and Safety

## Approach

- Undertake system design and analysis to identify pathways for meeting cost and performance targets.
- Conduct subsystem development and laboratory testing to confirm unit operation and suitability for complete system application.
- Combine subsystems into an overall integrated system that incorporates system controls and safety features.
- Conduct lab and field experiment testing to validate the complete system for performance, operability, and reliability.

## Accomplishments

Fuel Processing

- Five different fuel processors built and tested
  - Units ranging in size from 10 kg/day to 50 kg/day
  - Three units designed for low pressure operation
  - Two units designed for high pressure operation (up to 200 psig)
  - Latest designs of the small (10 kg/day) and larger (50 kg/day) pressurized fuel processors achieved efficiencies in the range of 70-75% (exceeding the DOE 2005 Technical Target)
  - Units incorporate compact steam generation, fuel reformer, single-stage low-temperature shift, and heat recovery into one package to reduce cost and footprint
  - Tests run using fuel processor run on ethanol
  - Various desulfurization materials evaluated for removing hydrogen sulfide and odorants from natural gas

Fuel Purification

- Developed test lab for collecting accurate performance and gas quality measurements
- Evaluated design concepts for multi-adsorbent, multi-functional pressure swing adsorption (PSA)
- Tested three different pre-commercial PSA technologies (SeQual, Air Products, Quest Air)
- Plans to develop two different metal membranes (Pd-Cu membrane from Hy9 Corporation and polybenzimidazole (PBI)-coated sintered metal membrane from Pall Corporation

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 containing full-scale three-bank storage cascade (pressure to 7500 psig) with capability for -40$^{o}$F to 150$^{o}$F testing
- Developed lab-based hydrogen dispenser with full instrumentation
- Performed high-pressure hydrogen mass flow meter tests using high-precision gravimetric scale to validate meter performance
- Conducted comprehensive hydrogen fast-fill tests
  - Three different cylinder types (Type 1, Type 3, Type 4)
  - Eleven different thermocouples mounted inside (in gas phase) and outside to fully quantify heating effects
  - Controlled tests run from -20$^{o}$F to 120$^{o}$F
  - Total of over 100 different controlled hydrogen fill tests run
- $H_2$ dispenser fill control algorithm developed and validated
- Patent applications filed
- Detailed programmable logic controller (PLC)-based program developed (254 executable steps) and implemented on low-cost controller
- Licensing and technology transfer discussions underway
- Commercial hydrogen dispenser built and tested in cooperation with GreenField Compression (Figure 1)

- Performed modeling to characterize dynamic heat transfer and temperature profiles throughout a hydrogen cylinder structure (Type 3 and Type 4) during and after fueling with high short-term temperatures (Figure 2)

Hydrogen Compression

- Primary (<200 psig) reciprocating compressor designed and built
  - Testing was unsuccessful
- Two-stage diaphragm compressor testing on-going

Hydrogen Storage

- Three-bank cascade storage built (7500 psig) using conventional ASME steel alloy storage containers
- Designed three-bank canopy storage system using composite pressure vessels
- Obtained lightweight composite tanks for use in a small-capacity cascade storage system and a large-capacity storage cascade

System Design and Economics

- Comprehensive subsystem and integrated 50 kg/day system design report completed
- System controls procured and programming underway
- Comprehensive 50 kg/day system economic model developed
  - Revised summary will be included in final report
- Conducted additional analyses to evaluate size effects
- Several technical papers presented
- Constructing public-access high-pressure hydrogen fueling station for operation at GTI's location near Chicago
- Developing 10-15 kg/day transportable hydrogen fueling station

**Figure 1.** Pre-Commercial Hydrogen Dispenser

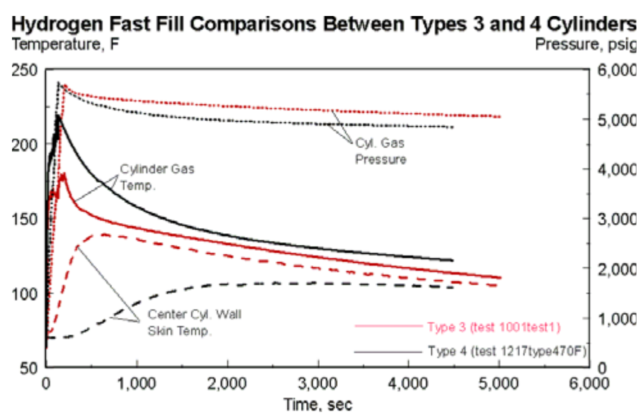


**Figure 2.** Thermal Modeling of Hydrogen Cylinders During Fast-Fill

## Future Directions

- Complete system integration and testing
- Work on public access dispensing capability using cardlock access
- Compile final report of results and conclusions
- Continue work with manufacturing partners to demonstrate and commercialize subsystems and complete system technology

## Introduction

A key impediment to expanded fuel cell vehicle use is hydrogen fueling infrastructure. The use of distributed hydrogen fueling systems is seen as an intermediate pathway to permit infrastructure development, with a future transition to a hydrogen pipeline delivery infrastructure. This project leverages the substantial natural gas delivery infrastructure by using onsite natural gas to hydrogen fueling systems.

Several key technologies are being developed in this project. This includes a compact, cost-effective, and efficient steam methane reformer and fuel-processing technology developed by GTI. An additional core effort is development of a hydrogen dispenser with an advanced filling algorithm that will permit accurate and complete filling of compressed hydrogen vehicles under a range of conditions. These advanced subsystems – reforming, fuel cleanup, compression, storage, and dispensing – are being incorporated into an integrated and cost-competitive small natural gas-to-hydrogen fueling station that will support hydrogen fueling infrastructure development and expansion. GTI is also producing a Mobile Hydrogen Unit that will be capable of producing up 15 kg/day using scaled-down versions of equipment used in the nominal 50 kg/day system.

The specific goal for this project is a fast-fill natural gas-to-hydrogen fueling system with 40-60 kg/day delivery capacity. DOE goals include providing hydrogen at costs of $3.00/kg or less.

## Approach

The project approach is to develop and test key subsystems (fuel processor, compression, fuel purification, storage, and dispensing) and then integrate these subsystems into an overall cost-effective hydrogen fueling solution. The project includes three phases: 1) Design, 2) Subsystem Development and Lab Testing, and 3) Field Testing.

## Results

The project began in February 2002 with a focus on subsystem and system design. A comprehensive design and analysis report was submitted in September 2002. This covered all of the key subsystems as well as a first-generation integrated system design. The footprint for the system (excluding hydrogen storage) is approximately 8' by 14'.

The development of the fuel processing subsystem, the heart of the overall system, is virtually completed. A compact steam methane reformer and low-temperature, single-stage shift conversion system has been tested that maximizes the hydrogen yield at high efficiency. Tests of the complete system indicate the ability to reliably obtain high hydrogen concentrations of 80% with low CO levels. The fuel processor has been designed to comply with appropriate fire safety standards. Initial prototypes were developed to operate at low natural gas pressures (below 15 psig). Due to technical challenges in developing or obtaining a single-stage reformate compressor, recent fuel processor units have been constructed to operate at 200 psig. Both smaller scale (10-15 kg/day) and larger scale (50-80 kg/day) fuel processors have exhibited thermal efficiencies in the range of 70-75%, with some potential to increase efficiency up to 80%.

GTI has constructed a full-scale hydrogen storage cascade and simulated dispenser within a large temperature-controlled environmental chamber. This facility stores high-pressure hydrogen gas in a three-bank cascade storage system. Temperature can be controlled from –40 to 70°C. The facility includes essential components of a hydrogen dispenser, including precision mass flow meter (provided by Emerson Process Controls), cascade controls, thermocouples, and precision pressure transmitters. Cylinder filling is gravimetrically validated using an ultra-high-precision, intrinsically safe scale.

A large number of tests on fast-filling of high-pressure hydrogen cylinders have been conducted under a range of starting ambient temperature conditions, starting pressure levels, varying time of fill, and other key parameters. These results were used with GTI's CHARGE H2 model to develop a hydrogen dispenser filling control algorithm (Hydrofill™). The Hydrofill algorithm allows accurate and complete filling of hydrogen cylinders over a wide range of operating conditions. The accuracy of the algorithm derives from its reliance on first-principle thermodynamics.

GTI and Greenfield Compression worked together to develop a pre-commercial hydrogen dispenser incorporating the GTI-developed Hydrofill algorithm. Initial validation testing has shown good performance, with additional testing ongoing.

GTI is working with Lincoln Composites to evaluate the use of Type 4 plastic-lined, composite pressure vessels for hydrogen fuel station cascade storage. The cost of these units, on a $/scf basis, look attractive even compared to conventional steel vessels. Design work has looked at the potential for using these lightweight containers integrated with canopy structures.

## Conclusions

- There are challenges with meeting system cost targets in the near term; a substantial element of the cost target rests on the price of natural gas.
- The application of a natural gas steam methane reformer-based fuel processing system is technically feasible.
- Fuel processor start-up time and dynamic response rates are acceptable for fast-fill stations that incorporate high-pressure cascade storage systems.
- Improved guidelines are needed for fuel quality requirements pertaining to use in hydrogen-powered fuel cell vehicles.
- Significant thermal effects are seen with fast filling of high-pressure hydrogen cylinders.
- Accurate filling of hydrogen vehicle containers can be achieved without on-board communications under a wide vary of conditions and scenarios.
- Composite pressure vessels are improving in cost relative to steel containers.

## FY 2005 Publications/Presentations

1. Various presentations have been made during the past year to numerous North American, European, and Asian companies.