VI.B.3 Development of a Natural Gas to Hydrogen Fuel Station

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Objectives

- Develop cost-competitive technology for distributed production of high-pressure hydrogen from natural gas to fuel hydrogen-powered vehicles.
- Design and test fast-fill natural gas-to-hydrogen fueling system with 40-60 kg/day delivery capacities (scalable to higher output levels).
- Demonstrate capability of producing high-purity, high-pressure hydrogen at $3.00/kg (at higher volumes of production)
- Demonstrate innovative, compact natural gas steam reforming system.
- Develop a hydrogen dispenser that can accurately, safely and cost effectively fill hydrogen vehicle containers in less than five minutes.

Contribution to Achievement of DOE Technology Validation Milestones

- **Milestone 6: Validate vehicle refueling time of 5 minutes or less.** Dispenser testing has shown ability to fill vehicles (5 kg capacity) in less than five minutes using a new dispenser design.
- **Milestone 11: Validate cost of producing hydrogen in quantity of $3.00/gge (untaxed, based on volume production).** GTI's economic models predict hydrogen costs below $3.00/kg at hydrogen station sizes of 750 kg/day and larger.

Accomplishments

Fuel Processing

- Five different fuel processors built and tested.
  - Size from 10 kg/day to 50 kg/day.
  - Three units designed for low pressure operation.
  - Two units designed for higher 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 75%, with peak values of 83% achieved (Figure 1, exceeding DOE 2010 Technical Target of 70%).
- Units incorporate compact steam generation, fuel reformer, single-stage low-temperature shift, and heat recovery – reducing package cost and footprint. U.S. patent issued on fuel processor design (#6,932,958).
- Tests run using fuel processor operating on ethanol.
- Various desulfurization materials evaluated for removing hydrogen sulfide and odorants from natural gas. New material evaluated with elevated performance characteristics.

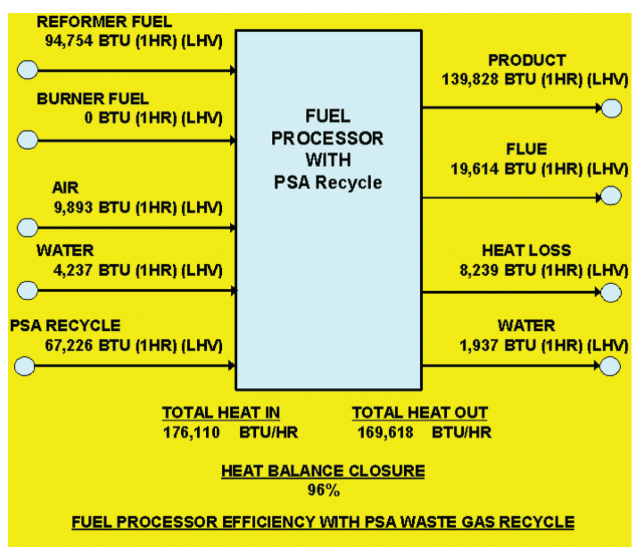

FIGURE 1. Fuel Processor Thermal Balance

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.
- Tested two different metal membranes: Pd-Cu membrane from Hy9 Corporation and PBI-coated sintered metal membrane from Pall Corporation (developed in cooperation with LANL).
- Incorporated PSA tail-gas recycle with custom-designed fuel processor burner for efficient operation.

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 (350 bar/5,075 psig).
  - Ran hundreds of cases using a wide matrix of starting conditions, end conditions, flow rates, cylinder types, etc.
  - Upgraded model to evaluate 700 bar/10,000 psig fill operation.
- Constructed full-scale high-pressure hydrogen test facility containing full-scale three-bank storage cascade (pressure to 500 bar/7,500 psig) with capability for -40°F to 150°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°F to 120°F.
  - Total of over 100 different controlled hydrogen fill tests run.
- Hydrogen dispenser fill control algorithm developed and validated.
- U.S. patent issued (#7,059,364) along with additional know how.
- Detailed PLC-based program developed (254 executable steps) and implemented on low-cost controller.
- Licensing and technology transfer begun; one license agreement to date.
- Commercial hydrogen dispenser built, tested and deployed in the field (Figure 2).
- 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.

Hydrogen Compression

- Primary (<200 psig) reciprocating compressor designed & built.
  - Testing was unsuccessful.
- Two-stage diaphragm compressor testing on-going (PDC Compressor).
- Evaluating oil-free multi-stage reciprocating hydrogen compressor with unique magnetic coupling drive from GreenField Compression (Figure 3).

Hydrogen Storage

- Three-bank cascade storage built (7,500 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 cascade storage cascade (Figure 4).

FIGURE 2. Hydrogen Dispenser Field Test

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.

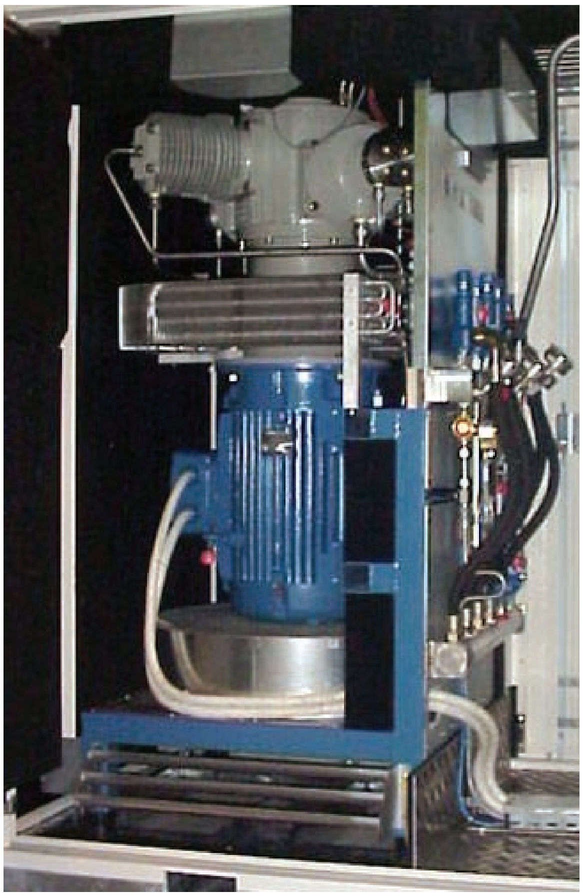

FIGURE 3. Novel Multi-Stage Hydrogen Reciprocating Compressor

FIGURE 4. Three-Bank Hydrogen Cascade Using Composite Pressure Vessels

- Conducted economics analysis to evaluate size effects and economics at system sizes of 750 kg/day and 1,500 kg/day. GTI's economic models predict hydrogen costs below $3.00/kg at hydrogen station sizes of 750 kg/day and larger (350 bar/5,075 psig).
- Several technical papers presented at NHA annual conferences and other technical forums.
- 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.
- Established technology transfer and licensing agreement with commercialization partner.
- Initiated follow-on deployment program with State of Texas; others in development.

Introduction

A key impediment to expanded fuel cell vehicle use is 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 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 used scaled-down versions of equipment used in the nominal 50 kg/day system.

Approach

The project approach is to develop and test key subsystems (main tasks include 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. The final system will be used as a public-access style hydrogen fueling station located at GTI's facilities near O'Hare Airport.

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 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 75 to 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 75% and higher. Peak efficiency and heat balance shows 83% efficiency (LHV basis).

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 showed good performance. An initial unit was implemented in the field (separate from this project). A picture of this installation is shown in Figure 2.

In a separate project funded in part by the State of Texas, GTI and GreenField Compression are evaluating use of a novel high-pressure, multi-stage reciprocating compressor. This unique compressor is completely oil free and uses a magnetic coupling to segment the drive motor from the sealed compressor (Figure 3).

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. Two different size three-bank hydrogen storage cascades were constructed (Figure 4).

Conclusions

1. The application of a natural gas steam methane reformer-based fuel processing system is technically feasible.
2. Fuel conversion efficiencies in excess of 75% are feasible (LHV basis) with integrated operation with hydrogen purification systems (e.g., PSA).
3. Fuel processor start-up time and dynamic response rates are acceptable for fast-fill stations that incorporate high-pressure cascade storage systems.
4. Improved guidelines are needed for fuel quality requirements and measurement techniques related to high-pressure hydrogen for fuel cell vehicles.
5. Significant thermal effects are seen with fast filling of high-pressure hydrogen cylinders.
6. Accurate filling of hydrogen vehicle containers can be achieved without on-board communications under a wide vary of conditions and scenarios.
7. Composite pressure vessels are improving in cost relative to steel containers.
8. System economics will be attractive as the demand for hydrogen develops and larger stations (in excess of 500 kg/day) become justified and highly utilized. Delivered costs of hydrogen below $3.00/kg are feasible in this scenario. In the interim, smaller stations will entail a higher delivered cost of hydrogen or benefit from incentives to offset capital costs.

Special Recognitions & Awards/Patents Issued

1. Two U.S. patents were issued related to the GTI fuel processor and the GTI-developed HydroFill™ hydrogen dispenser control algorithm.