Development of a Natural Gas-to-Hydrogen Fueling System

DOE Hydrogen & Fuel Cell Merit Review

William E. Liss
Gas Technology Institute

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Hydrogen Fueling Systems

Problem Statement/Challenges

- Overall Problem Statement
  - Making hydrogen competitive with gasoline ($/kg or $/vehicle mile traveled)
- Challenges
  - Flexible & efficient fuel processors
  - Fuel purity assurance
  - Long-life, efficient, clean compressors
  - Accurate dispensing/complete fills
  - System reliability
  - Safety
  - Capital outlay & return on investment

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Proposed Solution

- > 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 5000 psig dispensing

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Project Goals and Objectives

> Quantitative DOE Goals*
  – Cost: high-pressure hydrogen at <$3.00/kg by 2005
  – Fuel processing efficiency: 69% by 2005
  – Fuel purification:
    > PSA: 82% recovery by 2005**
    > Metal membranes: >70% recovery by 2005
  – Compression Energy: 94% by 2005

> Qualitative Goals
  – Minimize infrastructure investment cost and risk
  – Avoid high H_2 delivery costs and logistics challenges
  – Provide technology transfer to industry participants and stakeholders

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* From Table 3.1.2, ***Hydrogen, Fuel Cells & Infrastructure Technologies Program: Multi-Year RD&D Plan (Feb. 2005)***

** From prior Multi-year Plan

Program Participants

- Gas Technology Institute
  - Program manager, fuel processing subsystem, hydrogen dispenser fill controls, system integrator
- Working with & evaluating range of potential technologies
  - Production: GTI's fuel processor, Proton electrolyzer
  - Purification: FuelMaker, SeQual, Air Products, QuestAir, Hy9, others
  - Compression: PDC, FuelMaker, GreenField, ANGI, others
  - Storage: Lincoln Composites, Norris, Dynetek
  - Dispensing & Metering: GreenField, ANGI, Emerson, OPW, others

Plan & Approach

90% Complete

> Task 1: Fuel Reforming
– Increase efficiency
– Improve turndown
– Controls

Complete

> Task 2: Fast-Fill Testing
– Build SOA Test Facility
– Refine CHARGE thermodynamic model
– Conduct testing

80% Complete

> Task 3: H2 Dispenser
– Validate filling algorithm
– Component availability & cost
– Metering and fill accuracy
– Codes & safety

70% Complete

> Task 4: H2 Compressor
– Analytical design
– Tribology & materials
– Empirical testing
– Reformer/purifier interface

70% Complete

> Task 5: H2 Purification
– Adsorbent, membrane strategies
– Reformer/compressor interface

70% Complete

> Task 6: Design & Economics
– System design, model, and safety
– System controls
– Economic model

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Accomplishments*

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)

> **System Features Tested**

- Steam reforming, CO shift catalysts
- Burner safety and temperature monitoring features
- Internal radiation materials
- Methods for internal steam generation and heat recovery
- Ethanol fuel processor tests to validate multi-fuel reforming
- Various desulfurization adsorbents for H_2S & odorant removal

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

Accomplishments

Fuel Purification

- Developed test cell for collecting accurate performance and gas quality measurements
- Evaluated design concepts for multi-adsorbent, multi-functional PSA bed design
- Tested ultra-compact SeQual PSA system
  - Well integrated, appliance-like device
- Testing Air Products PSA system
- Schedule Testing
  - New compact QuestAir PSA system
  - Hy9 Corp. ultra-thin Pd-Cu membrane
  - Pall Corp. novel membrane PBI-based membrane on metal support (USDOE project)

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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)
  - Wide temperature range capability
- Developed lab-based hydrogen dispenser with full instrumentation
- Performed high-pressure hydrogen mass flow meter tests using high-precision gravimetric scale

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 phase) and outside to fully quantify heating effects
  - Controlled tests run from -20^{o}F to 120^{o}F
  - Total of 96 different controlled tests run
    - Ambient temperature ranging from -20^{o}F to 120^{o}F
- H2 dispenser fill control algorithm developed and validated
  - Patent applications filed
  - Detailed PLC-based program developed (254 executable steps) and implemented on low-cost controller
  - Licensing and tech transfer discussions underway (license is for control logic – licensees use own hardware)

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Accomplishments

Fuel Dispensing (cont)

- Commercial hydrogen dispenser built and in test
  - Working with GreenField Compression
- 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)
  - Will use information to help guide codes and standards efforts related to on-board vehicle storage and dispensers
    - What is the maximum temperature profile in the wall?
    - How does this align with material temperature limits?
    - What should be max temperature limits for hydrogen gas?
    - What are the implications in terms user driving range?

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Accomplishments

Hydrogen Compression

- Primary (<200 psig) reciprocating compressor designed & built
  - Testing was not successful
- Secondary compressor (up to 7500 psig) based on oil-free reciprocating compressor tested (original plan)
  - Due to timing/risk issues, shifted to conventional equipment
  - Two-stage diaphragm compressor undergoing testing

Hydrogen Storage

- Three-bank cascade storage built (7500 psig) using conventional ASME storage containers
- Designing three-bank canopy storage system using composite pressure vessels
  - Compare with requirements of International Fire Code
  - Lightweight composite tanks on order

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Accomplishments (cont.)

System Design and Economics

- Comprehensive subsystem and integrated 50 kg/day system design report completed
- 50 kg/day system skid constructed
- System controls procured and programming underway
- Comprehensive 50 kg/day system economic model developed
  - Several technical papers presented
  - Conducted additional analyses to evaluate size effects
  - Revised economic analyses will be compiled in final report
- Developing 10-15 kg/day transportable hydrogen fueling station
  - System construction and testing is underway

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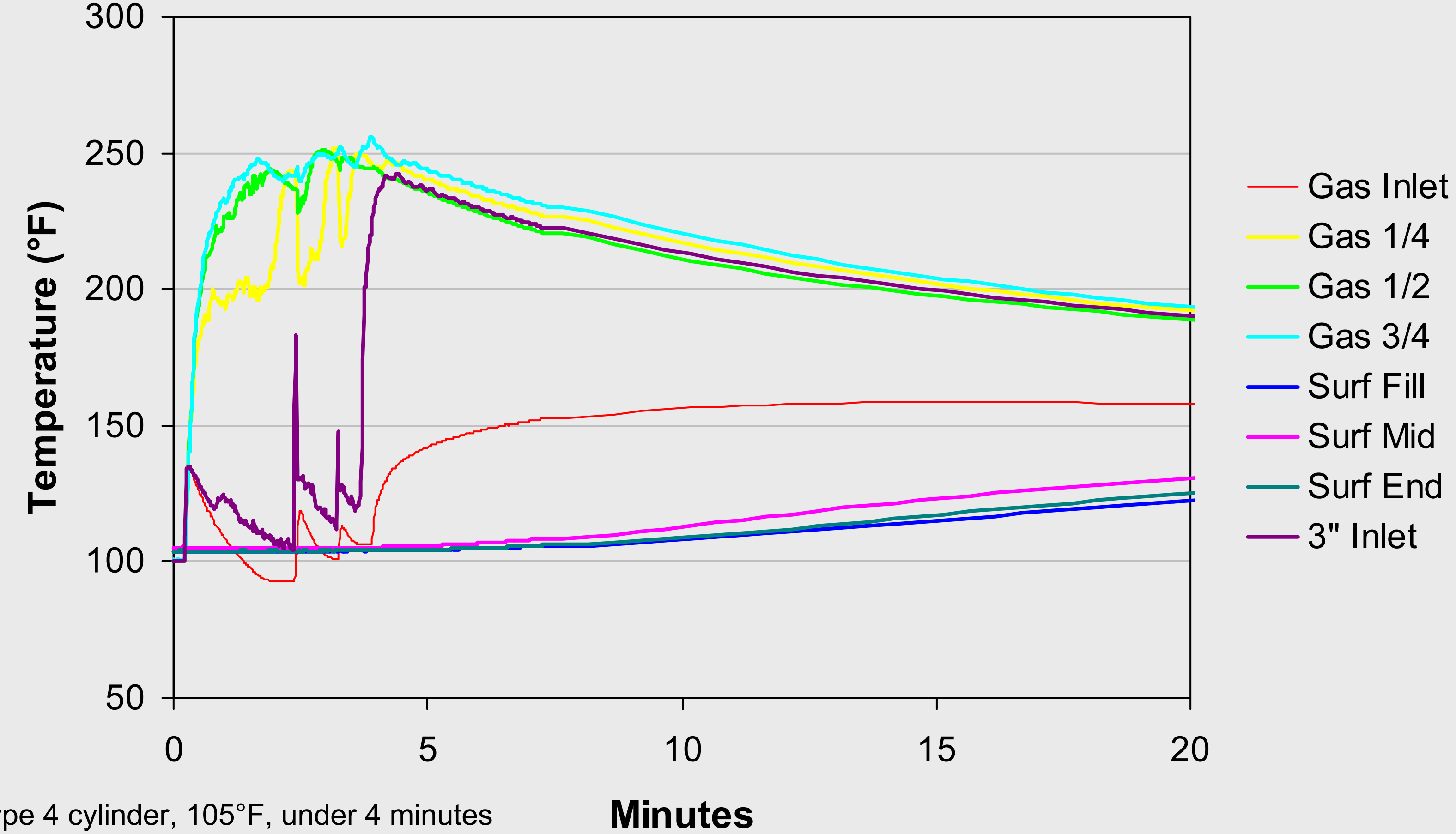
Hydrogen Cylinder Filling

> Highly dynamic process with temporal and spatial temperature dependencies



Type 4 cylinder, 105°F, under 4 minutes

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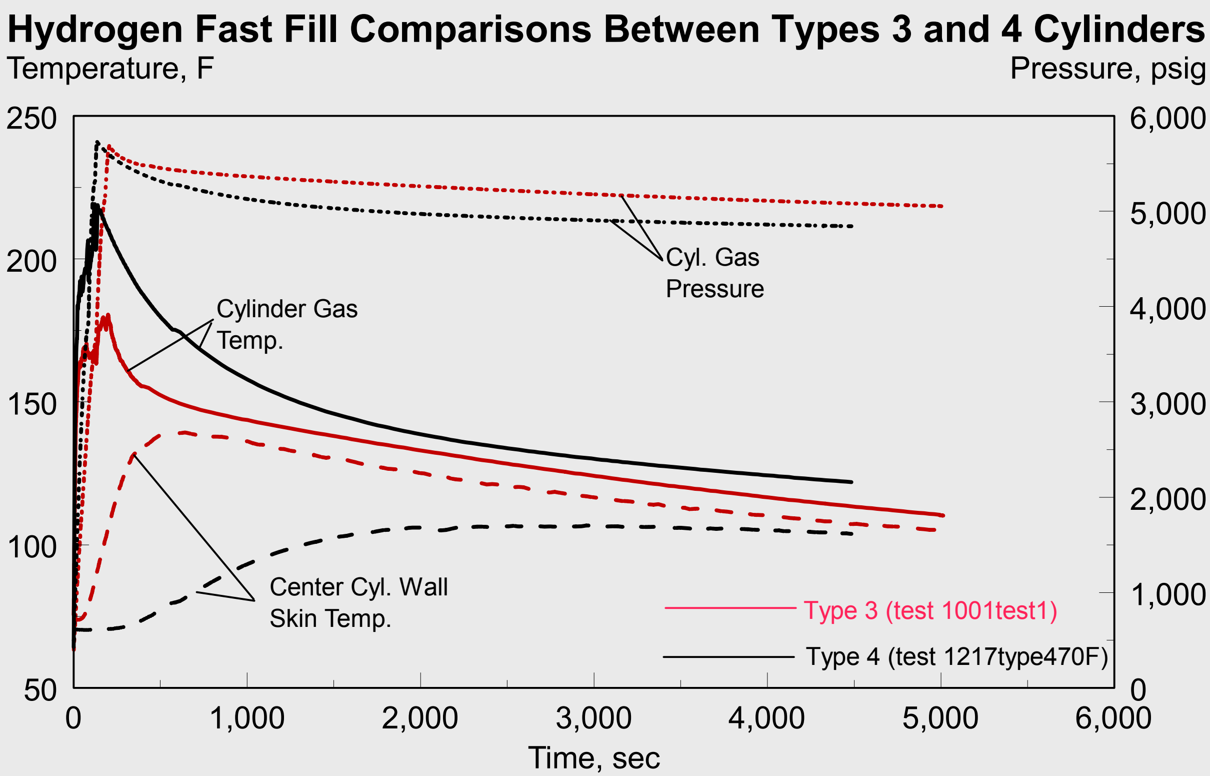
...there's more to the story



Graph shows real data along with summary heat transfer model results

Actual heat transfer model results contain more details on temperature profile through the container wall

Interactions and Collaborations

Gas Technology Institute

- Founding Member - National Hydrogen Association
- Member - U.S. Fuel Cell Council
- Secretary - SAE Fuel Cell Standards Committee
- CSA America Joint US/Canada Automotive Technical Committee
- International Code Council Ad Hoc Hydrogen Committee
- International Energy Agency Advanced Motor Fuels Annex
- U.S. TAG to ISO/TC 197 (ISO/CD 15869) and ANSI/NGV2 on hydrogen vehicle cylinder standards
- Technology exchange with numerous companies and organizations in U.S., Canada, Japan, China, Korea, Europe
- Presented on this work at various technical meetings
  - NHA, WHEC, others

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Next Steps

- Complete build-up and testing
  - 50 kg/day system
  - 10-15 kg/day system
- Continue efforts on technology development and optimization
- Continue efforts on tech transfer, licensing, and commercialization
  - Working with partners and stakeholders on various hydrogen station development and demonstration projects
  - Looking at other fuel options (LPG, ethanol)

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Conclusions

- Efficient, compact fuel processing feasible
  - 75 to 80% efficiency is possible
  - Units can start-up and shutdown
- Complete fill hydrogen dispenser algorithm 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 feasible
  - Challenge competing with gasoline on $/energy basis…need vehicle MPG benefit

Hydrogen Safety

> GTI has extensive hydrogen, high-pressure gas experience
  - Experienced specialized engineers & technicians
  - Use best practices for high-pressure lines and fittings
  - System design and testing conforms with fire codes
  - Real-time gas monitoring and safety systems
  - Company safety committee and training
  - Active in codes & standards development

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Contact Information

William E. Liss
Executive Director, Hydrogen Energy Systems
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, IL 60018
(847) 768-0753
william.liss@gastechnology.org

Mark E. Richards
Senior Engineer, Hydrogen Energy Systems
Gas Technology Institute
1700 South Mount Prospect Road
Des Plaines, IL 60018
(847) 768-0530
mark.richards@gastechnology.org

www.gastechnology.org