III.E.1 Hydrogen Regional Infrastructure Program in Pennsylvania*

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Air Products and Chemicals Inc. – Allentown, PA
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Savannah River National Laboratory – Aiken, SC

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*Congressionally directed project

Technical Barriers

The Hydrogen, Fuel Cells & Infrastructure Technologies Program (HFCITP) Multi-Year Research, Development and Demonstration Plan (MYRDDP) technical barriers (Delivery section, 3.2.4.2) addressed in Phase I of this project include:

(A) Lack of Hydrogen/Carrier and Infrastructure Options Analysis
(F) Hydrogen Delivery Infrastructure Storage Costs
(D) High Capital Cost and Hydrogen Embrittlement of Pipelines
(H) Storage Tank Materials and Costs
(I) Hydrogen Leakage
(J) Safety, Codes and Standards, Permitting and Sensors

Project Objectives	Project Accomplishments
Hydrogen Delivery	
Complete tradeoff analysis to determine the best H_2 delivery approach(es) in Pennsylvania	Completed a tradeoff analysis to determine the best hydrogen delivery approach(es) in Pennsylvania using the H2A model (Section 1).
Determine the feasibility of separating H_2 from H_2/NG blends at the point of use.	Determined the most feasible technologies for separating H_2 from H_2/NG blends at the point of use assuming H_2/NG co-transportation (Section 2).
Determine the feasibility of co-transporting hydrogen (H_2) and natural gas (NG) in existing pipelines.	Determined that co-transporting H_2 and NG in existing pipelines is technically feasible with 0 to 20% H_2; however, it is not economically feasible.
New Material Development	
Construct prototype materials for pipelines and compressed gas storage tanks.	Conducted material testing in a high pressure hydrogen environment for commonly available pipeline materials (Section 3).
	Developed damage mechanics using finite element analysis (FEA)-based and Weibull-based lifetime and survivability models to predict the useful life of pipeline materials using existing material test data (Section 3)
	Constructed and tested 10,000 psig high pressure H_2 prototype tanks (Section 4).
Hydrogen Sensor Development	
Establish capability of H_2-specific sensors to determine percent-level hydrogen in feed gas (including the H_2/NG blends) and ppm-level hydrogen for leaks.	Tested H_2-specific sensors for reliable operation in laboratory and field environments in the presence of natural gas and various contaminants (Section 5).
	Established a baseline of knowledge on the differences of NG versus H_2 leaks

Delivery Technical Targets

MYRDDP Target	Project
Carriers: $1.70 gallon gasoline equivalent (gge) of H_2 as a total cost contribution (from the point of H_2 production through dispensing at the refueling site) by 2010	DOE production target at the pump is $2.00 - $3.00/gge (delivered, untaxed) by 2015. Phase I Pennsylvania delivery scenarios forecast between 3.28 - 5.00gge of H_2. Values have not been assessed for carrier only, but will be for Phase II.
Carriers: 70% H_2 energy efficiency (from the point of H_2 production through dispensing at the refueling site) by 2010	Data gathered during Phase I for production to consumption, rather than carrier specific, energy efficiencies for various scenarios will be used to give carrier specific efficiencies in Phase II.
Pipelines: Transmission and Distribution – Understanding of the reliability (relative to H_2 embrittlement concerns and integrity)	Understanding increased with compiled material test information and models (forecasting effect in high pressure H_2 environment) developed for H_2 transport in line with that available for natural gas transport.
Hydrogen quality: Greater than 98% (dry basis)	Evaluated separation technologies that ensure hydrogen quality from natural gas >98% (dry basis).
Carriers: 6.6% H_2 content by weight and less than $300/kg	Using Van der Waals equation, a 5.2% H_2 content by weight was achieved with off the shelf prototype tanks. Cost/kg remains to be determined.
Pipelines: Transmission and Distribution - H_2 leakage as less than 2% of H_2 put into pipeline	Evaluated H_2 versus NG pipeline leakage.

Section 1: Pennsylvania Hydrogen Delivery Tradeoff Analysis

Introduction

The infrastructure to produce and distribute hydrogen is currently limited, and is not nearly capable of serving even one percent of our transportation needs. Such an infrastructure requires a significant investment in production facilities, distribution, and dispensing mechanisms.

Approach

For the pathways for hydrogen to be produced and delivered to a fueling station, both delivered hydrogen cost and total capital investment were estimated using an analysis that employs the DOE H2A model. The analysis considers variables including feedstock, labor, materials, operation and maintenance, energy cost, and the recovery of capital for 1%, 10%, and 30% light-duty vehicle demand scenarios. The key trade-offs were plant size, feedstock and production technology options, and delivery methods.

Results

For the 10% demand scenario, delivery methods vary depending on proximity to large metropolitan areas. Central production costs of serving the east region of the commonwealth (Figure 1), around Philadelphia, are $3.64/kg using coal gasification and pipeline. Other portions of the east region are served by liquid H_2 trucks. In the west region, central production using coal gasification (delivered by pipeline around Pittsburgh and the remainder of the west region by liquid truck) was determined to be $4.05/kg with increases to $3.90 and $4.08 for the east and west regions, respectively if CO_2 sequestration is included. For the 30% demand scenario, the costs are $3.28/kg for the east, and $3.48/kg in the west region, with increases to $3.54 and $3.74, respectively if CO_2 sequestration is included.

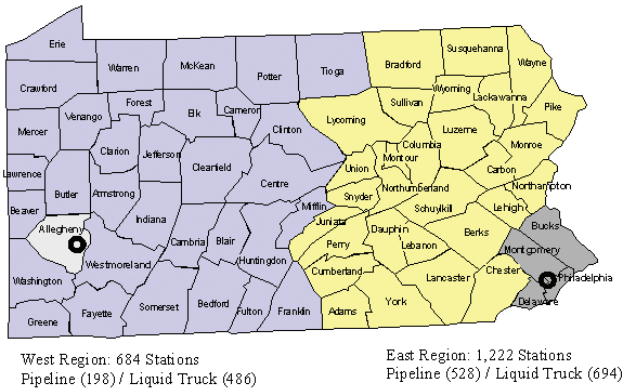

FIGURE 1. Two Plant Option and the Demand Centers for the 30 Percent Demand Scenario

Conclusions and Future Directions

Preferred delivery scenarios depend largely on the percent of H_2 demand, feedstock location/cost, production technology, and end user location with respect to large metropolitan areas. Two potential opportunities to improve upon the best delivered costs include decreasing feedstock costs and increasing the H_2

production volume. A detailed investigation on actual production and delivery costs for various feedstocks per region may provide reduced costs. In addition, a Mid-Atlantic Trade-off study would take advantage of a more cost-effective statistical metropolitan area.

Section 2: Comparative Analysis of Technologies for the Separation of Hydrogen from a Blended Hydrogen/Natural Gas Stream

Introduction

Using existing NG pipelines to transport H_2 may bridge the gap between current H_2 infrastructure and the vastly larger H_2 network needed in the future. One option is to co-transport H_2 in the same line with NG. If a co-transport scenario is adopted, then the H_2 will need to be separated from the H_2/NG blend at or near its point of use.

Approach

Various separations technologies were chosen from the large list of technologies available. For the selected separations technologies, the feasibility of separating H_2 from H_2/NG blends at the point of use was determined. The main inputs required to down select from all separation technologies were feed composition (% hydrogen), feed pressure, point of use flow rate, product (hydrogen) purity, and product delivery pressure. Simulations were conducted to determine how more conventional separation technologies would perform for this application, and approximate costs were evaluated to help prioritize the technologies.

Results

A variety of technologies can theoretically separate 20% H_2 from NG and produce 99.995% H_2 product. Cryogenic and organic membrane processes, combined with adsorption for final cleanup, are technically feasible.

Conclusions and Future Directions

Separation systems can be developed to separate dilute H_2 from natural gas to meet the requirements of fueling stations. The more cost effective technologies at this time are membrane/adsorption hybrid processes (Table 1). Research on smaller, modular separation technologies for distributed production may result in lower delivered costs.

TABLE 1. Relative Costs of Various Separation Technologies for NG/H_2 Co-Transport

Technology	Relative Capital Cost	Relative Power Cost	Relative Total Cost
Cryogenic + PSA	2.65	1.78	2.30
Sorption via Metal Hydrides	0.6-1.6	NA	NA
Organic Membrane + PSA	1.00	1.00	1.00
Pd Alloy Membrane	6.50	1.13	4.37
Inorganic Membrane + PSA / TSA	1.04	1.00	1.00

Note:
TSA = Temperature Swing Adsorption
PSA = Pressure Swing Adsorption

Section 3: Material Testing and Model Development for Hydrogen Transport

Introduction

One option for distribution of H_2 gas from a central production location to the end users is to distribute hydrogen, or a mixture of hydrogen and natural gas, at pressures up to 1,500 psig through the existing NG pipeline system. Some H_2 producers are currently transporting high purity hydrogen through retrofitted petroleum pipelines made of common materials, at very conservative pressures with minimal pressure cycling. An improved understanding of failure mechanisms and material degradation (such as hydrogen embrittlement) in commonly used pipeline materials in the presence of high pressure H_2 may assist in providing guidance through codes and standards for more economical use of existing pipelines.

Approach

Two separate modeling efforts (statistical and deterministic failure) were used to estimate the life expectancy or probability of failure of pipeline components and systems exposed to hydrogen gas. A modified Weibull (static and cyclic statistical crack growth analysis) and FEA analysis were used to understand the effects of H_2 embrittlement in legacy pipelines and to predict life expectancy and probability of failure. These models are updated with existing material test data to reflect failure due to both static and cyclic loading (i.e., corrosion fatigue). Tensile tests were also conducted in a high pressure H_2 environment.

Results

Governing equations were integrated into functions using NG with a known field failure rate. The functions were modified to reflect parameters observed from using material property data for the material exposed to a high pressure H_2 environment. Failure parameters (crack growth rate, probability of failure) were computed for the NG and H_2 conditions. A ratio was created to scale the NG data to the H_2 data. Existing material test data (from static or cyclic pressure loading tests) was input into functional variables to predict changes in the material properties.

Conclusions and Future Directions

The preliminary work in this project assumed an inverse linear relationship between hydrogen and mechanical properties for the models. Tensile testing with 106 Grade B carbon steel pipe demonstrated that the HAZ and weld metal are most susceptible to the presence of H_2 (Figure 2). Additional work is needed to gather mechanical property data for materials exposed to hydrogen which can then be used to validate or indicate changes to be made to the models.

Section 4: Design and Material Testing of an Advanced H2 Composite Overwrapped Pressure Vessel

Introduction

H_2 stored at ambient temperature under moderate pressure (25-35 MPa) is not economically efficient because of the need for large storage facilities due to the low energy density of H_2. H_2 storage density is one of the parameters used to determine storage efficiency. Other factors such as reliability, safety, and cost efficiency are of equal importance.

Approach

This study is comprised of the conceptual development of an advanced highly structurally efficient storage vessel for carriers and off-board storage of H_2 that results in cost and footprint reductions and the material testing results of a prototype 10,000 psi Type III Composite Overwrapped Pressure Vessel (COPV).

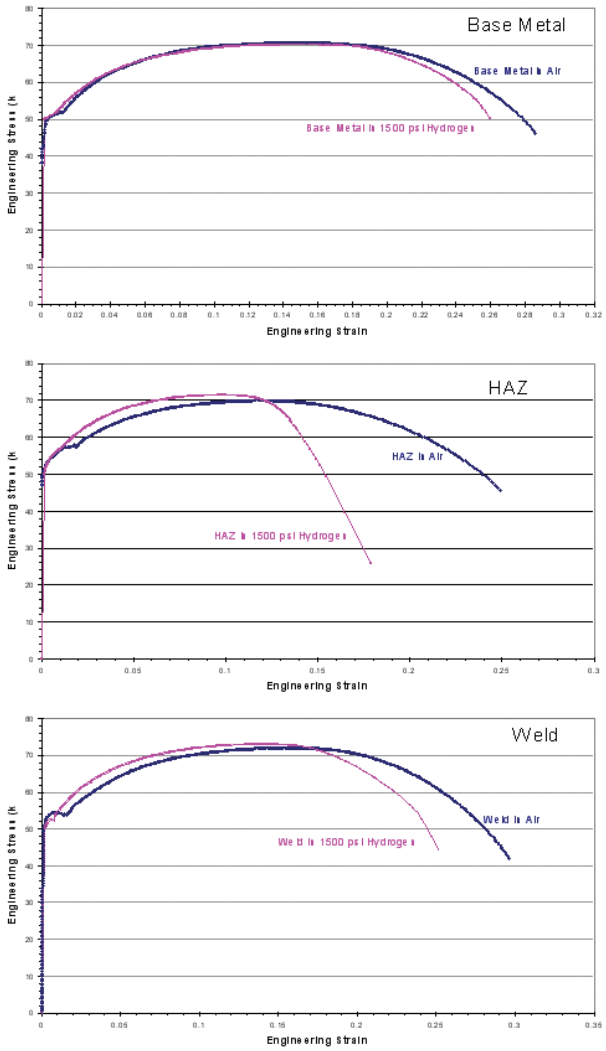

FIGURE 2. Tensile Curves for Base, Weld, and Heat Affected Zone (HAZ) of 106 Grade B

Results

Instead of a 30 mm laminate thickness, tanks with a 23 mm wall thickness using a polymer (epoxy) matrix reinforced with high-strength carbon fibers may provide as much as 23% of tank weight savings. This corresponds to 6.4% tank capacity-to-weight efficiency. As a baseline, an off-the-shelf 10,000 psi service pressure 7.5-liter Type III COPV was manufactured capable of nearly 26,000 psi resulting in a H_2 efficiency ratio (using van der Waals equation) of 5.2% (Figure 3).

Conclusions and Future Directions

Design optimization can increase the storage efficiency while reducing capital cost. An additional effort may be needed to verify that the COPV vendors are all using the same operational specifications and equations when calculating COPV H_2 storage efficiency.

FIGURE 3. Prototype Tank and Example of Burst Test Results

Section 5: H_2-Specific Sensor Assessment, Evaluation, Testing, and Leak Detection

Introduction

Advanced, low-cost hydrogen sensors or leak detection technologies are needed in the production, delivery, storage, and conversion application segments of a hydrogen economy.

Approach

An assessment of newly commercial or pre-commercial hydrogen sensor technologies was conducted. The following technologies were selected: palladium capacitor, carbon nanofiber, and palladium field effect transistor (FET, delineated as Sensor Technologies A, B, and C, respectively). Sensors were tested to defined protocols with custom designed test process/setup. Sensors were tested to validate performance specifications, durability, and resistance to interferents. Interferents included: hydrogen sulfide (H_2S), dimethyldisulfide (DMDS), carbonyl sulfide (COS), carbon monoxide (CO), and glycol, temperature, and humidity.

Results

No detection problems were found while operating in a natural gas environment. However after performance testing, sensor technology B was found to require further development before being considered for interference and field testing. Short term (< 1 day exposure) testing with sensor technologies A and C tested against low level (< 50 ppm_v) interferents (H_2S, CO) resulted in no problems being observed. Extended testing with less problematic interferents (COS, natural gas, DMDS, glycol, humidity) showed that only glycol caused some degradation in response.

Conclusions and Future Directions

At least two sensor technologies (palladium capacitor and palladium FET) exist with near-commercial status as fast, H_2-specific sensors without the need for oxygen. However, sensors need to pass safety certifications for intrinsically safe operation. For fast response, sensors should follow trends used in flammable gas detectors such as forced detection rather than diffusion and integration of physical/chemical resistant barriers to lengthen sensor life.

FY 2006 Publications/Presentations

Conference Proceedings and Presentations

1. Jeffrey R. Hufton, Mark Antkowiak, Eileen Schmura, *Separation of Hydrogen from Natural Gas – Key Technology for Transporting Hydrogen by Natural Gas Pipelines*, NHA Annual Hydrogen Conference 2006 Proceedings, "Global Progress Toward Clean Energy", Long Beach, CA, March 2006.

2. Eileen Schmura, Yuan Pang, Linda Eslin, *Delivery Infrastructure for Hydrogen and Natural Gas*, NHA Annual Hydrogen Conference 2006 Proceedings, "Global Progress Toward Clean Energy", Long Beach, CA, March 2006.

3. Paul Lemar, Paul Sheaffer, Eileen Schmura, *Pennsylvania Hydrogen Delivery Tradeoff Study*, NHA Annual Hydrogen Conference 2006 Proceedings, "Global Progress Toward Clean Energy", Long Beach, CA, March 2006.

Additional Presentations

1. Bob Dax, Junde Xu, Art Gurson, *Modeling of Hydrogen Effects on Materials for Hydrogen Transportation*, SRNL/ASME Materials and Components for the Hydrogen Economy Codes and Standards Workshop, Augusta, GA (August 29-30, 2005).

2. Eileen Schmura, *Natural Gas and Hydrogen Mixtures Working Team*, Hydrogen Pipeline Working Group Workshop, Augusta, GA (August 30-31, 2005).

3. Melissa Klingenberg, *Hydrogen Regional Infrastructure Program in Pennsylvania*, Hydrogen Pipeline Working Group Workshop, Augusta, GA (August 30-31, 2005).

4. Laurentiu Nastac, Andrey Troshko, Ankit Adhiya, Ashwini Kumar, Jeffrey Hufton, Pingping Ma, Hansong Cheng, David Zatko and Paul Wang, *Mathematical Modeling of Flow Stratification and Hydrogen Permeation in Natural Gas/Hydrogen Pipelines*, Material Science and Technology 2005, Hydrogen Economy Symposium, Pittsburgh, PA (September 27, 2005).

5. Dave Zatko, Lonnie O'Baker, *Hydrogen Specific Sensor Functional Evaluations*, NHA Annual Hydrogen Conference 2006, Long Beach, CA (March 2006).