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

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Air Products and Chemicals Inc. – Allentown, PA
HyPerComp Engineering Inc. – Brigham City, UT
Resource Dynamics Corporation – Vienna, VA
Savannah River National Laboratory – Aiken, SC

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Projected End Date: March 31, 2008

*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

<table>
<thead>
<tr>
<th>Project Objectives</th>
<th>Project Accomplishments</th>
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<tbody>
<tr>
<td><strong>Hydrogen Delivery</strong></td>
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<tr>
<td>Complete tradeoff analysis to determine the best H₂ delivery approach(es) in Pennsylvania</td>
<td>Completed a tradeoff analysis to determine the best hydrogen delivery approach(es) in Pennsylvania using the H₂A model (Section 1).</td>
</tr>
<tr>
<td>Determine the feasibility of separating H₂ from H₂/NG blends at the point of use.</td>
<td>Determined the most feasible technologies for separating H₂ from H₂/NG blends at the point of use assuming H₂/NG co-transportation (Section 2).</td>
</tr>
<tr>
<td>Determine the feasibility of co-transporting hydrogen (H₂) and natural gas (NG) in existing pipelines.</td>
<td>Determined that co-transporting H₂ and NG in existing pipelines is technically feasible with 0 to 20% H₂; however, it is not economically feasible.</td>
</tr>
<tr>
<td><strong>New Material Development</strong></td>
<td></td>
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<tr>
<td>Construct prototype materials for pipelines and compressed gas storage tanks.</td>
<td>Conducted material testing in a high pressure hydrogen environment for commonly available pipeline materials (Section 3).</td>
</tr>
<tr>
<td>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)</td>
<td>Constructed and tested 10,000 psig high pressure H₂ prototype tanks (Section 4).</td>
</tr>
<tr>
<td><strong>Hydrogen Sensor Development</strong></td>
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<tr>
<td>Establish capability of H₂-specific sensors to determine percent-level hydrogen in feed gas (including the H₂/NG blends) and ppm-level hydrogen for leaks.</td>
<td>Tested H₂-specific sensors for reliable operation in laboratory and field environments in the presence of natural gas and various contaminants (Section 5).</td>
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<td>Established a baseline of knowledge on the differences of NG versus H₂ leaks</td>
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Delivery Technical Targets

<table>
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<tr>
<th>MYRDDP Target</th>
<th>Project</th>
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<tr>
<td>Carriers: $1.70 gallon gasoline equivalent (gge) of H₂ as a total cost</td>
<td>DOE production target at the pump is $2.00 - $3.00/gge (delivered,</td>
</tr>
<tr>
<td>contribution (from the point of H₂ production through dispensing at the</td>
<td>untaxed) by 2015. Phase I Pennsylvania delivery scenarios forecast</td>
</tr>
<tr>
<td>refueling site) by 2010</td>
<td>between 3.28 - 5.00 gge of H₂. Values have not been assessed for</td>
</tr>
<tr>
<td>Carriers: 70% H₂ energy efficiency (from the point of H₂ production</td>
<td>carrier only, but will be for Phase II.</td>
</tr>
<tr>
<td>through dispensing at the refueling site) by 2010</td>
<td></td>
</tr>
<tr>
<td>Pipelines: Transmission and Distribution – Understanding of the reliability</td>
<td>Understanding increased with compiled material test information and</td>
</tr>
<tr>
<td>(relative to H₂ embrittlement concerns and integrity)</td>
<td>models (forecasting effect in high pressure H₂ environment) developed</td>
</tr>
<tr>
<td>Hydrogen quality: Greater than 98% (dry basis)</td>
<td>for H₂ transport in line with that available for natural gas transport.</td>
</tr>
<tr>
<td>Carriers: 6.6% H₂ content by weight and less than $300/kg</td>
<td>Using Van der Waals equation, a 5.2% H₂ content by weight was</td>
</tr>
<tr>
<td>Pipelines: Transmission and Distribution - H₂ leakage as less than 2% of</td>
<td>achieved with off the shelf prototype tanks. Cost/kg remains to be</td>
</tr>
<tr>
<td>H₂ put into pipeline</td>
<td>determined.</td>
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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 H₂ 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 CO₂ 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 CO₂ sequestration is included.

Conclusions and Future Directions

Preferred delivery scenarios depend largely on the percent of H₂ 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 H₂...
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\textsubscript{2} may bridge the gap between current H\textsubscript{2} infrastructure and the vastly larger H\textsubscript{2} network needed in the future. One option is to co-transport H\textsubscript{2} in the same line with NG. If a co-transport scenario is adopted, then the H\textsubscript{2} will need to be separated from the H\textsubscript{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\textsubscript{2} from H\textsubscript{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\textsubscript{2} from NG and produce 99.995% H\textsubscript{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\textsubscript{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>
<thead>
<tr>
<th>Technology</th>
<th>Relative Capital Cost</th>
<th>Relative Power Cost</th>
<th>Relative Total Cost</th>
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<tbody>
<tr>
<td>Cryogenic + PSA</td>
<td>2.65</td>
<td>1.78</td>
<td>2.30</td>
</tr>
<tr>
<td>Sorption via Metal Hydrides</td>
<td>0.6-1.6</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Organic Membrane + PSA</td>
<td>1.00</td>
<td>1.00</td>
<td>1.00</td>
</tr>
<tr>
<td>Pd Alloy Membrane</td>
<td>6.50</td>
<td>1.13</td>
<td>4.37</td>
</tr>
<tr>
<td>Inorganic Membrane + PSA / TSA</td>
<td>1.04</td>
<td>1.00</td>
<td>1.00</td>
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</table>

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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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\textsubscript{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).

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.
Section 5: H2-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 interferences. Interferences included: hydrogen sulfide (H2S), 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 ppmv) interferences (H2S, CO) resulted in no problems being observed. Extended testing with less problematic interferences (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, H2-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


Additional Presentations

