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

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Subcontractors:
- Air Products and Chemicals Inc., Allentown, PA
- Resource Dynamics Corporation, Vienna, VA
- HyPerComp Engineering Inc., Brigham City, UT
- Savannah River National Laboratory, Aiken, SC
- American Society of Mechanical Engineers, New York, NY

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Projected End Date: March 31, 2008

*Congressionally directed project

Objectives

Pennsylvania Hydrogen Delivery Studies and I-95 Corridor

- Determine Pennsylvania's (PA) economic delivery scenarios using regional cost of indigenous energy resources using the Department of Energy (DOE) H2A model.
- Assess the feasibility of a hydrogen infrastructure along the I-95 Corridor.

Steel Pipeline/Composite Overwrapped Pressure Vessels

- Characterize low carbon steel pipeline material properties by conducting mechanical testing in high pressure hydrogen.
- Improve composite overwrapped pressure vessels (COPVs) design and fabrication methods to concurrently target DOE cost and volumetric efficiency goals for off-board gaseous hydrogen storage.
- Monitor progress of United States COPV standards development and support data collection through mechanical testing of relevant composite materials.

Separations/Sensors

- Design a low-cost rapid pressure swing adsorption (RPSA) system capable of achieving hydrogen purity greater than 99.99%.
- Quantify the state of technology for beaded and structured adsorbents using experimental and numerical methods.
- Advance current hydrogen-specific sensors and sensor technologies to ensure reliable operation and performance in hydrogen applications.

Technical Barriers

This project addresses the following technical barriers from the Hydrogen Delivery section [1] of the DOE Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan (MYRD&DP):

(A) Lack of Hydrogen/Carrier and Infrastructure Options Analysis
(D) High Capital Cost and Hydrogen Embrittlement of Pipelines
(F) Gaseous Hydrogen Storage and Tube Trailer Delivery Costs
(G) Storage Tank Materials and Costs
(I) Hydrogen Leakage and Sensors
(J) Other Refueling Site/Terminal Operations
(K) Safety, Codes and Standards, Permitting

Technical Targets

The Hydrogen Regional Infrastructure Program in Pennsylvania project is conducting research in multiple areas. Insights gained from these studies are being used to address the following technical targets detailed in the Hydrogen Delivery section of the MYRD&DP:

Pennsylvania Hydrogen Delivery and the I-95 Corridor

- Total system cost contribution (from the point of hydrogen production through dispensing at the forecourt) $/kg of hydrogen: $1.70 (2012), <$1.00 (2017).

Steel Pipeline/Composite Overwrapped Pressure Vessels

- Storage tank purchased capital cost ($/kg of hydrogen stored): $500 (2010), $300 (2015).
- Volumetric capacity (kg hydrogen/liter of storage volume): 0.030 (2010), >0.035 (2015).

Separations/Sensors

- Total system cost contribution (from the point of hydrogen production through dispensing at the forecourt) $/kg of hydrogen: $1.70 (2012), <$1.00 (2017).
- Hydrogen purity >99.99%.
- Hydrogen leakage (% of hydrogen leakage from pipeline): <0.5% (2017).

Accomplishments

The following items are accomplishments to date for the Hydrogen Regional Infrastructure Program in Pennsylvania project:

Pennsylvania Hydrogen Delivery and the I-95 Corridor

- Gathered information on indigenous feedstocks for PA case study, including coal, coalbed methane, forestry and wood resources, municipal waste, livestock manure, landfills, wastewater, electricity (renewable and nuclear).
- Evaluated updated costs of using coal for hydrogen; preliminary results indicate the cost of hydrogen, using coal as a feedstock, has increased from the Phase I results.
- Gathered background information about the I-95 Corridor, including identifying major metropolitan statistical areas (MSA) and carbon monoxide emissions.

Steel Pipeline/Composite Overwrapped Pressure Vessels

- Accumulated tensile data for low carbon steel pipeline tested in high pressure hydrogen.
- Confirmed heat affected zone (HAZ) tensile performance is affected most by presence of hydrogen, followed by weld metal, and base metal, respectively.
- Demonstrated need to conduct fracture testing; designed specimens and test matrix.
- Fabricated, burst tested, and fatigue tested 12 Type III COPVs.
- Achieved weight efficiency primary target – based on DOE goals at start of project.

Separations/Sensors

- Continued adsorbent evaluations for use with RPSA units yielding high purity hydrogen.
- Characterized six new adsorbent samples using laboratory tests to measure adsorbent properties; results yielded two materials deserving further investigation for RPSA.
- Conducted reliability testing on three sensor technologies: palladium capacitor, carbon nanofiber, and palladium field effect transistor; palladium sensors were the best overall sensor technology tested.
- Coated palladium sensors were tolerant of hydrogen sulfide and provided accurate and rapid response times.

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Section 1: Pennsylvania Hydrogen Delivery and the I-95 Corridor

Introduction

Concurrent Technologies Corporation (*CTC*) is focusing on PA indigenous resources and the I-95 Corridor, with analytical support from Resource Dynamics Corporation (RDC), the research being conducted builds upon the Phase I trade-off study on the most economically feasible hydrogen delivery scenarios based on population density, existing natural gas pipelines, broad resource categories, production technologies, and transport capabilities using the DOE H2A model. The objectives of this project are to determine the lowest cost solution for delivered hydrogen throughout the State and along the I-95 Corridor by capitalizing on indigenous energy sources and strategic locations.

Approach

To identify the lowest cost solution for delivered hydrogen throughout PA, the project team is assessing the most economically feasible production location/method and delivery methods, and the tradeoffs between these methods using the H2A model. This project is examining developed and undeveloped indigenous energy resources, including waste coal, coalbed and coalmine methane, landfill methane, biofuels (biodiesel, ethanol, biomass), water, wind, clean coal (coal gasification), municipal solid waste, anaerobic digestion and nuclear for each economic region as well as the stakeholders and economic drivers to minimize the delivered hydrogen cost.

Examining the major MSAs in the Mid-Atlantic region surrounding the I-95 Corridor for hydrogen infrastructure needs under three progressively increasing demand scenarios, including 1%, 10%, and 30% of the current population of light-duty vehicles (LDVs) fueled by hydrogen. In these demand scenarios, prominent demand centers were identified and are used to define volume and distance relationships. These values are subsequently used as input to a robust life cycle cost analysis using the DOE H2A model comparing a multitude of hydrogen production and transportation options.

Results

To date, the majority of the PA research has been focused on identifying the viable resources and analyzing various scenarios with coal (see Table 1). Bituminous coal was found to be very prevalent in western PA and could easily provide 100% of the LDV demand. Coal also could provide 19 times more hydrogen compared to the next resource (manure) considered.

In regards to the I-95 Corridor work, the research has focused on characterizing the corridor and running preliminary cases looking at delivered costs. Through research, the I-95 Corridor was found to be the worst concentrated carbon dioxide source on the east coast and includes many ozone non-attainment areas. The corridor also contains several densely populated areas, 13% of U.S. population in less than 1% of land and 22 million LDVs (15% of the total market). The 1^{st}, 7^{th}, 11^{th}, and 19^{th} largest MSAs within the United States are also located along the I-95 Corridor. Combining various MSA (such as Philadelphia and Trenton) will lower the delivery cost of hydrogen. The research also found that total delivery cost for MSAs along the I-95 Corridor are less than $3.00/kg and lower delivery costs are realized with increased demand scenarios and combined MSAs.

TABLE 1. Hydrogen Cost using Coal as the Feedstock and a 30% LDV Demand

Coal Pricing Component	Statewide Average Price (Phase I)		Regional Pricing (Phase II)	
	East Plant	West Plant	East Plant	West Plant
Delivered Coal Price ($/Ton)	37.5	37.5	48.0	38.0
Hydrogen Production Cost ($/kg)	1.41	1.41	1.51	1.42
Hydrogen Delivery Cost ($/kg)	1.87	2.07	1.87	2.07
Delivered Hydrogen Cost ($/kg)	3.28	3.48	3.38	3.49

Conclusions and Future Directions

Over the next year, the team will continue to investigate PA indigenous energy resources by applying current coal prices used to conduct the Phase I analyses for a useful comparison with Phase II results. Evaluations of delivery scenarios will also continue to include optimum production and delivery options for other indigenous resources. A meeting with the various stakeholders will be held to understand possible impacts and gain their value added review.

Future research on the I-95 Corridor will investigate the impact of having multiple plants closer to demand centers to offer lower delivery cost and investigate potential locations. The impact of production economies of scale and production volume increase on initial capital investments will also be evaluated. Criteria for the replacement of liquid truck delivery with dedicated pipelines will also be established, and a meeting with stakeholders will be held to gain their input on the development of the I-95 Hydrogen Corridor.

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Section 2: Steel Pipeline/COPV

Introduction

The use of hydrogen as an energy carrier requires both delivery and storage. One potential delivery path is to transmit hydrogen through pre-existing steel pipelines, but the effects of hydrogen on the mechanical properties of the pipeline materials over time and at high pressure are not completely known. Accordingly, *CTC* is facilitating the mechanical testing of a representative steel pipeline in 1,500 pounds per square inch (psi) hydrogen with Savannah River National Laboratory (SRNL).

To address off-board hydrogen storage, *CTC* is working with HyPerComp Engineering Inc. (HEI) to engineer COPVs that are cost effective and volumetrically efficient. COPVs are intended for use in applications such as fueling station storage.

Approach

Three main activities are being conducted under the Steel Pipeline subtask. *CTC* is participating in the DOE's Pipeline Working Group and interfacing with the American Society of Mechanical Engineers (ASME) to assess and prioritize pipeline material mechanical test data requirements. *CTC* is also addressing a portion of those needs by facilitating and coordinating mechanical testing of pipeline steels in hydrogen with SRNL. Finally, the data being generated under those activities is being distributed to the hydrogen test community via publication.

To advance the state-of-the-art in off-board hydrogen storage, *CTC* has teamed with HEI to model, design, construct and test COPVs. In conjunction with this effort, *CTC* is collaborating with ASME to develop COPV standards.

Results

To date, steel pipeline specimens extracted from base metal, HAZ, and weld metal locations have been subjected to tensile testing in 1,500 psi hydrogen at SRNL. Those tests revealed that the effects of high pressure hydrogen are most pronounced on the HAZ material, with a lesser effect on weld metal and only a modest impact on base metal specimens.

Initial storage tank development, using a non-optimized design, resulted in COPVs displaying a service pressure of 10,000 psi, burst pressure of 25,433 psi, fatigue lifetime of 3,225 cycles from near zero to 10,000 psi, and a post drop (i.e., induced damage) fatigue lifetime of 2,575 under the same conditions. The volumetric storage efficiency target was exceeded; cost reduction remains a challenge and is being addressed via ongoing work.

Conclusions and Future Directions

CTC worked closely with SRNL to characterize the tensile properties of steel pipeline material systems in 1,500 psi hydrogen. The results of this testing were documented and shared with the Pipeline Working Group to address hydrogen embrittlement issues. *CTC* is continuing its work with the DOE, ASME, and SRNL to develop and distribute threshold stress intensity and fracture toughness data tested under similar conditions and facilitate codes development (Figure 1).

CTC worked with HEI to design and test Type III COPVs for off-board gaseous hydrogen storage while simultaneously addressing the DOE's cost and volumetric efficiency goals. *CTC* is continuing its work with the DOE, ASME, and HEI to design and test Type II COPVs (Figure 2), which are less costly compared to the Type III COPVs. The data generated through testing will be shared with the hydrogen community and assist ASME with codes. *CTC* will also quantify cost and efficiency numbers related to Type II COPVs.

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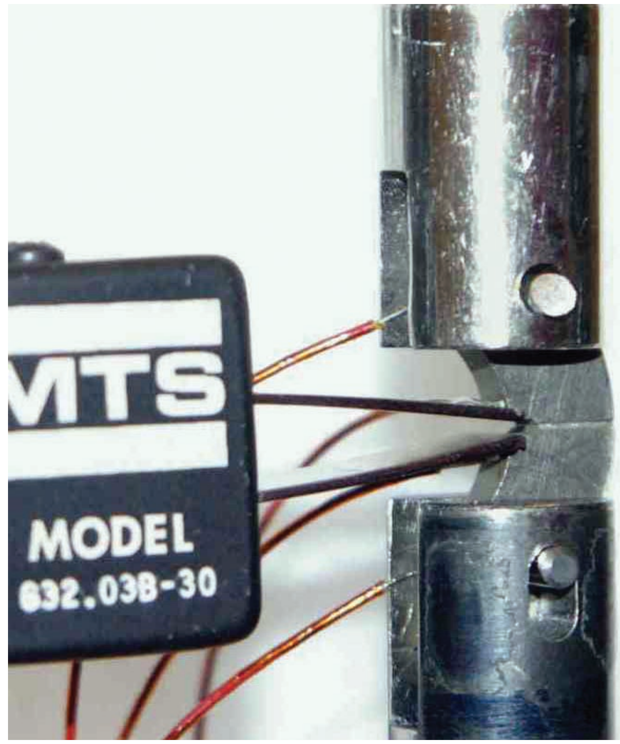

FIGURE 1. Fracture Toughness Specimen Tested in Air

FIGURE 2. Type II COPV with Sidewall and Hoop Failure

Section 3: Separations/Sensors

Introduction

The DOE is investigating alternate domestic energy sources as fuels to eliminate America's dependence on foreign oil. Although there are many technologies and energy sources being pursued, hydrogen has always been the fuel of choice for zero-emission power plants. As part of this project, two areas are being researched to facilitate reducing the cost and increasing the safety and reliability of distributed hydrogen production. These areas are advanced separation technologies and improved hydrogen-specific sensors for field application.

Approach

CTC has teamed with Air Products and Chemicals Inc. (APCI) to extend research in adsorbent technologies for hydrogen purification/separation. Using a RPSA test unit (Figure 3), *CTC* is working with APCI to determine the limits of conventional adsorbent technology versus next-generation adsorbents and identify under what conditions (size, flow rates, pressures, market applications) a hydrogen purifier has favorable cost and technical performance.

CTC is also working with APCI to control or eliminate the effects contaminants have on hydrogen-specific sensors and to extend the useable life of the sensors, as a minimum, to accommodate acceptable maintenance intervals. As part of this work, *CTC* and APCI are investigating existing contaminant mitigation sensor technologies and their key operating parameters. Prototype units of these technologies were created by APCI and tested in both laboratory and field settings. As time permits, modifications will be made to the prototype designs based on the initial test results and additional testing will be completed.

FIGURE 3. RPSA Test Unit

Results

Adsorbent research and testing in a RPSA test unit was the main focus of the separations work over the past year. Eight novel adsorbents were tested in the RPSA test unit consisting of feed, depressurization, purge, and re-pressurization steps. Feed step times from 2 to 12 seconds were considered, and the feed gases tested consisted of several different helium (He) mixtures. A relative comparison of adsorbent materials was then made based on their performance, especially as the feed step time was reduced. One adsorbent showed a He recovery of 80% using an 8 second feed step. Experiments with 2 second feed step cycles yielded 70% recovery, with improved productivity due to the lower cycle time. Selected experimental data were correlated by computer simulation. Another adsorbent produced in a unique geometry was also tested but was found to perform poorly. Finally, six new samples of adsorbents were obtained and characterized using laboratory adsorption tests. The materials were then ranked by mass transfer rate, adsorption capacity, and volumetric adsorption capacity. The results suggest that at least two of the materials deserve further attention in the RPSA test unit.

As part of the sensors work, performance testing showed that two sensor technologies (palladium capacitor and palladium field effect transistor) gave good responses when compared to the manufacturers' claims and described data. After completion of the sensor reliability testing, the sensor manufacturers were consulted to modify both sensors as follows in an attempt to reduce palladium degradation due to hydrogen sulfide composition:

- Palladium capacitor – additional coating added to reduce degradation.
- Palladium field effect transistor – designed-in degradation resistance.

After completion of the modifications, reliability testing was again conducted on the sensors, which showed the modifications did prevent palladium degradation.

Conclusions and Future Directions

Over the next year, the team will continue to search for better adsorbent technologies and improve the performance of the RPSA test unit. A methodology will be developed to package the adsorbent to ensure good gas-adsorbent contact, eliminate gas channeling, and minimize the pressure drop. Guidelines for scaling-up the device to higher flow rates and a preliminary design for a 5 normal meter^3/hour device will also be created.

Future sensors work will include the design of an intrinsically safe package to contain a safety hydrogen leak monitoring sensor system. An intrinsically safe guideline will also be developed along with defined safety performance criteria. Finally, a methodology required for bi-directional (wired/wireless) communications in hydrogen production, transport, and storage environments will be created.

FY 2007 Publications/Presentations

1. David Moyer, *Hydrogen Regional Infrastructure Program in Pennsylvania*, ASME 6th International Pipeline Conference, Calgary, Alberta, Canada (September 25, 2006).

2. David Moyer and Eileen Schmura, *Hydrogen Regional Infrastructure Program in Pennsylvania*, U.S. DOE Hydrogen Pipeline Working Group Meeting, Columbia, MD (September 27, 2006).

3. Paul Lemar and Eileen Schmura, *The Future of Pennsylvania Coal in a Hydrogen Economy*, 2006 International Pittsburgh Coal Conference, Pittsburgh, PA (September 25–28, 2006).

4. Eileen M. Schmura, Paul L. Lemar, Jr and Paul E. Sheaffer, *Pennsylvania Indigenous Energy Hydrogen Delivery Tradeoff Study*, NHA Annual Hydrogen Conference 2007, San Antonio, TX (March 2007).

5. Paul L. Lemar Jr., Paul E. Sheaffer, and Eileen Schmura, *Development of the I-95 Hydrogen Roadway*, NHA Annual Hydrogen Conference 2007, San Antonio, TX (March 2007).

6. M. Olson and K. Klug, Meeting the DOE's Goals for Compressed Hydrogen Gas in Off-board Tank Storage, to be published in NHA Annual Hydrogen Conference 2007 Proceedings, San Antonio, TX (March 2007).

References

1. DOE, "Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan," April 27th, 2007.