Hydrogen Regional Infrastructure Program in Pennsylvania

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PDP19

Overview

Timeline

- Start - September 1, 2004
- Finish - March 31, 2008
- 59% Complete

Budget

- Total project funding
  - DOE share - $5,917K
  - Contractor share - $1,183K
- Funding received in FY06
  - $990K
- Funding for FY07
  - $0

Barriers	Task	MYRDDP Reference
Lack of Hydrogen/Carrier and Infrastructure System Analysis	HD	3.2.4.2 A 3.1.1
Hydrogen Embrittlement of Pipelines	SM	3.2.4.2 D
Gaseous Hydrogen Storage Costs Storage Tank Materials and Costs	CM	3.2.4.2 F 3.2.4.2 G
Lack of Hydrogen/Carrier and Infrastructure Hydrogen Embrittlement of Pipelines	SP	3.2.4.2 A 3.2.4.2 D
Hydrogen Embrittlement of Pipelines Hydrogen Leakage and Sensors	SN	3.2.4.2 D 3.2.4.2 I

HD – Hydrogen Delivery, SM – Steel Materials, CM – Composite Materials, SP - Separations, SN - Sensors

Partners

- Air Products and Chemicals, Inc.
- Resource Dynamics Corporation
- Electric Power Research Institute
- HyPerComp Engineering, Inc.
- American Society of Mechanical Engineers
- Savannah River National Laboratory

Barriers, Objectives and Approach

Pennsylvania Hydrogen Delivery Studies and I-95 Corridor

- Barriers Addressed
  - Lack of Hydrogen/Carrier and Infrastructure (MYRDDP 3.2.4.2 A)
  - DOE's 2015 target of $2.00-$3.00/gge (delivered, untaxed) at the pump for hydrogen (H_2) (MYRDDP 3.1.1)
- Subtask Objectives
  - Analyze tradeoffs between alternative H_2 production and delivery approaches using commercial and near commercial options
  - Evaluate economic delivery scenarios for the I-95 Corridor. Assess the feasibility of hydrogen infrastructure along I-95 Corridor
  - Determine Pennsylvania's economic delivery scenarios using regional cost of indigenous energy resources (i.e., coal, landfill methane, biofuels, wind, water, municipal waste, anaerobic digestion and nuclear) using the DOE H2A model
- Approach
  - Build upon work completed under Phase I of Project's Infrastructure Analysis
  - Work with Resource Dynamics Corporation (RDC) to apply the DOE's H2A model and other analytic methods to the State of Pennsylvania and the I-95 Corridor
  - Capitalize on the Pennsylvania indigenous energy resources to identify the pathway for the lowest cost delivered hydrogen

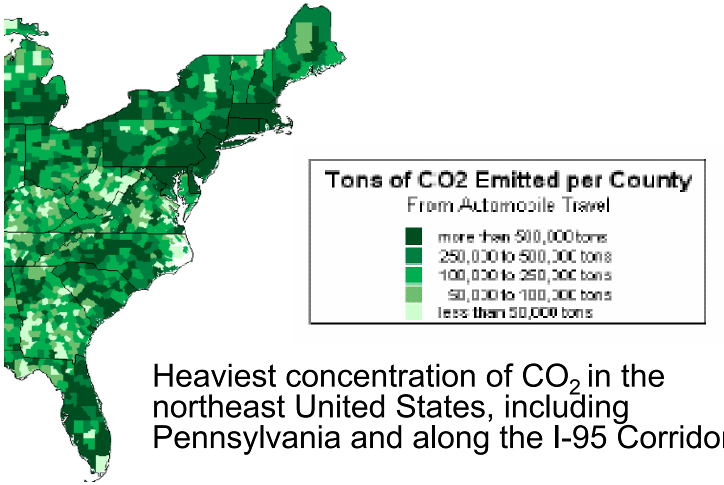
Technical Accomplishments

Why Investigate Hydrogen Infrastructure for Pennsylvania?

- Air quality is not just a California issue; Pennsylvania has similar problems
- Philadelphia Co. is one of the 10 worst ozone attainment counties in the US
- Allegheny Co. is one of the 10 worst particulate attainment counties in the US
- Transportation is a major contributor to both pollutants
- Pennsylvania transportation statistics are approximately 1/3 of California
- Pennsylvania adopted California's vehicle emissions standards in December 2006 to combat these pollutants
- Pennsylvania is rich with indigenous energy resources, which contribute to a lower cost solution for delivered hydrogen throughout the State

Transportation Statistics: Pennsylvania versus California			
Statistic	**Source**	**CA**	**PA**
Gasoline Sales (gal/d)	EIA, 2004	40,645,000	13,111,000
Gasoline Stations	Dept of Census, 2003	8,228	4,356
Population	Dept of Census, 2004	35,893,799	12,406,292
Area (sq. mi.)	Dept of Census, 2000	155,959	44,817
Vehicle Registrations (LDVs)	Federal Highway Administration, 2003	28,600,000	9,259,000
LDV per Capita	Calculated	0.80	0.75

LDV – light duty vehicle



Heaviest concentration of CO_2 in the northeast United States, including Pennsylvania and along the I-95 Corridor

Technical Accomplishments

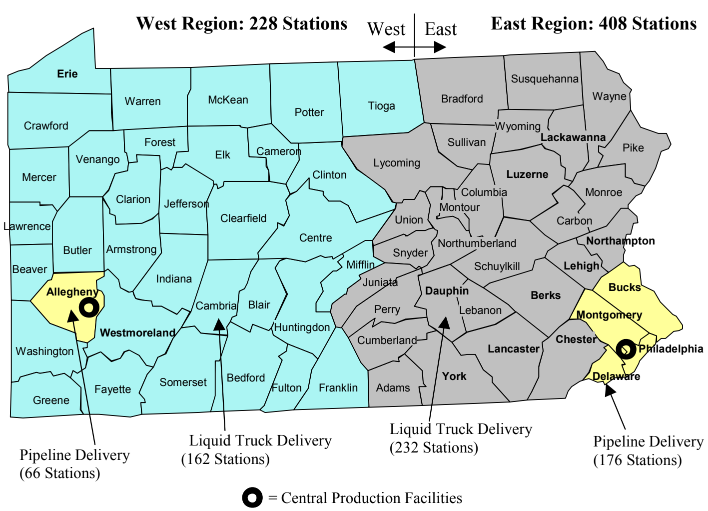
Pennsylvania Case Study - Phase I Results Summary

Approach

- Applied an innovative approach in conjunction with the DOE's H2A model; a combination of regional and county specific data applied to optimize delivered cost
- Pennsylvania coal as a feedstock for hydrogen was a critical aspect of the study. Multiple feedstocks (based on statewide averages), plant sizes, and delivery methods considered
- Determine the lowest delivered hydrogen cost based on life cycle cost analysis

Results

- Coal is the best feedstock to fuel the hydrogen economy in the State at higher demand levels
- Lowest delivered cost for 1% LDV penetration is $4.08/kg using distributed production and natural gas as the feedstock; applicable for entire state. Eliminates the cost of delivery
- Lowest delivered cost for 30% LDV penetration is $3.28/kg using central production, coal gasification, and a combination of pipeline and liquid truck delivery
- Generally, if carbon is sequestered, an increased cost is realized



30% Demand Scenario with Two Central Plants

		1% LDV Penetration		10% LDV Penetration		30% LDV Penetration	
		East	West	East	West	East	West
	Plant Size (kg/day)	74,000	18,000	428,000	224,000	1,283,000	718,000
NO CARBON REGULATION	Lowest Delivered Cost ($/kg)	$4.08	$4.08	$3.64	$4.05	$3.28	$3.48
	Production and Delivery Method	Distributed NG	Distributed NG	Central Station Coal Gasification; Pipeline/Liquid	Central Station Coal Gasification; Pipeline/Liquid	Central Station Coal Gasification; Pipeline/Liquid	Central Station Coal Gasification; Pipeline/Liquid
LOW CARBON	Lowest Delivered Cost ($/kg)	$4.08	$4.08	$3.90	$4.08	$3.54	$3.74
	Production and Delivery Method	Distributed NG	Distributed NG	Central Station Coal Gasification w Seq; Pipeline/Liquid	Distributed NG	Central Station Coal Gasification w Seq; Pipeline/Liquid	Central Station Coal Gasification w Seq; Pipeline/Liquid

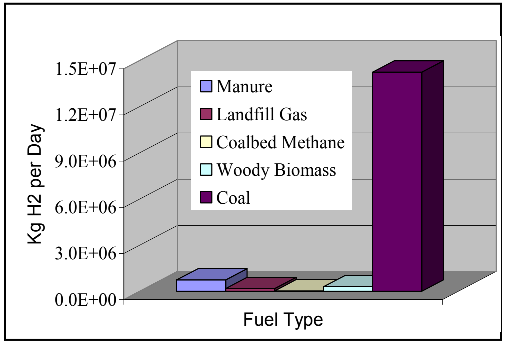
KEY:

(grey) = Central Station Production, Pipeline/Liquid Delivery (Pipeline for Philadelphia and Pittsburgh, Liquid Truck for remaining areas)

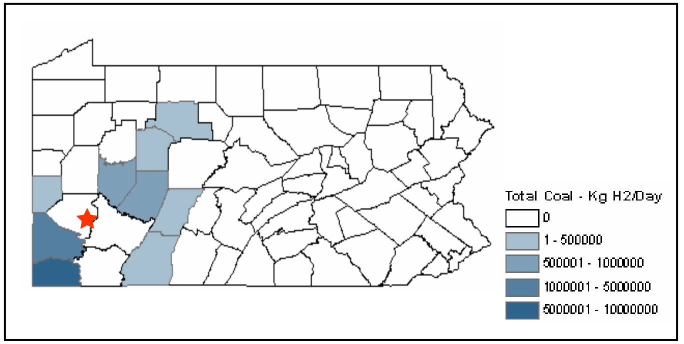
(cyan) = Distributed Natural Gas Production On-Site via Reformation (no Delivery Necessary)

Technical Accomplishments

Pennsylvania Indigenous Energy Options



Pennsylvania Energy Sources and Available Hydrogen



Pennsylvania Abundant Coal Resources in Close Proximity to Regional Central Production Plant

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

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

Approach

- Consider various indigenous energy resources within State boundaries as hydrogen feedstock options to reduce delivered hydrogen cost
- Apply DOE's H2A model using regional pricing in lieu of state average pricing

Results

- Feedstocks considered for Pennsylvania case study included coal, coalbed methane, forestry and wood resources, municipal waste, livestock manure, landfills, wastewater, electricity (renewable and nuclear)
- Bituminous coal is prevalent in western Pennsylvania and could easily provide 100% LDV demand
- Coal could provide 19 times more hydrogen compared to the next resource (manure) considered
- Preliminary results indicate the cost of hydrogen, using coal as a feedstock, has increased from the Phase I results. However, the delivered hydrogen cost is due to an increase in the coal feedstock price.

Technical Accomplishments

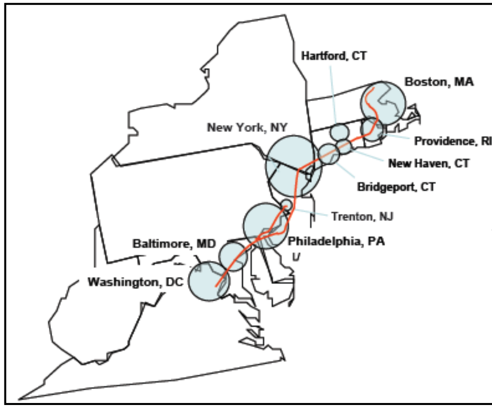
Establishing a Hydrogen Economy along the I-95 Corridor

<u>Approach</u>

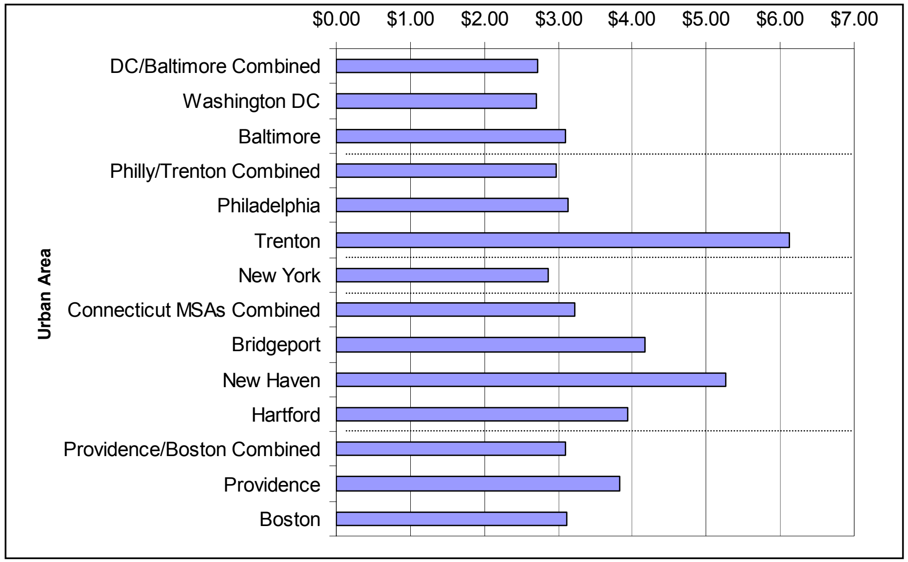
- Apply DOE H2A model leveraging knowledge gained assessing Pennsylvania
- Serve combined urban areas to build hydrogen volume
- Reach out to stakeholders to explore critical steps

<u>Results</u>

- I-95 Corridor worst concentrated carbon dioxide source on east coast and includes many ozone non-attainment areas
- I-95 Corridor contains densely populated areas, 13% of US population in less than 1% of land and 22 million light duty vehicles (15 % of US)
- Includes 1st, 7th, 11th, and 19th largest metropolitan statistical areas (MSA) in US
- Total delivery cost for MSAs along I-95 Corridor are less than $3.00/kg
- Lower delivery costs are realized with increased demand scenarios. Largest MSA approaches $2.25/kg at 30% demand level



The I-95 Corridor Begins with the Washington, DC MSA and leads though the Boston, MA MSA, which encompasses 10,500 square miles



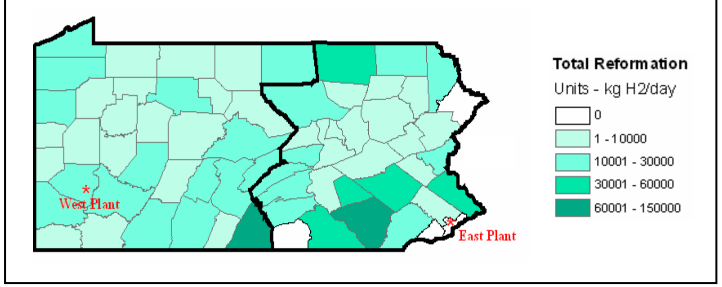
Hydrogen Delivery Cost ($/kg) for 1% Demand

Future Work

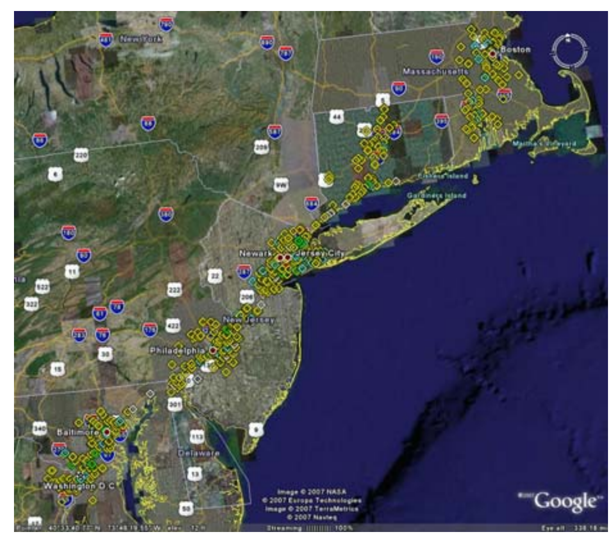
Pennsylvania Indigenous Energy and I-95 Corridor Studies

- Pennsylvania Indigenous Energy Options
  - Continue to investigate Pennsylvania indigenous energy resources. Apply current coal price to pertinent Phase I analyses for a useful comparison with Phase II results
  - Continue scenario evaluations to include optimum production and delivery options for other indigenous resources
  - Meet with stakeholders for their input to possible impacts and their value added review
  - Work with EPRI to assess current industrial hydrogen markets

- Establishing a Hydrogen Economy along the I-95 Corridor
  - Investigate multiple plants closer to demand centers to offer lower delivery cost and investigate potential locations
  - Assess the impact of production economies of scale
  - Evaluate the impact of production volume increases on initial capital investments
  - Establish criteria for when dedicated pipelines replace liquid truck delivery
  - Determine the impact of carbon sequestration on production costs from a coal feedstock
  - Meeting with stakeholders for their input as to how the I-95 Hydrogen Corridor should develop



Pennsylvania Indigenous Energy
Biogas and Coal Bed Methane Resources



Potential I-95 Hydrogen Fueling Station Locations

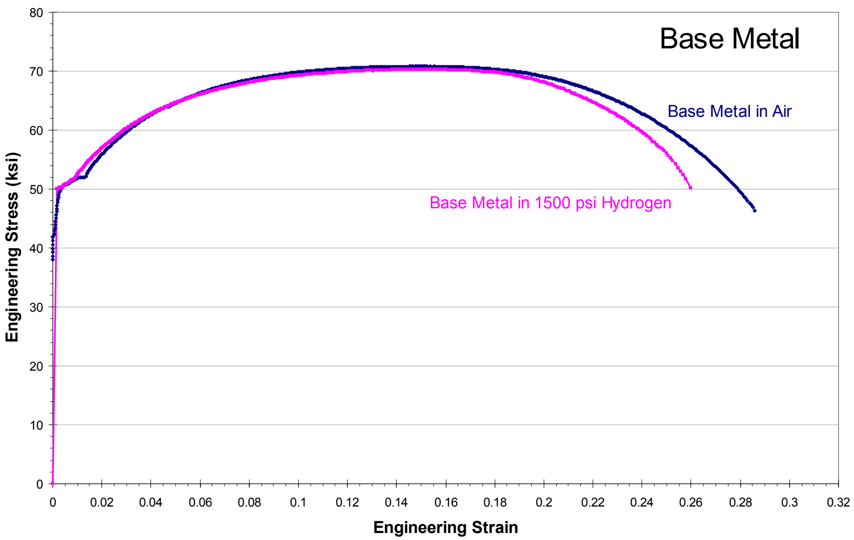
Barriers, Objective and Approach

Steel Pipeline Material

- Barrier Addressed
  - Hydrogen Embrittlement of Pipelines (MYRDDP 3.2.4.2 D)
- Subtask Objective
  - Aid characterization of pipeline material performance in H_2 by:
    - Conducting mechanical testing of pipeline materials in 1,500 psi H_2
    - Ensure that critical data requirements are being met while minimizing duplication of effort
- Approach
  - Participate in DOE Pipeline Working Group and interface with American Society of Mechanical Engineers (ASME) to assess data and test needs, test methods and quality control, and documentation needs
  - Facilitate and coordinate mechanical testing in hydrogen with Savannah River National Laboratory (SRNL)
  - Distribute generated test data to H_2 community

Technical Accomplishments

Steel Pipeline Material

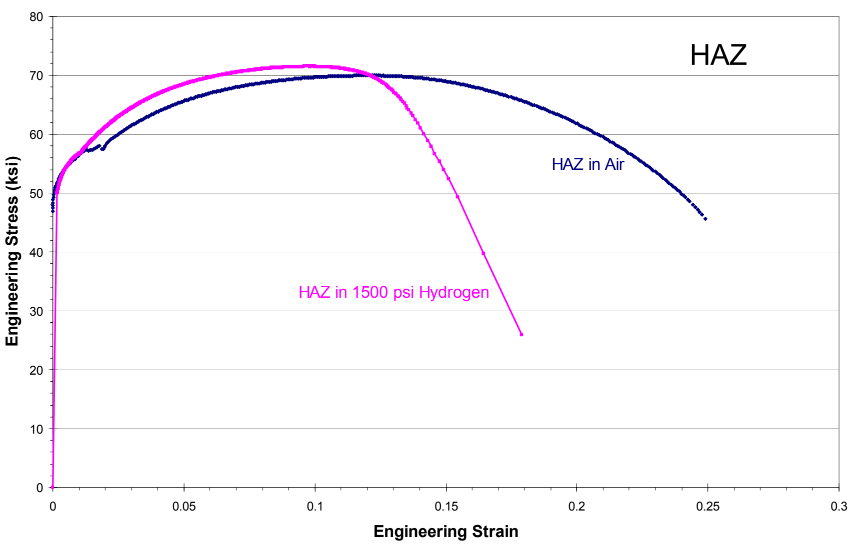


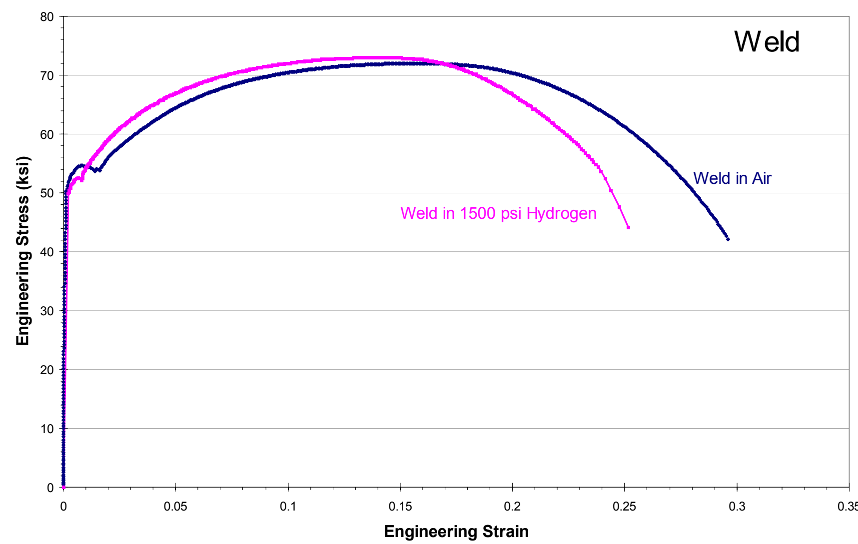
Tensile Test Conditions

- ASTM A-106 Grade B Carbon Steel
- Base Metal, Weld and Heat Affected Zone (HAZ)
- Crack 90 degrees to rolling direction (L-C orientation)
- Atmosphere: 100 ATM (H_2), 1 ATM (Air)
- Strain Rate: 10-4 /sec

Results

- Confirmed HAZ and weld metal demonstrate largest effect in the presence of H_2
- Confirmed HAZ as potential region of concern
- Demonstrated need to conduct fracture testing
- Accumulated tensile data for ferritic pipeline steel

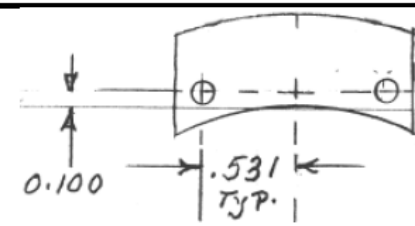
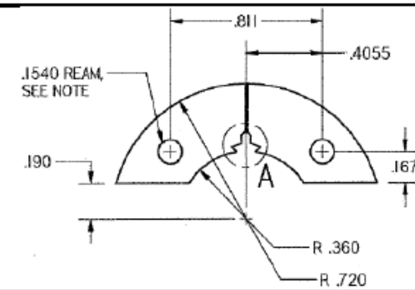




Ongoing and Future Work

Steel Pipeline Material

- Collaborating with SRNL to conduct mechanical testing (threshold stress intensity and fracture toughness) in 1,500 psi H_2
- Coordinating with ASME and DOE Pipeline Working Group (Testing Standards & Sample Standardization Working Team) to pursue other high-priority data capture
- Organizing workshop with ASME to create a prioritized material test matrix to facilitate code and standard development

Specimen Geometry	Specimen Location	Number of Tests	Environment
Threshold stress intensity testing			
	Base	2	Air
	Base	2	H_2
	HAZ	2	H_2
Note: Specimen will contain notch to be pin loaded	Weld	2	H_2
Fracture toughness testing			
	Base	3	Air
	HAZ	3	Air
	Weld	3	Air
	Base	3	H_2
	HAZ	3	H_2
	Weld	3	H_2
All specimens C-R orientation, extracted from ASTM A-106 (Grade B) 4″ O.D., 0.5″-thick pipe			

Barriers, Objective and Approach

Composite Overwrapped Pressure Vessels

- Barriers Addressed
  - Gaseous Hydrogen Storage Costs (MYRDDP 3.2.4.2 F)
  - Storage Tank Materials and Costs (MYRDDP 3.2.4.2 G)
- Subtask Objective
  - Advance gaseous hydrogen storage by:
    - Selecting appropriate constituent materials and improving Composite Overwrapped Pressure Vessels (COPV) design and fabrication to simultaneously target DOE cost and volumetric efficiency goals[1] for off-board gaseous hydrogen storage
    - Monitor progress of U.S. COPV standards development and support data acquisition through mechanical testing of relevant composite materials
- Approach
  - Team with HyPerComp Engineering, Inc. (HEI) to model, design, construct and test COPVs
  - Interface with American Society of Mechanical Engineers (ASME) to support and benefit from evolving COPV standards activity

[1] See “Ongoing and Future Work” slide for specific goals

Technical Accomplishments

Composite Overwrapped Pressure Vessels

- Fabricated, burst tested and fatigue tested twelve Type III COPVs
  - 7.75 liter water volume aluminum liner; 10,000 psi design pressure
  - Hoop and helical wrapped with carbon fiber
  - Designed to fail in sidewall
- Weight efficiency primary target – based on DOE goals at start of project[2]
  - 5.2% weight efficiency achieved with non-optimized design
  - 0.035 kg of hydrogen per liter of storage volume
  - Tank cost $4,700/kg of stored hydrogen (note that cost reduction is primary focus of ongoing work)

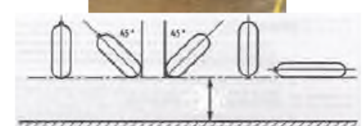
Burst Testing

COPV #	Burst Pressure (psi)
03280604	25,880
03080601	25,770
03220602	25,001
03270601	25,020
03280603	25,496
Avg. Burst Pressure	25,433
Standard Deviation	410.65
Coefficient of Variation	1.61%

Cyclic Fatigue Testing

COPV #	Cycles Achieved
03230601	3,161
03240601	3,466
03270602	3,047
Avg. Cycles Achieved	3,225
Standard Deviation	216.63
Coefficient of Variation	6.72%

Post Drop Cyclic Fatigue Testing



COPV #	Cycles Achieved after Drop
03270603	2,760
03280601	2,436
03280605	2,921
03290602	2,184
Avg. Cycles Achieved	2,575
Standard Deviation	329.72
Coefficient of Variation	12.80%

[2] DOE Multi-Year Research, Development and Demonstration Plan—Hydrogen Delivery (Revision 1, 2005; Table 3.2.2)

Ongoing and Future Work

Composite Overwrapped Pressure Vessels

- Focus on revised DOE goals for off-board gaseous hydrogen storage[3]
  - Construction and testing of improved COPVs
- Exploration of COPV serviceability modeling
  - To include mechanical testing of COPV constituent materials as input to component lifetime prediction

Off-Board Gaseous Hydrogen Storage Tanks (for forecourts, terminals, or other off-board storage needs)			
Category	2005 Status	FY2010	FY2015
Storage Tank Purchased Capital Cost ($/kg of H2 stored)*	$820	$500	$300
Volumetric Capacity (kg H2 /liter of storage volume)**	0.023	0.030	>0.035

* Storage Tank Capital Cost: These costs are based on the H2A Components Model V1.1. The model uses a current cost of $820 per kg of hydrogen stored for a 1,500 kg/day Forecourt station. This is based on quotes from vendors for steel tanks capable of 6,250 psi working pressure. The 2015 target cost is set to achieve the overall delivery cost objectives.

** Forecourt Storage Volumetric Capacity: The 2005 value is based on the specific volume of hydrogen at room temperature and 6,250 psi. The 2015 target is based on the specific volume of hydrogen at room temperature and approximately 12,000 psi. Off-board storage tank technology could use carriers as opposed to or in addition to compressed hydrogen as a means to store hydrogen. The most important target is system capital cost. However, the footprint for the storage must also be taken into consideration where space is limited such as at forecourts. For this reason, it is assumed that the hydrogen volumetric content of the storage volume should be at least as high as for 10,000 psi hydrogen gas.

[3] DOE Multi-Year Research, Development and Demonstration Plan—Hydrogen Delivery (Revision February 6, 2007; Table 3.2.2)

Barriers, Objectives and Approach

Separations and Sensors

SEPARATIONS

Subtask Objective

- Create a low cost Rapid Pressure Swing Adsorption (RPSA) system with the capability of achieving 99.995% purity hydrogen, which is required for the hydrogen economy
  - Range of Production:
    - 10 to 300 (normal cubic meters) Nm^3/hour at purity, 150 psig pressure
    - Focus on 50 – 100 Nm^3/hour (75 as basis)
  - Low capital, compact system
  - 99.995% hydrogen purity

Approach

- Conduct patent and technical literature search
- Structured adsorbent vendor search
- Demonstrate applicability of modeling software for packed bed RPSA
- Refurbish/start-up experimental RPSA Test Unit
- Contact select adsorbent vendors and conduct material evaluations
- Determine availability and suitability of RPSA components and investigate process packaging concepts

SENSORS

Subtask Objective

- Advance current hydrogen-specific sensors and sensor technologies to ensure reliable operation and performance in hydrogen applications

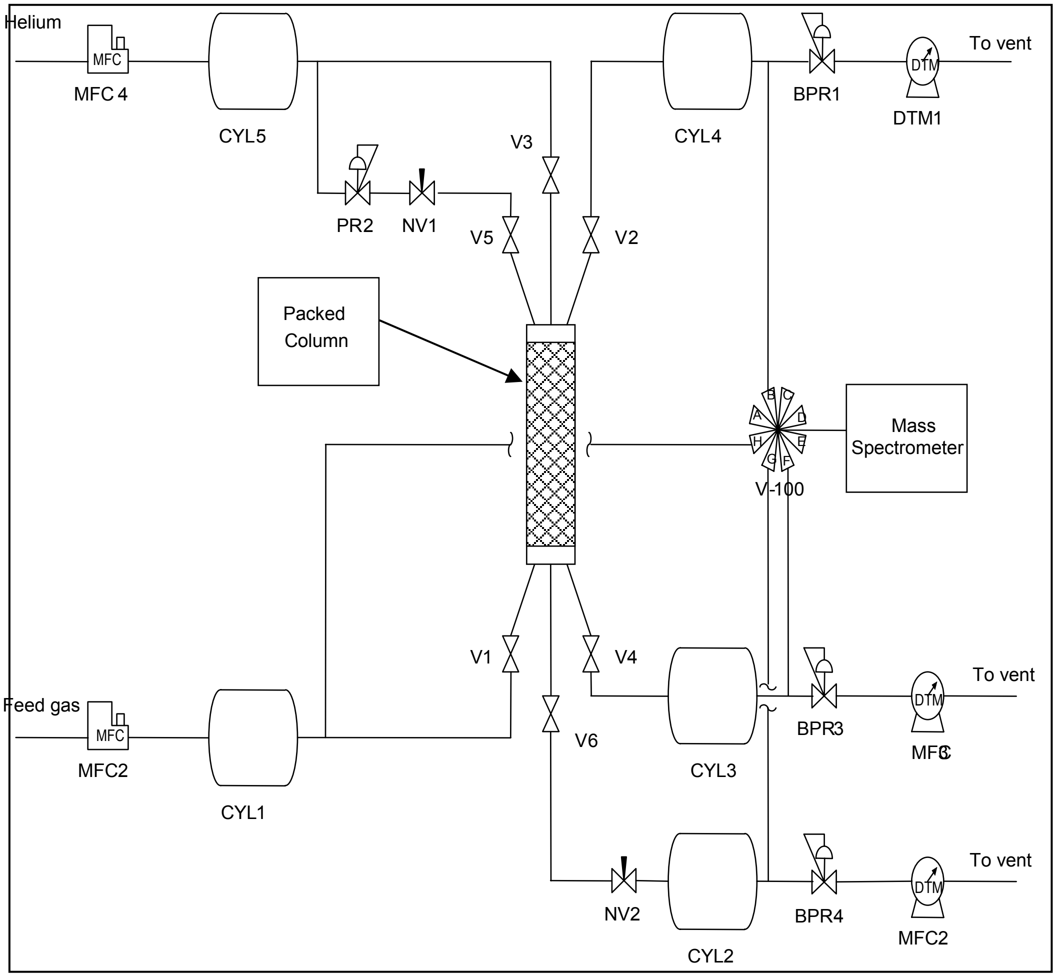
Approach

- Assess current commercial and pre-commercial hydrogen sensor technologies
- Down select sensor technologies that meet defined performance requirements
- Test selected sensors according to defined protocols with custom designed test process/setup
  - Evaluate hydrogen sensor performance in air, nitrogen, and natural gas environments
  - Study the affects of contaminants, temperature, and humidity
- Control or eliminate the effects contaminants have on hydrogen-specific sensors to extend their useable life
- Communicate results with sensor manufacturers so modifications can be implemented
- Help expedite commercialization of reliable H_2 sensors

Barriers	**Separations**	• Lack of Hydrogen/Carrier and Infrastructure Options Analysis (3.2.4.2 A) • High Capital Cost and Hydrogen Embrittlement of Pipelines (3.2.4.2 D)
	Sensors	• High Capital Cost and Hydrogen Embrittlement of Pipelines (3.2.4.2 D) • Hydrogen Leakage and Sensors (3.2.4.2 I)

Technical Accomplishments

RPSA Test Unit



*Where MFC = Mass Flow Controller; CYL = Cylinder; PR = Pressure Valve; NV = Needle Valve

RPSA Final Design:

- PLC-controlled
- No adsorbent hold-down units used
- Mass Spectrometer used to analyze feed and effluent compositions
- Assembly of the unit has been completed and adsorbent testing is now underway

Test Conditions for Adsorbent Evaluations:

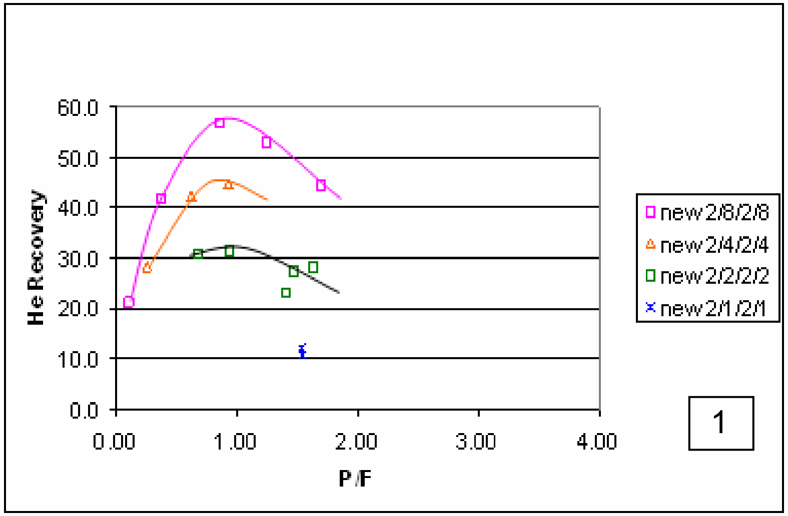
- Helium (He) used in place of Hydrogen during evaluations due to cost and safety reasons
- Process Steps:
  1)Feed gas 2)De-pressurize 3)Purge 4)Pressurize
- Pressure: 100 psig
- Temperature: Ambient
- Feed time range: 1-20 seconds
- Bed thickness range: 0.6 – 1.7mm
- Feed Gas Composition: 20% CO_2/He
- Purge/Feed Flow Ratio (P/F) Range: 0.25 – 2.50

Adsorbent Performance Ranked by Evaluating:

- The percent He recovery using several binary feed gases:
  - He + Carbon Dioxide (CO_2)
  - He + Nitrogen (N_2)
  - He + Carbon Monoxide (CO)
- Bed Size Factor (BSF) productivity – which is the ratio of the column volume to the He produced per hour

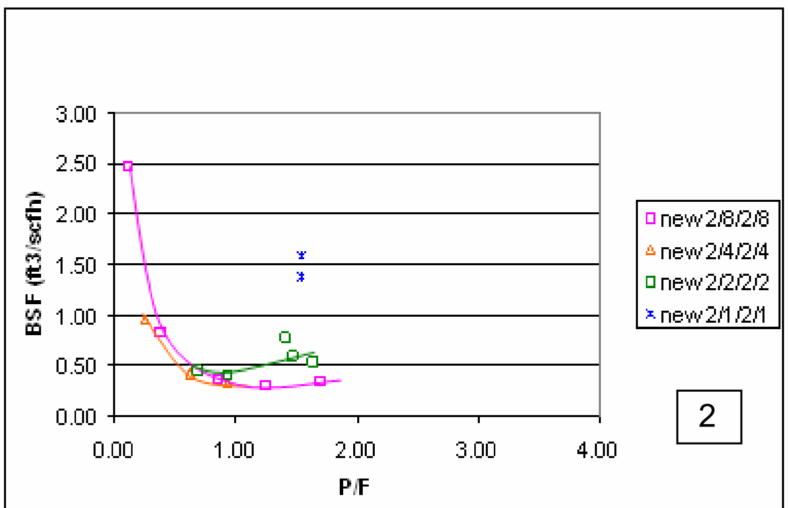
Technical Accomplishments

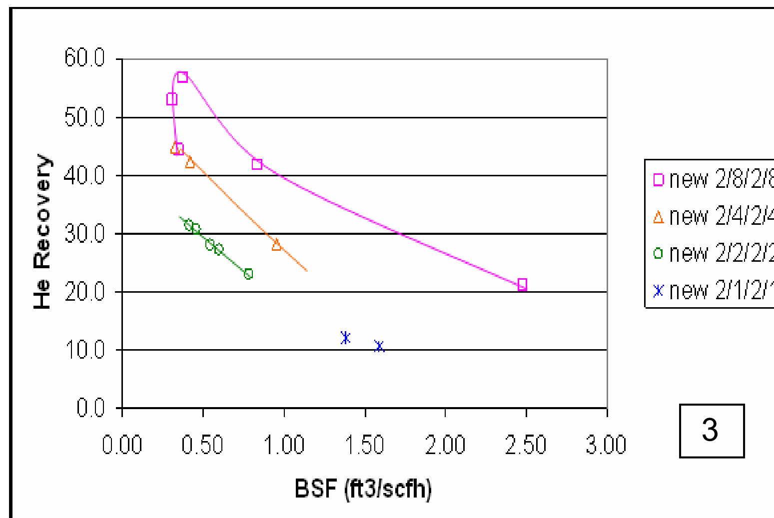
1st Adsorbent Evaluation (Gen2 Adsorbent)



Results:

- The optimal P/F ratio for this adsorbent is 1.0 based on the He recovery and BSF results
- Lower cycle times do not appear to affect the BSF; however, the He recovery is reduced when cycle times are dropped
- Fig. 3 shows that recovery can be maximized at a specific BSF value
- Goal of development work is to find adsorbent materials that yield data in the upper left hand corner of the plot in Fig. 3





Technical Accomplishments

Selected Sensor Testing

Sensor Reliability Test Protocols

Performance Testing
- Hydrogen concentration correlations – random sequence
- Statistics (R^2 of linearity, standard deviation)
- Hysteresis testing
- Repeatability
- Humidity and temperature effects

Durability Testing
- Operate sensors in a natural gas environment for extended times and record effects

Interference Testing
- Test the effects of natural gas components (i.e. CH_4, H_2S, H_2O)
- Test the effects of ambient air contaminants (i.e. CO, CO_2, motor fumes, field air)
- Hysteresis testing (repeated exposure to interferent, ex: H_2S)

Reliability Test Results

- Three sensors were selected for reliability testing: sensors A, B, and C
- Sensor B was eliminated from the test exercise due to humidity affects and initially low hydrogen measurements when the hydrogen levels were suddenly increased
- Performance testing showed that sensors technologies A and C gave good responses when compared to the manufacturers' claims and described data
- Although the interference testing showed some encouraging results, H_2S has been shown by other investigators to cause degradation of palladium-based sensors at high concentrations
- After completion of the sensor reliability testing, the manufacturers of sensors A and C were consulted to modify both sensors as follows in an attempt to reduce palladium degradation due to H_2S composition:
  - Sensor A (palladium capacitor) – additional coating added to reduce degradation
  - Sensor C (palladium field effect transistor) – designed-in degradation resistance
- Testing was then conducted on the modified sensors using 100 PPMv H_2S in N_2 for extended times and at increased pressures to determine the resistance to the degradation

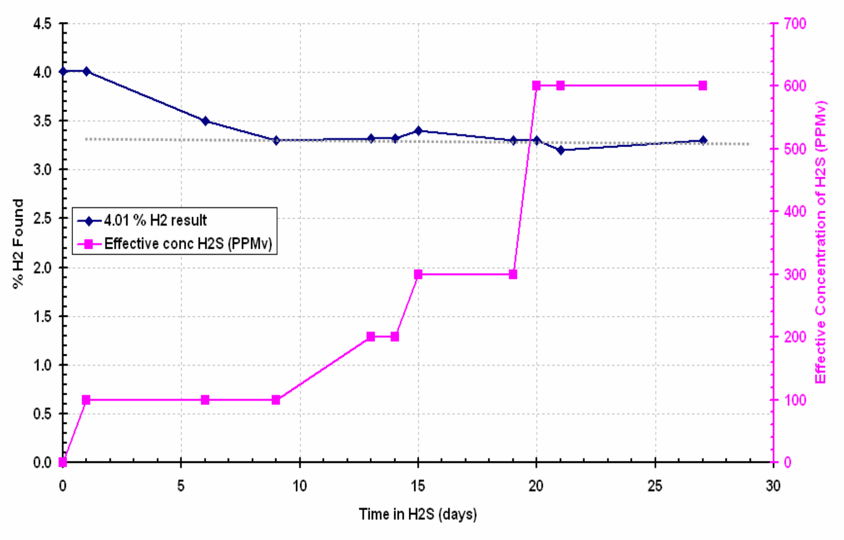
Technical Accomplishments

Modified Sensor Test Results

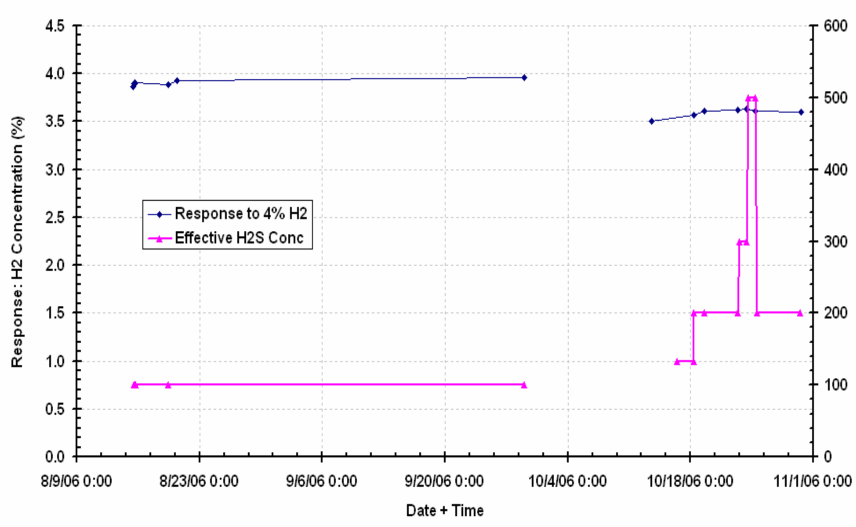
Test Results

- Testing showed that the modifications to both sensors A and C do prevent degradation of palladium by H_2S (the most aggressive sulfur contaminant in natural gas)
- Sensor C is an order of magnitude faster in response time than coated Sensor A
- Sensor A saw a drop in the H_2 result from 4% down to 3.3% - This is attributed to an electronic problem with this specific prototype sensor, which the manufacturer has corrected in a second generation; the fault was not due to the palladium sensor but to another electronic component which degraded with time in all of the prototypes used

Modified Sensor Testing Results



Modified Sensor Test Results Sensor A



Modified Sensor Test Results Sensor C

Future Work

Separations and Sensors

SEPARATIONS

- Continue limit of technology study on beaded and structured adsorbents
- Determine availability and suitability of RPSA components
- Develop and characterize structured adsorbent material and optimize adsorbent properties
- Develop methodology to package the adsorbent to ensure good gas-adsorbent contacting, to eliminate any channeling of the gas, and to minimize the pressure drop
- Optimize new process through modeling and experimental work
- Create guidelines for scaling up the device to higher flow rates will created
- Develop preliminary design for a 5 Nm^3/hour device

SENSORS

- Identify existing and emerging technologies from universities and national laboratories that could potentially mitigate the effects of contamination on H_2 sensor technologies
- Develop prototype units for laboratory and field testing. As time allows, modifications will be made to the prototype designs based on the initial test results and additional testing completed
- Design and construct an intrinsically safe package to contain a safety hydrogen leak monitoring sensor system
- Establish an intrinsically safe guideline and with independent testing facilities define safety performance criteria
- Determine methodology required for bi-directional (wired/wireless) communications in hydrogen production, transport, and storage environments