HYDROGEN REGIONAL INFRASTRUCTURE PROGRAM IN PENNSYLVANIA

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2006 DOE Hydrogen Program Review

May 16, 2006

PDP17

Overview

Timeline

- Award notification
  - September 1, 2004
- Contract start date
  - November 23, 2004
- Contract end date
  - March 31, 2007
  - POP extension requested
- 30% completed

Barriers

- Lack of H_2 carrier infrastructure options analysis
- High capital cost and H_2 embrittlement in pipe
- Need for high capacity/low weight and lower cost storage tanks
- H_2 leakage and need for reliable sensors

Budget

- Total project funding
  - DOE: $4,927K
  - Contractor: $1,235K
- FY04 funding $2,943K
- FY05 funding $1,984K

Partners

- Resource Dynamics Corporation
- Air Products and Chemicals Inc.
- Hypercomp Engineering
- Savannah River National Laboratory

Pennsylvania Hydrogen Delivery Tradeoff Study Objectives, Assumptions, and Key Options

Objectives

- Quantify tradeoffs between alternative hydrogen (H_2) production and delivery approaches
- Assess commercial and near commercial options
- Determine most economic delivery scenarios for Pennsylvania based on DOE's 2015 target of $2 – 3.00/gge of H_2

Assumptions

- H_2 delivery scenarios identified at 1, 10, and 30 percent of light duty vehicle (LDV) miles
- Lowest delivered H_2 cost based on life cycle cost analysis, capital charge 15% per yr, fixed operating 5%, variable cost 1%, and 80 month amortized equivalent life
- Lowest infrastructure investment

Key Tradeoff Options

- Feedstocks
  - Electrolysis of water
  - Reformation of natural gas, gasoline, or methanol
  - Gasification of coal or biomass
- Plant size
  - Distributed
  - Regional central station
- Delivery
  - Liquid or compressed gas truck
  - H_2 pipeline
  - Co-transport in natural gas pipelines
  - Distributed production

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Pennsylvania Hydrogen Delivery Tradeoff Study

Delivered Hydrogen Cost for 10% Demand Scenario

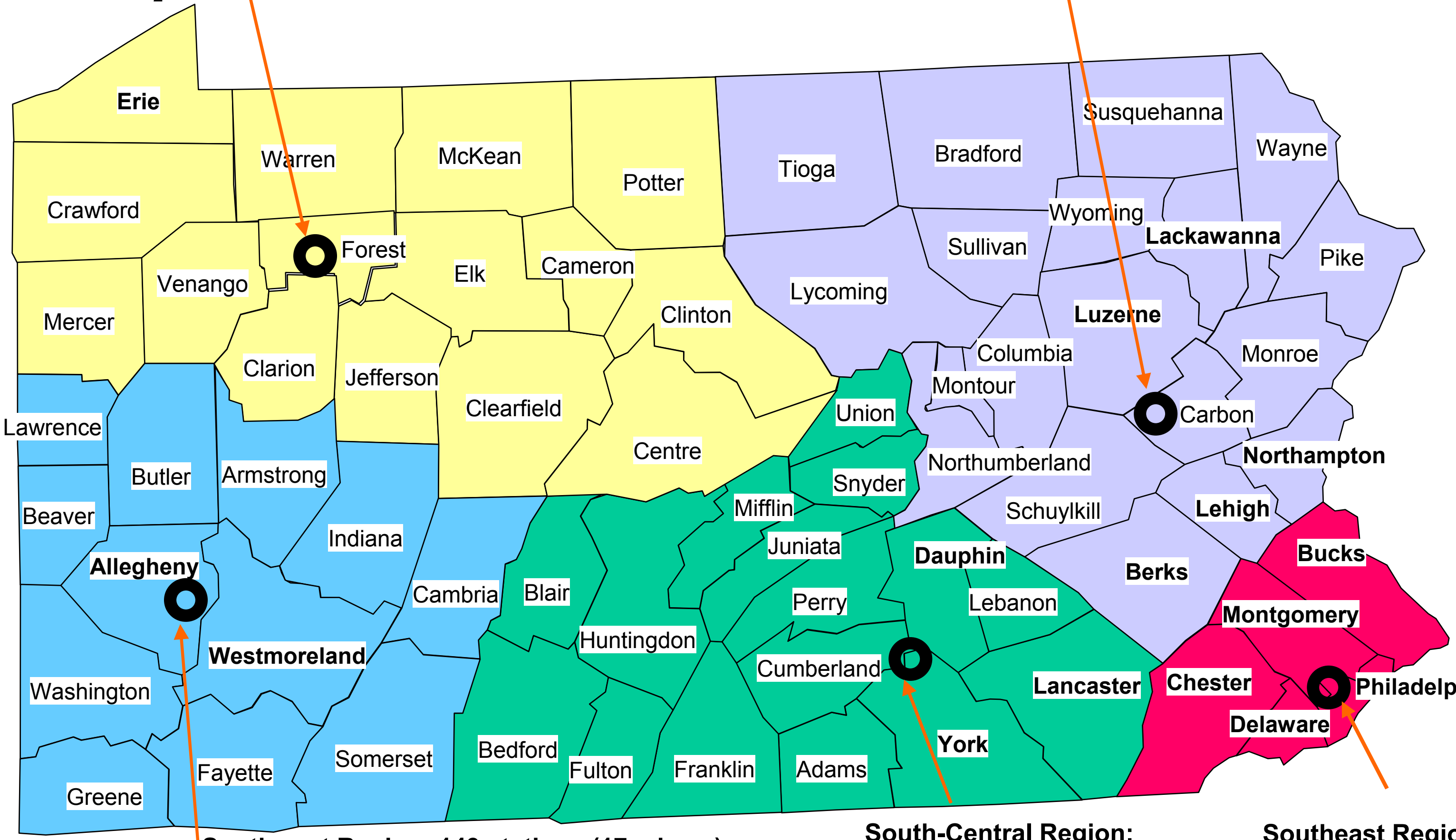
(U.S. dollars per kg)

Number of Central Station Plants	**2 Locations (3 plants)**			**5 Locations**						
Size (1000 kg/day)	224	374/2	Weighted	56	131	120	97	196	Weighted	Weighted
Distance (Miles)	49	39	Average	56	17	33	29	9	Average	"Best"
Electricity										
Electrolysis/Pipeline	6.14	6.16	6.15	12.46	5.80	6.87	7.17	4.99	6.59	**3.50**
Electrolysis/Cryogenic Liquid Truck	5.60	5.70	5.66	6.61	5.91	5.99	6.14	5.64	5.91	
Electrolysis/HP Tube Trailer	6.09	6.02	6.04	7.08	5.84	6.17	6.24	5.47	5.91	
Electrolysis/Distributed	9.79	9.79	9.79	9.79	9.79	9.79	9.79	9.79	9.79	
Natural Gas										
Steam Reformation/Pipeline	4.10	4.05	4.07	9.72	3.52	4.55	4.73	2.90	4.13	
Steam Reformation/Cryogenic Liquid Truck	4.01	4.04	4.03	**4.35**	4.09	4.13	4.18	3.99	4.09	
Steam Reformation/HP Tube Trailer	4.19	4.04	4.09	4.50	3.70	**3.99**	**3.95**	3.51	**3.78**	
Steam Reformation/Distributed	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	4.81	
Biomass										
Gasification/Pipeline	4.38	4.35	4.36	10.31	3.90	4.95	5.18	3.19	4.50	
Gasification/Cryogenic Liquid Truck	4.31	4.37	4.35	4.97	4.50	4.56	4.65	4.31	4.50	
Gasification/HP Tube Trailer	4.54	4.43	4.47	5.19	4.17	4.48	4.49	3.89	4.24	
Coal										
Gasification/Pipeline	**3.94**	**3.91**	**3.93**	9.82	**3.45**	4.49	4.72	**2.76**	**4.05**	
Gasification/Cryogenic Liquid Truck	4.05	4.12	4.09	4.71	4.24	4.30	4.40	4.06	4.24	
Gasification/HP Tube Trailer	4.17	4.05	4.10	4.78	3.79	4.10	4.10	3.52	3.86	
Gasoline										
Reformation/Distributed	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60	4.60	
Methanol										
Reformation/Distributed	5.38	5.38	5.38	5.38	5.38	5.38	5.38	5.38	5.38	

Pennsylvania Hydrogen Delivery Tradeoff Study
10% Demand Scenario Result
Proposed Central Plant Locations

Northwest Region: 53 stations (56 mi avg) =
39 county + 12 highway
~56,000 kg H_2 / day

Northeast Region: 114 stations (33 mi avg) =
100 county + 14 highway
~120,000 kg H_2 / day



Southwest Region: 143 stations (17 mi avg) =
128 county + 15 highway
~150,000 kg H_2 / day

South-Central Region:
92 stations (29 mi avg) =
79 county + 13 highway
~97,000 kg H_2 / day

Southeast Region:
257 stations (9 mi avg) =
249 county + 8 highway
~270,000 kg H_2 / day

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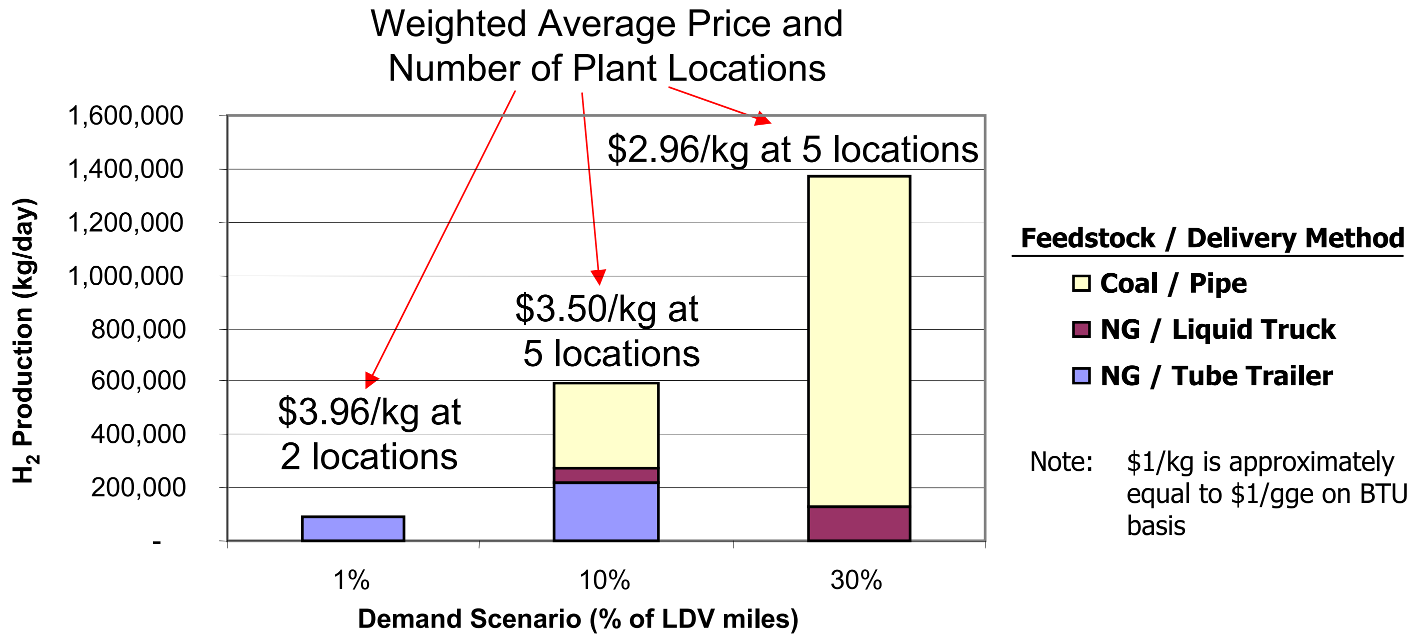
Pennsylvania Hydrogen Delivery Tradeoff Study Preliminary Results



Note: $1/kg is approximately equal to $1/gge on BTU basis

- Distance is very important due to cost of delivering H_2
  - Multiple plants closer to demand centers offer lower delivered price
  - Production economies of scale are less significant
- Long term cost reduction from feedstock cost and delivery infrastructure leads to long term cost reduction
  - As production demand increases, delivery scenarios using coal are cost competitive once the capital cost has been exceeded
  - As distribution increases, dedicated pipelines offer the lowest cost

Separation Technology Evaluation Objective, Requirement and Technologies

Objective Evaluate separation technologies for H_2 / NG co-transportation scenarios

Screening Requirements

- 1000 kg/d high purity H_2
  - 99.995% H_2
  - < 1 ppm CO, CO_2, CH_4
  - < 0.2 ppm sulfur
- Low cost
- Capable of handling odorants, heavy hydrocarbons
- Reject waste gas back to natural gas pipeline

Technologies Evaluated

- Cryogenic partial condensation
- Inorganic membranes
  - Zeolite, ceramic, carbon
  - Pd alloy membranes
- Organic membranes
  - Single pass or modules in series
- Adsorption/Absorption
  - Physical absorption
  - TSA, VSA, PSA
  - Metal hydrides
- Hybrid processes
  - Organic membrane + PSA
  - Inorganic membrane + TSA/PSA

Estimated process performance and separation cost to rank technologies for transmission pipeline scenario (feed gas 20% H_2 at 600 psig)

Red indicates technologies that passed initial screening requirements

Assumed feed gas composition (vol%) for technology evaluation

hydrogen	20
methane	75.92
ethane	2.00
propane	0.16
i-butane	0.024
n-butane	0.024
i-pentane	0.0080
n-pentane	0.0080
n-hexane	0.0080
nitrogen	1.28
carbon dioxide	0.56
oxygen	0.0080

Source: Union Gas Web Site

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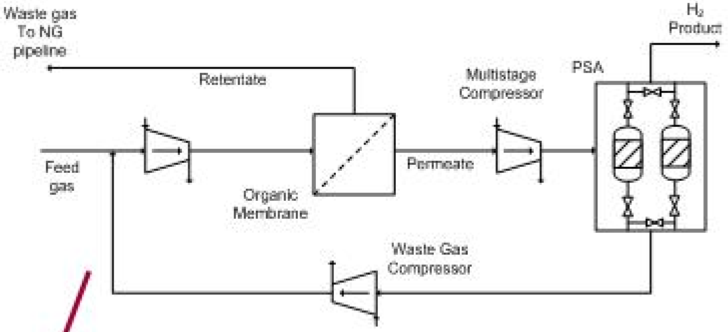
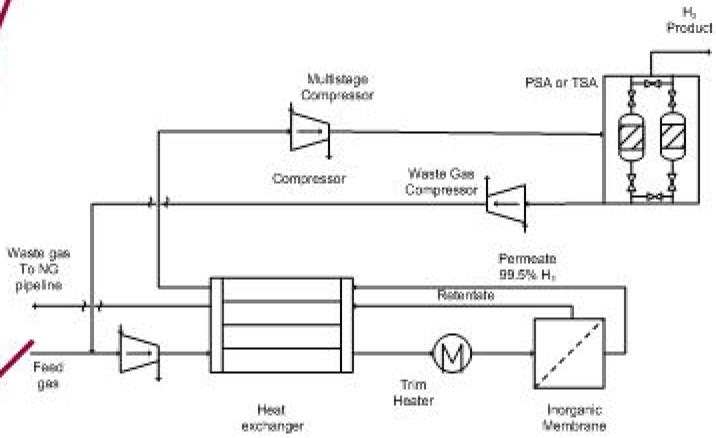
Separation Technology Evaluation
Relative Economics

Economic Assumptions

- Capital costs for major equipment from in-house evaluations or standard correlations (Ulrich, 1984)
- Capital charge 15% per yr, fixed operating 5%, variable cost 1%, 80 month life
- Electricity @ $0.06/kWh

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





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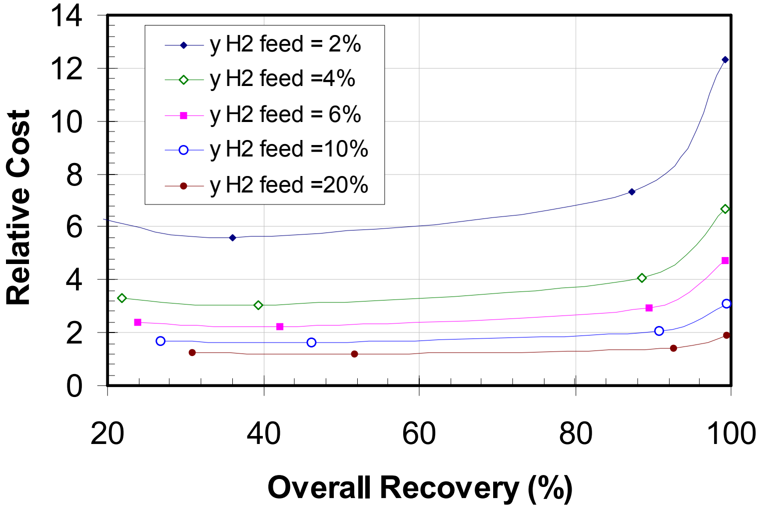
Hybrid membrane/adsorption processes appear to be the best economic choice

Separation Technology Evaluation Conclusions

- Separation of dilute H_2 from natural gas is feasible by cryogenic partial condensation, metallic membranes, hybrid membrane/adsorption, and (perhaps) metal hydride processes.
- Based on current information, the hybrid processes have the best economics
  - Organic membrane + PSA
  - Inorganic membrane + TSA/PSA
  - Membrane performs rough rejection of NG, adsorption unit provides final purification
- Separation cost increases dramatically for low feed gas pressure or low H_2 content. This, combined with high H_2 losses, makes using co-transport with separation economically infeasible for low pressure distribution pipeline systems.



Advanced Materials Objectives and Goals

***CTC* Objective**	***CTC* Approach**	**Targets**
Develop modeling tools that predict the life of H_2 containing pipelines and components	Utilize Weibull analysis (static and cyclic statistical crack growth analysis) and finite element analysis (FEA) to: • Understand the effects of H_2 embrittlement in legacy pipelines • Predict life expectancy and probability of failure	2010 total pipelines capital cost Transmission: $1 M/mile Distribution: $0.25 M/mile
Perform material testing	Review material test literature Develop a mechanical properties database of representative pipeline materials utilizing codes and standards from the American Society of Mechanical Engineers (ASME) and others	Maintain integrity of the pipeline relative to potential H_2 embrittlement or other issues causing cracks or failures
Develop and test a Type III composite overwrapped pressure vessel (COPV) for H_2 storage	Work with industry to obtain material test data from prototype tanks	Carriers H_2 content (% by Wt.) 2010 – 6.6 % 2015 – 13.2% Costs less than $300/kg

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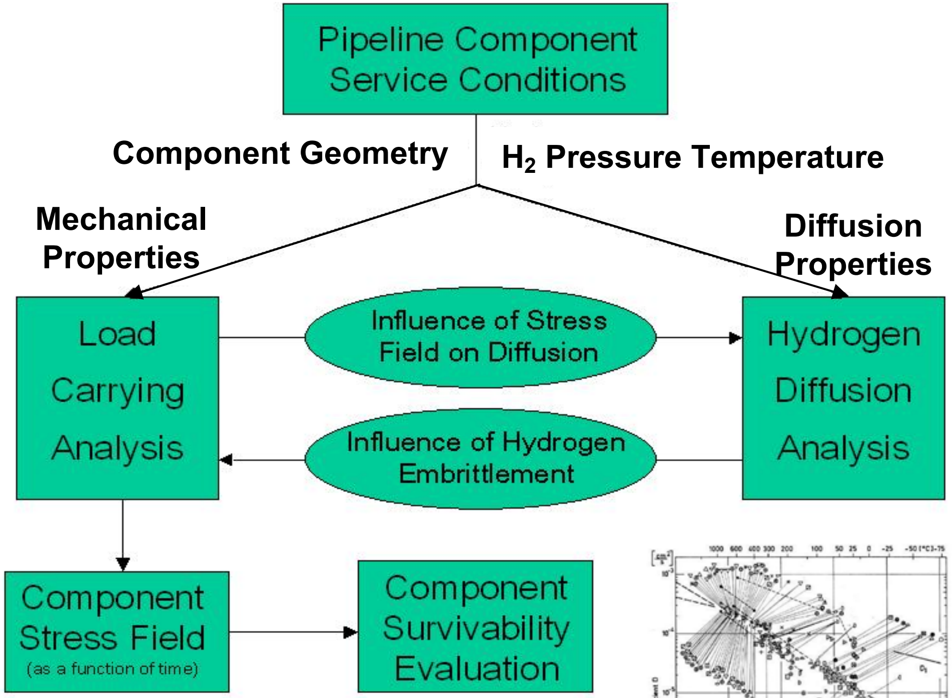
Advanced Materials
Analysis of Material Performance
(using Finite Element Analysis)



Pipeline Component Service Conditions

Component Geometry

H_2 Pressure Temperature

Mechanical Properties

Diffusion Properties

Load Carrying Analysis

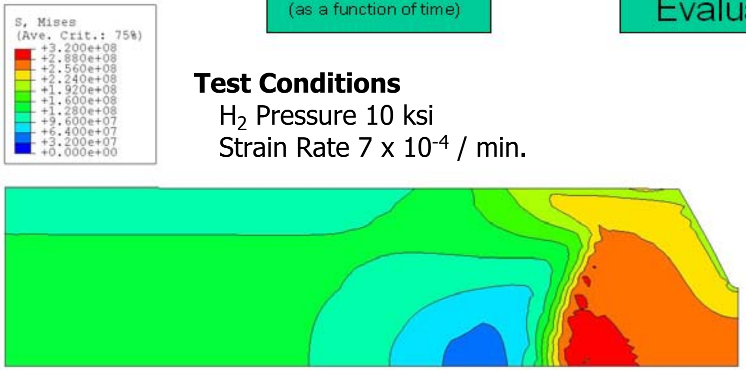
Influence of Stress Field on Diffusion

Hydrogen Diffusion Analysis

Influence of Hydrogen Embrittlement

Component Stress Field (as a function of time)

Component Survivability Evaluation

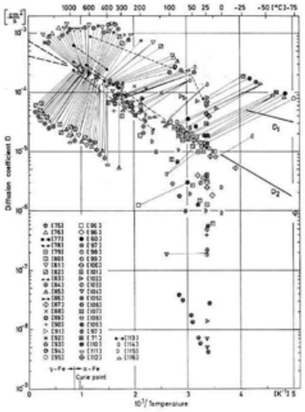


Test Conditions

H_2 Pressure 10 ksi

Strain Rate 7 x 10^{-4} / min.

FEA shows highest von Mises stress away from notched tensile specimen (quarter model), which implies material degradation from H_2 at the specimen surface



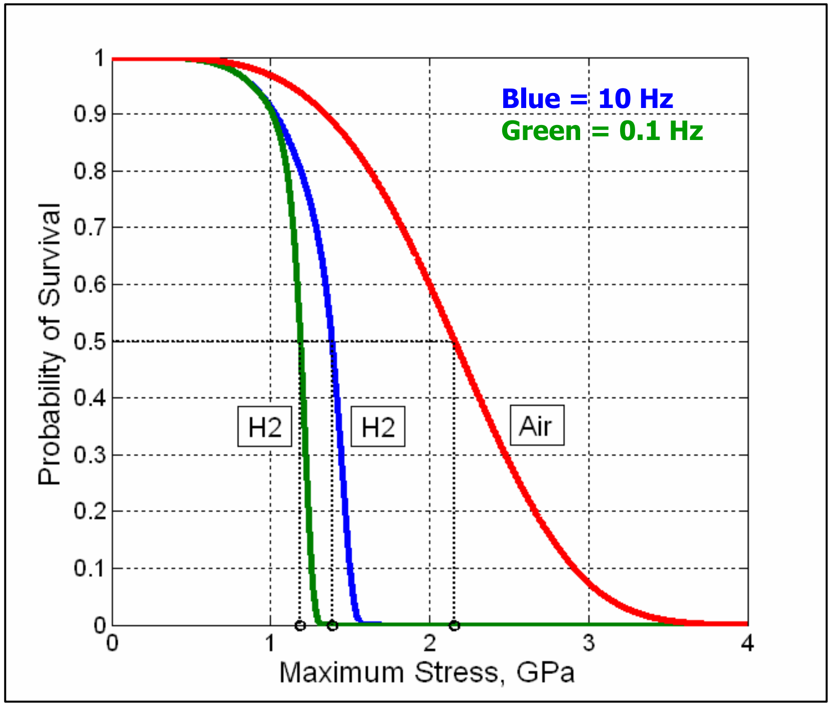
Z. Feng, L.M. Anovitz, J.G. Blencoe, and P.S. Korinko, “Hydrogen Permeability and Integrity of Hydrogen Delivery Pipelines,” 2005

Advanced Materials
Material Life Prediction

(using Modified Weibull Analysis)

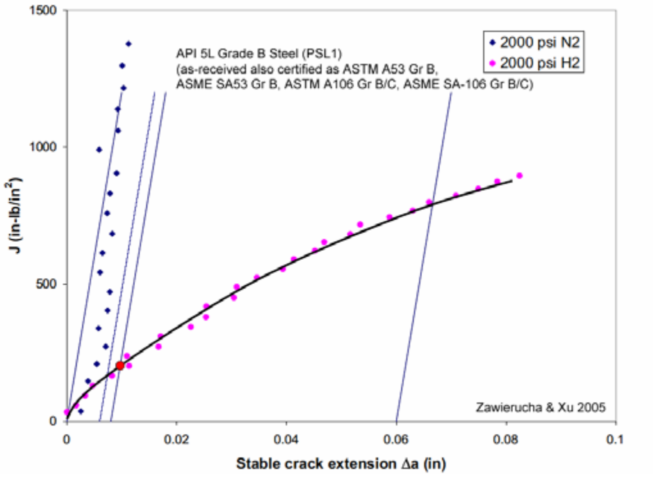
$$P_S = \exp\left[-\left(\frac{V}{V_0}\right)\left(\frac{t}{t_0}\right)^m\left\{\left(F_1(R)\frac{\sigma_{\max}}{\sigma_1}\right)^B + \left(\frac{f}{f_0}\right)^m\left(F_2(R)\frac{\sigma_{\max}}{\sigma_2}\right)^D\right\}\right]$$

(static term) (cyclic term)

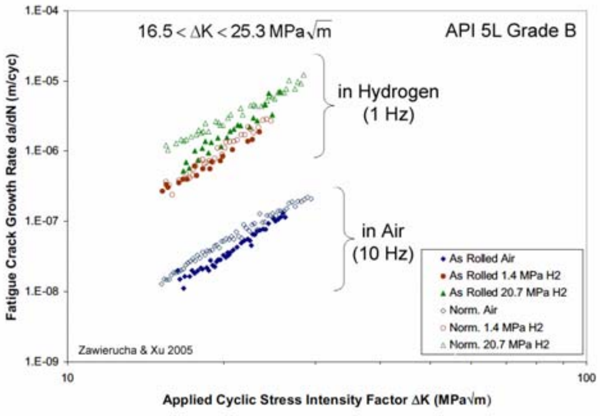


- Use will dictate required probability of survival (P_s). Could be 0.5, 0.99, etc
- Volume, number of cycles, and stress ratio (R) are fixed. Each curve is P_s vs. maximum stress, for a given environment (air or H_2) and loading frequency
- In air, the static term goes to zero (by setting sigma1 = large number); therefore dependence is not on time, but on load cycles (t x f = N)
- In H_2, lower frequency = longer time; therefore lower P_s for a given maximum stress
- For a given maximum stress, P_s is higher in air than in H_2

Advanced Materials
Material Test Literature Review of Carbon Steels



H_2 Effect on Fracture



H_2 Effect on Fatigue

Factors affecting mechanical properties

- Alloy type, sample preparation (pressurized H_2 gas environment vs. cathodic charge), H_2 concentration (including purity), test condition (temperature, H_2 pressure, strain rate, welding (e.g. Heat Affected Zone (HAZ))

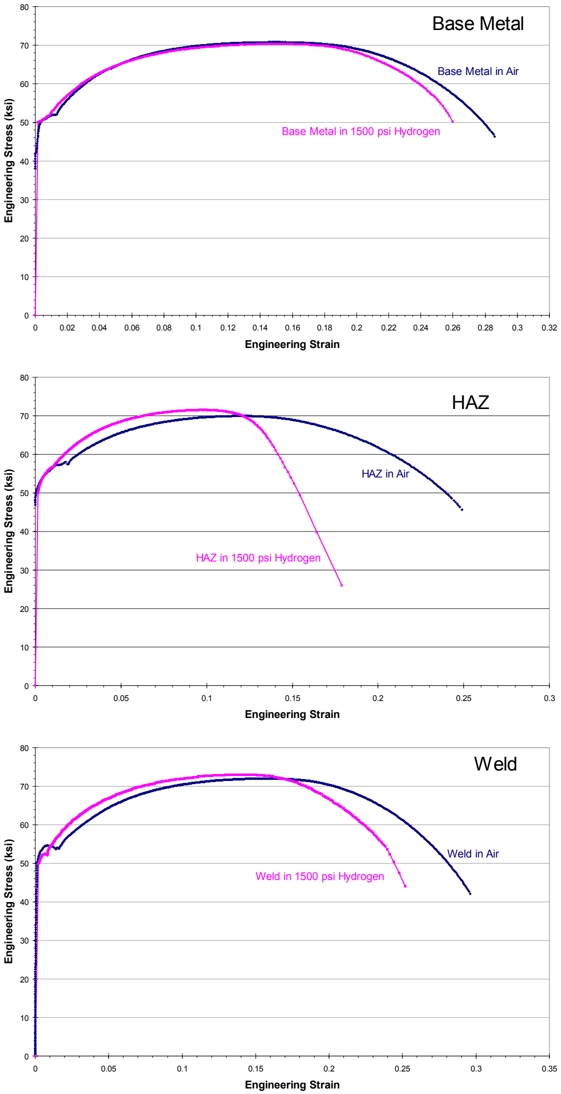
Tensile Properties

- Flow properties: yield stress and ultimate tensile strength (UTS)
  - Presence of H_2 can either increase or decrease the yield stress and UTS. The degree of variation depends on temperature and H_2 concentration)
- Ductility properties: reduction of area or failure strain
  - H_2 content consistently and may significantly decrease the ductility (temperature dependent)

Fracture Properties

- Threshold stress intensity factor (K_{th} or K_h)
  - H_2 pressure environment decreases K_{th} and may be yield stress depepndent
- Fracture toughness (K_c, J_c, or J-R curves)
  - Embrittlement by H_2 causes toughness reduction
- Fatigue (S-N, da/dN, and ΔK, etc.)
  - H_2 increases the fatigue crack growth rate and shortens the fatigue life

Advanced Materials
Mechanical Property Testing in Hydrogen



Tensile Curves for Base, Weld, and HAZ of 106 Grade B

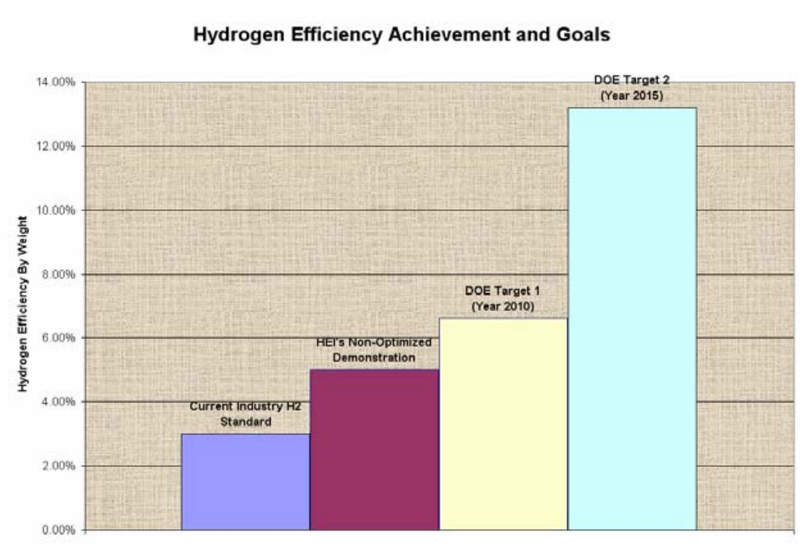
Tensile Test Conditions

- Alloys: 106 Grade B Carbon Steel
- Condition: Base Metal, Weld and HAZ
- Orientation: Crack perpendicular to rolling direction (L-C)
- 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
- Demonstrates need to conduct fracture testing
- Accumulated tensile data for ferritic pipeline steel materials

Advanced Materials
Development of a COPV for Hydrogen Storage



Results

- Developed a 10,000 psi service pressure 7.5 liter composite overwrapped pressure vessel capable of nearly 26,000 psi with a H_2 efficiency ratio of 5.01%
- Burst Test Results: 25,770 psi, 25,001 psi, 25,496 psi

H_2 Sensor and Leak Detection Objectives and Approach

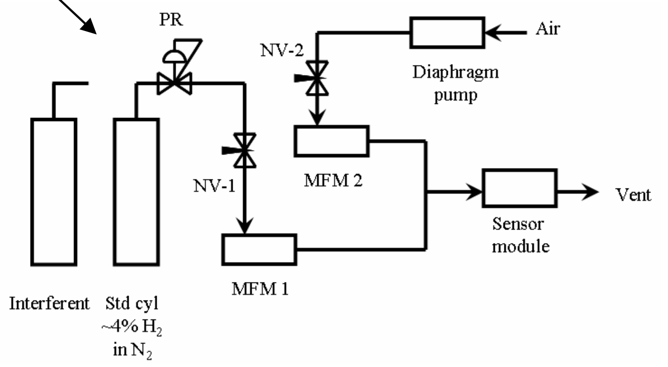
Objective

- Advance current H_2-specific sensors and sensor technologies so they can operate reliably in an industrial environment and perform as a reliable safety device in H_2 applications
- Evaluate leaks in H_2 pipelines and compare to leaks in NG pipelines

Approach

- Assess current commercial and pre-commercial H_2 sensor technologies
- Select sensor technologies, from assessment, that meet defined performance requirements
- Test selected sensors according to defined protocols with custom designed test process/setup
  - Evaluate H_2 sensor performance in air, nitrogen, and NG environments
  - Study the affects of contaminants, temperature, and humidity
- Communicate results and make recommendations to manufacturers for improvements
- Help expedite commercialization of reliable H_2 sensors

Sensor	Technology
A	Palladium Capacitor
B	Carbon Nanofibers
C	Palladium Field Effect Transistor (FET)



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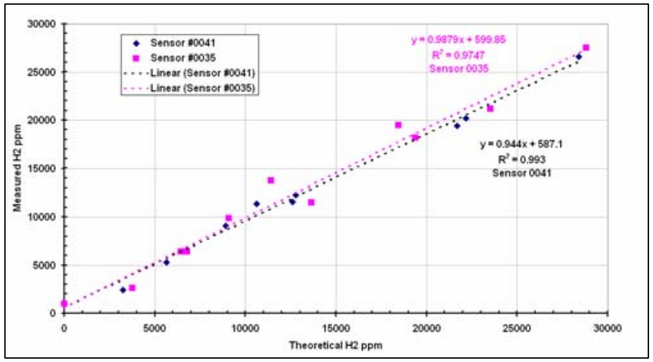
H_2 Sensor and Leak Detection Sensor Testing Protocols

- Performance Testing
  - H_2 concentration correlations – random sequence
  - Statistics (R^2 of linearity, standard deviation)
  - Hysteresis testing
  - Repeatability
  - Humidity and temperature effects

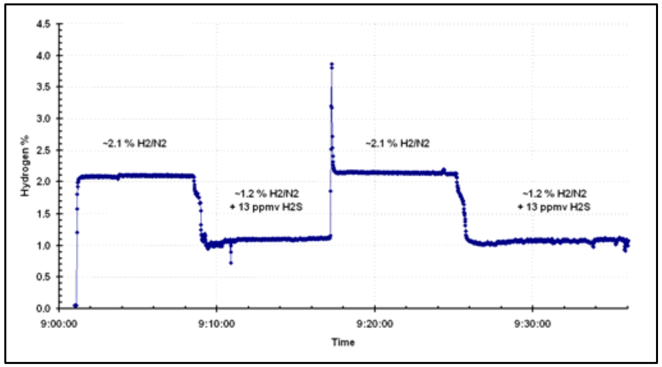
- Durability Testing
  - Operate sensors in a natural gas environment for extended times and record effects

- 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)

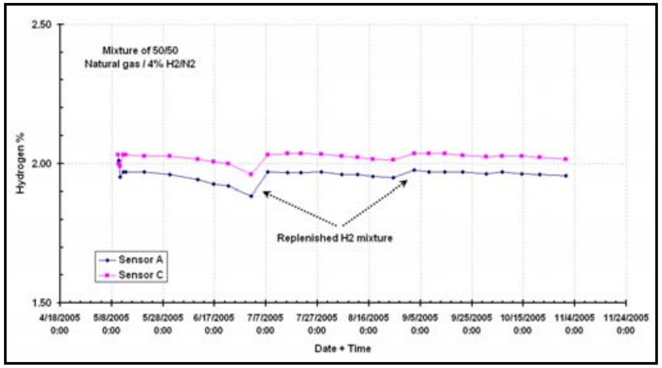
Performance Testing
R^2 Results from Sensor C



Exposure to H_2 and ~10 ppm_v H_2S
Results from Sensor A



Long Term Exposure to NG
Sensors A & C (Durability Test)



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H_2 Sensor and Leak Detection Results

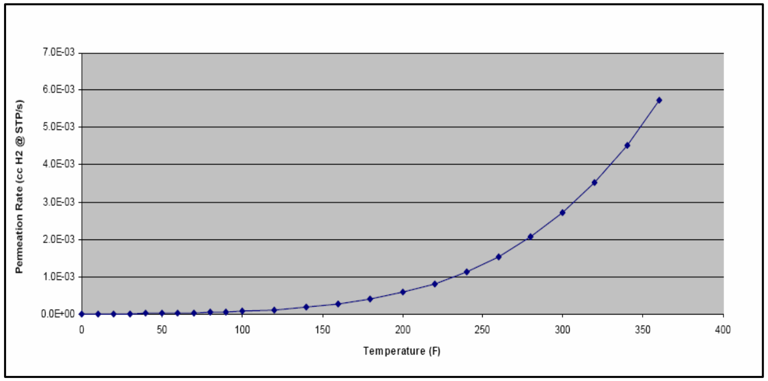
Sensor Advancement

- Palladium systems function as fast detecting, H2-specific sensors without the need for O_2
  - Performance in low O_2 documented
  - Speed of response documented

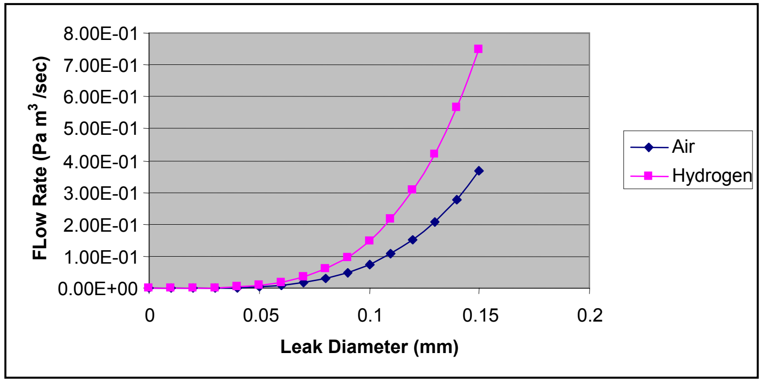
- At least two systems (palladium technology) exist with near-commercial status
  - Both companies are closer (1/2 – 1 yr estimate) to commercial status through user input

- H_2-specific sensors for deployment in H_2 infrastructure applications are achievable in the next 18-months
  - Deployment will be with robust sensors instead of lab-tested versions
  - Field rework has been minimized through user inputs

Leak Detection Information



Permeation of H2 vs temperature (iron pipe @ 1000psi)



Leak Rate Analysis

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Future Work

Pennsylvania Hydrogen Delivery Tradeoff Study

- Initial assessment of indigenous resources and infrastructure constraints and potential economics of infrastructure using renewable resources in Pennsylvania
- Investigate impacts of regional H_2 demand, examining the entire Mid-Atlantic region for economies of scale, focusing on major Metropolitan Statistical Areas (MSAs) such as Philadelphia-Camden-Wilmington (ranked 4th nationally) and Baltimore-Washington (7th)

Separations Technology Advancements

- Reduce NG / H_2 separation cost by using modular adsorbent

Future Work

Advanced Materials

- Develop material test matrix
- Continue testing at SRNL (high pressure H_2) and *CTC* (cathodic charging); verify data with ASME
- Update models using new test data
- Develop and test new composite pressure vessel designs targeting greater than 6.6% H_2 by weight and $300/Kg

H_2 Sensor and Leak Detection

- Complete funtional testing in uncontrolled field environment
- Develop operational cost analysis (based on natural gas industry)
- Continue the advancement of H_2-specific sensor systems
  - Intrinsic sensor packaging
  - Wireless communications
  - Physico-chemical coatings
  - Advanced sample capture
- Develop leak test standards for pre- and in-service testing protocols for H_2 systems
- Develop / test prototype H_2 permeation / leakage test devices

Back-up Slides

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Responses to Previous Year Reviewers' Comments

- **Congressionally-directed multi-year project. Need more focus on addressing program technical targets in Delivery Technologies.**

  <u>Pennsylvania Hydrogen Delivery Tradeoff Study</u>

  - 2015 Target: total cost contribution (from the point of H_2 Production through dispensing at the refueling site) equals $2 – 3/gge of H_2
    - Preliminary results are $3.96/kg, $3.50/kg, $2.96/kg, for 1%, 10%, and 30% H_2 demand, respectively ($1/kg = $1/gge on a BTU basis). Refer to Pennsylvania Hydrogen Delivery Tradeoff Study Preliminary Results slide.
    - Co-Transportation was examined as method to deliver H_2 via pipeline without the cost of installing new pipeline; however, it needs to be evaluated with the tradeoff of separation cost and amount H_2 recovered.
      - A simple case was evaluated using the best separation technology evaluated (refer to results of Separation Technology Evaluation slides) and investigated to give most H_2 recovery for the lowest cost within regulatory and safety boundaries (results shown in June 2005 DOE Technical Report). Preliminary results show a $.65/kg delivered H_2 cost difference between the lowest cost technology shown above and a simplified co-transportation scenario at 1% H_2 demand (Note: result does not include cost of lost H_2 passed on to natural gas consumer). Co-transportation scenario data not shown on Pennsylvania Hydrogen Delivery Tradeoff Study Preliminary Results slide.
  - Target H_2 quality >98% (dry basis)
    - Separation technology required to produce 99.995% H_2 or above. Refer to Separation Technology Evaluation Objective, Requirement and Technologies slide for more information.

Responses to Previous Year Reviewers' Comments (Continued)

- **Congressionally-directed multi-year project. Need more focus on addressing program technical targets in Delivery Technologies. (continued)**

  Advanced Materials

  (information contained on Advanced Materials Goals and Objectives slide)

  - 2010 Target: Total pipelines capital cost for transmission = \$1M/mile; for distribution = \$0.25M/mile
    - Developed modeling tools to predict the life of pipelines and components used to transport H_2. Refer to Advanced Materials Analysis of Material Performance and Material Life Prediction slides. Using material test data, models can be used to assist ASTM and ASME in codes and standards development that may help industry to relax operational constraints, thus reducing the number of new pipelines required to meet the increasing demand.
  - 2010 Target: Maintain integrity of the pipeline relative to potential H_2 embrittlement or other issues causing cracks or failures
    - Reviewed material test literature and worked with ASME, SRNL, SNL, and others through the DOE Material Testing Working Team to define highest priority tests and materials to be tested. Developed material test plan, conducted tensile stress tests in H_2 environment. Refer to Advanced Materials Mechanical Property Testing in Hydrogen slide. Existing data used for models described above, but additional test data is still needed.
  - 2010 Target: Carriers 6.6% H_2 content by wt. and cost less than \$300/kg
    - Testing prototype Type III gaseous H_2 storage tanks to evaluate against the targets

Responses to Previous Year Reviewers' Comments (Continued)

- **Congressionally-directed multi-year project. Need more focus on addressing program technical targets in Delivery Technologies. (continued)**

  H_2 Sensor and Leak Detection

  - 2010 Target: Leakage in Transmission and Distribution Pipelines less than 2% H_2 (Leakage based on the H_2 that permeates or leaks from the pipeline as a percent of the amount of H_2 put through the pipeline).
    - Sensors are one technology used to detect leaks. There are two main sensor types currently available:
      - Combustible gas detectors: These detectors are ineffective at distinguishing between H_2 and other combustible gases, therefore increased downtime is realized when these sensors are used.
      - Passive H_2-specific sensors: Existing sensors give numerous false positive results. Detection with these sensors is based on convection currents. Also, contaminants such as sulfur degrade these sensor.
    - Performance, interference, and field testing were conducted with H_2-specific sensors to increase sensor reliability. Advancements were made in a laboratory setting to create a direct-draw process for air sampling with the H_2-specific sensors
    - Gathered permeation and leak rate analysis information. Refer to the H_2 Sensor and Leak Detection Results Slide.

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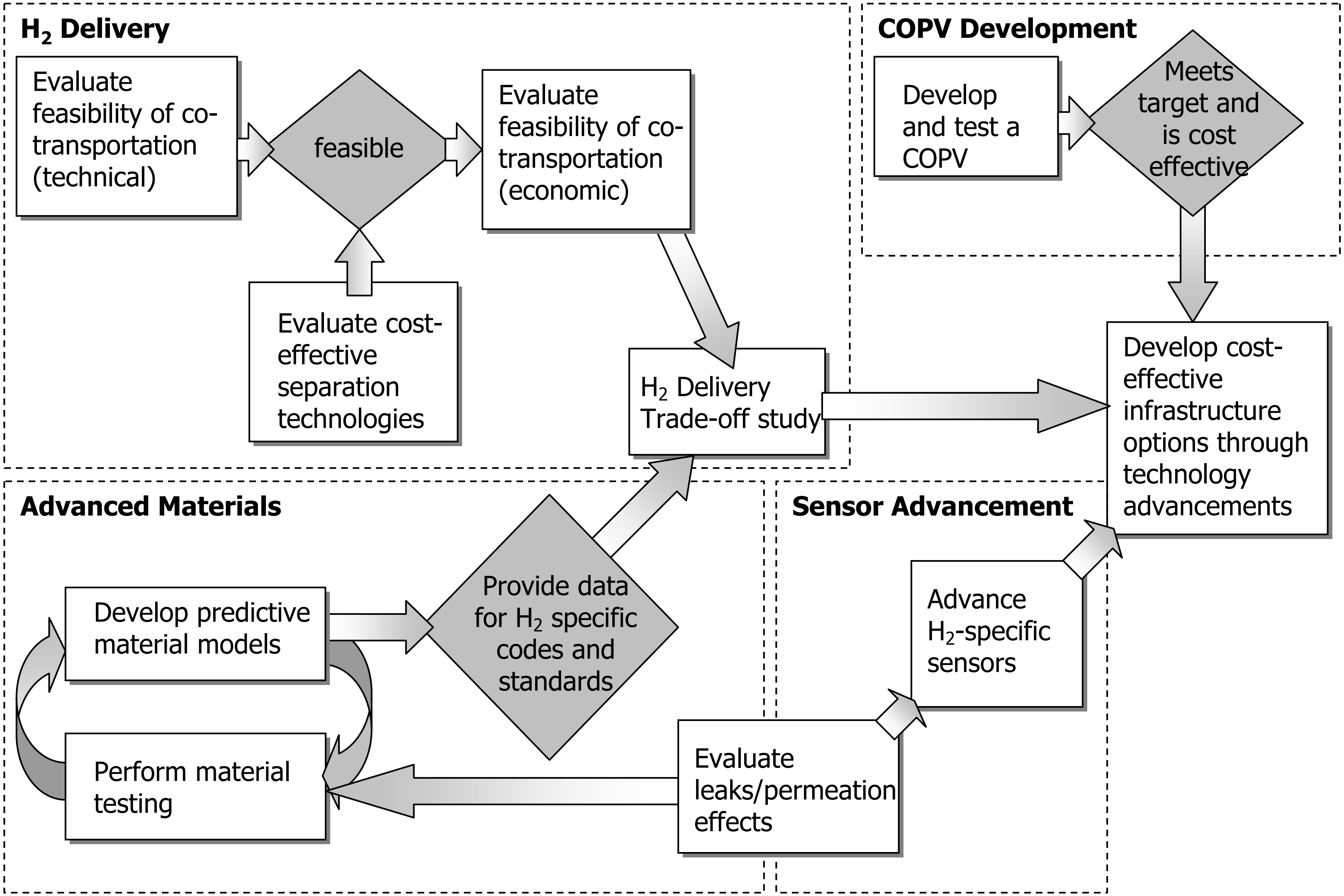
Responses to Previous Year Reviewers' Comments (Continued)

- **The project appears to be trying to meet too many objectives -- pipelines, storage tanks, demand forecasting - yet focuses on Pennsylvania, which may not be a realistic proxy for a U.S. rollout such that findings may not be transferable.**
  - Industry leaders and national laboratories to meet specific interrelated objectives.
  - Available resources made it possible to conduct research and development activities in multiple areas.
  - The following slide illustrates the inter-relationships between each of the objectives.

Responses to Previous Year Reviewers' Comments (Continued)



H_2 Delivery

Evaluate feasibility of co-transportation (technical)

feasible

Evaluate feasibility of co-transportation (economic)

Evaluate cost-effective separation technologies

H_2 Delivery Trade-off study

COPV Development

Develop and test a COPV

Meets target and is cost effective

Develop cost-effective infrastructure options through technology advancements

Advanced Materials

Develop predictive material models

Perform material testing

Provide data for H_2 specific codes and standards

Sensor Advancement

Advance H_2-specific sensors

Evaluate leaks/permeation effects

Responses to Previous Year Reviewers' Comments (Continued)

- **The project appears to be trying to meet too many objectives -- pipelines, storage tanks, demand forecasting - yet focuses on Pennsylvania, which may not be a realistic proxy for a U.S. rollout such that findings may not be transferable. (continued)**
  - Pennsylvania is a good study case because of its 15 discrete metropolitan areas, its similarity to California and its indigenous energy supplies. The metropolitan areas are similar to most areas in the US. PA is about 1/3 the size of CA, has about the same ratio of light duty vehicles, fueling stations, population and pollution non-attainment zones. Refer to the following slide for comparison between CA and PA.

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Responses to Previous Year Reviewers' Comments (Continued)

Statistic	Source	CA	PA
Gasoline Sales (1000 gpd)	EIA, 2004	40,645	13,111
Gas 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 Hwy Admin, 2003	28,600,000	9,259,000
LDV per capita	Calculated	.80	.75

Responses to Previous Year Reviewers' Comments (Continued)

- **Mixing H_2/NG in a pipelines will add costs of separation to the hydrogen costs, which are too high already**
- **Hydrogen costs should increase substantially due to additional separations costs**
  - Co-Transportation was examined as a method to deliver H_2 via pipeline without the cost of installing new pipeline; however, it needs to be evaluated with the tradeoff of separation cost and the amount of H_2 recovered.
    - A simple case was evaluated using the best separation technology evaluated (refer to results of Separation Technology Evaluation slides) and investigated to give most H_2 recovery for the lowest cost within regulatory and safety boundaries (results shown in June 2005 DOE Technical Report). Preliminary results show a $.65/kg delivered H_2 cost difference between the lowest cost technology shown in the Pennsylvania Hydrogen Delivery Tradeoff Study Preliminary Results slide and a simplified co-transportation scenario at 1% H_2 demand (Note: result does not include cost of lost H_2 passed on to natural gas consumer). Co-transportation scenario data not shown on Pennsylvania Hydrogen Delivery Tradeoff Study Preliminary Results slide.
- **Hydrogen sensors for hydrogen-in-air and hydrogen-in-methane are already available**
  - Existing sensors give numerous false positive results. Detection with these sensors is based on convection currents. Also, contaminants such as sulfur degrade these sensor.

Responses to Previous Year Reviewers' Comments (Continued)

- **Advantages relative to distributed reforming from natural gas are not apparent**
  - Distributed H_2 production can offer the lowest delivered H_2 cost when serving low-medium H_2 demand and a relatively dispersed population. Results from the *Pennsylvania Hydrogen Delivery Tradeoff Study* show that fueling stations with 1,000 kg/day natural gas reformers are the lowest cost option for the 1% demand scenario in the western portion of the state. As demand increases, larger central H_2 production plants benefit from factors such as capital cost economy-of-scale and lower feedstock costs. In more urban regions where the delivery distance from the central plant to the fueling station is lower, central production and pipeline or truck delivery are more economical at fairly low volumes because of factors such as low delivery and feedstock costs. Refer to the following slide for an assessment of central production as demand increases against 1000 kg/day distributed production.
  - If smaller distributed production systems are used to increase station counts or enhance single station reliability, distributed production only beats central station in regions with very low H_2 demands and extremely long average delivery distances from the central plant to the fueling station (well more than 100 miles). Refer to the following slide for an assessment of central production as demand increases against 329 kg/day distributed production.

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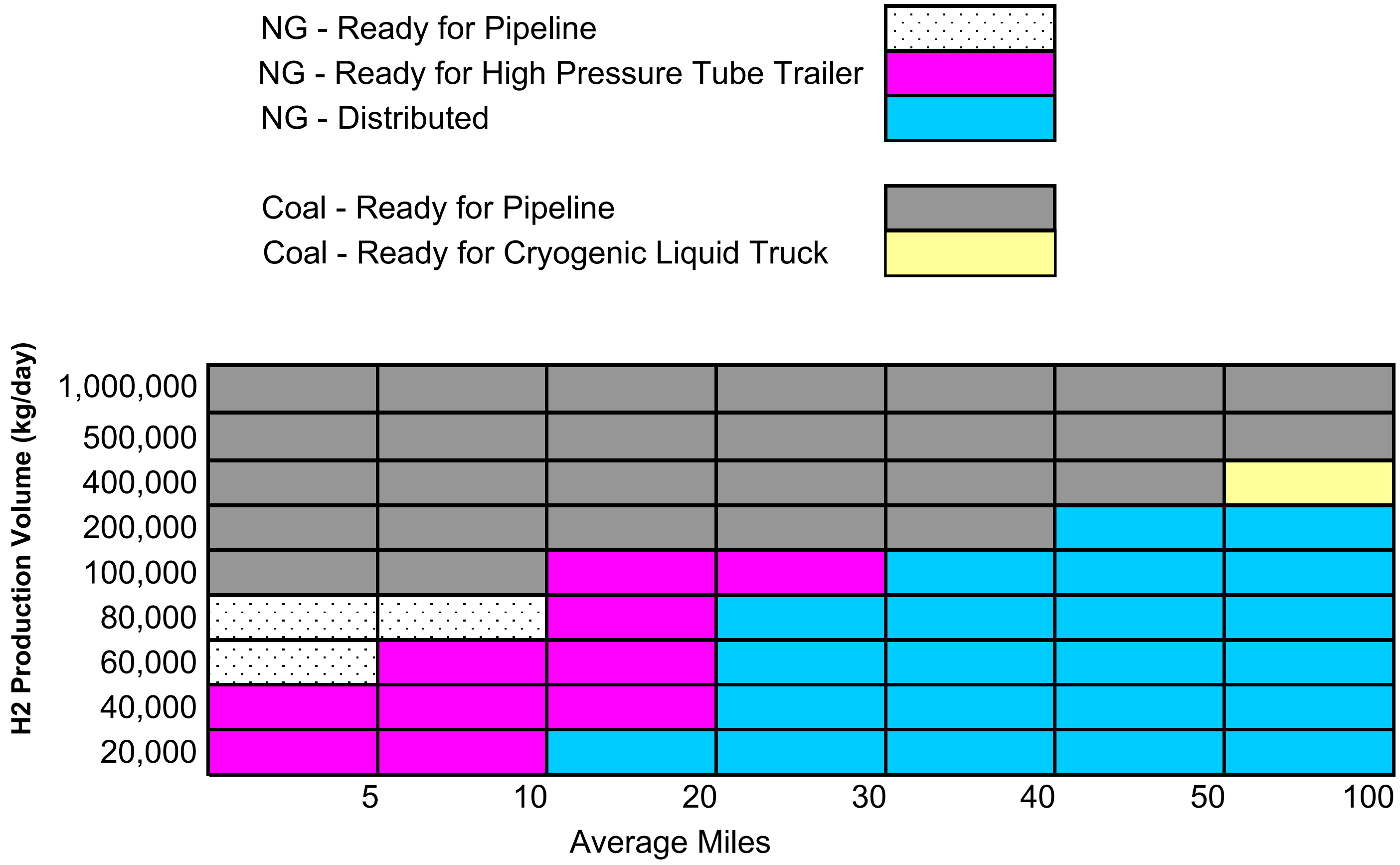
Responses to Previous Year Reviewers’ Comments



NG - Ready for Pipeline ░
NG - Ready for High Pressure Tube Trailer 🟪
NG - Distributed 🟦

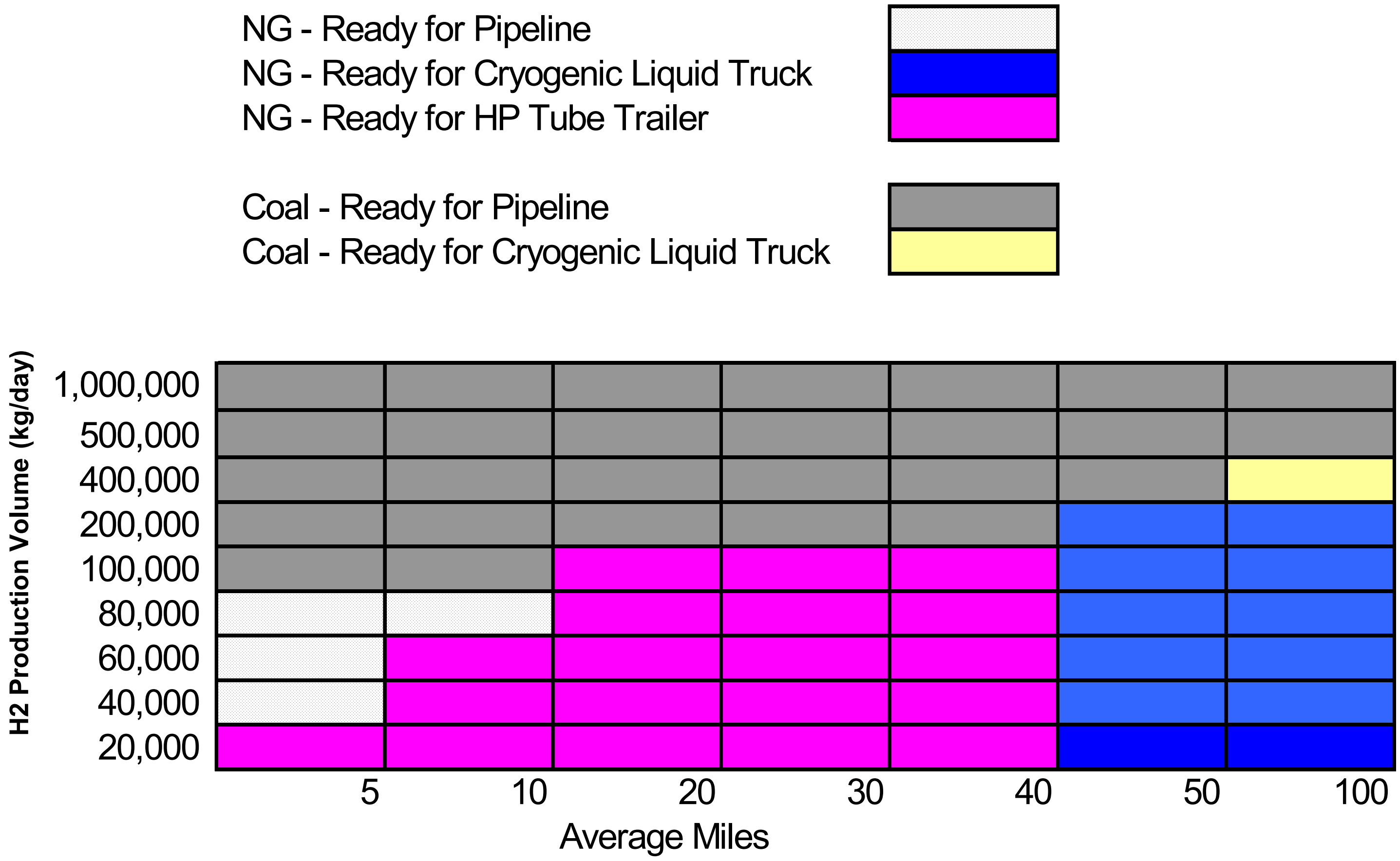
Coal - Ready for Pipeline ⬛
Coal - Ready for Cryogenic Liquid Truck 🟨

H2 Production Volume (kg/day)	5	10	20	30	40	50	100
1,000,000	⬛	⬛	⬛	⬛	⬛	⬛	⬛
500,000	⬛	⬛	⬛	⬛	⬛	⬛	⬛
400,000	⬛	⬛	⬛	⬛	⬛	⬛	🟨
200,000	⬛	⬛	⬛	⬛	⬛	🟦	🟦
100,000	⬛	⬛	🟪	🟪	🟦	🟦	🟦
80,000	░	░	🟪	🟦	🟦	🟦	🟦
60,000	░	🟪	🟪	🟦	🟦	🟦	🟦
40,000	🟪	🟪	🟪	🟦	🟦	🟦	🟦
20,000	🟪	🟪	🟦	🟦	🟦	🟦	🟦

Average Miles

1000 kg/day Distributed Production Capacity

Responses to Previous Year Reviewers' Comments



329 kg/day Distributed Production Capacity

Reports, Proceedings, and Presentations

DOE Technical Reports:

Concurrent Technologies Corporation, Hydrogen Regional Infrastructure Program in Pennsylvania, *Existing Natural Gas Pipeline Materials and Associated Operational Characteristics*, submitted to DOE under contract DE-FC36-04GO14229 (June 2005).

Concurrent Technologies Corporation, Hydrogen Regional Infrastructure Program in Pennsylvania, *Comparative Analysis of Technologies for the Separation of Hydrogen from a Blended Hydrogen/ Natural Gas Stream*, submitted to DOE under contract DE-FC36-04GO14229 (April 2006).

Concurrent Technologies Corporation; Hufton, Jeff, Air Products and Chemicals Incorporated, Hydrogen Regional Infrastructure Program in Pennsylvania, *Cost Effective Hydrogen / Natural Gas Separation in a Natural Gas Pipeline Delivery Scenario Technology Design Report*, submitted to DOE under contract DE-FC36-04GO14229 (April 2006).

Conference Proceedings:

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.

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

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.

Reports, Proceedings, and Presentations

Oral and Poster Presentations:

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)

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).

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

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

Eileen Schmura, Yuan Pang, Linda Eslin, *Deliver Infrastructure for Hydrogen and Natural Gas,* NHA Annual Hydrogen Conference 2006, Long Beach, CA (March 2006).

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

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, Long Beach, CA (March 2006).

Paul Lemar, Paul Sheaffer, Eileen Schmura, *Pennsylvania Hydrogen Delivery Tradeoff Study,* NHA Annual Hydrogen Conference 2006, Long Beach, CA (March 2006).

Critical Assumptions and Issues

Tradeoff Study

Assumption: At 1% light duty vehicle (LDV) penetration, 88 H_2 fueling stations have been assumed to be adequate. This is about 3.3% of the existing gasoline stations within the seven demand centers. Some studies cite that 10-30% fueling station penetration is required for customer convenience and to avoid the classic "chicken and egg" problem (no H_2 LDVs without H_2 fueling stations, no H_2 fueling stations without H_2 LDVs).

Solution: Explore whether 10-30% station penetration is valid and required. Examine the market experience from other non-gasoline fuels such as diesel, compressed natural gas, and E85 and their fueling station penetration status.

Assumption: Capital costs and other H_2 production, delivery, and dispensing performance parameters (e.g., efficiency, maintenance costs, etc.) are based on the NREL report titled *Hydrogen Supply: Cost Estimate for Hydrogen Pathways – Scoping Analysis* and DOE's H2A model. The assumption is that these numbers are accurate.

Solution: Independently verify all H_2 production, delivery, and dispensing capital costs and production performance parameters through extensive research and working with existing and potential H_2 producers.

Critical Assumptions and Issues (Cont.)

Co-Transportation Feasibility Study

Assumption: Natural gas pipeline materials are the limiting factor in determining the maximum amount of H_2 that can be co-transported with the natural gas.

Solution: This assumption was determined not to be the critical factor. A review of the current H_2 pipelines (new and converted older petroleum pipelines) show that the current low carbon steels are adequate for transporting pure H_2, although at reduced pressures. A review of the natural gas operational data, flow statistics, regulations end users' concerns indicated these issues, not materials will be the main constraints that will limit the H_2 concentration.

Separations

Assumption: A major hurdle for co-transporting H_2 in natural gas is development of a cost effective separation technology.

Solution: Research indicates that separation technologies are available for this task. Technologies were compared to determine which separations systems met design criteria and the DOE requirements for H_2 purity. Based upon this review, several separation technology options were developed. The best options were selected, preliminary costs were developed, and input into a simplified economic tradeoff analysis.

Critical Assumptions and Issues (Cont.)

Material Testing

Assumption: All test specimens are fully (100%) charged, the H_2 concentration is uniform across the thickness of the test specimen, and all specimens have equivalent H_2 concentrations. If the H_2 concentration is different, the mechanical properties should be related to the level of H_2 in the specimen.

Solution: Either conduct material testing in 100% H_2 environment or develop a procedure for measuring the H_2 concentration of specimens after testing. This is very difficult since the H_2 gas dissipates after testing.

Composite Tanks

Assumption: Liner material (either metal or polymer) is resistant to H_2 permeation throughout its life, thus protecting the composite wrap from exposure to H_2 gas.

Solution: Develop procedures to measure the permeation of materials after cyclic exposure to H_2 gas. That is, measure the permeation of liner materials prior to H_2 exposure and after a number of pressure cycles equivalent to the design life of the tank.

Critical Assumptions and Issues (Cont.)

H_2 Sensor Technologies

Assumption: H_2-specific sensors experience degradation during field use after passing laboratory testing in controlled factory environments.

Solution: Field test each system in real world environments so the sensors can be exposed to uncontrolled parameters. Conduct long term testing or accelerated life testing to catch problems before they become a problem for early technology adopters.