IV.D.6 Systems Engineering of Chemical Hydride, Pressure Vessel, and Balance of Plant for On-Board Hydrogen Storage

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Fiscal Year (FY) 2011 Objectives

The Pacific Northwest National Laboratory (PNNL) objectives address the critical engineering challenges currently limiting on-board hydrogen storage systems for light-duty fuel cell vehicles. Each of the project's objectives and tasks have been established to advance the state of the art in analysis, design and engineering for chemical hydride storage, pressure/containment vessel construction for metal hydride and cryogenic adsorbent systems, and component miniaturization for all systems to achieve PNNL, Hydrogen Storage Engineering Center of Excellence (HSECoE), and DOE goals.

- Demonstrate a high level of performance that meets DOE targets for key components (reactor, solids handling, and heat exchanger) of a solid chemical hydrogen storage system.
- Optimize the design of a chemical hydride storage bed and system performance through engineering including the establishment of bulk media and system kinetics data to aid in design activities.
- Reduce system volume and weight while optimizing system storage capability, fueling and dehydriding performance through application of microtechnology and associated architectures to the design of high-efficiency heat exchangers and balance-of-plant (BOP) components.
- Mitigate materials incompatibility issues associated with hydrogen embrittlement, corrosion, and permeability through suitable materials selection for vessel materials, heat exchangers, plumbing and BOP components.
- Demonstrate the performance of economical, compact lightweight vessels for a hybrid pressurized metal-hydride and adsorbent system, and containment vessel for a chemical hydride system.
- Guide design and technology down selection, Go/No-Go decision-making, and address vehicle and market impact through cost modeling and manufacturing tradeoff assessments of the three HSECoE prototype storage systems.

Achieving the objectives will enable PNNL, Savannah River National Laboratory (SRNL), and other HSECoE partners to demonstrate on-board hydrogen storage with the potential to meet 2015 DOE technical targets. This technology and design knowledge will be transferred to the participating automotive original equipment manufacturers and non-proprietary information and models will be made available to the fuel cell community, thus advancing the hydrogen market sector and production of future hydrogen-powered vehicles.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan:

General to All Storage Approaches

(A) System Weight and Volume
(B) System Cost
(C) Efficiency
(D) Durability/Operability
(E) Charging/Discharging Rates
(G) Materials of Construction
(H) Balance of Plant (BOP Components)
(I) Dispensing Technology
(J) Thermal Management
(K) System Life-Cycle Assessments
(O) Hydrogen Boil-Off

Off-Board Regenerable Specific

(S) By-Product/Spent Material Removal

Technical Targets

The HSECoE activities being conducted at PNNL range from process and reactor modeling and component design/engineering to technology application and prototype fabrication for demonstration. The final ultimate goal for the PNNL scope is to demonstrate, with Los Alamos National Laboratory (LANL) partners, a (100-g) scaled chemical hydrogen storage system that meets all the 2015 DOE storage performance targets. As a snapshot of progress to date, the spider chart in Figure 1 represents the principal 2010 DOE performance targets and status toward achieving those targets as a percentage. The DOE has established an initial in-process review gate of 40% for each of the targets except system cost; the dashed line represents this 40% threshold.

FY 2011 Accomplishments

- Demonstrated refueling feasibility using a solid hydrogen storage material with both pellets and powders. The pellets where capable of achieving 75-100% of the DOE's refueling (fill and drain) 2010 targets and the powders were capable of achieving 27-50% of the 2010 targets. Low density polyethylene was used as a surrogate of an 80:20 ammonia-borane (AB)/methyl cellulose (MC) mixture by weight. Based upon the results of these tests, pellet form factors are recommended for solid chemical hydride fuels over powders.
- Validated AB kinetic models using pressure-concentration-temperature (PCT) and larger scale testing.
- Demonstrated self-sustaining hydrogen release of AB/MC pellets without foaming at atmospheric pressure and at 10 bar (system design pressure).
- Validated and modeled a new design which combines the fuel storage tank with the reactor and hydrogen ballast tank into a single fixed-bed design. The simple design consists of a single tank with multiple beds. Each bed is thermally isolated from the others. Therefore as hydrogen is needed, a single bed is heated to release the hydrogen. A single bed was used to validate the design. COMSOL and Simulink were used to predict and improve the reactor performance.
- Completed the Simulink modeling for eight system configurations including the fixed bed design, fluid system (AB dissolved in ionic liquids [IL] or a chemical hydride slurry), reactive transport systems such as an auger design, and a tape/roller system. The fixed bed system was modeled with AB/MC, the reactive transport and fluid systems were modeled with solid AB/MC, alane, AB slurries, alane slurries, and AB/ionic liquids.
- Predicted, using Simulink models integrated with the Vehicle Model that hydrogen storage technologies based upon solid and/or fluid chemical hydrides can meet the DOE delivery targets. Multiple cases were examined with the integrated models including: UDDS+HWFET, US06, and Cold FTP.
- Discontinued work on the reactive transport (or auger) concept based on concept validation tests. Hydrogen was successfully produced using an auger type reactor with AB/MC as the chemical hydride; however, the auger tended to clog. Based on the results, work on the reactive transport systems was discontinued.
- Down selected from greater than eight designs to one design for Phase II. Any design requiring replacement canisters or cassettes was discontinued due to safety concerns. Reactive transport concepts were

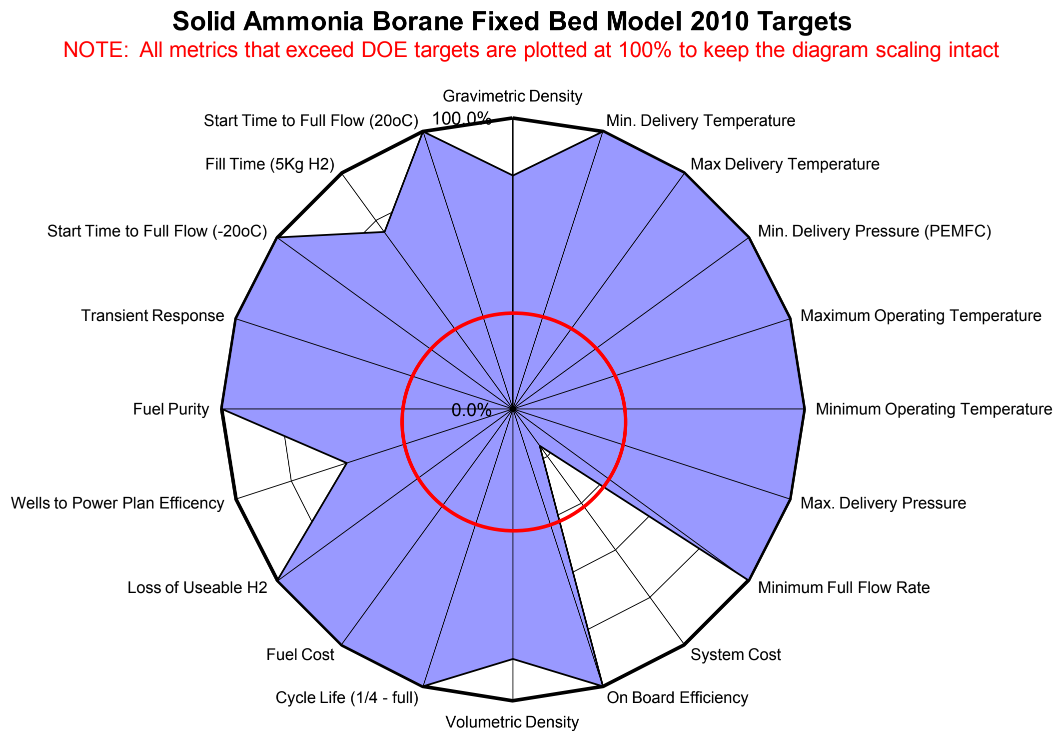

FIGURE 1. Progress toward achieving DOE performance targets for solid AB hydrogen storage. Fifteen targets are met at 100%, four targets met at >40% and system cost target at <40%.

discontinued based upon the results of the auger reactor testing. A fixed bed reactor concept was validated. The modeling and cost analysis revealed that a fixed bed reactor with a solid chemical hydride and fluid reactor (solid liquid slurry or AB in IL) would meet the DOE targets. Due to programmatic restraints, it was decided that only one design would go forward. After consultation with our HSECoE partners, including the manufacturers, it was decided to focus future efforts on the fluid system (slurries or AB in IL).

- Projected the mass and volume of four different systems including the metal hydride system, cryogenic adsorbent system, fixed bed reactor chemical hydride system and AB in IL system. As part of this work the heat exchangers and BOP components were sized, and vendors were identified. Care was taken to ensure that the materials were compatible with hydrogen, and the operational temperature and pressures. Value engineering to reduce the mass and volume of the BOP was begun.
- Completed the BOP catalogue which includes the vendor sources, materials of construction, mass, volume, operating temperatures, connection data (if applicable), and performance information (if applicable). This library will be made available to the public in FY 2012.
- Projected the storage system costs to be $9,200 and $4,800 for the metal hydride and chemical hydride systems when produced in high volumes (500,000 units/year). The cost of AX-21 material at high volumes was projected using models of the process as described in the literature. The projected cost was found to be ~$4/kg when made at high volumes. The complete system cost for the cryogenic adsorbent system is not complete since we have not received all the vender quotes. The single largest cost component for all the systems is the tank cost.
- Developed model to assess materials and design options for Tier 1-III pressure vessels.
- Assessed materials options and design options for Type IV liner materials.
- Developed experimental plan for burst testing Type IV pressure vessels under high and low temperature (cryogenic) thermal cycling.
- Optimized the vessel design in terms of cost and performance.
- Defined the geometry limitations for vessel size with manufacturers.

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Introduction

To date there has been multiple on-board vehicle-scale hydrogen storage demonstrations, including several studies to examine phenomena and characteristics that impact the engineering of hydrogen storage systems. However, none of these demonstrations have simultaneously met all of the DOE hydrogen storage sub-program goals. Additionally, engineering of new chemical hydride approaches specifically is in its infancy, with ample opportunity to develop novel systems capable of reaching the DOE targets for storage capacity. Toward this goal, PNNL is leading efforts as part of the HSECoE led by Savannah River National Laboratory (SRNL), to design and fabricate a 100 g of hydrogen scaled system based on solid or slurry chemical hydride storage media. This system is intended to be demonstrated at LANL at the conclusion of the HSECoE effort.

Approach

The PNNL actively contributes to the five technology areas established as part of the HSECoE led by SRNL. The goal of this center, and PNNL's role, is to develop and demonstrate low-cost, high-performing, on-board solid-state hydrogen storage through a fully integrated systems design and engineering approach.

PNNL targets six key objectives to optimize performance characteristics and reduce the size, weight, and cost of a solid-state hydrogen storage system. This is being accomplished through carefully engineering and integrating design approach, including application of advanced materials (structural and hydrogen storage), and assessments of manufacturing and cost impact based on established models/approaches for technology tradeoff or "viability" studies.

PNNL also serves multiple leadership roles within the HSECoE technology area structure to help facilitate collaboration across the center partnership and to feed technical results back through and disseminate to other center partners. Achieving the objectives enables PNNL, SRNL, and other HSECoE partners to demonstrate on-board hydrogen storage with the potential to meet 2015 DOE technical targets. This technology and design knowledge will be transferred to the participating automotive original equipment manufacturers, thus advancing the hydrogen market sector and production of future hydrogen-powered vehicles. As appropriate, the models, catalogues, and lessons learned will be made available to the general fuel cell community to accelerate fuel cell technology penetration into commercial applications.

Results

Chemical Hydride Modeling, Concept Validation, and Down Selection

Three types of models were under development in FY 2010: kinetic models, COMSOL, and Simulink models. During FY 2011 the kinetic models were validated, the COMSOL and Simulink models were completed, and the Simulink model was integrated with the Vehicle System Model.

The kinetic models were validated using PCT and large-scale experiments using neat AB and AB mixed with

MC. The results of the PCT tests indicated the amount of H_2 released and the rate of release were consistent with the predicted values (Figure 2). In addition, no foaming was observed on the AB/MC mixture. Since the PCT tests were limited to mg amounts of material, larger tests using gram quantities were done using a quartz tube with thermal imaging and in a stainless steel tube under pressure. The quantity and rate of release was consistent with the models. For the quartz tube testing a heating element was placed at the bottom of the tube with 2.5 g AB powder or pellets placed on top. The experiments revealed that heat did not sufficiently propagate in the AB powder to release all of the H_2 even when the heating element was raised to 400°C. We believe the AB in direct contact with the heating element reacted quickly, but also foamed. The foaming moved the AB out of the heated area and there was not sufficient thermal propagation for all of the AB to react. However, the AB/MC mixture completed reacted and there were no heat propagation issues. Approximately 3-4 minutes were required for the reaction to complete. To investigate the impact of pressure, 2.5 g of AB/MC was tested in a stainless steel tube under 10 bar of Argon. The reactor was heated in a furnace. The H_2 released at a faster rate (2.5 equivalents released in ~15 seconds). The spent AB/MC fuel was stickier than fresh fuel.

During FY 2011 we completed the initial chemical hydride reactor models and construct was completed. Four configurations were considered: solids reactor vessel, auger reactor, recirculating fluid system, and a new fixed bed reactor. The auger and fluid reactors were modeled using Simulink with solid AB, alane, AB slurries, alane slurries, and AB dissolved in an IL. The auger and fixed bed reactor models were integrated with the Vehicle Level Model and run through three cases: UDDS-HWFET, US06, and Cold FTP. The models indicated the H_2 demand could be met throughout the entire drive cycles for each of the cases studied (Figure 3).

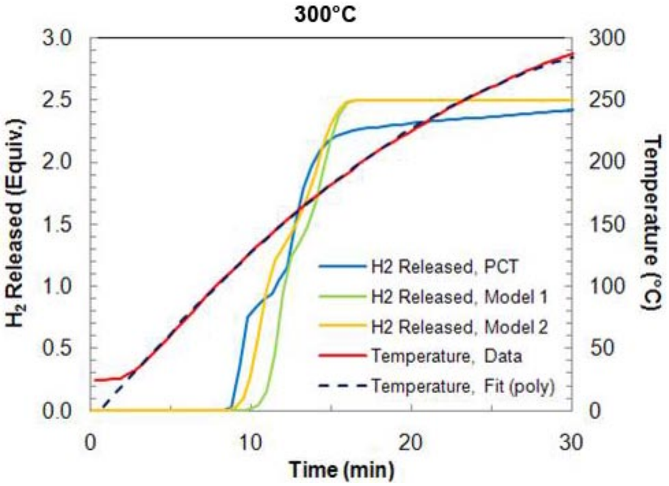

FIGURE 2. Kinetics of Solid AB/MC: Model Prediction vs. Experimental Results at 300°C

The fixed bed reactor concept was developed in FY 2011. The fixed bed reactor combined the hydrogen ballast tank, material storage tank and reactor into a single component. The fixed bed reactor consisted of eight thermally isolated sections in a single tank (Figure 4). The H_2 gas could flow freely between the sections to provide the ballast tank. When the H_2 pressure would decrease to a pre-specified level, a heat element would initiate the H_2 release reaction in one of the sections re-pressurizing the tank. At fueling the, AB beads could be pneumatically conveyed into and out of the bed and the tank re-pressurized. This reactor was modeled using COMSOL to predict pressure ranges, reaction rate, and reaction propagation to minimize the amount of heating required to initiate the reaction. The COMSOL model performance results were used in the Simulink models. The design concept was validated by the AB/MC experiments performed in a stainless steel tube at elevated pressure described previously.

In addition to the kinetic and fixed bed reactor experiments, auger reactor concept validation experiments

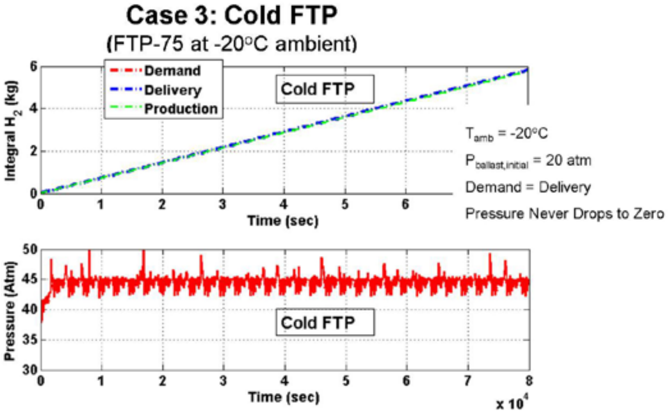

FIGURE 3. Results of AB in IL Chemical Hydride Simulink Model Integrated with the Vehicle Model Operating over the Cold FTP Case

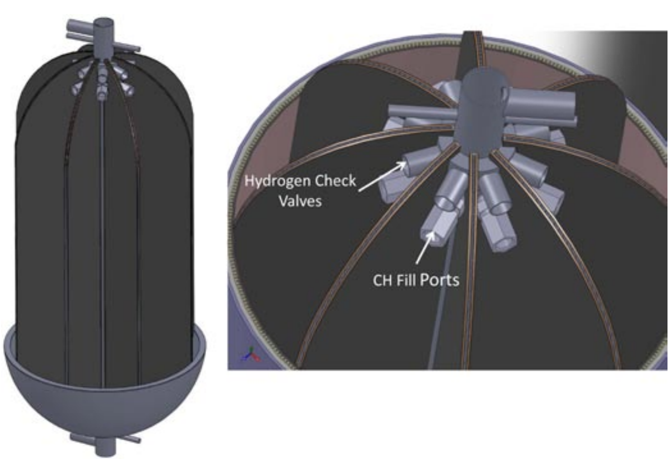

FIGURE 4. Conceptual Drawing of the Fixed Bed Reactor for Chemical Hydrides

were performed. An extruder for plastics was outfitted for hydrogen generation, by insulation, insertion of multiple thermocouples, and placed in a plastic case under an inert atmosphere to prevent any hydrogen generated from reacting with oxygen in the atmosphere. Hydrogen was successfully generated from the reactor with AB/MC as the chemical hydride simulant. However, the auger reactor consistently clogged. Due to the clogging issues, experimental and modeling work on this concept was discontinued early in FY 2011.

For a solid chemical hydride to be a viable solution for on-board hydrogen storage, material movement onto and off of the vehicle in a timely manner must be done. Movement of solid material onboard is being addressed by our partner United Technologies Research Center, or it can be avoided by using the fixed bed reactor. In FY 2010, we proposed using pneumatic conveyance for on/off boarding of the material. This concept was validated in FY 2011. The DOE target for fill time is 5.6 kg of H_2 in 4.7 minutes. Therefore, for AB/MC approximately 9.2 kg/minute must be transported to achieve the DOE target and >3.8 kg/min for the 40% requirement for the concept to be accepted to pass onto Phase II of the HSECoE project.[1] Since low density polyethylene (LDPE) has many of the same transport properties as AB and AB/MC, it was selected as a surrogate material for the tests. The pneumatic tests were done using a 2” heavy duty line vac (Exair) through 14–22 ft length of 2”plastic hose, either open ended or in/out of wedge shaped sections to simulate the fixed-bed tank. The tests were done with powder and beads of LDPE (Table1). For the open-ended tests, both the powder and pellets exceeded the DOE 2010 targets. However, when filling or draining from a vessel, the pellets exceeded the 40% minimum, but the powder did not. Based on the results of the test we recommend that a pellet form factor be used.

TABLE 1. Refueling Feasibility Test Results with LDPE

	Powder	Pellets
	kg/min (% target)	kg/min (% target)
Open-Ended (22′)	14-15 (>100%)	14-15 (>100%)
Fill (14′ hose)	2.5 (~27%)	5.4-6.9 (60-75%)
Drain (14′ hose)	4.5 (~49%)	4.8-9.2 (50-100%)

Finally, during FY 2011, the HSECoE had a Phase I to Phase II transition where only the most likely design would be selected for continued development. Obviously the auger design was not selected since it failed in concept validation. After consultation with HSECoE manufacturer partners and the DOE, it was determined that any concept requiring an tank exchange would not be acceptable since, among other reasons, the interlocks could not be guaranteed to operate safely over the life of the tank. However, both the fixed-bed reactor with solid chemical hydrides and the fluid reactor[2] with either AB dissolved in IL or an AB liquid slurry would meet or surpass the 40% target threshold. Due to concerns over the slight increase in stickiness of the spent AB/MC fuel compared to fresh fuel, HSECoE manufacturer input, and using our engineering judgment on the most likely to succeed candidate, it was decided to focus Phase II efforts on the fluid chemical hydride system.

Vessels

During FY 2011 the main task was to design a series of carbon fiber and metal- and polymer-lined tanks for use in metal hydride and cryo-compressed storage applications, using an ANSYS finite element model. The center needed to determine a realistic range of weights and volumes for the tanks. The initial model was to develop tables comparing different liner materials and pressure combinations that would give the system architects an initial estimate of tank weight and volume. The model has continued to be refined by working with our center partner, Lincoln Composites, for a more detailed analysis as the center works to minimize the tank weight and volume. For example, the model needed to allow the carbon fiber to realistically slide relative to the liner. The temperature drop caused by the initial cryo-state cool down causes the liner to shrink faster than the carbon fiber, so the carbon fiber did not carry the intended load. A model refinement has the two dissimilar materials now working together in a load sharing mechanism which now allows for proper tank liner sizing that will help minimize the fatigue stresses in the type III metal lined tank.

BOP/Costing

Working with the other HSECoE partners, PNNL developed a baseline mass, volume, and cost estimates for the systems under consideration. During Phase II, work will be done to minimize the BOP components and reduce the mass, volume and cost. The system architects and modelers provided PNNL system schematics with predicted temperatures, pressures, and flow rates. PNNL then sized the appropriate components (valves, heat exchangers, etc) and identified specific components from vendors. Using this information, a BOP Catalogue was developed which lists the device, volume, mass, cost, operating parameters, model numbers, and links to vendors. Dimensions and materials of construction were used to estimate the mass or volume for components which did not have the information available. Based on comments from the manufacturers and the Storage Tech Team, the storage systems were designed to be stand alone, or in other words we did not assume that any components from the fuel cell (i.e. radiator) or other vehicle systems could be shared. This limitation made the mass and volume projections larger than if the fuel cell, storage systems, heating, ventilation, and air conditioning, etc. were integrated. Table 2 contains the

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[1] This assumes simultaneous addition of fresh fuel and removal of spent fuel.

[2] See Annual Progress Report by HSECoE partner Troy Semelsberger of LANL.

mass and volume projections based on this bottoms-up approach (please note the 2010 targets were 0.045 kg H_2/kg and 0.028 kg H_2/L). In FY 2012 we plan on applying value engineering to minimize the largest, heaviest and most expensive components. For example, a pump for the coolant system for the metal hydride storage weighed 26 kg. We have identified an alternative which weighs only 2.3 kg, but requires an alternating current input and could not provide the needed flow. We are working with the vendor to project the size of a scaled up the system with a direct current input. This will need to be done with many of the BOP components, especially the storage vessels, in order to significantly reduce the mass of the system.

TABLE 2. Hydrogen Storage System Baseline Mass and Volume

	Calculated Mass/Volume	kg H_2/ System	Fraction of 2010 DOE Goal
Metal Hydride System			
Gravimetric Density	457.5 kg	0.0122	27%
Volumetric Density	488.7 L	0.0115	41%
ABMC Fixed Bed System			
Gravimetric Density	155.4	0.036	80%
Volumetric Density	236	0.0237	85%
AB IL Fluid System			
Gravimetric Density	147.85 kg	0.0378	82.6%
Volumetric Density	163.3 L	0.0344	122%
Cryogenic Adsorbent			
Gravimetric Density	145	0.0388	86%
Volumetric Density	238	0.0236	84%

Cost estimates were similarly done by a bottoms-up approach. Vendors identified in the BOP catalogue were contacted and provided estimates at production amounts of 10, 1,000, 10,000, 130,000 and 500,000 units per year (Table 3). Discounts were applied to the vendor estimates if the cost estimate was from a distributor and not the manufacturer. Progress ratios were applied to account for scaling, learning, and manufacturer requirements. These progress ratios were analogous to those used by the DOE in their fuel cell and Quantum tank cost estimates [1-2]. Oregon State University provided the cost estimate from their software for the combustor they are designing. Dynatek provided the tank price estimate. The AB cost, from the Dow presentation from the 2010 Annual Merit Review meeting, was $9/kg. For the metal hydride, sodium alanate plus a carbon additive to increase thermal conductivity was used as a surrogate with a cost range of $126 to $9/kg. For the cryogenic storage team directed us to use AX-21 for this cost estimate. Since there was no vendor source, we estimated the cost from the process described in the patent literature. The cost of AX-21 was estimated to be ~$4/kg. Unfortunately, we did not receive all of the vendor quotes for the cryogenic adsorbent system so the cost could not be calculated. For all the systems, the highest cost component was the storage vessel, with the hydrogen storage media a close second, and the BOP next. The HSECoE will be working on reducing the cost of the storage vessels in FY 2012.

TABLE 3. Estimated Storage System Baseline Costs

		Production Amount ($k)				
		10	1,000	10,000	130,000	500,000
Metal Hydride	Total Costs	$68.5k	$46.9k	$22.3k	$16.5k	$9.2k
	$/kWh					$49.3/kWh
Chem Hydride	Total Costs	$234k	$24.7k	$11.6k	$6.1k	$4.8k
	$/kWh					$25.6/kWh
Cryogenic Adsorbent	Total Costs	In Progress				
	$/kWh	In Progress				

Conclusions and Future Directions

- Solids and Materials Transport and System Design
  - Demonstrated on-off boarding of a solid material.
- Process Modeling and Engineering
  - Completed Simulink and COMSOL models:
    - Multiple designs
    - Multiple materials
  - Evaluated chemical hydride storage to predict that they can provide sufficient H_2 for the cold FTP drive cycle and the aggressive US06 drive cycles.
- Kinetics and Materials Property Measurements
  - Validated kinetic models with data.
  - Validated fixed bed reactor concept.
  - Discontinued Auger type reactor.
  - Completed reaction propagation tests.
  - Begun solid-liquid slurry work.
- BOP and Materials Reactivity and Compatibility
  - Completed BOP Library.
  - Detailed and sized BOP components for two chemical hydride systems, two metal hydride systems and cryogenic adsorbent systems.
  - Identified areas for decreasing mass and volume in BOP.
  - Identified technology gaps.
- Containment and Pressure Vessel Design
  - Developed cryogenic tank models:
    - Projected mass and volume of tanks.
    - Enables optimization of tank depending on pressure.

- Manufacturing and Cost Analysis
  - Completed cost analysis for metal hydride and chemical hydride systems.
  - Projected cost of AX-21 material $4/kg to $4.2/kg.
  - Initiated cost projection for cryo-sorbent system.

Future Work

For Phase II (FY 2012-FY 2013), the primary deliverable is detailed designs for a hydrogen storage system. To this end, we will:

Chemical Hydride System

- Detailed Design, Engineering and Analysis
  - Expand model to include additional physical properties.
  - Sensitivity analysis to determine the acceptable range of:
    - Viscosity
    - Settling/flocculation
    - Vapor pressure
    - Thermal stability
- Experimentally Validate Model Parameters
- Experimentally Validate Critical Components
- Solid-Liquid Slurry Development
  - Composition
  - Additives
- Work with HSECoE Partners in Detailed Design

BOP and Cost Analysis

- Value Engineering
  - Minimize mass and volume
  - Work with partners on BOP
  - Work with venders to push limits on components
- Pressure Vessel Engineering
  - Reduce cost, mass
  - Maintain safety
- Materials Compatibility/Reactivity
  - H_2 wetted material compatibility in components
- Cost Analysis
  - Complete cryo-sorbent
  - Work with partners, venders on reducing cost
  - Update analysis with detailed design

Patents Issued

1. Patent Application: Brooks, K., et.al. Variable Concentration Slurry Reactor System and Fixed Bed Reactor for Externally Regenerated Chemical Hydride System. Submitted. ID 16872-E

FY 2011 Publications/Presentations

Publications List

1. Devarakonda, M., Brooks, K.P., Rassat, S., and Rönnebro, E., "Systems Modeling, Simulation and Material Operating Requirements for Chemical Hydride Based Hydrogen Storage", International Journal of Hydrogen Energy (Submitted).

2. Rönnebro, E., Devarakonda, M., Brooks, K.P., Rassat, S., and Herling, D., "Dynamic Modeling and Simulation of Ammonia Borane Hydrogen Storage Systems", Proceedings of AIChE Annual Meeting, 2010.

3. Devarakonda, M., Holladay, J., Brooks, K.P., Rassat, S., and Herling, D., "Dynamic Modeling and Simulation Based Analysis of an Ammonia Borane (AB) Reactor System for Hydrogen Storage", ECS Transactions, 33(1), pp. 1959-1972, 2010.

4. Brooks, K.P., Devarakonda, M., Rassat, S., King, D.A., and Herling, D., "Systems Modeling of Ammonia Borane Bead Reactor for OnBoard Regenerable Hydrogen Storage in PEM Fuel Cell Applications", Proceedings of ASME 2010 Eighth Fuel Cell Science, Engineering and Technology Conference, Volume 1, ISBN: 978-0-7918-4404-5 pp. 729-734, 2010.

Presentations List

1. Brooks, K.P., Devarakonda, M.N., and Rassat, S.D., "Modeling of Chemical Hydrides in the HSECoE", SSAWG Annual Meeting, Denver, CO., Jan 11–12 2011.

2. Rönnebro, E., Devarakonda, M., Brooks, K.P., Rassat, S., and Herling, D., "Dynamic Modeling and Simulation of Ammonia Borane Hydrogen Storage Systems", AIChE Annual Meeting, Salt Lake City, UT., November 7–12, 2010.

3. Holladay, J., Brooks, K.P., Devarakonda, M., Rassat, S., King, D.A., and Herling, D., "Dynamic Modeling and Simulation Based Analysis of an Ammonia Borane (AB) Reactor System for Hydrogen Storage", 218th ECS Meeting, Las Vegas, NV., October 10–15, 2010.

4. Devarakonda, M., Brooks, K.P., Rassat, S., King, D.A., and Herling, D., "Systems Modeling of Ammonia Borane Bead Reactor for On Board Regenerable Hydrogen Storage in PEM Fuel Cell Applications", ASME 2010 Eighth International Fuel Cell Science, Engineering and Technology Conference, FuelCell2010-33272, Brooklyn, NY., June 14–16, 2010.

5. Rönnebro, E., Devarakonda, M., Brooks, K., Rassat, S., Simmons, K., Karkamkar, A., Herling, D., "Hydrogen Storage Materials Properties for Prototype System Concepts", Invited presentation, Hydrogen Technology Session at the Materials Challenges in Alternative & Renewable Energy Conference, Cocoa Beach, Florida, February 21–25, 2010.

6. Khalil, Y., Newhouse, N., Simmons, K., Dedrick, D., "Potential Diffusion-Based Failure Modes of Hydrogen Storage Vessels for On-Board Vehicular Use ," AIChE Annual Meeting, Salt Lake City, UT., November 7–12, 2010.

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1. Leavitt, M. and BA Johnson. January 2010. "Development of Advance Manufacturing Technologies for Low Cost Hydrogen Storage Vessel." DOE Hydrogen Program 2009 Annual Summary.

2. James, BD, GD Ariff, RC Kuhn. June 2002. "DFMA Cost Estimates of Fuel-Cell Reformer Systems at Low/Medium/High Production Rates." Presented at Future Car Congress 2002. Directed Technologies, Inc., Arlington, VA.