Research and Development Strategies for Compressed & Cryo-Hydrogen Storage Systems

Workshop Summary Report

Prepared by: Fuel Cell Technologies Program

Compressed & Cryo-Hydrogen
Storage Systems Workshops
February 14-15, 2011
Crystal City, Virginia

Research and Development Strategies for Compressed & Cryo-Hydrogen Storage Systems

Summary:

On February 14-15, 2011, the Systems Integration group of the National Renewable Energy Laboratory, in conjunction with the Hydrogen Storage team of the EERE Fuel Cell Technologies Program, hosted two days of workshops on compressed and cryo-hydrogen storage systems in Crystal City, VA. The overarching objective was to determine research, development and demonstration needs and technical pathways for these technologies, specifically identifying their unique requirements and issues that should be addressed that will enable the development and commercialization of these low-cost physical storage technologies.

The workshops brought together more than 50 developers, end users and experts from academia, industry (including fuel cell, automotive, oil and gas, aerospace, and chemical industries) and government, that are stakeholders in compressed and cryo-hydrogen storage technologies. The purpose of the compressed hydrogen storage workshop (Monday, February 14) was to identify strategies to lower the cost of highpressure hydrogen storage systems. Discussion focused on determining research strategies and technical pathways to lower costs while maintaining performance and safety and included three technical breakout sessions focused on 1) carbon fiber, 2) system balance of plant and 3) alternative materials and designs. The cryo-hydrogen storage system workshop (Tuesday, February, 15) focused on identifying the issues associated with performance and reliability of cryogenic hydrogen storage systems, including cryo-compressed and cryo-adsorption systems and included two technical breakout sessions on 1) R&D needs for technology validation and system balance of plant and 2) needs to facilitate development of codes and standards.

Sections 1 and 2 summarize the discussions that took place in the three breakout sessions.

Following the breakout sessions, each breakout group reported on the major findings. A wrap-up session was held to summarize the day's discussion where workshop participants provided final thoughts and proposed next steps and/or action items for the constituents and stakeholders.
Appendix A provides the workshop agenda, while Appendix B provides a list of the workshop participants. Additionally, Appendix C provides contact information for the workshop coordination team.

Major Findings

Compressed Hydrogen Storage System Workshop

- Since precursors are estimated to represent approximately 50% of the cost of carbon fibers, developing a low-cost precursor is a high-priority issue.

- Many of the fiber property requirements are end product dependent, which can lead to over-specification and drive up costs. Data sharing between carbon fiber and tank manufacturers and/or inexpensive standard test methods for measuring fiber properties could be used to alleviate these issues.
- Across all technologies, risk must be reduced in order to make the products more attractive to market. Development of stringent technical standards could help reduce risk in manufacturing of carbon fiber and furthermore, in manufacturing vessels.
- OEM's currently receive CF from manufacturers in small spools, which drives up labor costs by requiring frequent spool change-outs while manufacturing high-pressure tanks. Tank manufacturing OEM's could significantly reduce associated labor costs by receiving larger spools of CF.
- BOP components should move toward standardization to maximize economy-of-scale cost reductions and optimize the level of parts integration. The focus should be on process optimization and manufacturing development
- Hydrogen production and delivery infrastructure is unlikely to allow major modifications in hydrogen fueling stations to accommodate future options in the storage vessels once they are in place. Compressed hydrogen storage development efforts must build & maintain very close interfacing with the production and delivery teams to mutually meet requirements.

Cryo-Hydrogen Storage System Workshop

- Cryo-compressed and cryo-sorbent hydrogen storage systems present significant challenges on the structural and thermal stabilities of the vessel wall materials; to start to understand these effects there must be an effort to gather available data (i.e., NASA, DOE Lab, etc.) on composites & cryogenic components development and create data clearinghouse to consolidate knowledge; also identify industry experts and users.
- The energy penalty associated with hydrogen compression and liquefaction along with the potential for greenhouse gas production needs to be studied. Life-cycle analysis versus energy penalty is needed to determine the point at which market penetration makes the compression energy penalty significant.
- Global harmonization of regulations, codes and standards is critical to the deployment of fuel cell technologies in markets worldwide. The Global Technical Regulation (GTR) is the key harmonizing document that will contain critical components of SAE, CSA and ASME standards and efforts should be performed to integrate regulations for these new technologies.
- Approximately 90% of all development costs are in the qualification of vessels and/or systems, so OEMs cannot afford to repeat tests due to loosely defined testing protocols. Additionally, there are very limited certified testing facilities at each level of development/qualification (i.e., materials, component and system levels), so government funding of certified testing facilities could help reduce the development costs of these systems.
- Material, component and system level data is also needed for risk evaluation. Going forward, for insurance companies to insure these types of vessels and/or systems, data is needed for modeling, simulating and evaluating risk scenarios.

Section 1 - Research and Development Strategies for Compressed Hydrogen Storage Systems

The compressed H_2 storage systems workshop began with welcoming, introductions and workshop scope from DOE acting Hydrogen Storage Team Lead, Dr. Ned Stetson, and moved into a plenary session that included presentations by several experts from industry and national laboratories. Subjects within the scope of the workshop were i) the "on-board" storage system, ii) ambient temperature storage, and iii) materials of construction, manufacturing/processing while out-of-scope items included off-board compression, storage dispensing and cryo-storage. The presentations gave a comprehensive overview of the current state-of-the-art of compressed H_2 cylinders including the automotive OEMs perspective, cost analysis, carbon fiber development and a manufacturing perspective. The plenary presentations included the following:

- Wolfgang Oelerich, *GM/Opel*, "General Motors Perspective" http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_2_oelerich.pdf
- Jeff Rosenfeld, *TIAX LLC*, "Analysis of Compressed Hydrogen On-board Storage Systems" http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_3_rosenfeld.pdf
- David Warren, *ORNL*, "Lower Cost, Higher Performance Carbon Fiber" http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_4_warren.pdf
- Karl Nelson, *Boeing*, "Compressed Hydrogen Storage Workshop: Manufacturing Perspective." http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_5_nelson.pdf

Each of the plenary presentations generated significant discussions that were used to provide the framework for the technical breakout sessions. Three focused topics were defined and the workshop participants were divided according to interest and expertise into the three groups that addressed the following:

1) What are the RD&D needs required to lower the cost of carbon fiber for compressed H_2 tanks?
2) What are the RD&D needs required to lower the cost or reduce system balance of plant?
3) Are there alternative materials and or tank designs that could help to significantly reduce the cost of compressed H_2 storage?

Technical Breakout Group 1: What are the RD&D needs required to lower the cost of carbon fiber for compressed H_2 storage?

Inexpensive storage vessels for compressed hydrogen gas are critical to the widespread commercialization of hydrogen fuel cells in early market and light-duty vehicle applications. Currently high-pressure (i.e., 350 to 700 bar) storage vessels are constructed using expensive high-strength carbon fiber, such as Toray T700, in a composite matrix as an overwrap to contain the stress [1, 2, 3]. In fact, cost analyses have predicted that carbon fiber makes up approximately 80% of the cost of high pressure storage vessels [3]. Low-cost carbon fiber precursors, low-cost carbon fiber manufacturing processes or process optimization, alternative structural materials such as glass or other inexpensive fibers, and advanced fiber material characterization are all potential solutions to reducing the cost of carbon fiber and high-pressure tank manufacturing process. Before compressed hydrogen gas storage vessel technology can move forward to widespread applications, solutions must be developed to achieve substantial cost reductions.

Major Findings and/or Key Issues

- Precursors are estimated to represent approximately 50% of carbon fiber manufacturing costs!
- Data sharing between carbon fiber and tank manufacturers could allow use of a wider variability in produced carbon fiber.
- Need simple, inexpensive standard test methods for carbon fiber mechanical properties.
- Multi-fiber configurations could significantly increase fiber usage efficiency by distribution of translational forces across fibers.
- Higher volume (>20 lbs.) spools could significantly reduce labor costs for tank

1. Since precursors are estimated to represent approximately 50% of carbon fiber manufacturing costs, what are the requirements to develop low-cost carbon fiber precursors?

- Identify key fiber properties and requirements such as ultimate tensile strength, and tensile modulus for the application
- Perform parallel efforts to identify existing lower cost precursors that could successfully be made into fibers and develop new low-cost precursors to meet the application specifications
- Test precursors at pilot scale

2. How do we minimize variability and/or increase useable contents of currently produced carbon fiber?

- Need stringent QC parameters for process optimization
  - Currently, CF manufacturers do not share detailed QC information about spools requiring manufacturers to over-design for the worst case scenario. More complete data or data-sharing on material properties could be used to justify the use of CF that is deemed to be outside of acceptable ranges.

    - Currently there is no true standard to determine tensile strength of fibers. Manufacturers and OEMs need standard test methods for CF to ensure proper mechanical properties and/or to reduce wasted CF.
    - OEMs would benefit greatly by having a rapid method for determining mechanical properties of received CF since they get limited data from CF manufacturers
    - Alternatively, OEMs would benefit from more detailed CF spool material data from the manufacturers rather than average lot data, namely;
        - Histogram of tensile and modulus strengths.
    - CF manufacturers need inexpensive, advanced material characterization methods for in-line monitoring including;
        - Density during oxidation
        - Defect structure
        - Resistivity before/after carbonization.

3. Can inexpensive alternative fibers be used to replace/reduce amount of carbon fiber?

- A multi-fiber (CFs with different tensile strengths or different fibers) approach could take advantage of the different translational forces observed by the fibers to increase the fiber usage efficiency and reduce the cost of the fiber overwrap.
    - RD&D is needed to determine CF modulus compatibility and winding designs
- It would be useful to screen alternative fibers that have potential application in filament winding. The outcome would likely demonstrate multiple lower strength and cost fibers that could be used to replace current high strength CFs. Some significant variables would be durability, strain/strength, resin compatibility and interfacial adhesion, etc. Suggested fibers for screening include;
    - PAN based CF 34 to 67 Msi
    - Pitch based CF 90 to 125 Msi or higher
    - Metal coated CF of all modulus (Cu, Ni, Fe, Ag, etc.)
    - Fiber glass Type E,A, C, AR and S
    - Metal coated fiberglass of all types (Al, Cu, Ni, etc.)
    - Basalt fiber
    - Quartz fiber
    - Aramid type 29, 49 and generic
    - Zylon fiber of various modulus
    - Polyethylene fiber
    - Polyester fiber
    - Metal wire.

4. What are some of the "low hanging fruits" associated with carbon fiber that could be implemented to reduce the cost of high-pressure tank production?

- High volume packaging of CF – OEM's currently receive CF from manufacturers in spools of no larger than 20 lbs. which drives up labor costs by requiring frequent spool change-outs while manufacturing high-pressure tanks.

- CF manufacturers currently do not have the capability to perform high volume processing (>> 10-20 feet/min) due to equipment limitations, while analogous glass fiber can be manufactured at about two orders of magnitude faster. Investments in process optimization and machining equipment for high volume spooling would have an immediate impact on reducing the cost of CF.

Technical Breakout Group 2: What are the RD&D needs required to lower the cost or reduce system balance of plant?

Major Findings and/or Key Issues

- Safety requirements should be dependent on end-of-life performance (not on beginning-of-life).
- Life-cycle and reliability must be integrated to meet acceptable consumer safety. Standardized procedures for the qualification of BOP materials and components need to be developed and adopted by the hydrogen storage system developers and designers including procedures for qualification under cycling conditions (i.e., thermal, pressure, etc.).
- Move toward standardization of BOP components to maximize economy-of-scale cost reductions and optimize the level of parts integration. The focus should be on process optimization and manufacturing development

1. How do we reduce Balance of Plant (BOP) costs?

- The important BOP components are:
  - Tubing/fittings,
  - Tank valves,
  - Pressure regulators/transducers,
  - Fixtures/brackets,
  - Sensors-H_2, pressure, temperature, etc.,
  - Receptacles,
  - Pressure Relief Devices (PRD).
- OEMs need to analyze trade-offs between costs and market penetration looking at factors such as pressure and gravimetric density in order to fully define BOP requirements and functions.
  - The trade-off studies need to consider the interdependence of Cost/Performance/Safety factors.
  - The BOP cost drivers are primarily materials and system complexity.
  - Most BOP components are currently made of either high nickel content stainless steel (316L – 2% nickel) or aluminum (6061) which is very expensive.
  - Perhaps other materials of construction could be developed and substituted to reduce costs.
- BOP optimization requires trade-off of weight, cost and performance factors.
  - Component reliability must be traded-off versus life cycle costs.
  - Component reliability and performance requirements should be consistent with system function and projected cycle life might allow reduced component costs. For example, a more expensive valve with a response time 50 msec might be used as a BOP component where the system requires only a 1 second response allowing use of a less expensive component.
- Integration of BOP parts could optimize trade-off of system complexity versus part count.
  - Design studies that minimized part count while maintaining acceptable levels of system complexity could be very beneficial in reducing BOP costs.
  - Reducing the number of component vendors and standardization of components in the BOP would be desirable and could result in reduced costs.

2. Are there special BOP requirements related to multi-tank configurations?

- Single and multi-tank storage systems should be compared and analyzed to determine cost, performance and safety trade-offs.
- Do two tanks require double the BOP or is there a possibility of common BOP components (a parts list economy of scale)?
- Where would pressure reduction be accomplished in multiple tank systems and what are the implications on BOP?
- There are expanding alternative fuel markets in Asia and it should be worthwhile to determine what BOP components they use in hydrogen storage systems instead of focusing on current USA costs.

3. **What are the safety considerations related to BOP?**

- There is a definite need for uniform safety guidelines (which currently appear to be inconsistent) specifically for BOP components and subsystems.
  - DOE laboratories perform materials testing, but how is it communicated to outside users?
  - NASA has existing hydrogen standards but mostly for different operating conditions.
- Hydrogen compatibility is key where wetted surfaces need to be compatible under all reasonable circumstances.
  - Component interfaces and joining must be reliable and robust throughout operating life.
  - Nearly all of BOP materials are constructed of metals.
  - Japan presently requires 316L Stainless Steel construction for hydrogen systems.
- Safety requirements should be dependent on end-of-life performance (not on beginning-of-life).
- Life-cycle and reliability must be integrated to meet acceptable consumer safety. Standardized procedures for the qualification of BOP materials and components need to be developed and adopted by the hydrogen storage system developers and designers including procedures for qualification under cycling conditions (i.e., thermal, pressure, etc.).
- Materials and component testing data from DOE, NASA, & others should be collected and evaluated in a consistent manner.

4. A possible "path forward" to achieve lower BOP costs:

- Materials R&D
  - Enhance the understanding of hydrogen effects on BOP materials-of-construction,
  - Develop new high-performance, low-cost alloys that meet compatibility and safety requirements,
  - Develop lower-cost sealing materials (sealing surfaces, interfaces exposed to hydrogen),
  - Develop materials-of-construction that have required secondary functions (e.g. magnetic properties);

- Move toward standardization of BOP components to maximize economy-of-scale cost reductions and optimize the level of parts integration. The focus should be on process optimization and manufacturing development;
- Understand the implications of hydrogen fatigue on BOP components;
- Conduct a generalized BOP system reliability analysis with the goal of developing a "standardized" BOP functional schematic;
- Optimize pressure distribution within the BOP system keeping pressures as low as possible through as much of the system as possible;
- Actively involve BOP component manufacturers/experts with DOE & NASA researchers on both materials/components assessments and cost analysis/cost reduction studies.

Technical Breakout Group 3: Are there alternative materials and or tank designs that could help to significantly reduce the cost of compressed H_2 storage?

Major Findings and/or Key Issues

- Substantial cost reductions will require novel high-risk/reward concepts rather than incremental design or material changes to Type-3 and Type-4 carbon-wrapped tanks.
- Systematic trade studies should look for an optimized balance between performance and cost regarding operating pressures and vehicle demands.
- Total costs for hydrogen storage is a complex issue of designs and materials with unclear impacts of customer acceptance levels for higher performance.
- Hydrogen production and delivery infrastructure is unlikely to allow major modifications in hydrogen fueling stations to accommodate future options in the storage vessels once they are in place.

- Incremental design changes to current Type-3 & Type-4 carbon-wrapped tanks will not be sufficient to greatly lower their costs (Need better high risk/reward concepts)
  - Type-2 hoop wrap tanks are more viable for buses, utility/service vehicles if costs could be much lower than other configurations.
  - Type-4 tanks require alternative materials for liners (i.e., mylar, unlined, etc.) and for the aerospace carbon fibers (i.e., optimized commercial carbon, glass fibers, nanofibers, others?). However, validations of strength & permeation/leak integrity remain issues for lower cost/performance materials.
  - Would an intermediate operating pressure between 350 and 700 bar (i.e., ~500 bar) provide an optimized balance between performance & costs? Unaware of any trade study on the impact.
  - Develop multifunctional designs (e.g., incorporate the tank into vehicle as a structural component).
  - Re-examine metal options for tank construction that will remain hydrogen/ pressure compatible, but have lower material, processing, and/or fabrication costs.

- Extend storage vessel operating life by designing for refurbishment after a period of time for reuse.
  - Inspection & certification could be major issue with codes & standards and also a liability issue.

- Total costs of storage tanks and vehicle is a complex problem for determining where choices should be made for designs & materials.
  - Lack of comparable sales and customer data from existing vehicles to justify costs although recent information might come from CNG and EV sales.
  - Maturity of the hydrogen gas infrastructure could dictate storage options since suppliers are probably unwilling or unable to make significant changes in fuel stations after the first generation (i.e., won't build these systems twice).

- Compressed hydrogen storage development efforts must build & maintain very close interfacing with the production and delivery teams to mutually meet requirements.

References

[1] *System Level Analyses of Hydrogen Storage Options*, Proceeding of 2010 DOE Annual Merit Review, available on the DOE/FCT website: http://www.hydrogen.energy.gov/pdfs/review10/st001_ahluwalia_2010_o_web.pdf.

[2] *Analyses of Hydrogen Storage Materials and On-Board Systems*, Proceeding of 2010 DOE Annual Merit Review, available on the DOE/FCT website: http://www.hydrogen.energy.gov/pdfs/review10/st002_lasher_2010_o_web.pdf.

[3] *Technical Assessment of Compressed Hydrogen Storage Tank Systems for Automotive Applications*, September 2010, published on the DOE/FCT website: http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressedtank_storage.pdf.

Section 2 - Research and Development Strategies for Cryo-Hydrogen Storage Systems

The cryo-hydrogen storage systems workshop began with welcoming, introductions and a recap from the previous day's workshop on compressed H_2 storage from Dr. Stetson. Dr. Stetson then presented the guidelines of the workshop including the scope. Subjects within the scope of the workshop were i) the "on-board" system hardware, ii) materials of construction and design, and iii) on-board operation, while out-of-scope items included off-board compression, storage dispensing and overall efficiency (i.e., energy penalty for liquefaction, etc.). An abbreviated plenary session followed, which included presentations that framed the OEM perspective on cryogenic H_2 storage and a review of DOE-sponsored performance and cost analyses of cryogenic H_2 storage systems. The plenary presentations included the following:

- Tobias Brunner, *BMW*, "OEM Perspective on Cryogenic H_2 Storage"
  http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_7_brunner.pdf

- Rajesh Ahluwalia, *ANL*, "Performance Comparison and Cost Review."
  http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_8_ahluwalia.pdf

Succeeding the plenary session, an expert panel discussion was held where technology developers briefly presented cryo-hydrogen storage system technology updates followed by an open question and answer session. The expert panel included the following:

- Salvador Aceves, *LLNL*, Cryo-Compression Systems Development Status
  http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_9_aceves.pdf

- Richard Chahine, *UQTR Canada,* Sorption Storage Technology Summary
  http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_10_chahine.pdf

- David Chato, *NASA-Glenn*, NASA Perspectives on cryogenic H_2 storage
  http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/compressed_hydrogen2011_11_chato.pdf

Each of the morning presentations generated significant discussions that were used to provide the framework for the technical breakout sessions. Two focused topics were defined and the workshop participants were divided according to interest and expertise between two groups that addressed the following:

1) What are the key R&D tasks needed for cryo-hydrogen storage to validate the technologies? And what are the BOP needs?
2) What is needed to develop codes and standards for cryo-based storage technologies?

Technical Breakout Group 1: What are the key R&D tasks needed for cryo-hydrogen storage to validate the technologies? And what are the BOP needs?

Cryo-compressed and cryo-sorbent hydrogen storage systems present significant challenges on the structural and thermal stabilities of the vessel wall materials: For example, at the start of refueling the tank sees minimum pressure and an operational history dependent temperature between cryogenic and ambient. On the other hand, when refueling processes are complete, the tank experiences lower cryogenic (i.e., in range from ~20 K to ~100 K) temperatures and also much higher pressure causing the tank walls to experience maximum thermal and mechanical stresses immediately following refueling. Hence, vessel designs should incorporate appropriate factors of safety to ensure reliability and robustness. Improved strain gauges that operate at cryogenic temperatures are also needed for stress testing.

Major Findings and/or Key Issues

- Gather available data (i.e., NASA, DOE Lab, etc.) on composites & cryogenic components development and create data clearinghouse to consolidate knowledge; also identify industry experts and users.
- Need to identify industry experts and users and solicit their active participation in RD&D.
- Experimental validation of integrated cryogenic storage systems (not just materials) need to show that performance levels are met reliably and safely throughout end-of-life operations.
- The energy penalty associated with hydrogen compression and liquefaction along with the potential for green house gas production needs to be studied. Life-cycle analysis vs. energy penalty is needed to determine the point at which market penetration makes the compression energy penalty significant.

1. Tanks and tank systems R&D needed:

- Cryo-compatible resin systems and issues of temperature swings during processing/ fabrication.
- Temperature and pressure cycling effects across operating ranges; stress/strain model validation (whole tank experiments with appropriate pressurization techniques).
- Cryogenic thermal expansion (CTE) issues in liner-overwrap interface; issues of matrix cracking and auto-frettage in modeling and operation present a technology gap in the area of strength/design optimization
- Gather available data (i.e., NASA, DOE Lab, etc.) on composites and cryogenic component development and create data clearinghouse to consolidate knowledge; also identify industry experts and users.

2. Thermal management R&D needed:

- Efficient, lightweight MLVSI/thermal isolation systems: impact of outgassing, lifecycle, etc.; where reliable and durable insulation is a key issue for cryo-systems advanced development. Gather and standardize on reliable, transparent approaches to analysis.

- Outgassing needs to be minimized (and characterized) and vacuum requirements need to be defined to minimize radiation and conductive heat transfer losses.
- Boil-off as a function of vacuum in the multi-layer insulation (MLI) needs to be characterized. How good must the insulation finally be – needs to be determined. How much boil-off is acceptable from a design point of view?
- Optimization of insulation systems on a "per-application/best effort" basis with assistance of industry experts (i.e., the NASA "Lockheed Equation", which is not familiar to DOE/OEMs)
- Optimization of heat exchange (HX) approaches for cCH2 and adsorbent systems
- Powder bed heat/mass transport optimization for cryo-sorbents

3. BOP Components R&D needed to develop reliability at minimal cost (i.e., don't over specify the requirements):

- Conduct broad-based surveys of cryo/delta-P material compatibility (valves, seats, seals, wetted components, etc.) – contact DOE, NASA, DOT, & vendor organizations.
- Identify/develop cryo-valves that are leaktight, lightweight, and "inexpensive".
- Fuel sensors, gauges
- High pressure/flow rate H_2 pump/fan (gaseous and/or liquid)
- Safety devices (Pressure Relief Devices [PRDs], vent-combustor, etc.)
- Fittings/couplings, pressure systems assembly, etc.
- Filters to prevent powder and particulate migrations (mainly adsorbents)
- Getters to maintain vacuum levels in insulation volume & MLI layers.

4. General issues/questions:

- Particulate generation/powder decrepitation of sorbents due to thermal cycling
- What data are required for lowering safety factors in deployed systems?
- Considerations of near- vs. long-term issues for adoption of H_2 infrastructure (i.e., market penetration, business case validity, consumer behavior, etc.)
- General survey of industry/expert reliability and failure mode histories (as much as is available); how do we avoid the mistakes of the past?
- Consumer/customer safety issues need to be identified and addressed – failure mode analyses are needed. Simulation to study safety issues doesn't work – fully integrated systems safety testing including liquid delivery/production are needed (smaller scale testing may be sufficient).
- The energy penalty associated with hydrogen compression and liquefaction along with the potential for green house gas production needs to be studied. Life-cycle analysis vs. energy penalty is needed to determine the point at which market penetration makes the compression energy penalty significant.

Technical Breakout Group 2: What is needed to develop codes and standards for cryo-based storage technologies?

1. How do we ensure consistent codes and standards communicated globally?

> **Major Findings and/or Key Issues**
>
> - Global harmonization of regulations, codes and standards is critical to the deployment of fuel cell technologies in markets worldwide.
> - Approximately 90% of all development costs are in the qualification of vessels and/or systems, so OEMs cannot afford to repeat tests due to loosely defined testing protocols.
> - There are very limited certified testing facilities at each level of development/qualification (i.e., materials, component and system levels), so government funding of certified testing facilities could help reduce the development costs of these systems.
> - Material, component and system level data is also needed for risk evaluation. Going forward, for insurance companies to insure these types of vessels and/or systems, data is needed for modeling, simulating and evaluating risk scenarios.

- Global harmonization of regulations, codes and standards is critical to the deployment of fuel cell technologies in markets worldwide.
- The Global Technical Regulation (GTR) is a key harmonizing document that will contain critical components of SAE, CSA, ASME, etc. and other member country sourced standards.
- The GTR phase II will begin in 2011. Efforts should be performed to integrate regulations for new technologies such as cryo-based systems into the Phase II document.
- Automotive standards and component standards (SAE, CSA, ASME, etc.) may need a separate section that focuses on cryo-based technologies.

2. What are the R&D needs in order to ensure adequate codes and standards are developed?

- Currently, there is not adequate data or comprehensive lists of cryo-compatible materials
    - Need more comprehensive list of cryo-compatible materials (i.e., metals and composites)
    - Need characterization of low temperature H_2 compatibility of materials
    - Need to develop a list of cryo-compatible valve seals
    - Need more development on reliable venting relief valves as cryogenic vessels routinely need to be vented during operation
- Uniform and appropriate testing/qualification procedures are needed among all applications

    - Approximately 90% of all development costs are in the qualification of vessels and/or systems, so OEMs cannot afford to repeat tests due to loosely defined testing protocols.
    - There are very limited certified testing facilities at each level of development/ qualification (i.e., materials, component and system levels), so government funding of certified testing facilities could help reduce the development costs of these systems. Also, each development level needs appropriate life-cycle test procedures.
    - These testing procedures/standards should leverage previous requirements documents written internally within NASA and DOD. Need to ensure that any standards are performance based.
    - Research should be performed to develop new performance-based test procedures (e.g., new section in SAE J2579 devoted to cryo-test protocols)
- Material, component and system level data is also needed for risk evaluation. Going forward, for insurance companies to insure these types of vessels and/or systems, data is needed for modeling, simulating and evaluating risk scenarios.

Appendix A: Workshop Agendas

Monday, February 14, 2011 – <u>Compressed Hydrogen Storage Systems</u>

8:30 **Welcome/Introductions/Workshop objectives**
Ned Stetson, DOE

9:00 **OEM Perspective** (20 min presentation/20 min discussion)
Wolfgang Oelerich, GM/Opel

9:40 **Performance and Cost Analysis Review** (20 min presentation/20 min discussion)
Jeff Rosenfeld, TIAX

10:20 *Break* (10 minutes)

10:30 **Fiber Development Status** (20 min presentation/20 min discussion)
David Warren, ORNL

11:10 **Manufacturing Perspective** (20 min presentation/20 min discussion)
Karl Nelson, Boeing

11:50 **Review of morning discussions** (10 minutes)

12:00 *Lunch* (1 hour)

1:00 **Breakout session objectives and topics discussion**

2:00 **Breakout sessions**

3:00 *Break* (15 minutes)

3:15 **Breakout session summaries**

4:00 **General discussion on research needs and technical pathways**

4:45 **Wrap-up and discussion of Feb. 15th workshop**

5:00 *Adjourn*

Tuesday, February 15, 2011 – Cryogenic Hydrogen Storage Systems

8:30 **Welcome/Introductions/Workshop objectives/Recap of previous day**
Ned Stetson, DOE

9:00 **OEM Perspective on Cryogenic H_2 Storage** (20 min presentation/20 min discussion)
Tobias Brunner, BMW

9:40 **Performance Comparison and Cost Review** (20 min presentation/20 min discussion)
Rajesh Ahluwalia, ANL

10:20 *Break* (10 minutes)

10:30 **Expert Panel Discussion** (Members will each have 15 minutes for presentations)

- Cryo-Compression Systems Development Status
  Salvador Aceves, LLNL
- Sorption Storage Technology Summary
  Richard Chahine, UQTR Canada
- Cryogenic Tanks (CNG & H2) Manufacturing Perspective
  William Clinkscales, Structural Composites, Inc (invited)
- NASA Perspectives on cryogenic H_2 storage
  David Chato, NASA-Glenn

12:30 *Lunch* (1 hour)

1:30 **Review of morning discussions** (10 minutes)

1:40 **Breakout sessions**

3:15 *Break* (15 minutes)

3:30 **Breakout session summaries**

4:00 **General discussion on research needs and technical pathways**

4:45 **Wrap-up**

5:00 *Adjourn*

Appendix B: Final Participant Lists

Compressed Hydrogen Storage Systems Workshop (Day 1)
February 14, 2011
Crystal City, Virginia

Salvador Aceves
LLNL
925-422-0864
saceves@llnl.gov

Rajesh Ahluwalia
ANL
630-252-5979
walia@anl.gov

Larry Blair
DOE
505-259-5009
blairls@swcp.com

Bob Bowman
ORNL/DOE
rcbjr1967@gmail.com

Robert Boyd
Consultant
925-330-6838
boyd.hydrogen@gmail.com

Peter Bradley
NIST
303-497-3465
pbradley@boulder.nist.gov

Tobias Brunner
BMW Group
749-776-608-57224
Tobias.a.brunner@bmw.de

Robert Burgess
NREL
303-275-3823
Robert.burgess@nrel.gov

David Chato
NASA-GRC
216-977-7488
David.J.Chato@nasa.gov

Mike Clinch
Luxfer
Mike.Clinch@luxfer.net

Daniel Dedrick
SNL
925-294-1552
Dededri@sandia.gov

Mike Dohorty
NASA/Glenn Research Center
216-433-6641
Michael.P.Dohorty@nasa.gov

John Eihusen
Lincoln Composites
402-470-5031
jeihusen@lincolncomposites.com

Josh Gesick
NREL
josh.gesick@nrel.gov

Nathanael Greene
NASA-WSTF
575-202-2372
Nathanael.greene@nasa.gov

Kiyoshi Handa
Honda
81-28-677-6889
Kiyosh_handa@n.t.rd.honda.co.jp

Bruce Hardy
SRNL
803-646-4082
Bruce.hardy@srnl.gov

Aaron Harris
Nuvera
617-245-7592
aharris@nuvera.com

Barb Hennessey
DOT/NHTSA
202-366-4714
Barbara.Hennessey@dot.gov

Kevin Hofmaenner
BCS
202-586-3632
Kevin.hofmaenner@ee.doe.gov

Hamid Kia
GM
586-986-1215
Hamid.kia@gm.com

Mark Leavitt
Quantum Technology
949-399-4584
mleavitt@qtww.com

Scott McWhorter
DOE/SRNL
803-507-8543
Christopher.McWhorter@ee.doe.gov

Rana Mohtadi
Toyota
734-995-4012
Rana.mohtadi@tema.toyota.com

Karl Nelson
Boeing
206-313-2358
Karl.M.Nelson@boeing.com

Wolfgang Oelerich
GM
49-614-276-7626
Wolfgang.oelerich@gm.com

Grace Ordaz
DOE
202-586-8350
Grace.ordaz@ee.doe.gov

George Parks
ConocoPhillips
918-914-3420
fuelscience@gmail.com

Walt Podolski
ANL
630-252-7588
podolski@anl.gov

Carole Read
DOE
Carole.read@ee.doe.gov

Joe Reiter
JPL
818-354-4224
Joseph.W.Reiter@jpl.nasa.gov

Richard E. Ricker
NIST
301-975-6023
Richard.ricker@nist.gov

Carl Rivkin
NREL
303-275-3834
Carl.Rivkin@nrel.gov

Jeff Rosenfeld
TIAX
408-517-1562
Rosenfeld.jeff@tiaxllc.com

Ichiro Sakai
Honda
202-661-4400
ichiro_sakai@ahm.honda.com

Kevin L. Simmons
PNNL
509-375-3651
Kevin.simmons@pnl.gov

Lin Simpson
NREL
303-384-6625
Lin.simpson@nrel.gov

Ned Stetson
DOE
202-586-9995
Ned.stetson@ee.doe.gov

Dave Stinton
ORNL
865-574-4556
Stintondp@ornl.gov

Andrea Sudik
Ford
313-390-1376
asudik@ford.com

David A Tamburello
SRNL
803-725-7716
David.Tamburello@srnl.doe.gov

Pascal Tessier
Air Liquide
302-286-5493
Pascal.tessier@airliquide.com

Mark Trudgeon
Luxfer
951-232-6570
Mark.Trudgeon@luxfer.net

Bart A. Van Hassel
UTRC
860-610-7701
vanhasba@utrc.utc.com

Mike Veenstra
Ford
313-322-3148
mveestra@ford.com

C S Wang
GM
248-912-8390
c.wang@gm.com

Scott Weil
DOE
504-737-7346
Kenneth.weil@ee.doe.gov

Wei Zhang
ORNL
865-241-4905
zhangw@ornl.gov

Cryo-Hydrogen Storage Systems Workshop (Day 2)
February 15, 2011
Crystal City, Virginia

Salvador Aceves
LLNL
925-422-0864
saceves@llnl.gov

Rajesh Ahluwalia
ANL
630-252-5979
walia@anl.gov

Don Anton
SRNL
803-860-8771
Donald.anton@srnl.doe.gov

Larry Blair
DOE
505-259-5009
blairls@swcp.com

Bob Bowman
ORNL/DOE
rcbjr1967@gmail.com

Robert Boyd
Consultant
925-330-6838
boyd.hydrogen@gmail.com

Peter Bradley
NIST
303-497-3465
pbradley@boulder.nist.gov

Tobias Brunner
BMW Group
749-776-608-57224
Tobias.a.brunner@bmw.de

Robert Burgess
NREL
303-275-3823
Robert.burgess@nrel.gov

Mei Cai
GM
586-596-4382
Mei.cai@gm.com

Richard Chahine
UQTR
819-376-5139
Richard.chahine@uqtr.ca

David Chato
NASA-GRC
216-977-7488
David.J.Chato@nasa.gov

Mike Clinch
Luxfer
Mike.Clinch@luxfer.net

Daniel Dedrick
SNL
925-294-1552
Dededri@sandia.gov

Mike Dohorty
NASA/Glenn Research Center
216-433-6641
Michael.P.Dohorty@nasa.gov

John Eihusen
Lincoln Composites
402-470-5031
jeihusen@lincolncomposites.com

Josh Gesick
NREL
josh.gesick@nrel.gov

Nathanael Greene
NASA-WSTF
575-202-2372
Nathanael.greene@nasa.gov

Kiyoshi Handa
Honda
81-28-677-6889
Kiyosh_handa@n.t.rd.honda.co.jp

Bruce Hardy
SRNL
803-646-4082
Bruce.hardy@srnl.gov

Aaron Harris
Nuvera
617-245-7592
aharris@nuvera.com

Barb Hennessey
DOT/NHTSA
202-366-4714
Barbara.Hennessey@dot.gov

Kevin Hofmaenner
BCS
202-586-3632
Kevin.hofmaenner@ee.doe.gov

Hamid Kia
GM
586-986-1215
Hamid.kia@gm.com

Mark Leavitt
Quantum Technology
949-399-4584
mleavitt@qtww.com

Scott McWhorter
DOE/SRNL
803-507-8543
Christopher.McWhorter@ee.doe.gov

Rana Mohtadi
Toyota
734-995-4012
Rana.mohtadi@tema.toyota.com

Karl Nelson
Boeing
206-313-2358
Karl.M.Nelson@boeing.com

Wolfgang Oelerich
GM
49-614-276-7626
Wolfgang.oelerich@gm.com

Grace Ordaz
DOE
202-586-8350
Grace.ordaz@ee.doe.gov

George Parks
ConocoPhillips
918-914-3420
fuelscience@gmail.com

Walt Podolski
ANL
630-252-7588
podolski@anl.gov

Alex Raymond
JPL
818-354-1209
Alexander.w.raymond@jpl.nasa.gov

Carole Read
DOE
Carole.read@ee.doe.gov

Joe Reiter
JPL
818-354-4224
Joseph.W.Reiter@jpl.nasa.gov

Richard E. Ricker
NIST
301-975-6023
Richard.ricker@nist.gov

Carl Rivkin
NREL
303-275-3834
Carl.Rivkin@nrel.gov

Jeff Rosenfeld
TIAX
408-517-1562
Rosenfeld.jeff@tiaxllc.com

Ichiro Sakai
Honda
202-661-4400
ichiro_sakai@ahm.honda.com

Kevin L. Simmons
PNNL
509-375-3651
Kevin.simmons@pnl.gov

Lin Simpson
NREL
303-384-6625
Lin.simpson@nrel.gov

Ned Stetson
DOE
202-586-9995
Ned.stetson@ee.doe.gov

Dave Stinton
ORNL
865-574-4556
Stintondp@ornl.gov

Andrea Sudik
Ford
313-390-1376
asudik@ford.com

David A Tamburello
SRNL
803-725-7716
David.Tamburello@srnl.doe.gov

Pascal Tessier
Air Liquide
302-286-5493
Pascal.tessier@airliquide.com

Mark Trudgeon
Luxfer
951-232-6570
Mark.Trudgeon@luxfer.net

Bart A. Van Hassel
UTRC
860-610-7701
vanhasba@utrc.utc.com

Mike Veenstra
Ford
313-322-3148
mveestra@ford.com

C S Wang
GM
248-912-8390
c.wang@gm.com

Scott Weil
DOE
504-737-7346
Kenneth.weil@ee.doe.gov

Wei Zhang
ORNL
865-241-4905
zhangw@ornl.gov

Appendix C: Workshop Contact Information

Workshop Coordination Team:

Ned Stetson
Ned.stetson@ee.doe.gov

Bob Bowman
rcbjr1967@gmail.com

Larry Blair
blairls@swcp.com

Kevin Hofmaenner
Kevin.hofmaenner@ee.doe.gov

Mike Tuttelman
Mike_Tetelman@sra.com

Workshop Facilitation Team:

Ned Stetson
Ned.stetson@ee.doe.gov

Bob Bowman
rcbjr1967@gmail.com

Larry Blair
blairls@swcp.com

Scott McWhorter
Christopher.McWhorter@ee.doe.gov

For further information, contact:
Ned Stetson, U.S. Department of Energy (Fuel Cell Technologies Program, Office of Energy Efficiency and Renewable Energy)

Or see http://www1.eere.energy.gov/hydrogenandfuelcells/