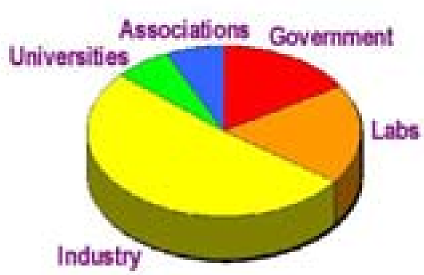
Manufacturing R&D for the Hydrogen Economy Workshop: Summary Report

About the Workshop

On July 13-14, 2005, representatives from the hydrogen, fuel cell, and manufacturing communities gathered in Washington D.C. to develop a roadmap for R&D on manufacturing for the hydrogen economy. The workshop was led by the U.S. Department of Energy, supported by the National Institute of Standards and Technology (NIST), and coordinated with the Manufacturing Research and Development Interagency Working Group (IWG) of the President's National Science and Technology Council. The roadmap resulting from the workshop will be used to guide R&D of critical manufacturing processes for high-volume production of hydrogen technologies, and is strongly linked to the President's Hydrogen Fuel Initiative.



► *The workshop attracted participants from a variety of organizations, including government, universities, associations, industry, and national labs.*

Participants in the Workshop on Manufacturing R&D for the Hydrogen Economy discussed the issues facing all aspects of manufacturing for hydrogen technologies. These technologies included (1) large-scale hydrogen production and delivery systems, (2) on board vehicle hydrogen storage systems, and (3) polymer electrolyte membrane (PEM) fuel cells. The recommendations resulting from this workshop outline the key technical challenges facing the manufacture of hydrogen components and systems today and identify priorities for research and development to overcome those challenges.

► *Background papers and presentations for the Workshop on Manufacturing R&D for the Hydrogen Economy can be viewed online at http://www.eere.energy.gov/hydrogenandfuelcells/wkshp_h2_manufacturing.html.*

Plenary Sessions

Speakers Doug Falkner, Acting Assistant Secretary for Energy Efficiency and Renewable Energy at DOE; Dale Hall Director of NIST's Manufacturing Engineering Laboratory; JoAnn Milliken, Chief Engineer of the DOE Hydrogen Program, and George Sverdrup, NREL's Hydrogen Program Manager opened the workshop with presentations on the President's Manufacturing Initiative, the President's Hydrogen Fuel Initiative, and a discussion of the goals of the workshop.

Following the plenary remarks, the workshop participants moved into production, storage, and fuel cell breakout groups.

Workshop results are contained in Attachment A.

►*Experts participated in parallel breakout sessions to discuss manufacturing R&D for hydrogen production and delivery, hydrogen storage, and fuel cells.*

Production and Delivery Session

Speaker Rick Zalesky (Chevron Technology Ventures) provided a background presentation for the production session.

Workshop participants discussed manufacturing R&D for the following production and delivery technologies:

- Natural gas/liquid reforming
- Hydrogen separation/purification/ gas clean up
- Electrolysis
- Delivery (bulk storage)

Storage Session

Speaker Andy Abele (Quantum Technologies) provided a background presentation for the storage session.

Workshop participants discussed manufacturing R&D for the following storage technologies:

- Compressed hydrogen systems
- Liquid hydrogen/cryogenic gas systems
- Chemical and solid state systems
- Balance-of-plant issues

Fuel Cell Session

Speaker Steve Mallison (Ballard Power Systems) provided a background presentation for the production session.

Workshop participants discussed manufacturing R&D for the following fuel cell technologies:

- Membrane-electrode assemblies
- Bipolar plates
- Fuel cell stack assembly
- Balance-of-plant issues

Presentations from these sessions are available at http://www.eere.energy.gov/hydrogenandfuelcells/wkshp_h2_manufacturing.html.

Attachment A: Workshop Results

- Production and Delivery
  - Natural Gas or Liquid Fuel Reformation
  - Electrolysis
  - Separation/Gas Cleanup
  - Delivery

- Fuel Cells
  - Bipolar & Cell Stack Assembly
  - Membrane Electrode Assembly
  - Balance of Plant (BOP)

- Storage
  - Compressed Gas Systems
  - Liquid Hydrogen, Cryogenic Chemical and Solid State Systems
  - Balance of Plant and Cross-Cutting Issues

Joining of Materials	Coatings	Heat Treatment	Materials Availability
High Priority			
• Develop joining methods to facilitate component integration - high reliability joining processes for combinations of dissimilar materials & specialized materials - micro-system fabrication for integrated systems • Develop joining methods for metals that do not require high temperatures	• Develop procedures for coating catalysts onto non-conformal surfaces - simple, standardized techniques (rather than "art") - non-destructive testing methods - flood and spray coating techniques - ink-jet coating for targeted applications • Study nickel coatings on cheaper metals to reduce volume of nickel - nickel for catalysts - alloys for brazing - for corrosion protection to meet potential environmental, health and safety concerns		• Develop materials and fabrication techniques appropriate for large-scale pressurized hydrogen storage
Medium Priority			
• Develop joining methods and approaches that can remove non-destructive testing requirements both in the shop and the field, e.g., improved and faster laser machining/welding			• Develop processes to build a stack that does not require break-in to reach maximum performance

Joining of Materials	Coatings	Heat Treatment	Materials Availability
Low Priority			
• Develop thin sheet bi-metal cladding in prototype quantities • Develop cost effective processes to replace braze foils in high temperature nickel brazing processes • Develop high production rate welding processes with minimum oxygen pick-up during welding (Develop models to identify welding fluxes) • Develop solid state joining methods (e.g., diffusion bonding) for parts subjected to higher temperatures where brazing will not work	• Develop improved pipeline coating techniques • Develop plasma coating methods, e.g., applications from semi-conductor industries • Develop new plasma techniques	• Identify and develop methods for heat treating in support of functional needs • Develop heat treating methods that are more cost effective (investment & time) for large complex geometries that produce high quality products	• Develop manufacturing methods for 3-in-1 catalyst particles (wherein a single vessel does all chemical/molecular transformation) These catalyst formulations must perform multiple functions • Improve particle size and shape control for membrane supports and catalysts • Develop a "materials of construction" resource for manufacturing (need to conduct accelerated testing to generate validated data) • Develop high strength weldable steels and their weldments such as SA517 and similar steels (It is difficult and costly to get these steels) • Develop processes for producing specialty materials for hydrogen systems in small quantities • Determine how to upscale / downscale catalyst materials from lab scale to industrial scale having similar process properties • Develop low cost nickel foam (for use in electrolysis Gas Diffusion Layer (GDL) – issues: - manufacturing in quantity - availability

Continuous Manufacturing	Other
High Priority	
• Develop accelerated testing methods to validate optimal materials and processes • Conduct R&D to manufacture large composite pressure vessels from filament to localized reinforced techniques - localized winding of carbon filaments for pressure vessels - NOTE this is similar to top vote-getter in Materials Availability category • Develop and apply methods and analysis tools for design for manufacturing	
Medium Priority	
• Develop stamping methods (particularly in smaller quantities) (e.g., in microchannel components and electrolyzers) • Utilize interdisciplinary teams to modularize the systems. (The objective is to reduce part count and permit "snap-together" manufacturing)	• Incorporate R&D findings into safety codes & standards dissemination of technology
Low Priority	
• Develop fabrication methods for large-area catalyst and membrane supports • Address quality control needs of volume manufacturing (e.g., statistical methods) • For electrolysis, develop (1) leak check systems and (2) electrical check and qualification processes • Develop robotic processes (to manufacture electrolysis modules) • Develop streamlined prototyping processes	• Standardize systems to metric for global applications incorporating hydrogen production requirements • Adopt agreed upon manufacturing and product standards early in the development cycle • Develop baseline breakdown of component and sub-comp costs and targets

Electrolysis cell components	Separator / bipolar plates	Balance of plant	Seals / Gas Diffusion Layer (substrate)
Recommendations from workshop participants on the manufacturing needs for electrolysis overlapped with many of the manufacturing needs identified in the Fuel Cell Breakout group. Areas of common interest are included in the following			
• Membrane - Develop in-line control strategy and techniques to detect and control input defects → develop instrumentation (sensors) • Catalyst layer - Develop understanding of electrode structure on performance/ durability and manufacturing to implement in high speed manufacturing processes • Develop fabrication methods for large-area catalyst and membrane supports • MEAs - Develop more flexible (agile), integrated, low cost manufacturing approaches that allow rapid evaluation of new materials / structures	• Develop high speed forming – stamping, molding processes • Develop high speed welding/joining processes • Develop rapid prototyping of flexible tooling	• Develop manufacturing methods for high performance, low temperature heat exchangers • Incorporate assembly automation into component and subsystem manufacture	• Develop processes for simpler, faster sealing between components and subsystems • Develop Design For Manufacture and Assembly processes for simplification and reduced parts count of subsystems and integrated systems

Palladium membrane purification	Pressure Swing Adsorption	Alternative cleanup systems & sensors	Balance of plant
Recommendations from workshop participants on the manufacturing needs for gas cleanup included technology development and materials research for some of the emerging technologies, e.g., microporous membranes and adsorbent technologies. These R&D activities are included herein for completeness, but they are considered outside the scope of manufacturing research and development.			
• Develop inexpensive palladium coating processes • Develop methods of activating surfaces to enhance coating adhesion (e.g. how to make palladium coatings stick to microporous layers)	• Improve manufacturing technologies for production of reaction vessels, compressors, and valves • Develop low cost manufacturing of adsorbents • Develop joining methods and approaches that can remove nondestructive testing requirements both in the shop and the field, e.g., improved and faster laser machining / welding	• Develop continuous manufacturing methods for adsorbents with application to structured supports • Develop real-time sensor technologies • Develop reliable and economic microporous membrane with low costs, and improve supports for microporous membranes	• Develop processes for simpler, faster sealing between components and subsystems • Develop Design For Manufacture and Assembly processes for simplification and reduced parts count of subsystems and integrated systems

Bi Polar Plates	Process Control (Testing, Metrology, Inspection)	Cell Stack Assembly	Other
High Priority			
• Develop high speed forming – stamping, molding processes • Develop high speed welding/joining processes		• Develop and demonstrate automated assembly, e.g., mechanized/robotic assembly processes	
Medium Priority			
• Develop rapid prototyping flexible tooling • Investigate continuous line manufacturing methods, similar to paper/roll processing	• Conduct modeling of manufacturing tolerances and warranty using Monte Carlo techniques • Develop detailed understanding of the effects of manufacturing variations on product performance; develop necessary specifications • Develop accelerated stack break-in procedures and understanding of conditioning from a fundamental level • Develop in-line testing to verify graphite plate microstructure defects • Develop measurement methods (optical based) • Develop processes / methodologies / technologies to reduce or eliminate dependence on inspection	• Develop high speed methods for pre-placing seals on plates • Develop simplified unit cell structure that allows for rapid stacking of individual cells • Develop leak testing technologies and processes to determine stack leakage • Develop processes/technologies to make every cell in a stack identical	• Build a stack that does not require break-in to reach maximum performance

Bi Polar Plates	Process Control (Testing, Metrology, Inspection)	Cell Stack Assembly	Other
Low Priority			
• Develop integrated design for manufacturing tools specific to fuel cells • Determine limits of manufacturing capability for making metal plates • Model resin dispersion in graphitic bipolar plates to optimize molding method • Develop real time monitoring of bipolar plate joining • Develop rapid staging thermo set or possibly microwave processes • Utilize high speed material handling and placement processes • Develop flow field designs that are less affected by fabrication tolerances (design concept) • Develop surface treatment for metallic plates that would eliminate membrane contamination (materials concept) • Establish selection criteria for materials as a knowledge base for manufacturing (materials concept)	• Develop bipolar plate inspection techniques using nondestructive testing methods: geometry, defects, density/ permeability flow field channel features • Develop rapid stack diagnostics • Develop rapid performance testing methods for bipolar plates including rapid scanning methods for flatness, thickness, surface roughness, and surface profiling • Develop rapid hydrogen leak measurement methods • Determine the effects of bipolar plate tolerances on cell/stack performance and life. Develop uniform metrics and methods for describing/communicating process capabilities to ensure supply chain efficiency • Identify and establish standard tolerances for flow field geometries, flatness and thickness	• Develop ultra-fast adhesion/bonding of monopolar plates to match 10 hertz manufacturing rates • Develop clamping methods to assure alignment and reduce stress due to contact and material expansion • Develop rapid pressure testing, stack conditioning and performance analyses • Develop seals integration with bipolar plates and MEAs for ultra-fast assembly • Develop high rate error-proofing to eliminate anode and cathode mix up • Conduct studies on the manufacture of external manifolds including mold modeling and tolerance studies • Develop understanding of the relationship between alignment of plates (flow fields) and fuel cell performance • Study load vs. time effects on stack skew (development activity) • Develop automated compression system that maintains stack at constant mechanical load • Establish automated assembly pilot facility that incorporates rapid material handling systems	• Develop processes for recycling precious metal catalysts

Membranes	Catalyst Layer	Seals	Gas Diffusion Layer (GDL)	Membrane Electrode Assembly (MEA)
		High Priority		
• Establish relationship between ex-situ measured properties and in-situ performance that can be an empirical, mathematical, or physical based expression defining the relationship between externally measurable properties and performance/durability • Develop sensors/hardware for in-line inspection of membranes (cross-cutting with MEAs and catalyst layers)	• Develop understanding of electrode structure on performance/ durability and manufacturing to implement in high speed processes	• Demonstrate an in-line, high speed process for producing an integrated MEA that meets automotive specifications and includes both an edge seal and an interfacial gasket (that seals with bipolar plates)		• Establish transfer function that establishes relationship between ex-situ measured properties and in-situ performance for MEAs. (Cross-cutting with Membrane topic) • Revisit DOE cost targets for all fuel cell stack components on a regular basis to identify and incorporate emerging manufacturing advances and ensure DOE cost targets are in concurrence with needs to make technology commercially viable • Develop more flexible (agile), integrated, low cost manufacturing approaches (i.e. printing—non vacuum) that allow rapid evaluation of new materials / structures at low capital investment and can easily incorporate advances in materials

Membranes	Catalyst Layer	Seals	Gas Diffusion Layer (GDL)	Membrane Electrode Assembly (MEA)
		High Priority		
				• Develop modeling/design tools (concurrent engineering tools, CAD-based software) for holistic design (trade-offs in manufacturing costs and quality) to help or better allocate cost targets and to integrate elements into the supply chain
		Medium Priority		
• Develop in-line control strategy and techniques to detect and control input defects → develop instrumentation (sensors) and demonstrate control at required operating (mfg) conditions	• Develop methods to manufacture new 3D electrode structures, i.e., translate lab structures to high volume, high speed manufacturing • Develop in-line methods to characterize electrode structures			• Develop an industry standard test for product performance and durability which MEA suppliers can use and refine processes

Membranes	Catalyst Layer	Seals	Gas Diffusion Layer(GDL)	Membrane Electrode Assembly (MEA)
Low Priority				
	• Develop high efficiency, high utilization collection and recycle techniques for catalysts with and understanding of quality requirements for recycled catalyst • Develop understanding of catalysts and electrode structure and the effects of imperfection/impurities on performance and durability • Develop strategy / control / instrumentation to avoid undesirable qualities in catalyst layer • Develop transfer function that describes relationship between catalyst loading parameters (including surface area) and product lifetime, performance and cost • Develop transfer function that describes relationship between 3-D macro / micro electrode structures and product quality • Develop transfer function that describes the relationship between catalyst coated membrane/gas diffusion layer (CCM/GDL) coating quality and ink rheology for catalyst inks	• Develop and demonstrate processes with high speed and continuous operation to integrate seals/gaskets into MEAs using polymers with processing/curing temperatures higher than maximum for membrane • Develop inspection technologies for evaluating seal quality	• Determine transfer function between GDL s mechanical and electrical properties and product quality	• Establish standard external MEA dimensions for width and length - units that all MEAs should be multiples of • Develop packaging of MEAs that enables a high speed, continuous cell stack assembly • Develop “flash’ burn-in and better imaging hardware /software and robotics for continuous cell stack assembly • Develop standards for communication and control of manufacturing processing and tools for MEA processing • Characterize manual manufacturing of MEA assembly and roll-to-roll processing methods for 5-layer and 7-layer MEAs • Develop transfer function(s) that relate critical manufacturing process parameters to cell performance

Membranes	Catalyst Layer	Seals	Gas Diffusion Layer(GDL)	Membrane Electrode Assembly (MEA)
Low Priority (continued)				
				• Develop and demonstrate processes to reduce discrete process steps in fabrication of MEAs • Develop flexible tooling for manufacturing MEAs to final shapes. Establish standardized humidity control for facilities and processes to fabricate MEAs

Water and Thermal Management	Reactant Management	Component Modules and Systems	Testing of Systems	General Considerations
High Priority				
• Develop manufacturing methods for high performance, low temperature heat exchangers	• Develop reactant sensors for hydrogen (fuel cell system and vehicle)	• Produce frameless, skinless fuel cell systems • Incorporate assembly automation into component and subsystem manufacture • Develop processes for simpler, faster sealing between components and subsystems • Develop flexible and automated manufacturing technologies for subsystem and system assembly	• Develop production process and hardware for rapid reliable leak testing	• Develop protocols for qualifying new materials for PEM systems and processes (materials issue) • Identify and develop manufacturing / assembly processes suitable for "interim" production volumes (5,000 – 50,000 power systems per year) • Develop prototyping technology for transition from 1,000s of power system production to 100,000s power systems
Medium Priority				
				• Develop remanufacturing / recovery / requalification technology for components & subsystems • Develop Design For Manufacture and Assembly processes for simplification and reduced parts count of subsystems and integrated systems

Water and Thermal Management	Reactant Management	Component Modules and Systems	Testing of Systems	General Considerations
Low Priority				
	• Demonstrate coating methods for hydrogen compatibility with low-cost BOP materials (material issue) • Develop low cost methods for forming tubing to handle hydrogen at pressure • Develop manufacturing methods and equipment for advanced materials used in BOP	• Identify appropriate level of modularization for subsystems / systems • Establish and verify manufacturing DFM processes for rapidly evolving individual blower-motor-pump housing- shafts-bearing into integrated unit (component design issue) • Develop polymers and polymer composites for BOP integrated assembly modules/subsystems	• Develop remote monitoring systems, manufacturing protocols and qualification standards • Establish and verify manufacturing processes for rapid system-power plant conditioning • Develop hydrogen compatibility test methods and standards for lower cost materials (materials issue)	• Develop procedures for designing life cycle tools and methodologies • Develop principles for Design for Manufacturing (DFM) (assembly and test) • Establish and verify “table” of material compatibility with different fluids / temperature / pressure of manufactured components (materials issue) • Determine and verify acceptable cleanliness levels for different manufacturing operations • Develop failure mode analyses for high volume BOP production • Answer materials questions for new components required to handle high –volume production and use with hydrogen • Develop low-cost tooling and advanced forming & joining technologies for intermediate production volumes that would precede automobile production

Water and Thermal Management	Reactant Management	Component Modules and Systems	Testing of Systems	General Considerations
Low Priority (continued)				
				• Develop generic, pre-competitive manufacturing information for automotive companies • Develop rapid, quick change tooling process and flexible manufacturing systems

Carbon Composite Tanks	Lower Cost Carbon Fiber	Conformable Tanks	Alternatives to Carbon Fiber
High Priority			
• Develop new manufacturing methods for composite tanks - Faster filament winding, new filament winding strategies, continuous vs. batch processing - New processes for applying resin matrix, such as tow-pregs for room temperature curing, wet winding processes • Develop fiber placement manufacturing of composite tanks	• Develop lower cost precursor for high strength fibers • Develop lower energy processes - microwave processing - plasma assisted oxidation - stabilization - surface treatment	• Develop new manufacturing methods for carbon fiber winding and fiber placement methods to allow production of modified cylindrical tank shapes	
Medium Priority			
• Develop tools for model-based simulation and process design of containment vessel manufacturing			
Low Priority			
• Develop new manufacturing methods to reduce the amount of carbon fiber per unit • Develop cost model for high pressure tank manufacture • Develop protocols for high volume DFMA for 700 bar components			• Demonstrate alternative materials to carbon fibers for composite tank manufacturing. (this is primarily a materials development issue)

Bladder-type Volume Exchange Assembly	Alternatives to Composites for Low/medium Pressure containers	Thermal Management Assemblies	Solid State Storage Material Processing
No high priority topics were recommended for non-compressed gas systems because (a) specific solid state and/or chemical systems for hydrogen storage have not been identified at this time, (b) no specific R&D issues were found pertaining to the manufacture of liquid hydrogen or cryogenic systems			
Medium Priority			
• Develop materials and assembly techniques for bladder-type volume exchange storage subsystems	• Develop new compatible materials that would reduce manufacturing costs		
Low Priority			
• Develop new manufacturing methods to reduce the amount of carbon fiber per unit • Develop cost model for high pressure tank manufacture • Develop high volume design for manufacturing and assembly (DFMA) procedures for 700 bar components	• Develop improved forming/extrusion processes for manufacturing metal tanks • Develop lightweight metal alloy-short fiber tanks • Develop particulate composite tanks • Develop lower cost substitute for the manufacture of low pressure cryogenic tanks	• Develop low cost manufacturing processes for compact, high efficiency thermal management assemblies	• Develop high throughput solid storage material processes

Standardization of Manufactured Components	Codes and Standards	Certification Methods	Recycle and Reuse of Materials
No specific R&D issues were identified concerning Balance of Plant components for storage systems in general. Cross cutting issues were found to be of low priority.			
Low Priority			
• Implement standardized manufactured components and subsystems for storage systems to reduce unit costs	• Assure that adopted codes and standards are not impediments to large scale manufacturing of storage components and systems	• Develop methods to certify storage systems and components when manufactured in large quantities • Develop non-destructive evaluation/non-destructive testing (NDE/NDT) techniques applicable to manufactured systems	• Develop recycling processes. Cost and reactivity of solid state storage materials necessitate the implementation of recycling processes into the manufacturing chain