2011 NREL/DOE HYDROGEN AND FUEL CELL MANUFACTURING R&D WORKSHOP REPORT

Contents

1 Introduction

Historically, the U.S. Department of Energy (DOE) Fuel Cell Technologies Program (Program), and its predecessor, the Hydrogen, Fuel Cells and Infrastructure Technologies Program focused R&D efforts on low-temperature, polymer electrolyte membrane (PEM) fuel cells, mostly for transportation applications. Beginning in 2009, the mission of the Program was expanded beyond PEM fuel cells to include high-temperature fuel cells, including molten carbonate, phosphoric acid and solid oxide fuel cells. The mission of the Program is to enable the widespread commercialization of a portfolio of hydrogen and fuel cell technologies through basic and applied research, technology development and demonstration, and diverse efforts to overcome institutional and market challenges.[1]

The Program is structured to address all areas that impact its mission. R&D sub-programs in hydrogen production, storage, and fuel cells address technology development needs in these areas and provide new materials and methods in collaboration with industry, national labs, and academia. Technology Validation, Systems Analysis and Market Transformation sub-programs address the demonstration, validation, and deployment of hydrogen and fuel cell systems, and carry out detailed analyses to evaluate the performance of and business case for these technologies in real applications. Successful achievement of the goals of these sub-programs leads to greater penetration of hydrogen and fuel cell technologies in the marketplace. Indeed, the domestic hydrogen and fuel cell industry is expected to become a major high-tech sector and worldwide interest in these technologies is growing. More than 15,000 fuel cell systems were shipped in 2010 worldwide, representing more than 80 MW of power.[2] As the market for hydrogen and fuel cells grows, the need for development of automation and manufacturing processes for mass production of these systems grows as well.

To meet the needs of increasing production volumes in the growing hydrogen and fuel cells industries, the Fuel Cell Technologies Program Manufacturing sub-program (Manufacturing) works with industry, universities and national laboratories to research, develop, and demonstrate high-volume fabrication processes to reduce cost while ensuring high quality products for hydrogen and fuel cell systems. This sub-program facilitates the development of a domestic supplier base for hydrogen and fuel cell technologies.[3] Activities currently supported under Manufacturing include development of:

- New processing techniques for high volume, high quality gas diffusion layer (GDL) and membrane electrode assembly (MEA) production
- In-line sensors and diagnostics for membrane electrode assembly and bipolar plate quality control
- New manufacturing methods for reducing the costs of type IV compressed hydrogen tanks

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[1] The Department of Energy Hydrogen and Fuel Cells Program Plan, 2011; http://www.hydrogen.energy.gov/pdfs/program_plan2011.pdf, as referenced on 2/1/12.

[2] 2010 Fuel Cell Technologies Market Report, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2010_market_report.pdf, as referenced on 2/1/12.

[3] Fuel Cell Technologies Program Multi-Year Research, Development and Demonstration Plan, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/index.html, as referenced on 2/1/12.

In 2005, the Program, along with the National Renewable Energy Laboratory (NREL) and the National Institute of Standards and Technologies (NIST), hosted a workshop[4] to identify needs and barriers to fuel cell manufacturing and create a roadmap[5] for future Program activities to address these needs. In accordance with the mission of the Program at that time, these activities focused primarily on PEM fuel cells. However, over the years since the workshop, technologies and markets have developed, and manufacturing has begun to transition from low volume to high volume. In addition, the scope of the Program has expanded to include high-temperature fuel cell technologies, which have not to date been addressed by the Manufacturing sub-program. Therefore, to obtain updated information on manufacturing needs and barriers, NREL and the Program hosted a Hydrogen and Fuel Cell Manufacturing R&D Workshop on August 11–12, 2011, in Washington, D.C.

The goal of the present workshop was to bring together key industry, university, and government representatives to discuss the critical issues facing all aspects of manufacturing of hydrogen and fuel cell products, including hydrogen production and delivery, hydrogen storage, and fuel cell components and systems. During the workshop, attendees discussed the current status, barriers, and R&D needs of manufacturing for relevant processes and systems. The workshop focused on key technical challenges to the manufacture of these systems today and on identifying priorities for research and development of the manufacturing processes needed to make hydrogen and fuel cells cost-competitive with incumbent technologies.

2 Overview

The overall purpose of the workshop was to identify and prioritize:

(1) Barriers to the manufacture of hydrogen and fuel cell systems and components
(2) High-priority needs and R&D activities that government can support to overcome the barriers.

A majority of the 75 workshop attendees identified themselves with a company that develops or manufactures components or systems related to fuel cells. Other affiliations include national labs and academia as presented in Table 1.

Table 1: Participation statistics for attendees to the Manufacturing workshop

Affiliation	Number
Industry	43
National Lab	13
Academia	4
DOE	9
Other	6

Speakers from DOE and industry gave plenary presentations to provide a programmatic and technical context for the workshop. Importantly, the status of manufacturing for the different hydrogen and fuel cell technologies was outlined. The following section provides a

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[4] Manufacturing R&D for the Hydrogen Economy Workshop: Summary Report, July 2005; http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_h2_manufacturing.html, as referenced on 2/1/12.

[5] Roadmap on Manufacturing R&D for the Hydrogen Economy, December 2005; http://www.hydrogen.energy.gov/pdfs/roadmap_manufacturing_hydrogen_economy.pdf, as referenced on 2/1/12.

summary of these plenary presentations.

2.1 Plenary Presentations

2.1.1 Hydrogen and Fuel Cell Technologies Overview; Sunita Satyapal

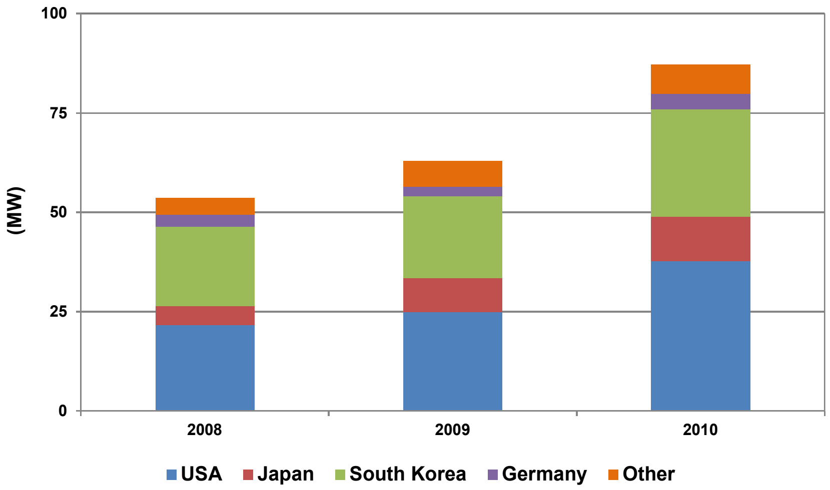

Figure 1: Growth of fuel cell commercialization identified as megawatts shipped (ref. 1 and ref. 6).

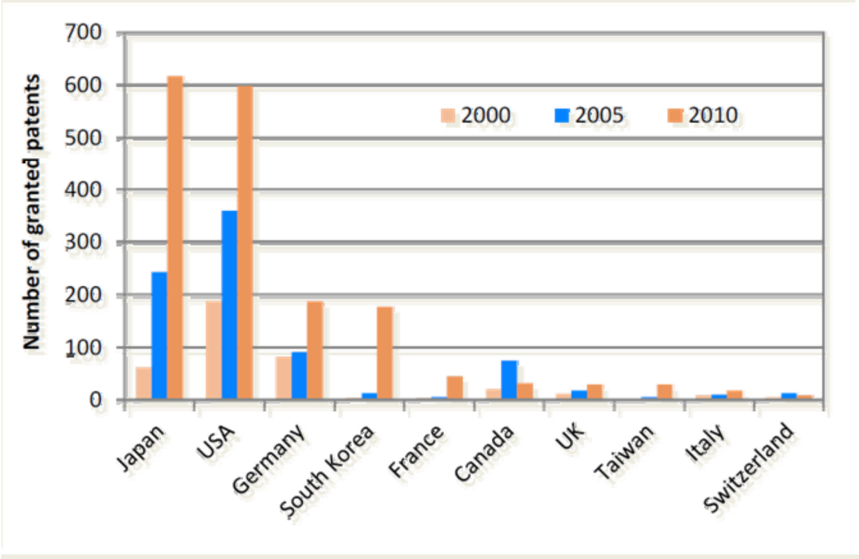

Figure 2: Annual fuel cell patents per country over the period 2000 to 2010 (ref. 1 and ref. 6).

Dr. Sunita Satyapal, the Program Manager of the Fuel Cell Technologies Program, welcomed the participants to the workshop and highlighted the commercialization advancements of fuel cell systems[6] from 2008 to 2010 when the fuel cell market grew with a 50% increase in the United States of MW shipped as shown in Figure 1.

Various market analyses[1] project that the global fuel cell market could reach $14 - $31 billion per year for stationary power, $11 billion per year for portable power, and $18 - $97 billion per year for transportation applications over the next 10 – 20 years. As shown in Figure 1, the United States has a leadership role in the fuel cell market; however, there is a serious challenge from South Korea. Japan's fuel cell development is an additional challenge to the U.S. as demonstrated by Japan's accelerated growth in patents granted. As indicated in

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[6] Sunita Satyapal, "Hydrogen and Fuel Cell Technologies Overview," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_satyapal.pdf

Figure 2, Japan's number of patents granted exceeded that of the U.S. in 2010.

Support of fuel cell and electrolysis system manufacturing in the U.S. is important to maintaining the U.S. as a leader in the fuel cell industry. A concern for the U.S is not to repeat the history of photovoltaic (PV) production with a shift in production leadership from the U.S. to Asia and Europe. The production history for PV is given in Figure 3.

In closing, Dr. Satyapal stated that the purpose of the Manufacturing workshop was to identify and prioritize:

- Challenges and barriers to manufacture of hydrogen and fuel cell systems and components
- R&D activities that government can support to overcome the barriers

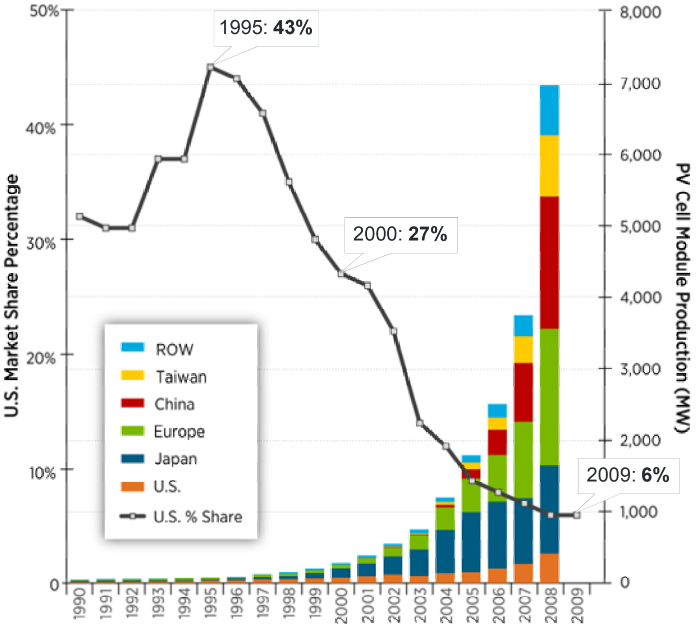

Figure 3: Production of PV by country and U.S. market share from 1990 to 2008. (ref. 6).

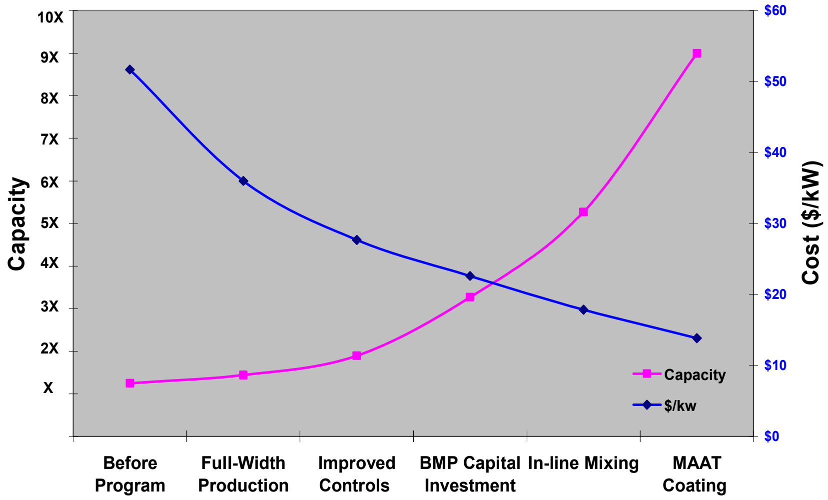

Figure 4: Reduction in cost (pink line) and increase in GDL production capacity (blue line). MAAT refers to many-at-a-time (ref. 7).

2.1.2 DOE's Fuel Cells Technologies Manufacturing Sub-program; Nancy Garland

Dr. Nancy Garland, the Technology Development Manager for the Manufacturing sub-program, reviewed the status of Department of Energy's projects for advancing hydrogen and fuel cell manufacturing technology.[7] The goal of the sub-program is expressed by:

"Research, develop and demonstrate technologies and processes that reduce the cost

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[7] Nancy Garland, "DOE's Hydrogen and Fuel Cell Technologies Manufacturing Sub-Program," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_garland.pdf

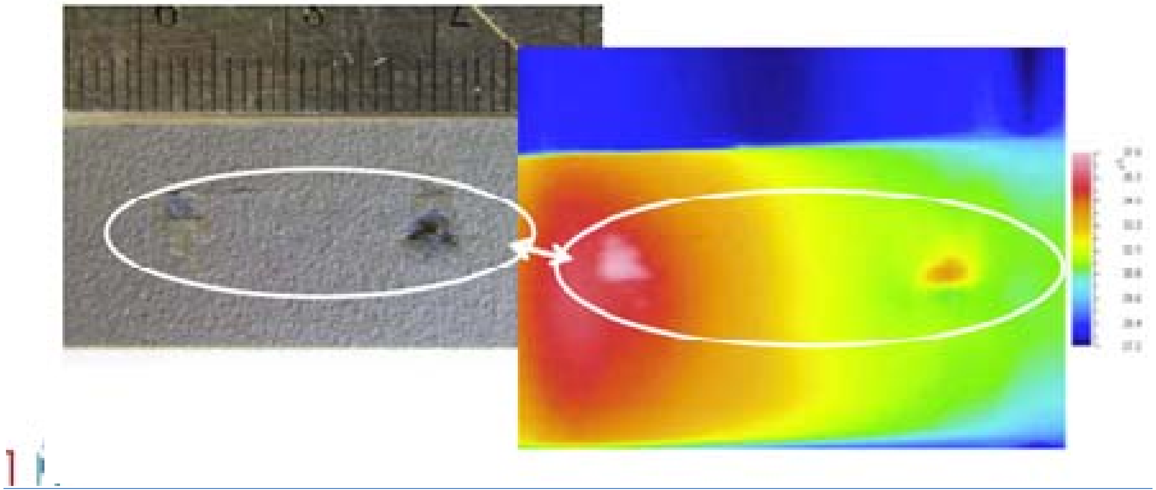

Figure 5: Measurement of micro-defects in GDL substrates using DC excitation and an infrared camera to detect thermal response of the GDL (ref. 7).

> *of components and systems for fuel cells, and hydrogen production, delivery, and storage; grow the domestic supplier base."*

Dr. Garland described the accomplishments of several of the manufacturing projects:

- Ballard Material Products has successfully improved the production capacity for GDLs by 4 times and decreased cost by 50% as shown in Figure 4. As the production capacity increased a concurrent reduction in GDL cost was obtained.
- W.L. Gore & Associates successfully increased MEA performance and reduced MEA and stack cost. Gore demonstrated a 25% increase in performance.
- NREL demonstrated areal imaging of catalyst layer uniformity and defects in GDL materials using direct current (DC) excitation and detection of the GDL's thermal response with an infrared camera. The measurement of GDL defects is shown in Figure 5.
- The team of Quantum Technologies, Boeing, Pacific Northwest National Laboratory (PNNL) and Lawrence Livermore National Laboratory has reduced the composite mass of carbon composite-filament wound hydrogen storage pressure vessels by nearly 23%.

The successes of the above projects and future projects will improve manufacturing efficiencies and production rates.

Dr. Garland reviewed the objectives and agenda for the Manufacturing Workshop and challenged the participants to clearly identify barriers to manufacturing and develop a family of recommendations for improving manufacturing of fuel cell systems.

2.1.3 DOE's Advanced Manufacturing Office; Leo Christodoulou

Dr. Leo Christodoulou is the Program Manager for the Department of Energy's new Advanced Manufacturing Office (AMO). He began his presentation[8] by stating that industry consumes 30% of the energy in the United States. Energy use in the U.S. is dominated by thermal processing.

Dr. Christodoulou then provided an overview of the new AMO, in comparison to the former Industrial Technologies Program. The mission of the AMO is to:

> *"Develop and demonstrate, at a "convincing scale", new energy-efficient processes and materials technologies (e.g., low-temperature membranes, aqueous-based processes).*
>
> *Develop broadly applicable, manufacturing processes that reduce energy intensity and efficiently direct energy to forming the product. Examples include additive manufacturing, selective heating, and out-of-the-autoclave composite manufacturing.*
>
> *Develop and demonstrate pervasive materials technologies that reduce life-cycle energy requirements for production of low-cost, high-performance products for high-value industries such as the renewable energy industry. Example materials include low-cost carbon fiber, low-cost titanium, resilient coatings, and lightweight magnet materials.*
>
> *Capture US manufacturing industry competitive advantage by Technology Deployment to industry that promotes: new flexible/adaptable processes and materials; real time process control; energy efficiency; workforce training; and, distributed manufacturing through a fast communications infrastructure."*

Dr. Christodoulou stated the AMO will invest in cross-cutting manufacturing engineering and development activities.

2.1.4 Automation Status; Gerry Sperrick

Mr. Sperrick is an independent manufacturing automation expert with extensive industrial experience at Allen Bradley, Hansford Manufacturing, and Progressive Machine and Design. He presented several slides identifying the many different types of automation that can be applied to manufacturing.[9] He specifically identified examples of hypothetical pre- automation to automation manufacturing of cell stacks.

Mr. Sperrick made several comments addressing fuel cell manufacturing:

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[8] Leo Christodoulou, "DOE's Advanced Manufacturing Office," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_christodoulou.pdf

[9] Garry Sperrick, "Automation Status," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_sperrick.pdf

- Fuel cell manufacturing is not much different than other assemblies or products being manufactured today.
- Manufacturing platform (material handling and integrated processes) is highly dependent on the needs of the manufacturer.

He proposed a radical (for fuel cell manufacturers) concept for accelerating and driving down the cost of fuel cell manufacturing through automation: “Make all Fuel Cells the same – Standardization of designs and common materials”. This concept follows the battery manufacturers approach to a commodity product: AAA batteries or D-cells for example.

2.1.5 Manufacturing Fuel Cell Manhattan Project; John Christensen

Mr. Christensen from NREL highlighted the results of the Manufacturing Fuel Cell Manhattan Project (MFCMP)[10] that was funded by the Office of Naval Research. The objectives of the MFCMP were to identify:

- Manufacturing cost drivers to achieve affordability
- Best practices for fuel cell manufacturing technology
- Manufacturing technology gaps
- Manufacturing projects to address these gaps

The MFCMP gathered fuel cell Subject Matter Experts (SMEs) at Montana Tech for two separate meetings to discuss and identify low-temperature PEMFC, high-temperature PEMFC, and solid oxide fuel cell (SOFC) manufacturing gaps and identify potential pathways to resolve these gaps. The initial meeting was held in the fall of 2010 and identified many of the gaps. A follow-on meeting in the spring of 2011 reviewed the results of the gap analysis and finalized the proposed R&D projects to address the gaps. A total of 70 manufacturing gaps were identified by the SMEs and 32 projects recommended by the SMEs to address manufacturing cost savings for fuel cell systems. Mr. Christensen identified the following manufacturing areas for the proposed projects:

- Production Automation
- Production Material
- Quality control (QC) during Manufacturing
- QC for Product
- Balance-of-plant (BOP) Hardware
- BOP Performance
- Materials
- Design Performance
- Design Controls

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[10] John Christensen, “Manufacturing Fuel Cell Manhattan Project,” NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_christensen.pdf

Follow-on programs were discussed by Mr. Christensen that included a forum for national laboratories and academia to report on new developments related to fuel cell manufacturing and capture of manufacturing needs and issues for Department of Defense (DOD) and DOE evaluation and action.

2.1.6 Low Temperature PEM Fuel Cell Manufacturing Needs; Duarte Sousa

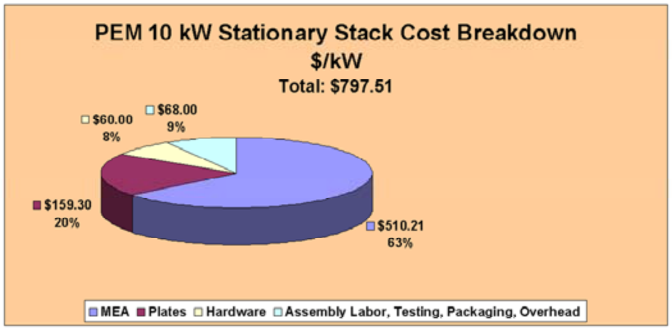

Figure 6: Cost breakdown of a 10-kW PEMFC stationary stack (ref. 11).

Mr. Sousa reviewed the results from the MFCMP on low temperature PEM fuel cell manufacturing needs.[11] Their analysis concluded that a 50% savings can be realized with current sustainable volumes of 5,000 units per year using the present technological infrastructure. A roadmap was developed that outlined how the fuel cell cost can be reduced.

The MEA was identified as the major cost driver in a 10-kW stack as illustrated in Figure 6. The MEA cost represents 68% of the stationary stack costs. The next largest cost component for the stack is the bipolar plates. A critical component to reducing the cost of the MEA is to reduce the platinum group metal content in the MEA to 0.15 g/m^2. A needed manufacturing advance is the development of robust methods of continuously coating catalyst segments or patterns on a moving web, which would increase the precious metal utilization. Development of direct catalyst coating on membranes would reduce labor cost and reduce yield loss of the catalyst.

For high-temperature PEM systems, the MFCMP recommends the development of paper GDLs. Mr. Sousa concludes a project to reduce the cost of PEM systems needs to:

1. Improve catalyst efficiency
2. Develop robust transfer functions: validate correlations between product design characteristics and performance, validate tolerances, and establish robust correlations between critical design characteristics and raw material and process variables.
3. For the Balance of Plant
    a. Obtain greater efficiency for heat exchangers
    b. Optimize humidifiers
    c. Improve anode and cathode gas and air delivery systems
    d. Use liquid metering pumps
4. Focus on transiting to automation and reducing manual operations
5. Improve fuel processing:
    a. Desulfurization of logistic fuels

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[11] Duarte Sousa, "Low Temperature PEM Fuel Cell Manufacturing Needs," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_sousa.pdf

2.1.7 Ceramic Fuel Cells; J. David Carter

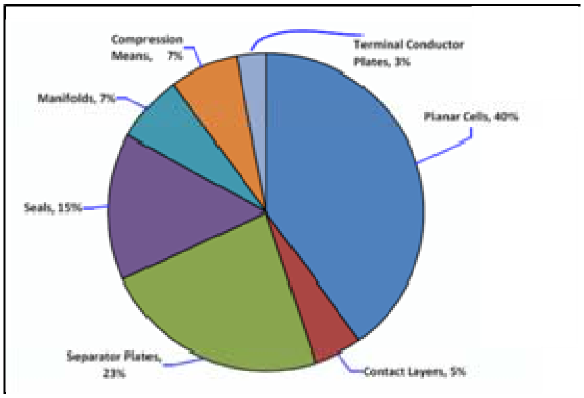

Figure 7: Cost breakdown for planar SOFCs (ref. 12).

Dr. Carter reported the results of the MFCMP's evaluation of solid oxide fuel cell (SOFC) manufacture.[12] The MFCMP ceramic fuel cells group identified the cost drivers, current best practices for manufacturing, and manufacturing gaps for the production of ceramic fuel cells. The MFCMP participants proposed projects to address these gaps and estimated cost savings resulting from these projects. The primary cost driver for planar SOFC is the planar cells followed by the separator plates as shown in Figure 7. The seals for the cell stack are the next largest cost driver. Other contributions to the cost of the SOFC stack are small in comparison to these three.

For tubular SOFCs, the cost drivers change with the power rating of the system. For SOFC rated at less than 500 W, the recuperator is 26% of the cost, current collection is 23%, the cell is 22%, and the insulation is 19%. For a SOFC rated greater than 500 W, the cell is 27% of the cost; the recuperator is 26% of the cost, and current collection 16% of the cost. The recommended projects for both planar and tubular SOFC stacks are research and development of:

- Protective coatings for metallic components (a materials issue not a manufacturing issue)
- Defect-free electrolyte layer application
- Low-cost, high-efficiency insulation (materials cost & applications/manufacturing cost)
- Automated assembly
- Stack assembly, commissioning, and testing
- Net shape manufacturing of manifolds and end plates
- Current collection winding for tubular SOFCs
- Ceramic powder characterization

Key manufacturing projects recommended for the ceramic fuel cell BOP are research and development of:

- Specification analysis for fuel cell power systems
- Low-cost, fuel-efficient tactical fuel processors for desulfurized fuels
- Low-cost, high-efficiency heat exchangers
- High-efficiency fuel processor for logistic and renewable fuels
- Manufacturing for cathode air delivery system pump-blower

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[12] J. David Carter, " Ceramic Fuel Cells (SOFC)," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_carter.pdf

2.1.8 Manufacturing Barriers to high temperature PEM commercialization; Emory DeCastro

Dr. DeCastro of BASF identified high volume manufacturing technologies as the key to mass market distributed generation.[13] The manufacturing barriers can be eliminated by design for manufacturing that would provide high throughput gas diffusion electrode production that would eliminate some of the cell and stack component gaskets, and would provide a pathway for the development of high speed lamination for large MEAs. Dr. DeCastro identified approaches used by BASF to eliminate some of the manufacturing barriers, e.g., ultrasonic lamination and in-line detection of defects to minimize scrap.

Dr. DeCastro recommended the development of a robust supply chain and standardization of many of the components. This standardization would lower the cost of components and is considered critical to widespread adoption of the high-temperature PEM stationary fuel cell systems.

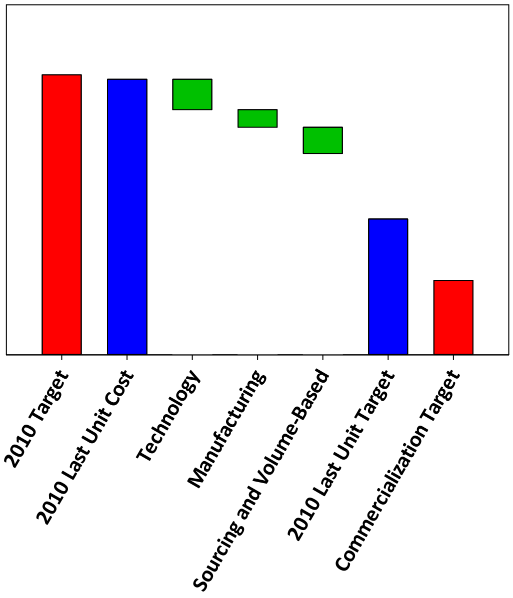

Figure 8: Cost targets and status for UTC Power PureCell® 400 (ref. 14).

2.1.9 High Temperature Fuel Cell (Phosphoric Acid) Manufacturing R&D; Sridhar Kanuri

Dr. Kanuri reported that the power plant cost for the UTC Power PureCell® Model 400 system will be reduced by incremental changes in technology and manufacturing.[14] He reported that the commercialization gap will be closed by 1) continuous manufacturing methods for cell components, 2) low cost fuel processing systems, and 3) high temperature BOP components.

Figure 8 is a waterfall chart of UTC Power's present cost projections (to protect the proprietary nature of the data the Y-axis is not labeled). The 2010 current cost meets their 2010 target; however the long term target is approximately 30% of the 2010 current cost. Dr. Kanuri identified these components to reduce cost to the 2012 targets: 1) technology advances, 2) manufacturing advances, and 3) sourcing and cost reduction associated with increased volume production.

Current cost reduction efforts include design changes to simplify manufacturing and assembly; before using Design For Assembly (DFA), the system had 4720 parts and after DFA, the system had 2688 parts, a

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[13] Emory DeCastro, "Manufacturing Barriers to High Temperature PEM Commercialization," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_decastro.pdf

[14] Sridhar Kanuri, "High Temperature Fuel Cell (Phosphoric Acid) Manufacturing R&D," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_kanuri.pdf

43% reduction. UTC Power is incorporating automated inspection methods to detect matrix layers defects that can be "touched up" and thereby reduce scrap.

Future manufacturing improvements planned by UTC Power include:

- Continuous manufacturing of electrodes
- Continuous manufacturing of net-shaped separators
- Reduced weight and volume of the power system
    - Improved activity of the catalyst and better heat transfer in the fuel processor will reduce the volume of the fuel processor sub-system by 50%
- Low-cost brazed plate heat exchangers that will reduce BOP costs for stationary power plants

In summary, Dr. Kanuri identified the capital and installation cost as a significant challenge for all stationary fuel cell power plants.

2.1.10 High Pressure Hydrogen Tank Manufacturing; Mark Leavitt

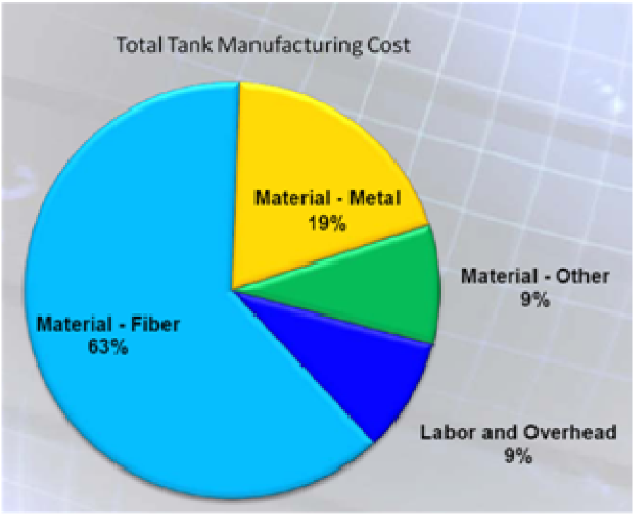

Figure 9: Breakdown of total tank manufacturing cost (ref. 15).

Mark Leavitt of Quantum Fuel Systems Technologies Worldwide, Inc. identified the high pressure hydrogen storage tank manufacturing barriers as cost, weight, unification of standards, and availability of automotive gaseous hydrogen components.[15] He further clarified the manufacturing barriers by identifying the cost breakdown for high pressure tank manufacturing as shown in Figure 9.

The cost assumptions for the breakdown are:

- 125 liter – 10,000 psi H_2 tank
- Traditional manufacturing processes
- Type IV (plastic liner) tank
- Annual production quantity of 10,000 units
- Carbon fiber cost at $15/lb
- Metal components are 316L stainless steel

From Figure 9, the fiber materials are identified as the largest (63%) cost component. Labor and overhead represent only 9% of the cost. Quantum cost reduction efforts focus on advanced manufacturing processes combining filament winding with fiber placement. The aim of this approach is

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[15] Mark Leavitt, "High Pressure Hydrogen Tank Manufacturing, "NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_plenary_leavitt.pdf

to reduce the use of costly fiber composite materials and to improve manufacturing efficiency. The successful result of the Quantum program is a nearly 23% reduction in composite mass from 76 kg to 59 kg.

Quantum has shown that a hybrid tank design with outside layers of the tank using lower cost fiber can reduce fiber cost with little or no impact on tank weight. The cost savings for this approach would be approximately 4%. Quantum is evaluating additional lower cost fibers as part of their manufacturing cost reduction program and designing the tanks to minimize the use of high cost fibers while maintaining the strength.

Automation of the high pressure tank manufacturing process can increase throughput, reduce product variation, and allow for more stringent design criteria of the high pressure tanks.

2.2 Breakout Sessions Structure and Topics

The workshop coordination team decided on six focused topics before the workshop to address the full scope of the Manufacturing sub-program and to break the topics into manageable and cohesive units to be addressed in the breakout sessions. The 75 workshop participants divided themselves according to interest and expertise into groups that addressed:

I. Polymer electrolyte membrane fuel cells and electrolyzers
  A. Cells and stacks
  B. Balance-of-plant
II. High temperature fuel cells (phosphoric acid, solid oxide, molten carbonate)
  A. Cells and stacks
  B. Balance-of-plant
III. Small fuel cell systems with hydrogen storage (< 1 kW)
IV. Hydrogen production and delivery

A facilitator led the discussion and a scribe documented the comments of the participants and the tenor of the discussion in each breakout session. The goals for each breakout session were to generate:

(1) A list of needs and barriers for hydrogen and fuel cell manufacturing
(2) Input on the highest priority challenges and opportunities for government support.

While the session facilitators rigorously pursued these goals, the goals were only partially met. Some breakout sessions produced highly detailed and focused lists of barriers and needs, while others produced general and broad inputs. In addition, complete prioritization of inputs was not achieved in all sessions. Likely factors affecting the type of output obtained from each session were the personal style of the facilitators, the composition of the attendees in terms of industry versus labs as well as the number of different companies represented, and the nature of the topic under consideration. For instance, both low and high temperature cell and stack breakout sessions (sessions IA and IIA) yielded very detailed and focused output, whereas the output from the portable fuel cell system with hydrogen storage session (session III) was quite general and broad in nature. In the following Evaluation section, the Workshop Coordination Team made every effort to identify, from the raw notes generated in the breakout sessions, the highest priority barriers and needs that fall under the purview of the Manufacturing subprogram.

3 Evaluation

The purpose and goals of the workshop are given in Section 2. As discussed, these goals were generally met, though to different degrees of breadth and detail for the different sessions. While the raw inputs from the participants (given in Appendix C) were extremely valuable and represent the voice of experts in the manufacture of hydrogen and fuel cell technologies, the Workshop Coordination Team undertook additional evaluation to obtain clearer insights into priority areas of focus for future support by the Manufacturing sub-program, and strategic directions for Manufacturing that lead to achieving the goals of the sub-program as well as supporting the overall goals of the Program.

We used three key criteria in the evaluation of the participant inputs. The first was relevance to Manufacturing. While the focus of the workshop was made clear within each session and was specifically discussed with the full group of attendees by Dr. Satyapal, the integrated nature of the topic of manufacturing inevitably led to discussion and suggestions that went beyond the boundaries of the Manufacturing sub-program. For example, technology development, especially in developing and expanding markets, flows directly into manufacturing development. This close integration results in difficulty defining the line between the two topics. Indeed, materials or design developments are often needed to enable further advances in manufacturing technology or transition from a low volume production method to high volume methods. In addition, DOE and its partner agencies have made significant efforts to demonstrate and deploy hydrogen and fuel cell systems since higher volume leads to lower costs. However, suggestions for activities to increase federally supported deployments, while strong validations of broader Program goals, are not within the scope of Manufacturing. Thus, **we made an effort to assess critically suggestions that may be out-of-scope to ensure relevant outcomes for the sub-program**. We did, however, want to make sure to capture these inputs for consideration by other Program areas. As such, these inputs are included in Appendix C, and are identified by italicized text.

The second key criterion in judging input was prioritization by the participants. Again, these inputs represent the voice of the experts and every effort was taken to understand the raw input and to preserve the rankings within each session. Therefore, **inputs that received a relatively high number of votes were deemed to be high-priority** while other inputs that received very few or no votes were deemed to be low-priority.

The third key criterion was the strategic value to the sub-program. In workshops attended by industry and labs, where specific areas of expertise and interest reside, some comments and suggestions may relate more strongly to the needs, methods, and plans of the individual participant than to those of the sub-program or the Program in general. We assessed the strategic importance of needs identified by the participants in comparison to work that is already being supported by the Manufacturing sub-program.

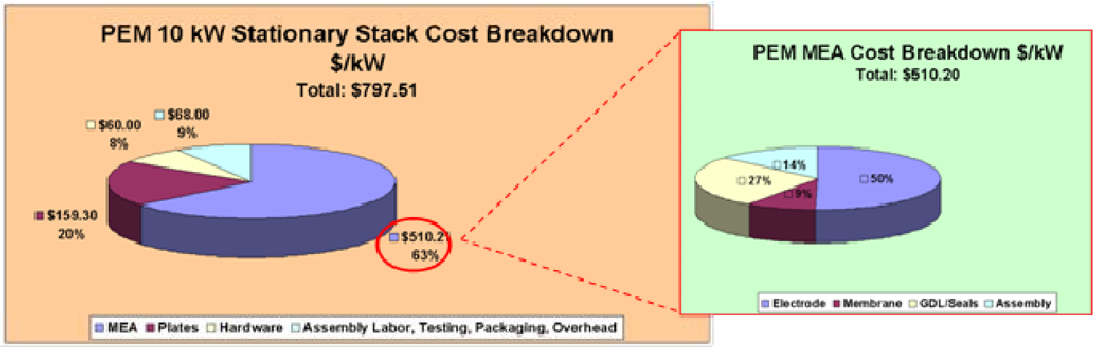

Figure 10: PEMFC stack and MEA cost breakdown presented by Ballard (ref. 16).

In particular, industry and lab projects are ongoing in several of the topic areas within Session IA. The workshop team must understand the interrelationships among all of the inputs and provide its evaluation of priority and applicability, given the broader picture of the Program. Ultimately, **we emphasized the inputs that best provide guidance to the sub-program and that best highlight gaps in current sub-program activities that are not being addressed elsewhere**. Application of these three criteria enabled us to identify the key needs and barriers to manufacturing and identify gaps in activities that lead to areas for future support.

3.1 Manufacturing Barriers and Needs for PEM Fuel Cells and Electrolyzers – Cells and Stacks

Session IA focused on manufacturing needs and barriers for MEAs, MEA components, bipolar plates, and stacks of low- (80-100°C) and high-temperature (>160°C) PEM fuel cells as well as PEM electrolyzers. While different processes and methods are used among these three systems, the materials are in many cases similar, and the potential exists for support of projects that would benefit multiple technologies. Duarte Sousa of Ballard Power Systems gave an introductory presentation on the status of cell and stack manufacturing.[16] He discussed current status and proposed directions forward for improving the manufacture of MEAs, plates, and stacks. Mr. Sousa reported that the MEA accounts for 63% of the cost of a 10-kW stationary fuel cell stack and that the platinum-containing electrode accounts for 50% of the cost of the MEA, as shown in Figure 10. Improvements in all aspects of MEA and stack manufacturing, including reduction of catalyst loading, improved understanding of how variability of materials and processes affects performance, elimination of processes that require transfer liners, patch coating, automated stack assembly, improved and lower cost bipolar plates, and improved stack conditioning methods, were identified as areas of opportunity to reduce stack costs by almost 50%.

Following the session introductory presentation, the session participants agreed upon a categorization of cell and stack topic areas within which to discuss and capture barriers and needs. The topics included: **GDLs, membranes/ionomers, electrodes, MEAs, bipolar plates, quality/inspection/process control, stack testing and conditioning, and stack assembly**. Within each of these categories, the group then brainstormed ideas about barriers and needs. These ideas were written on sticky notes, read and

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[16] Duarte Sousa, "PEM Stack Manufacturing: Industry Status," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_ia_sousa.pdf, as referenced on 2/1/12.

clarified, and then similar ideas were grouped as necessary. Seventy raw inputs[17] across these topics were obtained in this way. Subsequent prioritization by the participants, using dot stickers, typically led to one or two key needs within each topic area. In addition, clarification and further details regarding prioritization across the different topic areas within the session were obtained from a subset of the session participants. This second prioritization was extremely valuable, and led to more critical assessment of the inputs. As mentioned above, several projects that address manufacturing needs in PEM fuel cells are or have been supported by the sub-program. Ballard Material Products worked to increase the efficiency and throughput of GDL production processes. W.L. Gore & Associates is developing inks and processes to direct-coat electrode layers onto membranes. Rensselaer Polytechnic Institute is evaluating ultrasonic welding and pressing of MEAs and subassemblies, along with methods of adaptive process control. BASF Fuel Cell is developing inks and processes, as well as in-line quality measurement systems, for coating of catalyst layers onto GDLs. PNNL evaluated ink jet printing for directed coating of catalyst layers. Finally, NREL and NIST are both evaluating and developing quality control methods applicable to MEAs, MEA components, and bipolar plates. This ongoing work must be considered in assessing the strategic value of future projects for manufacturing PEM fuel cells and electrolyzers.

3.1.1 Key findings and gaps in current activities

We evaluated the prioritized inputs against the workshop evaluation criteria, as discussed above. While many of these inputs are being addressed in some manner by ongoing projects supported by the sub-program, it should be understood that each manufacturer will likely have different ideas about the best approach to address these needs, based on their unique combination of materials, processes, designs, and markets. One of the key, and widely agreed upon, outcomes of the session was that methods to increase the efficiency and decrease the scrap associated with electrode fabrication processes remain a high priority need, despite ongoing work. This point is well supported by the introductory presentation as well as numerous Program-supported cost analyses, which indicate that the platinum-containing catalyst is a cost driver for the stack,[18] as shown in Table 2. The

Table 2: Cost estimate for automotive PEM fuel cell stack as a function of annual production rate (ref. 18).

	2010				
Annual Production Rate	1,000	2,000	3,000	4,000	5,000
System Net Electric Power (Output)	80	80	80	80	80
System Gross Electric Power (Output)	87.91	87.91	87.91	87.91	87.91
Bipolar Plates (Stamped)	$1,684.28	$434.15	$439.95	$433.03	$429.07
MEAs					
Membranes	$5,184.51	$908.84	$562.23	$438.23	$230.78
Catalyst Ink & Application (NSTF)	$1,252.28	$700.37	$695.57	$698.62	$694.83
GDLs	$2,140.33	$1,111.35	$691.53	$537.04	$242.57
M&E Hot Pressing	$72.09	$9.98	$8.23	$8.36	$8.16
M&E Cutting & Slitting	$56.94	$4.42	$3.29	$3.02	$2.82
MEA Frame/Gasket	$469.80	$319.95	$311.95	$306.29	$301.42
Coolant Gaskets (Laser Welding)	$185.48	$26.48	$29.43	$27.39	$25.52
End Gaskets (Screen Printing)	$149.48	$5.06	$1.97	$1.25	$0.54
End Plates	$87.43	$33.55	$28.91	$26.21	$19.86
Current Collectors	$16.79	$7.18	$5.99	$5.54	$5.07
Compression Bands	$10.00	$8.00	$6.00	$5.50	$5.00
Stack Housing	$61.44	$7.54	$6.44	$5.87	$5.16
Stack Assembly	$76.12	$40.69	$34.95	$33.62	$32.06
Stack Conditioning	$170.88	$53.87	$47.18	$41.38	$28.06
Total Stack Cost	$11,617.87	$3,671.08	$2,873.61	$2,573.36	$2,030.92
Total Stack Cost ($/kW$_{net}$)	$145.22	$45.89	$35.92	$32.17	$25.39
Total Stack Cost ($/kW$_{gross}$)	$132.16	$41.76	$32.69	$29.27	$23.10

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[17] See appendix C.

[18] "Mass Production Cost Estimation for Direct H_2 EM Fuel Cell Systems for Automotive Applications: *2010 Update,"* September 30, 2010; B.D. James, J.A. Kalinoski, K.N. Baum; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/dti_80kwW_fc_system_cost_analysis_report_2010.pdf, as referenced on 2/1/12.

participants generally agreed that methods of fabrication involving direct coating of the electrode onto the membrane or GDL substrate required further development. This need is corroborated in the MFCMP.[19] The participants discussed a variety of methods and strategies regarding direct coating that could be explored. According to some of the participants, enabling development of membranes and/or membrane processing methods providing sufficient dimensional stability for the direct coating of electrodes may be needed. While developing new membrane compositions would be an activity under the Fuel Cells sub-program, that sub-program could consider development specifically to enable improved catalyst coating processes as part of a broader Manufacturing effort.

The participants identified a variety of needs regarding MEA fabrication. The key finding participants universally agreed upon, however, was the need for improved methods of final inspection of MEAs for leaks, shorts, membrane pinholes and other defects prior to assembly in a stack. Many participants commented on the large loss of time and increased overall cost, associated with tearing down a stack to remove a faulty cell identified during final stack testing. The results of the MFCMP study corroborated this need.

While the participants rated development of capabilities for higher paper GDL production speeds as a high priority, the only GDL producer in the session refuted this need, indicating that current roll-to-roll processes could support current and near-future volumes. The key findings in this area therefore focused on integration-type issues. The needs to decrease the brittleness of paper GDLs and to increase the strength of woven GDLs were strongly supported. While material formulation may be more appropriately addressed within the Fuel Cell R&D sub-program, if R&D activities to address the brittleness or strength of GDLs clearly contribute to the ability to improve manufacturing processes, those activities should be considered for future Manufacturing support. In addition, the participants agreed that the development of methods to reduce or eliminate protruding or loose fibers or other materials from the GDL surfaces is important to the integration of components into a high quality MEA.

While the participants supported both metal and non-metal bipolar plate designs, a key finding was the continued need for development of lower-cost fabrication processes, especially those that can reduce cost at low volumes. This need is not being addressed by currently supported projects.

Participants also agreed that improvements in stack assembly and testing methods are high priority needs; thus development of automated methods to assist assembly and testing was another key finding. These needs were also identified in the recent NREL assessment of the level of automation in combined heat and power (CHP) fuel cell manufacturing.[20] The participants indicated that the cost and time associated with conditioning and leak-checking stacks could be reduced by implementation of automation. The participants highlighted the need for methods to ensure proper alignment and proper

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[19] "Manufacturing Fuel Cell Manhattan Project," Office of Naval Research, January, 2012; http://www.dodb2pcoe.org/news_fuelcell2.aspx, as referenced on 2/1/12.

[20] "An Assessment of the Current Level of Automation in the Manufacture of Fuel Cell Systems for Combined Heat and Power Applications," M. Ulsh, D. Wheeler, P. Protopappas; NREL Technical Report TP-5600-52125; August, 2011; http://www.nrel.gov/hydrogen/pdfs/52125.pdf, as referenced on 2/1/12.

handling of both soft and hard-goods during automated assembly. While this key need is not being addressed as a primary topic by current Manufacturing-supported projects, some manufacturers of both low temperature[21] and high temperature stacks have addressed the automation of stack assembly; thus future work should ensure that lessons learned from the industry are taken into consideration, where confidentiality allows.

Finally, participants supported the need for continued cross-cutting development of quality control measurements, especially those applicable to continuous and automated fabrication processes. While needs were expressed in many areas, the most important were capabilities to monitor the uniformity of coated catalyst layers, on either membranes or GDLs and capabilities to perform final MEA testing. NREL and NIST, as well as some of the manufacturers themselves, are developing capabilities in this area. However, the participants identified the following areas that require further work: improvement and validation of measurement techniques for in-line use, techniques and methods to identify unacceptable variability or defects and then mark them for later removal in ways that minimize loss of surrounding material, and improving the basis of knowledge around the performance and durability effects of variability and defects such that product tolerances and specifications can be set based on systematic studies. These needs were broadly corroborated by both the MFCMP study and the NREL automation study.[20]

3.2 Manufacturing Barriers and Needs for PEM Fuel Cells and Electrolyzers – BOP

Session IB focused on needs and barriers to manufacture BOP for low- and high-temperature PEM fuel cells as well as PEM electrolyzers. The BOP refers to non-stack subsystems and components. While different system designs and configurations are used among these three systems, the operational modes and temperatures in many cases are similar enough that the potential exists for support of projects that would benefit multiple technologies. In a Program-supported cost analysis for transportation PEM fuel cells, Directed Technologies Incorporated concluded that BOP will contribute 45% to 50% of the component costs of systems being produced at high volume.[18] This analysis and others confirm the importance of understanding key needs and opportunities for the sub-program to support manufacturing advances in this area.

The session was initiated by two introductory presentations that described the status of BOP manufacturing for PEM electrolyzers and fuel cells. In his presentation, John Torrance of Proton OnSite (Proton) stated that the BOP represents two thirds of the capital cost for electrolyzers rated at 12 kg H_2 per day,[22] as shown in Figure 11.

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[21] Altergy Systems (2007); Altergy Systems Unveils the World's First Automated, High Volume Fuel Cell Assembly Line; Press Release, http://www.altergy.com/announcements/first_automated_assembly_line.asp, as referenced on 2/1/12.

[22] John Torrance, "Electrolyzer Manufacturing Progress and Challenges", NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_ib_torrance.pdf, as referenced on 2/1/12.

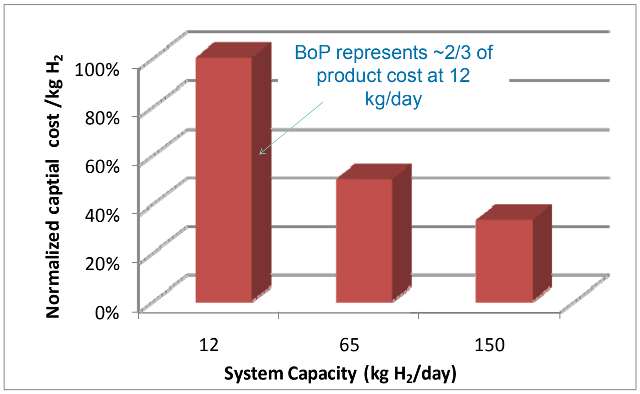

Figure 11: Normalized capital cost as a function of system capacity (ref. 21).

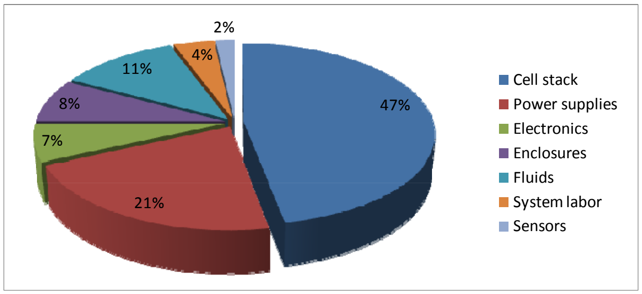

Figure 12: Cost breakdown for Proton OnSite HOGEN C electrolysis system generating 65 kg H_2/day (ref. 21).

Mr. Torrance reported that the contribution of BOP to capital cost decreases as the system capacity increases. For Proton's C-series electrolyzer that generates ~65 kg H_2/day, the BOP contribution to capital cost (including power supplies and electronics) is ~49% as shown in Figure 12. The system labor represents only 4% of the cost and the stack is 47% of the system cost.

Hydrogenics' David Frank[23] reported that two of the five major component sub-systems of the Hydrogenics electrolyzer would be improved by additional manufacturing R&D: the hydrogen clean-up and hydrogen compression sub-systems. He identified critical electrolyzer BOP and system manufacturing R&D needs as:

- Integrated BOP outsourced to third party suppliers for easier assembly
- Advanced (reliable, low cost, efficient and compact) hydrogen clean-up systems that are easily integrated
- Advanced hydrogen compression systems that are robust, low cost and easy to install
- Automation of Stack and BOP assembly

Mr. Frank also discussed Hydrogenics' PEM fuel cell systems BOP requirements and needs. Of their major fuel cell BOP subsystems, he identified two that would benefit from additional manufacturing R&D: the blower/compressor of the air delivery sub-system and tubing/manifolds/fittings for the hydrogen delivery sub-system. In particular, Mr. Frank attributed 90% of the parasitic power for a fuel cell to the blower/compressor, although the cooling pumps and fans were not included in this estimate. Mr. Frank reported that some major BOP components such as hydrogen recycle pumps, thermal control components, radiators, coolant pumps and components associated with power electronics were "standard" and did not require further manufacturing research and development. Previous Program-

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[23] David Frank, "DOE Fuel Cell Technologies Program Workshop: Manufacturing Progress and Barriers", NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_ib_frank.pdf, as referenced on 2/1/12.

sponsored analyses of PEM fuel cell manufacturing[24] identified power conditioning and power electronics as important development needs.

Mr. Frank stated that the fuel cell BOP and system manufacturing R&D needs are:

- Advanced blowers / compressors that are easy to integrate
- Hydrogen gas lines and manifolds that are robust, low cost and easy to source, certify and install
- Integrated BOP outsourced to third party suppliers for easier assembly
- Automation of stack and BOP assembly

Following the session introductory presentations, the participants agreed upon the following major topic areas for the BOP: **Reactant Management, Thermal Management, Controls, Mechanicals and Packaging, and Other**. Participants agreed that power electronics and power conditioning were topics outside the scope of the BOP discussion. They provided inputs on barriers and needs for each of the topic areas, as given in Appendix C. In subsequent discussions, the participants evaluated and prioritized the inputs for future support. The participants typically were not manufacturers of BOP components, but purchasers of components and subsystems for installation into their systems. As such, they focused more on the cost of BOP components rather than on manufacturing of BOP components.

Several projects relating to the development of specific BOP components are or have been supported by the Program. Honeywell developed an air compressor-expander-motor (CEM) system for PEMFC technology that is an integral component in the Argonne National Laboratory fuel cell system design developed for the Program.[25] W.L. Gore & Assoc. are developing humidifier materials for DOE; however, their project does not support humidifier hardware development. Honeywell Aerospace is developing thermal and water management systems, in particular heat exchangers and humidifiers, for PEM fuel cells.

3.2.1 Key findings and gaps in current activities

The participants clearly indicated that the costs of BOP components for fuel cells and electrolyzers were high across the board. In general, however, the participants did not suggest specific manufacturing advancements that would impact this situation. In addition, the participants suggested some activities, such as improvements in methods for removing sulfur impurities from carbonaceous fuels or the removal of carbon monoxide from reformed carbonaceous fuels, which are more appropriately addressed by other Program R&D activities.

However, a common theme emerged throughout the participants' discussion that constitutes the key finding of this session. This theme encompasses many of the individual inputs that were suggested. We identified the key finding as a need for the Program to facilitate an activity to develop common specifications for fuel cell and electrolyzer BOP components. The participants repeatedly commented

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[24] D. Wheeler and G. Sverdrup, "2007 Status of Manufacturing: Polymer Electrolyte Membrane (PEM) Fuel Cells", NREL Technical report 560-41655, March 2008.

[25] R. Ahluwalia, X. Wang, R. Kumar, "Fuel Cells Systems Analysis," DOE Hydrogen Program Annual Merit Review; Washington, D.C.; May, 2011; http://www.hydrogen.energy.gov/pdfs/review11/fc017_ahluwalia_2011_o.pdf, as referenced on 2/1/12.

that BOP components in all of these topic areas are either not designed for fuel cell or electrolyzer applications and thus incur performance penalties, or if they are, the volumes are so low that costs are excessive. As part of this key activity, the participants suggested that Design for Manufacturing and Assembly (DFMA) be applied during the development of standardized specifications to reduce part count and cost, and improve manufacturability. The participants suggested that the Program facilitate a working group (or working groups) attended by both fuel cell and electrolyzer manufacturers and BOP suppliers, to establish a consensus on standard specifications for heat exchangers, blowers, humidifiers, water separation systems, and other components and to consider a coordination of efforts between the fuel cell and electrolyzer manufacturers to leverage buying power using the standardized designs to further reduce cost. The benefit of this activity, beyond reduced costs and improved designs for BOP components is further development of the fuel cell and electrolyzer supply chain.

3.3 Manufacturing Barriers and Needs for High-temperature Fuel Cells – Cells and Stacks

Session IIA focused on cell and stack manufacturing issues for high temperature fuel cell technologies using SOFC, phosphoric acid (PAFC), and molten carbonate (MCFC) as the electrolyte. Current DOE targets call for reducing the equipment cost of residential (1-10 kW) CHP systems by 35% and medium scale (100 kW-3 MW) CHP systems by 71% (natural gas) to75% (biogas) below current costs.[3] The technologies considered have a range of maturity, and thus may face very different barriers. However, similarities in needs may also exist, which will enable DOE to support R&D that addresses two or all three fuel cell types.

Mark Richards of Versa Power Systems opened the session with a discussion on the state of solid oxide cell and stack manufacturing.[26] Mr. Richards reported the cost breakdown for SOFC cells and stacks as: materials for repeating components (73%), labor (22%), and materials for non-repeating components (5%). The cost breakdown is shown in Figure 13. Noting that 78% of the total cost of SOFC cells and stacks is in materials, Mr. Richards identified opportunities for cost reductions including developing lower cost

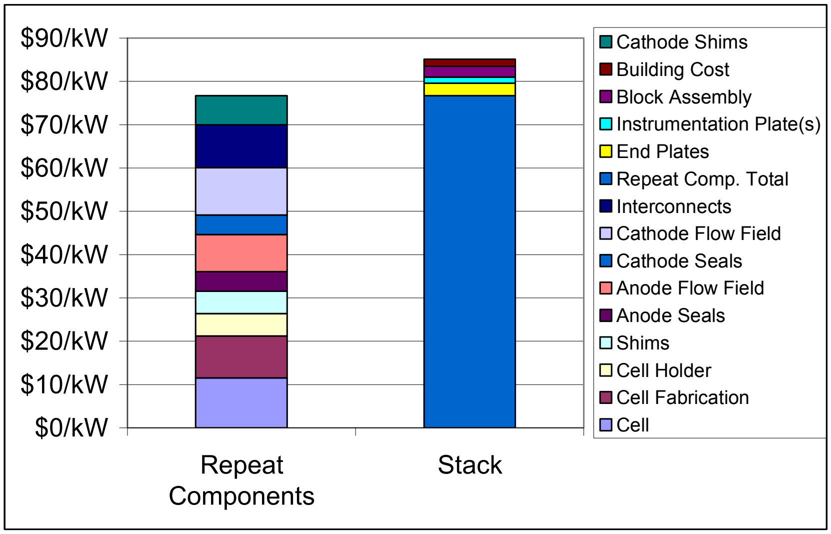

Figure 13: Stack cost breakdown for Versa Power's solid oxide fuel cell (ref. 26).

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[26] Mark Richards, "Solid Oxide Fuel Cell Manufacturing Overview," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_iia_richards.pdf, as referenced on 2/1/12.

materials, improving the efficiency of material processing methods, and in-line quality measurements of critical physical and chemical processes.

Figure 14: High temperature firing equipment for Versa Power's solid oxide fuel cells (ref. 26).

Following the introductory presentation, the session participants agreed to brainstorm and categorize cell and stack barriers and needs within two areas: **materials and processes**. For each of the three types of fuel cells within the scope of the session, these inputs were written on notecards, read and clarified, and then similar ideas grouped as necessary. Finally, each participant was given 8 votes to cast on the posted discussion points. In this way, the participants prioritized the inputs within each category (and within each fuel cell type). These raw data are provided in Appendix C.

3.3.1 Key findings and gaps in current activities

We evaluated the prioritized inputs against the workshop evaluation criteria, as discussed above. As opposed to the inputs for low temperature cells and stacks, some of which were addressed to some degree by ongoing projects, most of the inputs of this session are not currently being addressed by the Program. In assessing the breadth of inputs, we judged many to be on or across the line between manufacturing and technology development. For example, some inputs clearly related to BOP, and will be addressed in that (IIB) session. Similarly, the participants raised development of new materials, for example lower cost high temperature alloys and ceramics, as a need. While development of these materials may lead to the use of improved processes or methods, their development falls more appropriately into the Fuel Cell R&D sub-program (and should be captured as potential topics for future support by that sub-program). In addition, the participants frequently mentioned high capital costs for continuous and/or high temperature process equipment as an issue. While this is undoubtedly the case, processing equipment capital costs cannot be easily addressed by the Program. However, opportunities to increase the utilization, throughput, and efficiency of these high cost equipment platforms can assist in reducing overall manufacturing cost. Also, we gave strategic value to needs that apply to two or all three of the different types of fuel cells included in this session.

One key finding that clearly crossed all three fuel cell types was the need to reduce the cost and complexity of processing cell materials. This need could be addressed by transitioning from batch to continuous processes, replacing multiple process steps with a single step, or adopting more efficient, higher throughput processes. The participants suggested mixing, casting, and coating as strong candidates. Also, for molten carbonate and solid oxide, the participants included high temperature drying, sintering (including multi-layer), and other heat treatment processes, an example of which is shown in Figure 14. The findings of the NREL automation study[20] as well as the MFCMP[19] corroborate these key needs. These heat treatment processes significantly affect the manufacturing cost of high temperature cells by improving efficiency and throughput, enabling the use of less raw material or lower cost materials, and reducing waste. Support for development in this area would mirror the current Manufacturing sub-program activities in low temperature fuel cells.

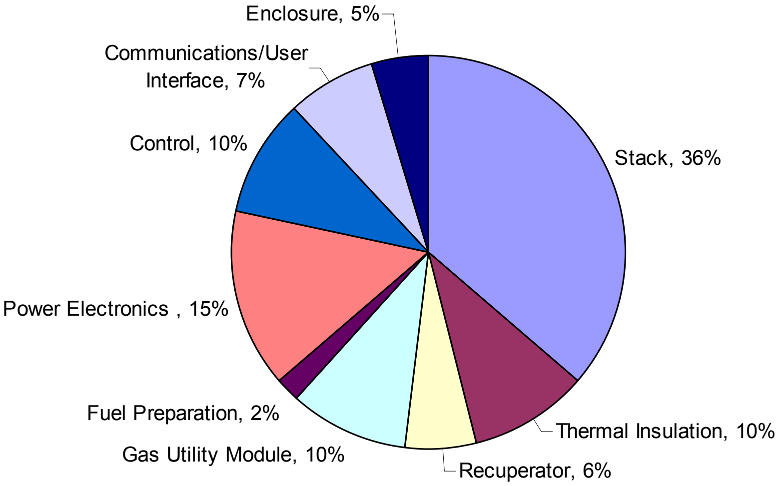

Figure 15: Cost breakout of Acumentrics' solid oxide fuel cell (ref. 27).

Improved and lower cost processes for fabrication of flow field/bipolar plates was another key finding applicable to both phosphoric acid and solid oxide fuel cells. Although the participants identified the same need for low temperature cells, it is unclear if transfer of process technologies between the two groups of fuel cells is possible because of the differences in plate material requirements.

Also similar to the inputs for low temperature cells and stacks, we identified the development of quality control techniques, especially those suitable for in-line application, as a key finding which cross-cut all three fuel cell technologies. The participants considered identification of visually apparent defects and measurement of physical and chemical properties of the cell materials during fabrication as high-priority needs. In addition, the participants suggested the development of quality assurance test methods to ensure that engineered powders meet product specifications. The results of the NREL automation and MFCMP studies corroborated these key findings, also.

3.4 Manufacturing Barriers and Needs for High-temperature Fuel Cells – BOP

This session focused on manufacturing needs and barriers for balance-of-plant for high-temperature fuel cells including solid oxide, molten carbonate, and phosphoric acid. As was the case for high-temperature cells and stacks, the similar operating conditions and system configurations, especially between solid oxide and molten carbonate, are expected to yield topics for future support that would benefit multiple technologies.

Two presentations on the status of high-temperature BOP manufacturing kicked off the session, one for solid oxide and a second for molten carbonate (the phosphoric acid technology was presented in the workshop plenary). Tony Litka reported that the balance-of-plant for Acumentrics' solid oxide fuel cell system is 49% of the system cost,[27] as shown in Figure 15. The SOFC stack and the power conditioning account for the other 51% of the cost. Three BOP components contribute 10% each to the cost: the recuperator, the controls, and the gas utility module.

Matti Lilback[28] presented the BOP status for of FuelCell Energy's (FCE) molten carbonate fuel cell system. He stated that gas cleanup costs account for 15-40% of initial capital depending on the gas source; pipeline natural gas cleanup is on the low end and anaerobic digester gas is on the high end. Optimizing the cleanup media to a site-specific gas is challenged by variations in digester gas feed quality and source. FCE's presentation identified additional issues for the high temperature BOP components including the need for long life, high temperature heat exchangers, cost-effective centrifugal fans, cost-effective water recovery systems, and cost-effective and robust heat recovery equipment.

Following the introductory presentations, the participants provided inputs on BOP manufacturing barriers and needs within each of the three fuel cell types, as shown in Appendix C, many of which diverged from those identified in the introductory presentations. The participants then ranked the inputs in order of priority. Only one currently-supported Program project addresses high-temperature fuel cells, so we consider key findings as gaps in the current Manufacturing related activities. The Program does support Acumentrics in the development of a 3-10-kW SOFC system.[29] In a 2011 Annual Merit Review presentation, Acumentrics reported the development of a process that eliminates a labor-intensive welding step by an in-house developed brazing technology.

3.4.1 Key findings and gaps in current activities

We evaluated the participants' inputs against the workshop evaluation criteria, as discussed above. Many of the suggestions in this session were judged to be materials or technology development needs, and thus more applicable to the scope of other Program elements. For example, the participants suggested development of oxidation resistant coatings and/or alloys, as well as improved brazing materials, for high temperature heat exchangers. While these needs are undoubtedly important, they fall within the scope of the Fuel Cell R&D sub-program. Similarly, industry participants representing all three fuel cell technologies strongly supported the development of improved sulfur removal processes. However, this suggestion again appeared to be more of a technology development need than manufacturing development. In addition, the participants called for multi-unit demonstrations which, while clearly of benefit to validate new manufacturing developments, are within the purview of the Market Transformation and/or Technology Validation sub-programs.

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[27] Tony Litka, "High Temperature BOP and Fuel Processing," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_iib_litka.pdf, as referenced on 2/1/12.

[28] Matti Lilback, "High Temperature BOP and Fuel Processing," NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; URL unavailable.

[29] Norm Bessette, "Development of a Low Cost 3-10kW Tubular SOFC Power System," DOE Hydrogen Program Annual Merit Review; Washington, DC; May, 2011; http://www.hydrogen.energy.gov/pdfs/review11/fc032_bessette_2011_o.pdf, as referenced on 2/1/12.

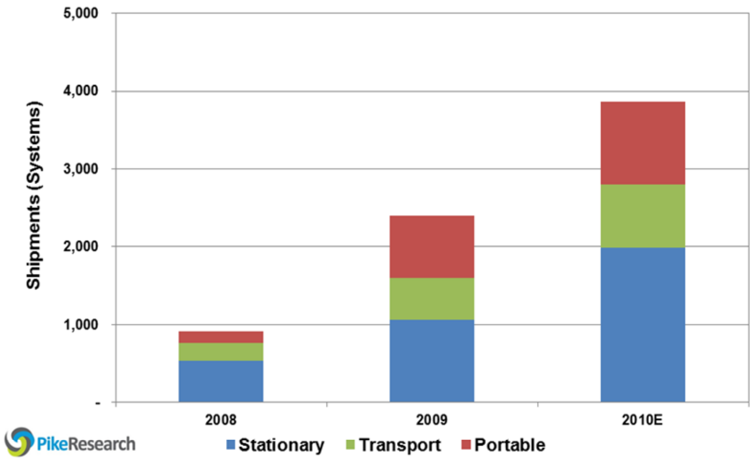

Figure 16: Growth of portable fuel cell shipments from 2008 to 2010 (2010 estimated) (ref. 2).

We therefore identified two key findings from this session; one related to manufacturing process development and the other, similar to the finding for PEMFC BOP, relates to standardization and supply chain development. The first key finding is the need for development of improved processes for forming thermal insulation. The participants recommended that both net shape fabrication and spraying may be applicable methods for development. The findings of the MFCMP study[9] corroborated this key need.

We identified the second key finding as the need for the Program to facilitate a broad, supply-chain based activity to support advances in component standardization and DFMA. The participants expected that identification of standard components would decrease costs. They also anticipated manufacturing advances from additional assessment of automation in the assembly of BOP components. The NREL automation study[20] also identified this key need.

3.5 Manufacturing Barriers and Needs for Small Fuel Cell Systems with Hydrogen Storage

Small fuel cell systems using stored hydrogen for the fuel range in power from 1-1000 Watts. The approach for storing the hydrogen varies from pressurized gas storage to the use of advanced materials, e.g., sodium borohydride. The military is the prime early adopter for these systems because small fuel cells (some of which are portable) provide a mission capability exceeding that of alternative portable power sources such as batteries. Large scale commercialization of small fuel cell systems requires a cost-competitive system, which can be achieved in part through reduced cost of manufacture.

Presentations on the status of commercialization of small fuel cell systems and portable hydrogen storage systems kicked off the session. First, Dr. Ned Stetson of the DOE Fuel Cell Technologies Program provided an overview of small fuel cell systems.[30] The overall fuel cell market has grown **by 36% between 2008 and 2010,**[2] **as graphically** shown in Figure 1, with continued growth in the United States, Japan, and South Korea. Portable fuel cell system shipments also continue to grow year to year as demonstrated in Figure 16.[2] The estimated number of portable fuel cell shipments in 2010 is just under 4,000 units, a four-fold increase over the two year period from 2008 to 2010.

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[30] Ned T. Stetson, “Small Fuel Cell Systems with Hydrogen Storage”, NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_iii_stetson.pdf, as referenced on 2/1/12.

Glenn Rambach of Trulite, in an overview of the commercialization space for fuel cell systems, described the inverse relationship between power system size and per unit power cost ($/kW).[31] At a power system size of 100 kW, the unit power costs are in the $10/kW range while at the 1-W size the unit costs are in the $10,000 - $100,000 /kW range. Mr. Rambach suggested the following key points:

- DOE R&D can help industry evaluate new technologies and improve hydrogen sources for current, revenue-producing products.
- DOE can facilitate industry access to resource subject matter experts and a data bank of the most current and relevant codes and standards, safety practices, and safety technologies.
- DOE can increase the availability of cost-effective hydrogen safety components.

Following the session introductory presentations, the participants agreed on categorization of their inputs into six areas: **Cost, Manufacturing, Standardization, Codes & Regulations, Market, and Targets.** Within these six groups, the participants provided their inputs on the manufacturing barriers and needs associated with this topic. Appendix C shows the full listing of inputs.

3.5.1 Key findings and gaps in current activities

The prioritized inputs were evaluated against the workshop evaluation criteria, as discussed above. In some cases, the participants suggested needs that are more relevant to the scope of other Program elements. For example, the participants suggested the simplification of standards and regulations as well as representation on rule-making committees. These beneficial activities should be considered by the Codes & Standards sub-program. The participants also suggested a government ‘guarantee-to-buy’ program to enable higher volumes and penetration. This need is better addressed by the Market Transformation sub-program. R&D needs were also brought up, such as low cost carbon fiber materials and renewed study of storage technologies that did not meet the DOE’s onboard storage targets but could be more successfully applied in small system applications.

The participants identified a variety of key needs that, in most cases, mirrored key findings from sessions IA and IB. These synergies reflect the high importance of the findings not only to cell and stack manufacturers, but to integrated system providers. We summarize these key findings here, and direct the reader to the sections on sessions IA (PEM stack and cell) and IB (PEM BOP) for further detail:

- Develop automation of MEA manufacturing
- Develop and implement systems for in-line quality control of MEA production
- Develop directed coating technologies to ensure registration and minimize waste in the application of the catalyst layer to the substrate
- Standardize MEA dimensions
- Standardize and apply DFMA to BOP
- Develop inexpensive methods to thermally insulate small SOFC systems

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[31] Glenn Rambach, “Hydrogen Storage Technologies,” NREL/DOE Hydrogen and Fuel Cell Manufacturing Workshop, Washington DC, August, 2011; http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mfg2011_iii_rambach.pdf, as referenced on 2/1/12.

3.6 Manufacturing Barriers and Needs for Hydrogen Production and Delivery

Widespread adoption of hydrogen fuel cells requires consumers to have access to cost-competitive hydrogen. Steam methane reforming of natural gas in centralized production facilities is projected to meet the DOE threshold cost of \$2-\$4/gge at high production volumes, but there are opportunities for lowering the manufacturing costs of building hydrogen fueling stations. Moreover, while the technology of storing hydrogen in compressed gas tanks is mature, the cost of manufacturing compressed tanks remains high due in large part to high cost of raw materials. Additionally, reliability issues in manufactured components and systems cause the overall cost of compression to be high. The participants discussed these subjects in session IV.

The participants agreed to break the session into three parts to address manufacturing needs and barriers in distributed hydrogen production, centralized hydrogen production, and compressed gas storage. Industry speakers from Nuvera, Air Products, and Lincoln Composites presented overviews in each of these areas, respectively.

Following the introductory talks, the participants identified barriers and needs for distributed hydrogen production, centralized hydrogen production, compressed hydrogen storage in tanks, as well as barriers and needs that cut across the three technologies. The industry representatives who gave the introductory talks for each topic led that respective discussion.

The Manufacturing sub-program currently supports one project related to these topics: Quantum Fuel Systems Technologies Worldwide, Inc. is developing advanced manufacturing technologies to decrease the cost of compressed hydrogen storage.

3.6.1 Key findings and gaps in current activities

The inputs from each of the three session topics were evaluated against the workshop evaluation criteria, as discussed above. Many of the inputs were more appropriate to the scope of other Program elements. The participants suggested that increased volumes would decrease manufacturing costs; a strong reality that nonetheless is more within the scope of Market Transformation. Many comments were related to the barriers associated with inconsistencies in the requirements and application of local codes for hydrogen production installations. Again, while these are very real needs, they relate to the scope of the Codes & Standards Program element. And finally, the participants voiced many materials development or testing needs, among them for high temperature seals, metal fatigue studies, catalyst and ion transport membrane development, and new/lower cost carbon fiber materials or substitutes, all of which fall within the scope of the Production & Delivery R&D Program element.

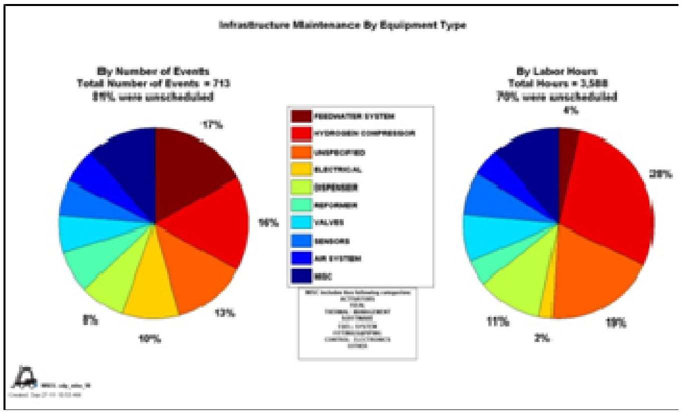

Figure 17: Maintenance events and associated labor hours associated with the hydrogen infrastructure for the material handling equipment demonstration project (ref. 32).

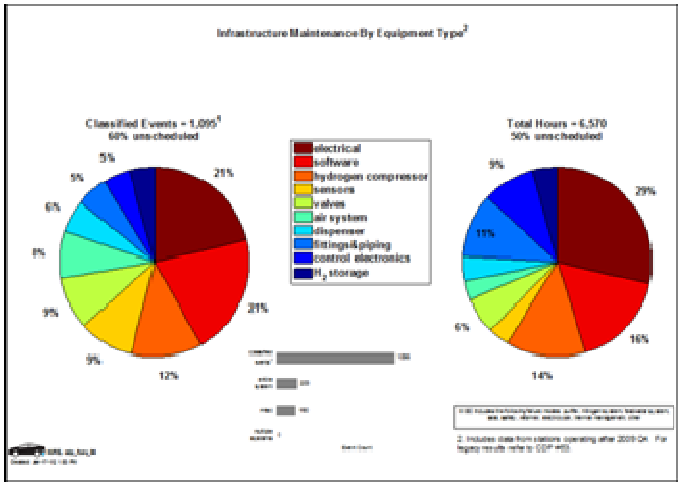

Figure 18: Maintenance events and associated labor hours for hydrogen vehicle Learning Demonstration fueling infrastructure (ref. 32).

We identified one clear key finding that cut across both distributed and centralized production areas as the need for more reliable hydrogen compressors. Figures 17 and 18 show real world maintenance data from federally supported demonstrations of hydrogen fueling infrastructure associated with material handling equipment (MHE) (Fig. 17) and light-duty vehicles (Fig. 18). For MHE infrastructure maintenance,[32] hydrogen compressors account for 16% of events and 28% of labor hours. For light-duty vehicles,[33] hydrogen compressors account for 12% of events and 14% of labor hours. These data clearly show a gap in current activities and strongly point to a future need for support.

We identified a second key finding, which cut across distributed production as well as compressed storage, as the need to integrate and implement in-use sensors for contaminant detection and early failure mode warning. Currently supported sub-program projects do not address this need.

Finally, we identified a third key finding, relating specifically to manufacturing tubes for compressed hydrogen storage, as the need for development of processes to fabricate larger diameter tubes. This improvement would reduce the costs of plumbing and assembly and increase space utilization. Currently supported sub-program projects do not address this need.

4 Recommendations

The ultimate purpose of this workshop was to identify and prioritize activities within the Manufacturing sub-program that the DOE could support to address the key barriers. We identified the key findings for

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[32] J. Kurtz, K. Wipke, S. Sprik, T. Ramsden, C. Ainscough, G. Saur, "Fall 2011 Composite Data Products: ARRA Material Handling Equipment," http://www.nrel.gov/hydrogen/cfm/pdfs/fall11_arramhe_cdps.pdf, as referenced on 2/1/12.

[33] K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, G. Saur, "All Composite Data Products: National FCEV Learning Demonstration With Updates Through January 18, 2012," http://www.nrel.gov/hydrogen/pdfs/54021.pdf, as referenced on 2/1/12.

each of the technical sessions held based on the participants' inputs and the evaluation criteria discussed at the beginning of this report. These key findings constitute the most important manufacturing needs of the industry as it works toward increasing penetration of hydrogen and fuel cell technologies into emerging markets as well as pioneering new markets. The following recommendations outline future actions the Program should consider:

4.1 Cells and Stacks

The Program should consider funding support of developments to assist the advancement of low- and high-temperature cell and stack manufacturing in the following key areas:

- Cell fabrication process development to increase throughput and efficiency and to decrease complexity and waste, especially related to electrode fabrication processes
- High temperature drying/firing/sintering process development to increase throughput and efficiency and decrease energy intensity
- Separator/bipolar/flow-field plate fabrication process development, including both metal and carbon/polymer composite materials
- GDL fabrication and handling process development, especially to improve strength, decrease brittleness, and reduce or eliminate loose or protruding fibers from the surfaces
- Stack assembly processes to increase throughput and repeatability and to improve alignment and registration of repeat parts
- Stack test and conditioning methods and processes to decrease the amount of time and equipment intensity currently required
- Quality control and quality assurance, for fabrication or acceptance of all cell materials as well as fuel cells/MEAs, to ensure appropriate methods exist to support the transition to high volume manufacturing processes

4.2 Balance-of-Plant

The Program should consider establishing and facilitating joint government/industry working groups, including both fuel cell manufacturers and BOP suppliers, with the following goals:

- Establish a framework of roles and responsibilities within which the Program and industry can cooperate
- Identify opportunities to standardize specifications for BOP equipment to enable designs that are specific to fuel cell and electrolyzer operating conditions and parameters and to enable increased buying power for system manufacturers
- Identify opportunities to apply DFMA analysis to standard designs to reduce part count and cost, and improve manufacturability
- Identify opportunities to explore and implement automation in the assembly of BOP components
- Implement the working group's recommendations
- Develop the fuel cell and electrolyzer supply chain to decrease costs and position the industry for increased growth

The Program should also consider funding support of developments to assist the advancement of fabrication processes for thermal insulation in BOP manufacturing.

4.3 Production & Delivery

The Program should consider funding support of developments to assist the advancement of production & delivery systems manufacturing in the following key areas:

- Hydrogen compressor manufacturing development to improve reliability
- In-use sensor integration to enable contaminant detection or early detection of failure modes
- Compressed gas tube fabrication processes to enable production of larger tubes

5 Appendices

5.1 Appendix A: Workshop Agenda

Thursday, August 11

Plenary (M. Ulsh, NREL)

9:00 Welcome and Program Overview (Dr. S. Satyapal, DOE)
9:10 Background/summary of DOE Hydrogen and Fuel Cell Manufacturing R&D activities (Dr. N. Garland, DOE)
9:20 DOE's Industrial Technologies Program Manufacturing Activities (Dr. L. Christodoulou, DOE)
9:30 Automation Status (G. Sperrick, PMD Automation)
9:55 Summary of DOD Manhattan Project (J. Christensen, NREL)
10:00 Low-Temperature (D. Sousa, Ballard)
10:15 High-Temperature (Dr. D. Carter, Argonne)
10:30 Morning Break
10:45 Summary of PEM FC Manufacturing (Dr. E. DeCastro, BASF)
11:15 Summary of High-Temp FC Manufacturing (S. Kanuri, UTC)
11:45 Summary of High Pressure Tank Manufacturing (M. Leavitt, Quantum)

12:15 Lunch

Technical Session IA: PEM cells/stack (Dr. N. Garland, DOE)

1:15 Invited Talk on industry status – stack manufacturing (D. Sousa, Ballard)
1:40 Breakout session – needs and barriers (M. Ulsh, NREL)
4:45 Session Summary/Wrap-up

Technical Session IIA: High Temperature cells/stack (T. Lucas, FCE)

1:15 Invited Talk on industry status – stack manufacturing (M. Richards, Versa)
1:40 Breakout session – needs and barriers (Dr. D. Carter, ANL)
4:45 Session Summary/Wrap-up

Technical Session III: Small Fuel Cell Systems with Hydrogen Storage (Dr. N. Stetson, DOE)

1:15 Invited Talk on industry status – (G. Rambach, TruLite)
1:40 Breakout session – needs and barriers (M. Lefenfeld, SiGNa)
4:45 Session Summary/Wrap-up
5:00 Adjourn

Friday, August 12

Technical Session IB: PEM/Electrolyzer BOP/system (Dr. W. Podolski, ANL)

8:30 Invited Talk on industry status – system (J. Torrance, Proton OnSite)
8:55 Invited Talk on industry status – other BOP (D. Frank, Hydrogenics)
9:20 Breakout session – needs and barriers (D. Wheeler, DJW Tech)

Technical Session IIB: High Temperature BOP/system (H. Ghezel-Ayagh, FCE)

8:30 Invited Talk on industry status – fuel processing and other BOP (T. Litka, Acumentrics)
8:55 Invited Talk on industry status - other BOP (M. Lilback, FuelCell Energy)
9:20 Breakout session – needs and barriers (S. Kanuri, UTC)

Technical Session IV: Production and Delivery (Dr. E. Miller, DOE)
8:30 Invited Talk on industry status – Centralized Production (B. Bonner, Air Products)
8:50 Invited Talk on industry status – Tube trailer design/manufacturing (Norm Newhouse, Lincoln Composites)
9:10 Invited Talk on industry status – Distributed Production (Dr. P. Rao, Nuvera)
9:20 Breakout session – needs and barriers (Dr. E. Miller, DOE)

Summary (Dr. N. Garland, DOE)
12:00 Summary Remarks IA
12:10 Summary Remarks IIA
12:20 Summary Remarks III
12:30 Summary Remarks IB
12:40 Summary Remarks IIB
12:50 Summary Remarks IV
1:00 Overall Summary, Next Steps, and Dismissal
1:10 Adjourn

5.2 Appendix B: Final Participant List

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NRL/UVA

Art Koonce
Sustainable HR Solutions

Brian Bonner
Air Products

Brian James
DTI/Strategic Analysis

Chetna Khosla Department Of
Energy

Chris Ainscough
NREL

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Treadstone

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Arkema

David Wood
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Norm Newhouse
Lincoln Composites

Norman Bessette
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Owen Hopkins
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PNNL

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Rebecca Morris
ACI Technologies

Rick Farmer
Department Of Energy

Robert Hershey
CPCUG

Robert Hyatt
CAMP/Montana Tech

Robert Rose
BTI

Rowland Travis
RRFC

Salvador Aceves
LLNL

Scott Swartz
NexTech

Sridhar Kanuri
UTC Power

Stephen Grot
Ion Power

Sujit Das
ORNL

Sunita Satyapal
Department Of Energy

Tequila Harris
Georgia Institute of Technology

Tim Norman
Giner

Tom Lucas
FuelCell Energy

Tom Mancino
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Tommy Rockward
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5.3 Appendix C: Raw Inputs

5.3.1 PEM Fuel Cells and Electrolyzers – Cells and Stacks

Italics indicate inputs participants agreed outside the scope of the Manufacturing subprogram.

Table 3: Stack testing and conditioning

Issue	Votes
Advanced conditioning process to reduce factory acceptance testing time	12
Ability to test individual cells before stacking	8
Stack testing - identifying leaks is time consuming - develop precise methods of leak testing a finished stack - develop methods for rapid leak detection and at low leak rates	8
Pre-conditioning MEA to decrease final stack conditioning time	2
Stack assembly: methods to remove defective cells once they have been identified	1

Table 4: Stack assembly

Issue	Votes
High volume stack assembly processes: reduced labor, improved automation	15
Manufacturing processes that support tight tolerance registration of stack components and some are flexible/sensitive to environmental conditions (e.g., humidity)	10
Alignment during compression/stacking. Methods of inspecting component alignment post-assembly (x-rays?)	5
Develop methods of handling flexible stack components during automated stack assembly	5
Need to explore other non-planar "out of box" stack approaches that may have manufacturability advantages	0
Need seal fabrication and deposition techniques with faster cycle times without compromising yield/properties	0
Sealing schemes for 5000 psi electrolyzer	0
Processes that support cost reduction in stack hardware (molding of manifolds)	0

Table 5: Gas diffusion layers

Issue	Votes
Better methods for making paper GDLs in high production quantities	12
Produce tougher (e.g. less brittle) paper GDLs; *mechanically strong non-woven substrate; improve strength (Fuel cell R&D)*	9
Limited material width (format sized); thickness tolerance variation	7
Reducing errant fibers, material shedding (fibers, carbonaceous material, etc.) leading to potential debris issues during downstream processing	6
Focus on processes that support low scrap	1
Reduction of high temperature processing steps: fewer steps, alternate processing	1

Optimize GDL performance for specific platforms/users; customer/supplier collaboration to understand product requirements	0
Need more fundamental research on functional requirements of GDL (Fuel cell R&D)	0
Low GDL surface to catalyst layer roughness	0

Table 6: Electrodes

Issue	**Votes**
How to apply ink directly to membrane; dual direct coating of CCM; *membrane dimensional change with deposition of current inks (Fuel cell R&D)*	20
Investigation of alternate catalyst coating processes enables better quality	5
Process that generates low scrap is needed due to high cost of ingredients	4
Higher precious metal utilization leading to lower platinum loading; gradient catalyst deposition tailored to reactant concentration	3
Low cost manufacturing process of high-activity cathode catalyst core-shell, etc.	2
Continuous processing of catalyst inks	2
High throughput heat processing	2
Defect detection and identification; online electrode QA measurements; etc.; lack of adequate uniformity of catalyst coating	1
Raw material specification and relationship to functional process performance	1
Improved uniformity and automation for small medium production	0
Good thickness loading uniformity across web/down web	0
Platinum cost and cost volatility	0
Direct coat microporous layer and catalysts coating possibly with varied microstructure in thickness direction of GDL	0
Develop patch coating processes	0
Eliminate over-tolerancing (dimensional and other performance metrics) through better design and processing.	0

Table 7: Membranes and ionomers

Issue	**Votes**
Need integrated membrane and direct electrode coating manufacturing processes; *develop a dimensionally stable membrane able to accept direct coating of catalyst layers; membrane material that does not stretch or wrinkle during downstream processing (Fuel cell R&D)*	14
On-line quality control; good thickness uniformity; uniform film with low defects; develop better approaches for automatically detecting membrane defects	13
Higher processing speeds for varying materials properties and thicknesses	3
Good control/tolerance on rheology to support downstream processes	3
Reduced cross-over of product gases in PEM electrolysis; scale up existing materials; *low cross over/improve durability; high performance specifications on durability and conductivity; need more mechanical durability while improving ionic conductivity (Fuel cell R&D)*	2
Relaxing specifications on ionomers and membrane products	1

Degassing membrane solutions before casting	0
Need higher temperature operation in 100% RH environment (Fuel cell R&D)	0

Table 8: Bipolar plates

Issue	**Votes**
Injection moldable composite resins with high electrical conductivity for BPP production to improve throughput	13
New forming technology for low cost at low volume metal plate forming; forming technology without crack of thin metal foil stamping	9
Automated dimensional, micro-crack, surface defect inspection; bar coding	3
Joining together of titanium foils and screens face-to-face; develop plate joining process	2
Faster throughput (cycle time)	1
Reduce cost of plate molding and curing operation by the addition of plastics or other technologies	1
High cost of bipolar plate stamping die; production yield; coating technology for both coolant and electrode sides	0
Improve yield and eliminate laser welding by coolant side coating with conductive corrosion resistant layer; coating before forming to reduce labor cost	0
Processes and inspect to improve tight thickness tolerance tether with flatness (minimal warping/bowing)	0

Table 9: Membrane electrode assembly

Issue	**Votes**
Automated inspection of completed MEAs: leak check, pinhole defects, electrical shorts	10
Continuous lamination processes that do not impact stiffness of GDL (as a finished MEA); continuous lamination processes that provide uniform pressure/temperature over area of contact; high speed lamination of 7 layer MEA with high tolerances; high speed fabrication technology	7
Cutting processes for 5 layer MEAs that do not result in a compromised membrane (due to impression of fibers, etc.); develop in line cutting and slitting methods for continuous MEAs and or MEA components	6
Need assembly processes that have the lowest waste or unused area of membrane and catalyst	6
barcoding/identifying of MEA; need GDL to MEA bonding methods with faster cycle times; develop robust methods of adhering GDLs to CCM; lower temp pressure and time during processing	3
Compatibility of up-stream process and materials with MEA assembly methods; standardization of spec. width of GDL vs. width of MEA; reduce scrap/improve yield	3
Combine distinct process steps (product layers) by consecutive or simultaneous laydowns	1
Develop/tweak materials formulations compatible with high speed assembly	0
Better alignment of layers; process development/improvement; registration tolerances for MEA components prior to binding	0

No standardized dimensions on MEAs means that a MEA manufacturer may need many tool sets to accommodate a range of customers' specific needs.	0
Transfer functions that can predict stack performance from MEA properties; poor understanding of exactly what constitutes a defect (some cosmetic variations may not cause degraded performance, but may lead to a component rejection for lack of knowledge).	0
Overcome size limitation for ultrasonic bonding.	0

Table 10: Quality/Inspection/Process control

Issue	Votes
Develop methods of identifying coating defects on a moving web, then rejecting single pieces downstream; defect detection after MEA assembly when defect may no longer be visible; ability to separate materials with defects from rolled goods with minimum production of scrap	15
Understanding critical to quality metrics and measurement techniques suitable for in process measurement; identification of critical few MEA quality metrics and development of continuous on-line measurement techniques for each	14
Quality/inspection measurements need to support increased production volumes	5
Need more correlation between sub-scale and full-scale MEA electrical measurements	1

5.3.2 PEM Fuel Cells/Electrolyzers BOP

Table 11: Topics discussed

Reactant Management • BOP Cost Drivers: humidifiers; air blowers/compressors; hydrogen blowers; reforming hydrogen; reformers • Hydrogen compatible materials: manifolds and tubing/connectors • Materials of construction: compatibility with oxygen/hydrogen/DI H_2O; current materials are expensive and difficult to process • High pressure custom vessels (water/gas phase separator); Design stack for vapor feed to eliminate phase separator and reduces dryer size and water polishing requirements. • Need gas tubing quick connects to simplify PEM FC BOP assembly
Thermal Management: • Heat exchangers
Controls: • Precision liquid/gas flow sensors/MFCs
Mechanicals and Packaging: • Modular mechanical components to simplify assembly
Other: • Fans and blowers need high-efficiency, 40k hours • Cost drivers: water removal; Manufacturing needs: implementation of membrane separators • Purification of H_2; low cost membrane technology • Membrane defect and pin hole detection

- Manufacturing cost model: robust, non-proprietary; to guide DOE decision making regarding best places to place resources
- Flexible manufacturing processes; today’s tech, not tomorrow’s tech; don’t want to spend CapEx each time material sets change
- Regulatory/Code Compliance: UL/CE/CSA components can be over/under engineered for Fuel Cell/Electrolyzer applications ; could be very expensive to develop and qualify alternatives

Table 12: Recommended solutions

Suggestion	Votes
Facilitate a manufacturing group for DOE to expand supply chain.	21
Develop low cost manufacturing of natural gas reformers (Fuel cell R&D)	18
Develop low-cost manufacturing of plastic interconnects and plumbing to replace metal fittings.	4
Develop non-proprietary manufacturing cost model with specific BOP inputs for electrolyzers. (Fuel cell and Production R&D)	1

5.3.3 High Temperature Cells and Stacks

Asterisks indicate issues that could be significant to two or three of the FC technologies.

Table 13: PAFC

Issue	Votes
Processing Costs (suppliers)	
* QC techniques Vision techniques (defects, fix on the line) Testing of materials (consistency) Conditioning (less for PAFC)	12
Bipolar Plates	4
Making & Applying Electrodes (carbon/polymer) (engineered raw material)	3
* Continuous processing Mixing vs. large batch Extrusion	3
Gas Diffusion Layer/Substrate	1
Fuel Processing	1
Equipment—CAPEX	0
Power Electronics	0
* Synergy with other technologies	0
Raw Materials	
Carbon, graphite, polymers, stainless steel, platinum (3-4%) (Fuel cell R&D)	0

Table 14: MCFC

Issue	Votes
Processes	
* High temperature thermal processing (equipment M&E)—single component	8
* Stack commissioning/conditions 5% of manufacturing cost	6
* Continuous mixing/particle size reduction (e.g. tape casting—maintaining dispersion properties) Design for performance vs. manufacturing _CAPEX, Process development time (barrier)_ Drying times Non-aqueous	1
Assembly—cell, stack Demonstration of high accuracy placement Design for assembly needed (e.g., part count, process step reduction)	0
Materials – cost drivers	
* High purity, corrosion resistant stainless steel (formed or stamped) (Fuel cell R&D)	1
Nickel, nickel alloy based (Fuel cell R&D)	0
* Ceramic components (engineered) (Fuel cell R&D)	0
Need accurate, low cost stamping processes	0
Interconnect (10-20%) also: life/endurance (Fuel cell R&D)	0

Table 15: SOFC

Issue	Votes
Processes	
Multi-layer/component sintering	14
Processing of interconnects, coatings & flow fields	8
Net shape manufacturing of manifolds	2
Throughput (better)	0
Continuous flow processes Impact of batch-to-batch variation on continuous processing	0
Seal application	0
* Stacking (automated)	0
Materials	
* Engineered Powder Low volume to suppliers Too much time qualifying Lot to lot variations _Availability (e.g. rare earth materials)_	6
Interconnect materials & coatings & fabrication & flow fields	4
Seal Materials (e.g., waste, technology) (Fuel cell R&D)	0
Collaboration between OEM & Powder Supplier	0

Materials & Process	
* Cathode #1 material headache Potential scale-up issue ($$s)	6
Current collection	5

Note: There were many more SOFC participants than PAFC and MCFC

Table 16: Conclusions

All three technologies could benefit from improved QC practices. The consensus was that automated visual methods would provide the best benefits.
All three technologies could benefit from automated stacking of cells
All three technologies could benefit from the development of continuous processes to mix materials.
MCFC and SOFC technologies could benefit from low-cost stack conditioning and commissioning procedures and equipment.
MCFC and SOFC technologies could benefit from reducing the capex and maintenance costs of high-temperature thermal processing equipment
SOFC technology could benefit from development of multi-component co-sintering processes
Manufacturing of engineered powders with defined properties is needed.
Cathode powder – acceptance testing and qualification for manufacturing is a major issue. (Similar for all powder materials)

5.3.4 High Temperature Fuel Cells BOP

Table 17: Barriers and R&D Needs

Issue	Votes
Multi-unit demonstrations to establish manufacturing methodologies—SOFC (both)	7
Low cost Air/fuel flow meters—SOFC (both)	6
Advanced manufacturing techniques for recuperator assembly—SOFC (both)	4
Manufacturing techniques for integral/internal reformers—SOFC (both)	3
Develop low cost, reliable fuel-gas (anode) HT Blower/recirculator—SOFC (both)	2
Low cost water flow metering device—SOFC (both)	0

Table 18: BOP Components Needs & Barriers

Issue	Votes
Coatings/Alloys for Recuperators/Heat Exchangers SOFC (not tube) • *Low cost alloys/coatings for high temperature Recuperators/Heat Exchangers (@low production volumes)*	13
Eliminate components and design for x/lean • MCFC, SOFC (tube), PAFC ○ Cost	11

○ Trade study ○ Assembly ○ Manufacturing ○ Automation	
Sulfur Removal • MCFC, PAFC, SOFC (tube) ○ Robust ○ Cost effective ○ *High capacity* ○ *Variety of odorants/operating conditions* ○ *Sulfur detectors/sensors* ○ *Low aromatic*	9
Fuel Processing/Pre-processing PAFC, SOFC (tube), MCFC • Improved heat transfer/kinetics leads to low manufacturing cost ○ Reduced welding ○ Reduce stainless steel use	7
Thermal insulation—SOFC (tube), PAFC, MCFC • Near net shape • MN R&D for spray insulation	6
Heat Recovery/Heat Exchangers—MCFC, SOFC (tube), PAFC • Brazing R&D to get to low cost heat exchangers ○ *Development of low cost braze materials* ○ Methods of braze application (e.g., braze foils, braze coatings, and masked deposition of braze materials for use with braze electrodeposition) • *Thermal cycle tolerant seals*	6
Flexible Fuel/fuel cleanup—PAFC, MCFC, SOFC (tube) ○ *Universal cleanup system* ○ Modularity capabilities	5
Flexible Electrical Architecture • 50 Hz/60 Hz • *Multiunit load sharing* • *Long life components (20 yrs)* • High efficiency • Robust grid • Standardization	5
Fuel and Water Measurement/Pumps • MCFC, PAFC, SOFC (tube) ➢ Actuators ➢ Cost effective ➢ High turndown valves	3
Water Management/Quality—PAFC, MCFC, SOFC (tube) • Uniform treatment	2
Component commonality • Collaborative • Cross industry	0

• Suppliers Excellence Alliance type initiative	
Hybrid Fuel Cells BOP—MCFC, SOFC (tube) • Control systems (hybrids) • Turbo expanders/gas turbine	0
Affordable control system • Flexible • Embedded microprocessors	0

5.3.5 Small Fuel Cell Systems with Hydrogen Storage

Table 19: High priority needs

Need faster growth of all materials needed in fuel cells (MT)
Hydrogen permeability and material selection (Fuel cell or Production R&D)
Thermal insulation
Application specific Working Group – especially BOP (blowers, cathodes, etc.)
Material cost, manufacturing to reduce material cost
Storage cost reduction, how do you drive markets?
Fuel cell stack and storage cost Stack – reduce Pt loading (Fuel cell R&D) Storage – reduce overall cost
(SC&S)
Lower cost carbon fiber (Storage R&D) Cheaper on a mass/unit strength basis Reduced safety standards (SC&S)
Manufacturing to reduce components, MEAs
Standardization

5.3.6 Hydrogen Production and Delivery

Table 20: Distributed hydrogen production

Lower cost carbon fibers (Storage R&D)
Lifecycle cost of compressors today are high** Unreliable – redundancy will help, but cost increases *R&D for new tech maybe necessary* *High temp seals (Storage R&D)* *Metal fatigue* – diaphragms are part of it – man tolerances High pressure gas delivery (instead of numerous compressors) Higher feed pressure to minimize compressor use
Process of installation – approvals (codes and standards); each AHJ has own standards *Needs to be streamlined with national standards (more education) (Education , SC&S)*
Manufacturing of hybrid distributed production system Adding redundancy to the system
Streamline process of installation and permitting costs (MT, SC&S)
Metal based catalyst replacement – metallic substrates (Production R&D)

Some substrate catalysts ready
Compact hydrogen purification systems – tech now Coating on a substrate
Volumes (MT)
Lower storage costs
Quality control – using PSA for cleanup
Low cost hydrogen purification (contaminant detector) sensing tech
Carbon capture & renewable aspects – eventually a man issue

Table 21: Compressed gas storage and delivery

Reducing cost of fiber and resin (raw) (Storage R&D)
Lower carbon safety factor – burst to service pressure (Storage R&D) *Testing cost* *Standards barrier (SC&S)*
Reduce cost to manufacture (volume issue) (MT)
Increase pressure of tubes; dedicated trailer for more efficient use of space
Facilitating regulatory approvals (SC&S, MT)
DOE encourage other than direct manufacturers involved
Injection molded dome
Liquid trucks – scale issue
Liquefaction process
Non-destructive testing – quality control Use extra sensors, etc. to notify need for visual inspection

Table 22: Central hydrogen production

Catalysis, cleanup – for large scale Constructability of large systems *Safety (construction)* *CO_2 capture & storage* *Renewable feedstocks (purification)* What to do on front end clean up? Need to modularize clean up products Could change up-front costs
Ion transport membrane (Production R&D) *Will be learning experience with scaling*
Large central production – need large compression Could be a hybrid type of production (mix with liquid for peaking)
Cost of installing a pipeline (P&D)

Table 23: Cross-cutting priorities

Compression reliability and cost
Volume production for cost savings (MT)

Catalyst solution alternatives (Production R&D)
Membrane alternatives (high and low temperature) (Production R&D) Reliable and cost effective manufacturing scale membrane fabrication
Combining technologies (e.g. production and storage systems for reliability)
Quality assurance, e.g. sensors systems for preventative maintenance