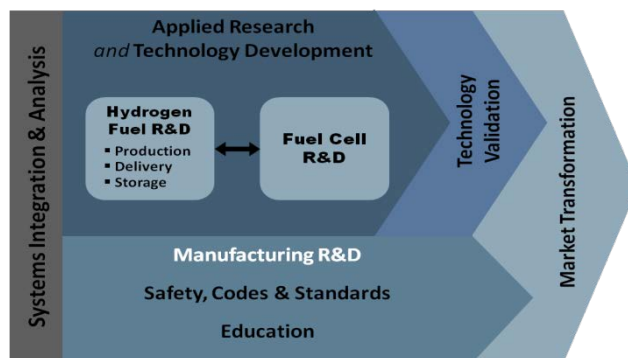


3.5 Manufacturing R&D

More than 15,000 fuel cell systems were shipped in 2010 worldwide,¹ representing more than 80 MW of power. 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 Manufacturing R&D sub-program works with industry, universities and national laboratories to research, develop, and demonstrate high-volume manufacturing processes to reduce cost while ensuring high quality products for hydrogen production, delivery and storage, as well as low and high temperature fuel cell systems. This sub-program facilitates the development of a domestic supplier base for hydrogen and fuel cell technologies.



3.5.1 Technical Goal and Objectives

Goal

Research, develop, and demonstrate technologies and processes that reduce the cost of manufacturing hydrogen production, delivery, storage, and fuel cell systems.

Objectives

- Develop manufacturing techniques to reduce the cost of automotive fuel cell stacks at high volume (500,000 units/year) from the 2008 value of \$38/kW² to \$21/kW by 2017.
- Develop fabrication and assembly processes to produce compressed hydrogen storage systems that cost 12% less than the current high-volume value of \$18/kWh for widespread commercialization of hydrogen fuel cell vehicles across most light duty platforms by 2017.
- Support efforts to reduce the cost of manufacturing components and systems to produce hydrogen at \$2-\$4/gge (2007 dollars) (untaxed, delivered, and dispensed) in 2020.

3.5.2 Technical Approach

This sub-program focuses on improving processes and reducing the cost of manufacturing components and systems for hydrogen and fuel cell applications. In addition, cross-cutting technologies (e.g., metrology) and capabilities will be developed, including modeling and simulation tools.

¹ excluding thousands shipped for toy/educational product applications

² http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mass_production_cost_estimation_report.pdf

Technical Plan — Manufacturing

The Manufacturing R&D sub-program:

- Identifies cost drivers of manufacturing processes
- Modifies manufacturing processes to eliminate process steps
- Reduces cost by implementing process control tools
- Reduces labor costs and improves reproducibility by increasing automation
- Reduces cost by improving manufacturing processes to improve yields and reduce scrap
- Scales-up laboratory fabrication methods to low-cost, high-volume production.
- Develops in-line diagnostics for component quality control and validates in-line
- Develops an understanding of the relationship between process parameters and product properties
- Quantifies the effect of defects in materials on performance and durability to understand the accuracy requirements for diagnostics.

Manufacturing R&D efforts focus on reducing the cycle times of the processes being developed. Research areas include approaches for:

- Significantly reducing the cost of the processes used to manufacture hydrogen and fuel cell components
- Rapidly defining and producing “production quality” tooling or approaches for simplifying and reducing the cost of tooling
- Increasing the uniformity and repeatability of fabrication.

Progress towards attaining the goals of Manufacturing R&D is tracked by assessing: (1) the reduction in cost of hydrogen production, delivery, storage, and fuel cell systems, and (2) the increase of manufacturing rates and annual manufacturing capacity.

These efforts will enable industry to:

- Meet customer requirements for hydrogen and fuel cell systems.
- Develop a competitive domestic supplier base for hydrogen and fuel cell system components.

3.5.3 Programmatic Status

Current Activities

Table 3.5.1 summarizes the FY 2011 activities in the Manufacturing R&D sub-program. Most activities are targeted towards polymer electrolyte membrane (PEM) fuel cells for automotive applications. Future funding opportunities will include all fuel cell types, (i.e., solid oxide, molten carbonate, phosphoric acid, polymer electrolyte, and alkaline) for all applications. Portable power from direct methanol fuel cells is covered primarily by the Department of Defense and is less likely to be a focus of DOE’s Manufacturing sub-program activities.

Currently, the Manufacturing R&D sub-program has one project aimed at developing new methods to manufacture Type IV pressure vessels for hydrogen storage. While the Storage sub-program is developing new materials (chemical hydrides, metal hydrides and sorbents) for hydrogen storage, a material-based system will not likely be scaled-up during the near term. As a result, the Storage sub-program is also focusing on high pressure gaseous storage as the path to near-term commercialization. The Manufacturing project on hydrogen storage is developing a new hybrid fabrication process for high pressure storage vessels by optimizing the elements of advanced fiber placement and commercial filament winding.

The Fuel Cell Technologies (FCT) Program does not currently sponsor any efforts focused on reducing the manufacturing cost of components and systems for production and delivery of hydrogen. To explore additional opportunities, NREL hosted a workshop in August 2011 on H₂ & FC Manufacturing R&D in Washington, D.C. with representatives from industry, academia, laboratories, and government. During the workshop, participants identified and prioritized needs and barriers to manufacturing hydrogen and fuel cell components and systems. Key suggestions included:

- **PEM Fuel Cells/Electrolyzers BOP:** Facilitate a manufacturing group for DOE to expand supply chain.
- **Electrodes:** Apply ink directly to membrane; dual direct coating of CCM; membrane dimensional change with deposition of current inks
- **PEM Fuel Cells/Electrolyzers BOP:** Develop low cost manufacturing of natural gas reformers high volume stack assembly processes: reduced labor, improved automation
- **Quality/Inspection/Process Control:** 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
- **SOFC:** Multi-layer/component sintering

Presentations and a summary of recommendations can be found in the workshop report at http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_h2_fc_manufacturing.html. The recommendations will support future funding opportunities.

The current Manufacturing portfolio includes projects focused on PEM fuel cells:

- Developing in-line defect diagnostics for quality control of membrane electrode assemblies (MEAs) and MEA components
- Reducing the fabrication costs of gas diffusion materials
- Developing processes that reduce steps and scrap in the production of MEAs
- Exploiting ultrasonic bonding to reduce the pressing cycle time of MEAs
- Quantifying the effect of variable dimensions in bipolar plates on fuel cell performance.

Some of these projects, such as in-line defect detection, are relevant to fuel cells other than PEM.

Table 3.5.1. Current Manufacturing Activities

Topic	Approach	Activities
PEM Fuel Cells		
Fuel Cell MEA Manufacturing R&D	Develop capabilities and knowledge related to in-line quality control that will assist manufacturers of PEM fuel cell MEA components in transitioning to high-volume manufacturing methods.	National Renewable Energy Laboratory: Developing diagnostics suitable for in-line quality control for MEAs and components. Investigating the effects of MEA component manufacturing defects on MEA performance and durability. Refining and validating models to predict the effects of local variations in MEA component properties.
Manufacturing of Low-Cost, Durable MEAs Engineered for Rapid Conditioning	Develop a unique, high-volume manufacturing process that will produce low-cost, durable, high-power density 3-layer MEAs that require little or no stack conditioning.	W.L. Gore & Associates: Developing a new process to reduce the use of intermediate backer materials, reducing the number and cost of coating passes, improving safety, and reducing process cost by minimizing solvent use and reducing required conditioning time and costs.
Adaptive Process Controls and Ultrasonics for High Temperature PEM MEA Manufacture	Enable cost-effective, high-volume manufacture of high-temperature proton exchange MEAs.	Rensselaer Polytechnic Institute: Achieving greater uniformity and performance of MEAs by adaptive process controls combined with <i>in situ</i> property sensing to the MEA pressing process and reducing MEA pressing cycle time through the development of novel, robust ultrasonic bonding processes for high-temperature PEM MEAs.
Flow Field Plate Manufacturing Variability and its Impact on Performance	Develop a pre-competitive knowledge base of engineering data relating bipolar plate manufacturing process parameters and dimensional variability to fuel cell performance variation.	National Institute of Standards and Technology (NIST): Fabricating cathode-side flow field plates with various well-defined combinations of flow field channel dimensional variations. Quantifying the effects of dimensional variations on single-cell fuel cell performance and correlating the results into required dimensional fabrication tolerance levels.
Non-Contact Sensor Evaluation for Bipolar Plate Manufacturing Process Control	Identify and evaluate the capability and uncertainty of commercially available non-contact, high-speed scanning technologies for applicability to bipolar plate manufacturing process control.	NIST: Identifying, developing, integrating, and/or evaluating high-speed non-contact sensors or system of sensors for application in process control of bipolar plates.
Optical Scatterfield Metrology for Online Catalyst Coating Inspection of PEM Soft Goods	Evaluate the suitability of optical scatterfield metrology as a viable measurement tool for <i>in situ</i> process control of catalyst coatings.	NIST: Engaging MEA manufacturers and industry experts in an effort to identify the critical parameters of the catalyst layer and to obtain samples that vary these parameters to enable conduction of a sensitivity study of the proposed technique.

Table 3.5.1. Current Manufacturing Activities (continued)		
Topic	Approach	Activities
High-Speed, Low-Cost Fabrication of Gas Diffusion Electrodes for MEAs	Reduce cost in fabricating the gas diffusion electrode (GDE) through the introduction of high-speed coating technology, with a focus on materials used for combined heat and power generation.	BASF Fuel Cell Inc.: Identifying key quality GDE metrics that relate directly to ink performance, developing an understanding of the forces behind ink stability, and introducing solution measurement methods that relate ink performance to the quality metrics.
Hydrogen Storage		
Advanced Manufacturing Technologies for Low Cost Hydrogen Storage Vessels	Develop new methods for manufacturing Type IV pressure vessels for hydrogen storage with the objective of lowering the overall product cost.	Quantum Fuel Systems Technologies Worldwide, Inc.: Develop new methods for manufacturing Type IV pressure vessels for hydrogen storage with the objective of lowering the overall product cost by optimizing composite usage through combining traditional filament winding and advanced fiber placement techniques and by exploring the usage of alternative fibers on the outer layers of the FW process.

3.5.4 Technical Challenges

Technical challenges in manufacturing hydrogen and fuel cell systems are summarized in this section.

Fuel Cells

The ramp-up to high-volume production of fuel cells will require quality control and measurement technologies consistent with high-volume manufacturing processes. Manufacturers will need process control strategies specific to producing fuel cell components to reduce or eliminate sampling and testing of components, modules, and subsystems.

As fuel cell manufacturing scales up, the relationships among fuel cell system performance, manufacturing process parameters, and variability must be clearly understood. Such understanding will likely play a major role in fuel cell system design, acceptable tolerances and specifications, and it is integral to implementing design for manufacturability. Modeling and simulation; better understanding of generic, cross-cutting manufacturing process technologies; reliable measurements; and standards will advance fuel cell manufacturing.

Manufacturing R&D is needed for:

- MEA production
- Gas diffusion media production
- Fuel cell stack assembly
- Stack conditioning and final testing
- Bipolar plate fabrication
- Quality control

Hydrogen Storage

The high cost of materials, particularly carbon fiber, is the primary issue with composite tank technology. The goal is to achieve a manufacturing process with: lower composite material usage, a lower cost fiber, and higher manufacturing efficiency. Current preliminary factory cost assessments of 350 bar and 700 bar one-tank, Type IV compressed gas systems (with 5.6 kg usable hydrogen) are \$29/kWh and \$36/kWh, respectively,³ at a low-volume production rate of 10,000 units/yr. These costs can be reduced through materials and process improvements and moving to higher volume manufacturing processes through advanced manufacturing R&D. Composite storage technology will most likely be employed in the near term for transportation applications and be essential for most materials-based approaches for hydrogen storage. The cycle time needs to be significantly reduced, which will require advances in filament winding processes or in the use of an alternative technology yet to be identified or developed. Reducing the amount of fiber used through fiber placement, and improvements in resin matrix technologies could greatly lower costs.

Hydrogen Production and Delivery

Currently, hydrogen production is capital-intensive. 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.

Manufacturing R&D is needed for:

- Improving the reliability and manufacturability of hydrogen compressors
- Implementation of in-use sensors to alert users of contaminants or impending component failure
- Fabrication of larger diameter hydrogen storage tubes
- Reducing the material cost for fiber-reinforced polymer pipeline

³ http://www.hydrogen.energy.gov/pdfs/progress11/iv_e_3_low_2011.pdf

- Composite tube trailer vessels that face not only challenges similar to other pressure vessels, but must also meet additional Department of Transportation requirements because of their relatively large size.
- Increasing the reliability and lowering the cost of compressors in dispensing systems. Need to show a pathway to lower cost of advanced compressors, e.g., by scale-up to high volume production

Cross Cutting Activities

Modeling and Simulation

Modeling and simulation can significantly advance the development and optimization of manufacturing processes. Mathematical models and modeling process integration are needed to evaluate the effects of various manufacturing techniques. Information on manufacturing process capabilities can be fed into component performance models to assess the impact of manufacturing variations. This will help to establish manufacturing process requirements (e.g., tolerances and quality assurance requirements), reduce manufacturing costs by relaxing noncritical tolerances, cut development times by generating more robust designs, and facilitate optimal solutions.

Quality Control and Process Control

Control technologies for manufacturing processes are needed to increase the reliability and quality of manufactured products while reducing cost. Low-cost systems are needed for monitoring and controlling manufacturing processes to produce the quantities of products that meet market requirements.

Metrology

Instruments that provide rapid and accurate measurements are needed to apply quality assurance techniques such as statistical process control. Metrology will provide quantitative information about a manufacturing process and its output. The ability to measure various process quantities such as leaks, microstructure defects, surface roughness, coating quality, and dimensional accuracy reliably, will enable cost-effective manufacturing. In-process measurements will allow manufacturers to establish statistical process capabilities and make adjustments to control process and component quality during operation. Current inspection techniques often require off-line measurements, manual inspection techniques, and even destructive tests. These approaches slow the manufacturing process and add cost. Non-destructive testing techniques that eliminate manual and time-consuming test and measurement processes are needed.

3.5.5 Technical Barriers

This section summarizes the technical and economic barriers that must be overcome to meet the Manufacturing R&D objectives.

Low-Temperature Fuel Cells

A. Lack of High-Volume Membrane Electrode Assembly Processes

Currently, some MEAs are prepared using decal transfer of the electrode to the membrane. New manufacturing methods are needed to fabricate MEAs involving direct coating of the electrode on the membrane or gas diffusion layer (GDL) substrate. Continuous lamination processes that do not impact stiffness of GDLs (as a finished MEA) and continuous lamination processes that provide uniform pressure/temperature over area of contact are needed.

B. Lack of High-Speed Bipolar Plate Manufacturing Processes

Both metal and non-metal bipolar plates are used in PEM fuel cells. Non-metal plate materials include expanded graphite and graphite-based composites. New technologies for forming low-cost bipolar plates at low volume are needed; these technologies are needed to produce plates without cracks that form when thin metal foil is stamped. More rapid production processes for graphite and metal plates need to be developed.

C. Lack of High Strength Gas Diffusion Media

Less brittle paper GDLs and stronger woven GDLs are needed. In addition to new approaches to produce stronger gas diffusion media, methods to reduce or eliminate protruding or loose fibers or other materials from the GDL surfaces are needed.

D. Lack of High-Speed Sealing Techniques

High-speed processes need to be developed to integrate MEA components incorporating edge and interfacial seals and gaskets. Merging the MEA sealing assembly process with the bipolar plate sealing in a continuous process could reduce the cost of stack assembly.

E. Lack of Improved Methods of Final Inspection of MEAs

New methods to inspect MEAs for leaks, shorts, membrane pinholes and other defects prior to assembly are needed. Currently a large loss of time and increased overall cost results when a stack is torn down to remove a faulty cell identified during final stack testing.

High-Temperature Fuel Cells

F. High Cost and Complexity of Processing Cell Materials

The processing of high temperature fuel cell materials is costly and can be complicated when materials are prepared in batches rather than by continuous processes, when multiple steps are required for processing, and/or when processes are inefficient and low throughput. Multi-layer/component casting, forming and sintering processes are needed for solid oxide fuel cells (SOFCs) while high temperature thermal processing techniques are needed for molten carbonate fuel cells (MCFCs) and SOFCs. Cells are stacked manually for all technologies leading to slow assembly.

(We note that some phosphoric acid fuel cell (PAFC) systems have automated cell and stack production.) Part count in the system is too high.

G. Lack of High-Speed Separator Plate and Current Collector Manufacturing Processes

The plate and current collector material requirements of low and high-temperature fuel cell systems are different so it is unclear if techniques developed to manufacture plates for low-temperature cells can be applied to high-temperature cells. Improved processing of interconnects, coatings, and flow fields are needed.

H. Lack of Processes for Forming Thermal Insulation

Formation of thermal insulation for high temperature fuel cell systems is often a manual, time consuming process. Net shape or other forming processes are needed to reduce cycle time and cost.

Cross-cutting Fuel Cell Barriers

I. Manual Stack Assembly

Development of automated methods to assist cell and stack assembly is needed. Implementation of these methods will reduce cycle time, improve repeatability and quality, and reduce cost. Methods to ensure proper alignment and proper handling of both soft and hard-goods are needed as well as cutting processes that do not damage cell materials.

J. Lack of Rapid, Low Cost Methods for Stack Conditioning and Final Testing

Reduction of the time and cost associated with conditioning and final testing of stacks is needed. Current processes can take hours to days, require expensive equipment, floor space, and gases.

K. Low Levels of Quality Control

Capabilities to monitor the physical and chemical uniformity of electrode and electrolyte layers, as well as to perform final quality testing of full MEAs and cells are needed. Development and validation of measurement techniques for in-line use will assist manufacturers in scale-up of processing to high volumes. Techniques to mark identified defects or regions of unacceptable variability for later removal in ways that minimize loss of surrounding material are needed. Improving the basis of knowledge around the performance and durability effects of variability and defects such that product specifications can be set based on systematic studies are needed. Quality assurance test methods to ensure that engineered powders meet process specifications are also needed.

L. Lack of Standardized Balance-of-Plant Components

Balance-of-plant components are either not designed for fuel cell applications and thus incur performance penalties or if they are, the volumes are so low that costs are excessive. Common specifications for fuel cell balance-of-plant (BOP) components do not exist. Design for Manufacturing and Assembly (DFMA) could be applied during the development of standardized specifications to reduce part count and cost, and improve manufacturability. High-volume manufacturing of balance-of-plant components and rapid assembly into the fuel cell power plant system need to be developed to reduce costs. Specific examples of BOP components needing developing are heat exchangers, liquid flow control and metering devices, blowers, and humidifiers.

We note that addressing the barrier of part standardization will require industry-wide collaboration including the fuel cell manufacturers as well as their MEA and BOP suppliers.

Hydrogen Storage

M. Lack of Low-cost Carbon Fiber

Currently, composite tanks require high-strength carbon fiber that costs from \$10-16/lb.⁴ Manufacturing R&D is needed to reduce the energy used to process carbon materials and increase the rate of carbonization processes for the carbon fiber, e.g., with microwave or plasma processing. In addition to improved carbonization processes, other steps in the process, such as oxidation and graphitization need to be improved.

N. Lack of Low-Cost Fabrication Techniques for Storage Tanks

New manufacturing methods are needed to reduce the cycle time, that is, the time to fabricate a single tank. Potential advances in manufacturing technologies include faster filament winding (e.g., multiple heads), new filament winding strategies and equipment, and continuous versus batch processing. New manufacturing processes for room temperature curing, wet winding processes, applying the resin matrix, and fiber-imbedded thermoplastics for hot wet winding should also be investigated. New hybrid manufacturing methods for carbon fiber winding and fiber placement manufacturing are needed. A cost model is needed to guide development of high-volume production processes for high-pressure composite tanks employing fiber placement technologies.

Hydrogen Production & Delivery

O. Lack of Reliable Hydrogen Compressors

Hydrogen compressors are unreliable and account for a significant fraction of maintenance events associated with the hydrogen infrastructure for material handling equipment and light-duty vehicles. Redundancy is employed to mitigate the unreliability but that increases lifecycle costs.

P. Lack of In-Use sensors

Integration of sensor systems to provide in-use indications of the needs for preventative maintenance or of the onset of known failure mechanisms is needed.

Q. Lack of Processes to Fabricate Large-Diameter, Low-cost Tubes for Compressed Hydrogen Storage

Processes to fabricate larger diameter tubes for compressed hydrogen storage need to be developed. The costs of plumbing and assembly are too high and space is poorly utilized. Throughput needs to be increased; winding, cure, and assembly are too slow.

⁴ Ibid.

3.5.6 Technical Task Descriptions

The technical task descriptions and the barriers associated with each task are presented in Table 3.5.2. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate sub-program.

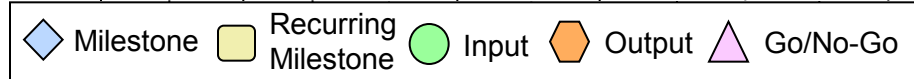
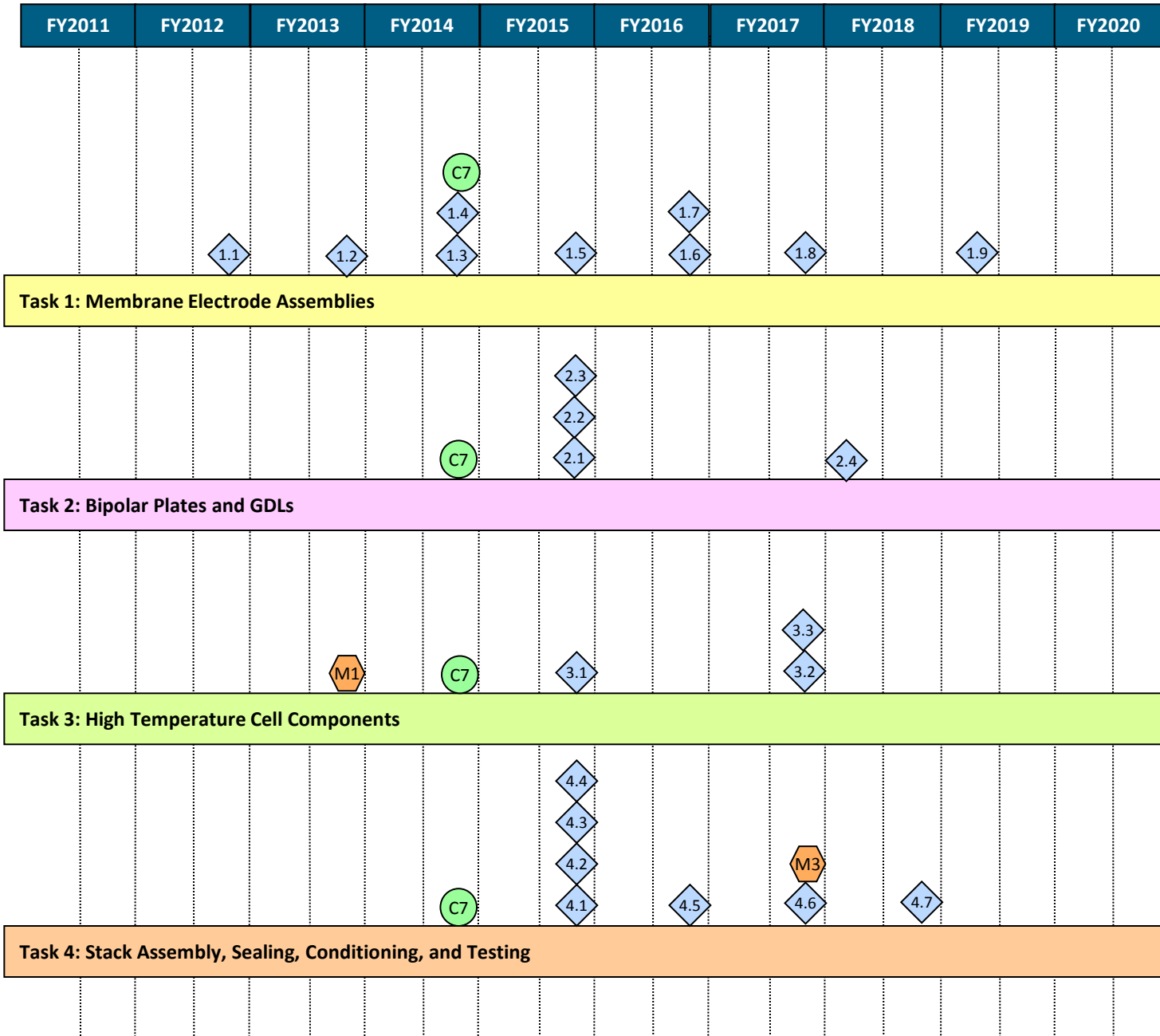
Table 3.5.2 Technical Task Descriptions		
Task	Description	Barriers
Low-Temperature Fuel Cells		
1	Membrane Electrode Assemblies <ul style="list-style-type: none"> Develop and demonstrate processes for direct coating of electrodes on membranes or gas diffusion media Develop and demonstrate highly uniform continuous lamination of MEA components Develop cell manufacturing processes that increase throughput and efficiency and decrease complexity and waste 	A
2	Bipolar Plates and GDLs <ul style="list-style-type: none"> Develop high-volume, low-cost processes for manufacturing graphite/resin and metal bipolar plates Develop low-cost bipolar plate fabrication processes that are applicable to low-rate production Develop rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates Develop GDL fabrication and handling processes, especially to improve strength, decrease brittleness, and reduce or eliminate loose or protruding fibers from the surfaces 	B,C
High-Temperature Fuel Cells		
3	Cell Components <ul style="list-style-type: none"> Develop cell fabrication processes, including casting, forming, sintering, and other thermal processing, to increase throughput and efficiency and to decrease complexity and waste Develop separator/bipolar/flow-field plate and current collector fabrication processes Develop net shape or other improved forming processes for thermal insulation 	F, G, H
Cross-Cutting Tasks		
4	Stack Assembly and Sealing <ul style="list-style-type: none"> Develop techniques to seal components rapidly and reliably Develop equipment capable of high-rate assembly of cell stacks using automated methods Develop processes and methods to assure proper alignment and handling of hard and soft goods during stack assembly Develop quality control instruments to assure specified compression on cell stack Develop methods and processes to decrease the amount of time and equipment intensity currently required for stack testing and conditioning 	D, I,J

Table 3.5.2 Technical Task Descriptions (continued)		
Task	Description	Barriers
5	Balance-of-Plant <ul style="list-style-type: none"> Support activities that lead to standardized specifications for BOP equipment Apply DFMA analysis to standard designs to reduce part count and cost, and improve manufacturability Support exploration and implementation of automation in the assembly of BOP components 	L
6	Quality Control and Modeling <ul style="list-style-type: none"> Develop automated and/or continuous in-line measurement of material properties and defects during cell and cell sub-assembly fabrication Develop methods to inspect full MEAs and cells for leaks, shorts, and membrane pinholes after pressing/lamination, prior to assembly into a stack Develop techniques to mark identified defect regions for later removal Develop correlations between manufacturing parameters/defects and performance/durability/life of MEAs Establish, validate and extend models that predict the effect of manufacturing variations on MEA performance 	E,K
Hydrogen Storage		
7	High-Pressure Composite Tanks <ul style="list-style-type: none"> Produce a cost model for high-pressure tank manufacture Develop new manufacturing methods for high-pressure composite tanks using hybrid tank design with lower cost carbon fibers on exterior Develop high-speed filament winding processes Develop fiber placement processes that reduce the amount of carbon fiber required Develop fabrication processes for larger diameter compressed gas tubes 	M, Q
Hydrogen Production & Delivery		
8	Components <ul style="list-style-type: none"> Develop manufacturing processes that improve the reliability of hydrogen compressors Integrate in-use sensors to detect contaminants or detect failures early Develop fabrication processes for large compressed gas tubes for tube trailers 	N, O, P

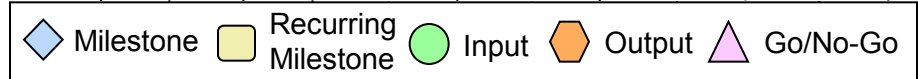
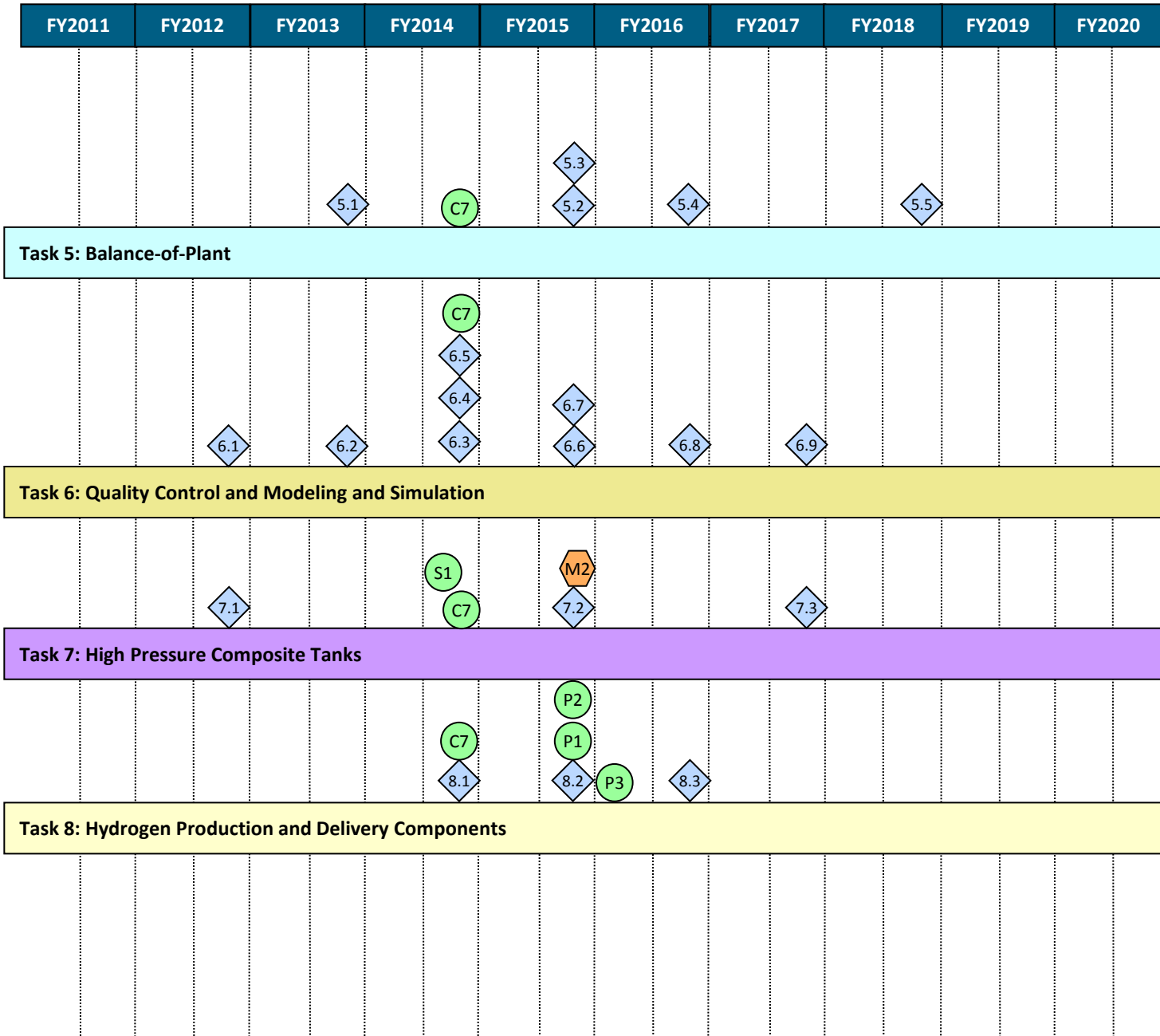
3.5.7 Milestones

The following chart shows the interrelationship of milestones, tasks, and supporting inputs from (and outputs to) other sub-programs to (from) the Manufacturing R&D sub-program.

Manufacturing Milestone Chart



Manufacturing Milestone Chart



Fuel Cells

Task 1: Membrane Electrode Assemblies	
1.1	Develop continuous in-line measurement for MEA fabrication. (4Q, 2012)
1.2	Reduce the cost of manufacturing MEAs by 25%, relative to 2008 baseline of \$126/kW (at 1,000 units/year). (4Q, 2013)
1.3	Develop processes for direct coating of electrodes on membranes or gas diffusion media (4Q, 2014)
1.4	Develop processes for highly uniform continuous lamination of MEA components (4Q, 2014)
1.5	Develop cell manufacturing processes that increase throughput and efficiency and decrease complexity and waste (4Q, 2015)
1.6	Demonstrate processes for direct coating of electrodes on membranes or gas diffusion media (4Q, 2016)
1.7	Demonstrate processes for highly uniform continuous lamination of MEA components (4Q, 2016)
1.8	Develop fabrication and assembly processes for PEM fuel cell MEA components leading to an automotive fuel cell system that cost \$30/kW. (4Q, 2017)
1.9	Develop fabrication and assembly processes for membranes that operate at $T > 150^{\circ}\text{C}$ with a projected durability of 60,000 hours. (2Q, 2019)
Task 2: Bipolar Plates and GDLs	
2.1	Demonstrate pilot scale processes for manufacturing bipolar plates that reduce cost at both low and high volume. (4Q, 2015)
2.2	Develop rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates. (4Q, 2015)
2.3	Develop GDL fabrication and handling processes, especially to improve strength, decrease brittleness, and reduce or eliminate loose or protruding fibers from the surfaces (4Q, 2015)
2.4	Develop manufacturing processes for PEM bipolar plates that cost $< \$3/\text{kW}$ while meeting other technical targets. (1Q, 2018)

Task 3: High Temperature Cell Components	
3.1	Develop and demonstrate cell fabrication processes to increase throughput and efficiency and to decrease complexity and waste (4Q, 2015)
3.2	Develop fabrication processes for separator, bipolar, and flow-field plates and current collectors (4Q, 2017)
3.3	Develop net shape or other improved forming processes for thermal insulation (4Q, 2017)
Task 4: Stack Assembly, Sealing, Conditioning and Testing	
4.1	Develop pilot scale processes for manufacturing of end plates and manifolds. (4Q, 2015)
4.2	Demonstrate pilot scale processes for assembling and sealing stacks. (4Q, 2015)
4.3	Develop processes and methods to assure proper alignment and handling of hard and soft goods during stack assembly (4Q, 2015)
4.4	Reduce the cost of PEM fuel cell stack assembly and testing by 50%, relative to 2008 baseline of \$1.68/kW (at 1,000 units/year). (4Q, 2015)
4.5	Develop processes and methods to decrease the amount of time and equipment intensity currently required for stack testing and conditioning (4Q, 2016)
4.6	Develop fabrication and assembly processes for PEM automotive fuel cell stacks that meet cost of \$30/kW. (4Q, 2017)
4.7	Develop fabrication and assembly processes for stacks with MEAs that operate at 120°C and meet membrane and MEA targets. (4Q, 2018)
Task 5: Balance-of-Plant	
5.1	Establish a plan, with industry input and guidance, to support activities leading to standardization of specifications and application of DFMA to BOP components (4Q, 2013)
5.2	Develop manufacturing methods to automate the production and assembly of BOP components (4Q, 2015)
5.3	Establish a public/private working group (or groups) for the standardization of BOP component specifications (4Q, 2015)
5.4	Develop manufacturing processes for air compression systems that have 80% efficiency at 25% of rated air flow. (4Q, 2016)
5.5	Develop manufacturing processes for humidifier modules with projected durability of 5,000 hours during RH cycling. (4Q, 2018)

Technical Plan — Manufacturing

Task 6: Quality Control and Modeling and Simulation	
6.1	Develop continuous in-line measurement for PEM MEA fabrication. (4Q, 2012)
6.2	Develop defect detection techniques in pilot scale applications for manufacturing MEAs and MEA components. (4Q, 2013)
6.3	Establish models to predict the effect of manufacturing variations on MEA performance. (4Q, 2014)
6.4	Demonstrate methods to inspect full MEAs and cells prior to assembly into stacks (4Q, 2014)
6.5	Validate and extend models to predict the effect of manufacturing variations on MEA performance. (4Q, 2014)
6.6	Demonstrate continuous in-line measurement for MEA and MEA component fabrication. (4Q, 2015)
6.7	Develop methods to mark identified defects for later removal (4Q, 2015)
6.8	Develop and demonstrate techniques and diagnostics for automated or continuous in-line measurement of high temperature cells and sub-assemblies during fabrication. (4Q, 2016)
6.9	Develop correlations between manufacturing parameters and manufacturing variability, and performance and durability of MEAs (4Q, 2017)

Hydrogen Storage

Task 7: High-Pressure Composite Tanks	
7.1	Produce manufacturing cost model for high pressure tanks (4Q, 2012)
7.2	Develop fabrication and assembly processes for high pressure hydrogen storage technologies that can achieve a reduction of 10% off the baseline cost of \$18/kWh for Type IV, 700 bar tanks. (4Q, 2015)
7.3	Develop fabrication processes for larger diameter compressed gas tubes (4Q, 2017)

Hydrogen Production & Delivery

Task 8: Components	
8.1	Develop manufacturing processes that improve the reliability of hydrogen compressors (4Q, 2014)
8.2	Demonstrate in-use sensors integrated with production and delivery systems (4Q, 2015)
8.3	Develop fabrication processes for large compressed gas tubes for tube trailers (4Q, 2016)

Outputs

- M1 Output to Fuel Cells: Report on high-speed, low-cost fabrication of gas diffusion electrodes for membrane electrode assemblies. (4Q, 2013)
- M2 Output to Storage: Report on fabrication and assembly processes for high pressure hydrogen storage tanks that cost 10% less than the baseline cost of \$18/kWh for Type IV, 700 bar tanks. (4Q, 2015)
- M3 Output to Fuel Cells: Report on fabrication and assembly processes for polymer electrolyte membrane fuel cells that meet the transportation fuel cell system cost target of \$30/kW. (4Q, 2017)

Inputs

- C7 Input from Safety, Codes and Standards: Materials reference guide and properties database. (4Q, 2014)
- P1 Input from Production: Hydrogen production system based on centralized biomass gasification technology producing hydrogen at a projected cost of \$2.10/kg at the plant gate. (4Q, 2015)
- P2 Input from Production: System based on distributed production of hydrogen from electrolysis at a projected cost of \$3.90/kg without compression, storage and dispensing. (4Q, 2015)
- P3 Input from Production: Hydrogen production system based on centralized electrolysis technology producing hydrogen at a projected cost of \$3.00/kg at the plant gate. (1Q, 2016)
- S1 Input from Storage: Update status of composite tank costs. (3Q, 2014)