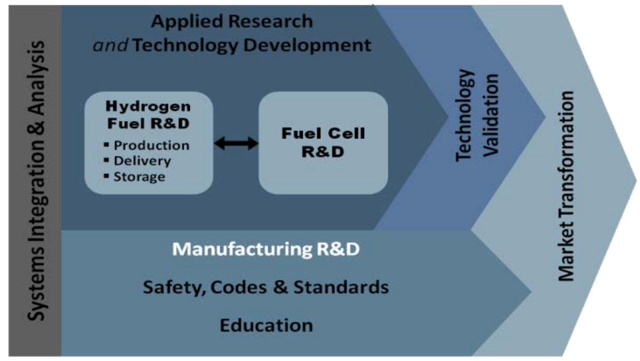
3.5 Manufacturing R&D



More than 35,000 fuel cell systems were shipped in 2013 worldwide,[1] representing more than 170 MW of power. As the market for hydrogen and fuel cells grows, the need for the 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 costs while ensuring high-quality products for hydrogen production, delivery, storage, and fuel cell systems. This sub-program also facilitates the development of a domestic supplier base and standardization of parts for hydrogen and fuel cell technologies and analyzes the factors (trade flows, availability of raw materials and components, interest rates, cost of capital, transportation costs, labor costs, degree of automation, etc.) that influence the decision on where to site manufacturing plants.

3.5.1 Goals and Objectives

Goals

Research, develop, and demonstrate manufacturing and supply chain technologies and processes that reduce the cost of manufacturing hydrogen production, delivery, storage, and fuel cell systems. Identify areas where the United States might have viable manufacturing opportunities.

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/kW to \$20/kW by 2020.[2]
- Develop fabrication and assembly processes to produce compressed hydrogen pressure vessels to enable a total onboard storage system cost of \$10/kWh for widespread commercialization of hydrogen fuel cell vehicles across most light-duty platforms by 2020, with an ultimate target of \$8/kWh.
- Support efforts to reduce the cost of manufacturing components and systems to produce and deliver hydrogen at <\$4/gge (2007 dollars) (untaxed, delivered, and dispensed) by 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.

The Manufacturing R&D sub-program supports activities to:

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[1] Excluding thousands shipped for toy/educational product applications, 2013 Fuel Cell Technologies Market Report, http://energy.gov/eere/fuelcells/downloads/2013-fuel-cell-technologies-market-report.

[2] *Mass Production Cost Estimation for Direct H_2 PEM Fuel Cell Systems for Automotive Applications: 2008 Update.* Brian D. James and Jeffrey A. Kalinoski, March 26, 2009. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mass_production_cost_estimation_report.pdf.

- Identify cost drivers of manufacturing processes
- Modify manufacturing processes to eliminate process steps
- Reduce labor costs and improve reproducibility by increasing automation
- Reduce cost by improving manufacturing processes to improve yields and reduce scrap
- Develop in-line diagnostics for component quality control and validate performance in-line
- Develop an understanding of the relationship between process parameters and product properties
- Quantify 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 can 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 the:

- Reduction in cost of hydrogen production, delivery, storage, and fuel cell components and systems, and
- Increase of manufacturing rates and annual manufacturing capacity.

These efforts will enable industry to:

- Meet customer requirements for hydrogen and fuel cell components and systems
- Develop a competitive domestic supplier base for hydrogen and fuel cell system components
- Standardize parts and components that are commonly used by all system integrators.

3.5.3 Programmatic Status

Current Activities

Table 3.5.1 summarizes the FY 2015 activities in the Manufacturing R&D sub-program. Most activities are targeted towards polymer electrolyte membrane fuel cells (PEMFCs) for automotive applications. Future work could include additional fuel cell types (i.e., molten carbonate, phosphoric acid, and alkaline). Solid oxide fuel cells fall under the purview of the Office of Fossil Energy. Portable power from direct methanol fuel cells does not reduce petroleum use and greenhouse gas emissions significantly and is not a priority of the U.S. Department of Energy’s (DOE’s) Manufacturing R&D sub-program activities.

The current Manufacturing R&D portfolio shown in Table 3.5.1 includes projects focused on quality control R&D, supply chain development, and analysis to understand the competitive landscape for hydrogen and fuel cell component manufacturing. While the projects are focused on PEMFCs, some of these projects such as in-line defect detection are relevant to other types of fuel cells.

Table 3.5.1. Current (2015) Manufacturing R&D Activities

Topic	Approach	Activities
Polymer Electrolyte Membrane Fuel Cells		
Fuel Cell Membrane Electrode Assembly (MEA) Manufacturing R&D	Develop capabilities and knowledge related to in-line QC that will assist manufacturers of PEMFC MEA components in transitioning to high-volume manufacturing methods.	**National Renewable Energy Laboratory (NREL)/Lawrence Berkeley National Laboratory (LBNL):** (1) develops diagnostics suitable for in-line QC for MEAs and components, (2) investigates the effects of MEA component manufacturing defects on MEA performance and durability, and (3) refines and validate models to predict the effects of local variations in MEA component properties.
Supply Chain Development		
Integrated Regional Technical Exchange Centers	Facilitate supply chain development for fuel cell and hydrogen systems through four regional technical exchange centers acting as clearinghouses for original equipment manufacturer (OEM) specifications, supply needs, and supply chain capabilities.	**Ohio Fuel Cell Coalition:** (1) establishes four Regional Technical Exchange Centers to increase communication between OEMs and hydrogen and fuel cell component suppliers, (2) establishes a nationwide, web-accessible database containing inputs from suppliers and OEMs along with a supplier contact list, and (3) assemble a working group to tackle component and subsystem standardization.
Fuel Cell and Hydrogen Opportunity Center	Facilitate supply chain development for fuel cell and hydrogen systems by developing a nationwide Fuel Cell and Hydrogen Opportunity Center with an internet-based communications database of suppliers that encourages the suppliers to become engaged in the hydrogen and fuel cell industry.	**Virginia Clean Cities at James Madison University:** (1) builds and populates a comprehensive communications database and (2) drives U.S. companies to the site via an aggressive outreach campaign. The database will allow for the release and maintenance of a directory tool for public interaction with the data.
Analysis of U.S. Hydrogen and Fuel Cell Manufacturing Global Competitiveness		
U.S. Clean Energy Hydrogen and Fuel Cell Technologies: A Competiveness Analysis	Conduct a global competitiveness analysis of hydrogen and fuel cell technologies manufacturing. Assess the state of global hydrogen and fuel cell markets.	**GLWN** carries out a complete detailed manufacturing analysis of fuel cell systems (automotive and stationary), high-pressure hydrogen storage systems, and key high-value hydrogen and fuel cell subsystems and components. The analysis spans systems and components manufactured in the United States, Europe, and Asia to determine the global cost leaders, best current manufacturing processes, key factors determining competitiveness, and potential means of cost reduction. GLWN works closely with NREL to ensure that this analysis is aligned with prior competitive analyses conducted in other renewable energy sectors.

Fuel cell electric vehicles are powered by hydrogen stored onboard the vehicles. The Fuel Cell Technologies Office (The Office) focuses its Hydrogen Storage R&D efforts on high-pressure tanks, seen as the pathway to commercialization in the near term. The Hydrogen Storage sub-program also supports materials development or discovery (chemical hydrogen storage, metal hydrides and sorbents) for hydrogen storage in the long term; a material-based system will not likely be scaled up during the near term.

Around 1,500 miles of steel pipeline is in service today to transport hydrogen to industrial end users; however, steel can be weakened by hydrogen embrittlement at high pressure, which can eventually lead to hydrogen leakage. Fiber-reinforced composite pipe (FRP) is a cost-effective alternative to steel pipelines for small-diameter pipelines (8” diameter or less). FRP is an existing commercial technology used in the oil and gas industry and is cheaper than steel because the pipeline can be spooled, which reduces labor costs. The Office plans to fund a Manufacturing R&D project developing new processes to reduce the cost of fabricating fiber-reinforced pipeline.

In 2011, NREL hosted a workshop on Hydrogen and Fuel Cell Manufacturing R&D. Participants at the workshop (industry, academia, and national laboratories) identified and prioritized needs and barriers to manufacturing hydrogen and fuel cell components and systems. Presentations and the full workshop report can be found at http://www.energy.gov/eere/fuelcells/hydrogen-and-fuel-cell-manufacturing-rd-workshop.

In 2013, NREL held the Office of Energy Efficiency and Renewable Energy (EERE) Quality Control Workshop. Government, industry, and other stakeholders discussed the current status of quality control and metrology in manufacturing processes relevant to the EERE offices; noted gaps in which current techniques are inadequate or missing altogether; discussed similarities in materials inspection and metrology needs across technologies; and identified opportunities for collaboration across EERE offices to address shared challenges. Presentations and the full workshop report can be found at http://energy.gov/eere/fuelcells/eere-quality-control-workshop.

3.5.4 Technical Challenges

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

Fuel Cells

One of the key challenges preventing the widespread commercialization of fuel cells is the high cost compared to incumbent technologies.[3] Reduction in the cost of key components and/or subsystems such as MEAs and their sub-components, bipolar plates, selected pumps, compressors, and fuel reformers could have an exponentially positive impact on product cost.[4] Standardization of product specifications and/or consolidating the supply chain could provide further opportunity to reduce material and product cost.[5] Increased demand and increased consistency of demand are often cited as key factors holding back further investment in advanced manufacturing and product improvements for fuel cells.[6]

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.

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[3] Fuel Cell Technologies Office Multi-Year Research, Development, and Demonstration Plan, Section 3.4—Fuel Cells. Updated November 2014. http://www.energy.gov/sites/prod/files/2014/12/f19/fcto_myrdd_fuel_cells.pdf.

[4] Manufacturing Sub-Committee Advanced Manufacturing Status and Opportunities to Accelerate Growth in Fuel Cell and Hydrogen Products, Manufacturing Subcommittee report to Hydrogen and Fuel Cell Technical Advisory Committee, December 12, 2014, to be posted.

[5] Ibid.

[6] Ibid.

As fuel cell manufacturing scales up, the relationships among fuel cell system performance, manufacturing process parameters, and variability of fuel cell properties must be clearly understood. Such understanding will likely play a major role in fuel cell system design and in the prescription of 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 all advance fuel cell manufacturing.

Hydrogen Storage

The high cost of materials, particularly carbon fiber, is the primary issue with composite tank technology. To overcome this challenge, tank manufacturing processes that are efficient and minimize waste are needed. Tank manufacturing processes alternative to conventional wet-wind processes that are more amenable to high-volume manufacturing and automation could be beneficial. Preliminary factory cost assessments of 350 bar and 700 bar one-tank, Type IV compressed gas systems (with 5.6 kg usable hydrogen in each tank) are $29/kWh and $33/kWh, respectively,[7] at a low-volume production rate of 10,000 units/yr. These costs can be reduced through materials and process improvements and by moving to higher volume manufacturing processes. Composite storage technology will most likely be used in the near term for transportation applications and be essential for most material-based approaches for hydrogen storage. The cycle time needs to be significantly reduced, which will require advances in filament winding processes or in alternative technologies.

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. The cost of building hydrogen fueling stations is too high and must be lowered. The lifetimes of high-pressure hydrogen compressors are shortened by the limited life of dynamic compressor seals due to thermal limitations of the seals. Mitigating reliability issues in manufactured compressor components and systems can decrease the overall cost of delivery.

The high cost of pipelines to deliver hydrogen is also an issue. Fiber-reinforced pipe is cheaper than steel, and pipe can be delivered in ½-mile long spools, whereas natural gas pipeline segments are typically installed in lengths of 40–80 feet. Segments are joined by compression fittings and sealed with O-rings. During fatigue testing, O-rings with insufficient hardness extrude from FRP joints, leading to failure of the joint. Failure of the O-ring increases the cost to install and maintain the pipeline.[8] Additionally, FRP is only available at relatively small diameters, limiting its use to distribution lines.

Cross-Cutting Activities

Supply Chain

The supply chain for hydrogen and fuel cells is not mature; thus, access to components and materials is limited. For many 700 bar refueling components, only one or two suppliers exist in the world.

Quality Control

Current inspection techniques often require off-line measurements, manual inspection techniques, and even destructive tests. These approaches slow the manufacturing process and add cost. Nondestructive testing techniques that eliminate manual and time-consuming test and measurement processes are needed. Mechanical

[7] DOE Fuel Cell Technologies Office Record #13010. "Onboard Type IV Compressed Hydrogen Storage Systems—Current Performance and Cost." http://hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf.

[8] "Fiber Reinforced Composite Pipelines." George Rawls and Thad Adams, May 15, 2013. http://www.hydrogen.energy.gov/pdfs/review13/pd022_adams_2013_o.pdf.

defects such as pinholes and cracks can degrade membrane and MEA performance and durability. Advanced tools and methods to inspect and quantify defects (possible interlayer delamination, voids, and locally constrained thickness inhomogeneities) in roll-to-roll goods are needed. Correlation of defect metrics to cell or device performance and lifetime is required to differentiate between fatal defects and ones that can be ignored. Defect marking, removal, and/or correction are needed as methods for differentiating between fatal defects and process drift. Process control for defect reduction is absent. Analyses to define and communicate the costs and benefits of in-line quality control (QC) as a function of material requirements and manufacturing processes, yields, volumes, and costs are lacking.

3.5.5 Technical Barriers

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

Fuel Cells

A. Lack of High-Volume MEA Processes

Currently, some MEAs are prepared using decal transfer of the electrode to the membrane. New manufacturing methods are needed to fabricate MEAs by direct coating of the electrode on the membrane or gas diffusion layer (GDL) substrate. Continuous lamination processes that do not impact the stiffness of GDLs 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 nonmetal bipolar plates are used in PEMFCs. Nonmetal 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 can form when thin metal foil is stamped. Faster production processes for graphite and metal plates need to be developed.

C. Lack of High-Strength Gas Diffusion Layers

Less brittle paper gas diffusion layers 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 by simplification.

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 lot of time is spent tearing down a stack to remove a faulty cell identified during final stack testing, leading to increased cost.

Cross-Cutting Fuel Cell Barriers

F. 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.

G. 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 and require expensive equipment, floor space, and gases.

H. Low Levels of Quality Control

Manufacturers need to monitor the physical and chemical structure of electrode and electrolyte layers, as well as perform final quality testing of full MEAs and cells. Development and validation of measurement techniques for in-line use will assist manufacturers in scaling up processing to high volumes. Techniques to mark identified defects or regions of unacceptable variability for later removal in ways that minimize scrap are needed. To set product specifications, systematic studies are needed to quantify the effects of variability and defects on performance and durability.

I. Lack of Standardized Balance-of-Plant Components

Balance-of-plant (BOP) components that are not designed for fuel cell applications can incur performance penalties. BOP components that are custom designed for fuel cell applications can be extremely expensive if the volumes are so low. Common specifications for fuel cell 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 BOP components and rapid assembly into the fuel cell power plant system need to be developed to reduce costs. Specific examples of BOP components needing development are heat exchangers, liquid flow control and metering devices, blowers, and humidifiers.

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

J. Lack of Low-Cost Carbon Fiber

Currently, composite tanks require high-strength carbon fiber that costs from $10–16/lb.[9] 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. Other processes such as oxidation and graphitization need to be improved.

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[9] DOE Fuel Cell Technologies Office Record #13010. "Onboard Type IV Compressed Hydrogen Storage Systems—Current Performance and Cost." http://hydrogen.energy.gov/pdfs/13010_onboard_storage_performance_cost.pdf.

K. 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 the development of high-volume production processes for high-pressure composite tanks employing fiber placement technologies.

Hydrogen Production & Delivery

L. 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 can be used to mitigate the unreliability, but that increases lifecycle costs.

M. 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.

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.

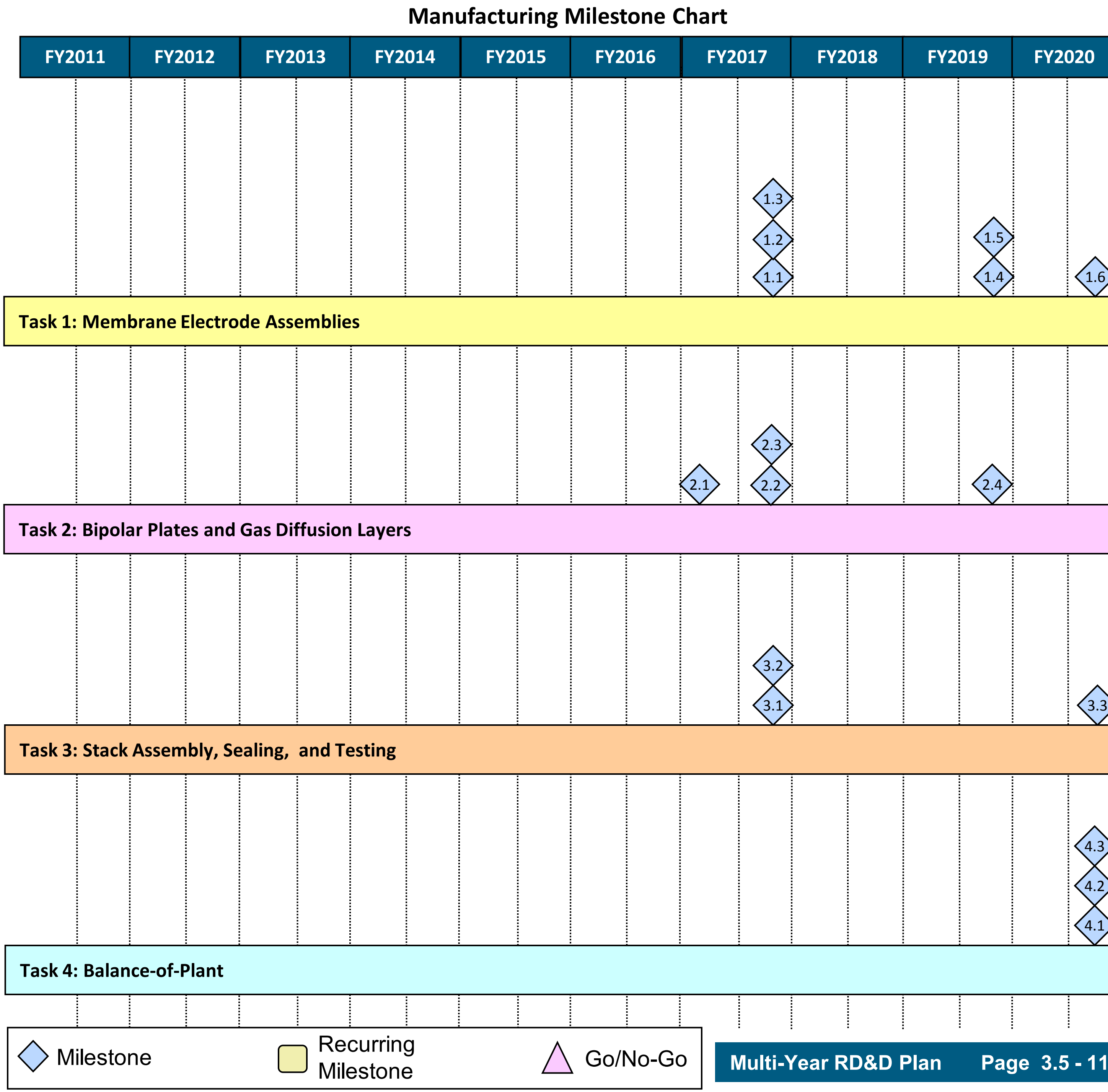
Table 3.5.2 Technical Task Descriptions

Task	Description	Barriers
Fuel Cells		
1	Membrane Electrode Assemblies • Develop and demonstrate processes for direct coating of electrodes on membranes • Develop and demonstrate highly uniform continuous lamination of MEA components • Develop continuous MEA manufacturing processes to increase throughput and efficiency and decrease complexity and waste	A
2	Bipolar Plates and Gas Diffusion Layers • 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

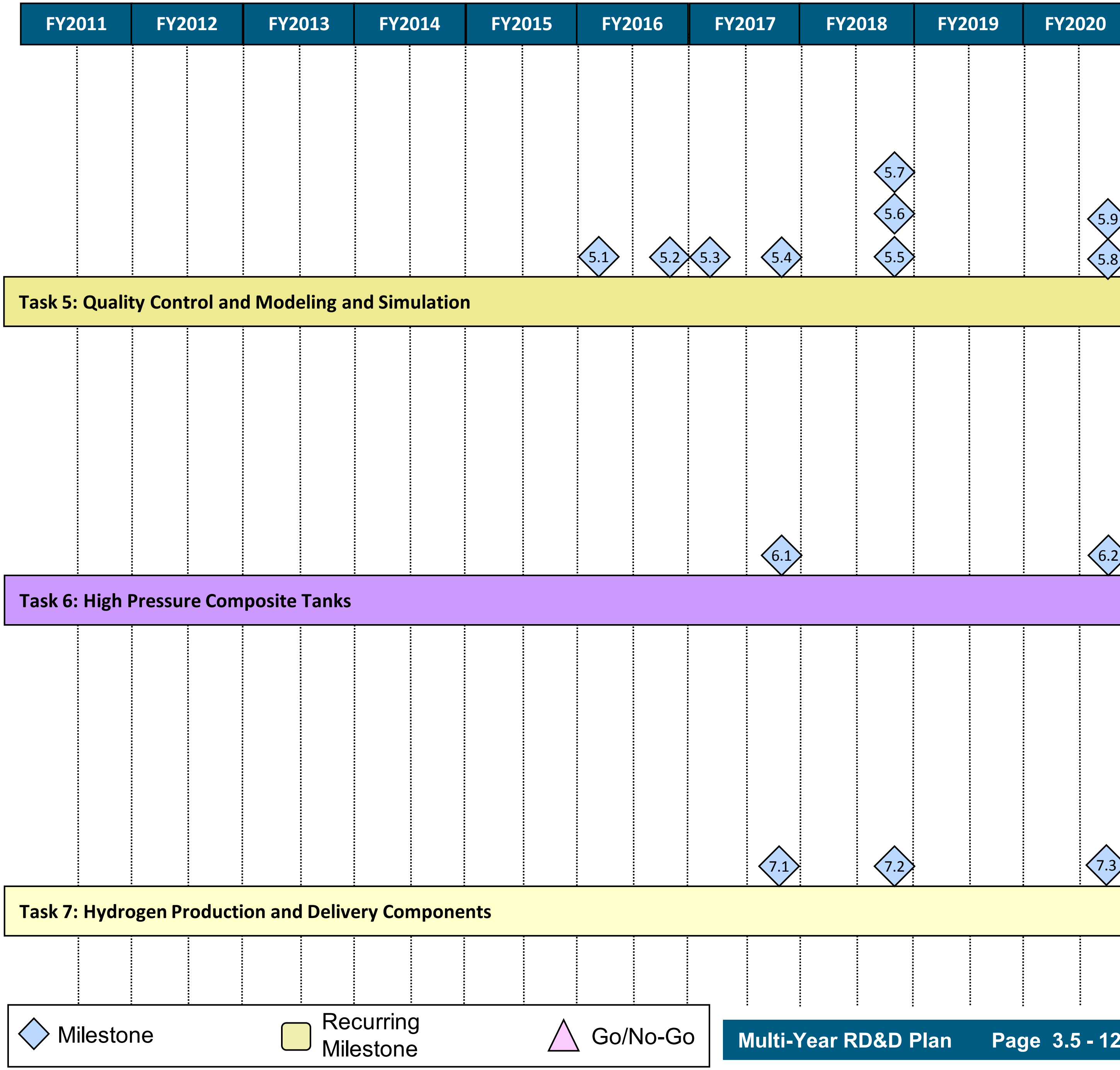
Table 3.5.2 Technical Task Descriptions		
Task	**Description**	**Barriers**
3	Stack Assembly, Sealing, and Testing • Develop techniques to seal components rapidly and reliably • Develop equipment capable of high-rate assembly of cell stacks using automation • Develop processes and methods to assure proper 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, F, G
4	Balance-of-Plant • 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 the exploration and implementation of automation in the assembly of BOP components	I
5	Quality Control and Modeling and Simulation • 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 or repair • 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 • Develop and commercialize in-line quality control techniques • Demonstrate quality control methods at production facility	E, H
Hydrogen Storage		
6	High-Pressure Composite Tanks • Develop new manufacturing methods for high-pressure composite tanks using • hybrid tank design with lower cost carbon fibers on exterior • Develop fiber placement processes that reduce the amount of carbon fiber required • Develop a process to manufacture low-cost carbon fiber precursor • Develop low-cost, high-volume manufacturing process for vacuum liner	J, K
Hydrogen Production & Delivery		
7	Components • Develop manufacturing processes that increase the reliability of hydrogen compressors • Integrate in-use sensors to detect contaminants or detect failures • Develop fabrication processes for large compressed gas tubes for tube trailers • Develop processes to manufacture low-cost, high-volume fiber-reinforced pipeline	L, M

3.5.7 Milestones

The following chart shows the interrelationship of milestones and tasks for the Manufacturing R&D sub-program from FY 2015 through FY 2020. The Manufacturing R&D sub-program inputs/outputs are summarized in Appendix B.


Manufacturing Milestone Chart
FY2011
FY2012
FY2013
FY2014
FY2015
FY2016
FY2017
FY2018
FY2019
FY2020
1.3
1.2
1.5
1.1
1.4
1.6
Task 1: Membrane Electrode Assemblies
2.3
2.1
2.2
2.4
Task 2: Bipolar Plates and Gas Diffusion Layers
3.2
3.1
3.3
Task 3: Stack Assembly, Sealing, and Testing
4.3
4.2
4.1
Task 4: Balance-of-Plant
Milestone
Recurring Milestone
Go/No-Go

Manufacturing Milestone Chart



Fuel Cells

Task 1: Membrane Electrode Assemblies	
1.1	Develop processes for highly uniform continuous lamination of MEA components. (4Q, 2017)
1.2	Develop processes for direct coating of electrodes on membranes or gas diffusion media. (4Q, 2017)
1.3	Develop continuous MEA manufacturing processes that increase throughput and efficiency and decrease complexity and waste. (4Q, 2017)
1.4	Demonstrate processes for direct coating of electrodes on membranes. (4Q, 2019)
1.5	Demonstrate processes for highly uniform continuous lamination of MEA components. (4Q, 2019)
1.6	Develop fabrication and assembly processes for PEMFC MEA components leading to an automotive fuel cell stack that costs $20/kW. (4Q, 2020)
Task 2: Bipolar Plates and Gas Diffusion Layers	
2.1	Develop manufacturing processes for PEMFC bipolar plates that cost <$3/kW while meeting all other technical targets. (1Q, 2017)
2.2	Develop rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates. (4Q, 2017)
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, 2017)
2.4	Demonstrate pilot-scale processes for manufacturing bipolar plates that reduce cost at both low and high volume. (4Q, 2019)
Task 3: Stack Assembly, Sealing, and Testing	
3.1	Develop processes and methods to ensure proper alignment and handling of hard and soft goods during stack assembly. (4Q, 2017)
3.2	Develop processes and methods to decrease the amount of time and equipment intensity currently required for stack testing. (4Q, 2017)
3.3	Develop fabrication and assembly processes for automotive PEMFC stacks that meet the cost of $20/kW. (4Q, 2020)
Task 4: Balance-of-Plant	
4.1	Develop manufacturing methods to automate the production and assembly of BOP components. (4Q, 2020)
4.2	Develop manufacturing processes for air compression systems that have 80% efficiency at 25% of rated air flow. (4Q, 2020)
4.3	Demonstrate manufacturing processes for humidifier modules with projected durability of 5,000 hours during RH (relative humidity) cycling. (4Q, 2020)

Task 5: Quality Control and Modeling and Simulation	
5.1	Establish models to predict the effect of manufacturing variations on MEA performance. (1Q, 2016)
5.2	Demonstrate improved sensitivity, resolution, and/or detection rate for MEA inspection methods. (4Q, 2016)
5.3	Validate and extend models to predict the effect of manufacturing variations on MEA performance. (1Q, 2017)
5.4	Design and commercialize an in-line QC device for PEMFC MEA materials based on NREL's optical reflectance technology. (4Q, 2017)
5.5	Develop correlations between manufacturing parameters and manufacturing variability, and performance and durability of MEAs. (4Q, 2018)
5.6	Demonstrate methods to inspect full MEAs and cells for defects prior to assembly into stacks in a production environment. (4Q, 2018)
5.7	Develop areal techiques to measure platinum (and other catalyst metals) quantitatively in an MEA. (4Q, 2018)
5.8	Implement demonstrated in-line QC techniques on pilot or production lines at PEMFC MEA material manufacturers. (4Q, 2020)
5.9	Develop imaging-based methods for 100% inspection of PGM loading in electrodes. (4Q, 2020)

Hydrogen Storage

Task 6: High-Pressure Composite Tanks	
6.1	Develop fabrication and assembly processes for high-pressure hydrogen storage technologies that cost \$12/kWh for Type IV, 700 bar tanks. (4Q, 2017)
6.2	Develop novel precursors and conversion processes capable of reducing the high-volume cost of high-strength carbon fiber by 25% from \$13 per pound to ~\$9 per pound. (4Q, 2020)

Hydrogen Production & Delivery

Task 7. Hydrogen Production & Delivery Components	
7.1	Develop low-cost fabrication processes for fiber-reinforced pipelines. (4Q, 2017)
7.2	Demonstrate in-use sensors integrated with production and delivery systems. (4Q, 2018)
7.3	Demonstrate manufacturing processes to lower cost and improve reliability of components for compression, storage, and dispensing (CSD) of hydrogen. (4Q, 2020)