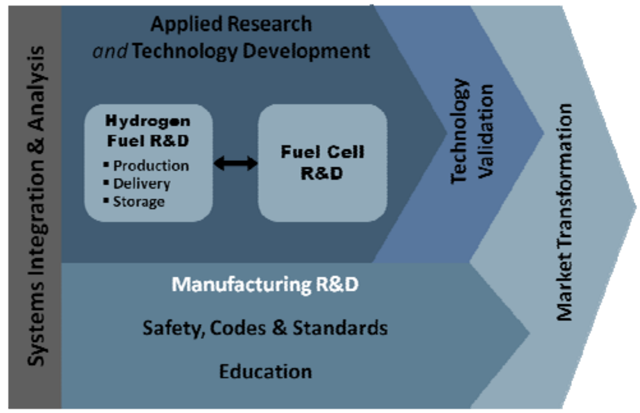
3.5 Manufacturing R&D



The Manufacturing R&D sub-program 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.

3.5.1 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

- Support efforts to reduce the cost of automotive fuel cell systems to $30/kW by 2017 by developing manufacturing techniques that reduce the system assembly and testing costs to less than $1/kW.
- Reduce the cost of manufacturing high-pressure hydrogen storage tanks by developing fabrication and assembly processes for high pressure hydrogen storage that achieve a cost of $6/kWh for widespread commercialization of hydrogen fuel cell vehicles across most light duty platforms.
- Support efforts to reduce the cost of hydrogen delivery from the point of production to the point of use of emerging regional consumer and fleet vehicle markets to <$2/gge by 2015.
- Support efforts to reduce the cost of manufacturing components and systems to produce hydrogen at $2-$4/gge (2007 dollars) (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 standards) and capabilities will be developed, including modeling and simulation tools.

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 developing technologies to minimize ex situ testing.
- Reduces cost by improving manufacturing processes to improve yields and reduce scrap.
- Scales-up laboratory fabrication methods to low-cost, high-volume production.
- Develops and validates in-line diagnostics for component quality control.
- 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.

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.

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

- Reducing the cost of the processes used to manufacture hydrogen and fuel cell components.
- Defining and producing "production quality" tooling or approaches for simplifying and reducing the cost of tooling.
- Reducing the cost of manufacturing equipment and therefore the total cost of parts.
- Increasing the uniformity and repeatability of fabrication.

Progress 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.

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 toward 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. This project is developing a new hybrid fabrication process for tanks by optimizing the elements of advanced fiber placement and commercial filament winding.

The Manufacturing sub-program does not currently sponsor any efforts focused on reducing the manufacturing cost of components and systems for production of hydrogen.

Projects focused on PEM fuel cells are: 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, and 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.
Reduction in Fabrication Costs of Gas Diffusion Layers (GDLs)	Reduce the fabrication costs of high-performance GDL products, while increasing manufacturing capacity and improving product uniformity.	**Ballard Material Products:** Developing and implementing new, high volume GDL process technologies.
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 manufacturing of high-temperature proton exchange MEAs.	**Rensselaer Polytechnic Institute:** Achieving greater uniformity and performance of MEAs by adaptive process controls combined with *in situ* 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.

Table 3.5.1. Current Manufacturing Activities		
Topic	**Approach**	**Activities**
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 *in situ* 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.
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.:** Improving the approach for stress analysis by taking the transition areas between the domes and the cylinders section into account.

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
- Bipolar plate fabrication
- Balance-of-plant subsystem assembly
- 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, 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 will 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

Currently, hydrogen production is capital-intensive and capital is a larger fraction of total cost for smaller hydrogen production facilities, such as those designed for distributed applications, compared to larger facilities. The higher per unit capital cost of the distributed systems is the result of site-specific fabrication of steam methane reforming systems and only low-volume manufacturing of electrolysis units of the size necessary for a distributed hydrogen network.

Manufacturing R&D is needed for:

- Joining reformer components
- Reformer reactor vessels
- Stamping and extruding reformer components
- Deposition of catalyst coatings onto nonconformable surfaces in reformers and electrolyzers

Manufacturing costs for reformers with water-gas shift reactors are typically high because the inherent high-temperature reforming process requires specialty metals that are machined, joined, and welded. Reformer pressure vessels are another source of high cost for hydrogen production. Forming and joining of component sections is currently labor-intensive and costly. Establishing automated manufacturing processes for forming, heat treating, and assembling the catalyst supports and welding and joining the reformer components can help reduce capital costs.

A standardized, automated method for applying catalyst coatings to nonconformable surfaces (e.g., applying catalysts directly to heat exchange surfaces or microchannel reactors) will facilitate high-volume manufacturing. This approach will also benefit the deposition of catalysts onto electrode substrates for electrolysis. Also, on-line quality assurance methods need to be developed for these applications.

Hydrogen Delivery

Challenges for manufacturing components and systems for hydrogen delivery include:

1. Lower the material cost for fiber-reinforced polymer pipeline; the current cost is ~10-20% greater than that of steel pipeline.
2. Meet Department of Transportation (DOT) requirements, in addition to challenges similar to other pressure vessels, for composite tube trailer vessels.
3. Increase the reliability and lower the cost of compressors in dispensing systems; need to show a pathway to lower the cost of advanced compressors, e.g., by scaling up to high volume production.

Cross Cutting Activities

Materials

A critical cross-cutting materials manufacturing issue is the reduction of the cost of the carbon fiber used in vehicular, tube trailer, and stationary hydrogen storage tanks. Currently, carbon fiber represents as much as 70% of the cost of these storage vessels.

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. These developments 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.

Knowledge Bases/Development

Information and knowledge about new materials and sealants, including their processibility, formability, machinability, and compatibility with other materials and gases are needed to support modeling efforts. Also, toxicity and life-cycle environmental impact data need to be collected and understood. Information is also needed on new process technologies and the fundamental correlations between manufacturing parameters and performance parameters. In many technology areas, the effect of variations caused by manufacturing is not understood sufficiently to establish appropriate tolerances and design practices.

Sensing 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 and Standards

Rapid and accurate measurement systems and devices 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 parameters such as leaks, microstructure defects, surface roughness, coating quality, and dimensional accuracy 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.

Related issues include the need for standard measurement methods and protocols of the manufacturing process and component performance parameters. Such standards will ensure uniformity in the supply chain, lower costs, reduced scrap, and high quality products.

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 Membrane Electrode Assembly Processes

New manufacturing methods are needed to fabricate advanced catalyst layers that meet the low precious metal targets. Most MEA fabrication processes include a hot-pressing stage that slows the throughput processing rate. More flexible, agile, integrated approaches are needed for MEA manufacturing as the design of MEAs evolve.

B. Lack of High-Speed Bipolar Plate Manufacturing Processes

New high-speed forming, stamping, and/or molding processes are needed that will maintain the high tolerance requirement of fuel cells for flow field dimensions, plate flatness, and plate parallelism. Production processes for graphite resin, natural flake graphite, and metal plates need to be developed. Rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates is needed.

C. 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.

D. Manual Stack Assembly

Automated processes to assemble fuel cell stacks rapidly must include precise alignment of MEAs, bipolar plates, and cooler plates to avoid mechanical stresses that can fracture and tear the membrane. Integration of computer aided design tools with technology and manufacturing development is needed to advance stack performance and reduce component costs.

E. Lack of Manufacturing Processes for Balance-of-Plant Components for Fuel Cell Systems

High-volume manufacturing for balance-of-plant components and rapid assembly into the fuel cell power plant system need to be developed to reduce costs.

F. Low Levels of Quality Control and Inflexible Processes

Systems to monitor manufacturing processes and control them to achieve required levels of productivity and quality are needed. In-line manufacturing process models and controls that are correlated with the performance and durability of the fuel cell components need to be developed. Modeling techniques for manufacturing processes need to be improved to expedite development of manufacturing systems for both components and complete fuel cell power plants. Diagnostics as varied as viscometers and X-ray fluorometers are needed for in-line quality control. Manufacturing process control is needed to ensure component uniformity during the assembly of fuel cell power plants.

Hydrogen Storage

G. High-Cost Carbon Fiber

Currently, composite tanks require high-strength carbon fiber that costs from $10-$16/lb.[1] Manufacturing R&D is needed to develop lower cost carbon materials through the use of cheaper fiber precursors and less energy-intensive or faster fiber carbonization processes, such as microwave or plasma processing. In addition to improved carbonization processes, other steps in the process, such as oxidation and graphitization need to be improved.

H. Lack of Carbon Fiber Fabrication Techniques for Storage Tanks

New manufacturing methods are needed to reduce 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

I. Lack of Automated Joining Processes

Component integration requires labor-intensive welding. Manufacturers need reliable, low-variability processes that can rapidly join dissimilar material combinations and enable leak-free hydrogen systems. Catalysts are commonly applied to reformer and electrolyzer components before the components are joined. High-temperature joining processes can damage or deactivate the catalysts. Low-temperature joining processes (e.g., laser or friction welding) that do not damage the catalyst coatings on the joined parts must be evaluated for these applications.

J. Lack of Low-Cost Coating and Cladding Processes

The alkaline electrolysis cell stack uses high quantities of titanium and nickel. The development of manufacturing methods to clad or plate low-cost substrates with these metals could reduce system cost.

[1] Law, K. (May 2011) "Cost Analyses of Hydrogen Storage Materials and On-Board Systems." Presented at the DOE Annual Merit Review & Peer Evaluation, May 11, 2011. http://www.hydrogen.energy.gov/pdfs/review11/st002_law_2011_o.pdf

K. Lack of Low-Cost Stamping and Extrusion Methods

Stamping and extrusion methods are needed to enable high-volume manufacturing of critical components (e.g., heat exchangers), which are currently machined and welded.

L. Lack of Continuous Manufacturing and Modularization Processes

Currently, all hydrogen production systems are custom-made; there are no modular systems. Standardized components are needed to permit assembly line production of hydrogen generators. Accelerated test methods and non-destructive evaluation techniques that can be used to rapidly screen materials and components during fabrication need to be developed.

M. Lack of Automated Coating Processes

Protective and catalytic coatings are an integral part of the reformer, electrolyzer, gas clean-up, and purification systems. In many cases, the surfaces are not flat and have fine details that must be adequately coated for the component to function properly. Automated methods for applying these coatings need to be developed.

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	**Membranes and Membrane Electrode Assemblies** • Develop continuous in-line measurement of properties and defects during MEA fabrication • Develop methods to measure alignment of MEA components during manufacture • Characterize the impact of membrane defects on MEA performance/durability/life • Develop correlations between manufacturing parameters and performance of MEAs • Establish models to predict the effect of manufacturing variations on MEA performance	A, F
2	**Bipolar Plates** • Develop high-volume, low-cost processes for manufacturing bipolar plates • Develop high-speed forming, stamping, and molding processes • Develop manufacturing processes for graphite resin, natural flake graphite, and metal plates • Develop rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates.	A, B, F

Table 3.5.2 Technical Task Descriptions		
Task	**Description**	**Barriers**
3	**Stack Assembly and Sealing** • Develop equipment capable of high-rate assembly of cell stacks using automated methods • Develop techniques to rapidly seal components • Develop quality control measuring devices to assure proper alignment of cell components and the compressive load on the cell stack • Develop alignment database, model, and equipment to assure proper alignment during stack assembly	C, D, F
4	**Balance-of-Plant** • Develop low-cost manufacturing methods for assembly of air, fuel, and water management systems into molded manifolds • Develop standard subsystem support to facilitate robotic assembly • Design balance-of-plant for robotic application of seals and welds • Develop sensors to monitor performance of fuel cell and leakage of reactants	E, F
Hydrogen Storage		

5	**Composite Materials for High-Pressure Tanks**
	• Develop manufacturing technologies for reducing the cost of carbon fiber
	  ○ Identify and develop low-cost precursors for carbon fiber
	  ○ Develop methods to convert precursor fibers into finished fiber packages
	  ○ Develop process control system for precursor fiber manufacturing methods
		G

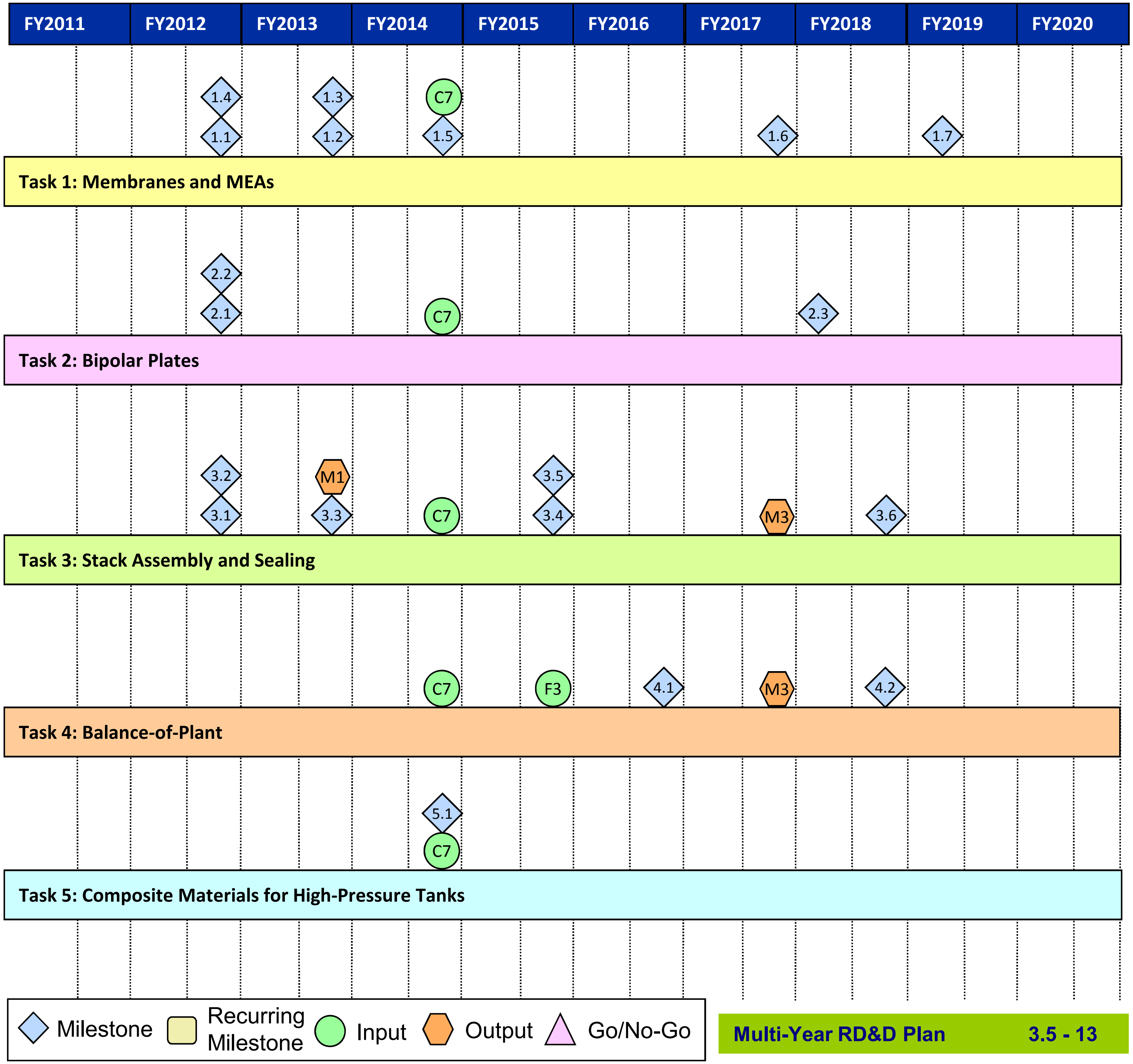
6	**High-Pressure Composite Tanks**
	• Produce a cost model for high-pressure tank manufacture
	• Develop new manufacturing methods for high-pressure composite tanks
	  ○ Develop high-speed filament winding processes
	  ○ Develop fiber placement processes that reduce the amount of carbon fiber required
		H

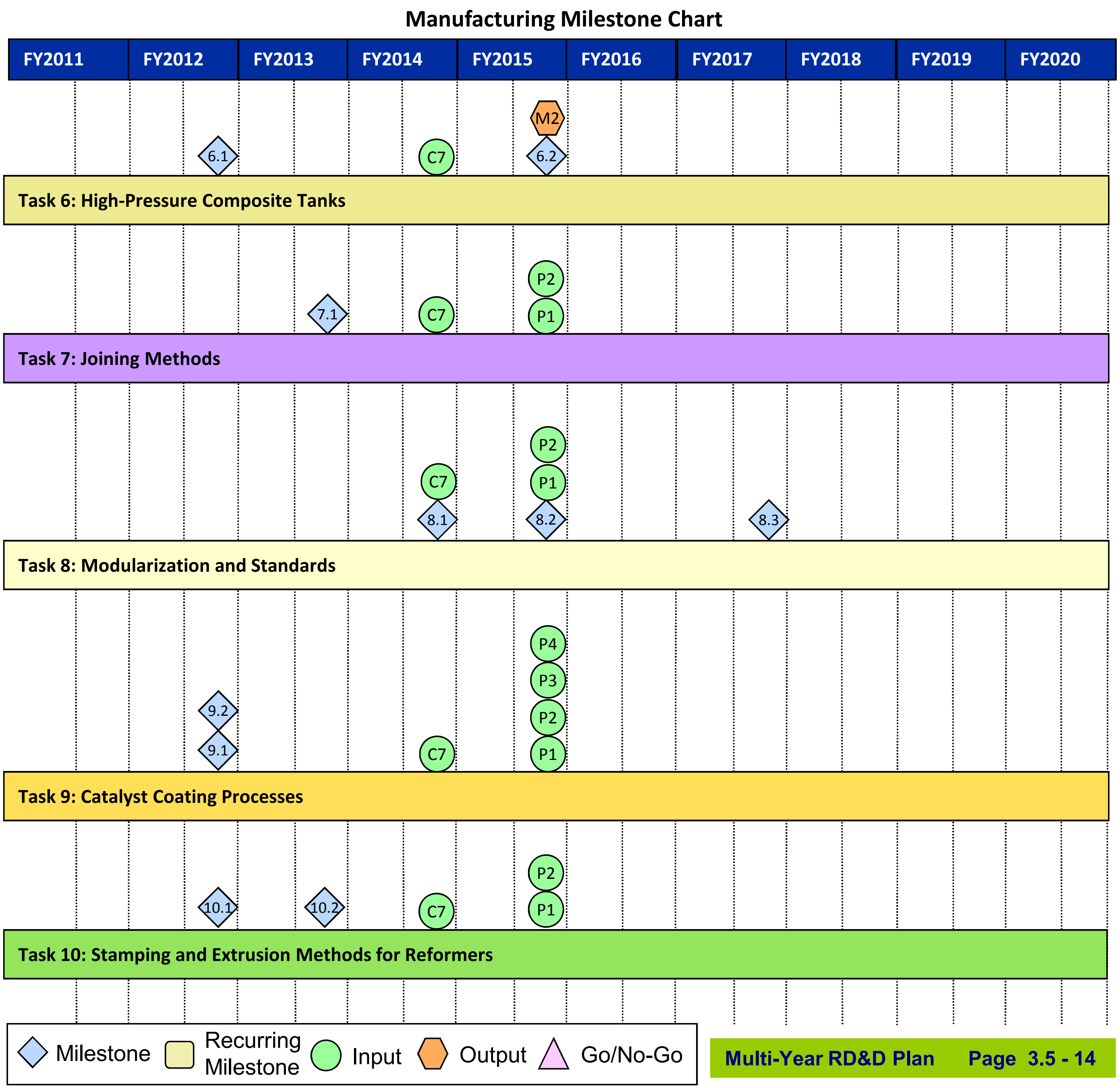
Hydrogen Production		
7	**Joining Methods** • Develop joining methods to facilitate component integration • Develop high-reliability, low-variability joining methods that can be rapidly, robotically processed and that are applicable to dissimilar material combinations • Develop brazing and bonding processes for manufacture of reformer reactors • Develop low-temperature, energy-efficient joining processes (e.g., laser or friction welding) that do not damage the catalyst coatings on the parts that are being joined	I
8	**Modularization and Standards** • Develop modular hydrogen reformers • Develop manufacturing standards for hydrogen reformers	L, M
9	**Catalyst Coating Processes** • Develop automated methods for applying catalyst coatings to non-conformable surfaces	J, M
10	**Stamping and Extrusion Methods for Reformers** • Develop stamping and extrusion methods for reactors and heat exchangers	K

3.5.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs, and technology outputs for the Manufacturing R&D sub-program.

Manufacturing Milestone Chart




Manufacturing Milestone Chart
FY2011
FY2012
FY2013
FY2014
FY2015
FY2016
FY2017
FY2018
FY2019
FY2020
M2
6.1
C7
6.2
Task 6: High-Pressure Composite Tanks
P2
7.1
C7
P1
Task 7: Joining Methods
P2
C7
P1
8.1
8.2
8.3
Task 8: Modularization and Standards
P4
P3
9.2
P2
9.1
C7
P1
Task 9: Catalyst Coating Processes
P2
10.1
10.2
C7
P1
Task 10: Stamping and Extrusion Methods for Reformers
Milestone
Recurring Milestone
Input
Output
Go/No-Go

Fuel Cells

Task 1: Membranes and MEAs	
1.1	Develop continuous in-line measurement for MEA fabrication. (4Q, 2012)
1.2	Demonstrate sensors in pilot scale applications for manufacturing MEAs. (4Q, 2013)
1.3	Establish models to predict the effect of manufacturing variations on MEA performance. (4Q, 2013)
1.4	Reduce the cost of manufacturing MEAs by 25%, relative to 2008 baseline of $63/kW (at 1,000 units/year). (4Q, 2013)
1.5	Develop continuous in-line measurement for MEA fabrication. (4Q, 2014)
1.6	Develop fabrication and assembly processes for polymer electrolyte membranes leading to an automotive fuel cell system that costs $30/kW. (4Q, 2017)
1.7	Develop fabrication and assembly processes for membranes that operate at T > 150°C with a projected durability of 60,000 hours. (2Q, 2019)

Task 2: Bipolar Plates	
2.1	Demonstrate pilot scale processes for manufacturing bipolar plates. (4Q, 2012)
2.2	Develop rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates. (4Q, 2012)
2.3	Develop manufacturing processes for PEM bipolar plates that cost <$3/kW while meeting all technical targets. (1Q, 2018)

Task 3: Stack Assembly and Sealing	
3.1	Develop automated pilot scale stack assembly processes. (4Q, 2012).
3.2	Develop pilot scale processes for manufacturing of end plates and manifolds. (4Q, 2012)
3.3	Demonstrate pilot scale processes for assembling stacks. (4Q, 2013)
3.4	Reduce the cost of PEM fuel cell stack assembly and testing by 50%, relative to 2008 baseline of $0.84/kW (at 1,000 units/year). (4Q, 2015)
3.5	Develop fabrication and assembly processes for polymer electrolyte membrane automotive fuel cells that cost $30/kW. (4Q, 2015)
3.6	Develop fabrication and assembly processes for stacks with MEAs that operate at 120°C and meet membrane and MEA targets. (4Q, 2018)

Task 4: Balance-of-Plant	
4.1	Develop manufacturing processes for air compression systems that have 80% efficiency at 25% of rated air flow. (4Q, 2016)
4.2	Develop manufacturing processes for humidifier modules with projected durability of 5,000 hours during relative humidity cycling. (4Q, 2018)

Hydrogen Storage

Task 5: Composite Materials for High-Pressure Tanks	
5.1	Complete knowledge base of material properties for alternatives to carbon fibers. (4Q, 2014)

Task 6: High-Pressure Composite Tanks	
6.1	Develop prototype sensors for quality control of high pressure composite tank manufacturing. (4Q, 2012)
6.2	Develop fabrication and assembly processes for high pressure hydrogen storage technologies that can achieve a cost of $6/kWh. (4Q, 2015)

Hydrogen Production

Task 7: Joining Methods	
7.1	Demonstrate pilot scale application of joining methods selected. (4Q, 2013)

Task 8: Modularization and Standards	
8.1	Complete development of standards for metrology of production systems. (4Q, 2014)
8.2	Reduce the cost of manufacturing components and systems for distributed reforming of biomass-derived renewable liquid fuels to achieve $5.10/gge (delivered). (4Q, 2015)
8.3	Reduce the cost of manufacturing a distributed electrolysis system at a projected cost of $3.70/kg without compression, storage, and dispensing. (4Q, 2017)

Task 9: Catalyst Coating Processes	
9.1	Demonstrate pilot scale, high volume manufacturing processes for electrolysis membrane assemblies. (4Q, 2012)
9.2	Demonstrate sensors in pilot scale applications for manufacturing electrolysis membrane assemblies. (4Q, 2012)

Task 10: Stamping and Extrusion Methods for Reformers	
10.1	Demonstrate pilot scale, high volume manufacturing processes for stamping and extrusion. (4Q, 2012)
10.2	Develop prototype sensors for quality control of stamping and extrusion. (4Q, 2013)

Outputs

M1 Output to Fuel Cells: Report on process for assembling stacks. (4Q, 2013)

M2 Output to Storage: Report on fabrication and assembly processes for high-pressure hydrogen storage technologies that can achieve a cost of $6/kWh. (4Q, 2015)

M3 Output to Fuel Cells: Report on fabrication and assembly processes for polymer electrolyte membrane automotive fuel cell that meets cost of $30/kW. (4Q, 2017)

Inputs

C7 Input from Safety, Codes, and Standards: Materials reference guide and properties database. (4Q, 2014)

F3 Input from Fuel Cells: Coolant system project results. (4Q, 2015)

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 renewable liquids at a projected cost of $5.00/kg without compression, storage and dispensing. (4Q, 2015)

P3 Input from Production: System based on distributed production of hydrogen from electrolysis at a projected cost of $3.70/kg without compression, storage, and dispensing. (4Q, 2015)

P4 Input from Production: Hydrogen production system based on centralized electrolysis technology producing hydrogen at a projected cost of $3.10/kg at the plant gate. (4Q, 2015)