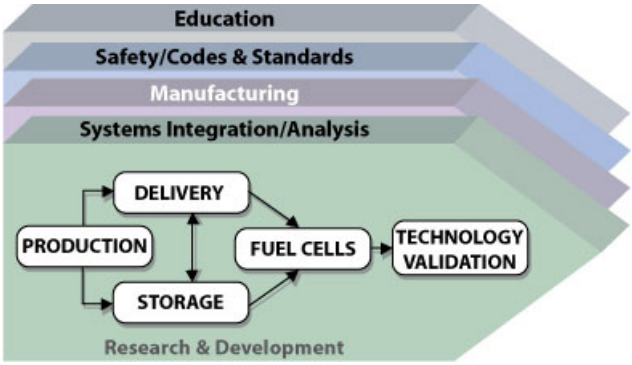
6.0 Manufacturing R&D



The Manufacturing Program element will work 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 Program element will facilitate the development of a domestic supplier base for hydrogen and fuel cell technologies.

6.1 Technical Goal and Objectives

Goal

Research, develop and demonstrate technologies and processes that reduce the manufacturing cost of hydrogen production, delivery, storage, and polymer electrolyte membrane (PEM) fuel cell systems.

Objectives

Fuel Cells.

- Presently, automotive fuel cell stacks are fabricated at low volume, and the costs of these stacks is approximately $3000 per kW. This is 50 times the projected cost of $60 per kW[1] for the same stack technology (2006) at high volume (500,000 units).The projected high-volume cost includes labor, materials, and capital expenditures, but does not account for manufacturing R&D investment. The objective of manufacturing R&D is to enable this factor of 50 cost reduction in automotive fuel cell stacks.

Hydrogen Storage.

- The current 10,000 psi gaseous storage system is estimated to cost $420 to $240/kWh. The Program's target for all on-board storage technologies is $2/kWh by 2015. (See Figure 3.3.4: Status of current technologies relative to key system performance and cost targets.) The objective of manufacturing R&D is to reduce the cost of making high-pressure carbon composite storage tanks by a factor of 9 from 2005 costs.

Hydrogen Production.

- The current distributed natural gas reforming system with a 1500 gge capacity per day has capital equipment costs of $3.1 million.[2] The Program's target is to reduce capital equipment costs to $580,000 for the same daily capacity by 2015. (See Table 3.1.2: *Technical Targets: Distributed Production of Hydrogen from Natural Gas.*) The current distributed water electrolysis system capital

[1] TIAX estimate for 80 kW automotive fuel cell systems

[2] "Cost of Distributed Hydrogen Production from Natural Gas," DOE Systems Integration Office, Independent Project Review. http://www.hydrogen.energy.gov/peer_review_production.html.

equipment cost is $900/kW.[3] The Program's target is $125/kW by 2017. The objective of manufacturing R&D is to reduce the cost of making components and subsystems for distributed natural gas reforming systems by a factor of 5 from 2006 costs.

6.2 Approach

This effort on Manufacturing R&D describes activities at the intersection of two Presidential Initiatives - the Manufacturing Initiative and the Hydrogen Fuel Initiative. To implement the President's Manufacturing Initiative, the National Science and Technology Council established the Interagency Working Group (IWG) on Manufacturing R&D. The IWG, led by the U.S. Department of Commerce, is coordinating and leveraging the current Federal efforts focused on manufacturability issues such as low-cost, high-volume manufacturing systems, advanced manufacturing technologies, manufacturing infrastructure, and measurements and standards. Manufacturing R&D for the Hydrogen Economy is one of three technical priorities of the IWG.

In July 2005, DOE, with support from the Department of Commerce's National Institute for Standards and Technology (NIST), conducted a Workshop on Manufacturing R&D for the Hydrogen Economy to identify the path forward to address these challenges. The workshop brought together industry, university, national laboratory, and government representatives to discuss the key issues facing manufacturing of fuel cells, hydrogen production and delivery systems, and hydrogen storage systems. Workshop participants identified key technical challenges that face the manufacture of hydrogen technologies and recommended priorities for manufacturing R&D to facilitate their commercialization. The Roadmap on Manufacturing R&D for the Hydrogen Economy, which incorporated these recommendations, forms the basis for the Hydrogen Program's manufacturing element.

This Program element summary focuses on hydrogen components and systems that will need to be manufactured during the initial transition to a hydrogen infrastructure. In addition, cross-cutting technologies and capabilities will be developed, e.g., metrology and standards, modeling and simulation tools for manufacturing processes, knowledge bases for manufacturing, design for manufacturing, and sensors and process control. Longer-term technologies under development through the Hydrogen Fuel Initiative will be addressed in later manufacturing R&D efforts. This manufacturing R&D Program element emphasizes the expected demand for hydrogen production, hydrogen storage, and fuel cells for stationary, portable and transportation applications.

The Manufacturing R&D subprogram will:

- Develop innovative, low-cost manufacturing technologies for new materials and material applications.
- Adapt and scale-up laboratory fabrication methods to low-cost, high-volume production.
- Establish and refine process and quality control manufacturing techniques while hydrogen and fuel cell technologies are still evolving.

[3] DOE Hydrogen Program, "Record 6002d: H2A MYYPP Current Forecourt Electrolysis Case (2006)," http://www.hydrogen.energy.gov/program_records.html.

- Develop and evaluate manufacturing processes to minimize total life cycle energy requirements and environmental effects.

This 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.

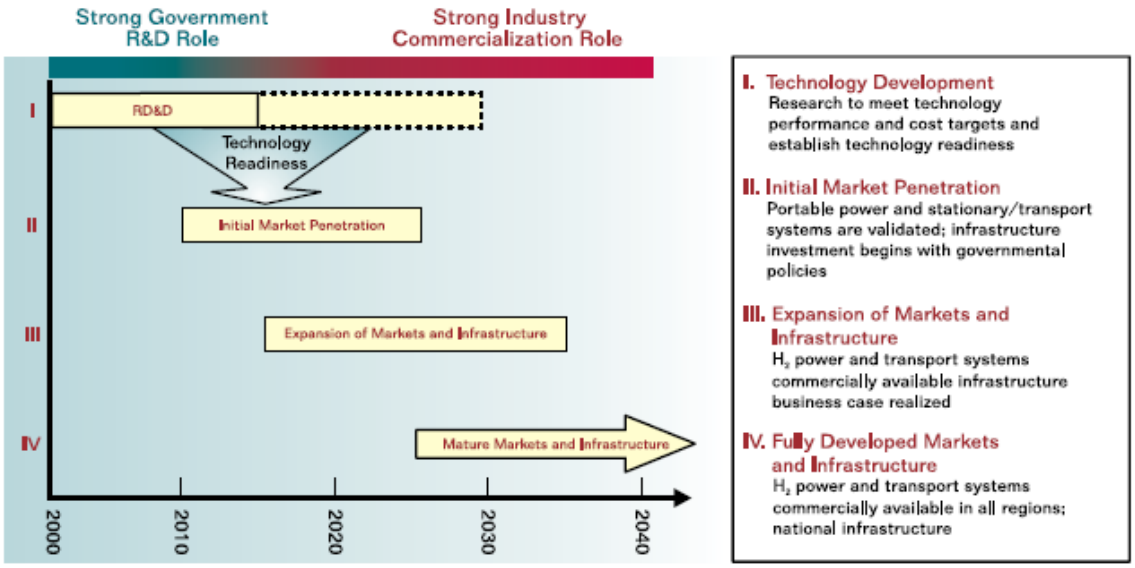


Figure 6.2.1: Manufacturing R&D will be conducted to enable initial market penetration.

Research investment will focus on reducing the cost of materials and/or components currently used (or planned for use) in existing technologies, as well as 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;
- Significantly reducing the cost of manufacturing equipment and therefore the total cost of parts;
- Increasing the uniformity and repeatability of fabrication.

Progress towards attaining the goals of manufacturing R&D will be tracked by assessing the ability of research to: (1) reduce the cost of hydrogen production, delivery, storage, and PEM fuel cell technologies, and (2) increase the manufacturing rate and annual manufacturing capacity with technologies suitable for scale-up.

6.3 Programmatic Status

PEM Fuel Cells

Fuel cell stacks and their respective components are in the early stages of manufacturing technology development. Fuel cells stacks are now fabricated with laboratory methods that have typically been scaled up in size, but do not incorporate high-volume manufacturing methods. Application of high throughput roll-processing methods for three-layer MEAs (membrane electrode assemblies, e.g., catalyst coated membranes) is reported by several companies. On the other hand, full five-layer MEA roll-processing is not well developed. The entire fuel cell power system is usually constructed by integrating subsystems (e.g., hydrogen and oxygen delivery, water management, thermal management); however, each subsystem is assembled separately by a labor-intensive process.

Fuel cell system costs have been estimated for high production volumes, i.e., 500,000 units per year. Manufacturing assumptions for the estimated high volumes of parts include plant capacity scaled to market size, manufacturing process capabilities consistent with high-volume production, and low scrap rates.

Hydrogen Storage

At the present time, relatively few components for onboard hydrogen storage are commercially available and these components are only manufactured in very small quantities.

The exceptional strength-to-weight ratio of carbon fiber composite tanks makes them prime candidates for use with materials-based, cryogenic, or high-pressure gas for both vehicular and stationary storage applications. Hence, manufacturing improvements that reduce the system unit cost and production cycle time of these components would have wide applicability to hydrogen storage systems in general.

The major limitations on manufacturing composite tanks are the material cost of high-strength carbon fibers and processes used for fiber winding/placement. Tank testing and certification processes can also add significantly to tank cost. Even with multiple fiber winding machines, production capacity is limited to a few units per day. In stark contrast, high-volume production would require a rate of approximately 80 units per hour for 500,000 units per year. Clearly, significant challenges must be overcome to cost-effectively manufacture units at a rate sufficient to meet demand for use with fuel cell systems during near-term deployment. In the long-term, based on research progress in developing low pressure approaches, additional manufacturing R&D to ensure low-cost and reliable conformable storage systems will likely be required.

Hydrogen Production

Because a large-scale delivery network will not be available in the near term, early hydrogen production technologies will likely be distributed reforming of natural gas or renewable liquid fuels (including ethanol or bio-oils), and distributed electrolysis. Today, hydrogen production is capital intensive; the capital contribution for small distributed hydrogen production facilities dominates. For distributed natural gas reforming systems, large capital contribution results from site-specific fabrication of fuel processing systems, which includes reformers, water-gas-shift catalyst beds, and pressure swing adsorption cleanup subsystems.

There is very limited manufacturing (none of which is automated) of electrolysis units in the size necessary for a distributed hydrogen fuel network for transportation. Manufacturing is focused on near ambient temperature alkaline and PEM electrolyzers. Synergistic manufacturing processes between PEM electrolyzers and fuel cells will be investigated. High-temperature solid oxide electrolyzers are currently not addressed in the Manufacturing R&D element because they are more suited to centralized, fossil energy based production systems. Since Manufacturing R&D is focused on near-term distributed production of hydrogen, hydrogen delivery technologies using central production pathways are not within the scope of the program in the near term.

Manufacturing R&D is required to reduce the high capital cost associated with establishing a distributed hydrogen generation network at existing refueling stations. Reducing the high capital cost by developing manufacturing facilities for pre-fabricating hydrogen generation systems and delivering the system modules to the generation sites will be required. Constructing modules that can be readily integrated into a hydrogen generation/delivery system and easily installed at a refueling station offers an approach to reducing costs by eliminating on-site construction and assembly of the individual components.

Current DOE manufacturing R&D projects are summarized in Table 6.3.1.

Table 6.3.1. Current Manufacturing Program Activities		
Challenge	**Approach**	**Activities**
PEM Fuel Cells		
Bipolar Plates Develop manufacturing processes for high-volume production of high-quality, uniform bipolar plates	Develop high-speed forming, stamping, and molding processes that deliver high tolerance control	**Nanotek Instruments:** Continuous in-line lamination of sheet molded composite (SBIR Project)
Hydrogen Storage		
Reduce the cost of high-strength carbon fiber	Develop a lower cost precursor for high-strength fibers	**ORNL:** Carbon fiber precursors and advanced processes to reduce carbon fiber placement cycle time.
Conformable high-pressure storage systems.	Investigate new manufacturing processes for applying the resin matrix, including tow-pregs for room temperature curing, wet winding processes, and fiber imbedded thermoplastics for hot wet winding	**Powdermet:** Advanced processes for carbon composite tanks (SBIR Project)
Hydrogen Production		
Reforming Manufacture of reaction vessels and components	Accelerated test methods to validate processes for machining metal components	**OMAX Corp:** Water jet-based machine tool design and testing on specialized components (SBIR Project)
Electrolysis Stack components	Advances in forming, joining, assembly of membrane, electrodes, cells	**Giner Electrochemical Systems LLC:** Laser welding and joining technologies (SBIR Project)

6.4 Technical Challenges

Technical challenges to manufacturing R&D are summarized in this section.

PEM Fuel Cells

The ramp-up to high-volume production of PEM 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, we must clearly understand the relationships among fuel cell system performance, manufacturing process parameters, and variability. Such understanding will likely play a major role in fuel cell 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 PEM fuel cell manufacturing.

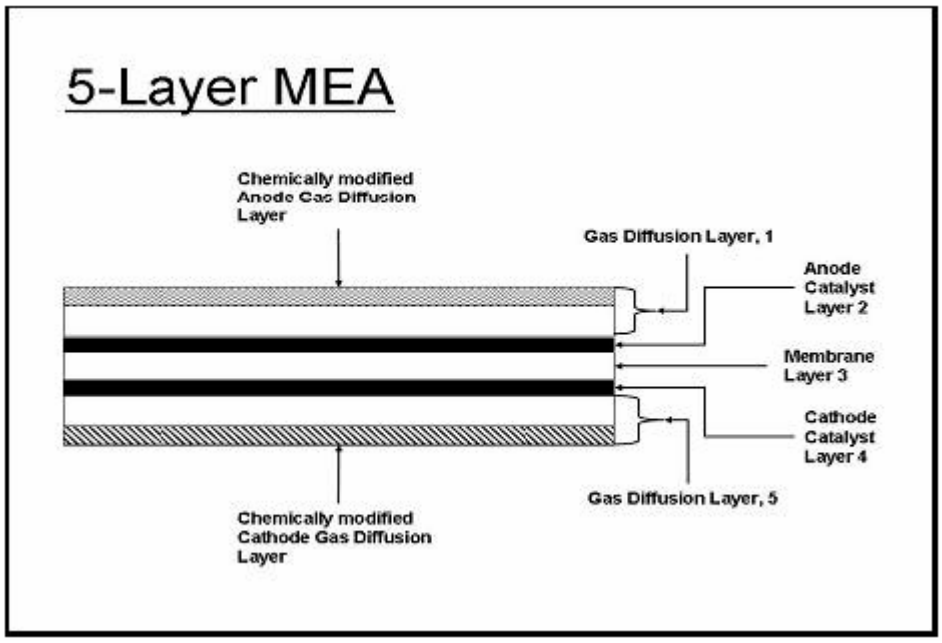


Figure 6.4.1 Components of a five-layer Membrane Electrode Assembly.[4]

[4] Source: Roadmap on Manufacturing R&D for the Hydrogen Economy. Department of Energy. Washington, DC. December 2005.

Manufacturing R&D is needed in the following critical technologies:

- Membrane electrode assembly
- Fuel cell stack assembly
- Bipolar plate fabrication
- Balance-of-plant subsystem assembly

Each of these technologies requires manufacturing processes that can be scaled to increasing production volumes.

Hydrogen Storage

Cost is the primary issue with composite tank technology. Manufacturing carbon fiber storage tanks for both vehicular and stationary storage at forecourt stations will require dramatic reductions in unit costs and fabrication times while ensuring required quality control. A critical challenge lies in the cost of the fiber and the manufacture of composite tanks. Current projections of the manufactured cost per unit for high production volumes are about a factor of nine above storage system targets, and it is estimated that about 40 - 70% of the unit cost is due to the base cost of the carbon fiber (approximately 40% of the fiber cost is due to the precursor and the remainder due to thermal processing). The FreedomCar and Vehicle Technology Program of EERE is seeking to develop a low-cost commercial carbon fiber utilizing new precursors and new heat treatment processes to reduce the cycle time. The strength of the final product fiber will be limited to approximately 3.6-5.7 ksi because this range is adequate for vehicle body components. However, carbon fiber composite high-pressure storage vessels will require a tensile strength of 10 ksi or greater.

Costs for compressed gas storage systems stored at 350 and 700 bar (5,000 and 10,000 psi) can be reduced by lowering the cost of carbon fiber through materials and process improvements and moving to higher volume manufacturing processes through advanced manufacturing R&D. R&D is needed as composite storage technology is most likely to be employed in the near term for transportation applications and will be needed for most materials-based approaches for hydrogen storage.

High-volume production rates cannot be met simply by increased capitalization of current manufacturing equipment. Most importantly, the cycle time needs to be significantly reduced, which will require significant 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 the capital contribution to its cost is larger for smaller hydrogen production facilities that are designed for distributed applications. The higher per unit capital cost of the distributed systems is the result of site-specific fabrication of fuel processing systems, which include reformers, water-gas shift catalyst beds, and pressure swing adsorption purification subsystems. Also, there is only low-volume manufacturing of electrolysis units of the size necessary for a distributed hydrogen network.

Manufacturing R&D for hydrogen production is needed for:

- Joining reformer components in reformers
- 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.

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.

Knowledge Bases

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 needs 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 reliably measure various process parameters such as leaks, microstructure defects, surface roughness, coating quality, dimensional accuracy, and other critical manufacturing process outputs 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.

6.5 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 (MEA) Processes

New manufacturing methods are needed to fabricate advanced catalyst layers that meet the low precious metal targets. Most membrane electrode assembly (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. Processes that permit the continuous manufacturing of five-layer and/or seven-layer MEAs, while maintaining the critical performance properties of the gas diffusion layer are needed.

B. Lack of High-Speed Bipolar Plate Manufacturing Processes

New high-speed forming, stamping, and molding processes are needed that will maintain the high tolerance requirement of PEM fuel cells for flow field dimensions, plate flatness, and plate parallelism. 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 rapidly assemble fuel cell stacks must precisely align 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 PEM 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 developed to expedite development of manufacturing systems for both components and complete fuel cell power plants. Leak detectors, other sensors for in-line quality control, and manufacturing process control are needed for assembly of fuel cell power plants.

Storage

G. High-Cost Carbon Fiber

Currently, composite tanks require high-strength fiber made from carbon-fiber grade polyacrylonitrile precursor. This high grade carbon fiber is currently approximately $15 to $20/kg. Manufacturing R&D is needed to develop lower cost, high quality polyacrylonitrile or alternate precursors and reduced energy or faster carbonization process for carbon fiber, 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. Developing and implementing advanced fiber processing methods has the potential to reduce cost by 50% as well as provide the technology basis to expand U. S. competitiveness in high-strength fiber manufacturing.

H. Lack of Carbon Fiber Fabrication Techniques for Conformable Tanks

New manufacturing methods are needed that can reduce the cycle time, that is, the per unit fabrication time. Potential advances in manufacturing technologies include faster filament winding (e.g., multiple heads), new filament winding strategies and equipment, and continuous versus batch processing (e.g., pultrusion process). New manufacturing processes for applying the resin matrix, including tow-pregs for room temperature curing, wet winding processes, and fiber imbedded thermoplastics for hot wet winding should also be investigated. New manufacturing methods for carbon fiber winding and fiber placement manufacturing are needed as well as methods to improve conformability of tanks by allowing modified cylindrical tank shapes to be manufactured. A cost model is needed to guide development of high-volume production processes for high-pressure composite tanks employing fiber placement technologies. Fiber placement technologies, which could reduce the amount of carbon fiber needed by as much as 20%-30%, could also lower unit costs.

Hydrogen Production

I. Lack of Automated Joining Processes

Component integration requires labor-intensive welding. Manufacturers need reliable, low-variability joining 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, which adds to the cost. The development of manufacturing methods to clad or plate low cost substrates with these metals could reduce system cost.

K. Lack of Low-Cost Stamping and Extrusion

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. Common, interchangeable 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.

6.6 Technical Task Descriptions

The technical task descriptions and the barriers associated with each task are presented in Table 6.6.1. Concerns regarding safety and environmental effects will be addressed within each task in coordination with the appropriate Program element.

Table 6.6.1 Technical Task Descriptions

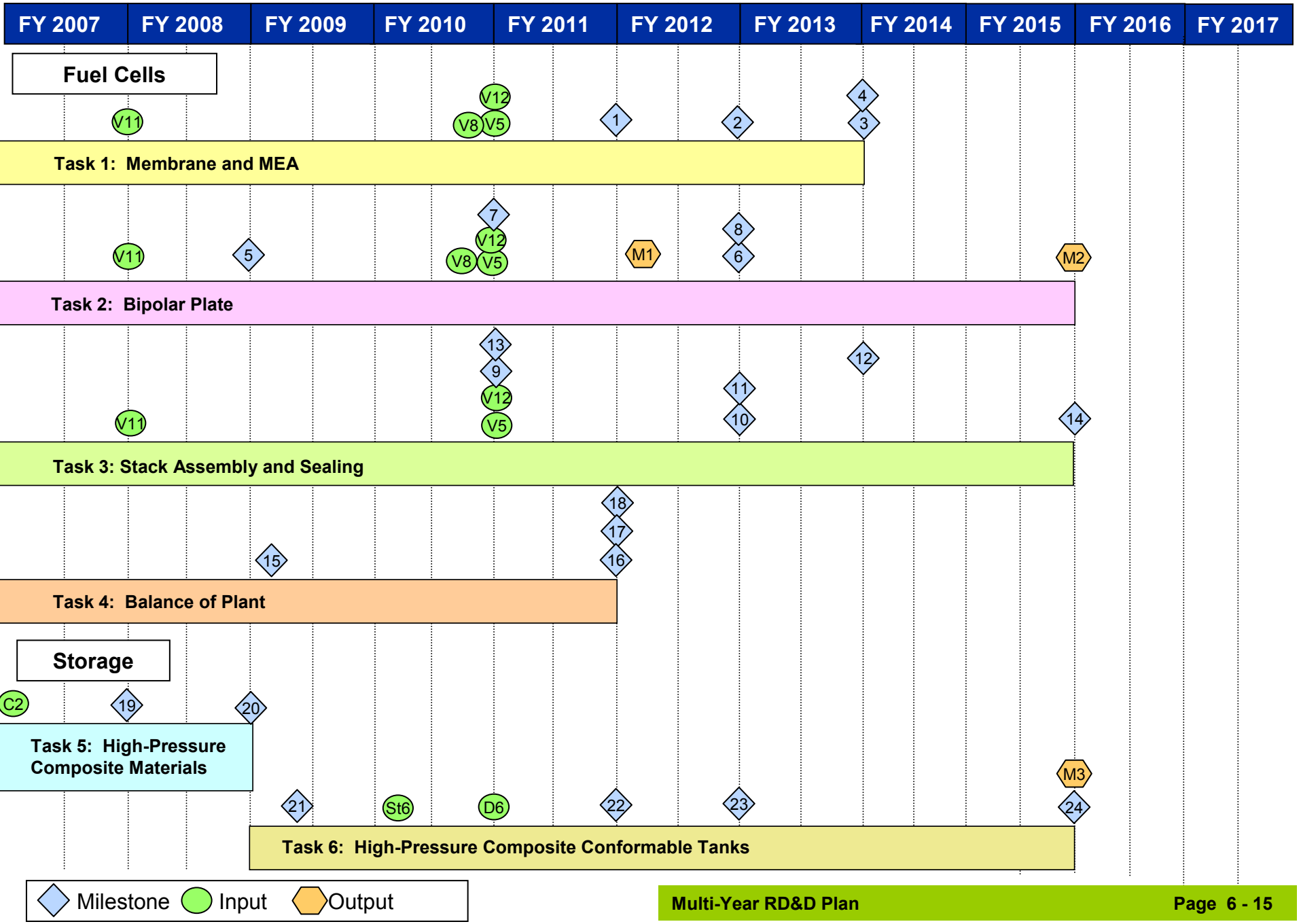
Task	Description	Barriers
Fuel Cells		
1	**Membrane and Membrane Electrode Assembly (MEA)** ▪ Develop continuous in-line measurement for MEA fabrication ▪ Develop methods to measure alignment of MEA components during manufacture ▪ Characterize membrane defects and their impact on MEA performance/durability/life ▪ Develop correlations between manufacturing parameters and performance/durability specifications for MEAs ▪ Establish models to predict the effect of manufacturing variations on MEA performance	A,F
2	**Bipolar Plate** ▪ 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
3	**Stack Assembly and Sealing** ▪ Develop equipment capable of high-rate assembly of cell stacks using automated and robotic methods ▪ Develop rapid-seal applications to assure sealing of components ▪ Develop quality control measuring devices to assure proper alignment of cell components and specified compressive load on 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 for molded manifolds for assembly of air, fuel, and water/temperature subsystems ▪ 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 reactant leakage	E, F

Table 6.6.1 Technical Task Descriptions (continued)		
Task	**Description**	**Barriers**
Hydrogen Storage		
5	**High-Pressure Composite Material** ▪ 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 Conformable Tanks** ▪ Produce cost model for high-pressure tank and conformable tank manufacture ▪ Develop new manufacturing methods for high-pressure composite tanks ○ Develop high-speed filament winding processes ○ Develop fiber placement processes that reduce the needed amount of carbon fiber	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 ▪ 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 nonconformable surfaces (e.g., deposition of catalysts onto electrode substrates for electrolysis)	J, M
10	**Stamping and Extrusion Methods for Reformers** ▪ Develop stamping and extrusion methods for reactors and heat exchangers	K

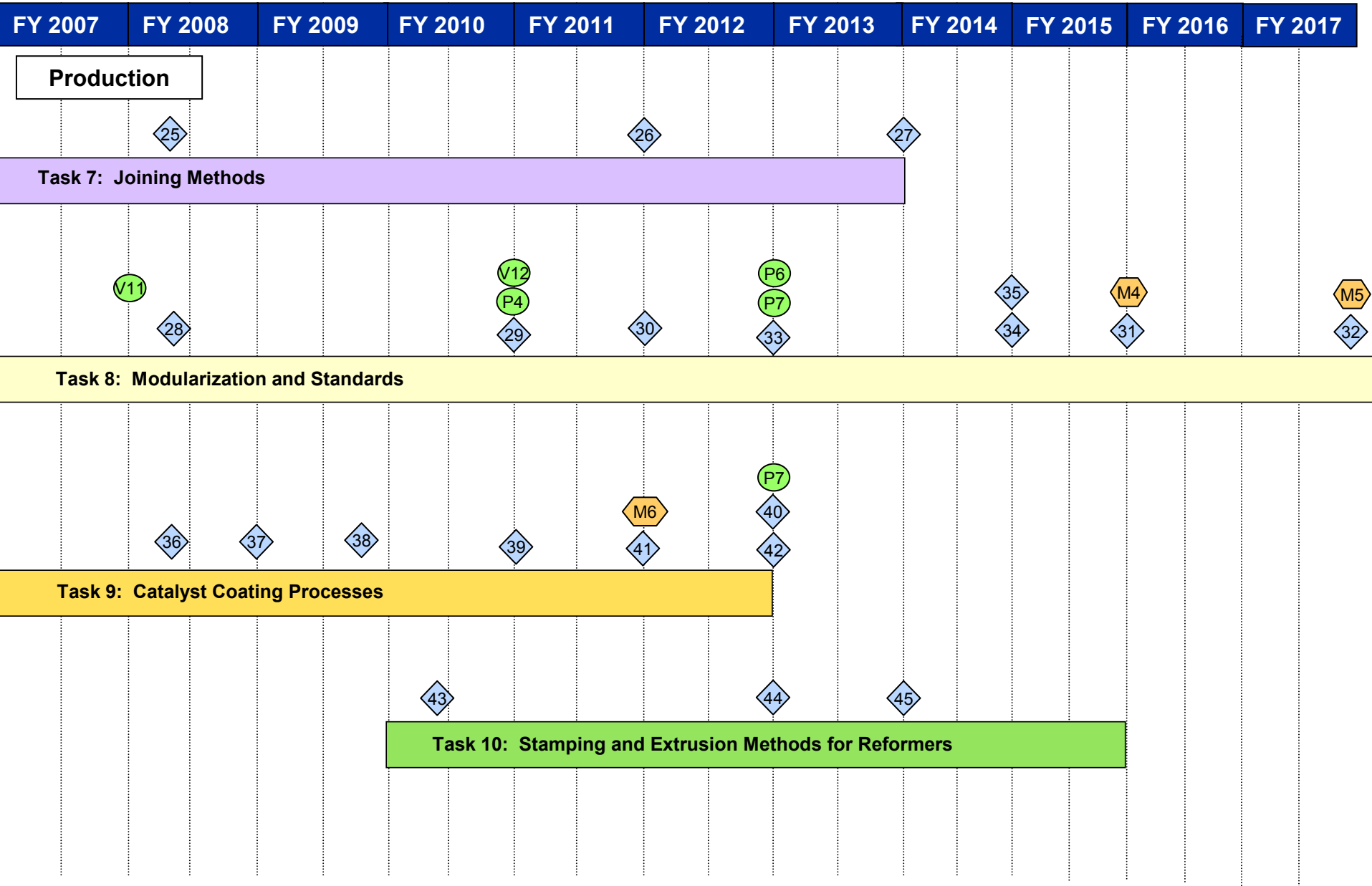
6.7 Milestones

The following chart shows the interrelationship of milestones, tasks, and supporting inputs from other Program elements for the Manufacturing function through FY2017.

Manufacturing R&D Tasks



Manufacturing R&D Tasks



Fuel Cells

Task 1: Membrane and MEA	
1	Develop prototype sensors for quality control of MEA manufacturing. (4Q, 2011)
2	Develop continuous in-line measurement for MEA fabrication. (4Q, 2012)
3	Demonstrate sensors in pilot scale applications for manufacturing MEAs. (4Q, 2013)
4	Establish models to predict the effect of manufacturing variations on MEA performance. (4Q, 2013)

Task 2: Bipolar Plate	
5	Select processes to be developed for manufacturing bipolar plates. (4Q, 2008)
6	Demonstrate pilot scale processes for manufacturing bipolar plates. (4Q, 2012)
7	Develop manufacturing processes for graphite resin, natural flake graphite, and metal plates. (4Q, 2010)
8	Develop rapid prototyping and flexible tooling specifically for the manufacture of bipolar plates. (4Q, 2012)

Task 3: Stack Assembly and Sealing	
9	Select stack assembly processes to be developed. (4Q, 2010)
10	Develop automated pilot scale stack assembly processes. (4Q, 2012).
11	Develop pilot scale processes for manufacturing of end plates and manifolds. (4Q, 2012)
12	Demonstrate pilot scale processes for assembling stacks. (4Q, 2013)
13	Complete development of standards for metrology of PEM fuel cells. (4Q, 2010)
14	Develop fabrication and assembly processes for polymer electrolyte membrane automotive fuel cell that meets cost of $30/kW. (4Q, 2015)

Task 4: Balance of Plant	
15	Select processes to be developed and metrics for manufacturing Balance Of Plant (BOP) components. (2Q, 2009)
16	Demonstrate manufacturing processes for air management subsystem components. (4Q, 2011)
17	Demonstrate manufacturing processes for water and thermal management subsystem components. (4Q, 2011)
18	Demonstrate manufacturing processes for BOP reactant (H_2 and O_2) management subsystem components e.g. flow/pressure/humidity controllers. (4Q, 2011)

Storage

Task 5: High-Pressure Composite Materials	
19	Complete knowledge bases for high-pressure storage systems. (4Q, 2007)
20	Complete development of standards for metrology of high-pressure storage systems. (4Q, 2008)

Task 6: High-Pressure Composite Conformable Tanks	
21	Select manufacturing technologies to be developed for high-pressure composite tanks (2Q, 2009)
22	Demonstrate pilot scale, high volume manufacturing processes for high-pressure composite tanks. (4Q, 2011)
23	Develop prototype sensors for quality control of high-pressure composite tanks manufacturing. (4Q, 2012)
24	Develop fabrication and assembly processes for high-pressure hydrogen storage technologies that can achieve a cost of $2/kWh. (4Q, 2015)

Production

Task 7: Joining Methods	
25	Select technologies to be developed for joining methods. (2Q, 2008)
26	Complete development of joining methods selected. (4Q, 2011)
27	Demonstrate pilot scale application of joining methods selected. (4Q, 2013)

Task 8: Modularization and Standards	
28	Select manufacturing technologies to be developed for hydrogen generators. (2Q, 2008)
29	Demonstrate pilot scale, high-volume manufacturing processes for hydrogen generators. (4Q, 2010)
30	Develop prototype sensors for quality control of hydrogen generators. (4Q, 2011)
31	Reduce the cost of manufacturing of distributed reforming of natural gas system to achieve $2.00/gge (delivered). (4Q, 2015)
32	Reduce the cost of manufacturing a distributed reforming of bio-derived renewable liquid fuels system to achieve $3.00/gge (delivered). (4Q, 2017)
33	Reduce the cost of manufacturing a distributed electrolysis system to achieve $3.70/gge (delivered). (4Q, 2012)
34	Complete knowledge bases for production systems. (4Q, 2014)
35	Complete development of standards for metrology of production systems. (4Q, 2014)

Task 9: Catalyst Coating Processes	
36	Select manufacturing technologies to be developed for producing electrolysis membrane assemblies. (2Q, 2008)
37	Develop specific technical targets for continuous fabrication of electrolysis membrane assemblies. (4Q, 2008)
38	Select analytical quality control processes to be developed. (3Q, 2009)
39	Develop pilot scale, high-volume manufacturing processes for electrolysis membrane assemblies. (4Q, 2010)
40	Demonstrate pilot scale, high-volume manufacturing processes for electrolysis membrane assemblies. (4Q, 2012)
41	Develop prototype sensors for quality control of electrolysis membrane assemblies manufacturing. (4Q, 2011)
42	Demonstrate sensors in pilot scale applications for manufacturing electrolysis membrane assemblies. (4Q, 2012)

Task 10: Stamping and Extrusion Methods for Reformers	
43	Select manufacturing technologies to be developed for stamping and extrusion. (2Q, 2010)
44	Demonstrate pilot scale, high-volume manufacturing processes for stamping and extrusion. (4Q, 2012)
45	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, 2012)

M2 Output to Fuel Cells: Report on fabrication and assembly processes for polymer electrolyte membrane automotive fuel cell that meets cost of $30/kW. (4Q, 2015)

M3 Output to Storage: Report on fabrication and assembly processes for high-pressure hydrogen storage technologies that can achieve a cost of $2/kWh. (4Q, 2015)

M4 Output to Production: Report on manufacturing of distributed reforming of natural gas system to achieve $2.00/gge (delivered). (4Q, 2015)

M5 Output to Production: Report on manufacturing a distributed reforming of bio-derived renewable liquid fuels system to achieve $3.00/gge (delivered). (4Q, 2017)

M6 Output to Production: Report on high-volume manufacturing processes for electrolysis membrane assemblies. (4Q, 2011)

Inputs

St6 From Storage: Final On-board hydrogen storage system analysis results of cost and performance; and down-select to a primary on-board storage system candidate. (1Q, 2010)

D6 From Delivery: Recommend refueling site stationary storage technology for validation. (4Q, 2010)

P4 From Production: Hydrogen production technology for distributed systems using natural gas with projected cost of $2.50/gge hydrogen at the pump, untaxed, assuming 500 manufactured units per year. (4Q, 2010)

P6 From Production: Hydrogen production technologies for distributed systems using renewable liquids with projected cost of $3.80/kg hydrogen at the pump, untaxed, assuming 500 manufactured units per year. (4Q, 2012)

P7 From Production: System making Hydrogen for $3.70/gge (delivered) from distributed electrolysis. (4Q, 2012)

V5 From Technology Validation: Technology Status Report & Re-Focused R&D Recommendations. (4Q, 2010)

V8 From Technology Validation: Final report on infrastructure, including impact of hydrogen quality for second generation vehicles. (3Q, 2010)

V11 From Technology Validation: Composite results of analyses & modeling from vehicle and infrastructure data collected under the learning demonstration project. (4Q, 2007)

V12 From Technology Validation: Final composite results of analyses & modeling from vehicle and infrastructure data collected under the learning demonstration project. (4Q, 2010)

C2 From Safety, Codes & Standards: Technical assessment of Standards requirements for metallic and composite bulk storage tanks. (3Q, 2006)