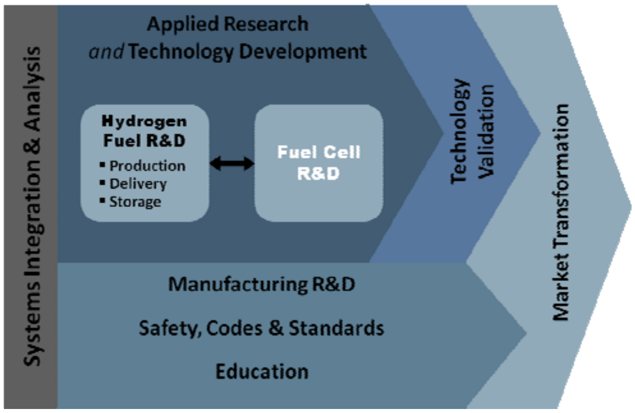
3.4 Fuel Cells



Fuel cells offer a highly efficient way to use diverse energy sources and, as a result, have demonstrated lower energy use and emissions when compared with conventional technologies. They also can be powered by emissions-free fuels that are produced from clean, domestic resources, helping to reduce the nation's dependence on imported petroleum. The largest markets for fuel cells today are in stationary power, portable power, auxiliary power units, and material handling equipment. Approximately 75,000 fuel cells had been shipped worldwide by the end of 2009[1] and approximately 15,000 additional fuel cells were shipped in 2010[2] (>40% increase over 2008). In transportation applications in the U.S., there are currently (August 2011): >200 fuel cell light duty vehicles, >20 fuel cell buses, and ~60 fueling stations. Several manufacturers, including GM, Toyota, Honda, Hyundai, and Daimler, have announced plans to begin commercializing fuel cell vehicles by 2015.

The Fuel Cells sub-program has been addressing the key challenges facing the widespread commercialization of fuel cells for diverse applications. The program supports fuel cells for stationary power due to their high efficiency and the potential to reduce our primary energy use for and emissions from electricity production. The Fuel Cells sub-program is also pursuing polymer electrolyte membrane (PEM) fuel cells as replacements for internal combustion engines (ICEs) in light-duty vehicles to increase vehicle efficiency and support the goals of reducing oil use in and emissions from the transportation sector. In addition, the program supports fuel cells for material handling equipment, portable power, and auxiliary power applications where earlier market entry could assist in the development of a fuel cell manufacturing base. The technical focus is on developing materials, components, and sub-systems, at the stack and system level, that enable fuel cells to achieve the Fuel Cells sub-program objectives, primarily related to system cost and durability.

For transportation applications, the Fuel Cells sub-program is focused on direct hydrogen fuel cells, in which the hydrogen fuel is stored onboard and is supplied by a hydrogen production and fueling infrastructure. Hydrogen production and delivery technologies are being developed in parallel with fuel cell development efforts. For distributed stationary power generation applications, fuel cell systems will likely be fueled with reformate produced from natural gas, liquefied petroleum gas (LPG, consisting predominantly of propane) or renewable fuels such as biogas from wastewater treatments plants. Fuel cells for auxiliary power units in trucks will likely use either diesel or LPG. In material handling equipment and small consumer electronics (portable power), hydrogen or methanol will likely be the fuel of choice for fuel cell systems.

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[1] RNCOS report, "Fuel Cell Industry Analysis," June 2011, http://www.rncos.com/Report/IM102.htm

[2] 2010 Fuel Cell Technologies Market Report, June 2011, http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/2010_market_report.pdf

3.4.1 Technical Goal and Objectives

Goal

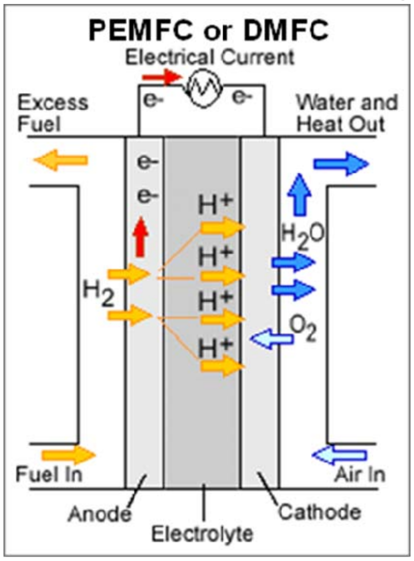
Develop and demonstrate fuel cell power system technologies for transportation, stationary and portable power applications.

Objectives

- By 2015, develop a fuel cell system for portable power (<250 W) with an energy density of 900 Wh/L.
- By 2017, develop a 60% peak-efficient, 5,000 hour durable, direct hydrogen fuel cell power system for transportation at a cost of $30/kW.
- By 2020, develop distributed generation and micro-CHP fuel cell systems (5 kW) operating on natural gas or LPG that achieve 45% electrical efficiency and 60,000 hours durability at an equipment cost of $1500/kW.
- By 2020, develop medium-scale CHP fuel cell systems (100 kW–3 MW) that achieve 50% electrical efficiency, 90% CHP efficiency, and 80,000 hours durability at a cost of $1,500/kW for operation on natural gas, and $2,100/kW when configured for operation on biogas.
- By 2020, develop a fuel cell system for auxiliary power units (1–10 kW) with a specific power of 45 W/kg and a power density of 40W/L at a cost of $1000/kW.

3.4.2 Technical Approach

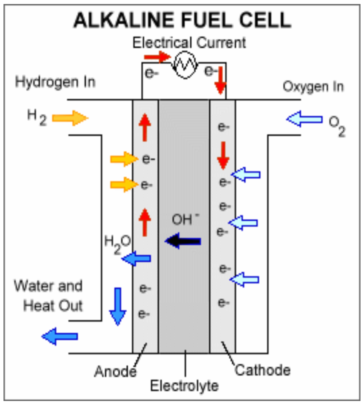
Fuel cell research and development (R&D) will emphasize activities aimed at achieving high efficiency and durability along with low material and manufacturing costs for the fuel cell stack. R&D to develop lower cost, better performing system balance-of-plant (BOP) components like air compressors, fuel processors, water and heat management systems, and sensors is also being pursued. Each application – light-duty vehicle transportation, material handling equipment, stationary power, auxiliary power units (APUs) for heavy-duty vehicles, and portable power for consumer electronics – has specific market-driven requirements for technology development.



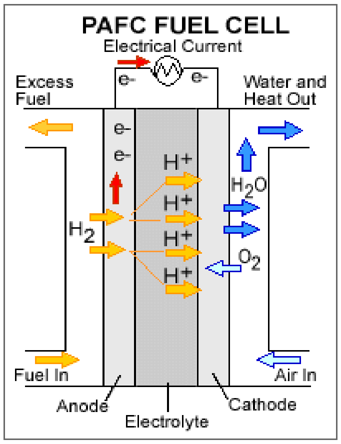
Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are being considered for applications that require faster start-up times and frequent starts and stops such as automotive applications, material handling equipment and backup power. For PEMFCs, continuing advancements are needed to minimize precious metal loading, improve component durability, and manage water transport within the cell. Membranes that are capable of operation at up to 120°C for automotive applications and above 120°C for stationary applications are needed for better thermal management. For this purpose, the development of polybenzimidazole-type (PBI-type) PEMFCs operating above 130°C has benefits. R&D is required to reduce cost and increase MEA durability of PBI-type PEMFCs. R&D is also required to reduce cost and improve durability of system BOP components, such as humidifiers and compressors.

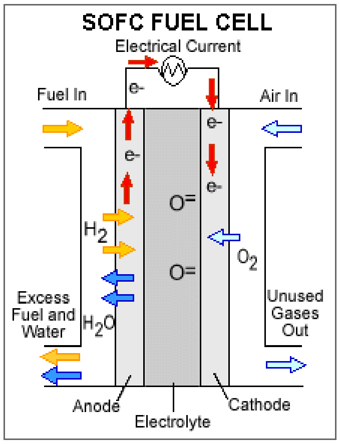
Direct Methanol Fuel Cells (DMFCs) are well suited for portable power applications in consumer electronic devices where the power requirements are low and the cost targets and infrastructure requirements are not as stringent as for transportation applications. A higher energy density alternative to existing technologies is required to fill the increasing gap between energy demand and energy storage capacity in these applications. Challenges for DMFCs include reducing methanol crossover to increase efficiency and simplifying the BOP, to increase energy and power density, improve reliability, and reduce cost.

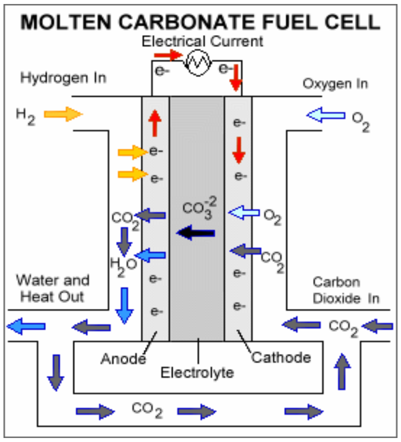
Alkaline Fuel Cells (AFCs) have long been used in space applications where pure hydrogen and oxygen are available. The advantage of AFCs to enable non-precious metal catalysis has been outweighed by the increased system complexity and difficulties of working with a liquid electrolyte, as well as issues with carbonate formation for most terrestrial applications. Alkaline membrane fuel cells (AMFCs) avoid or mitigate the shortcomings of traditional liquid AFCs and are being considered for applications in the W to kW scale. Challenges for AMFCs include tolerance to carbon dioxide, membrane conductivity and durability, higher temperature operation, water management, power density, and anode electrocatalysis.



Medium temperature (Phosphoric Acid) and high temperature (Solid Oxide and Molten Carbonate) fuel cells are more applicable where systems may run for extended periods without frequent start and stop cycles. These systems also have benefits in combined heat and power (CHP) generation, and offer simplified operation on fossil and renewable fuels. R&D needs for phosphoric acid-based fuel cells include methods to decrease or eliminate anion adsorption on the cathode, lower cost materials for the cell stack and BOP components, and durable electrode catalysts and support materials. For high-temperature Molten Carbonate Fuel Cell (MCFC) systems, R&D is needed to limit electrolyte loss and prevent microstructural changes in the electrolyte support that lead to early stack failure, and to develop more robust cathode materials. For Solid Oxide Fuel Cells (SOFCs), challenges include stack survivability during repeated thermal cycling, decreasing long start up times, and potential mechanical and chemical compatibility/reactivity issues between the various stack and cell components due to high temperature operation. For all these systems, improved fuel processing and cleanup, especially for fuel-flexible operation and operation on biofuels, are needed to improve durability and reduce system costs. Table 3.4.1 describes the different fuel cell types.







To meet the efficiency, durability and cost requirements for fuel cells, R&D will focus on identifying new materials and novel design and fabrication methods for electrolytes and electrolyte supports, catalysts and supports, gas diffusion media, cell hardware (including bipolar plates, interconnects and seals) and balance-of-plant components (e.g., compressors, radiators, humidifiers, fuel processors, etc.). Testing of new materials, designs, and fabrication methods will be carried out by industry, national laboratories, and universities. New R&D efforts will include demonstration in single cells or membrane electrode assemblies (MEAs), in stacks, and at the sub-system and system level. The Technology Validation sub-program (see Section 3.6), provides fuel cell vehicle and stationary power data under real-world conditions and, in turn, supplies valuable results to help refine and direct future activities for fuel cell R&D.

Table 3.4.1 Fuel Cell Types

Fuel Cell Type	Temperature	Applications
	Electrolyte / Charge Carrier	
Phosphoric Acid (PAFC) and Polymer / Phosphoric Acid	150–200° C	Distributed power Transportation
	H_3PO_4, Polymer/H_3PO_4 / H^+	
Polymer Electrolyte Membrane (PEMFC)	50–100° C	Distributed power Portable power Transportation
	Perfluorosulfonic acid / H^+	
Direct Methanol (DMFC)	50–100° C	Portable Power
	Perfluorosulfonic acid / H^+	
Alkaline (AFC)	25–75° C, 100–250° C	Portable Power Backup Power
	Alkaline polymer, KOH / OH^-	
Molten Carbonate (MCFC)	600–700° C	Distributed power
	$(Li,K,Na)_2CO_3$ / CO_3^{2-}	
Solid Oxide (SOFC)	500–1000° C	Electric utility Distributed power APUs
	Yttria–Stabilized Zirconia ($Zr_{.92}Y_{.08}O_2$) / O^{2-}	

3.4.3 Programmatic Status

Current Activities

Table 3.4.2 summarizes the FY 2011 activities in the Fuel Cells sub-program. Activities targeted toward polymer electrolytes include the identification and development of ionomers with increased conductivity (especially under conditions of low relative humidity and high temperature), increased mechanical and chemical durability, and reduced material costs. Failure mechanisms in fuel cells are being explored both experimentally and via modeling. Scalable fabrication processes for production of membranes, electrodes, MEAs, and bipolar plates are being designed. Catalysts with reduced precious metal loading, increased activity and durability, and lower cost (including non-precious metal catalysts), are under development. Bipolar plates with lower weight and volume and with negligible corrosion are being developed. To enable early-market entry of fuel cells, R&D on stationary and other applications such as material handling equipment, portable power and auxiliary power units is pursued. To gauge the status of the technology, the cost and performance of fuel cell components are benchmarked and evaluated.

Table 3.4.2 Current Fuel Cell Activities

Task	Approach	Activities
Electrolytes	• Develop / identify electrolytes and membranes/matrices (polymer, phosphoric/solid acid, anion-exchange, solid oxide, molten carbonate) with improved conductivity over the entire temperature and humidity range, increased mechanical, chemical, and thermal stability, with reduced/eliminated fuel cross-over • Fabricate membranes from ionomers with scalable fabrication processes, increased mechanical, chemical, and thermal stability and reduced cost • Perform membrane testing and characterization to improve durability	• **3M**: Membranes and MEA's for Dry, Hot Operating Conditions. • **Case Western Reserve University**: Rigid Rod Polyelectrolytes: Effect on Physical Properties: Frozen-in Free Volume: High Conductivity at Low RH • **Colorado School of Mines**: Novel Approaches to Immobilized Heteropoly Acid (HPA) Systems for High Temperature, Low Relative Humidity Polymer-Type Membranes • **Fuel Cell Energy, Inc.**: High Temperature Membrane with Humidification-Independent Cluster Structure • **Giner Electrochemical Systems**: Dimensionally Stable Membranes • **Los Alamos National Laboratory**: Resonance-Stabilized Anion Exchange Polymer Electrolytes • **University of Central Florida**: Lead Research and Development Activity for DOE's High Temperature, Low Relative Humidity Membrane Program • **Vanderbilt University**: Nano Capillary Network Proton Conducting Membranes for High Temperature Hydrogen/Air Fuel Cells

Table 3.4.2 Current Fuel Cell Activities		
Task	**Approach**	**Activities**
Catalysts/ Electrodes	• Develop electro catalysts with reduced precious metal loading, increased activity, improved durability / stability, and increased tolerance to air, fuel and system-derived impurities • Develop supports with reduced corrosion, lower cost, and increased non-PGM catalyst loading • Optimize electrode design and assembly • Develop anodes for fuel cells operating on non-hydrogen fuels	• **3M**: Advanced Cathode Catalysts and Supports for PEM Fuel Cells • **3M**: Durable Catalysts for Fuel Cell Protection During Transient Conditions • **Argonne National Laboratory**: Polymer Electrolyte Fuel Cell Lifetime Limitations: The Role of Electro catalyst Degradation • **Argonne National Laboratory**: Nanosegregated Cathode Catalysts with Ultra-Low Platinum Loading • **Brookhaven National Laboratory**: Contiguous Platinum Monolayer Oxygen Reduction Electro catalysts on High-Stability-Low-Cost Supports • **GM**: High-Activity Dealloyed Catalysts • **Illinois Institute of Technology**: Synthesis and Characterization of Mixed-Conducting Corrosion Resistant Oxide Supports • **Los Alamos National Laboratory**: The Science and Engineering of Durable Ultralow PGM Catalysts • **Los Alamos National Laboratory**: Engineered Nano-scale Ceramic Supports for PEM Fuel Cells. • **Lawrence Berkeley National Laboratory**: Molecular-scale, Three-dimensional Non-Platinum Group Metal Electrodes for Catalysis of Fuel Cell Reactions • **Northeastern University**: Development of Novel Non Pt Group Metal Electro catalysts for Proton Exchange Membrane Fuel Cell Applications • **National Renewable Energy Laboratory**: Extended, Continuous Pt Nanostructures in Thick, Dispersed Electrodes • **National Renewable Energy Laboratory**: WO_3 and HPA Based System for Ultra-High Activity and Stability of Pt Catalysts in PEMFC Cathodes • **Pacific Northwest National Laboratory**: Alternative and Durable High Performance Cathode Supports for PEM Fuel Cells • **University of South Carolina**: Development of Ultra-Low Platinum Alloy Cathode Catalyst for PEM Fuel Cells • **UTC Power**: Power Highly Dispersed Alloy Catalyst for Durability

Table 3.4.2 Current Fuel Cell Activities

Task	Approach	Activities
Membrane Electrode Assemblies, Gas Diffusion Media, and Cells	• Integrate membrane/electrolytes and electrodes • Expand MEA operating range addressing temperature and humidity range, improving stability, and mitigating effects of impurities. • Test, analyze, and characterize MEAs • Improve GDL/MPL performance and durability.	• **DuPont**: Analysis of Durability of MEAs in Automotive PEMFC Applications. • **Giner Electrochemical Systems, LLC**: Transport in PEMFC Stacks • **GM**: Investigation of Micro- and Macro-Scale Transport Processes for Improved Fuel Cell Performance • **Ion Power**: Corrugated Membrane Fuel Cell Structures • **CFD Research Corp.**: Water Transport in PEM Fuel Cells: Advanced Modeling, Material Selection, Testing, and Design Optimization • **Sandia National Laboratories**: Development and Validation of a Two-phase, Three-dimensional Model for PEM Fuel Cells • **Nuvera Fuel Cells**: Transport Studies Enabling Efficiency Optimization of Cost-Competitive Fuel Cell Stacks
Seals, Bipolar Plates, and Interconnects	• Optimize balance-of-stack components • Improve performance and durability of bipolar plates • Decrease cost of bipolar plates	• **Argonne National Laboratory**: Metallic Bipolar Plates with Composite Coatings • **Treadstone Technologies**: Low Cost PEM Fuel Cell Metal Bipolar Plates
Stack and Component Operation and Performance	• Improve technical understanding and characterization	• **Lawrence Berkeley National Laboratory**: Fuel-Cell Fundamentals at Low and Subzero Temperatures • **Plug Power, Inc.**: Air Cooled Stack Freeze Tolerance
Systems Operation and Performance	• Improve technical understanding and characterization	• No current activities
Systems BOP Components	• Develop chemical and temperature sensors for stationary applications • Develop air management technologies for stationary applications • Develop humidifiers • Develop thermal management technologies for fuel cell systems	• **Honeywell**: Development of Thermal and Water Management System for PEM Fuel Cell • **W.L. Gore**: Materials and Modules for Low-Cost, High Performance Fuel Cell Humidifiers

Table 3.4.2 Current Fuel Cell Activities		
Task	**Approach**	**Activities**
Fuel Processors	• Develop fuel-flexible fuel processors capable of generating a hydrogen-rich gas stream • Improve durability and tolerance to impurities • Integrate fuel processor subsystems eliminating reactor hardware, piping	• No current activities
Fuel Cell Systems	• Develop stationary fuel cell systems for Distributed Generation • Develop auxiliary power units • Develop portable power technologies	• **Arkema**: Novel Materials for High Efficiency Direct Methanol Fuel Cells • **Los Alamos National Laboratory**: Advanced Materials and Concepts for Portable Power Fuel Cells • **National Renewable Energy Laboratory**: Direct Methanol Fuel Cell Anode Catalysts • **University of North Florida**: New MEA Materials for Improved DMFC Performance, Durability, and Cost • **Acumentrics**: Development of a Low Cost 3-10kW Tubular SOFC Power System
Testing and Technical Assessment	• Perform cost analysis • Annually update technology status • Conduct tradeoff analysis • Develop protocols for testing • Experimentally determine long-term stack failure mechanisms • Experimentally determine system emissions • Perform independent testing to characterize component and stack properties	• **Argonne National Laboratory**: Fuel Cell Systems Analysis • **Ballard**: Development of Micro-Structural Mitigation Strategies for PEM Fuel Cells: Morphological Simulations and Experimental Approaches • **Directed Technologies, Inc.**: Mass-Production Cost Estimation for Automotive Applications • **Hawaii Natural Energy Institute**: The Effect of Airborne Contaminants on Fuel Cell Performance and Durability • **Los Alamos National Laboratory**: Durability Improvements through Degradation Mechanism Studies • **National Renewable Energy Laboratory**: Effect of System and Air Contaminants on PEMFC Performance and Durability • **NIST**: Neutron Imaging Study of Water Transport in Operating Fuel Cells • **University of Connecticut**: Effects of Impurities on Fuel Cell Performance and Durability • **Nuvera Fuel Cells**: Durability of Low Pt Fuel Cells Operating at High Power Density • **Argonne National Laboratory**: Fuel Cell Test

Table 3.4.2 Current Fuel Cell Activities		
Task	**Approach**	**Activities**
		Facility • **Los Alamos National Laboratory**: Accelerated Testing Validation • **Los Alamos National Laboratory**: Technical Assistance to Developers • **Oak Ridge National Laboratory**: Characterization of Fuel Cell Materials • **UTC Power**: Improved Accelerated Stress Tests Based on Fuel Cell Electric Vehicle Data

3.4.4 Technical Challenges

Cost and durability are the major challenges to fuel cell commercialization. Size and weight are approaching targets but further reductions are needed to meet packaging requirements for some commercial systems. Understanding of the effects of air, fuel, and system-derived impurities (including from the fuel storage system) needs to be improved, and mitigation strategies need to be identified and demonstrated. Cost, efficiency, and packaging of fuel cell balance-of-plant components are also barriers to the commercialization of fuel cells. For transportation applications, fuel cell technologies face more stringent cost and durability requirements. In stationary power applications, raising the operating temperature of PEMs to increase fuel cell performance will also improve heat and power cogeneration and overall system efficiency. Development of low-cost fuel processing and gas cleanup is required to enable fuel flexibility and enable the use of renewable fuels, such as biogas. Improving the durability at lower cost of high temperature fuel cell systems is also required. Fuel cell systems for portable power applications must have increased durability and reduced costs to compete with batteries. Likewise, fuel cells for auxiliary power must have longer durability and reduced costs to penetrate the market.

Transportation Systems

Light Duty Vehicles

The cost of fuel cell power systems must be reduced before they can be competitive with gasoline internal combustion engines (ICEs). Conventional automotive ICE power plants currently cost about $25-$35 / kW (August 2011); a fuel cell system needs to cost less than $30/kW for the technology to be competitive. A significant fraction of the cost of a PEM fuel cell comes from precious-metal catalysts that are currently used on the anode and cathode for the electrochemical reactions. Other key cost factors include the membrane, cell hardware, and balance-of-plant components.

The durability of fuel cell systems operating under automotive conditions is being evaluated under the Technology Validation Learning Demonstration Program. Results indicate a projected durability of up to 2,500 hours[3]. Fuel cell power systems will be required to be as durable and reliable as current automotive engines (i.e., 5,000 hour lifespan [150,000 miles equivalent] with less than 10% loss of performance by the end of life) and able to function over the full range of external environmental conditions (-40° to +40°C). Membranes are critical components of the fuel cell stack and must be able to perform over the full range of system operating temperatures and humidity. Current commercial membranes need humidification. External humidification adds cost and complexity to the system. The durability of catalysts is also an issue and can be compromised by platinum sintering and dissolution, especially under conditions of load-cycling and high electrode potentials. Carbon support corrosion is another challenge at high electrode potentials and can worsen under load cycling and high-temperature operation.

Fuel cell and stack hardware (bipolar plates, gas diffusion layers and seals) also need further development. Bipolar plates represent a significant fraction of stack weight, which must be reduced. Seal materials must be durable over the lifetime of a fuel cell and yield acceptable leak rates.

Air management for fuel cell systems is a challenge because today's compressor technologies are not suitable for automotive fuel cell applications. In addition, thermal and water management for fuel cells are issues. Fuel cell operation at lower temperatures creates a small differential between the operating and ambient temperatures necessitating large heat exchangers and humidifiers. These components increase the cost and complexity of the system and use some of the power that is produced, reducing overall system efficiency.

Buses

Transit bus applications represent a promising early-to-mid-term market for fuel cell technology. Central fueling of transit bus fleets facilitates introduction of hydrogen fuel in this market, and less stringent cost, weight, and volume criteria make implementation of fuel cell propulsion systems less challenging in transit buses than in other transportation applications.

Fuel cell buses have been undergoing research, development, and deployment for decades.[4] PAFC and PEMFC have been the primary fuel cell technologies considered in pure and battery or ICE hybrid systems operating on hydrogen, methanol, and natural gas.

A recent fuel-cell bus demonstration has achieved >10,000 operating hours in real-world-service with the original cell stacks and no cell replacement.[5] Fuel cell bus power plants are offered with a 12,000-hour or 5-year warranty, including air, fuel, and water management systems. Remaining fuel cell durability issues are difficult to identify and understand through field data. Development and implementation of accelerated stress tests (ASTs) are needed to shorten the time required to address durability issues for all drive cycles and hybridization strategies.

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[3] K. Wipke, *et al.*, *Controlled Hydrogen Fleet and Infrastructure Analysis*, http://www.hydrogen.energy.gov/pdfs/review11/tv001_wipke_2011_o.pdf

[4] L. Eudy *et al.*, *Fuel Cell Buses in U.S. Transit Fleets: Summary of Experiences and Current Status*, http://www.nrel.gov/hydrogen/pdfs/41967.pdf

[5] UTC Power Press Release, dated August 10, 2011, http://www.utcpower.com/pressroom/pressreleases/utc-power-fuel-cell-system-sets-world-record-achieving-10000-hr-durability

Because balance-of-plant components, power electronics, and power plant integration issues cause more forced shutdowns than the fuel cell system does, development of fuel cell powered buses should be done at the overall system level. Of course, hybridization strategy has a major effect on system design and technical requirements.

Although fuel cell durability increases have been realized and costs have been reduced, efficiency, durability, and cost targets (manufacturing, capital, operations, and maintenance) have not been met. Initial capital cost is particularly important.

Stationary Power Systems

Stationary fuel cells can be used in a broad range of commercial, industrial, and residential applications and can supplement or even replace power from the electrical grid. These fuel cells can be multi-megawatt systems for large centralized power generation, small units (e.g. 1 kW) for backup power, or 1 kW–3 MW systems for homes, buildings, and distributed generation applications, including CHP systems. Because fuel cells can be grid-independent and offer both high reliability and low emissions, they are attractive for critical load applications.

The advantages of fuel cells for distributed power generation include: elimination of transmission and distribution losses, low emissions, increased reliability, and reduction in bottlenecks and peak demand on the electric grid. Fuel cells can also provide the very high efficiencies inherent in CHP installations, with the potential to use more than 80% of the fuel energy, compared to the 45% to 50% combined overall efficiency of using electricity from coal or natural gas plants and thermal energy from on-site natural-gas combustion. Other benefits include their nearly silent and vibration-free operation, ability to use the existing natural gas fuel supply as well as biogas sources such as wastewater treatment plants and landfill gas facilities, low operation and maintenance requirements, and excellent transient response and load following capability.

Even though the specific performance requirements differ from transportation applications, some of the technical challenges for stationary fuel cell systems are the same. For example, the overall cost of these fuel cell power systems must be competitive with conventional/incumbent technologies or offer enhanced capabilities. However, stationary and other fuel cell systems have an acceptable price point considerably higher than transportation systems.

Performance of fuel cells for stationary applications for more than 80,000 hours has been demonstrated in PAFC installations, but other fuel cell technologies require durability improvements to achieve 80,000 hours of reliable operation over the full range of external environmental conditions (-40° to 40°C).

The low operating temperature of PEM fuel cells limits the amount of waste heat that can be effectively used in CHP applications. Technologies need to be developed that will allow higher operating temperatures and/or more effective heat recovery systems. Improved system designs that will enable higher CHP efficiencies are also needed. In addition, technologies that allow the thermal energy rejected from stationary fuel cell systems to be utilized in heating and cooling systems need to be evaluated. Fuel flexible processing systems are needed that take advantage of opportunity fuels from waste processing or bio-derived fuels.

Medium-scale CHP / Distributed Generation (100 kW–3 MW modular)

Phosphoric acid (PAFC) and molten carbonate fuel cells (MCFC) are being commercialized because of their modularity, the quality of waste heat, and their demonstrated durability (PAFC >80,000 and MCFC >40,000 hours). As the technology further matures, SOFCs are also making headway in this application.

The initial cost for PAFCs (capital equipment, manufacturing processes, installation, and warranty) needs to be reduced. Challenges to reducing these costs include increasing catalyst performance by reducing or eliminating anion adsorption and developing more durable and stable catalysts and catalyst support materials that enable stable operation over the extended life of the PAFC and PBI-type fuel cells. Development of lower cost materials for the cell stack (replacement of Teflon in the cell stack) and BOP is also a challenge.

Durability of MCFCs needs to be increased. More robust cathode materials must be developed to decrease the rate of cathode dissolution. Development of new electrolyte compositions to limit electrolyte loss, as well as new electrolyte supports with more durable microstructure, is needed to prevent early stack failure. Common technical challenges for MCFC and PAFC are reducing the system conditioning time and developing low-cost manufacturing methods.

SOFC stacks have demonstrated durability in excess of 25,000 hours. The high operating temperature can lead to compatibility and reactivity issues among the various cell and stack components, especially over extended operating times. The ability of the stack to survive repeated thermal cycling and the relatively long start up times are additional technical challenges. Lowering the operating temperature of SOFCs further will help resolve these challenges. R&D work funded by the Office of Fossil Energy is being leveraged to develop SOFCs for medium-scaled applications.

Micro Combined Heat and Power (1–10 kW)

High-temperature fuel cells, including (but not limited to) solid oxide and PBI-type fuel cells, are a key focus area of DOE's R&D activities for small scale stationary power generation because of their fuel flexibility, high efficiency, and potential for use in CHP applications. It is anticipated that residential CHP fuel cells will use primarily natural gas fuel to provide electrical power, heating, and hot water. Challenges for micro CHP applications include decreasing cost and increasing durability and cell component stability. The technical issues for PBI-type fuel cells and SOFC systems for micro CHP applications are similar to those described in the Medium-scale CHP/Distributed Generation section above.

Fuel Processing

Stationary/distributed generation systems often include a fuel processing sub-system to convert the raw fuel to clean hydrogen or synthesis gas for fuel cell consumption. Raw fuels include natural gas, LPG, and renewable fuels such as digester gas, landfill gas, biodiesel, alcohols, etc. These fuels need varying degrees of treatment depending on the initial composition and heating value and the type of fuel cell used. Military logistic fuels such as JP8 are not included here, but are covered by Department of Defense funding. The impurities cover a very broad range of deleterious compounds which vary depending on the raw fuel source type and geographical origin and include various sulfur-containing compounds, siloxanes, ammonia, and others.

The fuel processing sub-system can include but is not limited to the following components or process steps: raw fuel pre-treatment (e.g., desulfurization); reactors to convert the raw fuel into a hydrogen-rich stream (e.g., reformers); reactors to reduce carbon monoxide and increase hydrogen content (e.g., water-gas-shift); and separators and/or polishers to enrich and further clean the hydrogen stream (e.g., pressure-swing adsorption (PSA) and preferential oxidation (PROX)). Higher temperature fuel cells require less processing and therefore fewer components than listed above.

Significant issues for the fuel processing system are: fuel flexibility, durability, cost, fuel clean-up, impurity tolerance, thermal and physical integration, and cold start-up time. Current fuel processing systems need improved efficiency and reduced costs. Fuel processors can be improved by thermally and/or physically integrating the functions of the fuel processing sub-systems and by developing multi-functional catalysts to facilitate multiple reactions in the same reactor. Thermal and/or physical integration of the reactors can reduce cost and increase efficiency by eliminating reactor hardware, piping, and possibly sensors and controls. Multi-functional catalysts also increase efficiency and reduce cost by system simplification and component elimination. DOE will investigate combining sub-system functions into single reactors or closely integrating the thermal loads of the sub-systems.

A broad spectrum of deleterious compounds is found in the raw fuels (e.g., sulfur-containing compounds, siloxanes, and ammonia). These compounds may have adverse effects not only on the fuel cell but also on the fuel processing system. Specifically, but not exclusively, even the low levels of sulfur in natural gas could potentially have a poisoning effect on certain fuel processor catalysts and adversely affect system durability. Sulfur tolerance requirements are dependent on the type and quantity of sulfur species (e.g., hydrogen sulfide, mercaptans, or substituted dibenzothiophenes) in the fuel and the fuel processing sub-system under consideration, (e.g., steam reforming catalyst, autothermal reforming catalyst, and water gas shift catalyst). Therefore, some degree of clean-up may be required upstream of the fuel processor as well as immediately before the fuel cell and possibly between fuel processor sub-systems.

DOE will investigate broad-spectrum clean-up technologies to remove the impurities regardless of raw fuel composition and purity. Technologies are not restricted to sulfur and may be for upstream or intermediate impurity removal provided that the assumed composition and condition of the fuel stream entering the sub-system is realistic and supported by data.

DOE will investigate development of catalysts and hardware capable of generating fuel cell-grade hydrogen or reformate from a variety of renewable fuel sources (e.g., digester gas, landfill gas, biodiesel, and alcohols). In addition, research will be performed to develop an entire fuel processor system capable of taking in raw fuel at its inlet and delivering fuel cell quality hydrogen or reformate at the fuel processor outlet (the fuel cell inlet) that contains ≥ 1 g/min hydrogen.

Reversible Fuel/Flow Cells

Reversible fuel/flow cells, sometimes referred to as flow batteries, are of interest for energy storage applications, and hold promise as an enabler for implementation of intermittent renewable energy technologies. This technology allows for storage of excess energy during periods of low electricity demand which can then be used during times of peak demand. Some types of fuel/flow cells, such as hydrogen/halogen cells, are closely related to conventional fuel cells. Reversible fuel cells are capable of operating in both power production (fuel cell) and energy storage (electrolysis) modes. Advantages of reversible fuel/flow cell technology include high round-trip efficiency (60-90%), decoupled power and energy capacity, long cycle life, low self-discharge rate, and reliable and stable performance. Cost and durability are barriers to implementation of reversible fuel/flow cells, but leveraging of fuel cell R&D in the areas of membranes, electro catalysts, electrode architectures, bipolar plates, and diffusion media would result in cost reduction and durability improvements.

Auxiliary Power Units

Fuel cells can provide clean, efficient auxiliary power for trucks, recreational vehicles, marine vessels (yachts, commercial ships), airplanes, locomotives, and similar applications that have significant auxiliary power demands. In many of these applications, the primary motive-power engines are often kept running solely for auxiliary loads. This practice is inefficient, resulting in significant additional fuel consumption and emissions. Fuel cell APUs are being considered for terrestrial, aviation, and maritime applications. This section addresses only long-haul truck hotel applications. APUs for heavy duty vehicles represent a potential early market opportunity for fuel cell deployment. Significant fuel savings, as well as reduction in CO_2 and criteria pollutant emissions, may be achieved through more efficient fuel conversion and reduction in engine idling time. For the approximately 500,000 long-haul Class 7 and Class 8 trucks in the United States, emissions during overnight idling have been estimated to be 10.9 million tons of CO_2 and 190,000 tons of NO_X annually.[6] The use of auxiliary power units (APUs) for Class 7–8 heavy trucks to avoid overnight idling of diesel engines could save up to 280 million gallons of fuel per year and avoid more than 92,000 tons of NO_X emissions.[7] Further, emissions from idling and auxiliary power are likely to be the subject of increasing regulations in the future. Idling restrictions for heavy-duty highway vehicles have already been enacted in 28 states.[8] In 2008, the EPA adopted new requirements for limiting idling emissions from locomotives.

The main challenges for this application are the cost and the combination of the transient operation of the APU, the need to utilize the fuel onboard the vehicle (diesel) without adding additional requirements (i.e. no additional water for reforming), and the harsh environment (shock and vibrations on the vehicle). In addition, the APU unit must fit in the available space and not add unnecessary weight to the vehicle. Fuel cells for auxiliary power unit (APU) applications need to

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[6] Nicholas Lutsey, Christie-Joy Brodrick & Timothy Lipman, "Analysis of Potential Fuel Consumption and Emissions Reduction from Fuel Cell Auxiliary Power Units (APUs) in Long Haul Trucks," Elsevier Science Direct, Energy 32, September 2005. http://www.sciencedirect.com/science/article/pii/S0360544207001016

[7] Preferences Survey, American Transportation Research Institute (prepared for New York State Energy Research and Development Authority), February 2006. → http://www.atri-online.org/research/results/Idle%20Survey%20One%20Page%20Summary.pdf

[8] ATRI Compendium of Idling Regulations, http://www.atri-online.org/research/idling/ATRI_Idling_Compendium.pdf

have increased specific power and power density to meet packaging requirements for heavy-duty trucks.

Portable Power Systems

Fuel cell systems with higher energy density, power density, and specific power than existing technologies for applications less than 250 W are one focus area of DOE's R&D activities. It is anticipated that portable power applications, including battery chargers, consumer electronics, handheld terminals, unattended security devices, notebook PCs, and emergency response mobile communications, will provide an early market for fuel cell technologies. A high-energy density alternative to existing technologies is required to fill the increasing gap between energy demand and energy supply for these applications. Challenges for fuel cells for portable power include reducing cost (mainly by reducing catalyst loading), increasing efficiency (by reducing fuel crossover and increasing catalyst selectivity), and reducing the size of the system BOP.

Portable power R&D needs include development of electrodes with higher activity and selectivity, reduction of methanol crossover, and decrease in system volume and weight. Total life cycle efficiency improvement would have a positive impact on emissions reduction during operation and disposal. Flexible fuel capability (e.g., ethanol, butane), based on renewable fuels is attractive.

Backup Power and Material Handling Equipment

Backup power installations are recognized as one of the leading applications for fuel cells. Therefore, the Market Transformation Team is leading the DOE support of this application and no specific issues are being addressed in this section. It is assumed that fuel cell and system advances in the other applications will have a positive impact on back-up power fuel cell technology. Performance targets for these applications are being reached, including from demonstration projects supported by the American Recovery and Reinvestment Act of 2009.

Material handling equipment, including forklifts and yard dogs (tractor trailer type trucks used for moving freight trailers within a facility), are a leading application for fuel cells. Therefore, the Market Transformation Team is leading the DOE support of this application through deployments, and no specific issues are being addressed in this section. Fuel cell and system advances in the other applications will have a positive impact on material handling fuel cell technology.

Technical Targets

Tables 3.4.3 and 3.4.4 list the DOE technical targets specifically for integrated PEM fuel cell power systems and fuel cell stacks operating on direct hydrogen for transportation applications. These targets have been developed with input from the U.S. DRIVE Partnership, which includes automotive and energy companies, specifically the Fuel Cell Technical Team. Tables 3.4.5 through 3.4.6 list the DOE technical targets for stationary applications. These targets have been developed with input from developers of stationary fuel cell power systems.

Tables 3.4.7 and 3.4.8 list the DOE technical targets for portable power and auxiliary power applications, respectively. Tables 3.4.9 through 3.4.11 list DOE technical targets for automotive and stationary fuel cell systems humidifiers and automotive compressor/expander units. Tables 3.4.12

through 3.4.15 list DOE technical targets for PEM fuel cell components: membranes, electrodes / catalysts, membrane electrode assemblies and bipolar plates. These tables assist component developers in evaluating progress without testing full systems.

All targets must be achieved simultaneously; however, the status values are not necessarily from a single system.

Table 3.4.3 Technical Targets for Automotive Applications: 80-kW$_e$ (net) Integrated Transportation Fuel Cell Power Systems Operating on Direct Hydrogen [a]

Characteristic	Units	2011 Status	2017 Targets	2020 Targets
Energy efficiency[b] @ 25% of rated power	%	59	60	60
Power density	W / L	400[c]	650	850
Specific power	W / kg	400[c]	650	650
Cost[d]	\$ / kW$_e$	49[e]	30	30
Cold start-up time to 50% of rated power				
@–20°C ambient temp	seconds	20[f]	30	30
@+20°C ambient temp	seconds	<10	5	5
Start up and shut down energy[g]				
from -20°C ambient temp	MJ	7.5	5	5
from +20°C ambient temp	MJ	-	1	1
Durability in automotive drive cycle	hours	2,500[h]	5,000[i]	5,000[i]
Assisted start from low temperatures[j]	°C	–	-40	-40
Unassisted start from low temperatures[j]	°C	-20[f]	-30	-30

[a] Targets exclude hydrogen storage, power electronics and electric drive.

[b] Ratio of DC output energy to the lower heating value of the input fuel (hydrogen). Peak efficiency occurs at about 25% rated power.

[c] Based on input from the Technology Validation activity.

[d] Cost projected to high-volume production (500,000 systems per year). Target being re-evaluated by DOE and the U.S. DRIVE Fuel Cell Tech Team.

[e] The projected cost status is from a 2011 DTI study and will be periodically updated. The status is based on an analysis of state-of-the-art components that have been developed and demonstrated primarily through the DOE Program at the laboratory scale. Additional efforts would be needed for integration of components into a complete automotive system that meets durability requirements in real-world conditions.

[f] Based on average of status values reported at 2010 SAE World Congress. These systems do not necessarily meet other system-level targets.

[g] H_2 fuel energy (Lower Heating Value) to include the fuel energy required to account for the electrical energy consumed from cold start.

[h] Projected time to 10% voltage degradation from the Technology Validation activity.

[i] Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/guest/view_team.php?teams_id=17), Table 6, <10% drop in rated power after test.

[j] 8-hour soak at stated temperature must not impact subsequent achievement of targets.

Table 3.4.4 Technical Targets: 80-kW$_e$ (net) Transportation Fuel Cell Stacks Operating on Direct Hydrogen[a]

Characteristic	Units	2011 Status	2017 Targets	2020 Targets
Stack power density[b]	W / L	2,200[c]	2,250	2,500
Stack specific power	W / kg	1,200[c]	2,000	2,000
Stack efficiency[d] @ 25% of rated power	%	65	65	65
Cost[e]	\$ / kW$_e$	22[f]	15	15
Durability with cycling	hours	2,500[g]	5,000[h]	5,000[h]
$Q/\Delta T_i$[i]	kW/ºC	–	1.45	1.45

[a] Excludes hydrogen storage, power electronics, electric drive and fuel cell ancillaries: thermal, water and air management systems.

[b] Power refers to net power (i.e., stack power minus auxiliary power). Volume is “box” volume, including dead space.

[c] Average of data from selected proprietary and public sources.

[d] Ratio of output DC energy to lower heating value of hydrogen fuel stream. Peak efficiency occurs at about 25% rated power.

[e] Cost projected to high-volume production (500,000 stacks per year).

[f] Status is from 2011 DTI study and will be periodically updated.

[g] Projected time to 10% voltage degradation from the Technology Validation activity.

[h] Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), Table 6, <10% drop in rated power after test.

[i] $Q/\Delta T_i$ = [Stack power (90kW) x (1.25V - Voltage at Rated Power) / (Voltage at Rated Power)] / [(Stack Coolant out temp (°C) - Ambient temp (40°C)] Target assumes 90kW stack gross power required for 80 kW net power, and is to be measured using the polarization curve protocol in Table 5 of the U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267).

Table 3.4.5 Technical Targets: 1–10 kW_e Residential Combined Heat and Power and Distributed Generation Fuel Cell Systems Operating on Natural Gas[a]

Characteristic	2011 Status	2015 Targets	2020 Targets
Electrical efficiency at rated power[b]	34-40%	42.5%	>45% [c]
CHP energy efficiency[d]	80-90%	87.5%	90%
Equipment cost[e], 2-kW_{avg}[f] system	NA	\$1,200/kW_{avg}	\$1,000/kW_{avg}
Equipment cost[e], 5-kW_{avg} system	\$2,300 - \$4,000/kW[g]	\$1,700/kW_{avg}	\$1,500/kW_{avg}
Equipment cost[e], 10-kW_{avg} system	NA	\$1,900/kW_{avg}	\$1,700/kW_{avg}
Transient response (10 - 90% rated power)	5 min	3 min	2 min
Start-up time from 20°C ambient temperature	<30 min	30 min	20 min
Degradation with cycling[h]	<2%/1,000 h	0.5%/1,000 h	0.3%/1,000 h
Operating lifetime[i]	12,000 h	40,000 h	60,000 h
System availability[j]	97%	98%	99%

[a] Pipeline natural gas delivered at typical residential distribution line pressures.

[b] Regulated AC net/LHV of fuel.

[c] Higher electrical efficiencies (e.g. 60% using SOFC) are preferred for non-CHP applications.

[d] Ratio of regulated AC net output energy plus recovered thermal energy to the LHV of the input fuel. For inclusion in CHP energy efficiency calculation, heat must be available at a temperature sufficiently high to be useful in space and water heating applications. Provision of heat at 80°C or higher is recommended.

[e] Complete system, including all necessary components to convert natural gas to electricity suitable for grid connection, and heat exchangers and other equipment for heat rejection to conventional water heater, and/or hydronic or forced air heating system. Includes all applicable tax and markup. Based on projection to high-volume production (50,000 units per year).

[f] kW_{avg} is the average output (AC) electric power delivered over the life of system while unit is running.

[g] Strategic Analysis, Inc. preliminary 2011 cost assessment of stationary PEM system, range represents manufacturing volumes of 100 to 50,000 units per year.

[h] Durability testing should include effects of transient operation, startup, and shutdown.

[i] Time until >20% net power degradation.

[j] Percentage of time the system is available for operation under realistic operating conditions and load profile. Unavailable time includes time for scheduled maintenance.

Table 3.4.6 Technical Targets[a]: 100 kW–3 MW Combined Heat and Power and Distributed Generation Fuel Cell Systems Operating on Natural Gas[b]

Characteristic	2011 Status[c]	2015 Targets	2020 Targets
Electrical efficiency at rated power[d]	42-47%	45%	>50%[e]
CHP energy efficiency[f]	70-90%	87.5%	90%
Equipment cost, natural gas	$2,500-$4,500/kW[g]	$2,300/kW[h]	$1,000/kW[h]
Installed cost, natural gas	$3,500-$5,500/kW[g]	$3,000/kW[h]	$1,500/kW[h]
Equipment cost, biogas	$4,500-$6,500/kW[g]	$3,200/kW[h]	$1,400/kW[h]
Installed cost, biogas	$6,000-$8,000/kW[g]	$4,100/kW[h]	$2,100/kW[h]
Number of planned/forced outages over lifetime	50	50	40
Operating lifetime[i]	40,000–80,000 h	50,000 h	80,000 h
System availability[j]	95%	98%	99%

[a] Includes fuel processor, stack and ancillaries.

[b] Pipeline natural gas delivered at typical residential distribution line pressures.

[c] Status varies by technology.

[d] Ratio of regulated AC net output energy to the lower heating value (LHV) of the input fuel.

[e] Higher electrical efficiencies (e.g. 60% using SOFC) are preferred for non-CHP applications.

[f] Ratio of regulated AC net output energy plus recovered thermal energy to the LHV of the input fuel. For inclusion in CHP energy efficiency calculation, heat must be available at a temperature sufficiently high to be useful in space and water heating applications. Provision of heat at 80°C or higher is recommended.

[g] Current production volume (~30 MW per year).

[h] Includes projected cost advantage of high-volume production (totaling 100 MW per year).

[i] Time until >10% net power degradation.

[j] Percentage of time the system is available for operation under realistic operating conditions and load profile. Unavailable time includes time for scheduled maintenance.

Table 3.4.7.a Technical Targets: Portable Power Fuel Cell Systems (<2 Watt)[a]				
Characteristic	**Units**	**2011 Status**	**2013 Targets**	**2015 Targets**
Specific power[b]	W/kg	5	8	10
Power density[b]	W/L	7	10	13
Specific energy[b,c]	Wh/kg	110	200	230
Energy density[b,c]	Wh/L	150	250	300
Cost[d]	$/system	150	130	70
Durability[e,f]	hours	1,500	3,000	5,000
Mean time between failures[f,g]	hours	500	1,500	5,000

Table 3.4.7.b Technical Targets: Portable Power Fuel Cell Systems (10-50 Watts)[a]				
Characteristic	**Units**	**2011 Status**	**2013 Targets**	**2015 Targets**
Specific power[b]	W/kg	15	30	45
Power density[b]	W/L	20	35	55
Specific energy[b,c]	Wh/kg	150	430	650
Energy density[b,c]	Wh/L	200	500	800
Cost[d]	$/W	15	10	7
Durability[e,f]	hours	1,500	3,000	5,000
Mean time between failures[f,g]	hours	500	1,500	5,000

Table 3.4.7.c Technical Targets: Portable Power Fuel Cell Systems (100-250 Watts)[a]

Characteristic	Units	2011 Status	2013 Targets	2015 Targets
Specific power[b]	W/kg	25	40	50
Power density[b]	W/L	30	50	70
Specific energy[b,c]	Wh/kg	250	440	640
Energy density[b,c]	Wh/L	300	550	900
Cost[d]	$/W	15	10	5
Durability[e,f]	hours	2,000	3,000	5,000
Mean time between failures[f,g]	hours	500	1,500	5,000

[a] These targets are technology neutral and make no assumption about the type of fuel cell technology or type of fuel used. In addition to meeting these targets, portable power fuel cells are expected to operate safely, providing power without exposing users to hazardous or unpleasant emissions, high temperatures, or objectionable levels of noise. Portable power fuel cells are also expected to be compatible with the requirements of portable electronic devices, including operation under a range of ambient temperature, humidity, and pressure conditions, and exposure to freezing conditions, vibration, and dust. They should be capable of repeatedly turning off and on, and should have turndown capabilities required to match the dynamic power needs of the device. For widespread adoption, portable power fuel cell systems should minimize lifecycle environmental impact through the use of reusable fuel cartridges, recyclable components, and low-impact manufacturing techniques.

[b] This is based on rated net power of the total fuel cell system, including fuel tank, fuel, and any hybridization batteries. In the case of fuel cells embedded in other devices, only device components required for power generation, power conditioning, and energy storage are included. Fuel capacity is not specified, but the same quantity of fuel must be used in calculation of specific power, power density, specific energy, and energy density.

[c] Efficiency of 30% in 2013 and 35% in 2015 is recommended to enable high specific energy and energy density.

[d] Cost includes material and labor costs required to manufacture the fuel cell system and any required auxiliaries (e.g., refueling devices). Cost is defined at production rates of 50,000, 25,000 and 10,000 units per year for <2, 10–50, and 100–500 W units, respectively.

[e] Durability is defined as the time until the system rated power degrades by 20%, though for some applications higher or lower levels of power degradation may be acceptable.

[f] Testing should be performed using an operating cycle that is realistic and appropriate for the target application, including effects from transient operation, startup and shutdown, and off-line degradation.

[g] Mean Time Between Failures (MTBF) includes failures of any system components that render the system inoperable without maintenance.

Table 3.4.8 Technical Targets: Fuel Cell Auxiliary Power Units (1 to 10 kW_e) Operating on Ultra low Sulfur Diesel Fuel)

Characteristic	2011 Status	2013 Targets	2015 Targets	2020 Targets
Electrical efficiency at rated power[a]	25%	30%	35%	40%
Power density	17 W/L	30 W/L	35 W/L	40 W/L
Specific power	20 W/kg	35 W/kg	40 W/kg	45 W/kg
Factory cost, stack plus required BOP[b]	$750/kW[c]	$700/kW	$600/kW	$500/kW
Factory cost, system[d]	$2,000/kW	$1,400/kW	$1,200/kW	$1,000/kW
Transient response (10 to 90% rated power)	5 min	4 min	3 min	2 min
Start-up time from: 20 °C Standby conditions[e]	 50 min 50 min	 45 min 20 min	 45 min 10 min	 30 min 5 min
Degradation with cycling[f]	2.6%/1,000 h	2%/1,000 h	1.3%/1,000 h	1%/1,000 h
Operating lifetime[f, g]	3,000 h	10,000 h	15,000 h	20,000 h
System availability[h]	97%	97.5%	98%	99%

[a] Regulated DC net/LHV of fuel.

[b] Cost includes materials and labor costs to produce stack, plus any balance of plant necessary for stack operation. Cost defined at 50,000 unit/year production of a 5 kW system. Today's low-volume cost is expected to be higher than quoted status. Allowable cost is expected to be higher than the target for systems with rated power below 5 kW, and lower than the target for systems with rated power above 5 kW.

[c] Available cost status is that of a fuel cell stack only.

[d] Cost includes materials and labor costs to produce system. Cost defined at 50,000 unit/year production of a 5 kW system. Today's low-volume cost is expected to be higher than quoted status. Allowable cost is expected to be higher than the target for systems with rated power below 5 kW, and lower than the target for systems with rated power above 5 kW.

[e] Standby conditions may be at or above ambient temperature depending on operating protocol.

[f] Durability testing should include, at minimum, daily cycles to stand-by condition, and weekly cycles to full off condition (ambient temperature). The system should be able to meet durability criteria during and after exposure to vibration associated with transportation and highway operation, and during operation in a range of ambient temperature from -40 to 50 °C, a range of ambient relative humidity from 5% to 100%, and in dust levels up to 2 mg/m^3.

[g] Time until >20% net power degradation.

[h] Percentage of time the system is available for operation under realistic operating conditions and load profile. Scheduled maintenance does not count against system availability.

Table 3.4.9 Technical Targets: Cathode Humidification System for 80-kW$_e$ Transportation Fuel Cell Systems Operating on Direct Hydrogen

Characteristic	Units	2017 Targets
Maximum operating temperature	°C	>95
Maximum pressure differential between wet and dry sides	kPa	75
Maximum pressure drop at full flow (each side)	kPa	3.5
Water transfer at full flow[a]	$g\ s^{-1}$	5
Durability[b]	h	5,000
Maximum air leakage at full flow	%	0.5
Volume	L	5
Weight	kg	5
Cost[c]	$	100

[a] Dry air in: 3000 SLPM dry gas flow, 183 kPa (absolute), 80°C, 0% RH. Wet air in: 2600 SLPM dry gas flow, 160 kPa (absolute), 80°C, 85% RH.

[b] Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/guest/view_team.php?teams_id=17), <10% drop in water transfer at full flow.

[c] Cost projected to high-volume production (500,000 systems per year).

Table 3.4.10 Technical Targets: Cathode Humidifier Membrane for 80-kW$_e$ Transportation Fuel Cell Systems Operating on Direct Hydrogen

Characteristic	Units	2017 Targets
Maximum operating temperature	°C	>95
Maximum pressure differential between wet and dry sides	kPa	75
Water transfer flux at full flow[a]	$g\ min^{-1} cm^{-2}$	0.025
Durability[b]	h	5,000
Cost[c]	$\$/m^2$	10

[a] Dry air in: 0.23 SLPM/cm^2 dry gas flow, 183 kPa (absolute), 80°C, 0% RH. Wet air in: 0.20 SLPM/cm^2 dry gas flow, 160 kPa (absolute), 80°C, 85% RH.

[b] Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/guest/view_team.php?teams_id=17), <10% drop in water transfer at full flow.

[c] Cost projected to high-volume production (500,000 systems per year).

Table 3.4.11 Technical Targets: Air Compression System for 80-kW$_e$ Transportation Fuel Cell Systems Operating on Direct Hydrogen

Characteristic	Units	2011 Status	2017 Targets
Input power[a] at full flow[b] (with / without expander)	kW$_e$	11.0 / 17.3	8 / 14
Combined motor and motor controller efficiency at full flow[b]	%	80	90
Compressor / expander efficiency at full flow[b]	%	71 / 73	75 / 80
Input power at 25% flow[c] (with / without expander)	kW$_e$	2.3 / 3.3	1.0 / 2.0
Combined motor / motor controller efficiency at 25% flow[c]	%	57	80
Compressor / expander efficiency at 25% flow[c]	%	62 / 64	65 / 70
Input power at idle[d] (with / without expander)	W$_e$	600 / 765	200 / 200
Combined motor / motor controller efficiency at idle[d]	%	35	70
Compressor / expander efficiency at idle[d]	%	61 / 59	60 / 60
Durability	h	–	5,000
Number of startup and shutdown cycles		–	250,000
Turndown ratio (max/min flow rate)		20	20
Noise at maximum flow	dBA at 1 m	–	65
Transient time for 10-90% of maximum flow	s	1	1
System volume[e]	L	15	15
System weight[e]	kg	22	15
System cost[f]	$	960[g]	500

[a] Electrical input power to motor controller when bench testing fully integrated system. Fully integrated system includes control system electronics, air filter, and any additional air flow that may be used for cooling.

[b] Compressor: 92 g/s flow rate, 2.5 bar (absolute) discharge pressure; 40°C, 25% RH inlet conditions. Expander: 88 g/s flow rate, 2.2 bar (absolute) inlet pressure, 70°C, 100% RH inlet conditions.

[c] Compressor: 23 g/s flow rate, minimum 1.5 bar (absolute) discharge pressure; 40°C, 25% RH inlet conditions. Expander: 23 g/s flow rate, 1.4 bar (absolute) inlet pressure, 70°C, 100% RH inlet conditions.

[d] Compressor: 4.6 g/s flow rate, minimum 1.2 bar (absolute) discharge pressure; 40°C, 25% RH inlet conditions. Expander: 4.6 g/s flow rate, < compressor discharge pressure, 70°C, 20% RH inlet conditions.

[e] Weight and volume include the motor, motor controller.

[f] Cost target based on a manufacturing volume of 500,000 units per year.

[g] DTI cost model of the Honeywell 100,000 rpm machine, 2.5 bar (absolute), 92 g/s, dry air, 40°C: $960 including markup. TIAX 2009 estimate of Honeywell technology (compressor, expander, motor, motor controller) presented at 2010 Annual Merit Review and Peer Evaluation: $790 including 15% markup.

Table 3.4.12 Technical Targets: Membranes for Transportation Applications

Characteristic	Units	2011 Status [a]	2017 Targets	2020 Targets
Maximum oxygen cross-over[b]	mA / cm^2	<1	2	2
Maximum hydrogen cross-over[b]	mA / cm^2	<1.8	2	2
Area specific proton resistance at:				
Maximum operating temperature and water partial pressures from 40-80 kPa	Ohm cm^2	0.023 (40kPa) 0.012 (80kPa)	0.02	0.02
80°C and water partial pressures from 25-45 kPa	Ohm cm^2	0.017 (25kPa) 0.006 (44kPa)	0.02	0.02
30°C and water partial pressures up to 4 kPa	Ohm cm^2	0.02 (3.8 kPa)	0.03	0.03
-20°C	Ohm cm^2	0.1	0.2	0.2
Operating temperature	°C	<120	≤120	≤120
Minimum electrical resistance	Ohm cm^2	–	1,000	1,000
Cost[c]	\$ / m^2	–	20	20
Durability[d]				
Mechanical	Cycles with <10 sccm crossover	>20,000	20,000	20,000
Chemical	hours	>2,300	>500	>500

[a] Status represents 3M PFIA membrane (S. Hamrock, U.S. Department of Energy Hydrogen and Fuel Cells Program 2011 Annual Progress Report, (http://www.hydrogen.energy.gov/pdfs/progress11/v_c_1_hamrock_2011.pdf).

[b] Tested in MEA at 1 atm O_2 or H_2 at nominal stack operating temperature, humidified gases at 0.5 V DC.

[c] Costs projected to high-volume production (500,000 stacks per year).

[d] Protocol for mechanical stability is to cycle a 25-50 cm^2 MEA at 80°C and ambient pressure between 0% RH (2 min) and 90°C dew point (2 min) with air flow of 2 SLPM on both sides. Protocol for chemical stability test is to hold a 25-50 cm^2 MEA at OCV, 90°C, with H_2/air stoichs of 10/10 at 0.2 A/cm^2 equivalent flow, inlet pressure 150 kPa, and relative humidity of 30% on both anode and cathode. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), MEA Chemical Stability and Metrics (Table 3) and Membrane Mechanical Cycle and Metrics (Table 4).

Table 3.4.13 Technical Targets: Electrocatalysts for Transportation Applications

Characteristic	Units	2011 Status	Targets	
			2017	2020
Platinum group metal total content (both electrodes)[a]	g / kW (rated)	0.19[b]	0.125	0.125
Platinum group metal (pgm) total loading[a]	mg PGM / cm^2 electrode area	0.15[b]	0.125	0.125
Loss in initial catalytic activity[c]	% mass activity loss	48[b]	<40	<40
Electro catalyst support stability[d]	% mass activity loss	<10[b]	<10	<10
Mass activity[e]	A / mg Pt @ 900 $mV_{iR\text{-}free}$	0.24[b]	0.44	0.44
Non-Pt catalyst activity per volume of supported catalyst[e, f]	A / cm^3 @ 800 $mV_{IR\text{-}free}$	60 (measured at 0.8 V)[g] 165 (extrapolated from >0.85 V)[g]	300	300

[a] PGM content and loading targets may have to be lower to achieve system cost targets.

[b] M. Debe, U.S. Department of Energy Hydrogen and Fuel Cells Program 2011 Annual Merit Review Proceedings, May, 2011, (http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf)

[c] Durability measured in a 25-50 cm^2 MEA during triangle sweep cycles at 50 mV/s between 0.6 V and 1.0 V at 80°C, atmospheric pressure, 100% relative humidity, H_2 at 200 sccm and N_2 at 75 sccm for a 50 cm^2 cell. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), Electrocatalyst Cycle and Metrics (Table 1). Activity loss is based on loss of mass activity, using initial catalyst mass, at end of test.

[d] Durability measured in a 25-50 cm^2 MEA during a hold at 1.2 V in H_2/N_2 at 80°C, 150 kPa absolute, 100% relative humidity. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267), Catalyst Support Cycle and Metrics (Table 2). Activity loss is based on loss of mass activity, using initial catalyst mass, at end of test.

[e] Test at 80°C H_2/O_2 in MEA; fully humidified with total outlet pressure of 150 KPa; anode stoichiometry 2; cathode stoichiometry 9.5 (as per Gasteiger et al. Applied Catalysis B: Environmental, 56 (2005) 9-35).

[f] Volume = active area * catalyst layer thickness.

[g] P. Zelenay, H. Chung, C. Johnston, N. Mack, M. Nelson, P. Turner, G. Wu, FY 2011 Progress Report for the DOE Hydrogen Program, p. 816, U.S. Department of Energy, Feb. 2011, DOE/GO-102011-3178.

Table 3.4.14 Technical Targets: Membrane Electrode Assemblies				
Characteristic	**Units**	**2011 Status** [a]	**2017 Targets**	**2020 Targets**
$Q/\Delta T_i$[b]	kW/°C	–	1.45	1.45
Cost[c]	$ / kW	13 (without frame and gasket) 16 (including frame and gasket)[d]	9	7
Durability with cycling	hours	9,000[e]	5,000[f]	5,000[f]
Performance @ 0.8 V[g]	mA / cm^2	160	300	300
Performance @ rated power	mW / cm^2	845[h]	1,000	1,000

[a] First year for which status was available.

[b] $Q/\Delta T_i$ = [Stack power (90kW) x (1.25 V - Voltage at Rated Power) / (Voltage at Rated Power)] / [Stack Coolant out temp (°C) - Ambient temp (40°C)]. Target assumes 90kW stack gross power required for 80 kW net power, and is to be measured using the polarization curve protocol in Table 5 of the U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols (http://www.uscar.org/commands/files_download.php?files_id=267).

[c] Costs projected to high volume production (500,000 stacks per year).

[d] From DTI 2011 analysis (http://www.hydrogen.energy.gov/pdfs/review11/fc018_james_2011_o.pdf). Includes projected material and processing cost of membranes, catalysts, and diffusion media.

[e] From 3M (http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf). Membrane lifetime during 3M MEA cycling test was 9,000 hours, but performance degradation was not measured. Not all targets have been achieved by this MEA, nor were all status numbers reported derived from this MEA.

[f] Need to meet or exceed at temperatures of 80°C up to peak temperature. Based on U.S. DRIVE Fuel Cell Tech Team Cell Component Accelerated Stress Test and Polarization Curve Protocols, Tables 5 and 6 (http://www.uscar.org/commands/files_download.php?files_id=267, <10% drop in rated power after test.

[g] 0.8 V represents approximately ¼ rated power.

[h] Mark Debe, U.S. Department of Energy Hydrogen and Fuel Cells Program 2011 Annual Merit Review Proceedings, May, 2011, http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf.

Table 3.4.15 Technical Targets: Bipolar Plates

Characteristic	Units	2011 Status [a]	2017 Targets	2020 Targets
Cost[b]	$ / kW	5-10	3	3
Plate H_2 permeation coefficient[c]	Std cm^3/(sec cm^{2}Pa) @ 80°C, 3 atm 100% RH	N/A	$<1.3 \times 10^{-14}$ [d]	$<1.3 \times 10^{-14}$ [d]
Corrosion, anode[e]	μA / cm^2	<1	<1	<1
Corrosion, cathode[f]	μA / cm^2	<1	<1	<1
Electrical conductivity	S / cm	>100	>100	>100
Areal specific resistance[g]	Ohm-cm^2	0.03	0.02	0.01
Flexural strength[h]	MPa	>34 (carbon plate)	>25	>25
Forming elongation[i]	%	20–40	40	40

[a] Status is based on information found in 2010 & 2011 Annual Progress Reports – project description write ups of TreadStone Technologies, Inc. and Oak Ridge National Laboratory.

[b] Costs projected to high volume production (500,000 stacks per year), assuming MEA meets performance target of 1000 mW/cm^2.

[c] Per the standard gas transport test (ASTM D1434).

[d] Blunk, *et al*, J. Power Sources 159 (2006) 533-542.

[e] pH 3 0.1ppm HF, 80°C, peak active current $<1\times10^{-6}$ A/cm^2 (potentiodynamic test at 0.1 mV/s, -0.4V to +0.6V (Ag/AgCl)), de-aerated with Ar purge.

[f] pH 3 0.1ppm HF, 80°C, passive current $<5\times10^{-8}$ A/cm^2 (potentiostatic test at +0.6V (Ag/AgCl) for >24h, aerated solution.

[g] Includes interfacial contact resistance (on as received and after potentiostatic test) measured both sides per Wang, *et al*. J. Power Sources 115 (2003) 243-251 at 200 psi (138 N/cm^2).

[h] ASTM-D 790-10 Standard Test method for flexural properties of unreinforced and reinforced plastics and electrical insulating materials.

[i] Per ASTM E8M-01 Standard Test Methods for Tension Testing of Metallic Materials.

3.4.5 Technical Barriers

Of the many barriers discussed here, cost and durability present two of the most significant challenges to achieving clean, reliable, cost-effective fuel cell systems. While addressing cost and durability, fuel cell performance must meet or exceed that of competing technologies. Ultimately, operation of components and subsystems will be validated within the Technology Validation sub-program (see Section 3.6).

A. Durability

In the most demanding applications, realistic operating conditions include impurities in the fuel and air, starting and stopping, freezing and thawing, and humidity and load cycles that result in stresses on the chemical and mechanical stability of the fuel cell materials, components, and interfaces. Durability of PEMFC stacks, which must include tolerance to impurities and chemical and mechanical integrity, has not been established. Tolerance to air, fuel, and system-derived impurities (including the storage system) needs to be established. Sufficient durability of fuel cell systems operating over automotive drive cycles has not been demonstrated. Operation at low relative humidity (25–45 kPa water vapor at 80°C, or 40–80 kPa water vapor at maximum operating temperature), has not been demonstrated. Component degradation and failure mechanisms are not well understood, which makes development of effective mitigating strategies necessary.

Stationary fuel cells must achieve greater than 60,000 hours durability to compete against other distributed power generation systems and to allow for an acceptable return on investment to the end-user. The operating temperatures required for high temperature fuel cells place stringent durability requirements on materials and components, including the electrolyte, electrolyte support, and electrode. Improved durability under start-up and transient operation is also required for high temperature fuel cells. Durability of PBI-type fuel cells needs to be increased to that of conventional PAFC systems, for which established durability comes at a high cost. Research is also needed to understand failure mechanisms and develop mitigation strategies. Accelerated testing protocols need to be developed to enable projection of durability and to allow for timely iterations and improvements in the technology. State-of-the-art systems must also be benchmarked.

Regardless of application, system BOP component durability needs to be improved. The majority of fuel cell system failures and forced outages (~90% in automotive systems[9] and ~90% in micro CHP systems[10]) are the result of non-fuel cell stack BOP events.

B. Cost

For fuel cells and fuel cell systems to be commercially viable, significant reduction in cost is required. Materials and manufacturing costs for stack components need to be reduced. Low-cost,

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[9] Results from the Controlled Hydrogen Fleet and Infrastructure Demonstration and Validation Project, CDP #64, http://www.nrel.gov/hydrogen/docs/cdp/cdp_64.ppt

[10] P. Mocoteguy, International Workshop on Degradation Issues of Fuel Cells, Sept. 19-21, 2007 Hersonessos, Crete, Greece

high-performance membranes, high-performance catalysts enabling ultra-low precious metal loading, and lower cost, lighter, corrosion-resistant bipolar plates are required to make fuel cell stacks competitive. PEMFCs, PBI-type fuel cells, and PAFCs suffer from the necessity of relatively high PGM loading. This is particularly important for stationary power applications, where the need for enhanced durability and reformate tolerance requires the use of high PGM loadings, which in the case of PAFCs accounts for 4 to 6% of the current installed costs of the power plant.[11] Furthermore, for automotive applications, the cost of electrocatalyst is projected to be the largest single component of the cost of a PEMFC system manufactured at high volume.[12] The use of PGM-free catalysts will further reduce the cost of MEAs. For high-temperature fuel cells, such as MCFCs and SOFCs, PGM-free materials are available, but research is required to lower stack component costs, such as for cells and interconnects, as well as for system BOP components required for high-temperature operation. As an example, the strong economic incentive to use traditional, low cost metals (e.g., ferritic stainless steels) for the interconnect is a driving force for the development of lower temperature SOFCs.

Balance-of-plant components and subsystems specifically designed for use in fuel cell systems need development in order to achieve cost targets. For automotive fuel cell systems, system BOP constitutes about half the cost of the system.[11] For stationary primary power applications, the relatively high cost of the fuel processor needs to be addressed. One of the most important issues, and one that is not specific to any fuel cell type, is the development of a cost-effective process and sub-system for removing contaminants, especially those found in renewable fuels, which would considerably reduce overall cost and allow for fuel flexibility. For high temperature fuel cells, some of the BOP components (e.g., heat exchangers) need to operate at elevated temperatures. The temperature limitations on other components (e.g., anode recycle blower) can negatively impact the overall system efficiency.

C. Performance

Fuel cell and fuel cell system performance and efficiency must meet or exceed that of competing technologies to allow for market penetration and the inherent environmental benefits of the technology.

Cell Issues Affect Performance

Improved cell performance is required to ensure lower cost and enhanced durability for the range of fuel cell technologies. For instance, poor cathode kinetics cause overpotentials of 0.4 V or greater in state-of-the-art PEM fuel cells operating under typical conditions. This overpotential represents a loss at the cathode of approximately one-third of the theoretically available energy from a fuel cell. Therefore, cathode R&D is needed to meet efficiency targets simultaneously with other targets. Mitigation of catalyst dissolution/degradation during operation of low-temperature and high-temperature fuel cells drives higher performance and leads to lower cost. Power densities, especially

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[11] MCFC and PAFC R&D Workshop Summary report, U.S. Department of Energy, 2010. http://www1.eere.energy.gov/hydrogenandfuelcells/pdfs/mcfc_pafc_workshop_summary.pdf

[12] Brian James – Directed Technologies, Inc. The 2010 U.S. Department of Energy (DOE) Hydrogen and Fuel Cells Program and Vehicle Technologies Program Annual Merit Review and Peer Evaluation Meeting (AMR), Washington, DC."

at the higher voltages required for high-efficiency operation, are currently too low to meet cost and packaging targets. Higher power densities, across the technologies, could be achieved by increasing the ionic conductivity of the electrolyte and decreasing polarization losses of the electrodes. Novel electrolytes could achieve higher conductivities, but materials must meet operation requirements. Membrane performance under the extremes of automotive drive cycles for instance and the steady-state lifetime requirements for stationary applications have not been established. For low temperature fuel cells, conductivity under low humidity conditions needs to increase, and stable membrane performance at higher temperatures for both proton- and anion-conducting polymer electrolyte fuel cells needs to be achieved.

The chemical and electrical interface between the electrode and the electrolyte material can affect performance, with a poor interface resulting in higher electronic resistance and low utilization. Also, new electrolyte materials may require redesign of the electrode structure and interface to maintain performance. Interfacial contact resistance at the electrode/bipolar interface needs to be further reduced.

Stack Water Management Affects Performance

Effective management of the water produced in low-temperature fuel cells is needed to alleviate flooding and/or drying out of the membrane over the full operating temperature range. Ineffective water management leads to liquid-phase water blockage and mass-transport-limited performance or decreased proton conductivity as a result of dehumidification of the ionomer. Transportation and stationary fuel cells must be able to operate in environments where ambient temperatures fall below 0°C, a challenge for low-temperature fuel cells. R&D is needed to improve the designs of the gas diffusion layers, gas flow fields in bipolar plates, catalyst layers and membranes to enable effective water management and operation in subfreezing environments.

System Thermal and Water Management Affects Performance

Thermal and water management processes include heat and water use, cooling and humidification. Improved heat utilization, cooling, and humidification techniques are needed. The low operating temperature of PEM fuel cells results in a relatively small difference between the fuel cell stack operating temperature and ambient air temperature, which is not conducive to conventional heat rejection approaches and limits the use of heat generated by the fuel cell (approximately 50% of the energy supplied by the fuel). More efficient heat recovery systems, improved system designs, advanced heat exchangers and/or higher temperature operation of current systems are needed to utilize the low-grade heat and achieve the most efficient (electrical and thermal) systems, particularly for distributed power generation. The high quality heat generated by high temperature fuel cells leads to higher overall system efficiencies; however, the need to remove heat generated by the high temperature stacks can complicate stack/system design, as well as limit the operating power density and cell size. Improved techniques to manage water during start-up and shutdown at subfreezing temperatures are also needed.

System Air Management Affects Performance

Compressors/expanders specifically designed for low-temperature and high-temperature fuel cell applications are needed to minimize parasitic power consumption, while meeting packaging and cost requirements.

System Start-up and Shut-down Time and Energy/Transient Operation Affects Performance

Automotive fuel cell systems must start rapidly from any ambient condition with minimal fuel consumption. For stationary power applications, and especially for high-temperature fuel cells, rapid start-up and thermal cycling during operation is not anticipated, but transient times need to be minimized and stacks need to be designed to survive thermal upsets. Strategies to address start-up and shut-down time and energy such as the use of hybrid systems and/or stored hydrogen are needed. Fuel cell power plants will also be required to follow load variations, which are dependent on application.

3.4.6 Technical Task Descriptions

Table 3.4.16 describes the technical tasks that are the focus of R&D within the Fuel Cells sub-program. There is a direct correlation between these technical tasks and the current fuel cell activities listed previously in Table 3.4.2.

Table 3.4.16 Technical Task Descriptions

Task	Description	Barriers
1	**Electrolytes** Develop / identify electrolytes [polymer electrolyte membrane (80ºC ≤ T ≤ 120ºC), medium temperature electrolytes (phosphoric acid-based, solid acid) (150ºC ≤ T ≤ 500 ºC), liquid-fueled (non-H_2) fuel cell membranes, anion-exchange membranes, high temperature electrolytes/matrixes (e.g., solid oxide fuel cells, molten carbonate fuel cells] • Improve electrolyte conductivity, for both proton- and anion-conducting systems, over the entire temperature and humidity operating range. • Increase the mechanical/chemical/thermal stability of electrolytes over the entire temperature and humidity operating range • Reduce/eliminate fuel cross-over Fabricate Membranes from Ionomers • Design scalable membrane fabrication processes • Increase the mechanical/chemical/thermal stability of the membrane over the entire temperature and humidity operating range (e.g., up to 95 - 120°C for transportation systems, and >120°C for CHP systems) • Reduce the cost of membranes Perform Membrane/Electrolyte Testing and Characterization to Improve Durability • Evaluate the tolerance of the electrolyte material to air, fuel and system-derived impurities • Evaluate the mechanical stability of the membrane with relative humidity (RH) cycling • Identify chemical and mechanical degradation mechanisms • Develop strategies for mitigating degradation in performance and durability	A, B, C

Table 3.4.16 Technical Task Descriptions

Task	Description	Barriers
2	**Catalysts / Electrodes** Develop Improved Catalysts • Reduce/eliminate precious metal loading of catalysts for medium and high temperature fuel cells (T ≥ 150°C) • Reduce/eliminate precious metal loading of catalysts for low temperature fuel cells (60°C ≤ T ≤ 120°C) • Increase the specific and mass activities of catalysts • Increase the durability/stability of catalysts with potential cycling • Increase the tolerance of catalysts to air, fuel, and system-derived impurities • Test and characterize catalysts • Develop non-PGM catalysts for polymer electrolyte membrane fuel cells (oxygen reduction reaction) • Develop non-PGM catalysts for anion-exchange membrane fuel cells (hydrogen oxidation reaction and oxygen reduction reaction) • Increase catalyst utilization • Develop electrodes for high temperature fuel cells with enhanced activity and durability Develop Improved Catalyst Supports • Reduce corrosion of catalyst supports • Develop lower cost catalyst support materials and structures • Develop viable supports that allow increased loading and/or thickness of non-PGM catalyst layer Optimize Electrode Design and Assembly • Optimize catalyst/support interactions and microstructure • Develop anodes for fuel cells operating on non-hydrogen fuels	A, B, C

Table 3.4.16 Technical Task Descriptions

Task	Description	Barriers
3	**Membrane Electrode Assemblies, Gas Diffusion Media, and Cells** Integrate Membrane/Electrolytes and Electrodes • Optimize mechanical and chemical interactions of the catalyst, support, ionomer, and membrane • Minimize interfacial resistance • Integrate catalysts with membranes and GDLs into MEAs • Integrate catalysts with supports and electrolytes into robust high-temperature fuel cells Expand MEA/Cell Operating Range • Address freeze/thaw issues • Expand temperature and humidity range • Improve MEA/cell stability under voltage and humidity cycling • Develop techniques to mitigate effects of air, fuel, and system-derived impurities Test, Analyze, and Characterize MEAs • Characterize MEAs/cells before, during, and after fabrication and operation • Test cells, MEAs and short stacks Improve GDL/MPL Performance and Durability • Optimize GDL pore structure, morphology, and physical properties • Optimize GDL coatings to improve water management and stable operation • Develop materials and structures with reduced area-specific resistance • Understand corrosion and aging effects on GDL/MPL	A, B, C
4	**Seals, Bipolar Plates, and Interconnects** Optimize Balance-of-Stack Components • Develop high temperature stack interconnects • Develop high temperature stack seals • Develop electrolyte reservoir plates for PAFCs Improve Performance of Bipolar Plates • Decrease weight and volume • Develop coatings to eliminate plate corrosion Decrease Cost of Bipolar Plates • Evaluate the use of different materials and coatings Improve Durability of Bipolar Plates • Identify degradation mechanisms • Develop strategies/technologies for mitigating degradation	A, B, C

Table 3.4.16 Technical Task Descriptions		
Task	**Description**	**Barriers**
5	**Stack and Component Operation and Performance** Improve Technical Understanding/Characterization • Develop, validate, and use models to address impurity effects • Develop, validate, and use models to address durability/degradation • Develop, validate, and use models of freeze/thaw effects on fuel cell operation • Develop and validate component performance models using most recent data • Identify long term stack failure mechanisms through experimentation • Develop models describing mass transport with experimental validation • Optimize MEA and stack water management, including freeze/thaw issues	A, B, C
6	**Systems Operation and Performance** Improve Technical Understanding/Characterization • Develop, validate, and use models to address impurity effects • Develop, validate, and use models to address durability/degradation • Mitigate system issues • Develop methods to minimize electrolyte losses from PAFC matrix • Develop methods to minimize CO_2 migration in alkaline fuel cells • Develop methods to ensure robust and fast start up times for high-temperature fuel cells (SOFC, MCFC)	A, C
7	**System BOP Components** Develop Chemical and Temperature Sensors for Stationary Applications (500-1100°C) • Decrease costs • Improve durability and reliability of fuel cell sensors Develop Air Management Technologies (Blowers) for Stationary Applications (500-1100°C) • Meet performance, packaging, and cost requirements • Minimize parasitic power • Reduce noise level Develop Air Management Technologies (Blowers, Compressors/Expanders) for Transportation Applications • Meet performance, packaging, and cost requirements • Minimize parasitic power Develop Humidifiers for Transportation applications • Increase efficiency, durability, and reliability • Develop humidification materials and concepts • Minimize parasitic power • Develop lightweight, low cost materials to enable compact humidifiers Develop Thermal Management Technologies for Fuel Cell Systems • Develop coolants that are non-toxic and have low electrical conductivity	A, B, C

Table 3.4.16 Technical Task Descriptions

Task	Description	Barriers
8	**Fuel Processors** Develop Fuel-Flexible Fuel Processors • Develop catalysts and hardware capable of generating hydrogen-rich gas stream • Meet cost requirements Improve Durability and Tolerance to Impurities • Develop low-cost gas clean-up subsystems Integrate Fuel Processor Subsystems • Eliminate reactor hardware, piping, and possibly sensors and controls • Integrate thermal loads of the subsystems	A, B, C
9	**Fuel Cell Systems** Develop Stationary Fuel Cell Systems for Distributed Generation (DG) including CHP • Improve system durability • Improve stack performance with reformate • Increase system electrical and thermal efficiency • Reduce cost Develop Auxiliary Power Units • Develop fuel cell system that operates on reformate • Design, build and test APUs under real-world conditions • Reduce cost Develop Portable Power Technologies • Develop membranes with minimal methanol crossover • Design, build, and test portable power systems under real-world conditions • Reduce cost	A, B, C

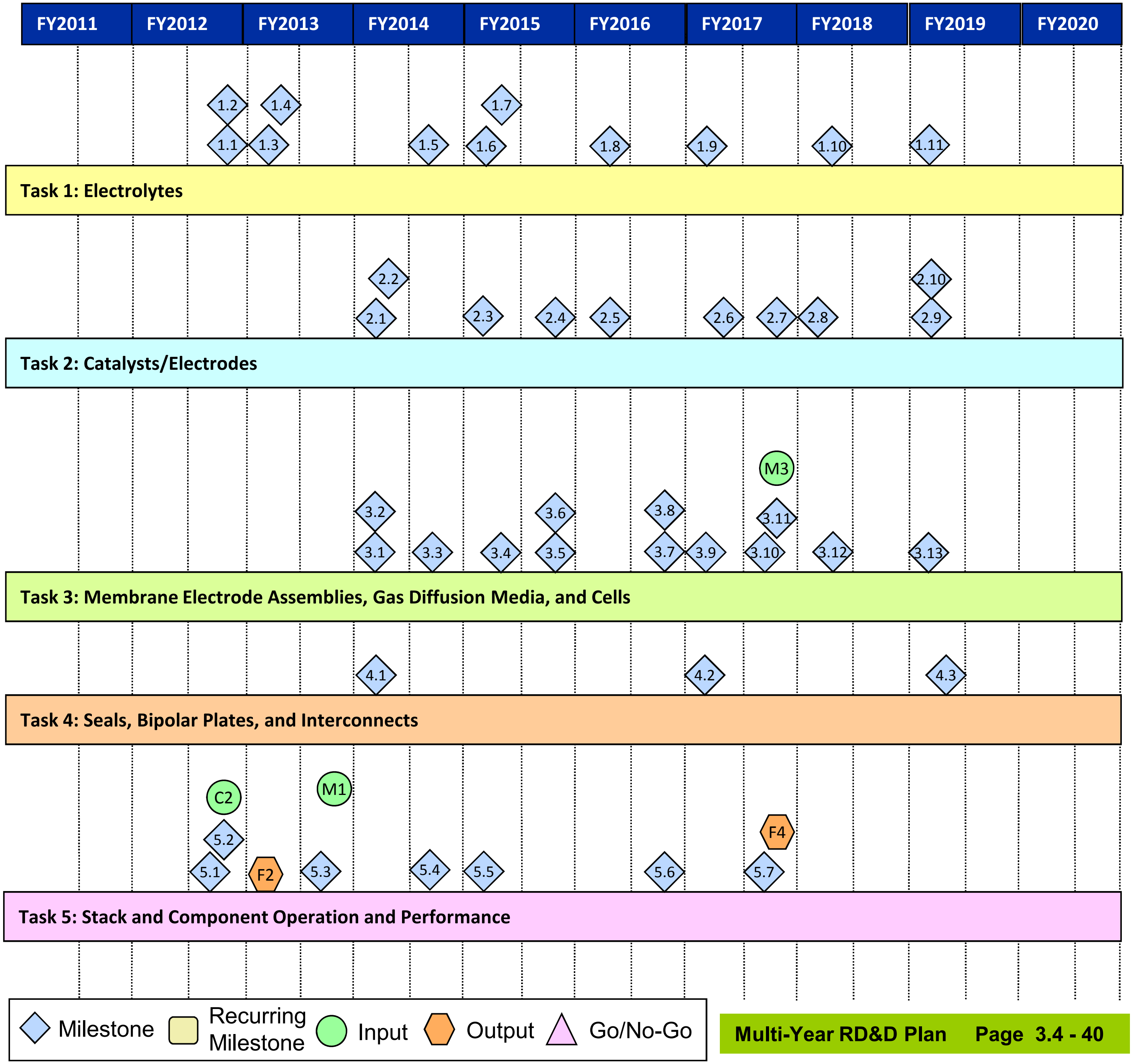
Table 3.4.16 Technical Task Descriptions

Task	Description	Barriers
10	**Testing and Technical Assessments** Perform Cost Analysis of Stationary, Portable, and Transportation Applications • Perform cost analyses for automotive and bus applications • Perform cost analyses for stationary power and emerging market applications including APUs, back-up power and material handling (forklifts) Annually Update Technology Status Conduct Tradeoff Analysis • Rated power design points vs. performance and efficiency • Start-up energy and start-up time • Hydrogen quality level vs. durability and performance Develop Protocols for Testing • Develop accelerated testing to project durability for stationary fuel cell applications Experimentally Determine Long-Term Stack Failure Mechanisms Experimentally Determine System Emissions Perform Independent Testing to Characterize Component and Stack Properties Before, During, and After Operation	A, B, C

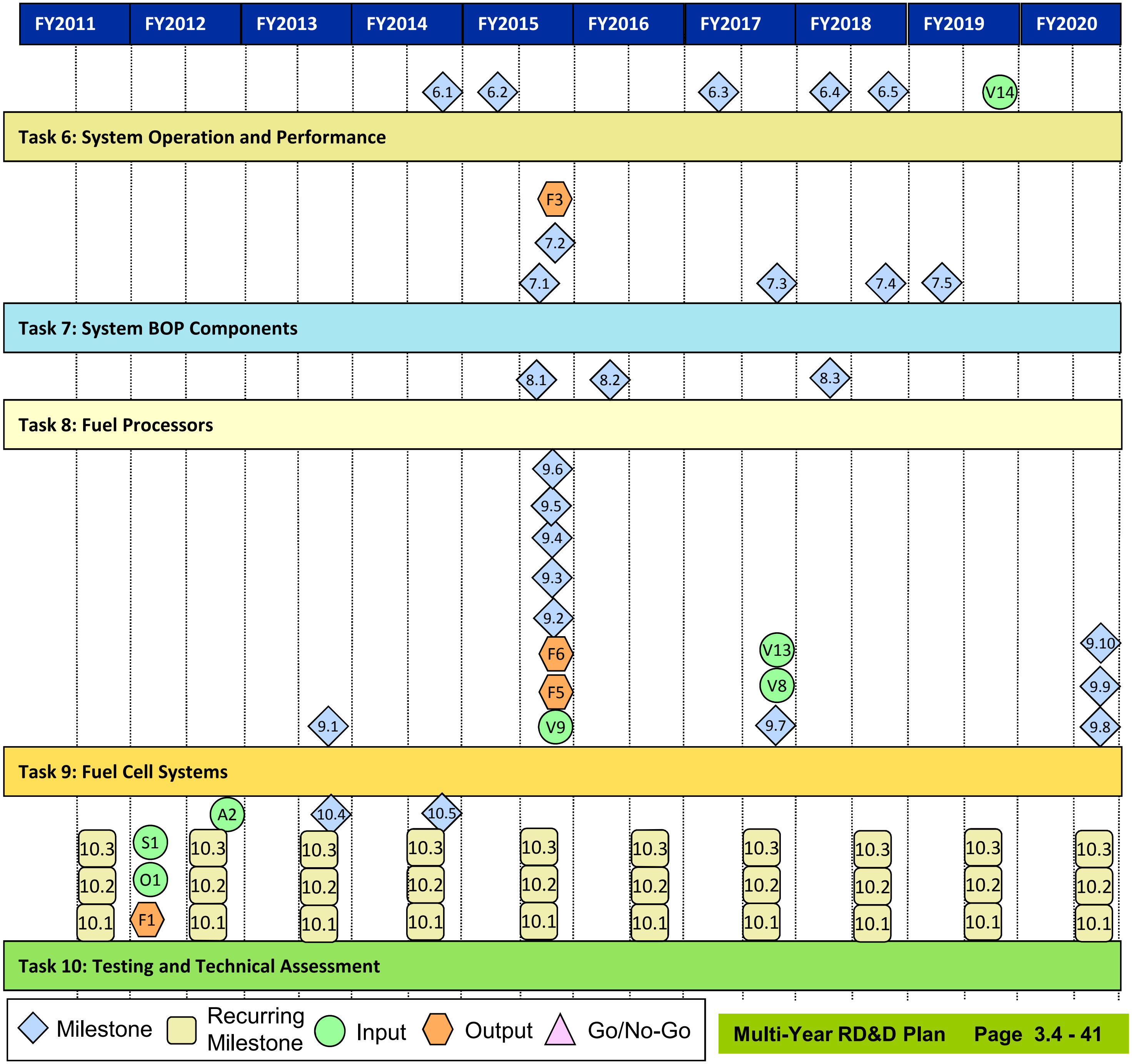
3.4.7 Milestones

The following chart shows the interrelationship of milestones, tasks, supporting inputs and technology program outputs for the Fuel Cell sub-program from FY 2011 through FY 2020. This information is also summarized in Appendix B: Input/Output Matrix.

Fuel Cells Sub-program Milestone Chart



Fuel Cells Sub-program Milestone Chart



Task 1: Electrolytes	
1.1	Demonstrate multiple freeze/thaw cycles. (4Q, 2012)
1.2	Evaluate membrane tolerance to impurities (fuel, air, and system derived) and compare to membrane target. (4Q, 2012)
1.3	Develop membranes that have methanol permeability of less than $5x10^{-8}$ cm^2/sec. (1Q, 2013)
1.4	Demonstrate an anion-exchange membrane that retains 99% of original ion exchange capacity for 1000 hours in hydroxide form at T > 80^oC. (2Q 2013)
1.5	Develop PEM membrane for transportation that meets area specific resistance ≤ 0.02 Ω-cm^2 at 120°C and 40 kPa water partial pressure. (3Q, 2014)
1.6	Develop membranes that have methanol permeability of less than $1x10^{-8}cm^2$/sec. (1Q, 2015)
1.7	Evaluate membrane technologies for >5,000 hour durability operating at >80°C. (2Q, 2015)
1.8	Develop an alternative electrolyte for PAFCs that does not poison anodes, has vapor pressure lower than that of phosphoric acid, and has ionic conductivity >0.65 S/cm. (2Q, 2016)
1.9	Develop a PEM membrane for transportation with area specific resistance ≤ 0.02 Ω-cm^2 at 120°C and 40 kPa water partial pressure, and durable for 20,000 voltage cycles and 500 hours chemical durability testing. (1Q, 2017)
1.10	Develop a membrane for operation at T > 150°C with a projected durability of 60,000 hours. (2Q, 2018)
1.11	Demonstrate electrolytes for high-temperature fuel cells with a projected durability of 80,000 hours. (1Q, 2019)

Task 2: Catalysts/Electrodes	
2.1	Characterize catalysts that have undergone durability testing using the DOE durability protocol. (1Q, 2014)
2.2	Demonstrate catalyst support initial mass loss of less than 10%. (2Q, 2014)
2.3	Develop catalysts with 0.14 g_{PGM}/kW at rated power. (1Q, 2015)
2.4	Develop anode for DMFC applications with an activity of 150 mA/cm^2 at 0.6V, at a loading of <2.7 mg Pt/cm^2 (4Q, 2015)
2.5	Demonstrate electrodes in high-temperature fuel cells that meet 60,000 hour durability. (2Q, 2016)
2.6	Develop a PGM-free catalyst with an activity of 300 A/cm^3 at 800 mV. (2Q, 2017)
2.7	Develop catalysts with 0.125 g_{PGM}/kW at rated power. (4Q, 2017)
2.8	Develop PAFCs with advanced catalysts and catalyst layer deposition methods to enable 50% reduction in PGM loading compared to the baseline of 0.7 mg/cm^2 (anode + cathode). (1Q, 2018)
2.9	Demonstrate electrodes in high-temperature fuel cells that meet 80,000 hour durability. (1Q, 2019)
2.10	Demonstrate durability of 30,000 cycles for PGM-free catalyst with less than 40% loss of initial activity. (1Q, 2019)

Task 3: Membrane Electrode Assemblies, Gas Diffusion Media, and Fuel Cells	
3.1	Develop MEA that will tolerate start-stop transient operation and fuel starvation excursions. (1Q, 2014)
3.2	Develop improved gas diffusion materials to enable time stable operation at high power density >40,000 hours for stationary applications. (1Q, 2014)
3.3	Evaluate methods to mitigate effects of fuel, air and system-derived impurities. (3Q, 2014)
3.4	Develop a membrane electrode assembly that can operate above 150 °C with a projected durability of 40,000 hours. (2Q, 2015)
3.5	Evaluate short stack with improved MEAs against 2017 membrane and MEA targets. (4Q, 2015)
3.6	Evaluate progress toward extending durability to >5000 hours with automotive cycling. (4Q, 2015)
3.7	Demonstrate PAFC with reduced anion poisoning resulting in a 25% increase in a real power density compared to baseline value of 160 mW/cm^2. (4Q, 2016)
3.8	Demonstrate anion-exchange membrane technologies in MEA/single cells with non-PGM catalysts that maintain performance higher than 350 mW/cm^2 for 2000 hours at T > 80°C. (4Q, 2016)
3.9	Demonstrate MEA performance of 1000 mW/cm^2 at rated power at a high-volume projected cost of $9/kW. (1Q, 2017)
3.10	Demonstrate MEA performance of 250 mW/cm^2 at 0.8 V while meeting catalyst loading targets. (3Q, 2017)
3.11	Demonstrate short stack with improved MEAs meeting 2017 membrane and MEA targets. (4Q, 2017)
3.12	Report on status of MEA/cell durability to meet stationary fuel cell target of >60,000 hours. (2Q, 2018)
3.13	Develop a membrane electrode assembly/cell assembly that can operate above 150 °C with a projected durability of 60,000 hours. (1Q, 2019)

Task 4: Seals, Bipolar Plates, and Interconnects	
4.1	Develop PEM bipolar plates with a cost less than or equal to $5/kW while meeting other technical targets. (1Q, 2014)
4.2	Develop PEM bipolar plates with a cost less than or equal to $3/kW while meeting other technical targets. (1Q, 2017)
4.3	Develop interconnect that is durable for 20,000 hours with less than 20% degradation SOFC APU stack performance. (2Q, 2019)

Task 5: Stack and Component Operation and Performance	
5.1	Demonstrate a fuel cell stack for micro-CHP applications with > 40% electrical efficiency and >80% total efficiency. (3Q, 2012)
5.2	Determine durability and performance degradation of cells with novel flow-field architecture and low Pt loading (0.1 mg_{Pt}/cm^2) operated at high current densities (>2.5 A/cm^2) relative to 15 μV/h/cell at 1 A/cm^2. (4Q, 2012)
5.3	Develop model describing mass transport in PEMFCs and experimentally validate within 10%. (3Q, 2013)
5.4	Demonstrate successful mitigation of the impact of major airborne contaminants on stack operation. (3Q, 2014)
5.5	Determine effect of system impurities on stack performance. (1Q, 2015)
5.6	Demonstrate high-temperature (>500 °C) stack durability of greater than 60,000 hours. (4Q, 2016)
5.7	Demonstrate 120°C MEA in a PEMFC stack – meeting membrane and MEA target. (3Q, 2017)

Task 6: System Operation and Performance	
6.1	Determine effect of system impurities on BOP component performance. (4Q, 2014)
6.2	Evaluate durability of truck APU, determine degradation issues, and assess against durability target of 15,000 hours. (2Q, 2015)
6.3	Evaluate status of automotive fuel cell system durability and assess against target of 5,000 hours. (2Q, 2017).
6.4	Evaluate status of bus fuel cell system durability and assess against target of 18,000 hours. (2Q, 2018)
6.5	Report on status of fuel cell system durability to meet stationary fuel cell target of >60,000 hours. (4Q, 2018)

Task 7: System BOP Components	
7.1	Increase air compression system motor and controller efficiency to 80% at 25% of rated air flow. (3Q, 2015)
7.2	Experimentally validate coolant with 5000 hours durability. (4Q, 2015)
7.3	Develop a humidifier module with projected durability of 5,000 hours during RH cycling, and water transfer rate at 80ºC of 5 grams per second. (4Q, 2017)
7.4	Develop low-cost, high-temperature chemical sensors for high-temperature fuel cell systems (500-1100ºC) with a durability of >60,000 hours. (4Q, 2018)
7.5	Demonstrate anode recirculation blower with durability of 80,000 hours. (2Q, 2019)

Task 8: Fuel Processors	
8.1	Demonstrate sulfur removal to provide fuel cell grade reformate. (3Q, 2015)
8.2	Demonstrate siloxane removal from landfill gas to provide fuel cell grade reformate. (2Q, 2016)
8.3	Demonstrate stationary fuel cell stack operating on LPG, natural gas, landfill gas, and anaerobic digester gas. (2Q, 2018)

Task 9: Fuel Cell Systems	
9.1	Develop truck APU with projected durability of 10,000 hours, at a cost of $1400/kW, operating on standard ultra-low sulfur diesel. (4Q, 2013)
9.2	Develop truck APU with projected durability of 15,000 hours, at a cost of $1200/kW, operating on standard ultra-low sulfur diesel. (4Q, 2015)
9.3	Develop a portable fuel cell system (100-250 W) with a durability of 5,000 hours and an energy density of 900 Wh/L at a cost of $5/W. (4Q, 2015)
9.4	Develop a portable fuel cell system (10-50 W) with a durability of 5,000 hours at a cost of $7/W. (4Q, 2015)
9.5	Demonstrate micro-CHP at 42.5% electrical efficiency, 87.5% CHP efficiency and projected durability of 40,000 hours. (4Q, 2015)
9.6	Demonstrate medium-scale CHP at 45% electrical efficiency, 87.5% CHP efficiency, and projected durability of 50,000 hours. (4Q, 2015)
9.7	Develop a 60% peak-efficient, 5,000 hour durable, direct hydrogen fuel cell power system for transportation at a cost of $30/kW (at high volumes). (4Q, 2017)
9.8	Demonstrate micro-CHP at 45% electrical efficiency, 90% CHP efficiency and projected durability of 60,000 hours. (4Q, 2020)
9.9	Demonstrate medium-scale CHP at 50% electrical efficiency, 90% CHP efficiency, projected durability of 80,000 hours, at a cost of $2,100/kW operating on biogas. (4Q, 2020)
9.10	Develop a fuel cell system for APUs with specific power of 45 W/kg and power density of 40 W/L. (4Q, 2020)

Task 10: Testing and Technical Assessments	
10.1	Test and evaluate fuel cell systems and components such as MEAs, short stacks, bipolar plates, catalysts, membranes, etc. and compare to targets. (3Q, 2011 thru 3Q, 2020)
10.2	Update fuel cell technology cost estimate for 80 kW transportation systems and compare it to targeted values. (3Q, 2011 thru 3Q, 2020)
10.3	Update fuel cell technology cost estimates for material handling, backup power units, primary power, and combined heat and power systems, and compare to target values. (3Q, 2011 thru 3Q, 2020)
10.4	Provide higher frame capabilities from neutron imaging, up to 100 frames per second in response to user needs. (4Q, 2013)
10.5	Develop a 10-fold accelerated test for high-temperature fuel cell durability testing. (4Q, 2014)

Outputs

F1 Output to Storage and Systems Integration: Cost of the baseline automotive fuel cell system. (1Q, 2012)

F2 Output to Storage: Effect of impurities from storage materials on fuel cells. (1Q, 2013)

F3 Output to Manufacturing: Coolant system project results. (4Q, 2015)

F4 Output to Technology Validation and Systems Integration: Provide automotive stack test data from documented sources indicating performance status. (4Q, 2017)

F5 Output to Technology Validation and Systems Integration: Provide micro-combined heat and power system test data from documented sources indicating performance status. (4Q, 2015)

F6 Output to Technology Validation and Systems Integration: Provide auxiliary power unit system test data from documented sources indicating performance status. (4Q, 2015)

Inputs

A2 Input from Systems Analysis: Cost of competing vehicle powertrain. (4Q, 2012)

C2 Input from Safety, Codes, and Standards: Hydrogen fuel quality standard (SAE J2719). (3Q, 2012)

M1 Input from Manufacturing: Report on process for assembling stacks. (4Q, 2013)

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

O1 Input from Vehicle Technologies Program: U.S. Drive baseline vehicle system architecture (e.g., hybridization) and fuel economy. (1Q, 2012)

S1 Input from Storage: Cost of automotive onboard hydrogen storage system. (1Q, 2012)

V8 Input from Technology Validation: Complete validation of commercial fuel cell combined heat and power systems that demonstrate 45% efficiency and 50,000 hour durability. (4Q, 2017)

V9 Input from Technology Validation: Report on the validation of residential fuel cell micro combined heat and power systems that demonstrate 40% efficiency and 25,000 hour durability. (4Q, 2015)

V13 Input from Technology Validation: Report on the status of validation of 15,000 hour truck auxiliary power unit durability target. (4Q, 2017)

V14 Input from Technology Validation: Report on the status of validation of 5,000 hour durability target. (4Q, 2019)