V. FUEL CELLS

V.0 Fuel Cells Sub-Program Overview

Introduction

The Fuel Cells Sub-Program supports research, development, and demonstration of fuel cell systems, including fuel cell stack components, fuel processors for stationary applications, and balance-of-plant (BOP) components. The portfolio of projects covers a broad range of technologies including polymer electrolyte membrane fuel cells (PEMFCs), direct methanol fuel cells and solid oxide fuel cells (SOFCs). The sub-program has shifted its main focus from long-term transportation to near-term applications of fuel cells, including distributed power (primary and backup), portable power, auxiliary power units (APUs), materials handling equipment, and specialty vehicles. Fuel cell technology already provides sufficient performance and durability to be competitive with alternative technologies in some of these applications, while in others modest improvements are required. Commercialization of fuel cells and deployment in these early-market applications is expected to lead to further improvement in performance, durability, and cost, while inducing growth in the domestic fuel cell manufacturing and supplier base. In the long term, continuing technological progress will allow fuel cells to expand into applications and markets that have more stringent technical and cost requirements. The growth of current markets and expansion into broader markets, including the light-duty vehicle market, will allow fuel cell technologies to have significant economic, energy security, and environmental benefits on a national scale.

As part of the American Recovery and Reinvestment Act, 13 new projects were initiated in Fiscal Year 2009 to accelerate the commercialization and deployment of fuel cells. The new funding will support immediate deployment of fuel cell systems in emergency backup power, portable, material handling, and combined heat and power (CHP) applications. The DOE funding for these projects is approximately $42M. An additional 28 new projects were initiated following a 2008 solicitation/lab call. These projects include research and development (R&D) for catalysts with reduced Pt-group metal (PGM) content, as well as PGM-free catalysts. New projects also include fuel cell degradation and durability studies, fuel cell transport studies, portable power R&D, and development of innovative fuel cell concepts. The DOE funding for these projects is approximately $113M.

Goal

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

Objectives

- By 2011, develop a distributed generation PEMFC system operating on natural gas or liquefied petroleum gas that achieves 40% electrical efficiency and 40,000 hours durability at $750/kW.[1]
- By 2010, develop a fuel cell system for consumer electronics (<50 W) with an energy density of 1,000 Wh/L.
- By 2010, develop a fuel cell system for APUs with a specific power of 100 W/kg and a power density of 100 W/L.
- By 2010, develop a 60% peak-efficient, durable, direct hydrogen fuel cell power system for transportation at a cost of $45/kW; by 2015, a cost of $30/kW.

FY 2009 Technology Status

The focus of the sub-program is on materials, components, and enabling technologies that will contribute to the development of low-cost, reliable fuel cell systems. Cost and durability are the major challenges for fuel cell systems. Air, thermal, and water management for fuel cells are also key issues. Power density and specific power are approaching targets, but further increases are needed to meet

[1] Milestone delayed from 2010 to 2011 due to appropriations shortfall and Congressionally directed activities.

packaging requirements of commercial systems. Efforts continue to evaluate, understand, and mitigate degradation mechanisms by the national laboratories, universities, and fuel cell developers. These efforts are being enhanced by the use of advanced imaging techniques for in situ and post-mortem analysis of fuel cell stacks and membrane electrode assemblies.

The tasks in the Multi-Year Research, Development and Demonstration Plan, to be updated in 2009, are organized around components (membranes, electrodes, membrane electrode assemblies (MEAs), gas diffusion layers, bipolar plates, seals, and BOP components), supporting analysis, and benchmarking and characterization activities. Task areas are also included for early market fuel cell applications including stationary, portable power, and APUs, and for development of innovative concepts for fuel cell systems.

Targets, which vary by application, have been established for metrics such as fuel cell cost, efficiency, durability, power density, specific power, transient response time, and start-up time. Key performance indicators include cost for transportation fuel cells R&D and electrical efficiency for stationary fuel cells R&D. As shown in Figure 1, the cost of a hydrogen-fueled 80-kW_e fuel cell power system projected for high volume production (500,000 units/year) has been estimated to be $73/kW (assuming 2008 technology), a *23% reduction* from the 2007 cost of $94/kW. The assessment was validated by an independent review panel in FY 2009.[2] Cost reduction was a result of stack component costs being reduced through ongoing R&D efforts. As stack costs are reduced, BOP components are responsible for a larger percentage of costs.

For stationary systems, on-going projects show good progress toward higher electrical efficiency, lower cost and improved durability. At the same time, targets for both stationary and portable applications are being reassessed in accordance with realistic commercialization requirements and with feedback from stakeholders and experts in the field. In this respect, a Request for Information was issued seeking input from stakeholders and the research community on proposed performance, durability, and cost targets for fuel cells for residential CHP applications and APUs. The targets are driven by consumer expectations for CHP and APU applications, rather than by the operating parameters or constraints of specific technologies.

[2] The report of the independent review panel is available at http://www.nrel.gov/docs/fy09osti/45457.pdf.

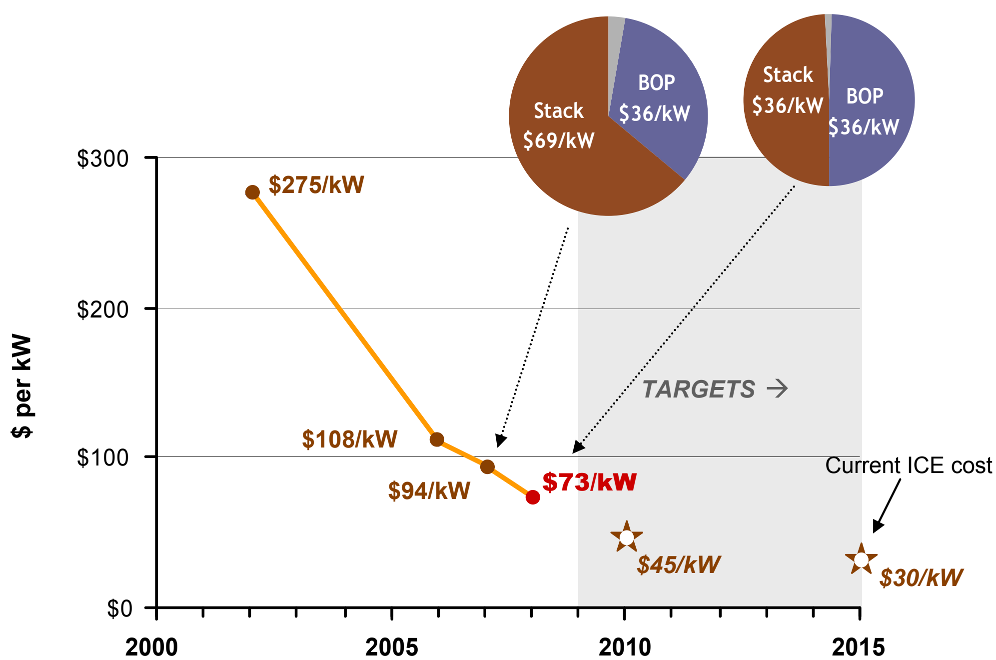

FIGURE 1. Current Modeled Cost of an 80-kW System Based on Projection to High-Volume Manufacturing (500,000 units/year)

FY 2009 Accomplishments

Continued progress toward meeting 2010 and 2015 technical and cost targets occurred during FY 2009. Notable technological advances in several component areas have led to significant improvements in performance and durability, with decreased cost.

Innovative Catalyst and MEA R&D Enables Lower Fuel Cell Cost

Decreases in fuel cell system cost are, to a large extent, limited by the high catalyst cost associated with the use of Pt and other PGMs. Reducing the loading of Pt and other PGMs, without compromising performance, is therefore a key path to decreasing system cost. Notable progress in developing catalysts with high activity at low loading was made during 2009 at Brookhaven National Laboratory (BNL), where novel core-shell electrocatalyst structures are being investigated for application in fuel cell cathodes. Innovative new PGM-based nanostructured catalysts developed at BNL in FY 2009, consisting of a Pt shell, a core containing PGMs other than Pt, and a Pd interlayer in between the core and the shell, have high activity for the oxygen reduction reaction (ORR). The ORR performance of these new catalytic materials at 0.9 V is as high as 1.2 A/mg_{Pt} and 0.34 A/mg_{PGM}, comparing favorably with the baseline Pt/C catalyst activity of 0.13 A/mg_{Pt}. These new catalysts also show better durability than previously reported core-shell materials and state-of-the-art Pt/C catalysts. For example, a Pt_{ML} /Pd_{ML}/Pd_3Ir/C catalyst has been shown to lose approximately 20 mV in ORR performance after 30,000 potential cycles, compared to approximately 40 mV lost by a standard Pt/C catalyst under the same conditions. Even lower performance losses have been demonstrated with other core-shell catalysts, including a Pt_{ML}/Pd_3Fe/C catalyst, with an ORR performance loss of less than 5 mV after 28,000 potential cycles. While most core-shell catalysts to date have been synthesized in small, laboratory-scale batches, *Cabot Fuel Cells* demonstrated industrial scale-up of Pt-Pd/C core-shell catalysts to gram-scale quantities in 2009, maintaining the catalyst's superior performance relative to Pt. These and other advancements in PGM-based catalysts represent significant progress in 2009 toward improvement of fuel cell performance and reduction in fuel cell cost through minimization of PGM loading.

Efforts to further reduce or even eliminate PGMs from cathode catalysts also showed progress in 2009. Los Alamos National Laboratory (LANL) developed two independent paths toward high-performance PGM-free fuel cell cathodes, based on Fe_3Co/polyaniline/C and Fe/cyanamide/C catalysts with volumetric activities of 27 and 54 A/cm^3 at 0.80 V, respectively. These activities represent a five-fold and an eleven-fold improvement over the most active non-noble catalyst investigated as of the previous year. With plans for further optimization of the catalyst compositions, as well as major modification of the as yet unoptimized electrode structures, the program is on track to meet the 2010 non-PGM catalyst activity target of 130 A/cm^3.

3M has played a significant role in the major reduction in fuel cell system cost achieved over the past few years. Ongoing R&D at 3M in 2009 led to further decreases in PGM loading, and reduction in cost, with improvement in performance and durability. In 2009, 3M demonstrated a new baseline MEA with PGM loading of 0.15 mg/cm^2, a *40% decrease in loading since 2008*. On a power-specific basis, the new baseline loading is 0.18 g/kW, a *33% decrease in loading since 2008*. In single-cell testing, the new baseline MEA loading is already below the 2015 target levels of 0.2 mg/cm^2 and 0.2 g/kW. The continued success of 3M in achieving better performance with lower PGM loading has allowed precious metal content to be decreased to within an order of magnitude of that used in automotive internal combustion engine systems. The successful use of such low PGM loadings indicates that large-scale implementation of durable, high-performance automotive fuel cell systems will not require an increase in PGM production to levels far beyond the scale of current mining and extraction operations. Progress by 3M and others in reducing PGM loading over the last five years is illustrated in Figure 2. The recent success of 3M in achieving very good performance at low catalyst loading is augmented by demonstration of the excellent durability of 3M MEAs. In addition to achieving 7,300 hours of operation under voltage cycling, as reported in 2008 and duplicated in 2009, the 3M MEA *exceeded* DOE's set lifetime targets for minimal surface area and performance loss under open circuit voltage hold tests by *more than 300%*.

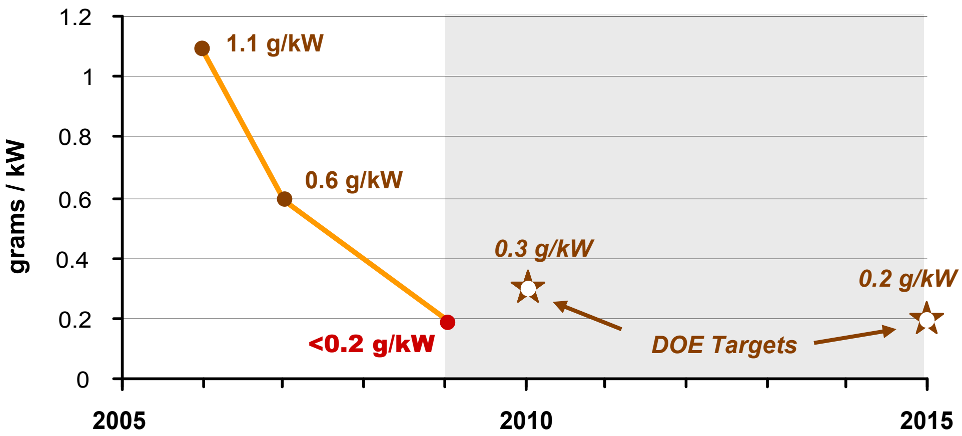

FIGURE 2. State-of-the-art total PGM loading in a fuel cell stack as determined by USCAR Fuel Cell Tech Team. DOE targets are also shown for comparison. 2009 data is a projection based on single-cell testing.

Innovative Membrane Materials Achieve High Conductivity under Hot, Dry Conditions

Current fuel cells containing state-of-the-art perfluorosulfonic acid (PFSA)-based membranes require humidification of inlet streams. The necessary humidification system represents a major component of fuel cell system cost. Work is underway to develop high-temperature membranes capable of operating at low relative humidity (RH), which would decrease or eliminate the cost, bulk, and system complexity associated with humidification. Major progress in development of such membranes occurred during FY 2009. *Giner Electrochemical Systems* demonstrated a dimensionally-stabilized low equivalent weight PFSA membrane with conductivity at least 2.5 times that of Nafion® under hot, relatively dry conditions, exceeding the DOE 2009 conductivity milestone of 0.1 S/cm at 120°C and 50% RH. Low-RH conductivity greatly exceeding that of Nafion® was also demonstrated at *Case Western Reserve University*, where a rigid-rod PEM was developed with conductivity *100 times that of Nafion®* at 15% RH. Nanofiber composite network PEMs developed at *Vanderbilt* demonstrate another path toward meeting set DOE membrane performance targets, with an inorganic-doped low equivalent weight PFSA nanofiber network providing conductivity meeting the DOE 2009 conductivity milestone, while an inert polymer matrix provides excellent mechanical properties.

Impurities Projects Assist in the Development of Fuel Purity Standards

As fuel cells approach a level of development that can support commercialization, real-world issues such as the development of fuel purity standards have received increased attention. Research at LANL on the effect of impurities on fuel cell performance and durability contributes to this effort. In FY 2009, LANL examined the effects on fuel cell performance and durability of potential hydrogen contaminants including H_2S, hydrocarbons, and NH_3. At levels likely to be present in H_2 fuel, common C_1-C_3 hydrocarbons (ppm levels) were found to have minimal impact on fuel cell performance. In contrast, ppm levels of NH_3 in the fuel inlet stream were found to result in significant performance degradation through cationic poisoning of the membrane and/or electrode ionomer. Studies of the NH_4^+ removal mechanism revealed negligible electrochemical oxidation, with removal of dissolved NH_4^+ in the water effluent from the fuel cell representing the largest contribution to the slow performance recovery following exposure to NH_3. Similarly, sub-ppm levels of H_2S in H_2 fuel also caused significant performance loss, with degradation occurring due to catalyst poisoning in both the anode and the cathode. The ability of a contaminant in the anode inlet to cause degradation of the cathode demonstrates the important role of contaminant crossover in performance degradation. In addition to examining potential fuel impurities, potential air impurities, including SO_2 and NO_2, were examined, revealing significant performance degradation due to catalyst poisoning. Potential contaminants arising from corrosion of fuel cell stack components, including metal ions, were found to cause major performance degradation due to membrane/ionomer poisoning, validating cation impurity models developed as a part of the project. These efforts in impurities testing will assist in identifying permissible levels of contaminants in H_2 fuel, as well as identifying operating conditions and component designs to optimize fuel cell performance and mitigate the effects of impurities from H_2 fuel and other sources.

Pt Recycling: Increased Yield at Lower Process Cost

Since the Pt cost is a large fraction of total system cost, Pt recovery during fuel cell disposal is a critical aspect of cost reduction. With the value of Pt in used MEAs on the order of $300 per kg of MEA material, based on an estimated Pt cost of $1,000 per troy ounce, effective Pt recovery is imperative. R&D at BASF on efficient, low-cost Pt recycling has yielded a method of Pt recovery involving either granulating or cryo-milling, followed by a single-step oxidative leaching procedure. The simplified leaching process can be performed in a single vessel. Both preparation techniques enable *cost effective recovery of 98% of Pt* from used MEAs without hydrogen fluoride release. Operated commercially, the processes require little manual labor and generate minimal waste (solid residue of the leached MEAs).

Successful International Collaboration Demonstrates Development of Commercial CHP Fuel Cell System

Plug Power's NextGenCell project, which involved a significant collaboration and cost-sharing between the U.S. and the European Union, was completed in 2009. The project resulted in the development of a high temperature, stationary, reformate-based PEM CHP fuel cell system based on commercial requirements. The project enabled MEA, stack, reforming and power electronics technologies to be explored, down-selected and developed, with progress made toward achieving DOE technical targets. By the end of the project, design verification testing against commercial requirements was completed.

Demonstrated Fuel Cell Technology for APU Applications

In 2009 a Delphi APU employing an SOFC successfully powered the electrical system and air conditioning of a Peterbilt Model 386 truck under conditions simulating a 10-hour night. The device provides an alternative to running a truck's main diesel engine to power auxiliary electrical loads during rest periods, thereby lowering emissions of CO_2 and criteria pollutants, reducing noise, and saving fuel.

Budget

The President's 2010 budget request (subject to Congressional appropriation) calls for approximately $63M for the Fuel Cells sub-program, and emphasizes R&D on materials, stack components, BOP subsystems, and integrated fuel cell systems for stationary, portable, and transportation applications. Examples of applications include distributed CHP fuel cells, APUs to reduce fuel consumption and emissions in heavy-duty vehicles, small fuel cells for portable power, and fuel cells as backup power for critical infrastructure. A technology-neutral approach is pursued, and multiple primary fuel sources are considered, including bio-derived renewable fuels such as methanol, fuels derived from other renewable resources, and fossil fuels such as diesel and natural gas. Figure 3

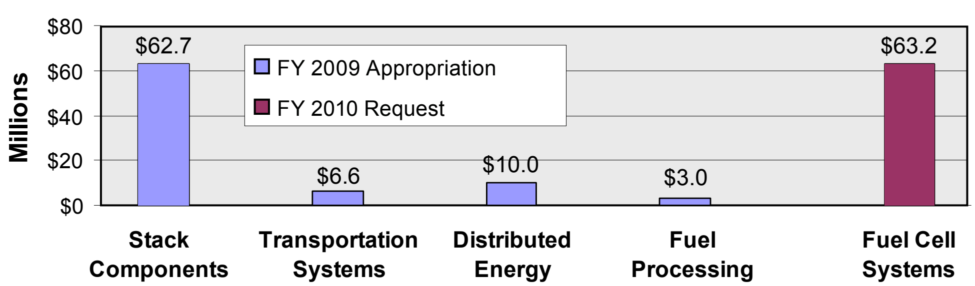

FIGURE 3. 2009 Congressional Appropriation and 2010 Budget Request

shows the 2010 budget request in comparison to the sub-program topic breakdown of the 2009 Congressional appropriation.

2010 Plans

In FY 2010, R&D activities will be focused on developing fuel cells suitable for use in several key applications, as well as improving component properties for key fuel cell technologies. Catalyst R&D activities will include PGM-based and non-PGM catalyst systems. The focus of PGM-based catalyst R&D will be on approaches that increase activity and utilization of current PGM and PGM alloy catalysts. Non-PGM catalyst investigations will focus on providing a better understanding of catalytically active sites and determining the oxygen reduction reaction mechanisms on these sites. Activities will also include investigation of durable catalysts to enhance stability under start-stop conditions. In situ studies will examine the effects of catalyst-support interactions, catalyst particle size, and catalyst structure. Innovative fuel cell component structures will also be investigated. Non-carbon support projects will develop materials with superior corrosion resistance and with electrical and structural properties that exceed the properties of carbon.

Work will continue on development of high-temperature membranes that reduce the need for humidification, allow better catalyst performance, reduce the negative effects of impurities, and decrease the size of the cooling system. Further R&D activities will include development of high-performance MEAs that incorporate the advanced membrane materials developed in FY 2009. Work will also continue on development of bipolar plates and seals that are inexpensive and corrosion resistant. In addition, R&D on gas diffusion layers will continue, improving water management characteristics and enhancing fuel cell performance.

Research on fuel cell system degradation will include development of integrated degradation models at the component, interface, and cell levels. The performance of MEAs in single cells and short stacks will be evaluated, and progress will be compared to DOE targets. Investigation and quantification of the effects of impurities on fuel cell performance will continue, including parametric studies of the effect of poisons on cell performance and durability, identification of poisoning mechanisms and recommendations for mitigation, and modeling of impurity effects on cell performance and durability. Results will provide further input on development of fuel cell standards.

Water management R&D will focus on the development of novel humidification materials that are inexpensive, durable, and able to support high performance operation in all operating environments, while meeting size and weight restrictions. Projects will examine concepts for novel water management devices and fuel cell system configurations that facilitate water management. Fuel cell system performance modeling will assist in optimization of water management devices and system configurations. Third-party evaluation of fuel cell stacks and systems will increase as these technologies mature.

Portable power R&D will focus on reducing anode and cathode catalyst loadings, while improving power density. R&D will also be directed toward development of membranes with increased proton conductivity, reduced methanol crossover, and improved water management. New R&D work on innovative anion-conducting low-temperature fuel cells will be initiated, with potential uses in portable power and other fuel cell applications. The focus of this work in FY 2010 will be on development of novel membrane materials with high anionic conductivity and high chemical stability.

Auxiliary power R&D will focus on developing fuel cell systems for heavy-duty trucks. Cell conductivity, catalyst performance, and chemical degradation issues will also be addressed. As targets are re-evaluated with feedback from stakeholders and the research community, a more pragmatic progress assessment will be made. In FY 2010, SOFC hardware will be tested for potential application as an APU on heavy-duty trucks. Results from these tests will help to assess the impact of the critical issues on SOFC performance and to direct future R&D efforts.

The sub-program's effort in facilitating fuel cell technology development for CHP applications will continue and be expanded. This will involve a 'technology-neutral' stance where PEMFC, SOFC, and other fuel cell technologies are included. In similar fashion to DOE's cost analysis approach to fuel cells for light-duty vehicle applications, current cost will be projected and independently validated for

CHP applications, targets for cost, performance, and durability will continue to be updated, and R&D needs will continue to be identified.

Sub-program activities will include promoting early adoption of fuel cell systems to validate performance, durability, and reliability through field testing. These efforts will lead to cost reduction and an increase in fuel cell stack durability, enabling fuel cells to transition from a niche market to a robust portfolio of applications, allowing the economic and environmental benefits that are shown in niche applications to expand into larger markets.

FY 2010 will see the continuation of existing projects and of those awarded in FY 2009, as well as a new initiative focusing on addressing urgent issues regarding near-term applied fuel cell technology. As technical targets are reassessed, R&D needs will be defined. Decreased cost with enhanced performance and durability would allow increased commercialization in early markets, enabling progress in fuel cell technology for more challenging, long-term applications. As stack component cost reduction continues, BOP component R&D will increase to facilitate an overall decrease in system cost. As the sub-program's direction extends further beyond direct H_2 PEMFCs, R&D needs for the advancement of alkaline and other fuel cell technology will also be examined.

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