BREAKTHROUGH VEHICLE DEVELOPMENT

FUEL CELLS (Revised October 29, 2004)

1. Research & Development Program for Fuel Cell Power Systems

Goal

The goal of the work program is to promote the development of a fuel cell power system for an automotive powertrain that meets the FreedomCAR objective.

Objective

- A 60% peak energy-efficient, durable, direct hydrogen fuel cell power system that, including hydrogen storage, achieves a power density of 220 W/L and a specific power of 325 W/kg, at a cost of $45/kW ($30/kW by 2015), with a range of over 300 miles. [1]

2. Status of Fuel Cell Technology

a. *Attractive Attributes of Direct Hydrogen Fuel Cells for Future Automotive Application*

- High energy efficiency over the full range of driving conditions (urban/highway Federal Test Procedure). Engineering improvements offer promise to exceed fuel efficiency of competing technologies.
- Zero tailpipe emissions.
- Low noise and vibration relative to conventional powertrains.
- Modular and relatively flexible packaging.

b. Background (Technology Status as of September 2003)

- Although invented in the mid-1800s, fuel cells were first used during the 1960s to generate electrical power on NASA spacecraft, using hydrogen and oxygen stored on-board. Fuel cells powered the life-support systems and mission equipment, and provided drinking water for the astronauts.
- The Polymer Electrolyte Membrane (PEM) fuel cell (PEMFC) is the leading fuel cell candidate for automotive applications [higher power density and faster start-up than other fuel cells]. Other fuel cell technologies that will require much greater development to meet automotive requirements are: Solid Oxide Fuel Cells (SOFCs) [high power density and the ability to operate on any fuel, but slow start-up] and Direct Methanol Fuel Cells (DMFCs) [fuel reformer not needed, but

[1] The range target is based on an aerodynamic, 2500-lb vehicle.

specific to methanol fuel, lower power density and lower efficiency than other fuel cells, stack designs not demonstrated, and limited fuel availability].

- Fuel cells have been used as stationary power sources where constraints on weight, volume, and packagability are minimal. Utility applications have been focused on phosphoric acid fuel cells (PAFCs), molten carbonate fuel cells (MCFCs), and SOFCs. Phosphoric acid fuel cell units of 200 kW have been produced; 2-MW MCFCs and 220-kW tubular-SOFCs are being demonstrated. More than 200 PAFC systems have been installed all over the world — in hospitals, nursing homes, hotels, office buildings, schools, utility power plants, and an airport terminal, providing primary or backup power. Installed between 1994 and 1997, PAFCs are operating at 30 U.S. Department of Defense bases. Methane-powered PAFCs are now operating at a number of landfills and wastewater treatment facilities in Connecticut, New York, Massachusetts, Oregon, and Japan. One ONSI system in New York, for example, in operation since 1997, produces over 1.6 million kWh of electricity per year at reduced emission levels. Residential PEM fuel cell units, typically 5–7 kW in size, are being developed and demonstrated by several companies, including IdaTech and Plug Power.

- Fuel cell buses have been demonstrated by DOE/Georgetown, DOT, Ballard Power Systems in Palm Springs, Chicago, and Vancouver, and DaimlerChrysler (NEBUS) in Hamburg and Stuttgart. Many other companies, such as Renault, MAN, Neoplan, Thor/UTC Fuel Cells, and Toyota, are demonstrating fuel cell buses throughout Europe and Japan. In the U.S., SunLine Services Group (Palm Desert, CA) operates a fleet of fuel cell vehicles and is the site of a hydrogen dispensing station. Many fuel cell bus demonstrations are planned for the near future through the California Fuel Cell Partnership (CaFCP) and other organizations. For example, 30 DaimlerChrysler "Citaro" fuel cell buses were delivered to cities in Europe beginning in May 2003, at a price of US$1.2 million each. The buses will operate on compressed gaseous hydrogen and have a top speed of 50 mph (80 kmph) and a range of 185 miles (300 km).

- Fuel cell powered taxis, built by Zevco were tested on the streets of London. The cabs ran on alkaline fuel cells (5-kW_e trickle chargers) and batteries and cost about US$7,500 more than a conventional diesel cab. More recently, Da Capo Fuel Cell Ltd., which had bought the technology rights from ZeTec Power (Zevco and Elenco merged to form ZeTec Power) had scraped all but two of the cabs and these two cabs were obtained and are being refurbished by Cenergie, Fuel Cell Control Ltd, and Norsk.

- Numerous PEM fuel cell automobiles have been demonstrated:
  - Ford unveiled the hydrogen-powered P2000 fuel cell demonstration vehicle in 1998 and the methanol-powered fuel cell vehicle FC5 in 2000. In October 2000, Ford introduced the world's first production-prototype, direct-hydrogen powered fuel cell vehicle. Based on Ford's Focus platform, the Focus FCV is Ford's second generation hydrogen-fueled, fuel-cell-powered vehicle. In April of 2002, Ford launched its third generation of the Focus Fuel Cell Vehicle

(FCV). Major improvements include a 5000 psi hydrogen tank, which gives the Focus FCV a range of about 180 to 200 miles, and horse power comparable to the current standard Focus with an internal combustion engine. This is done with the addition of a mild hybrid Sanyo battery system, Ballard Mark 902 stack, integrated powertrain, and regenerative braking system. Ford is working toward launching a small production fleet in 2004 that will support collaborative development and demonstration fleets throughout the world.

– Beginning with the NECAR 1 in 1994, DaimlerChrysler introduced a series of increasingly advanced fuel cell vehicles, operating on a variety of fuels including compressed and liquid hydrogen, methanol, gasoline and sodium borohydride. In 2002, NECAR 5, running on methanol, completed the first cross-country trip in a fuel cell vehicle, traveling from San Francisco to Washington, D.C., in 12 days. The Chrysler Town & Country Natrium, introduced in December 2001, operates on sodium borohydride, a non-flammable compound made from borax that produces zero greenhouse emissions. The fuel system gives Natrium a range of more than 300 miles with no loss of passenger or cargo space. By the end of 2004, DaimlerChrysler plans to have real-world experience with more than 100 fuel cell vehicles, including the F-Cell, based on the Mercedes-Benz A-Class, Citaro buses, and Sprinter vans.

– General Motors unveiled the methanol-powered GM Opel Zafira fuel cell minivan in 1999, which is powered by its seventh generation fuel cell system. In 2000, GM announced the hydrogen-powered Precept Fuel Cell Concept Car. In August 2001, GM introduced a Chevrolet S-10 Fuel Cell Pickup concept vehicle with their Gen III fuel cell engine operating on ultra-low-sulfur gasoline. The HydroGen1, GM's prototype fuel cell vehicle unveiled in 2001, can start in temperatures as low as –40˚C (–40˚F). In January 2002, GM unveiled the "x-by-wire" AUTOnomy vehicle concept developed from the ground up for fuel cell propulsion. General Motors launched its Washington, DC-based fleet of HydroGen3 hydrogen-powered fuel cell vehicles in May, 2003 with a kick-off event on Capitol Hill attended by more than 40 members of the House and Senate. The vehicles are expected to remain "in town" through the end of 2005 and will be used to give ride and drive opportunities to legislators, regulators, environmentalists and other policy makers. Personalized ride and drive experiences are an excellent way to familiarize these key individuals with the advanced state of GM's expertise in hydrogen and fuel cell technology, as well as to serve as a starting point for discussions on challenges which must be addressed before the technology can be successfully commercialized. The DC demonstration program will also feature the nation's first hydrogen pump at a Shell retail gas station. In addition to serving as a fuel source for the HydroGen3s, the Shell station will be an integral part of the public demonstration activities--specifically, the refueling process and associated hydrogen infrastructure.

– Nearly every major automaker in the world has announced or demonstrated a fuel cell powered concept vehicle and/or prototype, including Toyota, Honda, Nissan, Mazda, Renault, Hyundai, Fiat, Peugeot, and Volkswagen. One exception is BMW, which has focused its development efforts on hydrogen-powered internal combustion engines (ICEs), using fuel cells for auxiliary power only.

The hydrogen-powered Honda FCX was certified to ZEV standards by the California Air Resources Board (CARB) and U.S. EPA in July 2002, the only fuel cell vehicle certified by California for every day commercial use. The city of Los Angeles leased the first of five FCXs from Honda in December of 2002. Honda plans to lease about 30 fuel cell cars in California and Japan during the next two to three years. The company currently has no plans, however, for mass-market sales of fuel cell vehicles or sales to individuals.

In July of 2002, Toyota announced plans to market about 20 fuel cell hybrid passenger vehicles in Japan and the U.S. over a period of 12 months beginning late 2002. Toyota has since provided both the University of California at Irvine (UCI) and the University of California at Davis with two each of the "market-ready" FCHVs, which are based on the Highlander SUV model. The first two vehicles delivered to the schools in December 2002 have logged more than 6,000 miles. The latest two FCHVs delivered in September 2002 have been improved for U.S. use, including left-hand drive operation, improved braking performance, and a new navigation system. Including the three FCHVs under test at the California Fuel Cell Partnership and one at Toyota Motor Sales, U.S.A., a total of 8 Toyota FCHVs are currently under test in the U.S.

- Other examples of fuel cells in transportation and related equipment include golf carts, forklifts, mining vehicles, cranes, bikes, scooters, water taxis, and boats. Fuel cells are also being considered for locomotives, trucks, and marine vessels, and for auxiliary power in cars and trucks.

- In its efforts to accelerate the development of fuel cell vehicles, the California Fuel Cell Partnership (CaFCP) opened its headquarters facility in West Sacramento, CA, in November 2000. The Partnership includes eight major automobile companies (General Motors, DaimlerChrysler, Ford, Toyota, Honda, Hyundai, Nissan, and Volkswagen) and fuel cell technology partners (Ballard Power Systems and UTC Fuel Cells). Other members include energy providers (BP, ExxonMobil, Shell, Texaco, and Methanex), and government agencies (the California Air Resources Board, California Energy Commission, South Coast Air Quality Management District, U.S. Department of Energy, and the Department of Transportation). Associate members include Air Products, Praxair, Pacific Gas & Electric, Proton Energy Systems, Stuart Energy Systems, AC Transit, SunLine Transit, and Santa Clara Transit. Over the next several years, more than 50 fuel cell-powered cars will be demonstrated on California roads under real-world conditions, and twenty to twenty-five fuel cell buses will be demonstrated in regular transit operations. Under the auspices of the Partnership, Ballard Power Systems shipped the first fuel cell bus powered by a pre-commercial fuel cell engine to the SunLine Transit Agency in Palm Springs, CA.

Collaborative work to encourage fuel cell vehicle commercialization will continue at the California Fuel Cell Partnership through 2007. The group's original charter called for joint activities through 2003.

- For the automotive application, fuel cell systems are not yet competitive with the ICE in terms of performance, packaging, cost, high-volume manufacturability, and on-board fuel storage. The ICE powertrain manufacturing costs are about $25–35/kW. For high volume penetration of the automotive market in the U.S., fuel cell systems designed for 5000-hour life must be cost competitive with the ICE technology. The projected manufacturing cost of direct hydrogen fuel cell systems is approximately $120/kW (excluding the cost of the hydrogen storage subsystem). The estimated current manufacturing cost of fuel cell systems, produced in low volumes, is about $10,000/kW.
- Issues yet to be resolved for viable automotive applications are:
  - Adequate durability under long-term start/stop use and varying ambient conditions;
  - Reduced platinum usage;
  - Lower manufacturing cost;
  - Shorter start-up and transient response times;
  - Compact, lightweight balance-of-plant components, e.g., compressors, humidifiers, and heat exchangers;
  - Adequate on-board hydrogen storage[2]; and
  - Appropriate fuel infrastructure[3].

  Economic issues include fuel cell manufacturing capitalization, potential costs of a new fueling infrastructure, and competition from other technologies.
- During 1994–2000, the Partnership for a New Generation of Vehicles (PNGV) technology development strategy was focused on developing full-scale (50 kW), functional, integrated PEMFC systems operating on multiple liquid fuels (gasoline and alcohols). This effort included the development of highly efficient fuel cell stack systems and on-board fuel-flexible fuel processors. Pre-competitive R&D at the National Laboratories addressed materials and component development. These technology developments enabled vehicle designers to integrate fuel cell systems into fuel cell concept vehicles.
- In 2000, following successful development of functional, integrated 50-kW systems, the government shifted focus to the R&D of materials, components and other enabling technologies to reduce the cost of fuel cell systems. In addition, DOE emphasized R&D of hydrogen storage materials and hydrogen refueling technologies.
- Executives from DaimlerChrysler Corporation, Ford Motor Company, and General Motors Corporation joined Secretary of Energy Spencer Abraham in January 2002 to announce a new cooperative automotive research (CAR)

[2] Other FreedomCAR and Hydrogen Fuel Initiative Tech Teams

partnership between the U.S. Department of Energy and the U.S. Council for Automotive Research (USCAR).

The vision of FreedomCAR is petroleum-free cars and light trucks. The program will focus on the high-risk research needed to develop enabling technologies (e.g., fuel cells, the ability to produce hydrogen from domestic renewable sources, etc.) without sacrificing freedom of mobility, freedom of vehicle choice, or affordability.

USCAR recognizes that altering the overall U.S. petroleum consumption pattern will require a multi-tiered approach, including policy and research programs. The transportation sector has a significant role to play in addressing this challenge, and success from FreedomCAR research initiatives will contribute to broader national goals and objectives.

The long-term transition of vehicles from gasoline to hydrogen is viewed as critical in reducing the environmental impact of the personal transportation sector. This will require the development of breakthrough technologies to enable mass production of affordable hydrogen-powered fuel cell vehicles as well as the hydrogen-fueling infrastructure to support them.

FreedomCAR also will continue support for other technologies that have the potential to dramatically reduce oil consumption and environmental impacts.

This transition will require a significant investment by the automotive OEMs, the energy providers, and the federal government, as well as a concerted long-term effort. Mechanisms will be created to facilitate proactive interaction with automotive suppliers, the energy industry and other appropriate parties. The ultimate vision of success is energy stability, energy security, and a lessened impact of transportation on our environment.

- Progress toward technical targets was assessed during 2004, and as a result, the technical targets were updated. The timeline for achieving the technical and cost targets required for fuel cell vehicle commercialization is 2015 (as shown in Tables 1 through 10).

c. *Technology R&D Trends*

- Current R&D on fuel cell system components for automotive applications is aimed primarily at increasing durability and reducing cost:

  Durable electrodes with low precious metal content;

  High-volume fabrication processes for membrane-electrode assemblies (MEAs) and bipolar plates;

  Improved air electrode performance to raise cell voltage, increase fuel cell stack efficiency, and reduce the number of cells per stack;

  Membranes that operate at higher temperatures (e.g., 120°C for transportation and 150°C for stationary applications) and low humidity to facilitate heat rejection and increase CO tolerance of the anode;

Compact, lightweight, efficient balance-of-plant components, such as air compressors, humidifiers, heat exchangers, and sensors;

Durability studies and accelerated aging test methods, and

Systems analysis and analytical capability.

- Most government-funded U.S. fuel cell R&D efforts include competitive industry-based projects that are cost-shared with the government as well as pre-competitive R&D carried out at the National Laboratories.
- Technology validation, defined as confirmation that fuel cell components can be incorporated into a complete system solution that meets vehicle performance and operating targets under realistic operating scenarios, is an increasingly important program element. The Technology Validation program element will implement tests of fuel cell vehicles and collect data under real world operating conditions to determine whether the vehicle technical targets have been met. Results of the validation program will be used to provide feedback on progress, efficiently manage the fuel cell vehicle R&D program, and provide program redirection as needed.

d. State of Development

The 2004 status of the fuel cell system and subsystem development toward FreedomCAR targets is captured in Tables 1 through 10. For fuel cell stack subsystems, significant challenges remain for achieving cost, reliability, and durability targets. Component level targets have been developed to assist developers in evaluating the state of technology development that would support achievement of the fuel cell system targets without developing full systems. Fuel processor subsystems development previously supported by FreedomCAR has been discontinued. In August 2004, a review of on-board fuel processing activities was conducted and concluded that, based on the current state of the technology; it was unlikely that on-board fuel processing would improve sufficiently to support the transition to a hydrogen economy. The decision was supported by several key conclusions:

- The Hydrogen Fuel Initiative accelerated the hydrogen technology development and lessened the contribution that on-board fuel processing could make as a transitional technology;
- Current fuel processing technologies do not meet the technical and economic targets and there is no clear path forward to meet the more difficult targets necessary for full integration in fuel cell vehicles (see Table 9);
- Competing technologies are available today, and only marginal improvement is expected in efficiency and emissions between a gasoline, hybrid-electric vehicle and a fuel cell vehicle operating on gasoline.

3. Product Development Challenges & Potential Solutions

Remaining technical challenges for viable fuel cell vehicles are the following.

a. Robustness, durability, and reliability for real-world usage profile

Fuel cell systems with long-term durability (>5000 hours) under dynamic load following, start/stop operation, road vibration/shock and climate conditions must be demonstrated. Approaches for attaining durability and reliability in automotive applications must include materials selection, component designs, and system architecture to accommodate:

- Robust high performance membranes that tolerate a wider range of operating temperatures and hydration and are resistant to attack by free radicals;
- Durable catalysts that are less sensitive to contaminants and cell voltage reversal;
- Gas diffusion layers (GDLs) that are optimized for improved water management capability;
- Bipolar plate materials that enable durable and corrosion-resistant/defect free coatings;
- Simplified system architecture;
- Testing procedures and conditions that represent real world usage, dynamic load following, start/stop and climate variations;
- Development of accelerated aging test protocols;
- Systems that can withstand road vibration, shock, and wet/winter conditions;
- Dynamic computer models for design and process optimization that have been validated with experimental data;
- Mature in-situ analytical tools for investigating water/thermal management issues (membrane hydration, water behavior in GDL, MEA and gas flow channels etc.), transient behavior, MEA and stack degradation;
- Diagnostic procedures and non-destructive evaluation equipment to monitor production quality;

b. Start-Up Capability

For customer acceptance, fuel cell systems must have adequately short start-up time, e.g. within 15 seconds from normal ambient temperatures (20°C) and 30 seconds from –20°C. The fuel cell system may use stored energy such as electrical energy in batteries at start-up. However, fuel economy suffers when energy is used to warm up the vehicle before it can be driven, so start-up energy should be minimized. Targets are shown in Table 1, 2 and 9. Enabling technologies for rapid start up include:

- Adequate performance of MEAs in sub-zero temperatures;
- Thin and low-mass bipolar plates;

- Optimized water management of the fuel cell stack to reduce dependence on humidification subsystems or eliminate them;
- Optimized hybrid control systems where start-up and shut down power is supplied by stored energy, e.g. high-power batteries, or ultracapacitors); and
- Improved water-gas-shift catalysts/reactors.

c. Cost

Cost (and other) targets for fuel cell systems, subsystems, and components are indicated in Tables 1 through 10. Recent estimates of the current cost of system materials and production projected to high volume (~$120/kW for systems operating on direct hydrogen) indicate opportunities for cost reduction, e.g., for MEAs from $200/kW to $5/kW. Principal R&D efforts focus on:

- Less expensive electrolyte membrane precursor materials and low-cost fabrication methods for membrane sheets;
- Minimal loading of precious metal catalysts on electrodes and improved utilization of PEMFC catalysts with lower loadings of precious metals;
- High-volume fabrication processes for MEAs and bipolar plates;
- Non-precious metal catalysts for fuel cell stack;
- Bipolar plate designs based on less-expensive materials and corrosion-resistant coatings, and with simpler manufacturing requirements;
- Simplified fuel cell system architecture;
- Efficient air management through low-cost, compact compressors, low-pressure stack designs, improved cathodes;
- Development of processing technologies to reduce carbon component fabrication costs;
- Rapid, high-volume production techniques for fuel cell components and systems (e.g., thin film coating) for dependable, high quality manufacture; and
- Development of high-volume production techniques for polymer electrolyte membranes, membrane electrode assemblies, and bipolar plates.

d. System Efficiency

Efficiency of the fuel cell system is a crucial attribute that impacts fuel economy and CO_2 emissions. Under actual driving profiles, the fuel cell system operates at partial load, approximately 15 to 30% of rated power. This is the range where the efficiency of the fuel cell system has the most impact on fuel economy and emissions. The fuel cell stack and system should be optimized to achieve high efficiency in this power range. Higher performance MEAs and higher efficiency of air compressors are necessary. System targets are shown in Table 1. Related component targets for the MEA are shown in Tables 3 through 5, bipolar plates in Table 6, sensors in Table 7 and the compressor/expander in Table 8. Hydrogen quality targets are shown in Table 10.

- Higher activity of catalyst for electrodes and higher performance of MEAs under lower operating pressure and stoichiometric ratio;
- Higher efficiency of air compressor;
- Optimized hybrid system concepts and control strategy;
- Optimized fuel cell system concepts to recover the waste energy;

e. Volume, Weight, and Packagability

Weight and packagability of fuel cell stacks and ancillary components, in particular, thermal management, are major challenges for automotive applications. Targets are shown in Table 1. Weight and size reductions are to be achieved by the following:

- Improved electrolytes and electrodes for greater current densities and power capabilities;
- Improved bipolar plate designs using thinner and lighter materials; and
- Lighter, smaller ancillary components, such as air compressors, humidifiers, and heat exchangers, that improves dynamic response and handling of load surges.

f. Manufacturability

Needs include:

- Rapid, high-volume production techniques for fuel cell components and systems (e.g., thin film coating) for dependable, high quality manufacture;
- Diagnostic procedures and non-destructive evaluation equipment to monitor production quality; and
- Development of high-volume production techniques for polymer electrolyte membranes, membrane electrode assemblies, and bipolar plates.

4. Technical Targets and Schedule

Table 1 summarizes the system performance specifications and targets for automotive PEMFC systems operating on direct hydrogen.

5. R&D Tasks and Component Technical Targets

Tasks:
The program for achievement of the enabling R&D technical objectives (Table 1) consists of the following R&D tasks. The corresponding component technical targets are listed in Tables 2 through 8.

Task 1 — Membrane/MEA Development

- Relate the polymeric properties, such as molecular weight distribution and equivalent weight, to the membrane's physical properties, such as hydration, mechanical strength, ionic conductivity, gas permeability, tolerance to impurities, resilience, and chemical stability.
- Relate the physical properties of the membrane to constituent polymer synthesis methods and membrane fabrication methods.
- Develop interrelationships between physical properties, polymeric properties, and synthesis/fabrication methods to tailor the membrane's properties for fuel cell applications and high-volume manufacture.
- Develop thin membranes with low resistivity and wider operating condition range.
- Develop advanced membranes and MEAs capable of operating at a range of temperatures from -20°C to 120°C (see Tables 3 and 4).
- Demonstrate/evaluate advanced MEAs in sub-scale stacks (5–10 kW).

Task 2 — Electrode Optimization

- Characterize physical microstructure and chemical composition of catalysts as a function of their performance in anodes (fuel electrodes) and cathodes (air electrodes) in fuel cells.
- Characterize and optimize alloy catalysts to reduce the overpotential at the cathode and improve the impurity tolerance of the anode.
- Improve gas-diffusion media and current collectors for increased current densities over a wider range of operating conditions.
- Coordinate design development with attention to manufacturing challenges.
- Demonstrate/evaluate improved electrodes in MEAs and sub-scale stacks (5–10 kW).

Task 3 — Bipolar Plate Development

- Develop bipolar plates (combined separator, flow field, and current carrier) that are much thinner and lighter than todays machined graphite plates to improve the power density of PEMFC systems and enable cold start capability. Alternative approaches to costly machined plates include:
  - One-piece, near-net-shape, carbon/carbon bipolar plate/diffuser;
  - Low-cost metallic bipolar plate, possibly coated with a low-corrosion metal, graphite, or a conducting polymer; and
  - Low-cost polymer bipolar plate with low resistivity.
- Coordinate design development with attention to manufacturing challenges.
- Demonstrate/evaluate bipolar plate in sub-scale stacks (5–10 kW).

Task 4 — High-Volume Fabrication Processes for Fuel Cell Stack Components

- Develop electrode fabrication processes (catalyst deposition) that are amenable to low-cost, high-volume manufacturing.
- Develop MEAs and MEA fabrication processes that are amenable to low-cost, high-volume manufacturing.
- Develop low-cost, high-volume manufacturing processes for bipolar plates.
- Demonstrate performance of stack components (MEAs and bipolar plates) made by high-volume processes in sub-scale stacks.

Task 5 — Control & Ancillary Systems

- Develop compact, low-cost, efficient air compressors or compressors/expanders.
- Optimize control and ancillary subsystems for overall fuel cell system performance.
- Develop sensors for diagnostics and control.
- Coordinate design development with attention to manufacturing challenges.
- Develop sensors, e.g., for CO and H_2, suitable for automotive fuel cell systems.
- Develop efficient and compact humidifiers and heat exchangers.

Task 6 - Fuel Cell Modeling

- Create an overall fuel cell system model that fully accounts for all mass and energy flows and simulates steady-state performance over an ambient temperature range, cold starts, and transient response.
- Conduct simulation studies to guide fuel cell system design and support development of control strategies.
- Provide simulation results to FreedomCAR System Analysis Technical Team for projection of fuel cell vehicle mass and capabilities.

Task 7 – Analytical Tools

- Develop both global and local analytical tools to evaluate water management in the fuel cell stack and MEAs for both global and local thermal uniformity and transient behaviors.

6. Existing Federal R&D

Relevant fuel cell development for automotive applications is being conducted under government/industry programs sponsored primarily by DOE, and to a lesser extent by DOT and other government agencies. The related R&D is summarized in Tables 11 and 12 and in Appendix A.

Table 1. FreedomCAR Technical Targets for Automotive-Scale (80-kW net) Integrated Fuel Cell Power Systems Operating on Direct Hydrogen[a]

Characteristic	Units	Calendar Year			
		2004 Status	2005	2010	2015
Energy efficiency[b] @ 25% of rated power	%	59	60	60	60
Energy efficiency @ rated power	%	50	50	50	50
Power density	W/L	450[c]	500	650	650
Specific power	W/kg	420[c]	500	650	650
Cost[d]	$/kW	120	100	35	25
Transient response (time from 10% to 90% of rated power)	sec	<3	2	1	1
Cold start-up time to maximum power					
@ –20ºC ambient temperature	sec	120	60	30	30
@ +20ºC ambient temperature	sec	60	30	15	15
Emissions		Zero	Zero	Zero	Zero
Durability[e]	hours	1000	2000[f]	5000[g]	5000[g]
Survivability[h]	°C	-20	–30	-40	-40

[a] Targets exclude hydrogen storage and are based on an aerodynamic 2500-lb vehicle. All targets must be met simultaneously.

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

[c] Based on corresponding data in Table 2 divided by 3 to account for ancillaries.

[d] Includes projected cost advantage of high-volume production (500,000 units per year).

[e] Performance targets must be achieved at the end of the durability time period.

[f] Includes thermal cycling.

[g] Includes thermal and realistic driving cycles.

[h] Achieve performance targets after 8-hour cold-soak at temperature.

Table 2. Technical Targets: 80-kW_e (net) Transportation Fuel Cell Stacks Operating on Direct Hydrogen[a]

Characteristic	Units	Calendar Year			
		2004 status	2005	2010	2015
Stack power density [b]	W/L	1,330[c]	1,500	2,000	2,000
Stack specific power	W/kg	1,260[d]	1,500	2,000	2,000
Stack efficiency[e] @ 25% of rated power	%		65	65	65
Stack efficiency[d] @ rated power	%		55	55	55
Precious metal loading[f]	g/kW	1.3	2.7	0.3	0.2
Cost[g]	\$/kW_e	75	65	25	20
Durability[h]	hours		>2,000[i]	>5,000[j]	>5,000[j]
Transient response (time for 10% to 90% of rated power)	sec	1	2	1	1
Cold startup time to rated power					
@ –20ºC ambient temperature	sec	120	60	30	30
@ +20ºC ambient temperature	sec	<60	30	15	15
Survivability[k]	ºC	-40	-30	-40	-40

[a] Excludes hydrogen storage and fuel cell ancillaries: thermal, water, air management systems.
[b] Power refers to net power (i.e., stack power minus auxiliary power). Volume is "box" volume, including dead space, and is defined as the water-displaced volume times 1.5 (packaging factor).
[c] Average of GM, Ballard, Toyota stacks from FuelCells.org, April 2004
[d] Average of GM and Ballard stacks from FuelCells.org, April 2004 and Honda press release
[e] Ratio of output DC energy to lower heating value of hydrogen fuel stream. Peak efficiency occurs at about 25% rated power.
[f] Equivalent total precious metal loading (anode + cathode): 0.1 mg/cm^2 by 2010 at rated power. Precious metal target based on cost target of <\$3/kW_e precious metals in MEA [@\$450/troy ounce (\$15/g), <0.2 g/kW_e]
[g] High-volume production: 500,000 units per year.
[h] Performance targets must be achieved at the conclusion of the durability period; durability includes tolerance to CO, H_2S and NH_3 impurities.
[i] Includes thermal cycling.
[j] Includes thermal cycling and realistic driving cycles.
[k] Performance targets must be achieved at the end of 8-hour cold-soak at temperature.

Table 3. FreedomCAR Technical Targets for MEAs

Characteristic	Units	Calendar year			
		2004 Status[a]	2005	2010	2015
Membrane Conductivity at Operating temperature	S/cm °C	0.1 ≤80	0.1 ≤120	0.1 ≤120	0.1 ≤120
at Ambient Temp. (20°C)	S/cm	0.07	0.07	0.07	0.07
at -20°C	S/cm	0.01	0.01	0.01	0.01
Cost[b]	$/kW	200	100	10	5
Durability	Hours	1000[c]	>4000[d]	>5000[e]	>5000[e]
Survivability	°C	-20	-30	-40	-40
Total catalyst loading (both electrodes)[f]	g/kW (rated)	1.1	2.7	0.33	0.20
Performance @ 0.25 power (0.8V)	mA/cm^2 mW/cm^2	200 160	250 200	400 320	400 320
Performance @ rated power	mW/cm^2	400	800	1280	1280
Extent of performance degradation over lifetime[g]	%	10	10	10	10
Thermal cyclability in presence of condensed water		Yes	Yes	Yes	Yes

[a] Status is present day 80°C unless otherwise noted: targets are for new membranes/MEAs
[b] Based on PBI membrane costs projected to mass manufacturing, 500,000 stacks per year
[c] Continuous operation
[d] Includes thermal cycling
[e] Includes thermal and realistic driving cycles
[f] Equivalent total precious metal loading (anode + cathode): 0.1 mg/cm^2 by 2010 at rated power. Precious metal target based on cost target of <$3/kW precious metals in MEA [@$450/troy ounce ($15/g), < 0.2 g/kW_e].
[g] Degradation target includes factor for tolerance of the MEA to impurities in the fuel and air supply

Table 4. FreedomCAR Technical Targets for Membranes

Characteristic	Units	Calendar year			
		2004 Status[a]	**2005**	**2010**	**2015**
Membrane Conductivity at operating temperature[b]	S/cm	0.1	0.1	0.1	0.1
at Ambient Temp. (20°C)	S/cm	0.07	0.07	0.07	0.07
at -20°C	S/cm	0.01	0.01	0.01	0.01
Oxygen crossover	mA/cm^2	5	5	2	2
Hydrogen crossover[c]	mA/cm^2	5	5	2	2
Cost	$\$/m^2$	200	200	20	20
Operating Temperature	°C	≤80	≤120	≤120	≤120
Durability	Hours	1000 [d]	4000 [e]	5000[f]	5000[f]
Survivability	°C	-20	-30	-40	-40
Thermal cyclability in presence of condensed water		Yes	Yes	Yes	Yes

[a] Status is present day 80°C unless otherwise noted: targets are for new membranes/MEAs
[b] For temperatures above 80°C, testing should be done at 0.5 atm absolute humidity (corresponds to 25% RH at 120°C). For temperatures below 80°C, tests should be run at saturation.
[c] Tested in MEA
[d] Continuous operation
[e] Includes thermal cycling
[f] Includes thermal cycling and realistic driving cycles

Table 5 Technical Targets: Electrocatalysts

Characteristic	Units	2004 Status		Targets		
		Cell	Stack	2005	2010	2015
PGM Total Content	g/kW rated	0.6	1.1	2.67	0.33	0.20
PGM Total Loading	mg PGM/cm^2 electrode area	0.45	0.80	0.70	0.20	0.10
Cost	\$/kW [a]	9	16.5	40	5	3
Durability	Hours	>2000	2000 near steady state	2000 w/ drive cycle	5000 w/ drive cycle & start/stop	5000 w/ drive cycle & start/stop
Mass Activity	A/mg_{Pt} @900$mV_{iR\text{-}free}$	0.28	0.11	0.30	0.44	
Specific Activity	µA/cm^2 @ 900$mV_{iR\text{-}free}$	550	180	600	720	
Non-Pt Catalyst Activity per volume of supported catalyst	A/cm^3	8	N/A	50	>130	

[a] based on platinum cost of \$450/troy ounce = \$15/g, and loading < 0.2 g/kW_e

Table 6. Technical Targets: Bipolar Plates

Characteristic	Units	Status 2004	DOE Target
Cost	$/plate	2 projected	$10/kW
Weight	kg/kW	0.36	<1
H_2 Permeation Rate	$cm^3\ sec^{-1}\ cm^{-2}$ @ 80°C, 3 atm (equivalent to <0.1 mA/cm^2)	$<2 \times 10^{-6}$	$<2 \times 10^{-6}$
Corrosion	$\mu A/cm^2$	TBD	<1[a]
Electrical Conductivity	S/cm	>600	>100
Resistivity	ohm/cm^2	TBD	0.02
Flexural Strength	psi	>5000	>600 (crush)
Flexibility	% deflection at mid-span	1.5 to 3.5	3 to 5

a May be as low as 1 nA/cm^2 if all corrosion product ions remain in ionomer.

Table 7. FreedomCAR Technical Targets for Sensors for Automotive Fuel Cell Systems[a]

Sensor	Requirements
Hydrogen in ambient air	• Measurement range: 1–5% • Temperature range: –30 to 80°C • Response time: under 1 sec • Accuracy: <5% full scale • Gas environment: ambient air, 10–98% RH range • Lifetime : 5 years • Interference resistant (e.g., hydrocarbons)
Hydrogen in fuel processor output	• Measurement range: 25–100% • Operating temperature: 70–150°C • Response time: 0.1–1 sec for 90% response to step change • Gas environment: 1–3 atm total pressure, 10–30 mol% water, 30–75% total H_2, CO_2, N_2 • Accuracy: ≤2% full scale
Carbon Monoxide	**(a) Stored H_2 at 99.999% at transportation fueling station** • 0.1 – 0.5 ppm • Operational temperature: <150°C • Response time: 0.1–1 sec • Gas environment: bone dry hydrogen at 1-700 atm total pressure • Accuracy: <2% full scale **(b) Reformate from stationary fuel processor to PEM stack** • 100–1000 ppm CO sensors • Operational temperature: 250°C • Response time: 0.1–1 sec • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: <2% full scale **(c) Between shift reactors and PSA** • 0.1–2% CO sensor 250–400°C • Operational temperature: 250–400°C • Response time: 0.1–1 sec • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, CO, N_2, H_2O at 1–3 atm total pressure • Accuracy: <2% full scale
Sulfur compounds (H_2S, SO_2, organic sulfur)	**a.) H_2 to storage, ambient temperature** **b.) From fuel processor** • Operating temperature: up to 300°C • Measurement range: 0.05–0.5 ppm • Response time: <1 min at 0.05 ppm • Gas environment: H_2, CO, CO_2, hydrocarbons, water vapor

Flow rate of fuel processor output	• Flow rate range: 30–300 SLPM • Temperature: 0-100°C • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Ammonia	• Operating temperature: 70–150°C • Measurement range: 0.5-5 ppm • Selectivity: <1 ppm from matrix gases • Response time: < 1 minute at 0.5 ppm • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure
Temperature	• Operating range: –40 to 150°C • Response time: in the –40 to 100°C range <0.5 sec with 1.5% full scale accuracy; in the 100–150°C range, a response time <1 sec with 2% full scale accuracy • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm total pressure • Insensitive to flow velocity
Relative humidity for cathode and anode gas streams	• Operating temperature: 0–110°C • Relative humidity: 20–100% • Accuracy: 1% full scale • Gas environment: high-humidity reformer/partial oxidation gas: H_2 30–75%, CO_2, N_2, H_2O, CO at 1–3 atm
Oxygen at cathode exit	• Measurement range: 0–50% O_2 • Operating temperature: 30–110°C • Response time: <0.5 sec • Accuracy: 1% full scale • Gas environment: H_2, CO_2, N_2, H_2O at 1–3 atm total pressure
Differential pressure in fuel cell stack	• Range: 0–1 psi or (0–10 or 1–3 psi, depending on the design of the fuel cell system) • Temperature range: 30–100°C • Survivability: –40°C • Response time: <1 sec • Accuracy: 1% full scale • Size: $\leq$1 in^2, usable in any orientation • Other: Measure pressure in the presence of liquid and gas phases

[a] Sensors must conform to size, weight, durability (10-15 years), and cost constraints of automotive applications.

Table 8. FreedomCAR Technical Targets for Compressor/Expander (C/E) Units[a]

Characteristic	Units	2004 Status	2005 Target	2010 Target
Input Power [a] at Full Load, 40°C Ambient Air				
Overall Motor/Motor Controller Conversion Efficiency, DC Input	%	85	85	85
80-kW_e Unit-Hydrogen/Air w Expander/wo Expander	kW_e	–	6.3/13.8	5.8/13.2
Input Power at Full Load, 20°C Ambient Air, 80-kW_e Proposed Demonstrator Only				
80-kW_e Unit Hydrogen/Air (with Expander / without Expander)	kW_e	–	5.4/12.8	4.8/12.3
Compressor/Expander Efficiency at Full Flow (C/E Only)[b]				
80kW_e Unit Hydrogen/Air	%	–	75/80	80/80
Compressor/Expander Efficiency at 20-25% of Full Flow (C/E Only)				
80-kW_e Units, Hydrogen/Air	**%**			
Compressor at 1.3 PR/Expander at 1.2 PR	%			60/50
System Volume [c]				
80-kW_e Unit-Hydrogen/Air	L	–	–	15
System Weight [c]				
80-kW_e Unit-Hydrogen/Air	kg	–	–	15
System Cost [d]				
80-kW_e Unit-Hydrogen/Air	$	–	–	400
Turndown Ratio				
80-kW_e Units-Hydrogen/Air		–	–	10
Noise at Maximum Flow(excluding air flow noise at air inlet and exhaust)				
80-kW_e Units-Hydrogen/Air	dB(A) at 1 m	–	–	65
Transient Time for 10-90% of Maximum Airflow	sec	–	1 sec	1 sec

[a] Input power to the **<u>shaft</u>** to power a compressor/expander, or compressor only system, including a motor/motor controller with an overall efficiency of 85%. 80-kW_e compressor/expander unit for hydrogen/air flow------91 g/sec (dry) maximum flow for compressor, compressor outlet pressure is specified to be 2.5 atm. Expander (if used) inlet flow conditions are assumed to be 94 g/sec (at full flow), 80°C, and 2.2 atm.

[b] The pressure ratio is allowed to float as a function of load on the fuel cell system load. Inlet temperature and pressure used for efficiency calculations are 20-40ºC and 2.5 atm.

[c] Weight and volume include the motor and motor controller.

[d,] Cost targets based on a manufacturing volume of 100,000 units per year, includes cost of motor and motor controller.

Table 9. On-Board Fuel Processing 2004 Go/No-Go Demonstration Criteria, Ultimate Targets, and Status of On-board Fuel Processing

Attribute	Units	2004 Demo Criteria	Current Status (2/2004)	Ultimate Target	Probability of Reaching Ultimate Target
Durability	hours	2000 and >50 stop/starts	1000	5,000 and 20,000 starts	high
Power density	W_e/L	700	700	2,000	medium
Efficiency	%	78	78	>80	high
Start-up Energy	MJ/50kWe	<2	7	<2	low
Start-up Time (+20°C)	sec	<60 to 90% traction power	600	<30 to 90% <2 to 10%	low
Transient Response	sec	<5, 10% to 90% and 90% to 10%	10	<1, 10% to 90%, and 90% to 10%	low
Turndown	ratio	20:1	20:1	> 50:1	high
Sulfur Content	ppb	<50 out from 30 ppm in	130	<10 out from 30 ppm in	medium
Cost	$/k$W_e$	n/a	65	<10	low

Table 10: Hydrogen Quality

Impurity	Level
Sulfur	10 ppb
CO	1 ppm
CO_2	100 ppm
NH_3	1 ppm
NMHC on a C-1 basis	100 ppm
O_2, N_2, Ar	< 2%
particulates	Conform to ISO 14687

Table 11. Relationship of DOE Fuel Cell Program to Other Programs

Relationship to Other Programs

Coordinated Areas	Organizations
Hydrogen, Fuel Cell Vehicles, Codes & Standards, Education	Other HFCIT Sub-Program Areas: Hydrogen Production Team Hydrogen Storage Team Technology Validation Safety and Codes/Standards Education and Outreach
Stationary Fuel Cells	DOE Office of Fossil Energy National Energy Technology Laboratory Office of Distributed Energy and Electric Reliability
Propulsion Subsystems, Vehicle System Modeling, Lightweight Materials, Cooperative Automotive Research for Advanced Technology (CARAT), Graduate Automotive Technology Education (GATE)	Office of FreedomCAR and Vehicle Technologies
Fundamental Fuel Cell R&D	DOE Office of Basic Energy Sciences in the Office of Science
Other Federal Government Fuel Cell Development and Demonstrations	Department of Transportation National Aeronautics and Space Administration Department of Defense Defense Advanced Research Projects Agency National Institute of Standards and Technology National Science Foundation
State Agency Fuel Cell Activities	Illinois Department of Commerce and Community Affairs South Coast (California) Air Quality Management District California Fuel Cell Partnership California Air Resources Board California Energy Commission Northeast Sustainable Energy Association Ohio Fuel Cell Initiative
International Activities	International Energy Agency (Asia, Europe, Canada) European Union International Standards Organization International Code Council International Partnership for the Hydrogen Economy
Codes & Standards, Education	U.S. Fuel Cell Council Society of Automotive Engineers Electric Drive Transportation Association National Fire Protection Association National Hydrogen Association

Table 12. Current Listing of DOE Contractors and Projects Directly Relevant to Automotive Applications

Contractor	Project
Transportation Power Systems	
Argonne National Laboratory	Fuel Cell Systems Analysis
National Renewable Energy Laboratory	Fuel Cell Vehicle Systems Analysis
TIAX	Cost Analysis of Fuel Cell Stacks/Systems
UTC Fuel Cells	Atmospheric Fuel Cell Power System for Transportation
Ion Power, Inc.	Platinum Recycling Technology Development
Engelhard	Platinum Group Metal Recycling Technology Development
Cummins	Fuel Cell Auxiliary Power Units
Delphi	Fuel Cell Auxiliary Power Units
Transportation Systems Components	
Honeywell	Turbocompressor for PEM Fuel Cells
Mechanology LLC	Development & Testing of a High-Efficiency, Integrated Compressor/Expander based on Torroidal Intersecting Vane Machine Geometry
Advanced Fluid Technologies, Inc.	Complex Coolant Fluid for PEM Fuel Cell Systems – Phase I SBIR
Fuel Cell Stack Subsystem and Components	
De Nora	Integrated Manufacturing for Advanced Membrane Electrode Assemblies
UTC Fuel Cells	Development of High-Temperature Polymeric Membranes and Improved Cathode Catalysts
3M (three awards)	Advanced MEA's for Enhanced Operating Conditions Novel Approach to Non-Precious Metal Catalysts MEA and Stack Durability for PEM Fuel Cells
Big Sky Economic Development	Membrane Durability Study
Superior Micropowders	Development of High-Performance, Low-Pt Cathodes Containing New Catalyst and Layer Structure.
Porvair Corp.	Scale-Up of Carbon/Carbon Composite Bipolar Plates
Oak Ridge National Laboratory	Cost-Effective Surface Modification for Metallic Bipolar Plates
Case Western Reserve University	High-Temperature Polymer Membranes for Fuel Cells
Los Alamos National Laboratory	Electrodes for Polymer Electrolyte Membranes for Fuel Cell Operation on H_2/Air
Arkema	Development of a Low-Cost, Durable Membrane and Membrane Electrode Assembly for Stationary and Mobile Fuel Cell Applications
DuPont Fuel Cells	Enabling Commercial PEM Fuel Cells with Breakthrough Lifetime Improvements
Lawrence Berkeley National Laboratory	New Electrocatalysts for Fuel Cells
Naval Research Laboratory	Low-Platinum Hydrous Metal Oxide for PEMFC Cathodes
Brookhaven National Laboratory	Low-Platinum Loading Catalysts for Fuel Cells
Los Alamos National Laboratory	Direct Methanol Fuel Cells
Jet Propulsion Laboratory	Development of Advanced Cathode Catalysts

University of South Carolina	Novel Non-Precious Metals for PEMFC: Catalyst Selection Through Molecular Modeling and Durability Studies
Honeywell	Development of a Thermal and Water Management System for PEM Fuel Cells
Plug Power	Development of a Polybenzimidazole-based, High Temperature Membrane and Electrode Assemblies for Stationary and Automotive Applications
Ballard	Development, Characterization, and Evaluation of Transition Metal/Chalcogen Based Cathode Catalysts for PEM Fuel Cells
Farassis Energy, Inc.	Novel Combinatorial Approach to the Development of Cathode Catalysts for Fuel Cells – Phase II SBIR
NuVant Systems, Inc.	Improved Fuel Cell Cathode Catalysts Using Combinatorial Methods – Phase II SBIR
T/J Technologies, Inc.	Low-Cost, High Performance PPSA-Based PEM Fuel cell Membrane – Phase I SBIR
Fuel Processing Subsystem and Components to be completed in FY 2005	
Argonne National Laboratory	Water-Gas Shift Catalysts
Argonne National Laboratory	Catalysts for Autothermal Reforming
Catalytica	Plate-Based Fuel Processing System
Argonne National Laboratory	Quick Starting Fuel Processors
Pacific Northwest National Laboratory	Steam Reformation of Hydrocarbon Fuels
University of Michigan	Fuel Processors for PEM Fuel Cells
Oak Ridge National Laboratory	Selective Catalytic Oxidation of Hydrogen Sulfide
Nuvera	Advanced High Efficiency Quick Start Fuel Processor for Transportation Applications
Cross-Cutting Fuel Cell Characterization and Evaluation	
National Institute of Standards and Technology	Non-Destructive Study of H_2O Transport Mechanism Inside Operating PEMFCs Using Neutron Imaging Techniques
Argonne National Laboratory	Bipolar Plate-Supported Solid Oxide Fuel Cell
Pacific Northwest National Laboratory	SOFC Auxiliary Power Units for Truck Applications
Oak Ridge National Laboratory	Microstructural Characterization of PEM Fuel Cells
Oak Ridge National Laboratory	Fiber Optic Temperature Sensor for PEM Fuel Cells Monitoring
UTC Fuel Cells	Development of Sensors for Automotive PEM-Based Fuel Cells
Honeywell Sensing and Controls	Sensor Development for PEMFC Systems

Appendix A. Existing Federal R&D

Relevant fuel cell development for automotive applications is being conducted under government/industry programs sponsored primarily by DOE, and to a lesser extent by DOD and other government agencies. The related R&D is summarized below and in Table 10.

a. *Department of Energy* (http://www.eere.energy.gov/hydrogenandfuelcells)

Energy Efficiency and Renewable Energy (EERE)

- A list of the current DOE contractor and National Laboratory projects is provided in Table 11. Extended abstracts of these projects can be found in the Hydrogen, Fuel Cells, and Infrastructure Technologies 2003 Annual Progress Report available on the DOE website.
- The Hydrogen Fuel Cells, and Infrastructure Technologies Program Fuel Cells Section is also supporting the R&D of fuel cells for portable and auxiliary power. Portable power fuel cells will likely be the first high-volume market for fuel cells; the resulting manufacturing capability will help reduce the cost of automotive PEM fuel cells. R&D awards resulting from a DOE solicitation for fuel cell systems for portable and auxiliary power applications will be announced late 2003.

Office of Fossil Energy (FE) (http://www.seca.doe.gov)

- The Solid State Energy Conversion Alliance (SECA) program within the DOE Office of Fossil Energy is supporting the development of solid oxide fuel cells (3-10 kW) that can be mass-produced in modular form at $400/kW. The objective of the SECA program is to put reliable fuel cells into a more compact, modular, and affordable design to allow widespread penetration into high volume stationary, transportation(e.g. APUs), and military markets.

Office of Science (SC) (http://www.sc.doe.gov)

- The Office of Science supports basic science projects on fuel cells at Universities and the National Laboratories. R&D activities include the development of novel PEM electrolytes with improved properties, the fabrication of membrane electrode assemblies, and mathematical modeling of PEM fuel cells and fuel cell stacks.

b. *Defense Advanced Research Projects Agency (DARPA)* (http://www.darpa.mil)

- The DARPA program supports research on both direct methanol fuel cells and solid oxide fuel cells. The programs are primarily targeted at the 20-watt level, as there are many military applications that would benefit, e.g., small robots, future soldier systems, micro-air vehicles. Successful development of a 20-watt system will enable scaling to other sizes of interest to DoD. DARPA also supports the development of a fuel processors that produce hydrogen from liquid fuels such as methanol, butane, JP-8 diesel, or diesel for integration with microscale **(**10- to 500-mW_e **)** PEM fuel cells.

c. *Department of Transportation (DOT)* (http://www.dot.fta.gov)

- The DOT fuel cell program (administered through the Federal Transit Administration) is focused on the development and demonstration of fuel cell transit buses and possible future locomotive applications. Buses present a unique niche market that is highly suitable to take advantage of the environmental benefits of fuel cells and address the numerous challenges associated with a shift to a hydrogen economy.

d. National Science Foundation (NSF) (http://www.nsf.gov)

- The NSF Small Business Innovative Research programs address the development of fuel cell components, such as catalysts, bipolar plates, and fuel processors. The NSF also provides support for basic fuel cell research at universities.

e. National Aeronautics and Space Administration (NASA)

- The NASA-sponsored R&D focuses on reducing the weight and size of direct hydrogen-fueled PEMFCs. PEMFC is currently being tested to provide day and night flight capability to the solar-electric Helios Prototype by providing nighttime electrical power to the aircrafts motors, avionics, and experimental payloads. NASA is also supporting the development of solid-oxide fuel cells that operate at substantially lower temperatures than current designs with the objective of making this kind of fuel cell both cheaper to manufacture and easier to fuel.

f. Department of Commerce/NIST/ATP (http://www.atp.nist.gov)

- The Advanced Technologies Program (ATP) within the National Institute of Standards and Technology (NIST), which is an agency within the Department of Commerce, helps accelerate the development of innovative technologies for broad national benefit by co-funding R&D partnerships with the private sector. ATP provides support for the development of DMFC, PEM and solid-oxide fuel cells, including the development and testing of components and complete systems. Applications supported include small stationary as well as portable power.