USDRIVE

DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Fuel Cell Technical Team Roadmap

June 2013

This roadmap is a document of the U.S. DRIVE Partnership. U.S. DRIVE (Driving Research and Innovation for Vehicle efficiency and Energy sustainability) is a voluntary, non-binding, and nonlegal partnership among the U.S. Department of Energy; USCAR, representing Chrysler Group LLC, Ford Motor Company, and General Motors; Tesla Motors; five energy companies — BP America, Chevron Corporation, Phillips 66 Company, ExxonMobil Corporation, and Shell Oil Products US; two utilities — Southern California Edison and DTE Energy; and the Electric Power Research Institute (EPRI).

The Fuel Cell Technical Team is one of 12 U.S. DRIVE technical teams ("tech teams") whose mission is to accelerate the development of pre-competitive and innovative technologies to enable a full range of efficient and clean advanced light-duty vehicles, as well as related energy infrastructure.

For more information about U.S. DRIVE, please see the U.S. DRIVE Partnership Plan, www.vehicles.energy.gov/about/partnerships/usdrive.html or www.uscar.org.

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Mission and Scope[1]

Mission

Promote the development of a fuel cell power system for an automotive powertrain that meets the U.S. DRIVE Partnership (United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability) goals.

Scope

The Fuel Cell Technical Team (FCTT) conducts the following activities:

- Reviews and evaluates materials and systems research regarding fuel cells for light-duty vehicles and provides feedback to the U.S. Department of Energy (DOE) and Partnership stakeholders.
- Generates goals and performance targets for fuel cells for automotive applications.
- Collaborates with other technical teams and assists the Partnership with transportation fuel cell technologies.

U.S. DRIVE Partnership Goals

1) Enable reliable hybrid electric, plug-in hybrid and range-extended electric, and battery electric vehicles with performance, safety, and costs comparable to or better than advanced conventional vehicle technologies, supported by the widespread availability of electric charging infrastructure.

2) **Enable reliable fuel cell electric vehicles with performance, safety, and costs comparable to or better than advanced conventional vehicle technologies, supported by viable hydrogen storage and the widespread availability of hydrogen fuel.**

3) Significantly improve the efficiency of vehicles powered by advanced internal combustion powertrains and vehicle fuel systems while protecting the environment.

4) Improve the efficiency of all vehicle types by using lightweight materials to reduce vehicle mass.

Source: "U.S. DRIVE," United States Council for Automotive Research LLC, http://www.uscar.org/guest/partnership/1/us-drive.

[1] For more information about other fuel cell applications not covered by the U.S. DRIVE Fuel Cell Tech Team, as well as information on fuel cells, fuel cell benefits, fuel cell stack, and components, please visit: http://www1.eere.energy.gov/hydrogenandfuelcells/.

Key Issues and Challenges

Durability and cost are the primary challenges to fuel cell commercialization, as shown in Figure 1.

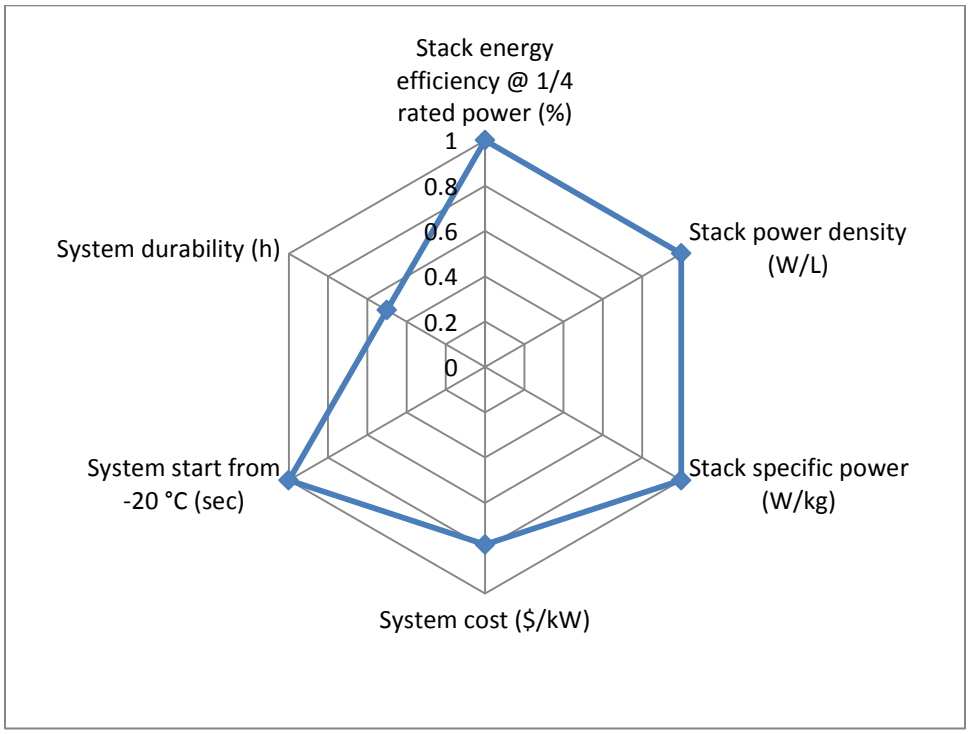

Figure 1. Fuel Cell Targets versus Status
(The blue line indicates the status as a fraction of the targets)

Durability

Transportation fuel cell systems must compete with automotive internal combustion engines (ICEs) and other alternative technologies. To be competitive in the market, fuel cell systems must have durability similar to current ICE systems. The FCTT has identified a durability target of 5,000 hours (equivalent to 150,000 miles of driving) with less than 10% loss of performance. Fuel cell systems must also function over the full range of operating conditions. The desired operating range can encompass operating temperatures from well below the freezing point to above the boiling point of water and operating humidity levels ranging from dry to wet. Furthermore, automotive driving generates transient and cyclic power demands that result in conditions that exacerbate degradation. Fuel cell systems must be demonstrated with long-term durability (≥5,000 hours) under dynamic load following, start/stop operation, road vibration/shock, and ambient conditions.

Cost

To contend with incumbent and future competing technologies, the cost of automotive fuel cell systems needs to be competitive, either on a life cycle cost or initial cost basis. This cost must be achieved while

ensuring that systems provide the performance and durability that automotive customers experience with ICE systems. The U.S. DRIVE FCTT's automotive fuel cell system target is $40/kilowatt (kW) by 2020.[2] There is a significant gap between the current cost estimate and the target cost. Manufacturing has not yet reached the high volumes required to achieve economies of scale. In addition, the cost is highly dependent on the price of materials, which include precious metal catalysts. Reducing the amount of high-cost materials in the fuel cell will reduce overall system cost.

Current Status and Targets

The current status and targets of key fuel cell attributes are shown in Figure 1. Because fuel cell vehicles have not yet been commercialized, little data under real-world usage are publicly available. The primary data sources used to determine the current status of these attributes are technical publications and reports from government research and development (R&D) programs. The status of fuel cell start-up time, efficiency, and durability are based on data analysis from the Fuel Cell Electric Vehicle (FCEV) Learning Demonstration at the National Renewable Energy Laboratory (NREL),[3] sponsored by DOE. The status of fuel cell cost is based on the automotive fuel cell cost analysis study performed by Strategic Analysis, Inc. (SA),[4] also sponsored by DOE.

Power density and specific power are important attributes for light-duty vehicles; however, power density and specific power values at the fuel cell ***system*** level are highly dependent on the overall system design and layout of components rather than the fuel cell technology itself. The power density and specific power at the fuel cell ***stack*** level better represent the technology status. Recent fuel cell stacks are already exceeding the power density and specific power targets of 2.5 kW/L and 2.0 kW/kg, respectively.

As for durability, the latest results from company fleets participating in the FCEV Learning Demonstration indicate the highest company-average projected durability is 2,500 hours with 10% stack voltage degradation. This projection is significantly lower than the durability target of 5,000 hours.

The SA 2012 cost study projects the cost of automotive fuel cell systems to be $51/kW (assuming high-volume [500,000 units per year] production levels and a platinum price of $1,550/troy ounce). This projected cost already assumes some significant R&D outcomes, such as very low platinum (Pt) catalyst loading. Although the cost study uses aggressive technical assumptions, it does not achieve the fuel cell system cost target of $40/kW. Other than durability and cost, current fuel cell system and stack values are already close to technical targets.

The 2020 technical targets and current status values are shown in Tables 1-8. The fuel cell system cost target is $40/kW; the costs of the stack and specific components are provided as guidelines for technology developers and are based on high-volume production assumptions. The fuel cell stack guideline is $20/kW. Accordingly, $20/kW is a guideline for balance of plant (BOP). Subcomponent targets were developed based on fuel cell system and stack targets. Each item in a subcomponent target table is to be

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[2] Based on 2010 dollars and high-volume production (500,000 fuel cell stacks per year). The DOE 2011 Multi-Year Research, Development and Demonstration (MYRD&D) Plan is focused on a stretch target of $30/kW by 2017 (http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf). The original $30/kW target for fuel cell systems to be competitive with gasoline internal combustion engines was developed in the 2002 timeframe through U.S DRIVE's predecessor partnership. DOE is assessing stakeholder input through a formal Request for Information before potential target revisions. Any necessary adjustments to the DOE targets will be made during the next revision of the MYRD&D Plan.

[3] National Renewable Energy Laboratory, K. Wipke et al., *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*, NREL/TP -5600-54860, July2012, http://www.nrel.gov/hydrogen/pdfs/54860.pdf.

[4] B. James and A. Spisak, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2012 Update*, pp. 54-55, Award Number DE-EE0005236, produced by Strategic Analysis Inc., Arlington, VA (Washington, DC: U.S. Department of Energy, October 18, 2012, Revision 4).

thought of as a guideline for subcomponent or material level research and development. Therefore, an individual item of each subcomponent target table is not to be considered as a strict pass/fail criterion.

Table 1. Technical Targets for Automotive-Scale (80 kW_e net) Fuel Cell System Operating on Hydrogen[a]

Characteristic	Units	Status	2020 Target
Energy efficiency[b] @ 25% of rated power	%	60[c]	60
Power density	W/L	640[d]	650
Specific power	W/kg	659[e]	650
Cost[f]	$/kW$_e$	51[f]	40
Cold start-up time to 50% of rated power			
@ -20°C ambient temp	sec	20[g]	30
@ +20°C ambient temp	sec	<10[g]	5
Durability in automotive load cycle	hours	2,500[h]	5,000
Unassisted start from[i]	°C	-30[j]	-30

[a] Target includes fuel cell stack, BOP, and thermal system, and excludes hydrogen storage, battery, electric drive, and power electronics.

[b] Ratio of direct current (DC) output energy to the lower heating value (LHV) of the input fuel (hydrogen).

[c] W. Sung, Y. Song, K. Yu, and T. Lim, "Recent Advances in the Development of Hyundai-Kia's Fuel Cell Electric Vehicles," *SAE Int. J. Engines* 3.1 (2010): 768-772, doi: 10.4271/2010-01-1089.

[d] J. Juriga, *Hyundai Motor Group's Development of the Fuel Cell Electric Vehicle*, May 10th, 2012, http://www.hydrogen.energy.gov/pdfs/htac_may2012_hyundai.pdf.

[e] U. Eberle, B. Muller, and R von Helmolt, *Energy & Environmental Science* 5 (2012): 8780.

[f] Based on 2010 dollars, Pt cost of $1,550/troy ounce, and cost projected to high-volume production (500,000 fuel cell stacks per year); Status: B. James and A. Spisak, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2012 Update*, pp. 54-55, Award Number DE-EE0005236, produced by Strategic Analysis Inc., Arlington, VA (Washington, DC: U.S. Department of Energy, October 18, 2012, Revision 4).

[g] Based on average of status values reported at 2010 SAE World Congress (W. Sung, Y-I. Song, K-H Yu, T.W. Lim, SAE-2-10-01-1089). These systems do not necessarily meet other system-level targets.

[h] Projected time to 10% voltage degradation, as reported in K. Wipke et al., *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*, NREL/TP -5600-54860, July2012, http://www.nrel.gov/hydrogen/pdfs/54860.pdf.

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

[j] Press Release: *Honda Demonstrates the FCX Concept Vehicle,* Sep 25, 2006, http://www.world.honda.com/news/2006/4060925FCXConcept and Associated Press, *Toyota develops a new fuel cell hybrid,* June 6, 2008, http://www.nbcnews.com/id/25004758/.

Table 2. Technical Targets for Fuel Cell Stack[a]

Characteristic	Units	Status	2020 Target
Stack power density[b]	W/L	3,000[c]	2,500
Stack specific power	W/kg	2,000[d]	2,000
Stack efficiency[e] @ 25% of rated power	%	65[f]	65
$Q/\Delta T_i$ [g]	kW/°C	1.9[h]	1.45
Cost[i] (guideline)	$/kW$_e$	24[i]	20
Durability with cycling[j]	hours	2,500 [k]	5,000
Robustness (cold operation)[l]			0.7
Robustness (hot operation)[m]			0.7
Robustness (cold transient)[n]			0.7

[a] Target includes membrane electrode assembly (MEA), bipolar plates, and stack hardware, and excludes balance of plant (BOP) and thermal system.

[b] Power refers to net power (i.e., stack power minus projected BOP power). Volume is "box" volume, including dead space in the stack enclosure.

[c] Press Release: *Toyota Motor Company Announces Status of its Environmental Technology Development, Future Plans*, Sep 24, 2012, http://www2.toyota.co.jp/en/news/12/09/0924.pdf.

[d] M. Hanlon, "Nissan doubles power density with new Fuel Cell Stack," Oct 13, 2011, http://www.gizmag.com/nissan-doubles-power-density-with-new-fuel-cell-stack/20156/.

[e] Ratio of output DC energy to LHV of hydrogen fuel stream.

[f] U. Eberle, B. Muller, and R von Helmolt, *Energy & Environmental Science*, 5 (2012): 8780.

[g] $Q/\Delta Ti$ = [stack power (90 kW) × (1.25 V – voltage at rated power)/(voltage at rated power)]/[(stack coolant out temp (°C) – ambient temp (40°C)]. Target assumes 90 kW stack gross power required for 80 kW net power, measured using the protocol for a polarization curve found in Table A-5 of Appendix A.

[h] Based on a voltage of 0.67 V and stack coolant outlet temperature of 80°C.

[i] Guideline based on 2010 dollars, Pt cost of $1,550/troy ounce, and cost projected to high-volume production (500,000 fuel cell stacks per year). Status: B. James and A. Spisak, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2012 Update*, pp. 54-55, Award Number DE-EE0005236, produced by Strategic Analysis Inc., Arlington, VA (Washington, DC: U.S. Department of Energy, October 18, 2012, Revision 4).

[j] Based on the U.S. DRIVE FCTT protocol for determining cell/stack durability found in Table A-6 of Appendix A, <10% drop in rated power after test.

[k] Projected time to 10% voltage degradation, as reported in K. Wipke et al., *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*, NREL/TP -5600-54860, July 2012, http://www.nrel.gov/hydrogen/pdfs/54860.pdf.

[l] Ratio of fuel cell stack voltage at 30°C to fuel cell stack voltage at 80°C operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table A-5 of Appendix A. A 25°C dew point is used only for 30°C operation.

[m] Ratio of fuel cell stack voltage at 90°C to fuel cell stack voltage at 80°C operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table A-5 of Appendix A. A 59°C dew point is used for both 90°C and 80°C operations.

[n] Ratio of fuel cell stack voltage at 30°C transient to fuel cell stack voltage at 80°C steady-state operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table A-5 of Appendix A. A 25°C dew point is used only for 30°C operation. 30°C transient operation is at 1 A/cm^2 for at least 15 minutes then lowered to 0.1 A/cm^2 for 3 minutes without changing operating conditions. After 3 minutes, the current density is returned to 1 A/cm^2. The voltage is measured 5 seconds after returning to 1 A/cm^2.

Table 3. Technical Targets for MEAs

Characteristic	Units	Status	2020 Target
$Q/\Delta T_i$ [a]	kW/°C	1.9 [b]	1.45
Cost	$/kW	17 [c]	14
Durability with cycling [d, e]	Hours	9,000 [f]	5,000
Performance @ 0.8 V [g]	mA/cm^2	311	300
	mW/cm^2	248	250
Performance @ rated power [e]	mW/cm^2	845 [h]	1,000
Robustness (cold operation) [i]			0.7
Robustness (hot operation) [j]			0.7
Robustness (cold transient) [k]			0.7

[a] $Q/\Delta T_i$ = [Stack power (90 kW) × (1.25 V – voltage at rated power)/(voltage at rated power)]/[stack coolant out temp (°C) – ambient temp (40°C)]. Target assumes 90 kW stack gross power required for 80 kW net power, measured using the protocol for a polarization curve found in Table A-5 of Appendix A.

[b] Based on a voltage of 0.67 V and stack coolant outlet temperature of 80°C.

[c] Guideline based on 2010 dollars, Pt cost of $1,550/troy ounce, and cost projected to high-volume production (500,000 fuel cell stacks per year) Status: B. James and A. Spisak, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2012 Update*, pp. 54-55, Award Number DE-EE0005236, produced by Strategic Analysis Inc., Arlington, VA (Washington, DC: U.S. Department of Energy, October 18, 2012, Revision 4).

[d] Based on the U.S. DRIVE FCTT protocol for determining cell/stack durability found in Table A-6 of Appendix A, <10% drop in rated power after test.

[e] Need to meet or exceed at temperatures of 80°C up to peak temperature, measured using the polarization curve protocol found in Table A-5 of Appendix A.

[f] M. Debe, 3M, "Advanced Cathode Catalysts and Supports for PEM Fuel Cells," DOE Hydrogen and Fuel Cells Program Annual Merit Review, May 2011, 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.)

[g] Target must be met at 150 kPag outlet pressure. Status reference: 311 mA/cm^2 is the mean value for duplicate 3M 2012 Best of Class NSTF MEAs: Anode = 0.03Pt/NSTF, Cathode = 0.121Pt3Ni7/NSTF, (0.151 $mgPGM/cm^2$ total), 3M 825EW 24μ PEM, Baseline 2979/2979 GDLs, Baseline Quad Serpentine Flow Field, operated at 90°C cell temperature with subsaturated inlet humidity and anode/cathode stoichs of 2.0/2.5 and at 150 kPag anode/cathode reactant outlet pressure. 248 mW/cm^2 status was calculated: 311 mA/cm^2 multiplied by 0.8V.

[h] M. Debe, 3M, "Advanced Cathode Catalysts and Supports for PEM Fuel Cells," DOE Hydrogen and Fuel Cells Program Annual Merit Review, May, 2011, http://www.hydrogen.energy.gov/pdfs/review11/fc001_debe_2011_o.pdf.

[i] Ratio of fuel cell stack voltage at 30°C to fuel cell stack voltage at 80°C operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table A-5 of Appendix A. A 25°C dew point is used only for 30°C operation.

[j] Ratio of fuel cell stack voltage at 90°C to fuel cell stack voltage at 80°C operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table A-5 of Appendix A. A 59°C dew point is used for both 90°C and 80°C operations.

[k] Ratio of fuel cell stack voltage at 30°C transient to fuel cell stack voltage at 80°C steady-state operation at 1.0 A/cm^2, measured using the protocol for a polarization curve found in Table A-5 of Appendix A. A 25°C dew point is used only for 30°C operation. 30°C transient operation is at 1 A/cm^2 for at least 15 minutes then lowered to 0.1 A/cm^2 for 3 minutes without changing operating conditions. After 3 minutes, the current density is returned to 1 A/cm^2. The voltage is measured 5 seconds after returning to 1 A/cm^2.

Table 4. Technical Targets for Membranes

Characteristic	Units	Status[a]	2020 Target
Maximum operating temperature	°C	120	120
Area specific proton resistance at:			
Maximum operating temp and water partial pressures from 40 to 80 kPa	Ohm cm^2	0.023 (40 kPa) 0.012 (80 kPa)	0.02
80°C and water partial pressures from 25 to 45 kPa	Ohm cm^2	0.017 (25 kPa) 0.006 (44 kPa)	0.02
30°C and water partial pressures up to 4 kPa	Ohm cm^2	0.02 (3.8 kPa)	0.03
-20°C	Ohm cm^2	0.1	0.2
Maximum oxygen crossover[b]	mA/cm^2	<1	2
Maximum hydrogen crossover[b]	mA/cm^2	<1.8	2
Minimum electrical resistance[c]	Ohm cm^2		1,000
Cost[d]	$\$/m^2$	18[e]	20
Durability[f]			
Mechanical	Cycles w/<10 sccm crossover	>20,000	20,000
Chemical	hours	>2,300	500

[a] Status represents 3M PFIA membrane (S. Hamrock, 3M, *Membranes and MEAs for Dry, Hot Operating Conditions*, DOE 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] Measure in humidified N_2/N_2 at 0.5 V DC at 80°C.

[d] Guideline based on 2010 dollars and costs projected to high-volume production (500,000 fuel cell stacks per year).

[e] B. James and A. Spisak, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2012 Update*, pp. 54-55, Award Number DE-EE0005236, produced by Strategic Analysis Inc., Arlington, VA (Washington, DC: U.S. Department of Energy, October 18, 2012, Revision 4).

[f] Based on the MEA chemical stability and metrics (Table A-3) and membrane mechanical cycle and metrics (Table A-4) described in Appendix A.

Table 5. Technical Targets for Electrocatalysts

Characteristic	Units	Status	2020 Target
Platinum group metal (PGM) total content[a]	g/kW rated	0.14[b]	0.125
PGM total loading[a]	mg PGM/cm^2 electrode area	0.15[b]	0.125
Loss in catalytic (mass) activity[c]	%	37[d]	40% loss of initial
Loss in high current density performance	mV	10[d]	30 at 0.8 A/cm^2 (Table A-1)
Loss in high current density performance	mV	10[e]	30 at 1.5 A/cm^2 (Table A-2)
Mass activity[f]	A/mg$_{PGM}$ @ 900 mV$_{iR\text{-}free}$	0.47-0.67[b]	0.44
Non-PGM catalyst activity per volume of supported catalyst[f,g]	A/cm^3 @ 800 mV$_{iR\text{-}free}$	60[h]	300

[a] PGM (Pt, Ir, Os, Ru, Rh, and Pd) content and loading targets may have to be lower to achieve system cost targets. The cost impact of the use of other precious metals, e.g., Au and Re, also needs to be considered.

[b] 50 cm^2 with Pt_3Ni_7, M. Debe, 3M, "Advanced Cathode Catalysts and Supports from PEM Fuel Cells," DOE Hydrogen and Fuel Cells Program 2012 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress12/v_d_1_debe_2012.pdf.

[c] See Table A-1 of Appendix A.

[d] M. Debe, 3M, "Advanced Cathode Catalysts and Supports from PEM Fuel Cells," DOE Hydrogen and Fuel Cells Program 2012 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress12/v_d_1_debe_2012.pdf, 30,000 cycles 0.6-1.0V, 50mV/sec, 80/80/80ºC, 100 kPa (abs), H_2/N_2.

[e] M. Debe, 3M, "Advanced Cathode Catalysts and Supports from PEM Fuel Cells," DOE Hydrogen and Fuel Cells Program 2012 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress12/ v_d_1_debe_2012.pdf, 1.2 V for 400 hrs at 80ºC, H_2/N_2, 150 kPa (abs), 100% relative humidity.

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

[g] Volume = active area multiplied by catalyst layer thickness.

[h] P. Zelenay, H. Chung, C. Johnston, N. Mack, M. Nelson, P. Turner, and 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 6. Technical Targets for Bipolar Plates

Characteristic	Units	Status	2020 Target
Plate cost[a]	$/kW	4[b,c]	3
Plate weight	kg/kW	<0.4[c,d]	0.4
Plate H_2 permeation coefficient[e]	Std $cm^3/(sec\ cm^2\ Pa)$ @ 80°C, 3 atm 100% RH	$<2 \times 10^{6}$ [f]	1.3×10^{-14}
Corrosion anode[g]	$\mu A/cm^2$	no active peak[h]	1 and no active peak
Corrosion cathode[i]	$\mu A/cm^2$	<0.1	1
Electrical conductivity	S/cm	>100[j]	100
Areal specific resistance[k]	Ohm cm^2	0.006[h]	0.01
Flexural strength[l]	MPa	>34 (carbon plate)	25
Forming elongation[m]	See note m	20-40[n]	See note m

[a] Guideline based on 2010 dollars and costs projected to high-volume production (500,000 fuel cell stacks per year), assuming MEA meets performance target of 1,000 mW/cm^2.

[b] Based on 50% utilization of active area on the whole plate surface, stainless steel foil cost at historical average of $2/lb, 1 W/cm^2 power density, and projected 500,000 fuel cell stacks/year production.

[c] C.H. Wang, Treadstone, "Low-cost PEM Fuel Cell Metal Bipolar Plates," DOE Hydrogen and Fuel Cells Program 2012 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress12/v_h_1_wang_2012.pdf.

[d] Based on the 0.1 mm thick stainless steel foil.

[e] ASTM D-1434: Standard Test Method for Determining Gas Permeability Characteristics of Plastic Film and Sheeting.

[f] J. Mawdsley, Argonne National Laboratory, "Metallic Bipolar Plates with Composite Coatings," DOE Hydrogen and Fuel Cells Program 2011 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress11/v_h_2_mawdsley_2011.pdf.

[g] Guideline, not to be used as a pass/fail criterion: pH 3, 0.1 ppm HF, 80°C, potentiodynamic test at 0.1 mV/s, -0.4 V to +0.6 V [Ag/AgCl], de-aerated with argon purge.

[h] A. Kumar, M. Ricketts, and S. Hirano, "Ex-situ evaluation of nanometer range gold coating on stainless steel substrate for automotive polymer electrolyte membrane fuel cell bipolar plate," *Journal of Power Sources* 195 (2010): 1401-1407, September 2009.

[i] Guideline, not to be used as a pass/fail criterion: pH 3, 0.1 ppm HF, 80°C, potentiostatic test at +0.6 V [Ag/AgCl] for >24 hours, aerated solution. Status reference: C.H. Wang, Treadstone, "Low-cost PEM Fuel Cell Metal Bipolar Plates," DOE Hydrogen and Fuel Cells Program 2012 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress12/v_h_1_wang_2012.pdf.

[j] O. Adrianowycz, GrafTech, "Next Generation Bipolar Plates for Automotive PEM Fuel Cells," DOE Hydrogen and Fuel Cells Program 2009 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress09/v_g_2_adrianowycz.pdf.

[k] Measured across the bipolar plate; includes interfacial contact resistance (on as received and after potentiostatic test), measured both sides at 200 pounds per square inch (138 N/cm^2), H. Wang, M. Sweikart, and J. Turner, "Stainless steel as bipolar plate material for polymer electrolyte membrane fuel cells," *Journal of Power Sources* 115 (2003): 243-251.

[l] ASTM-D 790-3: Standard Test Method for Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials. Status references: 2007 Porvair Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress07/v_b_3_haack.pdf, states 35 MPa and GrafTech 2009 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress09/v_g_2_adrianowycz.pdf, states >55Mpa.

[m] 40%, per ASTM E8M-01: Standard Test Method for Tension Testing of Metallic Materials, or demonstrate ability to stamp generic channel design with width, depth, and radius.

[n] M. Brady, Oak Ridge National Laboratory, "Nitrided Metallic Bipolar Plates," DOE Hydrogen and Fuel Cells Program 2010 Annual Progress Report, http://www.hydrogen.energy.gov/pdfs/progress10/v_l_1_brady.pdf.

Table 7. Technical Targets for Air Compression System

Characteristic	Units	Status	2020 Target
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 start-up 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
Cost[f]	$	842[g]	500

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

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

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

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

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

[f] Guideline based on 2010 dollars and costs projected to high-volume production (500,000 fuel cell stacks per year).

[g] Brian D. James and Andrew B. Spisak, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Application: 2012 Update*, pp. 20, October 18, 2012, Revision 4.

Table 8. Technical Targets for Cathode Humidification System and Humidifier Membrane

Characteristic	Units	Status[a]	2020 Target
Maximum operating temperature	°C	110-125	95
Maximum pressure differential between wet and dry sides	kPa	75	75
Maximum pressure drop at full flow (each side)	kPa	<3	3.5
Water transfer at full flow[b]	g s^{-1}	7.35 BOL 5.5 after 5,000 hr	5
Durability (<10% transport loss)[c]	hours	5,000	5,000
Maximum air leakage at full flow	%	0.5	0.5
Volume	L	4.3	5
Weight	kg	2.7	5
Humidifier membrane water transfer flux at full flow[b]	g min^{-1} cm^{-2}	>0.03	0.025
System cost[d]	$	99	100
Humidifier membrane cost[d]	$/$m^2$		10

[a] Final Report, Gore DE-EE0000465, *Materials and Modules for Low Cost, High performance Fuel Cell Humidifiers,* February 2013.
[b] Dry air in: 3,000 SLPM dry gas flow, 183 kPa (absolute), 80°C, and 0% RH. Wet air in: 2,600 SLPM dry gas flow, 160 kPa (absolute), 80°C, and 85% RH.
[c] Based on U.S. DRIVE FCTT component accelerated stress test and polarization curve protocols (see Appendix A), <10% drop in water transfer at full flow.
[d] Guideline based on cost projected to high-volume production (500,000 systems per year).

Gaps and Technical Barriers

Durability

Current fuel cell systems have demonstrated durability of tens of thousands of hours in stationary applications, but they have shown much lower durability under automotive type conditions. Results from the FCEV Learning Demonstration have shown an increase in durability over the last two generations of fuel cell stacks, with an average fleet durability increasing from 821 hours for Generation 1 vehicles (2003-2005 stack technology) to 1,062 hours for Generation 2 vehicles (2005-2007 stack technology) and 1,748 hours for vehicles operated after the fourth quarter of 2009 (2007-2009 stack technology).

The second-generation vehicle results indicate that the highest single-team average projected time to 10% voltage degradation was 2,521 hours.[5] This durability status is an improvement, but it is still substantially short of the target of 5,000 hours. It is also important to consider that the 10% voltage loss criterion, which is used for assessing progress toward FCTT targets, may differ from the end-of-life criterion defined by original equipment manufacturers (OEMs). There are many systems that can successfully operate beyond 10% voltage loss, and the amount of degradation allowable is considered proprietary information. Some sensitivity to this parameter was investigated, but that study was limited by the number of operating hours and errors associated with extrapolating durability significantly beyond the number of operating hours. For first-generation vehicles, which have more operation time and fewer extrapolations, increasing the percentage from 10% degradation to 30% degradation roughly doubled the projected durability.

[5] K. Wipke, S. Sprik, J. Kurtz, T. Ramsden, C. Ainscough, and G. Saur, *National Fuel Cell Electric Vehicle Learning Demonstration Final Report*, NREL/TP-5600-54860 (Golden, CO: National Renewable Energy Laboratory, July 2012), http://www.nrel.gov/hydrogen/pdfs/54860.pdf.

Higher durability has been reported for newer technology in the laboratory environment. NREL has determined an average projected time in laboratory tests of 4,000 hours to 10% degradation for automotive applications, still short of the target.[6] However, it is important to note for automotive and other motive power fuel cell applications, considerable gaps exist between degradation observed in the laboratory and degradation observed in the field. NREL's forklift durability projections show significant differences between laboratory results (average projection is 14,600 hours to 10% degradation) and in service under real-world conditions (average projection is approximately 3,000 hours to 10% degradation). Causes for these discrepancies might include differences between the operating conditions in the laboratory tests and the actual conditions in the field, as well as the inclusion of newer technology in the laboratory tests.

Durability and cost are both related to catalyst loading, and it is unclear from the NREL composite data what catalyst loadings were used to achieve the durability reported. For example, one method to decrease the amount of Pt is to increase the Pt surface area through better dispersions and smaller particle sizes. However, larger particles have shown better durability, and particle size has been identified as one of the main properties determining durability.[7] Attempting to decrease cost by increasing the dispersion and decreasing particle size to meet the cost target would decrease durability.

Cost

Recent estimates of the current cost of an 80 kW automotive fuel cell system (materials and production) projected to high volume are approximately $51/kW at 500,000 units/year.[8] This figure is $11/kW greater than the target, indicating that cost must be reduced. On a life cycle cost basis, operating costs are directly linked to fuel costs and efficiency. Changes in the cost of gasoline, hydrogen, or other competing fuels will change the point at which the life cycle costs of a fuel cell vehicle are comparable to life cycle costs of an ICE vehicle. Abundant natural gas supplies could lead to decreases in the cost of hydrogen from natural gas reforming, which would lower life cycle costs for fuel cell electric vehicles, enabling a higher cost for the fuel cell system equipment itself.

The fuel cell cost estimate is based on the initial performance of systems demonstrated in the laboratory, and it does not take into account that these systems do not have the durability needed to compete with ICE vehicles. Cost and durability targets must be met simultaneously. Some strategies to reduce cost, such as decreasing catalyst loading, have led to decreased durability.

Manufacturing volume is not at the high production levels assumed in the SA fuel cell cost study; these volumes will not occur until fuel cell vehicles have captured a significant portion of the market. At today's low production volume and at volumes for introduction into the market, actual costs are much higher than those projected at high volume. At high production volumes, more than half of the system cost is due to BOP components. BOP components are relatively mature technologies and it is difficult to achieve significant cost savings in this area. However, BOP costs can be reduced by improving stack performance and thus lowering BOP component requirements. Of the fuel cell stack costs at high volume,

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[6] J. Kurtz, K. Wipke, S. Sprik, and G. Saur, "Fuel Cell Technology Status – Voltage Degradation," 2012 DOE Annual Merit Review (presentation, U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Merit Review, Arlington, VA, May 17, 2012), http://www.hydrogen.energy.gov/pdfs/review12/fc081_kurtz_2012_o.pdf.

[7] D. Myers, X. Wang, N. Kariuki, et al., "Polymer Electrolyte Fuel Cell Lifetime Limitations: The Role of Electrocatalyst Degradation" (presentation, U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Merit Review, Arlington, VA, May 2012), http://www.hydrogen.energy.gov/pdfs/review12/fc012_myers_2012_o.pdf.

[8] B. James and A. Spisak, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2012 Update*, pp. 54-55, Award Number DE-EE0005236, produced by Strategic Analysis Inc., Arlington, VA (Washington, DC: U.S. Department of Energy, October 18, 2012, Revision 4).

the highest portion is due to the catalyst and catalyst ink application (nearly half the cost), followed by the bipolar plate (approximately a quarter of the cost) and the membrane (approximately a tenth of the cost).

Strategies to Overcome Barriers and Achieve Technical Targets

Durability and cost, the two main barriers to development of a fuel cell power system for an automotive powertrain, are interrelated. The targets for durability and cost must be met simultaneously. In addition, strategies to address cost must do so without negatively impacting durability, and strategies to address durability must not negatively impact cost. To ensure this relationship is taken into account, cost and durability are being addressed for each fuel cell system subcomponent area under development in the DOE research portfolio: catalysts, membranes, bipolar plates, and BOP.

Table 9 identifies the current areas of focus for DOE-funded projects addressing automotive fuel cells and the barriers they address.

Table 9. DOE Efforts Addressing Automotive Fuel Cell Durability and Cost

Research Area	Cost	Durability
Catalyst/electrode development	X	X
Degradation studies		X
Transport studies	X	X
Membrane development	X	X
Impurity studies	X	X
BOP	X	X
Analysis/characterization studies	X	X
Bipolar plate and seal studies	X	X

Durability

The strategy to address durability involves identifying degradation mechanisms and developing approaches for mitigating their effects. The fundamentals of aging are studied at the component and MEA levels using a combination of in situ tests and ex situ experiments to isolate and understand the different degradation modes. Researchers have identified several fundamental degradation modes, including the following:

- Surface area and activity loss due to catalyst dissolution
- Catalyst particle growth and agglomeration
- Activity loss due to catalyst support corrosion
- Degradation due to corrosion of the bipolar plates
- Voltage loss due to increasing contact resistance between individual components
- Membrane degradation due to chemical attack and mechanical stress
- Catalyst and membrane performance loss due to contamination

Several projects look at developing models to predict MEA degradation and provide guidance for how to further improve MEA durability.

Catalyst degradation is one of the limiting factors affecting durability. To address the catalyst degradation modes, researchers are investigating nanostructured alloy particles, dealloyed nanoparticles, nanostructured thin films, and extended thin film surfaces to try to obtain more stable and more active catalysts. Researchers are also attempting to develop alloy catalysts that protect the base transition metals

from the corrosive fuel cell environment by forming nanostructured materials in which Pt segregates to the surface. Another strategy under investigation to increase catalyst durability is adding oxygen evolution reaction catalysts to the cathode and anode to decrease the local potentials seen during start-up/shutdown cycles and during cell reversal. Catalyst support corrosion is also a durability issue, especially during start-up/shutdown and cell reversal. To address this, several researchers are investigating alternative carbon supports and metal oxide supports. Researchers are pursuing all of these strategies while also attempting to reduce Pt and PGM loading to decrease cost.

Studies on transport and degradation in MEAs are seeking to better understand the losses at the interfaces. Changes in hydration levels can lead to large mechanical stresses in the membranes that lead to membrane degradation. Membrane projects are looking at the durability of new membranes and at improved supports to reduce degradation due to mechanical stresses during operation. Modeling and experimental efforts are underway to better understand the water transport and local hydration levels in the MEA.

Bipolar plate corrosion can lead to increased voltage drop due to increased contact resistance. In addition, corrosion products can leach into the MEA and poison the ionomer in the catalyst layer or the membrane. Transition metal cations can move (via ion exchange) into the ionomer, leading to decreased proton conductivity. Some of these cations can catalyze formation of radicals that degrade the membrane. Researchers are pursuing strategies to prevent these degradation modes, including developing new conductive coatings for metallic bipolar plates to decrease corrosion.

Cost

Cost is addressed through materials and component development, assisted by a combination of analysis and characterization studies. The analysis and characterization studies allow R&D program managers to determine the limiting factors on performance and focus materials development efforts where they can have the most impact. Materials development provides higher-performance and lower-cost alternatives to current components. The SA cost study investigated the sensitivity of automotive fuel cell system cost to a number of key parameters; results are shown in Figure 2 and Table 10. [9]

[9] B. James and A. Spisak, *Mass Production Cost Estimation of Direct H_2 PEM Fuel Cell Systems for Transportation Applications: 2012 Update*, p. 54-55, Award Number DE-EE0005236, produced by Strategic Analysis Inc., Arlington, VA (Washington, DC: U.S. Department of Energy, October 18, 2012, Revision 4).

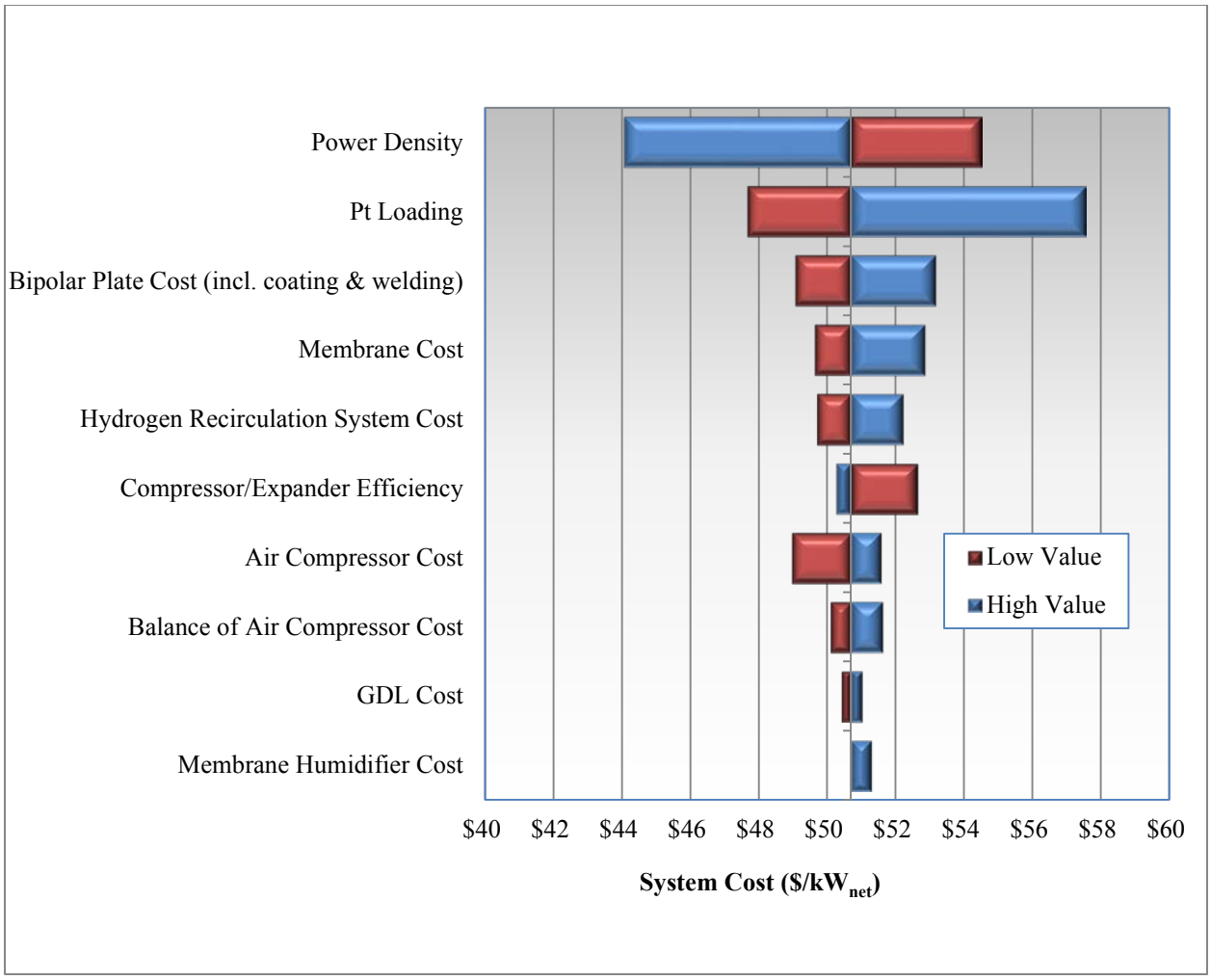

Figure 2. Sensitivity of Fuel Cell System Cost to Key Parameters

Table 10. Basis for Upper and Lower Bounds on Each Parameter

System Cost ($/kWnet), 500,000 systems/year				
Parameter	**Units**	**Low Value**	**Base Value**	**High Value**
Power Density	**mW/cm^2**	833	**984**	1,464
Pt Loading	**mgPt/cm^2**	0.15	**0.196**	0.3
Bipolar Plate Cost (incl. coating & welding)	**cost multiplier**	0.667	**1.0**	1.5
Membrane Cost	**cost multiplier**	0.5	**1**	2
Hydrogen Recirculation System Cost	**$/system**	$160.25	**$240.38**	$360.57
Compressor/Expander Efficiency	**cost multiplier**	0.90	**1**	1.03
Air Compressor Cost	**cost multiplier**	0.8	**1**	1.1
Balance of Air Compressor Cost	**$/system**	$97.53	**$146.30**	$219.45
GDL Cost	**$/m^2**	$3.23	**$4.45**	$5.80
Membrane Humidifier Cost	**$/system**	$52.94	**$52.94**	$100.00

Due to the high sensitivity of cost to power density, one strategy to reduce cost is increasing power density by operating at higher current densities, which decreases stack active area. Lower stack active area reduces the required amount of Pt catalyst, membrane, and diffusion media. Transport processes, especially transport of water, can limit performance at high power density.

As part of the FCTT's strategy to reduce cost, researchers are conducting studies to understand mass transport in a fuel cell. Efforts include developing and validating transport models as well as tools and analysis techniques to measure materials transport properties and determine local water content in an MEA during operation. These tools will help materials suppliers and OEMs optimize materials and designs to provide better performance at high power density and reduce system size and costs.

Researchers are also developing new materials with increased performance. Figure 2 shows the high sensitivity of system cost to Pt catalyst loading. Scientists are developing catalysts with increased activity to reduce the amount of PGM, and specifically Pt, needed per unit of active area. This strategy is focused on the cathode oxygen reduction reaction (ORR) catalyst because ORR is the limiting step of the overall fuel cell reaction. Efforts are focused on reducing the Pt content through development of bi- and tri-metallic catalysts, including dealloyed nanoparticle catalysts and extended thin film alloy catalysts, as well as developing non-PGM catalysts based on nitrogen complexes of base transition metals and carbon-nitrogen-based catalysts.

Figure 2 suggests that another strategy to reduce cost is to address BOP costs (air compressor, humidifier, etc.). While scientists are conducting some research on BOP air handling and water management systems, BOP components are relatively mature technologies and it is difficult to achieve significant cost savings with research in this area. In addition to pursuing direct BOP component development to reduce costs, researchers are conducting work that can lead to system simplification and elimination or downsizing of BOP components. One method to simplify BOP is the development of membranes and MEAs that can operate under hot-dry conditions. Membranes that can operate under hotter conditions can reduce the size of the cooling system, while membranes that can operate without external humidification can allow for elimination of the humidifier portion of the BOP, resulting in substantial cost savings. In a parallel effort, researchers are working to reduce the cost of the humidifier membrane and humidification system in the

event that efforts to develop PEM fuel cell membranes that operate without humidification are unsuccessful. Work to increase fuel cell stack power density can also lower BOP component requirements, reducing BOP size and costs.

Bipolar plates account for a large fraction of the stack costs. Efforts to reduce bipolar plate costs include designing bipolar plates using less expensive materials and manufacturing corrosion-resistant coatings with simpler methods. Researchers are also pursuing less expensive electrolyte membrane precursor materials and low-cost fabrication methods for membrane sheets.

Within the U.S. DRIVE Partnership, the FCTT interacts with the Hydrogen Storage, Hydrogen Delivery, Hydrogen Codes and Standards, and Hydrogen Production Tech Teams. Areas of intersection include hydrogen quality requirements and fuel cell requirements for hydrogen delivery from onboard storage (e.g., flow rates required, storage required), as well as appropriate division of system cost targets, etc. Interactions with the Vehicle Systems Analysis Tech Team are ongoing to determine vehicle level targets that will make fuel cell vehicles competitive with other technologies, including advanced ICE vehicles.

Appendix A: FCTT AST and Polarization Curve Protocols for PEMFCs

U.S. DRIVE Fuel Cell Technical Team
Cell Component Accelerated Stress Test and Polarization Curve Protocols for PEM Fuel Cells
(Electrocatalysts, Supports, Membranes, and Membrane Electrode Assemblies)
Last Revision: January 14, 2013

Fuel cells, especially for automotive propulsion, must operate over a wide range of operating and cyclic conditions. The desired operating range encompasses temperatures from below the freezing point to well above the boiling point of water, humidity from ambient to saturated, and half-cell potentials from 0 to >1.5 volts. Furthermore, the anode side of the cell may be exposed to hydrogen and air during different parts of the driving and start-up/shutdown cycles.

The severity in operating conditions is greatly exacerbated by the transient and cyclic nature of the operating conditions. The cell/stack conditions cycle, sometimes quite rapidly, between high and low voltages, temperatures, humidities, and gas compositions. The cycling results in physical and chemical changes, sometimes with catastrophic results.

This document describes test protocols to assess the performance and durability of fuel cell components intended for automotive propulsion applications. The goal of this testing is to gain a measure of component durability and performance of electrocatalysts and supports, membranes, and membrane electrode assemblies (MEAs) for comparison against DOE and U.S. DRIVE targets. The resulting data may also help to model the performance of the fuel cell under variable load conditions and the effects of aging on performance.

These protocols are intended to establish a common approach for determining and projecting the durability of polymer electrolyte membrane (PEM) fuel cell components under simulated automotive drive cycle conditions.

This document is not intended to be comprehensive, as there are many issues critical to a vehicular fuel cell (e.g., freeze/thaw cycles) that are not addressed at this time. Additional issues will be addressed in the future. Furthermore, it is recognized that the cycles specified herein have not been fully correlated with data from fuel cell stacks and systems operated under actual drive cycles. Therefore, additional tests to correlate these results to real-world lifetimes are needed, including actual driving, start/stop, and freeze/thaw cycles.

The durability of catalysts can be compromised by platinum (Pt) particle growth and dissolution, especially at high electrode potentials; this sintering/dissolution is accelerated under load-cycling. Durability of catalyst supports is another technical barrier for stationary and transportation applications of PEM fuel cells. Corrosion of high-surface-area carbon supports poses significant concerns at high electrode potentials and is accelerated during start/stop cycles and during higher temperature operation (>100°C).

Membranes are another critical component of the fuel cell stack and must be durable and tolerate a wide range of operating conditions, including humidity ranging from 20% to 100% relative humidity (RH) and temperatures ranging from -40 to 120°C for transportation applications and >120°C for stationary applications. The low operating temperature and the humidity requirements of current membranes add complexity to the fuel cell system that impacts the system cost and durability. Improved membranes are needed that perform better and are less expensive than the current generation of polymer membranes.

The associated testing protocols and performance metrics are defined in Table A-1 for electrocatalysts, Table A-2 for catalyst supports, Table A-3 for membrane/MEA chemical stability, and Table A-4 for membrane/MEA mechanical durability, respectively, as derived from References 1 and 2.

The specific conditions and cycles are intended to isolate effects and failure modes and are based on assumed, but widely accepted, mechanisms. For example, the electrocatalyst cycle is different from the support cycle because these two cycles suffer from different degradation mechanisms under different conditions. Similarly, membrane/MEA chemical degradation is distinguished from mechanical degradation.

Durability screening at conditions and under cycles different from those presented herein are acceptable if the developer can provide convincing evidence that the cycle/conditions does not compromise the separation/isolation of degradation mechanisms.

Data to be reported, if applicable, at each point on the polarization curves and during steady-state and variable load operation include, but are not limited to, the following:

- Ambient temperature and pressure
- Cell voltage
- Cell current and current density
- Cell temperature
- Cell resistance, if available (along with test conditions)
- Fuel inlet and outlet temperature
- Fuel flow rate
- Fuel inlet and outlet pressure
- Fuel inlet dew point
- Air inlet and outlet temperature
- Air flow rate
- Air inlet and outlet pressure
- Air inlet dew point
- Fuel and air quality
- Coolant inlet temperature
- Coolant outlet temperature
- Coolant flow rate

Pre-test and post-test characterization of cell and stack components should be performed according to the developer's established protocols. At the discretion of the developer, tests should be terminated when hydrogen crossover exceeds safe levels.

Table A-5 contains the polarization curve protocols referenced in Tables 1 and 2 of this document. Table A-6 contains the protocol for determining cell/stack durability corresponding to the 5,000-hour U.S. DRIVE Fuel Cell Tech Team durability target.

References

1. Mark Mathias et al., "Two Fuel Cells in Every Garage?" *Interface* 14.3 (Fall 2005): 24-35, http://electrochem.org/dl/interface/fal/fal05/IF8-05_Pg24-35.pdf.
2. Mark Mathias et al. "Can Available Membranes and Catalysts Meet Automotive PEMFC Requirements?" *Prepr. Pap.-Am Chem. Soc., Div. Fuel Chem.,* 49.2 (2004): 471-474, http://web.anl.gov/PCS/acsfuel/preprint%20archive/Files/49_2_Philadelphia_10-04_1010.pdf.

Table A-1. Electrocatalyst Cycle and Metrics
Table Revised March 2, 2010

Cycle	Triangle sweep cycle: 50 mV/s between 0.6 V and 1.0 V. Single cell 25-50 cm^2	
Number	30,000 cycles	
Cycle time	16 seconds	
Temperature	80°C	
Relative humidity	Anode/cathode 100/100%	
Fuel/oxidant	Hydrogen/N_2 (H_2 at 200 sccm and N_2 at 75 sccm for a 50 cm^2 cell)	
Pressure	Atmospheric pressure	
Metric	**Frequency**	**Target**
Catalytic mass activity*	At beginning and end of test minimum	≤40% loss of initial catalytic activity
Polarization curve from 0 to ≥1.5 A/cm^2**	After 0, 1k, 5k, 10k, and 30k cycles	≤30 mV loss at 0.8 A/cm^2
ECSA/cyclic voltammetry***	After 10, 100, 1k, 3k, 10k, 20k, and 30k cycles	≤40% loss of initial area

* Mass activity in A/mg @ 150 kPa abs, backpressure at 857 mV iR-corrected on 6% H_2 (bal N_2)/O_2 (or equivalent thermodynamic potential), 100% RH, 80°C normalized to initial mass of catalyst and measured before and after test.
** Polarization curve per Fuel Cell Tech Team Polarization Protocol in Table A-5.
*** Sweep from 0.05 to 0.60 V at 20 mV/s, 80°C, and 100% RH.

Table A-2. Catalyst Support Cycle and Metrics
Table Revised January 14, 2013

Cycle	Triangle sweep cycle: 500 mV/s between 1.0 V and 1.5 V; run polarization curve and ECSA; repeat for total 400 h. Single cell 25-50 cm^2	
Number	5,000 cycles	
Cycle time	2 seconds	
Temperature	80°C	
Relative humidity	Anode/cathode 100/100%	
Fuel/oxidant	Hydrogen/nitrogen	
Pressure	Atmospheric	
Metric	**Frequency**	**Target**
Catalytic activity*	At beginning and end of test, minimum	≤40% loss of initial catalytic activity
Polarization curve from 0 to ≥1.5 A/cm^2**	After 0, 10, 100, 200, 500, 1k, 2k, and 5k cycles	≤30 mV loss at 1.5 A/cm^2 or rated power
ECSA/cyclic voltammetry***	After 0, 10, 100, 200, 500, 1k, 2k, and 5k cycles	≤40% loss of initial area

* Mass activity in A/mg @ 150 kPa abs, backpressure at 857 mV iR-corrected on 6% H_2 (bal N_2)/O_2 (or equivalent thermodynamic potential), 100% RH, 80°C normalized to initial mass of catalyst and measured before and after test.
** Polarization curve per Fuel Cell Tech Team Polarization Protocol in Table A-5.
*** Sweep from 0.05 to 0.6 V at 20 mV/s, 80°C, and 100% RH.

Table A-3. MEA Chemical Stability and Metrics
Table Revised December 10, 2009

Test condition	Steady-state OCV, single cell 25-50 cm^2	
Total time	500 hours	
Temperature	90°C	
Relative humidity	Anode/cathode 30/30%	
Fuel/oxidant	Hydrogen/air at stoics of 10/10 at 0.2 A/cm^2 equivalent flow	
Pressure, inlet kPa abs (bara)	Anode 150 (1.5), cathode 150 (1.5)	
Metric	**Frequency**	**Target**
F^- release or equivalent for non-fluorine membranes	At least every 24 hours	No target – for monitoring
Hydrogen crossover (mA/cm^2)*	Every 24 hours	$\leq$2 mA/cm^2
OCV	Continuous	$\leq$20% loss in OCV
High-frequency resistance	Every 24 hours at 0.2 A/cm^2	No target – for monitoring
Shorting resistance**	Every 24 hours	>1,000 ohm cm^2

* Crossover current per USFCC "Single Cell Test Protocol" Section A3-2, electrochemical hydrogen crossover method.
** Measured at 0.5 V applied potential, 80°C, and 100% RH N_2/N_2. Compression to 20% strain on the GDL.

Table A-4. Membrane Mechanical Cycle and Metrics
(Test Using an MEA)
Table Revised December 10, 2009

Cycle	Cycle 0% RH (2 min) to 90°C dew point (2 min), single cell 25-50 cm^2	
Total time	Until crossover >2 mA/cm^2 or 20,000 cycles	
Temperature	80°C	
Relative humidity	Cycle from 0% RH (2 min) to 90°C dew point (2 min)	
Fuel/oxidant	Air/air at 2 SLPM on both sides	
Pressure	Ambient or no backpressure	
Metric	**Frequency**	**Target**
Crossover*	Every 24 hours	$\leq$2 mA/cm^2
Shorting resistance**	Every 24 hours	>1,000 ohm cm^2

* Crossover current per USFCC "Single Cell Test Protocol" Section A3-2, electrochemical hydrogen crossover method.
** Measured at 0.5 V applied potential, 80ºC, and 100% RH N_2/N_2. Compression to 20% strain on the GDL.

Table A-5. Fuel Cell Tech Team Polarization Protocol

Test Point #	Current Density [A/cm^2]	Anode Inlet H_2% (balance N_2) inlet/dry	Anode H_2 Stoich [-]	Anode Dewpoint Temp [°C]	Anode Inlet Temp [°C]	Anode Pressure Outlet [kPaabs]	Cathode Inlet O_2% inlet/dry	Cathode Inlet N_2% inlet/dry	Cathode O_2 Stoich [-]	Cathode Dewpoint Temp [°C]	Cathode Inlet Temp [°C]	Cathode Pressure Outlet [kPaabs]	Cell/ Stack Control Temp [°C]	Temp pt. Run Time min	Set Point Transit Time s
Break-in															
B1	0.6	100%	1.5	59	80	150	21%	79%	1.8	56	80	150	80	20	0
Reduction															
R1	0	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	1	0
R2	0	100%	1.5	59	80	150	0%	100%	1.8	59	80	150	80	Until V>0.1V	0
Polarization curve															
P1	0.2	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P2	0.4	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P3	0.6	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P4	0.8	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P5	1	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P6	1.2	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P7	1.4	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P7	1.6	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P8	1.8	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P9	2	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P10	1.8	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P11	1.6	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P12	1.4	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P13	1.2	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P14	1	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P15	0.8	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P16	0.6	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0

Table A-5. (Cont.)

Test Point #	Current Density [A/cm^2]	Anode Inlet H_2% (balance N_2) inlet/dry	Anode H_2 Stoich [-]	Anode Dewpoint Temp [°C]	Anode Inlet Temp [°C]	Anode Pressure Outlet [kPaabs]	Cathode Inlet O_2% inlet/dry	Cathode Inlet N_2% inlet/dry	Cathode O_2 Stoich [-]	Cathode Dewpoint Temp [°C]	Cathode Inlet Temp [°C]	Cathode Pressure Outlet [kPaabs]	Cell/ Stack Control Temp [°C]	Temp pt. Run Time min	Set Point Transit Time s
P17	0.4	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P18	0.2	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P19	0.1	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P20	0.05	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P21	0.02	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P22	0.05	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P23	0.1	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0
P24	0.2	100%	1.5	59	80	150	21%	79%	1.8	59	80	150	80	3	0

Stoichs for points below 0.2A/cm^2 at 0.2A/cm^2 equivalent flow

Table A-6. Protocol for Determining Cell/Stack Durability

Test Point #	Current Density [A/cm^2]	Anode Inlet H_2% (balance N_2) inlet/dry	Anode H_2 Stoich [-]	Anode Dew point Temp [°C]	Anode Inlet Temp [°C]	Anode Pressure outlet [kPaabs]	Cathode Inlet O_2% inlet/dry	Cathode Inlet N_2% inlet/dry	Cathode O_2 Stoich [-]	Cathode Dew point Temp [°C]	Cathode Inlet Temp [°C]	Cathode Pressure Outlet [kPaabs]	Cell/ Stack control Temp [°C]	Test pt. Run Time min	Set Point Transition time s	Worst-Case Response Transition Time s
Wet w/load cycling																
RH1	0.02	80%	96	83	85	101.3	21%	79%	108	83	85	101.3	80	0.5	0	2
RH2	1.2	80%	1.6	83	85	101.3	21%	79%	1.8	83	85	101.3	80	0.5	0	2
RH3	0.02	80%	96	83	85	101.3	21%	79%	108	83	85	101.3	80	0.5	0	2
RH4	1.2	80%	1.6	83	85	101.3	21%	79%	1.8	83	85	101.3	80	0.5	0	2
RH5	0.02	80%	96	83	85	101.3	21%	79%	108	83	85	101.3	80	0.5	0	2
RH6	1.2	80%	1.6	83	85	101.3	21%	79%	1.8	83	85	101.3	80	0.5	0	2
RH7	0.02	80%	96	83	85	101.3	21%	79%	108	83	85	101.3	80	0.5	0	2
RH8	1.2	80%	1.6	83	85	101.3	21%	79%	1.8	83	85	101.3	80	0.5	0	2
RH9	0.02	80%	96	83	85	101.3	21%	79%	108	83	85	101.3	80	0.5	0	2
RH10	1.2	80%	1.6	83	85	101.3	21%	79%	1.8	83	85	101.3	80	0.5	0	2
Trans1	0.6	80%	2	70	80	101.3	21%	79%	2	70	80	101.3	80	2	0	30 (dew point)
Dry w/load cycling																
RH11	0.1	80%	5	53	80	101.3	21%	79%	5	53	80	101.3	80	0.5	0	30 (dew point)
RH12	0.02	80%	25	53	80	101.3	21%	79%	25	53	80	101.3	80	0.5	0	2
RH13	0.1	80%	5	53	80	101.3	21%	79%	5	53	80	101.3	80	0.5	0	2
RH14	0.02	80%	25	53	80	101.3	21%	79%	25	53	80	101.3	80	0.5	0	2
RH15	0.1	80%	5	53	80	101.3	21%	79%	5	53	80	101.3	80	0.5	0	2
RH16	0.02	80%	25	53	80	101.3	21%	79%	25	53	80	101.3	80	0.5	0	2
RH17	0.1	80%	5	53	80	101.3	21%	79%	5	53	80	101.3	80	0.5	0	2
RH18	0.02	80%	25	53	80	101.3	21%	79%	25	53	80	101.3	80	0.5	0	2
RH19	0.1	80%	5	53	80	101.3	21%	79%	5	53	80	101.3	80	0.5	0	2
RH20	0.02	80%	25	53	80	101.3	21%	79%	25	53	80	101.3	80	5	0	2

Appendix B: Acronyms and Abbreviations

μA	microampere
A	ampere
abs	absolute
Ag	silver
AgCl	silver chloride
atm	atmosphere
BOP	balance of plant
cm	centimeter
dBA	decibel A scale
DC	direct current
DOE	U.S. Department of Energy
ECSA	electrochemical surface area
EPRI	Electric Power Research Institute
FCEV	Fuel Cell Electric Vehicle
FCTT	Fuel Cell Technical Team
g	gram
GDL	gas diffusion layer
h	hour
H_2	molecular hydrogen
HF	hydrofluoric acid
ICE	internal combustion engine
iR	internal resistance
kg	kilogram
kPa	kilopascal
kW	kilowatt
kWe	kilowatt-electric
L	liter
LHV	lower heating value
m	meter
mA	milliampere
MEA	membrane electrode assembly
mg	milligram
MJ	megajoule
MPa	megapascal
mV	millivolt
mW	milliwatt
N	nitrogen
N_2	molecular nitrogen
NREL	National Renewable Energy Laboratory
O_2	molecular oxygen
OCV	open circuit voltage
OEM	original equipment manufacturer
ORR	oxygen reduction reaction
Pa	pascal
PEM	polymer electrolyte membrane

PGM	platinum group metal (Pt, Ir, Os, Ru, Rh, Pd)
ppm	parts per million
Pt	platinum
$Q/\Delta T_i$	[Stack power (90 kW) × (1.25 V – voltage at rated power)/(voltage at rated power)]/[(stack coolant out temp (°C) – ambient temp (40°C)]
R&D	research and development
RH	relative humidity
s, sec	second
SA	Strategic Analysis, Inc.
sccm	standard cubic centimeter(s) per minute
SLPM	standard liters per minute
U.S. DRIVE	United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability
USFCC	U.S. Fuel Cell Council (now the Fuel Cell and Hydrogen Energy Association)
V	volt
W	watt