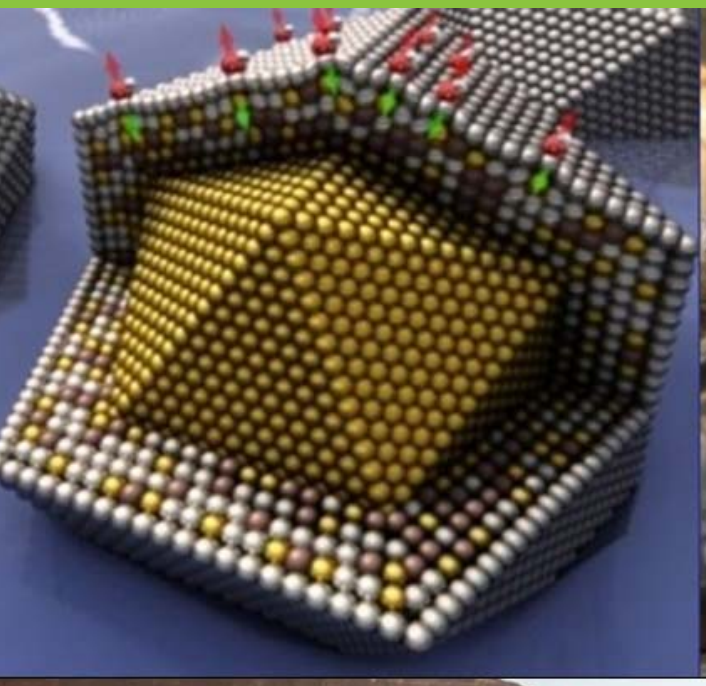
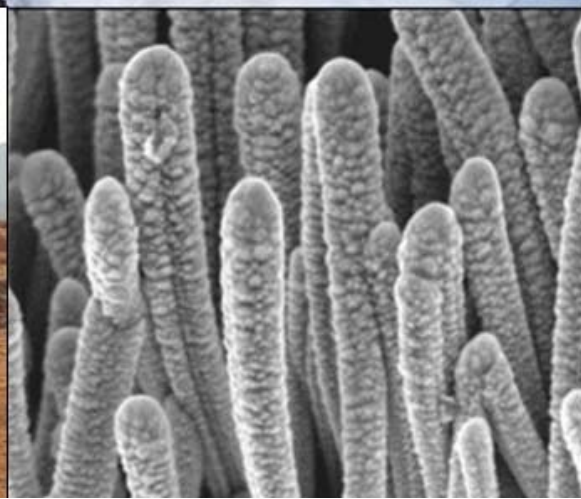
USDRIVE
DRIVING RESEARCH AND INNOVATION FOR VEHICLE EFFICIENCY AND ENERGY SUSTAINABILITY

Fuel Cell Technical Team Roadmap

November 2017



This roadmap is a document of the United States Driving Research and Innovation for Vehicle 汽车 efficiency and Energy sustainability (U.S. DRIVE) Partnership. U.S. DRIVE is a voluntary, non-binding, and non-legal partnership among the U.S. Department of Energy; USCAR, representing FCA US LLC, Ford Motor Company, and General 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 ten 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.doe.gov/eere/vehicles/vehicle-technologies-office-us-drive or www.uscar.org.

Cover Photo: (clockwise from top left) Platinum base core shell catalyst computer generated model, National Renewable Energy Laboratory thin-film roll-to-roll manufacturing machine, Nanostructured thin film (NSTF) catalyst microscopic image, and U.S. Army Chevrolet Colorado hydrogen fuel cell electric vehicle

Above Photo: 2016 Ford Fusion FCEV Prototype

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Acknowledgements

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Mission and Scope[1]

Mission

Perform research and development to enable fuel cell power systems for automotive powertrains that meet the United States Driving Research and Innovation for Vehicle efficiency and Energy sustainability (U.S. DRIVE) Partnership 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.

U.S. DRIVE Fuel Cell Tech Team Goal:

Engage in research and development to enable the advancement of a direct hydrogen fuel cell power system for transportation applications that can achieve 8,000 hour durability and be mass produced at a cost of $35/kW by 2025.

[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: https://energy.gov/eere/fuelcells/fuel-cell-technologies-office.

Key Issues and Challenges

Current status is compared to targets in Figure 1. The key challenge is to decrease cost and increase power density while simultaneously improving durability. Several approaches to decrease cost or improve performance have negative impacts on durability.

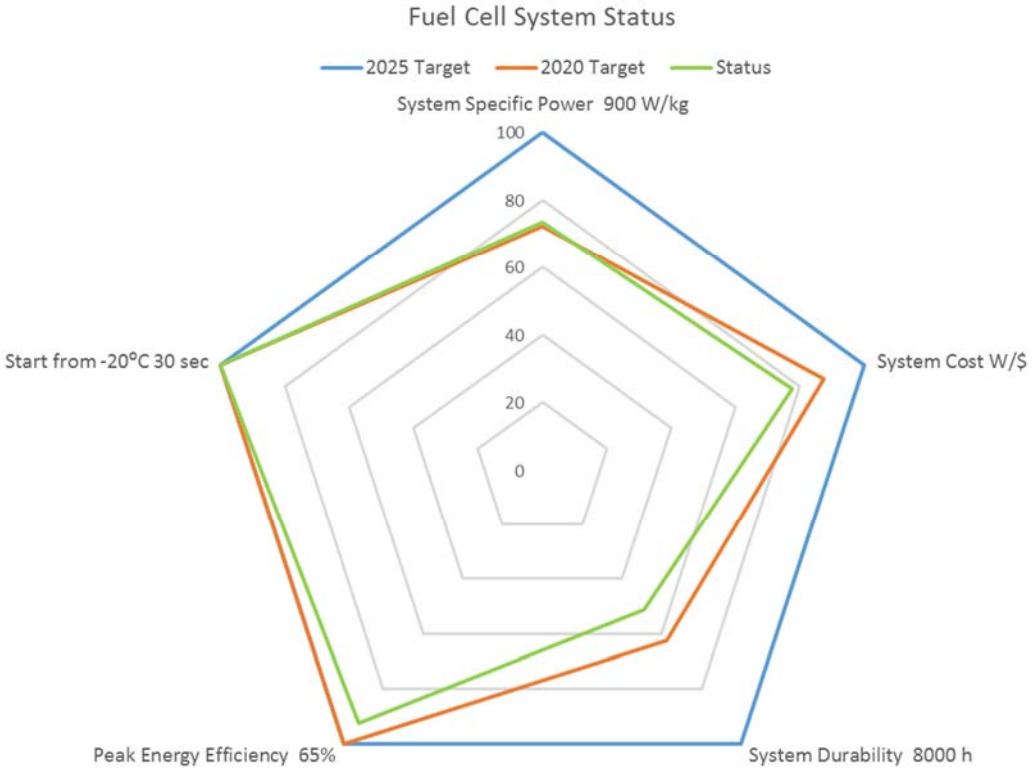

Figure 1. Fuel Cell System Status versus Targets
(The green line indicates the status as a fraction of the targets)

Durability

Transportation fuel cell systems must compete with automotive internal combustion engines (ICEs) and other alternative technologies. Fuel cell systems must have durability similar to current ICE systems to be competitive in the market. The FCTT has identified a durability target of 8,000 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 automotive 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 behavior generates transient and cyclic power demands that result in conditions that exacerbate degradation. Fuel cell systems must be demonstrated with long-term durability (≥8,000 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 $35/kilowatt (kW) by 2025.[2] There is a significant gap between the current cost estimate and the target cost. Cost reduction, along with increases in fuel cell stack power density, are necessary to be competitive in the future. Current ICE engines reach power densities of ~950 W/kg and are expected to increase in the future.[3,4] In order to be competitive, fuel cell power densities must also increase.

Current Status and Targets

The current status and targets of key fuel cell attributes are shown in Figure 1. Due to the low number of commercial fuel cell vehicles, 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) sponsored by the DOE Energy Efficiency and Renewable Energy Fuel Cell Technologies Office (EERE FCTO).[5] The status of fuel cell cost is based on the automotive fuel cell cost analysis study performed by Strategic Analysis, Inc. (SA)[6] 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 just 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 2020 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 4,100 hours with 10% stack voltage degradation. This projection is approaching the 2020 target of 5,000 hours but significantly lower than the 2025 target of 8,000 hours.

The SA 2017 cost study projects the cost of automotive fuel cell systems to be $45/kW (assuming high-volume [500,000 units per year] production levels and a platinum price of $1,550/troy ounce)[6] and $50/kW at a volume of 100,000 units per year. Although this projected cost already assumes some significant R&D outcomes, such as low platinum (Pt) catalyst loading (0.125 mg/cm^2), it does not achieve the 2025 fuel cell system cost target of $35/kW.

The 2025 technical targets, guidelines, and current status values are shown in Tables 1-5. The fuel cell system cost target is $35/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

[2] Based on 2017 dollars and high-volume production (500,000 fuel cell stacks per year). The DOE 2016 Multi-Year Research, Development and Demonstration (MYRD&D) Plan is focused on an ultimate target of $30/kW (https://energy.gov/sites/prod/files/2016/10/f33/fcto_myrdd_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] https://en.wikipedia.org/wiki/Ford_EcoBoost_engine#Specifications_2

[4] https://energy.gov/sites/prod/files/2016/06/f32/ace000_singh_2016_o_web.pdf

[5] National Renewable Energy Laboratory, *National Fuel Cell Electric Vehicle Learning Demonstration* http://www.nrel.gov/hydrogen/images/cdp_lab_03.jpg

[6] B. James, Fuel Cell Systems Analysis, *2017 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C.*, https://www.hydrogen.energy.gov/pdfs/review17/fc163_james_2017_o.pdf).

guideline is $17.50/kW, which is half of the system cost. Accordingly, $17.50/kW is the 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 a guideline for subcomponent or material level research and development. Therefore, an individual item in a 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	2025 Target
Peak Energy Efficiency [b]	%	60 [c]	65	65
Specific power	W/kg	659 [d]	650	900
Cost [f]	$/$kW_e$	45 [e]	40	35
Cold start-up time to 50% of rated power				
@ -20°C ambient temp	sec	20 [f]	30	30
@ +20°C ambient temp	sec	<10 [f]	5	5
Durability in automotive load cycle	hours	4130 [g]	5,000	8,000
Unassisted start from [h]	°C	-30 [i]	-30	-30

[a] Target includes fuel cell stack, BOP, and thermal system. Target 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] U. Eberle, B. Muller, and R von Helmolt, *Energy & Environmental Science* 5 (2012): 8780.

[e] Based on 2017 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, Fuel Cell Systems Analysis, *2017 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C.,* https://www.hydrogen.energy.gov/pdfs/review17/fc163_james_2017_o.pdf).

[f] 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.

[g] Fuel Cell Stack Operation Hours and Voltage Durability, as reported by J. Kurtz et al., CDP FCEV 21, May 2016, https://www.nrel.gov/hydrogen/assets/images/cdp_fcev_21.jpg

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

[i] Press Release: *Honda Demonstrates the FCX Concept Vehicle,* Sep 25, 2006, http://news.honda.com/newsandviews/article.aspx?id=3798-en and Associated Press, *Toyota develops a new fuel cell hybrid,* June 6, 2008, http://www.nbcnews.com/id/25004758/.

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

Characteristic	Units	Status	2025 Target
Stack specific power [b]	W/kg	2,000 [c]	2700
Heat Rejection ($Q/\Delta T_i$) [d]	kW/°C	1.9 [e]	1.45
Cost[f] (guideline)	$/kW$_e$	19.1 [f]	17.5
Durability with cycling[g]	hours	4100 [h]	8,000

[a] Target includes membrane electrode assembly (MEA), bipolar plates, and stack hardware. Excludes 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] 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/.

[d] $Q/\Delta T_i$ = [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 P-6 of Appendix A.

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

[f] Guideline based on 2017 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, Fuel Cell Systems Analysis, *2017 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C.,* https://www.hydrogen.energy.gov/annual_review17_proceedings.html.

[g] Based on the U.S. DRIVE FCTT protocol for determining cell/stack durability found in Table P-7 of Appendix A, <10% drop in rated power after test.

[h] Projected time to 10% voltage degradation, as reported by NREL, *National Fuel Cell Electric Vehicle Learning Demonstration* https://energy.gov/sites/prod/files/2014/03/f11/learning_demo_final_report.pdf

Table 3. Technical Targets for MEA and Catalysts

Characteristic	Units	Status	2025 Target
Heat Rejection ($Q/\Delta T_i$) [a]	kW/°C	1.45 [b]	1.45
MEA Cost	$/kW	11.8 [c]	10
Platinum group metal (PGM) total content [d]	g/kW rated	0.125:105 (150,250 kPa) [e]	≤ 0.10
Durability with cycling [f, g]	Hours	4100	8,000
Performance @ 0.8V	mW/cm^2	306 [e]	300
Performance @ rated power guideline [g]	mW/cm^2	890;1190 (150,250 kPa) [e]	1,800
Robustness (cold operation) [h]		Not tested	0.7
Robustness (hot operation) [i]		Not tested	0.7
Robustness (cold transient) [j]		Not tested	0.7
Loss in catalytic (mass) activity	%	40 [e]	≤40% loss of initial
Loss in performance at 0.8 A/cm^2	mV	20 [e]	≤ 30 (Table P-1)
Electrocatalyst support stability	% mass activity loss	Not tested	≤ 40 (Table P-2)
Loss in performance at 1.5 A/cm^2	mV	>500 [e]	≤ 30 at 1.5 A/cm^2 (Table P-2)
Mass activity [k]	A/mg$_{pgm}$ @ 900 mV$_{iR\text{-}free}$mV	0.6 [e]	0.44
PGM-free catalyst activity [k]	A/cm^2 @900 mV$_{iR\ free}$ A	0.021 [l]	0.044 [m]

[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 P-6 of Appendix A.

[b] Based on a voltage of 0.67 V and stack coolant outlet temperature of 94°C.

[c] Based on 2017 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, Fuel Cell Systems Analysis, *2017 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C.*, https://www.hydrogen.energy.gov/pdfs/review17/fc163_james_2017_o.pdf).

[d] 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. Loading of < 0.1 mg PGM/cm^2 is recommended, however it may not be necessary to meet the g/kW target.

[e] A. Kongkanand, Highly-Accessible Catalysts for Durable High-Power Performance, *2017 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C.*, https://www.hydrogen.energy.gov/pdfs/review17/fc144_kongkanand_2017_o.pdf

[f] Based on the U.S. DRIVE FCTT protocol for determining cell/stack durability found in Table P-7 of Appendix A, <10% drop in rated power after test.

[g] Need to meet or exceed at temperatures of 80°C up to peak temperature, measured using the polarization curve protocol found in Table P-6 of Appendix A.

[h] Ratio of fuel cell stack voltage at 30°C to fuel cell stack voltage at 80°C operation at 1.5 A/cm^2, measured using the operating conditions found in Table P-6 of Appendix A, allowing 15 minutes for temperature stability. A 25°C dew point is used only for 30°C operation.

[i] Ratio of fuel cell stack voltage at 90°C to fuel cell stack voltage at 80°C operation at 1.5 A/cm^2, measured using the operating conditions found in Table P-6 of Appendix A, allowing 15 minutes for temperature stability. A 59°C dew point is used for both 90°C and 80°C operations.

[j] Ratio of fuel cell stack voltage at 30°C transient to fuel cell stack voltage at 80°C steady-state operation at 1.5 A/cm^2, measured using the operating conditions found in Table P-6 of Appendix A. A 25°C dew point is used only for 30°C

operation. 30°C transient operation is at 1.5 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 1.5 A/cm^2. The voltage is measured 5 seconds after returning to 1.5 A/cm^2.

[k] 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.

[l] P. Zelenay (LANL), private communication.

[m] Target is equivalent to PGM catalyst mass activity target of 0.44 A/mg$_{pgm}$ at 0.1 mg$_{pgm}$/cm^2.

Table 4. Technical Targets for Membranes

Characteristic	Units	Status [a]	2025 Target
Preferred maximum operating temperature	°C	120	120
Area specific proton resistance at:			
120°C and water partial pressures 40 kPa	Ohm cm^2	0.054 (40 kPa) 0.019 (80 kPa)	0.02
95°C and water partial pressure 25 kPa	Ohm cm^2	0.027 (25 kPa) (at 80°C .02 at 25 kPa, .008 at 45 kPa)	0.02
30°C and water partial pressures up to 4 kPa	Ohm cm^2	0.018	0.03
-20°C	Ohm cm^2	0.2	0.2
Maximum oxygen crossover [b]	mA/cm^2	0.6	2
Maximum hydrogen crossover [b]	mA/cm^2	1.9	2
Minimum electrical resistance [c]	Ohm cm^2	1635	1,000
Cost [d]	$\$/m^2$	15.9 [e]	17.5
Durability [f]			
Mechanical	Cycles w/<10 sccm crossover	24,000	20,000
Chemical	Hours with <5 mA/cm^2 crossover or <20% loss in OCV	614	500
Combined chemical/mechanical	Cycles until <5 mA/cm^2 crossover or <20% loss in OCV	Not Tested	20,000

[a] Status represents 3M PFIA membrane (M. Yandrasits, 2017 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C., https://www.hydrogen.energy.gov/pdfs/review17/fc109_yandrasits_2017_o.pdf

[b] 14 µm PFIA membrane with nanofiber support. M. Yandrasits (3M), private communication, February 1, 2016.

[c] Measure in humidified N_2/N_2 at 0.5 V DC at 80°C.

[d] Guideline based on 2017 dollars and costs projected to high-volume production (500,000 fuel cell stacks per year).

[e] B. James, Fuel Cell Systems Analysis, *2017 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C.*, https://www.hydrogen.energy.gov/pdfs/review17/fc163_james_2017_o.pdf

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

Table 5. Technical Targets for Bipolar Plates

Characteristic	Units	Status	2025 Target
Plate cost[a] (guideline)	$/kW	5.40 [b,c]	2
Plate weight (guideline)	kg/kW	<0.4 [c,d]	0.18
Plate H_2 permeation	Std $cm^3/(sec\ cm^2\ Pa)$ @ 80°C, 3 atm 100% RH	$<2 \times 10^{-6}$ [f]	$2x10^{-6}$
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)	>40
Forming elongation [m]	%	20-40 [n]	40 [m]

[a] Guideline based on 2017 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] Based on SA cost estimate, B. James, Fuel Cell Systems Analysis, *2017 Annual Merit Review and Peer Evaluation Meeting, Washington, D.C.*, https://www.hydrogen.energy.gov/pdfs/review17/fc163_james_2017_o.pdf

[d] Based on 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] R. Blunk, F. Zhong, J. Owens, J. Power Sources 159, 533, 2006.

[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, -0.2 V to +0.4 V [SHE], de-aerated with argon purge. And potentiostatic tests as well.

[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 +1.0 V [SHE] 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. Plate needs to pass the electrical conductivity requirement after the corrosion test.

[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 cathode corrosion 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 >55 Mpa.

[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_1_1_brady.pdf.

Gaps and Technical Barriers

Durability

NREL's Learning Demonstration provides independent validation of on-road FCEVs and has shown a four-fold increase in maximum projected durability of fuel cell systems in the last ten years. The maximum projected durability, which is the projected time to 10% voltage degradation for the fleet that displays the best average durability, has increased from 950 hours in 2006 to 2,500 hours in 2009 to 4,130 hours in 2016. In 2016, the maximum operating hours recorded for a single FCEV was 5,648 hours.[7] 目前用车实测的时长为5648小时

Despite the improvements in durability, current status is still short of the target of 8,000 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). 整车企业 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, 推断 increasing the percentage from 10% degradation to 30% degradation roughly doubled the projected durability. 要求小于10%性能衰减的限制仍有待考量

Higher durability has been reported for newer technology in the laboratory environment. Laboratory durability tests to 10% degradation have shown an average projected time to 4,000 hours and a maximum time to 13,129 hours.[8] 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. 实验室测试结果与上车实测的结果存在巨大差异

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.[9] Attempting to decrease cost by increasing the dispersion and decreasing particle size to meet the cost target would decrease durability. 寿命与成本之间存在复杂的相互制约

Cost

Recent estimates of the current cost of an 80 kW automotive fuel cell system (materials and production) projected to high volume are approximately $45/kW at 500,000 units/year[10] and $50/kW at 100,000 units/year. $45/kW is $10/kW greater than the 2025 target, indicating that cost must be continue to be

[7] J. Kurtz, et al., *National Fuel Cell Electric Vehicle Learning Demonstration,* https://energy.gov/sites/prod/files/2014/03/f11/learning_demo_final_report.pdf

[8] J. Kurtz, et al., *National Fuel Cell Electric Vehicle Learning Demonstration,* https://energy.gov/sites/prod/files/2014/03/f11/learning_demo_final_report.pdf

[9] 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.

[10] B. James, J. Huya-Kouadio, C. Houchins, "Fuel Cell Systems Analysis," 2017 DOE Annual Merit Review (presentation, U.S. Department of Energy Hydrogen and Fuel Cells Program Annual Merit Review, Washington, D.C., June 8, 2017), https://www.hydrogen.energy.gov/pdfs/review17/fc163_james_2017_o.pdf).

以全生命周期成本为基础
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. For example, 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 so it is difficult to achieve significant cost savings in this area. However, BOP costs can be reduced by improving stack performance, thus lowering BOP component requirements. Of the fuel cell stack costs at high volume, 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).

通过提高堆的性能来减少对BOP的需求

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.

相互关联的

Table 6 identifies the current areas of focus for DOE-funded projects addressing automotive fuel cells and the barriers they address.

Table 6. DOE Efforts Addressing Automotive Fuel Cell Durability and Cost

Research Area	Durability	Cost
Testing and Technical Assessment	✓	✓
MEAs, Cells and Other Stack Components (includes Bipolar Plates)	✓	✓
Catalysts and Electrodes	✓	✓
Membranes/Electrolytes	✓	✓
Fuel Cell Performance and Durability	✓	✓

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 membrane electrode assembly (MEA) levels using a combination of in situ 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 have looked 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. Researchers are investigating nanostructured alloy particles, dealloyed nanoparticles, nanostructured thin films, and extended thin film surfaces 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. 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 platinum group metal (PGM) loading to decrease cost.

Studies in MEAs are seeking to better understand degradation and transport losses at the MEA level. Modeling and experimental efforts are underway to better understand the oxygen and water transport and local hydration levels in the MEA. Local transport losses in the catalyst layer are limiting performance at low catalyst loadings and these losses increase with time, especially for alloy catalysts. Studies are underway to understand these losses and how they change with degradation, including efforts to quantify the impact of catalyst degradation on properties such as water uptake, proton conductivity, and oxygen permeability of the catalyst layer ionomer. Membrane projects are looking at the durability of new membranes and at improved supports to reduce degradation due to mechanical stresses during operation.

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.

Meanwhile, system level solutions can be implemented to mitigate material degradations to improve the system durability. Studies of fuel cell performance and durability are investigating better understanding of failure modes and factors of stresses for the usage profiles. The improved knowledge base can be leading to the development of system controls of mitigation and/or performance recovery if applicable.

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 7. [11]

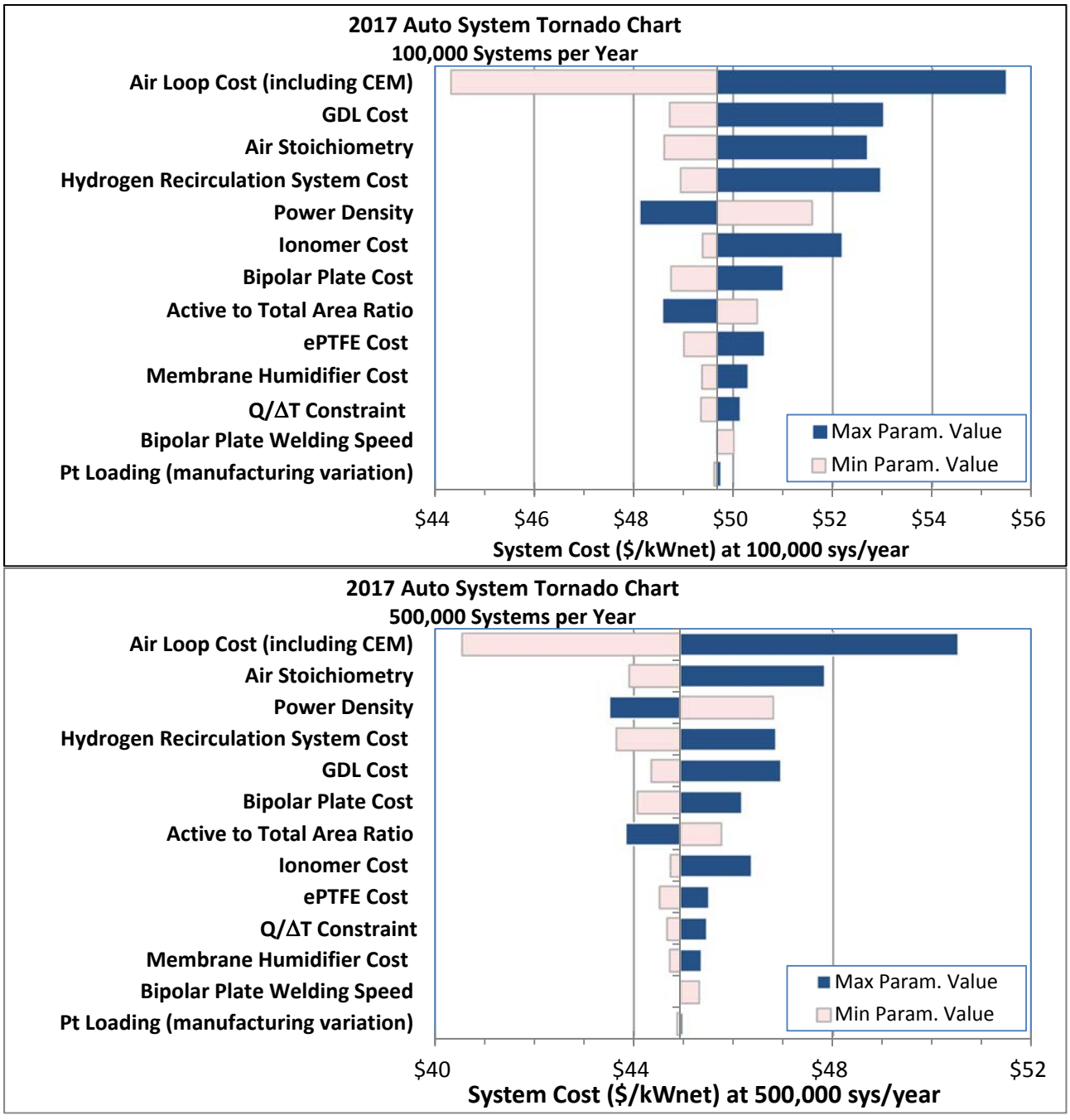

Figure 2. Sensitivity of Fuel Cell System Cost to Key Parameters at 100,000 and 500,000 systems/year

[11] Brian D. James, Jennie M. Huya-Kouadio, Cassidy Houchins , *Mass Production Cost Estimation of Direct H2 PEM Fuel Cell Systems for Transportation Applications: 2017 Update*, produced by Strategic Analysis Inc., Arlington, VA.

Table 7. Basis for Upper and Lower Bounds on Each Parameter

2017 Auto Technology Monte Carlo Analysis, 500k sys/year				
Parameter	**Unit**	**Minimum Value**	**Likeliest Value**	**Maximum Value**
Power Density	**mW/cm^2**	986	**1095**	1205
Pt Loading	**$mgPt/cm^2$**	0.124	**0.125**	0.126
Ionomer Cost	**$/kg**	$67.41	**$112.35**	$500.00
GDL Cost	**$/$m^2$ of GDL**	$3.00	**$5.91**	$16.00
Bipolar Plate Welding Speed	**m/min**	2.5	**7.5**	7.5
Air Stoichiometry		1.3	**1.5**	2
Membrane Humidifier Cost	**$/system**	$51.77	**$69.03**	$103.55
Compressor Effic.	**%**	64.7%	**71%**	80%
Expander Effic.	**%**	71.6%	**73%**	80%
Motor/Controller Effic.	**%**	75%	**80%**	84.6%
Air Compressor Cost		$500.00	**$719.28**	$863.14
Balance of Air Compressor Cost	**$/system**	$122.06	**$183.00**	$311.09
Hydrogen Recirculation System Cost	**$/system**	$254.82	**$308.16**	$556.11
EPTFE Cost	**$/$m^2$ of EPTFE**	$3.00	**$6.00**	$10.20
Active to Total Area Ratio		0.55	**0.625**	0.8
Bipolar Plate Material Cost	**$/kg**	$12.22	**$13.19**	$15.83
Bipolar Plate Forming Cost	**$/kW**	$1.12	**$1.60**	$2.08
Bipolar Plate Coating Cost	**$/kW**	$0.74	**$0.92**	$1.10

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, 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 or eliminating 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 PGM-free catalysts based on nitrogen complexes of base transition metals and carbon-nitrogen-based catalysts.

Due to the high sensitivity of cost to power density, another 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 can limit performance at high power density. Large performance losses are observed at high current densities on low-Pt cathodes due to local oxygen transport resistances near the catalyst particle.

As part of the FCTT's strategy to reduce cost, researchers are conducting studies to understand and overcome these local mass transport losses in a fuel cell. Efforts involve developing and validating transport models, tools, and analysis techniques to measure materials properties and determine structure property relationships in an MEA, and investigating new MEA structures and materials to reduce these

losses. Examples include efforts to develop characterization techniques to map the catalyst, catalyst support, ionomer and pore structures in the cathode, and correlate the structures to performance at high current density. These tools will help materials suppliers and OEMs optimize materials and catalyst layer designs to provide better performance at high power density and reduce system size and costs.

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 polymer electrolyte membrane (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: June 30, 2017

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 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 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 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 able to 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 P.1 for electrocatalysts, Table P.2 for catalyst supports, Table P.3 for membrane/MEA chemical stability, and Table P.4 for membrane/MEA mechanical durability, respectively, as derived from References 1 and 2. Table P.5 defines the protocol and metrics for combined membrane chemical/mechanical testing in a MEA.

Table P.6 contains a protocol for polarization testing and Table P.7 defines a protocol for drive cycle durability. An unmitigated startup/shutdown cycle protocol is presented in Table P.8 and a protocol for MEA recovery in Table P.9.

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 P.10 contains the polarization curve protocols referenced in Tables 1 and 2 of this document. Table P.11 contains the protocol for determining cell/stack durability corresponding to the 8000-hour U.S. DRIVE Fuel Cell Tech Team durability target.

Protocols for Testing PEM Fuel Cells and Fuel Cell Components

Testing protocols for fuel cells and fuel cell components, developed in partnership with the U.S. DRIVE Fuel Cell Technical Team, are delineated in Tables P.1 through P.9.

The electrocatalyst protocol in Table P.1 is designed to assess cathode electrocatalyst durability through the use of a voltage square wave, in which successive cycles of surface oxidation and reduction cause accelerated catalyst degradation. The protocol uses a voltage range similar to that which is expected for an automotive drive cycle, and it seeks to maximize catalyst degradation while minimizing support corrosion. The protocol was designed to test PGM-based catalysts on carbon-based supports, and it may need to be modified to test different classes of materials.

Table P.1 Electrocatalyst Cycle and Metrics		
Cycle	Square wave cycle: steps between 0.6 V (3 s) and 0.95 V (3 s) with rise time of ~0.5 s or less; run polarization curve and ECSA at specified intervals. Single cell 25–50 cm^2	
Number	30,000 cycles	
Cycle time	6 s	
Temperature	80°C	
Relative humidity	Anode/cathode 100/100%	
Fuel/oxidant	H_2/N_2 (H_2 at 200 sccm and N_2 at 75 sccm for a 50-cm^2 cell)	
Pressure	Atmospheric pressure	
Metric [a]	**Frequency**	**Target**
Catalytic mass activity [b]	At beginning and end of test, minimum	<40% loss of initial catalytic activity
Polarization curve from 0 to >1.5 A/cm^2 [c]	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

[a] A protocol such as the one shown in Table P.9 should be used to recover reversible losses prior to measuring each metric.

[b] Mass activity in A/mg @ 150 kPa abs back pressure at 900 mV iR-corrected on H_2/O_2, 100% RH, 80°C, anode stoichiometry 2; cathode stoichiometry 9.5. A minimum hold time of 15 min is recommended, with the mass activity calculated based on the average current during the last 1 min. Multiple points should be measured at low current, and the 0.9 V iR-free potential should be determined based on these measurements. Measured ORR current may be corrected for H_2 crossover. Based on the protocol published by Gasteiger et al., *Applied Catalysis B: Environmental*, 56 (2005): 9–35.

[c] Polarization curve per protocol in Table P.10.

The catalyst support protocol in Table P.2 uses a rapid triangle wave voltage cycle to accelerate catalyst support corrosion while minimizing degradation of the catalyst itself. The potential range used in this protocol is similar to that which would occur in an unmitigated system start-up or shutdown. The protocol was designed to test PGM-based catalysts on carbon-based supports, and it may need to be modified to test different classes of materials.

Table P.2 Catalyst Support Cycle and Metrics		
Cycle	Triangle sweep cycle: 500 mV/s between 1.0 V and 1.5 V; run polarization curve and ECSA at specified intervals. Single cell 25–50 cm^2	
Number	5,000 cycles	
Cycle time	2 s	
Temperature	80°C	
Relative humidity	Anode/cathode 100/100%	
Fuel/oxidant	H_2/N_2	
Pressure	Atmospheric	
Metric [a]	**Frequency**	**Target**
Catalytic activity [b]	At beginning and end of test, minimum	≤40% loss of initial catalytic activity
Polarization curve from 0 to ≥1.5 A/cm^2 [c]	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

[a] A protocol such as the one shown in Table P.9 should be used to recover reversible losses prior to measuring each metric.

[b] Mass activity in A/mg @ 150 kPa abs back pressure at 900 mV iR-corrected on H_2/O_2, 100% RH, 80°C, anode stoichiometry 2; cathode stoichiometry 9.5, normalized to initial mass of catalyst and measured before and after test. Based on the protocol published by Gasteiger et al., *Applied Catalysis B: Environmental*, 56 (2005): 9–35. Measured ORR current may be corrected for H_2 crossover.

[c] Polarization curve per protocol in Table P.10.

The MEA chemical stability protocol in Table P.3 uses a continuous hold at open-circuit voltage to accelerate the production of free radicals, which cause degradation of the membrane and other MEA components.

Table P.3 MEA Chemical Stability and Metrics (Test Using an MEA)		
Test condition	Steady-state OCV, single cell 25–50 cm^2	
Total time	500 h	
Temperature	90°C	
Relative humidity	Anode/cathode 30/30%	
Fuel/oxidant	H_2/air at stoics of 10/10 at 0.2 A/cm^2 equivalent flow	
Pressure, outlet kPa abs	Anode/cathode 150/150	
Metric	**Frequency**	**Target**
F^- release or equivalent for nonfluorinated membranes	At least every 24 h	No target—for monitoring
Hydrogen crossover (mA/cm^2) [a, b]	Every 24 h	≤15 mA/cm^2
OCV [b, c]	Continuous	Initial OCV ≥ 0.95 V, <20% OCV decrease during test
High-frequency resistance	Every 24 h at 0.2 A/cm^2	No target—for monitoring
Shorting resistance [d]	Every 24 h	>1,000 ohm cm^2

[a] Tested in MEA on H_2, 80°C, fully humidified gases, 1 atm total pressure. See M. Inaba et. al., *Electrochimica Acta*, 51 (2006): 5746.

[b] Hydrogen crossover and OCV targets should be achieved at 0 kPa pressure differential and at 50 kPa anode overpressure relative to cathode, providing sensitivity to global membrane thinning and to hole formation, respectively.

[c] A protocol such as the one shown in Table P.9 should be used to recover reversible losses at least once every 24 h and prior to measuring each metric.

[d] Measured at 0.5 V applied potential, 80ºC, 100% RH N_2/N_2. Compression to 20% strain on the GDL.

The membrane mechanical protocol in Table P.4 tests membrane durability through the use of humidity cycling, which induces repeated swelling and contraction of the membrane, accelerating the formation and growth of membrane cracks and holes.

Table P.4 Membrane Mechanical Cycle and Metrics (Test Using an MEA)		
Cycle	Cycle 0% RH (2 min) to 90°C dew point (2 min), single cell 25–50 cm^2	
Total time	Until crossover >15 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 back pressure	
Metric	**Frequency**	**Target**
Crossover [a]	Every 24 h	≤15 mA/cm^2 [b]
Shorting resistance [c]	Every 24 h	>1,000 ohm cm^2

[a] Tested in MEA on H_2, 80°C, fully humidified gases, 1 atm total pressure. See M. Inaba et. al., *Electrochimica Acta*, 51 (2006): 5746. Crossover recorded after 2 min of drying under 0% RH conditions. Hydrogen crossover target should be achieved at 0 kPa pressure differential and at 50 kPa anode overpressure, providing sensitivity to global membrane thinning and to hole formation, respectively.

[b] For air or N_2 testing, an equivalent crossover metric of 0.1 $sccm/cm^2$ at a 20 kPa pressure differential, 80°C, and 100%RH may be used as an alternative.

[c] Measured at 0.5 V applied potential, 80°C and 100% RH N_2/N_2. Compression to 20% strain on the GDL.

The chemical/mechanical protocol in Table P.5 examines the combined effects of humidity cycling and radical formation on membrane durability. Although chemical and mechanical degradation occur through different mechanisms, each mode can accelerate the other mode such that membranes that appear to have good chemical stability and good mechanical stability may fail when chemical and mechanical stresses are present concurrently.

Table P.5 Membrane Combined Chemical/Mechanical Cycle and Metrics (Test Using an MEA)		
Cycle	Cycle 0% RH (30 s) to 90°C dew point (45 s), single cell 25–50 cm^2	
Total time	Until crossover >15 mA/cm^2 or 20,000 cycles	
Temperature	90°C	
Relative humidity	Cycle from 0% RH (30 s) to 90°C dew point (45 s) [a]	
Fuel/oxidant	H_2/air at 40 sccm/cm^2 on both sides	
Pressure	Ambient or no back pressure	
Metric	**Frequency**	**Target**
F- release or equivalent for Nonfluorine membranes	At least every 24 h	No target—for monitoring
Hydrogen crossover (mA/cm^2) [b, c]	Every 24 h	<15 mA/cm^2
OCV [c, d]	Continuous	Initial wet OCV ≥ 0.95 V, <20% OCV decrease during test
High-frequency resistance	Every 24 h at 0.2 A/cm^2	No target—for monitoring
Shorting resistance [e]	Every 24 h	>1,000 ohm cm^2

[a] Step durations of 30 s dry and 45 s wet were selected in testing at LANL so that the HFR at the end of the dry step was 2.5 times the HFR at the end of the wet step, which is approximately equal to the HFR ratio that occurs when running the mechanical test (Table P.4). Depending on the hardware used, these step times may need to be adjusted to achieve the same HFR variation.

[b] Tested in MEA on H_2, 80°C, fully humidified gases, 1 atm total pressure. See M. Inaba, et. al., *Electrochimica Acta*, 51 (2006): 5746. Crossover recorded after 2 min of drying under 0% RH conditions.

[c] Hydrogen crossover and OCV targets should be achieved at 0 kPa pressure differential and at 50 kPa anode overpressure, providing sensitivity to global membrane thinning and to hole formation, respectively.

[d] A protocol such as the one shown in Table P.9 should be used to recover reversible losses at least once every 24 h and prior to measuring each metric.

[e] Measured at 0.5 V applied potential, 80°C, 100% RH N_2/N_2. Compression to 20% strain on the GDL.

The polarization protocol in Table P.6 provides a standardized way to test MEA performance in different operating regimes, and it should be used as specified in the target tables to assess progress toward performance and durability targets.

Table P.6 Polarization Protocol [a]						
Test Point #	Current Density (A/cm^2)	Anode H_2 Stoich.	Cathode Inlet O_2% (Dry Basis)	Cathode Inlet N_2% (Dry Basis)	Cathode O_2 Stoich.	Test Point Run Time (min)
Break-In						
B1	0.6	1.5	21%	79%	1.8	20
Reduction						
R1	0	1.5	21%	79%	1.8	1
R2	0	1.5	0%	100%	1.8	Until V<0.1V
Polarization Curve						
P1	0.2	1.5	21%	79%	1.8	3
P2	0.4	1.5	21%	79%	1.8	3
P3	0.6	1.5	21%	79%	1.8	3
P4	0.8	1.5	21%	79%	1.8	3
P5	1	1.5	21%	79%	1.8	3
P6	1.2	1.5	21%	79%	1.8	3
P7	1.4	1.5	21%	79%	1.8	3
P7	1.6	1.5	21%	79%	1.8	3
P8	1.8	1.5	21%	79%	1.8	3
P9	2	1.5	21%	79%	1.8	3
P10	1.8	1.5	21%	79%	1.8	3
P11	1.6	1.5	21%	79%	1.8	3
P12	1.4	1.5	21%	79%	1.8	3

Table P.6 Polarization Protocol [a]						
Test Point #	Current Density (A/cm^2)	Anode H_2 Stoich.	Cathode Inlet O_2% (Dry Basis)	Cathode Inlet N_2% (Dry Basis)	Cathode O_2 Stoich.	Test Point Run Time (min)
P13	1.2	1.5	21%	79%	1.8	3
P14	1	1.5	21%	79%	1.8	3
P15	0.8	1.5	21%	79%	1.8	3
P16	0.6	1.5	21%	79%	1.8	3
P17	0.4	1.5	21%	79%	1.8	3
P18	0.2	1.5	21%	79%	1.8	3
P19	0.1	1.5	21%	79%	1.8	3
P20	0.05	1.5	21%	79%	1.8	3
P21	0.02	1.5	21%	79%	1.8	3
P22	0.05	1.5	21%	79%	1.8	3
P23	0.1	1.5	21%	79%	1.8	3
P24	0.2	1.5	21%	79%	1.8	3

[a] The following parameters are constant throughout the test: anode inlet composition of 100% H_2 (excluding water vapor) at 80°C, humidified to 59°C dew point, 250 kPa_{abs} outlet pressure; cathode feed at 80°C, humidified to 59°C dew point, 250 kPa_{abs} outlet pressure; cell/stack control temperature of 80°C; set-point transition time of 0 s. The anode and cathode flow rate stoichiometric ratios are 1.5 and 1.8, respectively, for currents of 0.2 A/cm^2 or greater, with 0.2 A/cm^2 equivalent flows used at lower currents (affected points highlighted in gray).

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The drive-cycle protocol in Table P.7 should be used as specified in the target tables to test system, stack, and MEA lifetime. The protocol incorporates operating conditions that are expected to occur during typical operation of a fuel cell vehicle, but it excludes conditions associated with unmitigated start-ups and shutdowns, freeze operation, fuel starvation, and system fault conditions.

Table P.7 Drive-Cycle Durability Protocol [a, b, c]									
Test Point #	Current Density (A/cm^2)	Anode H_2 Stoich.	Anode Dew Point Temp. (°C)	Anode Inlet Temp. (°C)	Cathode O_2 Stoich.	Cathode Dew Point Temp. (°C)	Cathode Inlet Temp. (°C)	Test Point Run Time (min)	Worst-Case Response Transition Time (s)
Wet with Load Cycling									
RH1	0.02	96	83°	85°	108	83°	85°	0.5	2
RH2	1.2	1.6	83°	85°	1.8	83°	85°	0.5	2
RH3	0.02	96	83°	85°	108	83°	85°	0.5	2
RH4	1.2	1.6	83°	85°	1.8	83°	85°	0.5	2
RH5	0.02	96	83°	85°	108	83°	85°	0.5	2
RH6	1.2	1.6	83°	85°	1.8	83°	85°	0.5	2
RH7	0.02	96	83°	85°	108	83°	85°	0.5	2
RH8	1.2	1.6	83°	85°	1.8	83°	85°	0.5	2
RH9	0.02	96	83°	85°	108	83°	85°	0.5	2
RH10	1.2	1.6	83°	85°	1.8	83°	85°	0.5	2
Trans1	0.6	2	70°	80°	2	70°	80°	2	30 (dew point)
Dry with Load Cycling									
RH11	0.1	5	53°	80°	5	53°	80°	0.5	30 (dew point)
RH12	0.02	25	53°	80°	25	53°	80°	0.5	2
RH13	0.1	5	53°	80°	5	53°	80°	0.5	2
RH14	0.02	25	53°	80°	25	53°	80°	0.5	2
RH15	0.1	5	53°	80°	5	53°	80°	0.5	2
RH16	0.02	25	53°	80°	25	53°	80°	0.5	2
RH17	0.1	5	53°	80°	5	53°	80°	0.5	2
RH18	0.02	25	53°	80°	25	53°	80°	0.5	2

Table P.7 Drive-Cycle Durability Protocol [a, b, c]									
RH19	0.1	5	53°	80°	5	53°	80°	0.5	2
RH20	0.02	25	53°	80°	25	53°	80°	5 [d]	2

[a] The following parameters are constant throughout the test: anode inlet composition of 80% H_2/20% N_2 (excluding water vapor), cathode inlet composition of 21% O_2/79% N_2 (excluding water vapor), anode and cathode outlet pressures of 101.3 kPa_{abs}, cell/stack control temperature of 80°C, and set-point transition time of 0 s.

[b] Drive-cycle testing reflects only degradation losses associated with wet and dry cyclic operation. Other relevant stressors, including start-up/shutdown and freeze operation, are not included in this test.

[c] A protocol such as the one shown in Table P.9 should be used to recover reversible losses at least once every 24 h.

[d] The 5-min hold in step RH20 is intended to represent a system idle point.

The start-up/shutdown protocol in Table P.8 involves the passage of a hydrogen/air front, similar to the front that is expected during unmitigated start-ups and shutdowns of a fuel cell system. This front can cause rapid degradation of catalyst supports and other cell components through large potential swings, local combustion, and radical formation. Several OEMs have demonstrated the ability to mitigate stop-start degradation of catalyst supports via system design/controls. Thus, an MEA that does not pass the Catalyst Support Cycle durability test may still be acceptable for OEMs that employ such system mitigation.

Table P.8 Unmitigated Start-Up/Shutdown Durability Protocol [a]								
Total time		5,000 cycles will take ~10 d, with 500 cycles/d (~19.5 h) and up to 5.5 h for characterization						
Temperature		35°C						
Pressure		101.3 kPa						
Characterization		Polarization curve, ECSA, and impedance spectra should be measured at 80°C, 100% RH. Characterization should be repeated approximately every 24 h (~500 cycles).						
Step	**Step Name**	**Duration (s)**	**Voltage (V)**	**Current (A/cm²)**	**Load**	**Anode Gas [b]**	**Anode Stoich.**	**RH**
1	FC Operation	60 [c]		0.4	On	H_2	1.2	100
2	Pre-shutdown	10	1		On	H_2	0	100
3	Shutdown	5			Off	Air	Varies [d]	0
4	Idle	55			Off	Air	1 (at 0.1 A/cm²)	0
5	Start-up	10	1		On	H_2	1.2 (at 1.0 A/cm²)	100
Metric			**Target**			**Guideline**		
Voltage at 1.2 A/cm²	<5% change		Voltage at 1.2 A/cm²	<5% change		Voltage at 1.2 A/cm²	<5% change	
ECSA		<20% change	ECSA		<20% change	ECSA		<20% change
HFR at 0.02 and 1.2 A/cm²		<5% change	HFR at 0.02 and 1.2 A/cm²		<5% change	HFR at 0.02 and 1.2 A/cm²		<5% change
LFR at 0.02 and 1.2 A/cm²		<10% change	LFR at 0.02 and 1.2 A/cm²		<10% change	LFR at 0.02 and 1.2 A/cm²		<10% change

[a] Several OEMs have demonstrated the ability to mitigate stop-start degradation of catalyst supports via system design/controls. Thus an MEA that does not pass the Catalyst Support Cycle durability test may still be acceptable for OEMs that employ such system mitigation.

[b] Anode gas is H_2 or air, depending on step. Cathode gas should be air at a flow rate corresponding to a stoichiometry of 2 at 1.0 A/cm² current for all steps.

[c] Attain steady-state operation before moving to Step 2.

[d] Anode flow rate must be defined by specific cell architecture, and it should correspond to an average residence time of 0.3 s. Cell voltage should decrease to < 0.1 V within 1 s (~3 volumetric exchanges).

Various degradation mechanisms are expected to occur during fuel cell testing, including both reversible and irreversible mechanisms. The MEA recovery protocol in Table P.9 should be used as specified in the target tables to recover the reversible losses prior to performance testing.

Table P.9 MEA Recovery Protocol [a]

Step	Step Name	Anode Comp.	Anode Flow (SLPM)	Cathode Comp.	Cathode Flow (SLPM)	Duration (s)
1	N_2 soak	100% N_2	2	100% N_2	4	120
2	Air soak	N/A	0	Air	4	900
3	N_2 soak	100% N_2	2	100% N_2	4	120
4	H_2 soak	100% H_2	2	N/A	0	600
5	H_2-air back on	100% H_2	2	Air	4	5

[a] The following parameters are constant throughout the test: anode and cathode inlet RH = 100%, anode and cathode outlet pressure = 150 kPa abs. Cell temperature should be set to the temperature of the upcoming diagnostic test.

Table P.10 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 P.10 (Cont.)

Test Point #	Current Density	Anode Inlet H_2% (balance N_2)	Anode H_2 Stoich.	Anode Dewpoint Temp	Anode Inlet Temp	Anode Pressure Outlet	Cathode Inlet O_2%	Cathode Inlet N_2%	Cathode O_2 Stoich.	Cathode Dewpoint Temp	Cathode Inlet Temp	Cathode Pressure Outlet	Cell/ Stack Control Temp	Temp pt. Run Time	Set Point Transit Time
	[A/cm^2]	inlet/dry	[-]	[°C]	[°C]	[kPaabs]	inlet/dry	inlet/dry	[-]	[°C]	[°C]	[kPaabs]	[°C]	min	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

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

Table P.11 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 with 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