## Joint ANL-JRC Scientific and Technical Report

**ANL 13/03**
**JRC-80646**

# Fuel Cell Testing Protocols:
# An International Perspective

**Chemical Sciences and Engineering Division, Argonne National Laboratory, Argonne, IL, USA**
**European Commission, Joint Research Centre**
**Institute for Energy and Transport,**
**Petten, The Netherlands**

**About Argonne National Laboratory**

Argonne is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC
under contract DE-AC02-06CH11357. The Laboratory's main facility is outside Chicago,
at 9700 South Cass Avenue, Argonne, Illinois 60439. For information about Argonne
and its pioneering science and technology programs, see www.anl.gov.

**About Joint Research Centre-Institute for Energy and Transport**

As the Commission's in-house science service, the Joint Research Centre's mission is to provide EU policies with independent, evidence-based scientific and technical support throughout the whole policy cycle.

Working in close cooperation with policy Directorates-General, the JRC addresses key societal challenges while stimulating innovation through developing new standards, methods and tools, and sharing and transferring its know-how to the Member States and international community.

Key policy areas include: environment and climate change; energy and transport; agriculture and food security; health and consumer protection; information society and digital agenda; safety and security including nuclear; all supported through a cross-cutting and multi-disciplinary approach.

**Availability of This Report:**

This report is available, at no cost, at
http://www.osti.gov/bridge.
It is also available on paper to the
U.S. Department of Energy and its contractors,
for a processing fee, from:
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831-0062
phone (865) 576-8401
fax (865) 576-5728
reports@adonis.osti.gov

**European Commission**
Joint Research Centre
Institute for Energy and Transport

**Contact information**
Dr. Georgios Tsotridis
Address: Joint Research Centre, Postbus 2
1755ZG, Petten, The Netherlands
E-mail: georgios.tsotridis@jrc.nl
Tel.: +31 22456 5656
http://iet.jrc.ec.europa.eu/

ANL-13/03
JRC-80646

# Fuel Cell Testing Protocols:
# An International Perspective

**Authors:**
Ira Bloom,[1] John K. Basco,[1] Lee K. Walker,[1] Thomas Malkow,[2]  Giancarlo DeMarco,[2]
Antonio Saturnio,[2] and Georgios Tsotridis[2]

[1]Chemical Sciences and Engineering Division, Argonne National Laboratory
[2]European Commission, Joint Research Centre-Institute for Energy and Transport

**March 2013**

# CONTENTS

# NOTATION

The following is a list of acronyms, abbreviations, and units of measure used in this document.

## GENERAL ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| DOE | U.S. Department of Energy |
| DST | dynamic stress test |
| | |
| ECE | Economic Commission for Europe |
| EU | European Union |
| | |
| FCHEA | Fuel Cell Hydrogen Energy Association |
| FCTes$^{QA}$ | Fuel Cell Testing, Safety, and Quality Assurance |
| FCTESTNET | Fuel Cell Testing and Standardization Network |
| | |
| IEC | International Electrotechnical Commission |
| | |
| PEMFC | Polymer-electrolyte membrane fuel cell |
| | |
| UNEC | United Nations Economic Commission |
| US | United States |
| USDRIVE | US Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability |

## UNITS OF MEASURE

| | |
|---|---|
| A | ampere(s) |
| cm$^2$ | square centimeter(s) |
| h | hour(s) |
| km | kilometer(s) |
| mA | milliampere(s) |
| min | minute(s |
| mV | millivolt(s) |
| s | second(s) |

# EXECUTIVE SUMMARY

An overview of international polymer-electrolyte fuel cell (PEMFC) test procedures is presented.  This overview is the first step in the global harmonization of testing methods.  Many techniques and procedures determining stack performance and durability are discussed.  Each approach has differences that may or may not impact the data and data quality.  Through experiments, it was found that differences in the results from two methods for measuring sequential polarization curves are minimal.  Answers to questions regarding differences in the aging duty cycles need to be determined experimentally.  The results of these experiments are expected to help the harmonization process, to facilitate the understanding of test results, and, possibly, to accelerate the commercialization of PEMFCs.

# 1  INTRODUCTION

Polymer-electrolyte membrane fuel cells (PEMFCs) are being considered for automotive applications.  As these devices reach maturity, there is a global need to understand how organizations characterize the performance and durability of PEMFCs and stacks.  Thus, facile information exchange is needed to accelerate their commercialization.  Starting with the same understanding of the basic electrochemistry of PEMFCs, organizations such as the US Department of Energy (DOE), the Fuel Cell Hydrogen Energy Association (FCHEA),[1] those in the European Union (EU), and the International Electrotechnical Commission/Technical Committee 105/Work Group 11 (IEC) have proposed and published many different methods to characterize the two fundamental properties of PEMFCs—performance and durability.

Thus, there are efforts in the US, the EU, and elsewhere to standardize and harmonize these different methods.  For example, framework program projects in the EU have been undertaken in the area of PEMFC single cell testing to harmonize testing methods.  The projects, such as FCTESTNET[2] and FCTes$^{QA}$[3] [1,2], investigated every aspect of single cell testing, including test plan preparation; and temperature, pressure, humidity, voltage, and current measurement.  The product, a uniform testing protocol, was then validated in a round-robin experiment in the EU and the US.  Parts of the testing protocol were included in a technical specification published by the IEC [3].

The next logical step in the harmonization process is to collect and compare testing protocols that are or could be used to characterize the performance and durability of automotive-class PEMFC stacks.  The discussion that follows is the first step in this process.

Implicit in the next part of the discussion are the following.  First, the stack test is conducted according to safe laboratory practices when working with potentially large quantities of flammable gases, such as hydrogen, and high voltage and current.  As these may vary from location to location, no further details can be offered.  Second, the stack developer has provided basic information regarding the operation of the stack.  That is, the developer should provide pressure, voltage, current, and temperature limits along with the preferred dew points for the fuel (usually hydrogen) and oxidant (usually air); the preferred utilizations of these reactant gases; and the expected range of differential pressures at points in the fuel cell, including the pressure differential across the membrane.  And third, a test plan describing the experiments and how the experiments will be performed has been written.  The test conditions should be in accord with the specified operating conditions of the given stack.  If tests outside the specified operating environment are planned, these conditions should be discussed with the developer.

---

[1] The Fuel Cell Energy Association was formerly known as the US Fuel Cell Council.

[2] Fuel Cell Testing and Standardization Network, contract no. ENG2-CT-2002-20657

[3] Fuel Cell Testing, Safety, Quality Assurance, contract No. 020161

## 2  GENERAL STRUCTURE OF A STACK TEST

The objective of testing is to gather enough information about the stack to understand its performance and/or durability without reaching failure.  Here, failure means that the performance of the stack does not meet the goal set by a sponsor or standards organization.  For example, the DOE and USDRIVE[4] have published technical targets for fuel cells in transportation [2,3].  Among these are the durability target of 5,000 h in an automotive drive cycle by 2010, and the time it takes for the stack performance to decline by 10% under cycling conditions [4].

There are two types of stack testing, performance and durability.  A performance test is limited to measuring the current-voltage (i-V) curve or power characteristics of the stack.  This is typically done by means of polarization curves and short-term, constant-power tests.  A durability test provides some means to age the stack, usually by electrochemically cycling it.  During the durability test, a metric is used to determine the changes in stack performance.  This can be part of the cycling method or a distinct set of tests.

Some test methods and procedures are described further below.  This is not meant to be an exhaustive compilation, but, rather, a means of comparing and contrasting the methods that are in common use, such as polarization curves and stack durability measurement.  The test protocols are separated according to general category, performance, and durability.

### 2.1  Performance Characterization

This group of tests establishes the performance of the stack at a given time.  Typically, polarization curves are used to measure the voltage vs. current response of the stack.  The protocols are quoted or paraphrased from the references cited.

| Organization | Test |
|---|---|
| DOE, USDRIVE [5,6] | Sequential polarization curve<br><br>This test is performed to establish the voltage vs. current (or current density) response of the stack under testing.<br><br>If the active area of the stack is known:  A polarization curve at current levels of 0, 10, 200, 500, 700, 1000, 1200, and 1500 mA/cm$^2$ (or maximum current density possible) will be attempted at constant fuel and oxidant stoichiometries at all of these operating points.  A |

---

[4] USDRIVE stands for US Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability.  It is a partnership between the US government and the automotive, electric utility, and fuels industries to provide a forum for a pre-competitive information exchange.

| Organization | Test |
|---|---|
| | stabilization time of 15 min will be used at each current level with data averaged over the last 5 min.  The curve will be completed with monotonically increasing and then decreasing current densities. |
| | If the active area of the stack is not known:   A polarization current at evenly spaced steps, typically every 10%, from 0 to the maximum current specified by the developer will be attempted at constant fuel and oxidant stoichiometries at all operating points.  A stabilization time of 15 min will be used at each current level with data averaged over the last 5 min.  The curve will be completed with monotonically increasing and then decreasing current densities.  Both the current-increasing and –decreasing portions of the data are reported. |
| | Random Polarization Curve |
| | This test is performed to eliminate the possible effects of humidification introducing artifacts into the measured response.  In the decreasing-current section of the curve, the response could be artificially higher due to the enhanced humidification of the membrane at the maximum current point. |
| | The same values of either current or current density from the sequential curves will be used.  A 15-min stabilization time at each measurement point will be used, as in the above.  The current densities will be varied randomly rather than monotonically.  Each current density level will occur twice in the sequence, but the same current density will not be used for two successive points. |
| IEC [3] | Sequential polarization curve |
| | Two methods are specified in these protocols, constant flow and constant reactant-gas-to-current stoichiometry.  These methods could be used on a stack; they are currently proposed for cell-level testing. |
| | *"…Constant flow*:  Set the flows of the reactant gases to those recommended by the developer for the maximum current ($i_{max}$). Measure the $i$-$V$ characteristics in the current range of 0 to $i_{max}$, using the following current steps:  0, 2, 5, 10, 20, 30, 50, 70, 90, and 100% of $i_{max}$.  Allow a minimum of 5 min (stack voltage +/- 5 mV) at each current value before measuring the stack voltage. |
| | *Constant stoichiometry:*  Set the flows of the reactant gases to the stoichiometry recommended by the developer.    Maintain  the stoichiometry throughout the test.  Measure the $i$-$V$ characteristics in the current range of 0 to $i_{max}$, using the following current steps:  0, 2, 5, 10, 20, 30, 50, 70, 90, and 100% of $i_{max}$.  Allow a minimum of 5 min |

| Organization | Test |
|---|---|
| | (stack voltage +/- 5 mV) at each current value before measuring the stack voltage…." |
| FCTESTNET[7] | Sequential Polarization Curve<br><br>This test is performed using constant stoichiometry (reactant gas to current ratio).  Apply densities of 0, 2, 5, 10, 15, 20, 25, 30, 40, 50, 60, 70, 80, 90, and 100% of the maximum rated current densities in sequentially increasing and decreasing order.  The starting point can be any value in the list, and the lower current densities may be omitted.  The dwell time at each current density is defined in the test plan as a given time or when the voltage reaches a certain degree of stability.  Only the current-decreasing portion of the data is reported. |

## 2.2  Durability Testing

After completing characterization, the fuel cell stack may be subjected to an aging period, depending on the needs of the test.  After the fuel cell reaches operating conditions, the PEMFC stack is subjected to a continuous repetition of the required duty cycle.

In the US, the stack is cycled for 100 to 125 h, and its performance is characterized by a reference performance test.  Typically, the reference performance test consists of a single sequential polarization curve; cycling then resumes.  The age-characterization process continues until either the stack accrues a set number of cycles or fails to meet a performance criterion, such as a maximum of 20% decline in power.

Similar to the group of tests for stack performance, the following protocols are quoted or paraphrased from the references cited.  The duty cycles are briefly described in the following table.

| Organization | Test |
|---|---|
| United Nations Economic Commission (UNECE) World Forum for Harmonization of Vehicle Regulations [9] | New European Driving Cycle (NEDC, Economic Commission for Europe [ECE] R15)<br><br>The basic duty cycle is shown in Fig. 1.  The NEDC is meant to assess emissions and fuel economy in passenger cars in a European city.  The cycle consists of four urban driving cycles (0 to 780 s) and an extra-urban cycle (780 to 1200 s). |
| USDRIVE [8] | The USDRIVE Technical Team proposed two cycles, "wet" and "dry."  These methods could be used on a stack; they are currently proposed for cell-level testing. |

| Organization | Test |
|---|---|
| | Fig. 2 shows the wet duty cycle; both are similar in structure.  The differences are in the amount of humidification used and the maximum current density applied.  The "wet" protocol uses 92% relative humidity.  The "dry" version uses 25% relative humidity, and, thus, relies on self-humidification to keep the membrane hydrated.  The "dry" protocol also uses a lower maximum current density, 0.1 A/cm$^2$, as compared to that used in the "wet" protocol, 1.2 A/cm$^2$. |
| DOE, FCHEA [10] | Dynamic Stress Test (DST)<br><br>The DST profile was based on the actual power demands of a van during city driving.  It was then simplified and used for battery testing.  The DST duty cycle shown in Fig. 3 represents the battery test profile after being changed for fuel cell testing.  All recharge steps were omitted. |
| FCTESTNET, IEC [3,11,12] | FCTESTNET proposed two duty cycles shown in Figs. 4a and 4b.  These methods could be used on a stack; they are currently proposed for cell-level testing [11] and stack testing [12].  They are meant to introduce different degrees of stress on the stack during the aging process.  The IEC uses these duty cycles as part of its Technical Specification on single cell testing. |
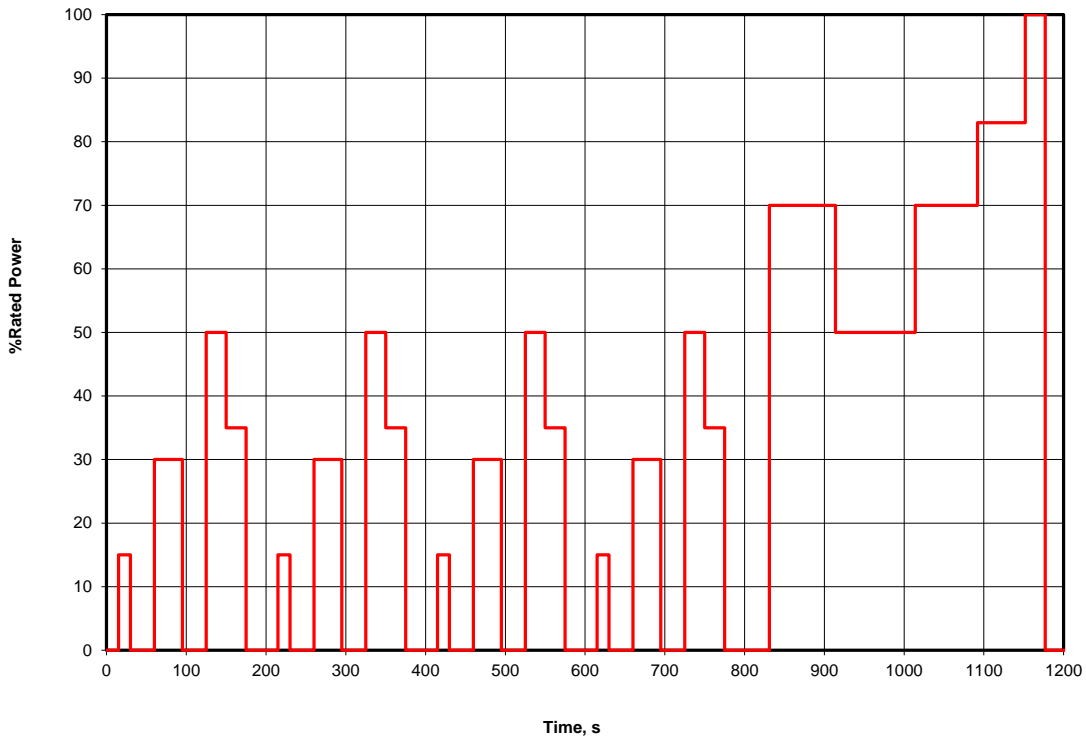


Fig. 1.  New European Driving Duty Cycle (ECE R15).  This profile was adapted from the original R15 cycle by relating speed to power and squaring the pulses.  Adapted from Ref. 9.
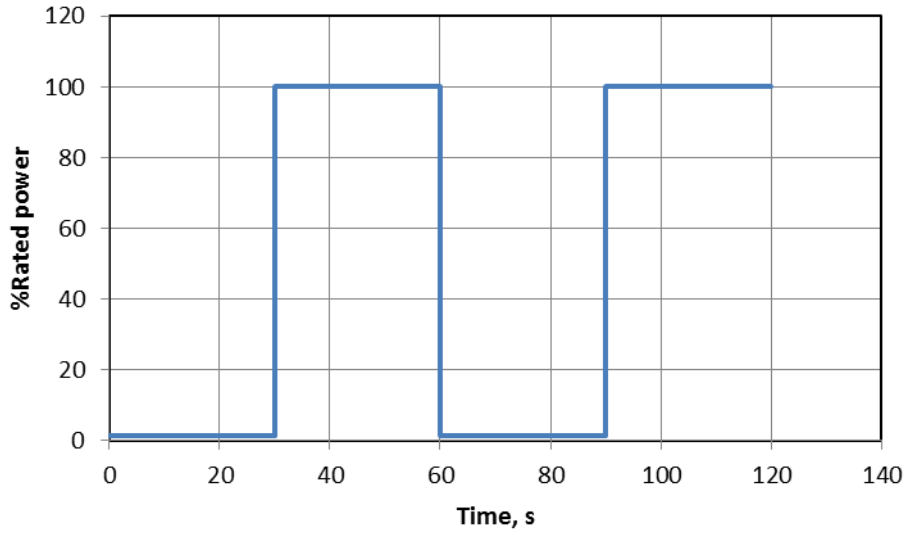
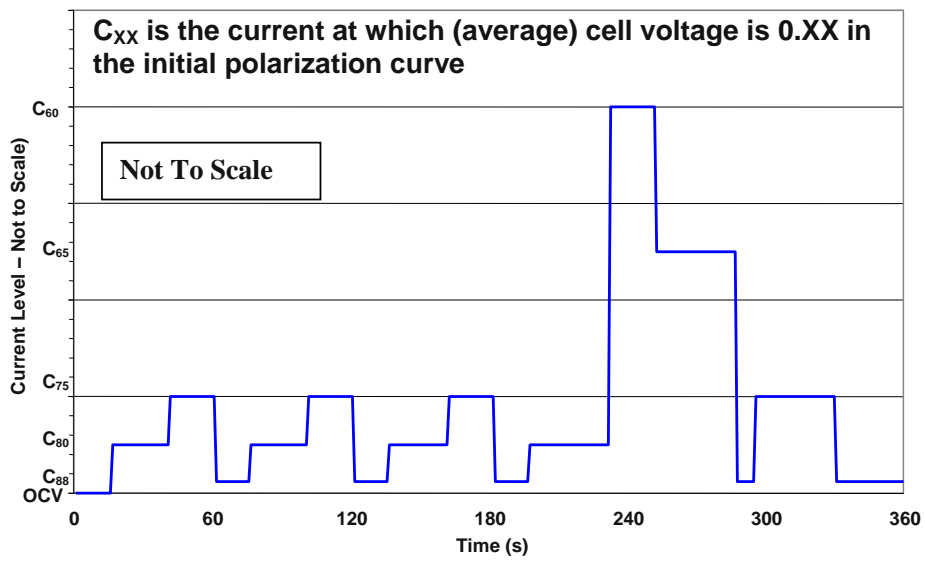Fig. 2. USDRIVE duty cycle (wet). Adapted from Ref. 10.



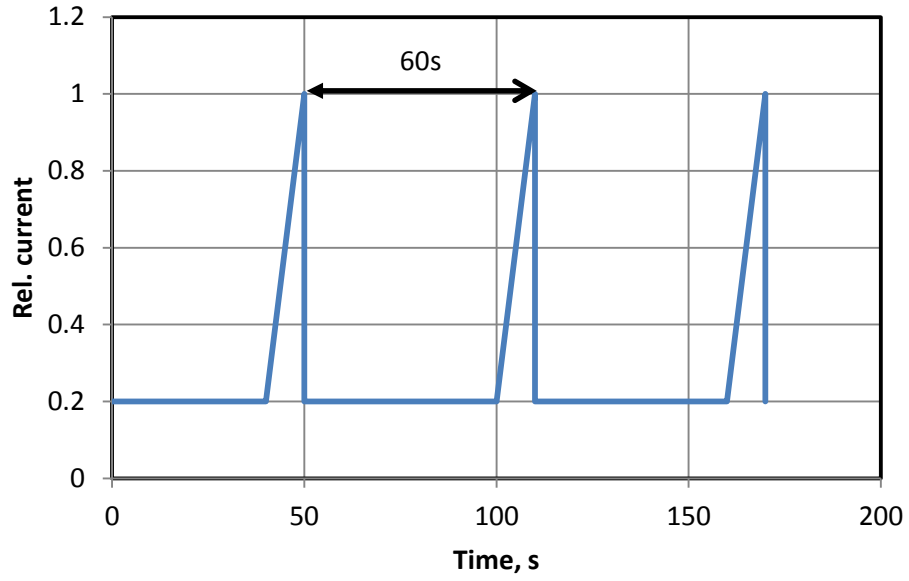Fig. 3. The DST duty cycle used for fuel cell testing. Adapted from Ref. 10.

Fig. 4a. One duty cycle proposed by FCTESTNET.
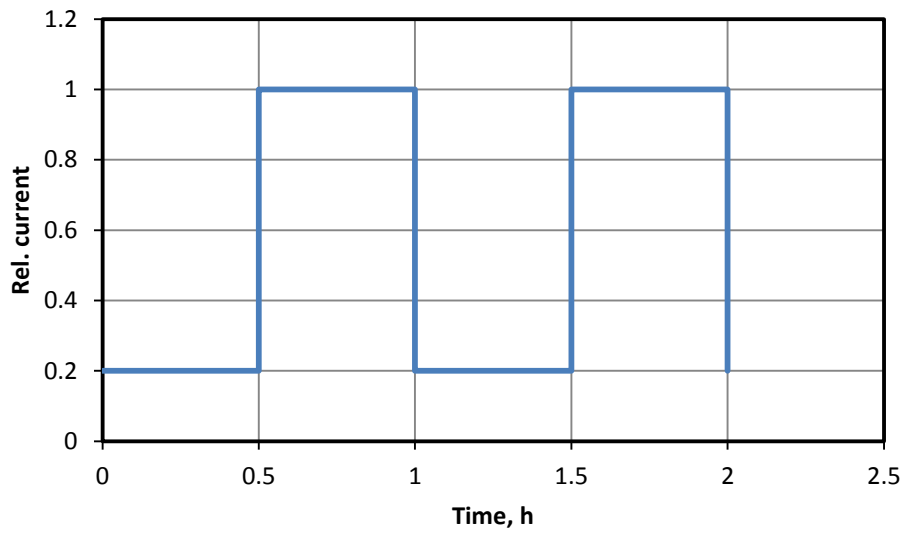Adapted from Ref. 11.



Fig. 4b. Another duty cycle proposed by FCTESTNET. Adapted
from Ref. 12.

# 3  DISCUSSION

It is well known that fuel cells perform differently when arranged in stacks as compared to single cells.  Single cells are tested in a very controlled environment where the temperature and the distribution of reactants tend to be quite uniform.  This is not the case in a fuel cell stack; there are non-uniformities present that can impact performance and durability. Even though the stack configuration tends to have higher power and conversion efficiencies than a single cell, the cell voltages are often not uniform. These non-uniformities arise, in part, from the reactant/product concentration gradients, and water and thermal management strategies that are used in a stack. Properly designing a stack requires different considerations from those in designing a single cell.  The stack requires a system for the removal of product water and heat, a gas manifold to facilitate the uniformity of the supply of the reactants to all cells, and a series of highly conductive electrical contacts between cells.  The reactants are usually fed in parallel to each cell in the stack, possibly leading to uneven reactant flow, which, in turn, affects cell voltages and temperature distribution across the stack.   Both temperature and cell voltage distribution impact stack performance.  Indeed, even the accumulation of water in the flow channels can affect stack durability.  Thus, it is clearly evident that single cell performance, alone, is not sufficient to predict the performances of cells in stacks.

The above procedures demonstrate the similarities and differences in the methods used to characterize performance and to age the stack.  If we examine the sequential polarization curve protocols proposed by FCTESTNET and DOE, for example, the former allows the polarization experiment to start at any value in the range of interest.  The latter allows it to start at 0 $mA/cm^2$ (0% of the maximum current or open circuit voltage).   In principle, starting at 0% and proceeding monotonously to a maximum current level can produce a well-humidified polymer electrolyte membrane.  In turn, its solvent (water) content dependent ionic conductivity will be higher, thereby its resistance will be lower during the current-decreasing portion of the i-V curve, yielding higher performance in terms of stack voltage and power.

If one were to start the FCTESTNET protocol at a value of 50% of the maximum current or higher, it is possible that the membrane would not be as well humidified as that produced in the DOE protocol, yielding lower performance.  Initial results indicate that the magnitude of the difference is quite small [13,14].

DOE added the random polarization curve to remove the possibility of the abovementioned artifact.  The random curve may also represent the response of the stack to the ever-varying load of the vehicle.  Indeed, it is slightly more complex than the other protocols described, but it can yield additional insights into stack behavior.

Many duty cycles have been proposed to age the stack, from simple square waves (high/low current cycles) to complex ones representing vehicle power demands. Each duty cycle embodies a given set of assumptions and objectives.  For example, the ECE R15 duty cycle represents the vehicular demands in a typical European city, where

the average vehicle speed is on the order of 20 km/h.  In contrast, the DST duty cycle represents those demands in a typical US city with higher vehicle speeds, about 40 km/h.  Again, the exact magnitude of the difference in stress placed on the stack by these two exemplary duty cycles is not known.

## 4  SUMMARY

An overview of the PEMFC test proceedings was presented, which is the first step in the global harmonization of testing methods.  Many techniques and philosophies regarding how to determine stack performance and durability were presented.  Each approach has differences that may or may not impact the data and data quality.  As mentioned previously, experimentally, the differences in the results from the two methods to measure sequential polarization curves are minimal.  Answers to questions regarding differences in the aging duty cycles need to be determined experimentally.  The results of these experiments are expected to help the harmonization process, to facilitate the understanding of test results, and, possibly, accelerate the commercialization of PEMFCs.

## ACKNOWLEDGMENTS

## REFERENCES

1.  R. Bove, T. Malkow, A. Saturnio, and G. Tsotridis, PEM fuel cell stack testing in the framework of an EU-harmonized fuel cell testing protocol: Results for an 11 kW stack, *Journal of Power Sources* 180 (1) 452–460, 2008.

2.  T. Malkow, A. Saturnio, A. Pilenga, G. De Marco, M. Honselaar, and G. Tsotridis, Assessment of PEFC performance by applying harmonized testing procedure, *International Journal of Energy Research* 35 (12) 1075–1089, 2011.

3.  IEC62282-7-1, Single cell test protocol, April 2010.

4.  DOE Multi-year program plan, March 2011, http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/pdfs/fuel_cells.pdf.

5.  USDRIVE Target Tables, Aug. 2011, http://www.uscar.org/commands/files_download.php?files_id=279.

6.  DOE Durability Test Plan, April 2005.

7.  FCTes$^{QA}$ Test Module TM PEFC ST 5-3, Version 2010-04-30, EUR 24126 EN 2009.

8.  "Cell Component Accelerated Stress Test and Polarization Curve Protocols for Polymer Electrolyte Membrane Fuel Cells," USDRIVE Partnership Fuel Cell Technical Team, December 16, 2010.

9.  ECE R15, 1970, http://en.wikipedia.org/wiki/New_European_Driving_Cycle.

10. "Protocol on Fuel Cell Component Testing: Suggested Dynamic Testing Protocol (DTP)," Joint Hydrogen Quality Task Force, Document USFCC 04-068, Rev A, May 1, 2006 (www.fchea.org).

11. FCTESTNET PEFC TM SC5-4, Accelerated aging procedure for single cell, V. 1.2, Oct. 2006.

12. FCTESTNET PEFC TM ST5-7, Measuring voltage and power as function of current density following a dynamic profile versus time. Dynamic load cycling aging profile, Oct. 2006.

13. I. Bloom, L.K. Walker, J.K. Basco, T. Malkow, G. De Marco, and G. Tsotridis, 2010 Fuel Cell Seminar & Exposition, October 18–21, 2010, San Antonio, TX.

14. I. Bloom, L. K. Walker, J.K. Basco, T. Malkow, G. De Marco, and G. Tsotridis, ECS Transactions – 2010 Fuel Cell Seminar & Exposition, Vol. 30, "Degradation in PEM Fuel Cells," Feb. 2011.

ISBN 978-92-79-29460-0

9 789279 294600

European
Commission