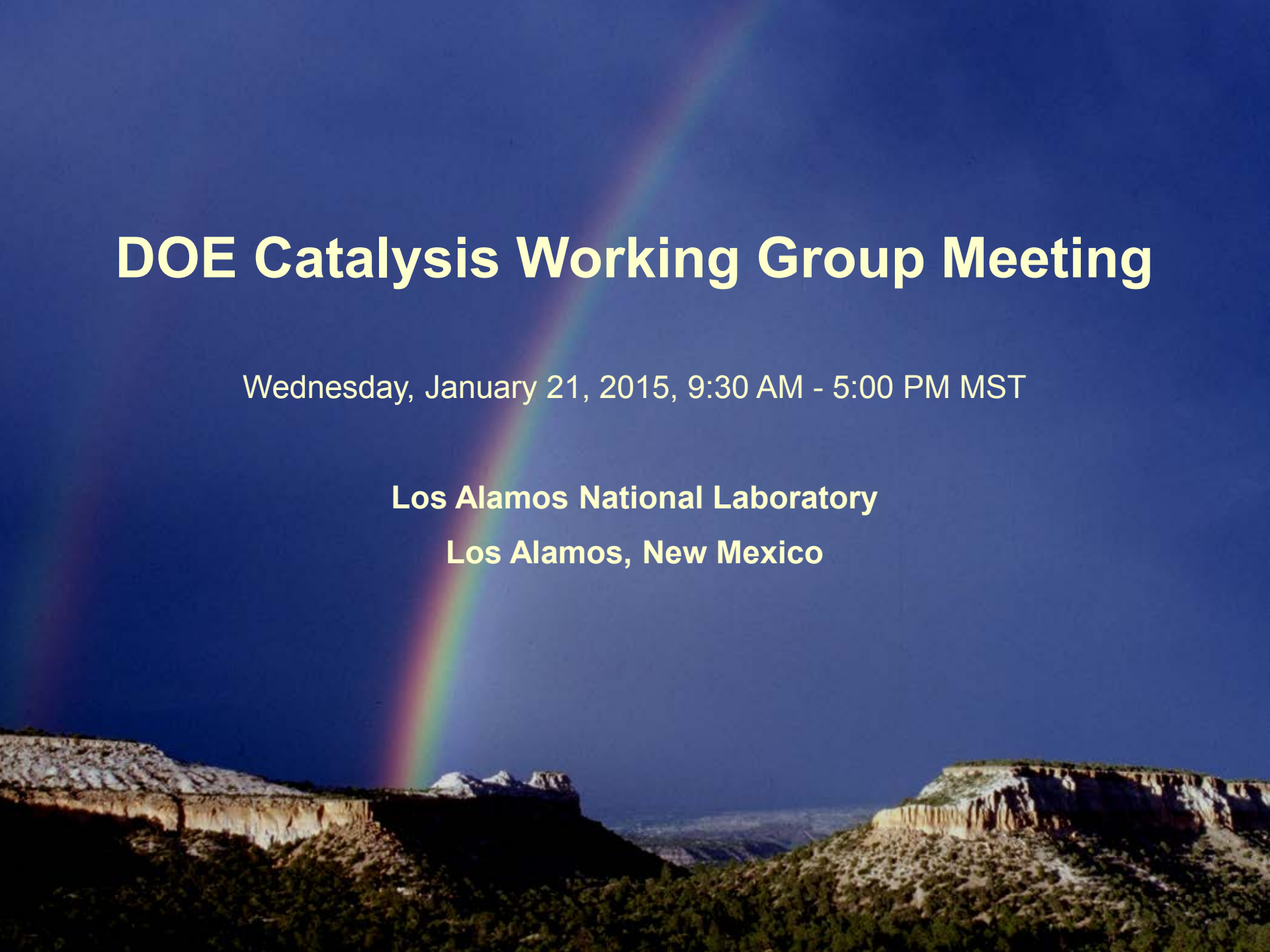


DOE Catalysis Working Group Meeting

Wednesday, January 21, 2015, 9:30 AM - 5:00 PM MST

Los Alamos National Laboratory

Los Alamos, New Mexico

DOE CATALYSIS WORKING GROUP MEETING

January 21, 2015

Los Alamos National Laboratory, Los Alamos, New Mexico
Quantum Institute Room, MPA-11, Building SM-40, Technical Area 3 (TA-3)

Co-Chairs: Piotr Zelenay (LANL) and Nancy Garland (DOE)

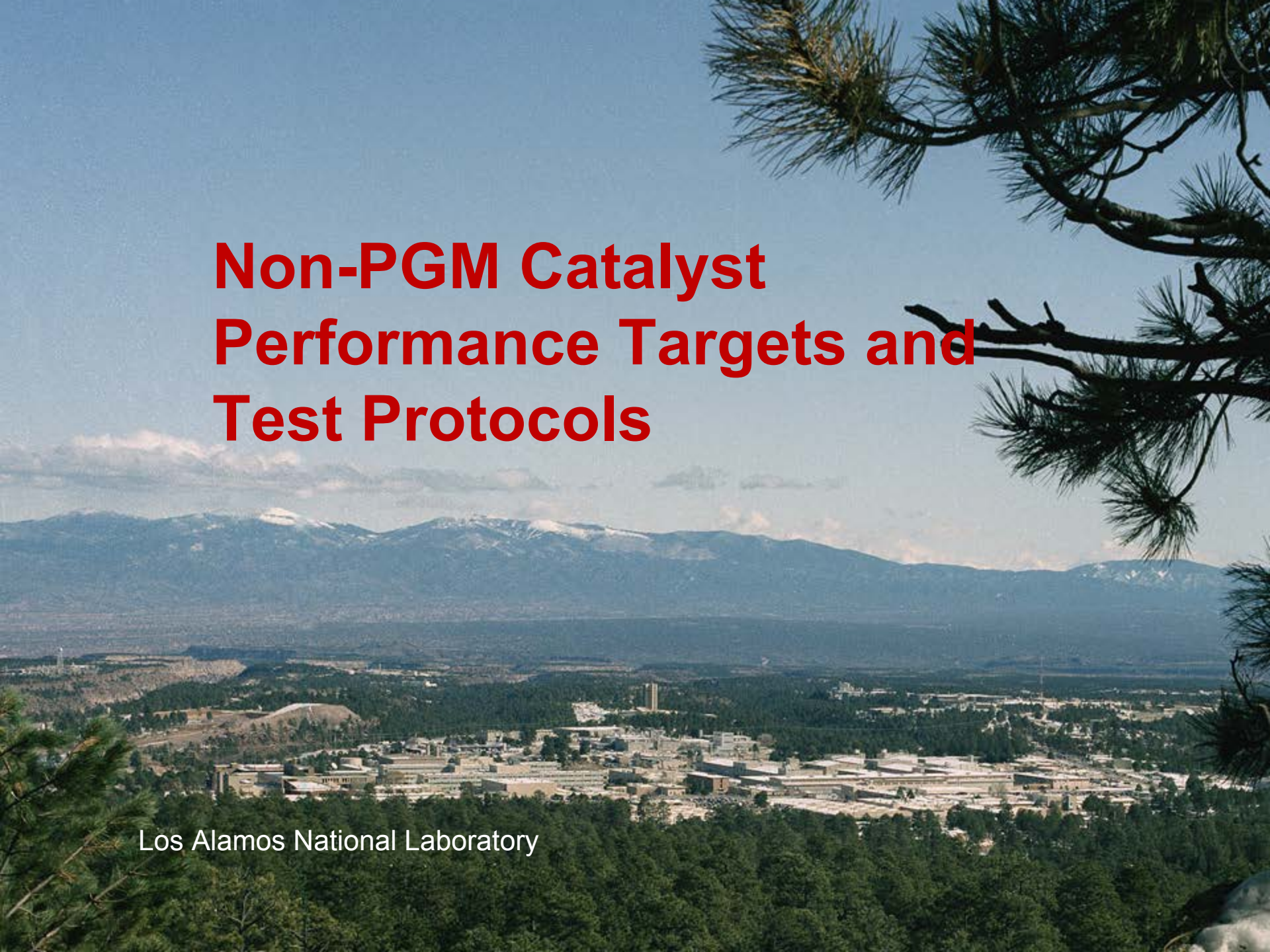
Agenda

(All times MST)

8:30 - 9:00	**Arrival; coffee, soft drinks, bagels & doughnuts**
9:00 - 9:05	*Welcome and Introduction* Nancy Garland (DOE) and Piotr Zelenay (LANL)
9:05 - 11:15	Final Discussion of Non-Precious Metal Catalyst Performance Targets and Protocols
9:05	*Summary of the Process to Date* Piotr Zelenay (LANL)
9:35	*Discussion* Plamen Atanassov (UNM) Scott Calabrese Barton (Michigan State) Nilesh Dale (Nissan) Barr Halevi (Pajarito Powder) Di-Jia Liu (ANL) Sanjeev Mukerjee (Northeastern) Other participants welcome
11:00	*Summary and Path Forward* Nancy Garland (DOE)
11:15 - 11:55	*Microstructural Characterization of Non-PGM ORR Catalysts* Karren More (ORNL)
11:55 - 13:15	**Lunch in LANL Cafeteria** (short walk; no host)
13:15 - 13:55	*Catalysts with Ultra-Low PGM Content* Vojislav Stamenkovic (ANL)
13:55 - 14:20	*Improving Stability and Activity of Pt Monolayer in Non-Pt Core-Shell Electrocatalysts* Radoslav Adzic (BNL)

14:20 - 15:00	*Microstructural Characterization of Extended Surface PGM Catalysts by Advanced Electron Microscopy Methods* David Cullen (ORNL)
15:00 - 15:15	*Challenge of Catalyst Scale-up for MEA Integration* Madeleine Odgaard (IRD Fuel Cells)
15:15 - 15:45	*Scale-up Challenges of Novel (Pt-centric) Catalysts* Bryan Pivovar (NREL)
15:45 - 16:10	*Engendering Poison Tolerance in PGM Catalysts; Possible New Directions in Electrocatalysis* Sanjeev Mukerjee (Northeastern University)
16:10 - 16:20	*Very Brief Account from Electrocatalysis-Relevant Discussion at Durability Working Group in Chicago Last December* Rod Borup (LANL)
16:20 - 16:40	Catalysis Working Group – Near-Future Tasks
16:40 - 17:00	Miscellaneous items; wrap-up
17:00	Adjourn

19:00 **Dinner at "Dinner for Two", 106 N. Guadalupe, Santa Fe**
(no host)



Non-PGM Catalyst Performance Targets and Test Protocols

Los Alamos National Laboratory

Discussion of Non-PGM ORR Catalyst Targets

Already addressed three times at CWG meetings in Arlington, VA on May 15, 2013; Golden, CO on December 18th, 2013 (update); and Washington, D.C. on June 16, 2014

- Areal current density the only measure of catalyst performance
- Volumetric activity no longer part of the metrics
- Current density specified at more than one voltage to address both the catalyst activity (efficiency) and electrode-design (power) requirements, *e.g.* 0.85 V (increase relative to the present reference voltage value) and 0.60 V, respectively.
- Targets not tied to any specific catalyst loading, electrode thickness, etc.
- No *iR* correction; no Tafel extrapolation to the reference voltage
- Fuel cell performance targets on O_2 (1.0 bar O_2) and air (0.2 bar O_2?)
- Realistic fuel cell operating conditions to be used: humidification, stoich, etc.
- Durability targets consistent with those for Pt-based ORR catalysts
- Potential/voltage cycling in air rather than nitrogen
- No RDE target; a screening tool only

Stakeholders Comments on Targets

- The long-term non-PGM catalyst performance targets should be derived from the overall system targets that would allow a non-PGM fuel cell system to be competitive with an IC engine system, similar to how the Pt system targets were derived. The over-arching system targets that need to be met are **cost**, **efficiency**, and **durability**. A secondary target is **heat rejection** at rated power. (ANL)
- Given that for current Pt systems catalyst cost is ~ ½ the stack cost, if we had a zero cost catalyst we could have twice as much of all the other components and have a system with the same cost as the Pt system, i.e. the power density of a system with a "free" catalyst would need to be at a minimum ½ that of a Pt system. Assuming then that we meet the cost targets at the Pt system performance targets, and that the ratio of costs remains similar, this then implies the following loading independent target for non-PGM MEA performance at rated power (1000 mW/cm^2)/2: **500 mW/cm^2**. (ANL)
- The efficiency should match the Pt system efficiency. For the Pt system we have used an estimate of peak efficiency rather than determine efficiency at the most common point in the drive cycle. We have assumed to date that this is at ¼ power, and for Pt catalysts have used 0.80 V or 64% efficiency point. Therefore, the target for non-PGM performance should be 64% efficiency at ¼ power = 64% efficient at 125 mW/cm^2. This implies: **156 mA/cm^2 at 0.80 V**. (ANL)
- Durability needs to be the same as for a PGM system, *i.e.* loss of catalytic activity of **< 40%**, to meet end-of-life performance requirements after **5000 hrs**. (ANL)

Stakeholders Comments on Targets

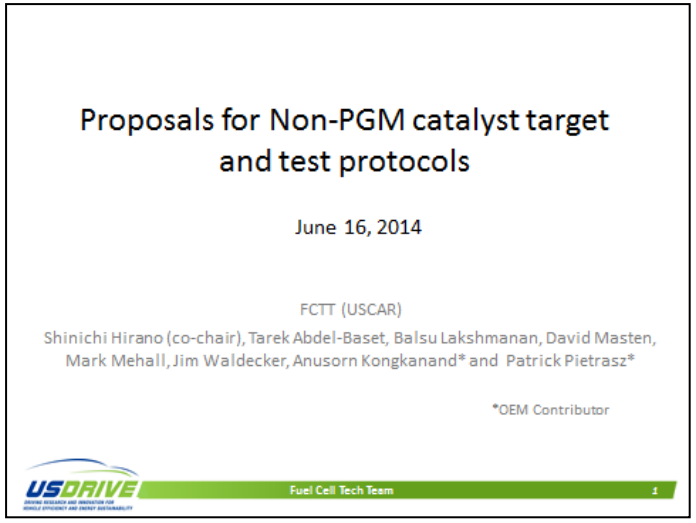
- **Volumetric activity target should be eliminated entirely** and replaced by two design points: one at **0.80 V** and one at **0.60 V**. Those two design points should be for well-defined MEA test conditions, including membrane thickness. **No iR correction**. (UNM)
- Maintain 'volumetric activity target' but instead of using extrapolation to estimate activity at 0.80 V set for a measured activity target of **11 A/cm^3 at 0.90 V**, ***iR*-corrected**. (Equivalent to 300 A/cm^3 at 0.80 V assuming 70 mV/dec Tafel slope.) Consistent criteria between PGM and non-PGM will enable ready comparison. In addition, measurements at low current density will mitigate device variation, such as ohmic resistances. (GM)
- **Keep 0.80 V as a design point**, do not prematurely exclude new formulations and research groups. The practical design point of 0.60 V will assure appropriate physical morphology, "ink integration" and MEA design. Agrees with the expressed needs of three automotive manufacturers in Japan, claiming primary interest in the performance between 0.75 V and 0.55 V. (UNM)
- Strongly recommend testing under **fully humidified pure O_2 at higher stoich** (*e.g.*, **9.5**) in order to understand kinetics and local oxygen transport. Conditions recommended in the December CWG meeting (lower O_2 stoich or use of air) are inappropriate. (GM)
- **No target for RDE measurements**. (GM)
- Do we have/need 2017 **targets on air**? (Ballard)
- The non-PGM system needs to meet the **heat rejection requirement** of **Q/ΔTi < 1.45**. (ANL)

Summary of Responses

- Areal current density the only measure of catalyst performance – **agreement**
- Areal current density specified at more than one point (voltage) to address both the catalyst activity (efficiency) and electrode-design (power) requirements, e.g. 0.85 V or 0.90 V (increase relative to the present reference voltage value) and 0.60 V, respectively.

  – **agreement** on two-point approach (with one exception when maintaining volumetric activity is preferred); **disagreement** on the value of higher voltage
- Targets not tied to any specific catalyst loading, electrode thickness, etc. – **agreement**
- Volumetric activity no longer part of the metrics – **disagreement**
- No *iR* correction – **disagreement**
- No Tafel extrapolation to the reference potential (voltage) – **agreement**
- Fuel cell performance targets on O_2 (1.0 bar O_2) and air (0.2 bar O_2?) – **no clear preference**
- Realistic fuel cell operating conditions: humidification, stoich, etc. – **agreement** on most, **disagreement** on stoich
- Durability targets consistent with those for Pt-based ORR catalysts – **agreement**
- Potential/voltage cycling in air rather than nitrogen – **no clear preference**
- No RDE target; a screening tool only – **agreement**

FCTT Comments on Targets and Test Protocols: Background


Proposals for Non-PGM catalyst target and test protocols

June 16, 2014

FCTT (USCAR)

Shinichi Hirano (co-chair), Tarek Abdel-Baset, Balsu Lakshmanan, David Masten, Mark Mehall, Jim Waldecker, Anusorn Kongkanand* and Patrick Pietrasz*

*OEM Contributor

USDRIVE Fuel Cell Tech Team 1

- Non-PGM ORR catalyst is expected to be an opportunity to enable **further cost reduction** of fuel cell system beyond an achievement of the low PGM loading ORR catalyst.
- Therefore, target should be to achieve **equivalent performance** (power density) of PGM ORR catalyst without using PGM materials rather than equivalent cost (cost neutral).
- Target and test protocols of PGM ORR catalyst (Tables 3 and 5, FCTT Roadmap, July 2013) are applied, except metrics with respect to PGM amount.
- **All targets are MEA based**. No target is defined for RDE test, but RDE data can be reported for screening purpose.
- No interim target is defined. Technical progress should be reported toward the target.

FCTT Comments: MEA Targets

- MEA targets in Table 3, FCTT Roadmap is equally applicable for the MEA with non-PGM catalyst

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

FCTT Comments: Catalysts Activity and Durability Targets

Activity:

- In the Table 5 of FCTT Roadmap, volumetric activity target of non-PGM catalyst ORR activity should be replaced by following ORR activity target (equivalent performance).

Metrics	Target*	Test Protocols
ORR activity target	> 0.044 A/cm^2 at 0.9V$_{iR\text{-}corrected}$	Roadmap Table 5, footnote [f]

* Target is equivalent to advanced PGM catalyst mass activity performance 0.44 A/mg$_{PGM}$ at 0.1 mg$_{PGM}$/cm^2.

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

- No extrapolation
- Report fraction of two-electron ORR
- Report the thickness of catalyst layer and Tafel slope

Durability:

- Less than 30 mV loss at 0.8 A/cm^2 after 30,000 cycles
- Cycling: 0.6 - 1.0 V, 50 mV/s, 80°C, H_2/N_2, atmospheric pressure
- ORR polarization curves recorded after 10, 100, 1,000, 3,000, 10, 000, 20,000, and 30,000 cycles (details in FCTT Roadmap, Table A-1)

Electrocatalysts

Table 5. Technical Targets for Electrocatalysts

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

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

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

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

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

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

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

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

[h] P. Zelenay, H. Chung, C. Johnston, N. Mack, M. Nelson, P. Turner, and G. Wu, FY 2011 Progress Report for the DOE Hydrogen Program, p. 816, U.S. Department of Energy, Feb. 2011, DOE/GO-102011-3178.

Comments on Fuel Cell (MEA) Testing

- **Pressure** and **RH** should be defined and included. (IRD)
- Humidity? 60% and 100% **RH**. (Ballard)
- Spell out operating conditions – **RH**, **stoich** (maybe RH 50%, cathode stoich of ~ **2.5-3.0**). (LANL).
- Why such a **high stoichiometry**? A value of **1.8** or **2.0** would be more realistic and consistent with the desire to obtain data closer to application operation conditions. This comment also applies to the proposed durability protocol. (HNEI)
- What's the purpose of **cycling between 0.2-1.1 V**? Why not **0.2-1.0 V** (*i.e.* OCV)? In order to simulate high potentials for startup/shutdown one needs ~ 1.4-1.5 V. (LANL)
- Upper potential limit of 1.1 V may be too low. Since we are targeting automotive applications where startup/shutdown is such an important factor, it may be useful to set a higher UPL (*e.g.*, **1.3 V**) as an **additional target** for direct comparison with PGM catalysts. (Ballard)
- **Cycling between 0.2-1.1 V**: How to handle in case we are testing a promising catalyst but OCV is ~ 0.9 V? (IRD)
- Fuel cell testing: **Leave off** or **not state 5 cm^2**.(LANL)
- Recommend **reporting** current density at 0.70 V on H_2/O_2 and 0.60 V on H_2/air. (GM)
- Testing should be done under the **same conditions as specified for Pt MEA testing**. (ANL)

Comments on Fuel Cell (MEA) Testing

- **MEA test parameters**. (GM)

Electrode thickness	> 100 μm
Temperature	80°C
Data acquisition	4 min/point (average and report the last min)
Pressure (anode/cathode)	150 $kPa_{abs,out}$
Relative humidity	100%
Stoich	2.0/9.5

Note: *iR-correction is encouraged for H_2/O_2 measurements; no correction for H_2/air.*

Proposed Non-PGM ORR Activity & Durability Protocol: RDE

- **Test conditions:**
  - 0.2 mg cm^{-2}; 0.1 mg cm^{-2}; 0.6 mg/cm^{-2} (activity & durability)
  - 25°C, 0.1 M H_2SO_4
  - O_2 in activity testing; N_2 and O_2 in activity and durability testing;
  - Ionomer content and deposition method optimized for particular catalyst
  - 900 rpm
- **Cycling:**
  - between 0.2 V and 1.1 V *vs.* RHE
  - 50 mV s^{-1}
  - 0, 500, 1000, 5000 cycles
- **Reporting:**
  - OCP (at galvanostatic zero current)
  - Steady-state polarization plots – constant potential, 25 mV increments, from OCP down (constant-current plots also allowed)
  - Report change in $E_{1/2}$ (V) and change in OCP (V)

Comments on Electrochemical (RDE) Testing

- Mention **RRDE** to emphasize the need to assess peroxide levels. **Peroxide yield** should be reported. (HNEI)
- Report RDE results in both acid and **alkaline electrolyte**, *i.e.*, H_2SO_4 and KOH. (IRD)
- Should **perchloric acid** be considered instead of sulfuric acid to facilitate comparisons with Pt-based catalysts? (HNEI).
- Upper potential limit of 1.1 V may be too low. Since we are targeting automotive applications where startup/shutdown is such an important factor, it may be useful to set a higher UPL (*e.g.*, **1.3 V**) as an **additional target** for direct comparison with PGM catalysts. (Ballard)
- It is important to test catalysts with **different loadings** to evaluate possible impact on 2- or 4-electron transfer and the impact of oxygen diffusion within catalyst layers. (Ballard)
- For consistency with Pt/C research, use a rotation rate of **1600 rpm** and **0.1 M $HClO_4$** in RDE work. If H_2SO_4 is used the activity of NPMC will appear artificially higher than it truly is when compared to Pt/C. (Ballard)

Comments on Electrochemical (RDE) Testing

- **Test parameters** for activity measurements in RDE. (GM)

	Linear Sweep Voltammetery (LSV)
Electrolyte	0.1 M $HClO_4$ or 0.05 M H_2SO_4
RDE disk	GC
Counter electrode	Pt gauze/Au gauze/Graphite & frit-isolated
Reference electrode	RHE
Working electrode	Saturated O_2
Temperature	25°C
Voltage Range	0.05 - 1.00 V
Scan Rate	5 mV/s
Scan Direction	Anodic (0.05→1.0 V)
# of Scans	Average of 3 scans per electrode; 3 electrodes per catalyst
Analysis	Kinetic current @ 0.90V (no background or ohmic correction)

Notes: *(1) LSV might not be appropriate with thick and high electrocapacitive non-PGM electrode. In this case steady-state measurement may be more appropriate. (2) In order to appropriately measure kinetic current on thin film, one must do a loading/thickness study to determine the film diffusion resistance prior to reporting the activity value.*

Discussion Today

- **Alignment of non-PGM targets and test protocols with those established for PGM catalysts and PGM-based MEAs**
- **Discussion of FCTT recommendations versus stakeholders' comments**
- **Are intermediate performance targets needed? If so, what should they be?**
- **Role of RDE/RRDE activity and durability testing in the development of non-PGM ORR electrocatalysts**
- **"Mimicking" fuel cell test protocols in RDE/RRDE testing – Should there be an appendix to CWG recommendations to FCTO?**
- **Proposed submission date: Friday, March 13, 2015**
- **Volunteers for helping with preparation of recommendations for the Program Office**
- **Else?**

Backup

Proposed Non-PGM ORR Catalyst Activity Protocol (LANL & UNM): Fuel Cell

- **Test conditions:**
  - 25 or 50 cm^2; smaller cell, *e.g.*, 5 cm^2 allowed though not recommended
  - 80°C
  - O_2 and air, stoich 3.0
- **OCV measurement** at O_2 and air, stoich 3.0
- **Fuel cell polarization plots:**
  - O_2 and air, stoich 3.0
  - Current density (mA cm^{-2}) measured at two voltages: 0.90 V or 0.85 V and 0.60 V
  - As recorded data reported with HFR (Ω cm^2) provided at both voltages

Proposed Non-PGM ORR Durability Protocol: Fuel Cell

- **Test conditions:**
  - 25 or 50 cm^2; smaller cell, *e.g.*, 5 cm^2 allowed though not recommended
  - 80°C
  - N_2 and air (stoich 3.0)
  - Ionomer content and deposition method optimized for particular catalyst
- **Cycling:**
  - between 0.2 V and 1.1 V
  - 50 mV s^{-1}
  - 500, 1000, 5000, 10000, 30000 cycles
- **Reporting:**
  - OCV
  - Polarization plots (steady-state; up & down)
  - Current density (mA cm^{-2}) measured at two voltages: 0.90 or 0.85 V and 0.60 V
  - As recorded data reported with HFR (Ω cm^2) provided

Comments on Targets and Protocols

LANL (Rod Borup)**:**

- Fuel cell testing: *Spell out operating conditions (RH, stoich – maybe 50% inlet RH and cathode stoich of ~ 2.5 – 3.0)* (LANL).
- Fuel cell testing: *Leave off or not state 5 cm^2; it contradicts reasonable operating stoichs* (LANL).
- Fuel cell testing (AST): *What's the purpose of cycling between 0.2 and 1.1 V? Why not 0.2 and 1.0 (i.e. OCV)? In order to simulate high potentials for startup/shutdown one needs ~ 1.4 – 1.5 V* (LANL).

Comments on Targets and Protocols

HNEI (Jean St-Pierre)**:**

- Electrochemical testing: *Mention RRDE to emphasize the need to assess peroxide levels?* (HNEI).
- Fuel cell testing: *Why recommend such a high stoichiometry? A value of 1.8 or 2 would be more realistic and consistent with the desire to obtain data closer to application operation conditions. This comment also applies to the proposed durability protocol* (HNEI).
- Electrochemical testing: *Should perchloric acid be considered instead to facilitate comparisons with Pt based catalysts?* (HNEI).
- Electrochemical testing: *The peroxide yield should be added to this list* (HNEI).

Comments on Targets and Protocols

UNM (Plamen Atanassov)**:**

- Targets: *Volumetric activity target should be eliminated entirely and replaced by two design points: one at 0.80 and one at 0.60 V. Those two design points should be for well-defined MEA test conditions, including membrane thickness. We prefer those to be reported with no iR correction.* (UNM)
- Targets: *Keep 0.80 V as a design point. Many new formulations will not be discarded and many researches will be incorporated into the field as they attain 0.8 V target. The practical design point of 0.60 V will introduce the need for physical morphology, ink integration and MEA design. Consulting with three automotive manufacturers reveals that they all care about performance between 0.75 and 0.55 V. The practical target at 0.60 V will challenge the field and, when combined with the 0.80 V target, will eliminate the fixation on operation at ultra-low current densities.* (UNM)

Comments on Targets and Protocols

IRD (Madeleine Odgaard)**:**

- Fuel cell testing: *Pressure and RH% should be defined and included.* (IRD)
- Fuel cell testing: *Cycling between 0.2-1.1 V: How to handle in case we are testing a promising catalyst but OCV is ~0.9 V. Impact of the upper voltage limit ?* (IRD)
- Electrochemical testing*: Report RDE results in both acid and alkaline electrolytes (i.e., H_2SO_4 and KOH).* (IRD)

Comments on Targets and Protocols

GM (Anusorn Kongkanand)**:**

- Targets: *Maintain 'volumetric activity target' but instead of extrapolating for activity at 0.80 V set for a measured activity target of 11 A/cm^3 at 0.90 V iR-corrected. (This is what was used to calculate the 300 A/cm^2 at 0.80 V assuming 70 mV/dec Tafel slope, and the same as a 100 µm thick 4× PGM catalyst at 0.90 V. Consistent criteria between PGM and non-PGM will enable ready comparison. In addition, measurement at low current density will mitigate device variation such as ohmic resistances. (We believe discrepancy seen with different membrane thickness might be due to ohmic correction at higher current density).* (GM)
- Targets: *Still do not recommend having any target for RDE measurements.* (GM)
- Targets: *Strongly recommend testing under fully humidified pure O_2 at higher stoich (e.g., 9.5) in order to understand kinetic and local oxygen transport. Those recommended in the December CWG meeting (lower O_2 stoich or use of air), is inappropriate.* (GM)
- Fuel cell testing: *Recommend reporting current density at 0.70 V in H_2/O_2 and 0.60 V in H_2/air.* (GM)

Comments on Targets and Protocols

- Fuel cell testing: *MEA test parameters* (GM)

Electrode thickness	> 100 μm
Temperature	80°C
Data acquisition	4 min/point (average and report the last min)
Pressure (anode/cathode)	150 $kPa_{abs,out}$
Relative humidity	100%
Stoich	2.0/9.5

Note: *iR-correction is encouraged for H_2/O_2 measurements; no correction for H_2/air.*

Comments on Targets and Protocols

- Electrochemical testing: *Test parameters for activity measurements in RDE* (GM)

	Linear Sweep Voltammetery (LSV)
Electrolyte	0.1 M $HClO_4$ or 0.05 M H_2SO_4
RDE disk	GC
Counter electrode	Pt gauze/Au gauze/Graphite & frit-isolated
Reference electrode	RHE
Working electrode	Saturated O_2
Temperature	25°C
Voltage Range	0.05 - 1.00 V
Scan Rate	5 mV/s
Scan Direction	Anodic (0.05→1.0 V)
# of Scans	Average of 3 scans per electrode; 3 electrodes per catalyst
Analysis	Kinetic current @ 0.90V (no background or ohmic correction)

Notes: *(1) LSV might not be appropriate with thick and high electrocapacitive non-PGM electrode. In this case steady-state measurement may be more appropriate. (2) In order to appropriately measure kinetic current on thin film, one must do a loading/thickness study to determine the film diffusion resistance prior to reporting the activity value.*

Comments on Targets and Protocols

Ballard (Silvia Wessel)**:**

- Targets: *Do we have/need 2017 targets on air?* (Ballard)
- Fuel cell testing: *Humidity? 60% and 100% RH* (Ballard)
- Fuel cell testing and electrochemical testing: *Upper potential limit of 1.1 V may be too low. Cycling to 1.1 V is not a bad start, as NPMC are generally prepared using high surface area carbons. They would likely be destroyed by going to even 1.3 V. Since we are also targeting automotive applications where startup/shutdown is such an important factor, it may be useful to set a higher UPL (e.g., 1.3 V) as an additional target for direct comparison with PGM catalysts.* (Ballard)
- Electrochemical testing: *It is important to test catalysts with different loadings to evaluate the possible impact on 2- or 4-electron transfer mechanism, and the impact of oxygen diffusion within catalyst layers.* (Ballard)
- Electrochemical testing: *For consistency with Pt/C research, it would be best to suggest a rotation rate of 1600 rpm and 0.1 M $HClO_4$ for the RDE work. While the impact of HSO_4^- adsorption on the active site for NPMCs may not be significant (at least compared to HSO_4^- adsorption on Pt) it would still be best to have consistency between Pt/C and NPMC work. This is actually very important considering that researchers in the NPMC field will almost certainly be comparing their catalysts to Pt/C catalysts. If this comparison is performed in H_2SO_4, the activity of the NPMC will appear artificially higher than it truly is when compared to Pt/C*. (Ballard)

Comments on Targets and Protocols

ANL (John Kopasz)**:**

- Targets: *The long-term non-PGM catalyst performance targets need to derive from the overall system targets that would allow a non-PGM fuel cell system to be competitive with an IC engine system, similar to how the Pt system targets were derived. The over-arching system targets that need to be met are cost, efficiency, and durability. A secondary target is heat rejection at rated power.* (ANL)
- Targets: *Given that for current Pt systems catalyst cost is ~ ½ the stack cost, if we had a zero cost catalyst we could have twice as much of all the other components and have a system with the same cost as the Pt system, i.e. the power density of a system with a "free" catalyst would need to be at a minimum ½ that of a Pt system. Assuming then that we meet the cost targets at the Pt system performance targets, and that the ratio of costs remains similar, this then implies the following target for a non-PGM MEA (independent of the loading). Non-PGM MEA performance at rated power (1000 mW/cm^2)/2 = 500 mW/cm^2.* (ANL)
- Targets: *The efficiency should match the Pt system efficiency. For the Pt system we have used an estimate of peak efficiency rather than determine efficiency at the most common point in the drive cycle. We have assumed to date that this is at ¼ power, and for Pt catalysts have used 0.80 V or 64% efficiency point. Therefore, the target for non-PGM performance should be 64% efficiency at ¼ power = 64% efficient at 125 mW/cm^2. This implies 156 mA/cm^2 at 0.80 V.* (ANL)

Comments on Targets and Protocols

- Targets: *Durability needs to be the same as for a PGM system, i.e. loss of catalytic activity of < 40%, to meet end-of-life performance requirements after 5000 hrs.* (ANL)
- Targets: *The non-PGM system will still need to meet the heat rejection requirement of* $Q/\Delta Ti < 1.45$. (ANL)
- Fuel cell testing: *Testing should be done under the same conditions specified for Pt MEA testing.* (ANL)

Summary (Old - AMR 2014)

- Responses generally dependent on whether non-PGM catalysts are viewed as:

  (a) subject of continuing materials development and engineering effort

  or

  (b) relatively mature technology that should match Pt in real-life systems

- **Targets:** **(1)** majority favoring elimination of the volumetric activity target and its replacement it with current density targets at two voltage values; agreeing on the lower voltage (0.60 V), disagreeing on the higher voltage (from 0.80 V to 0.90 V); **(2)** majority favoring durability targets to be as those for Pt; disagreeing on the range of cycling; **(3)** no support for RDE performance targets; **(4)** no specific values proposed for areal current-density targets

- **Fuel cell (MEA) testing:** **(1)** cathode stoichiometry and cycling range the most controversial points; **(2)** RH to be specified (100% most popular)

- **Electrochemical testing:** **(1)** cycling range the most controversial point; **(2)** H_2O_2 should be reported; **(3)** various electrolytes proposed (issue unlikely to become controversial)