Resonance-Stabilized Anion Exchange Polymer Electrolytes

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Project ID: FC043
Overview

Timeline

| Project start | September 2009 |
| Project end   | March 2012    |
| Percent complete | 100%         |
| a. Polymer & ionomer synthesis | (100%) |
| b. Catalyst preparation | (100%) |
| c. MEA processing & testing | (100%) |
| d. Degradation study | (100%) |

Budget

| Total funding | $ 1,320 K |
| Funding for FY10 | $ 528 K |
| Funding for FY11 | $ 330 K |

No cost shared

Barriers

B. Cost
C. Electrode performance
A. Durability

Partners

Project lead

Los Alamos National Laboratory
Yu Seung Kim (PI)
Dae Sik Kim
Andrea labouriau
Hoon Jung

Subcontractor

Sandia National Laboratory
Cy Fujiomoto (Ext. PI)
Michael Hibbs

Jet Propulsion Laboratory
Charles Hays (Ext. PI)
Daniel Konopka
Michael Johnson
Michael Errico
Poyan Bahrami

Interactions

Cellera Technologies (Shimpshon Gottesfeld)
Advanced Industrial Science and Technology (Yoong-Kee Choe)
Ovonic Fuel Cells (Rob Privette)
Objectives

Demonstrate an improved alkaline membrane fuel cell (AMFC) performance and durability using advanced polymer electrolyte membranes, ionomers and non-precious catalysts

**Major tasks**

- **FY 09 & 10:** Synthesis of anion exchange membranes and ionomers
- **FY 10 & 11:** Characterization of catalyst and AMFC performance
- **FY 11 & 12:** AMFC durability test and durability mechanism

### Technical Barriers, Targets and Results

<table>
<thead>
<tr>
<th>ISSUES</th>
<th>Technical Barriers</th>
<th>Technical Target</th>
<th>FY 09-10</th>
<th>FY 10-11</th>
<th>FY 11-12</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>Membrane</td>
<td>Conductivity</td>
<td>$\sigma &gt; 50$ mS/cm</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>120 mS/cm</td>
</tr>
<tr>
<td></td>
<td>Stability</td>
<td>&gt; 500 h in NaOH soln. 60°C</td>
<td>×</td>
<td>√</td>
<td>√</td>
<td>672 h</td>
</tr>
<tr>
<td></td>
<td>Tensile properties</td>
<td>Stress: &gt; 10 MPa, Strain: &gt; 10%</td>
<td>×</td>
<td>×</td>
<td>√</td>
<td>25 MPa, 30%</td>
</tr>
<tr>
<td>Ionomer</td>
<td>Backbone structure</td>
<td>Perfluorinated</td>
<td>√</td>
<td>√</td>
<td>√</td>
<td>M-Nafion®-FA-TMG</td>
</tr>
<tr>
<td></td>
<td>Conductivity</td>
<td>&gt; 50 mS/cm → 20 mS/cm&lt;sup&gt;b&lt;/sup&gt;</td>
<td>×</td>
<td>√</td>
<td>√</td>
<td>20 mS/cm</td>
</tr>
<tr>
<td></td>
<td>Stability</td>
<td>&gt; 500 h in NaOH soln.</td>
<td>−</td>
<td>−</td>
<td>×</td>
<td>7% after 72 h</td>
</tr>
<tr>
<td>Catalyst</td>
<td>Element</td>
<td><em>Non-precious metal or carbon</em></td>
<td>−</td>
<td>√</td>
<td>√</td>
<td>CNT/CNP cat.</td>
</tr>
<tr>
<td></td>
<td>ORR activity</td>
<td>&gt; 0.9 V ($E_{1/2}$)</td>
<td>−</td>
<td>√</td>
<td>√</td>
<td>0.95 V ($E_{1/2}$)</td>
</tr>
<tr>
<td>AMFC performance</td>
<td>Maximum power</td>
<td>&gt; 200 mW/cm² in H₂/Air</td>
<td>−</td>
<td>√</td>
<td>√</td>
<td>466 mW/cm²</td>
</tr>
<tr>
<td></td>
<td>Durability</td>
<td>&lt; 10% for 800 h</td>
<td>−</td>
<td>−</td>
<td>×</td>
<td>~50% for 300 h&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

<sup>a</sup> Values in the original proposal

<sup>b</sup> Conductivity target for ionomer was lowered as we achieved MEA performance target with low conductive ionomers

<sup>c</sup> Mostly due to the cation stability and water management issue; ionomer and polymer backbone degradation is negligible
Synthesis of Polyaromatic Anion Exchange Membranes for Durability Study

**Synthesis and properties of polyaromatic AEMs**

- **BTMA Functionalized Partially Fluorinated Poly(Arylene Ether) (F-PAE)**
- **BTMA Functionalized Non-Fluorinated Poly(Arylene Ether Sulfone) (NF-PAES)**
- **BTMA Functionalized Wholly Aromatic Poly(Phenylene) (Aminated TetraMethyl PolyPhenylene (ATM-PP))**

- **BTMA : Benzyl TetraMethyl Ammonium**

<table>
<thead>
<tr>
<th>Sample</th>
<th>Counter ion</th>
<th>$M_w \times 10^3$ a (g/mol)</th>
<th>IEC (meq./g)</th>
<th>WU (wt.%)</th>
<th>$\sigma$ b (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-PAE</td>
<td>Cl⁻</td>
<td>150</td>
<td>2.5</td>
<td>99</td>
<td>46</td>
</tr>
<tr>
<td>NF-PAES</td>
<td>Br⁻</td>
<td>87</td>
<td>2.2</td>
<td>43</td>
<td>15</td>
</tr>
<tr>
<td>ATM-PP1</td>
<td>Br⁻</td>
<td>61</td>
<td>1.7</td>
<td>72</td>
<td>30</td>
</tr>
<tr>
<td>ATM-PP 2</td>
<td>Br⁻</td>
<td>77</td>
<td>1.6</td>
<td>64</td>
<td>35</td>
</tr>
<tr>
<td>ATM-PP 3</td>
<td>Br⁻</td>
<td>196</td>
<td>1.7</td>
<td>70</td>
<td>37</td>
</tr>
</tbody>
</table>

- $^a$ measured by GPC using the parent polymers
- $^b$ measured at 80°C using salt form membranes

- **Stress-strain behavior of AEM parent polymers**

- High molecular weight polyaromatic AEMs were prepared
- Mechanical properties of the AEMs are strongly influenced by chemical structure and molecular weight
- **Highlight**: Stress: > 25 MPa & Elongation: > 30% at 50% RH

**Membrane mechanical milestone (> 10 MPa stress & 10% strain) achieved with F-PAE, NF-PAE and ATM-PP 3**
Aryl-Ether Cleavage of Poly(arylene ether) AEMs*

Membrane treatment

- **a**: 0.5 M HCl (or HBr) for 30 min (or 2 h);
- **b**: 0.1 M NaOH for 1 h, room temp. after **a**;
- **c**: 0.5 M NaOH for 30 min, room temp. after **a**
- **d**: 0.5 M NaOH for 1 h, 80°C after **a**
- **e**: 0.5 M HCl (or HBr) for 30 min (or 2 h) after **d**
- **f**: 0.5 M NaOH for 1 h 80°C after **e**
- **g**: 0.1 M NaOH for 2 h & 0.5 M NaOH for 100 h at 80°C

**Phenol formation (FTIR) after treatment**

- FTIR results indicated phenol formation of poly(arylene ether) (PAE) based AEMs after membrane treatment → Nucleophilic displacement takes place in the aryl-ether linkage of the PAE backbones
- Mechanical properties of the AEMs are greatly influenced by the AEM backbone degradation

**Highlight**: No backbone degradation observed in poly(phenylene) AEMs

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*C. Fujimoto et al., manuscript was submitted 2012
**Impact of Polymer Structure on AMFC Performance**

**Membrane**: fluorinated poly(arylene ether) AEM (F-PAE, LANL) and poly(phenylene)-based AEMs with three different molecular weight (ATM-PP, SNL); **Test conditions**: \( \text{H}_2/\text{O}_2 \) at 80°C

### Effect of molecular weight on AMFC performance

<table>
<thead>
<tr>
<th>Sample</th>
<th>F-PAE</th>
<th>ATM-PP 1</th>
<th>ATM-PP 2</th>
<th>ATM-PP 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>( M_w \times 10^3 ) (g/mol)</td>
<td>150</td>
<td>61</td>
<td>77</td>
<td>196</td>
</tr>
<tr>
<td>HFR (Ω cm(^2))</td>
<td>0.23</td>
<td>1.67</td>
<td>1.23</td>
<td>0.21</td>
</tr>
</tbody>
</table>

\( ^a \) measured by GPC using the parent polymers

- The AEMs having low Mw (ca. < 100 K) showed poor AMFC performance due to the possible interfacial failure during MEA processing
- Negligible interfacial issue for high Mw F-PAE and ATM-PP
- F-PAE MEA showed catastrophic failure at 55h probably due to the AEM degradation

**Highlight**: No catastrophic failure for ATM-PP 3 MEA during 300 h life test

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**Effect of backbone degradation**

For F-PAE and ATM-PP 3; **Test conditions**: \( \text{H}_2/\text{O}_2 \) at constant voltage of 0.3 V, at 80°C

- **F-PAE** showed catastrophic performance failure at 55h
- **ATM-PP 3** retained stable performance during 300 h life test

\( ^b \) supporting information for analysis methodology

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* C. Fujimoto et al. manuscript was submitted 2012
Stability of Perfluorinated Anion Exchange Ionomers

### Synthesis and properties of perfluorinated AEMs

- Phenyl guanidinium has much better stability than sulfone guanidinium under high pH conditions.
- Trace of degradation after the treatment for phenyl guanidinium functionalized perfluorinated ionomers is due to the hydrolysis of amide group rather than polymer backbone or cation degradation.

**Highlight:** Stable perfluorinated ionomers were prepared by introducing electron donating spacer

- Ionomer milestone (perfluorinated ionomer with conductivity > 20 mS/cm and stability) achieved.

#### Stability after soaking in 0.5 M NaOH at 80°C

<table>
<thead>
<tr>
<th>Sample</th>
<th>IEC (meq./g)</th>
<th>WU (wt.%)</th>
<th>ςa (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FY 11-12</td>
<td>M-Nafion®-FA-TMG</td>
<td>0.70</td>
<td>10</td>
</tr>
<tr>
<td>FY 10-11</td>
<td>M-Nafion®-TMG</td>
<td>0.90</td>
<td>18</td>
</tr>
</tbody>
</table>

* measured with hydroxide form at 80°C
Stability of Benzyl Tetramethyl Ammonium Cations (ex-situ)

- Benzyl tetramethyl ammonium (BTMA) is stable at 60°C; However, ~ 10 % IEC loss after 9 days at 90°C was observed under high pH conditions
- Anion conductivity loss of BTMA functionalized F-PAE and ATM-PP 3 was observed at 0.5 M NaOH at 80°C over 100 h
- Polymer backbone degradation has a little impact on conductivity
- Comparing the ether cleavage degradation of PAEs, the BTMA cation degradation was much slower

*C. Fujimoto et al. manuscript was submitted 2012

**Membrane**: poly(phenylene) based AEM (ATM-PP, SNL) and crosslinked polystyrene based AEM (AHA, Tokuyama) (cf. PAE based AEMs became too brittle to handle after 1-2 days); **Test conditions**: 4 M NaOH (aqueous), no stirring; IEC measured with back titration

**Membrane**: Poly(phenylene) based AEM (ATM-PP, SNL) and poly(arylene ether) based AEM (F-PAE, LANL); **Test procedures**: 1st step: AEMs were prepared in their salt forms and were immersed in 0.1 M NaOH at 80°C for 10, 30, 60 and 120 min and followed by rinsing those in boiling water for 1 h to remove any residual NaOH; 2nd step: AEMs were immersed in 0.5 M NaOH solution at 80°C for various time intervals

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**IEC change as a function of time**

**Anion conductivity change as a function of time**

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4 M NaOH

- ATM-PP 90 C
- ATM-PP 60 C
- Tokuyama 60 C

0.1 M NaOH 80°C

- F-PAE
- ATM-PP 3

0.5 M NaOH 80°C

- Time (days)
- Time (min)
- Time (h)

IEC (meq/g)
Conductivity (mS/cm)
Stability Tetramethyl Guanidine Aqueous Solution (ex-situ)

**ORR study:** under O₂ sparging with anodic and cathodic scans at a rate of 1 mV/s, between a potential range of 1.0 V to ~ 0.2 V; A separate set of scans between 1.0 and 0.8 V for the kinetically limited region

**CV Cycling:** 0.0 to 1.1 V RHE (clockwise cycles) in 0.1 M TMG purged with sparging and blanketing Ar gas; Durability test 2 L of 0.1 M TMG was mixed and allowed to sit in open air for 2 months

- Tetramethylguanidine (TMG) showed electro-catalytic activity; The current at 0.9 V is similar to conventional KOH electrolytes but is less favorable at lower potential due to the probable adsorption to the Pt surface
- TMG and its byproducts can adsorb onto the Pt surface below ~0.8 V, obscuring the transition between typical kinetic and mass-limiting regions during oxygen reduction; This effect is especially pronounced at low rpm (low oxygen concentrations)

**Highlight:** The TMG electrolyte showed remarkable stability after two months, with some signs of increasing resistivity such as the positive potential shift of the H-desorption peak

Stability of Benzyl and Phenyl Guanidinium (ex-situ)

Stability of benzylpentamethyl guanidinium*

Highlight: Phenylpentamethyl guanidinium was stable at 4 M NaOH, 90°C for 72 h

*B. Hibbs, C. Fujimoto, T. Lambert, D.S. Kim, Y.S. Kim, NAMS 2011, June 6, 2011
- Alpha carbon in benzyl-guanidinium is weak site due to the nucelophilic substitution. Also hydrogen on the alpha carbon is very acidic
- Activation energies of center carbon of benzyl and phenyl guanidinium for addition and carbonyl formation are similar

Next: The stability comparison with benzyl tetraalkyl ammonium is under investigation at AIST

*Yoong-Kee Choe, unpublished results, AIST
Stability Comparison BTMA vs. Phenyl Guanidinium \(\text{(in-situ)}\)

**Cation Degradation**

**Cation functionalized ionomers**

![Chemical structures of M-PAES-TMG and F-PAE](Image)

* Polymers were synthesized from FY 11 tasks

**Durability of ionomer (phenyl guanidinium vs. benzyl ammonium)**

**Membrane**: Benzyl tetramethyl ammonium functionalized poly(phenylene) (ATM-PP 3, 50 \(\mu\)m thick); **Catalyst**: Pt black (3 mg/cm\(^2\)) for anode and cathode; **Ionomer for catalyst layer**: M-PAES-TMG and F-PAE; **testing conditions**: \(H_2/O_2\) at 60\(^\circ\)C; **Durability test**: Constant voltage of 0.3 V for 300 h

<table>
<thead>
<tr>
<th>Sample</th>
<th>IEC (meq./g)</th>
<th>WU (wt.%)</th>
<th>(\sigma) (mS/cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-PAES-TMG</td>
<td>1.0</td>
<td>10</td>
<td>35</td>
</tr>
<tr>
<td>F-PAE</td>
<td>2.4</td>
<td>85</td>
<td>100</td>
</tr>
</tbody>
</table>

- The stability of phenylpentamethyl guanidinium and benzyltetramethyl ammonium functionalized PAEs were compared when used as ionomer in the catalyst layer
- Spectroscopic results indicated that central carbon of pentamethyl guanidinium is the weakest site which is consistent with quantum chemical modeling

**Highlight**: Phenyl guanidinium cation was substantially more stable than BTMA after 300 h durability test (2 vs. 69 \(\mu\)V/dec h)
Cycling stability in 0.1 M NaOH

Morphology and ORR activity of CNT/CNP catalyst

- Novel CNT/CNP composite catalyst was prepared from nitrogen containing compound and carbon black
- Both Pt and CNT/CNP catalyst showed excellent stability under high pH conditions up to after 10,000 potential cycles
- The CNT/CNP showed high activity after 5,000 potential cycles (ca. $E_{1/2} = 0.95$ V)

**Highlight:** Durability of electro-catalyst is no issue and the electrochemical activity of CNT/CNP catalyst is excellent

*Catalyst ORR activity milestone ($E_{1/2} > 0.9$ V) achieved*
AMFC Performance & Degradation

**Materials for MEA fabrication**

- **AEM & hydrocarbon ionomer:** ATM-PP 3
- **PF ionomer:** M-Nafion®-FA-TMG

- **Membrane:** BTMA functionalized poly(phenylene) (ATM-PP 3, 50 μm thick);
- **Catalyst:** Pt black (3 mg/cm²) for anode and cathode;
- **Ionomer** for catalyst layer: M-Nafion-FA-TMG and ATM-PP 3

**H₂/O₂ initial performance comparison between HC and PF ionomer**

<table>
<thead>
<tr>
<th>Ionomer</th>
<th>IEC (meq./g)</th>
<th>WU (wt.%)</th>
<th>σa (mS/cm)</th>
<th>HFR (ohm cm²)</th>
<th>Maximum Power density (mW/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>60°C</td>
<td>80°C</td>
</tr>
<tr>
<td>ATM-PP 3</td>
<td>1.7</td>
<td>100</td>
<td>120</td>
<td>0.215</td>
<td>0.174</td>
</tr>
<tr>
<td>M-Nafion®-FA-TMG</td>
<td>0.7</td>
<td>10</td>
<td>20</td>
<td>0.165</td>
<td>0.134</td>
</tr>
</tbody>
</table>

* measured with hydroxide form at 80°C

- Membrane electrode assemblies for AMFC were prepared from LANL decal process using the AMFC materials
- The MEA using M-Nafion®-FA-TMG showed superior performance to the MEA using ATM-PP 3

**Highlight:** Maximum power density reached to 577 mW/cm² at 80°C under H₂/O₂ conditions

*High AMFC performance using hydrocarbon AEM and resonance stabilized perfluorinated ionomer was demonstrated*
**H₂/Air AMFC Performance**

- **H₂/CO₂ free air AMFC performance** showed excellent performance.
- Additional loss for H₂/normal air (CO₂ = 390 ppm) conditions was observed; The performance loss was significant at low current region, indicating some water management problems possibly due to the bicarbonate/carbonate issue at lower current density. Further study for the performance loss is required.

**Highlight:** Maximum power density reached to 466 mW/cm² at 80°C under H₂/CO₂ free Air conditions.

*Membrane:* BTMA functionalized poly(phenylene) (ATM-PP 3, 50 μm thick); **Catalyst:** Pt black (3 mg/cm²) for anode and cathode; **Ionomer** for catalyst layer: M-Nafion®-FA-TMG.
AMFC Performance & Degradation

**Durability of BTMA-functionalized Poly(phenylene)s (in-situ)**

**Membrane:** BTMA functionalized poly(phenylene) (ATM-PP 3, 50 μm thick); **Catalyst:** Pt black (3 mg/cm²) for anode and cathode; **Ionomer** for catalyst layer: M-Nafion®-FA-TMG; **Life test conditions:** constant voltage under full hydration

- The AMFC performance degradation depends on cell operating conditions; Large portion of current loss at low voltage conditions is due to water management issue which is recoverable loss.* However, HFR increase mostly reflects the AEM degradation
- AEM degradation rate increased with decreasing cell voltage and increasing operating temperature

*see supporting information*
**AMFC Degradation Summary**

### Ex-situ testing in NaOH aqueous solution

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Degradation* (time, NaOH, Temp.)</th>
<th>Slide page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polymer</strong></td>
<td>Poly(arylene ether) Aryl ether linkage</td>
<td>Fast ((g)) (&lt; 1, \text{h}, 0.5, \text{M}, 80^\circ, \text{C})</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Poly(phenylene)</td>
<td>Stable</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Perfluorinated</td>
<td>Stable</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Amide linkage</td>
<td>Slow ((g)) ((72, \text{h}, 0.5, \text{M}, 80^\circ, \text{C}))</td>
<td>7</td>
</tr>
<tr>
<td><strong>Cation</strong></td>
<td>Tetramethyl guanidine aqueous soln.</td>
<td>Slow ((g)) ((2, \text{month}, \text{TMG 0.1 M, 25}^\circ, \text{C}))</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Benzyl tetra methylammonium</td>
<td>Slow ((g)) (&lt; 100, \text{h}, 0.5, \text{M, 80}^\circ, \text{C})</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Sulfone penta methyl guanidinium</td>
<td>Fast ((g)) (&lt; 1, \text{h}, 0.5, \text{M, 80}^\circ, \text{C})</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>Phenyl penta methyl guanidinium</td>
<td>Stable</td>
<td>10</td>
</tr>
<tr>
<td><strong>Electro-catalyst</strong></td>
<td>Platinum/carbon</td>
<td>Stable</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>CNT/CNP</td>
<td>Stable</td>
<td>13</td>
</tr>
</tbody>
</table>

### In-situ AMFC testing

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>Degradation (time, Temp.)</th>
<th>Slide page</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Polymer</strong></td>
<td>Poly(arylene ether)</td>
<td>Moderate ((c)) ((55, \text{h}, 80^\circ, \text{C}))</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>Poly(phenylene)</td>
<td>Stable</td>
<td>6</td>
</tr>
<tr>
<td><strong>Cation</strong></td>
<td>Benzyl tetramethyl ammonium (AEM)</td>
<td>moderate ((g)) ((100, \text{h}, 80^\circ, \text{C}))</td>
<td>16</td>
</tr>
<tr>
<td></td>
<td>Phenyl pentamethyl guanidinium (ionomer)</td>
<td>Slow ((g)) (&lt; 100, \text{h}, 80^\circ, \text{C})</td>
<td>12</td>
</tr>
<tr>
<td><strong>AEM-electrode interface</strong></td>
<td>AEM with Mw &lt; 100 K</td>
<td>Unstable ((c))</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>AEM with Mw &gt; 100 K</td>
<td>Stable</td>
<td>6</td>
</tr>
<tr>
<td><strong>Electro-catalyst</strong></td>
<td>Platinum/carbon</td>
<td>Stable</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td>CNT/CNP</td>
<td>Stable</td>
<td>13</td>
</tr>
<tr>
<td><strong>Water management</strong></td>
<td>Hydrocarbon ionomer</td>
<td>Fast ((g))</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Perfluorinated ionomer</td>
<td>Moderate ((g))</td>
<td></td>
</tr>
</tbody>
</table>

*\(g\): gradual loss; \(c\): catastrophic loss

- In general, the degradation rate of AMFC materials was faster under *ex-situ* conditions than under *in-situ* test; however other degradations such as membrane-electrode interface or water management issue played greater role in *in-situ* AMFC testing.

**Highlight:** Materials developed from this project (appeared in yellow box) showed at least comparable durability to the state-of-the-art AMFC materials.
Project Summary

Relevance: Alkaline membrane fuel cells may enable non-precious metal catalysts and avoid or mitigate the shortcomings of traditional liquid AFCs

Approach: Develop highly stable and conductive anion exchange polymer electrolytes using resonance stabilized guanidinium cations and perfluorinated ionomer

Technical Accomplishments and Progress:
- Demonstrated good H₂/O₂ and H₂/air AMFC performance (> 450 and 550 mW/cm², respectively) at 80°C
- Established several synthetic pathways to prepare stable anion exchange polymer electrolytes and carbon based non-precious metal catalysts
- Explored degradation phenomena for polymer backbones, cations and ionomers and ranked the stability both under ex-situ and in-situ conditions

Technology Transfer/Collaborations: Active partnership with Ovonic Fuel Cells and Cellera Inc.; Several patent applications were filed for technology transfer

Proposed Future Research: Catalyst-ionomer interaction and further improvement on stability, conductivity and mechanical properties of polymer electrolytes
Technical Back-Up Slides
Decoupling Degradation from in-situ AMFC testing

1. Unrecoverable loss includes:
   AEM degradation, ionomer degradation, catalyst degradation and interfacial degradation; AEM and ionomer cation degradation are the major contributors

2. Recoverable loss includes:
   AEM dehydration and local flooding depending on operating conditions

3. Catastrophic failure is mostly due to:
   AEM backbone failure (this failure accompanied by OCV decrease)

4. Unrecoverable loss (AEM related) includes:
   AEM degradation and interfacial degradation: In all cases with few exception, AEM degradation

5. Recoverable loss (AEM related) is due to:
   AEM dehydration

6. Catastrophic failure is mostly due to:
   AEM backbone failure (this failure accompanied by OCV decrease)

Separated from current density and HFR behavior, the ionomer degradation rate was measured from Tafel slope change