Aqueous-Soluble Organic Flow Battery Chemistry with Long Lifetime in Weak Alkaline Electrolyte

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Research supported in part by OE award DE-AC05-76RL01830 through PNNL subcontracts 304500 (7/1/2016-5/31/2017 with extensions through 4/30/18) and 428977 (9/10/2018-9/9/2020)

Wind production vs grid demand

PV production vs grid demand

Power vs. time (3 weeks)

DOE OE Peer Review Santa Fe, NM 2018-09-26
Alkaline Benzoquinone Flow Battery

DHBQ

Figure 2. DHBQ and its resonance-stabilized dianions.

- Lowest cost
- Lowest Lifetime

Capacity fade in aqueous-soluble organics is time-denominated, not cycle-denominated

Unbalanced compositionally-symmetric cell cycling experiment

**Both sides** MV, 50% State of Charge, 0.1 M, glove box (OCV = 0)

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Unbalanced compositionally-symmetric cell cycling experiment

**Both sides** MV, 50% State of Charge, 0.1 M, glove box (*OCV = 0*)

Capacity fade rate: 0.002%/cycle
Extrapolates to 20% loss after 1000 cycles

Capacity fade rate: 1.5%/day
Extrapolates to 20% loss after 13 days

Finite lifetime electrolyte vs. Vanadium

Replacement Cost Ratio ≡ $\frac{\text{replacement cost per year}}{\text{vanadium capital cost} - \text{organic capital cost}}$

Finite lifetime electrolyte vs. Vanadium

*Replacement Cost Ratio* \( \equiv \frac{replacement \text{ cost per year}}{vanadium \text{ capital cost} - organic \text{ capital cost}} \)

e.g.:
Vanadium cost = 100
Organic cost = 30,
but loses 15% capacity per year.
Ratio = 15%*30/(100-30)
= 0.064

⇒ 20 year project breaks even at 2.3% discount rate (if no additional costs)

“Methuselah” Quinone: Symmetric Cell Cycling

Unbalanced compositionally-symmetric cell cycling experiment:

*Both sides 2,6-DBEAQ*  
(2,6-di-butanoate ether anthraquinone)  
50% SOC *(OCV: 0)*, glove box

“Methuselah” Quinone: Symmetric Cell Cycling

Unbalanced compositionally-symmetric cell cycling experiment:

*Both sides 2,6-DBEAQ (2,6-di-butanoate ether anthraquinone)*
50% SOC (**OCV: 0**), glove box

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Methuselah Quinone: Symmetric Cell Cycling, pH 12

Unbalanced compositionally-symmetric cell cycling experiment:

Both sides 2,6-DBEAQ
(2,6-di-butanoate ether anthraquinone)
50% SOC (OCV: 0), glove box
0.1 M, pH 12 KOH

Methuselah – Fe(CN)$_6$ full cell performance

Negolyte: 5 ml of 0.5 M 2,6-DBEAQ at pH 12 (10 mM KOH); solubility 0.6 M (32 Ah/L)
Posolyte: 38 ml of 0.3 M potassium ferrocyanide, 0.1 M potassium ferricyanide at pH 12; solubility 1.25 M (34 Ah/L)

Theoretical energy density: 17 Wh/L

- Fumasep$^\text{®}$ E-620K (20 um sulfonated polyaryletherketone), < $25/m^2$ at scale
- DBEAQ permeability: $5.3 \times 10^{-13}$ cm$^2$/s, 50% crossover in 3000 yr.
- Ferricyanide permeability: $4.4 \times 10^{-12}$ cm$^2$/s, 50% crossover in 200 yr.
- Four SGL39AA electrodes per side
- Viton gasket
Methuselah – Fe(CN)$_6$ full cell cycling

Galvanostatic cycling @ 100 mA/cm$^2$ between 1.4 and 0.6 V with potential holds every 20 cycles until current < 2 mA/cm$^2$

Negolyte: 0.5M 2,6-DBEAQ, pH 12 (5 ml) Solubility: 0.6 M (32 Ah/L)

Posolyte: 0.3M ferro, 0.1M ferri, pH 12 (38 ml) Solubility: 1.25 M (34 Ah/L)

Theoretical E/V: 17 Wh/L

Fumasep® E-620K (20 um sulfonated polyaryletherketone, IEC 1.7 meq/g)

4 SGL39AA electrodes per side

Viton gasket

Estimate of anthraquinone (DHAQ and AQDS) mass production cost vs. production scale

Source: Borealis Technology Solutions LLC

<table>
<thead>
<tr>
<th>Negative Electrolyte</th>
<th>Positive Electrolyte</th>
<th>Capacity loss (%/day)</th>
<th>Energy Density (Realized / Theoretical, in Wh L⁻¹)</th>
<th>Voltage (V)</th>
<th>Year</th>
<th>Merits</th>
<th>Limitations</th>
</tr>
</thead>
<tbody>
<tr>
<td>2,7-AQDS</td>
<td>Br₂ / hydrobromic acid</td>
<td>1.9</td>
<td>23 / 35</td>
<td>0.86</td>
<td>2014</td>
<td>Low cost; Highest power density</td>
<td>Inadequate lifetime; Toxic bromine</td>
</tr>
<tr>
<td>2,6-DHAQ</td>
<td>ferro/ferricyanide</td>
<td>4.6</td>
<td>6.8 / 9.2</td>
<td>1.2</td>
<td>2015</td>
<td>Low cost; Non-toxic, less corrosive (pH 14)</td>
<td>Inadequate lifetime; Reduced ion conductivity w.r.t. proton; Modest [Fe(CN)₆]³⁻/⁴⁻ solubility</td>
</tr>
<tr>
<td>Alloxazine</td>
<td>ferro/ferricyanide</td>
<td>1.2</td>
<td>7.1 / 11</td>
<td>1.13</td>
<td>2016</td>
<td>High CE; High ACA capacity</td>
<td>Inadequate lifetime; Reduced ion conductivity w.r.t. proton; Modest [Fe(CN)₆]³⁻/⁴⁻ solubility</td>
</tr>
<tr>
<td>BTMAP-Vi</td>
<td>BTMAP-Fc</td>
<td>0.03</td>
<td>13 / 20</td>
<td>0.75</td>
<td>2017</td>
<td>Neutral pH; Record calendar life; Low crossover</td>
<td>Low voltage; High resistance AEM</td>
</tr>
<tr>
<td>1,4-DHBQ</td>
<td>ferro/ferricyanide</td>
<td>10</td>
<td>9.2 / 12.4</td>
<td>1.21</td>
<td>2017</td>
<td>Lowest cost; High DHBQ capacity</td>
<td>Inadequate lifetime; Reduced ion conductivity w.r.t. proton; Modest [Fe(CN)₆]³⁻/⁴⁻ solubility</td>
</tr>
<tr>
<td>2,6-DBEAQ</td>
<td>ferro/ferricyanide</td>
<td>0.01 (symm) 0.04 (full)</td>
<td>6.5 / 17.2</td>
<td>1.05</td>
<td>2018</td>
<td>Long calendar life; Low crossover; pH 12 operation</td>
<td>Modest [Fe(CN)₆]³⁻/⁴⁻ solubility; Unknown mass-production cost; Full-cell vs. symmetric cell fade rate mystery</td>
</tr>
</tbody>
</table>
Acknowledgments

Not pictured: Dr. Yunlong Ji, Dr. Yan Jing, Daniel Pollack, Emily Kerr, Professor William Hogan, Professor Ted Betley, Saraf Nawar, Rebecca Gracia, Sidharth Chand, Tyler Van Valkenburg, Bilen Aküzüm, Ryan Duncan, Dr. Süleyman Er, Dr. Xudong Chen, Prof. Maurizio Salles, Dr. Changwon Suh, Louise Eisenach, Jennifer Wei

Back to front, left to right:
• Michael Marshak, Brian Huskinson, Prof. Shmuel Rubinstein, Zhengjin Yang, David Kwabi, Danny Tabor
• Rafa Gómez-Bombarelli, Andrew Wong, Sungjin “James” Kim, Michael Gerhardt, Joel Veak
• Eugene Beh, Kaixiang Lin, Lauren Hartle, Marc-Antoni Goulet, Prof. Sergio Granados-Focil
• Prof. Alán Aspuru-Guzik, Prof. Michael Aziz, Prof. Roy Gordon, Liuchuan Tong, Qing Chen, Diana De Porcellinis, Alvaro Valle

Financial Support:
Harvard U Ctr for the Environment
Harv School of Engrg & Appl Sci
Harvard Physics Department,
NSF Grad Rsch Fellowship

Agencies with logos:

[Logos of various funding agencies]