Glass Dielectrics for DC Bus Capacitors

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Objectives

• The overall objective is to build glass capacitors with high temperature reliability. Glass capacitors are capable of operating at 140°C and 650V (Power Electronics and Electric Motors - PEEM Goal*).

• The research directly addresses the DOE PEEM requirements for HEV/EV/PHEV power modules that do not need internal cooling.

• Leverage the substantial investment has occurred in flat panel display glass for the development for high-temperature capacitors. Addresses the DOE PEEM requirements for low cost.

• Specific March 2011 – May 2012 objective is to demonstrate that glass can be wound into a capacitor configuration, similar to polymer film capacitors.

*DOE-PEEM published capacitor specs are in supplemental slides
## Milestone Slide

<table>
<thead>
<tr>
<th>Month/Year</th>
<th>Milestone or Go/No-Go Decision</th>
</tr>
</thead>
<tbody>
<tr>
<td>May-11</td>
<td>Milestone: High temperature dielectric breakdown system. Design and construct a system with 30 kV max voltage and at temperature range of 25°C to 150°C</td>
</tr>
<tr>
<td>Dec-12</td>
<td>Milestone: Test coiled glass capacitor at high voltage (&gt;1kV) and 140°C.</td>
</tr>
</tbody>
</table>
Approach and Strategy

• Approach: Glass is a promising high temperature material that can be incorporated into a capacitor structure.

• FY12 approach is to demonstrate a coiled capacitor from flexible flat panel display glass.

  Flexibility demonstration of flat panel display glass

  Commercially available thicknesses of 50 µm

  Experimental glass available in thicknesses of 5 µm
Approach and Strategy

- Use low-cost flat panel display glass in a DC Bus capacitor
- Reduce the total volume of a DC Bus capacitor by incorporating glass materials in the capacitor construction
- Glass has a substantially higher melting point (1400°C) than the melting point of plastics (150°C) that are presently used in capacitors

Volume of 1000 μF 600V capacitors in a Hybrid Electric Power Converter

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Present State-of-the-Art</th>
<th>Future Glass Capacitor</th>
</tr>
</thead>
<tbody>
<tr>
<td>85°C Rating</td>
<td>Volume = 1.4 - 2 Liters</td>
<td>Volume = 1.2 - 2 Liters</td>
</tr>
<tr>
<td>125°C Rating</td>
<td>Volume = 21.6 Liters</td>
<td>140°C Rating</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Volume = 21.6 Liters</td>
</tr>
</tbody>
</table>
Technical Progress: Benchmarking State-of-the-Art Power Capacitors

• Specifications for State-of-the-Art SBE capacitors*
  – Volume of the 600 V 1000 μF component is 1.8 L
  – Ripple current at 105°C is 20% of the 85°C value. Excellent performance for a capacitor made from polypropylene.

• Glass capacitor projected performance
  – Dielectric volume for a 600 V 1000 μF capacitor with 10 μm thick glass film is 1.9 L.
  – No ripple current decrease between 85°C and 140°C. Projection based on dielectric breakdown data and dielectric loss data at high temperature.

• Glass has a substantially higher melting point (1400°C) than the melting point of polymers (150°C) that are presently used in film capacitors

* SBE Power Ring Part # 700D10896-348

Benchmarked in FY11
Dielectric Strength Characterization of Flat Panel Glass Under Conditions Relevant to Electric Vehicles

Breakdown Strength vs Temperature

Data obtained in FY12
Glass Coil Capacitor Fabrication

**Draw Glass Ribbon**
- Thin glass ribbon is manufactured by a down-draw process and redrawn to reduce the ribbon thickness.
- The key challenge is to produce glass ribbon from 50µm to 10 µm.

**Deposit Electrode**
- Electrodes are placed on top and bottom surfaces of glass ribbon and candidate electrodes include copper foil, aluminum and silver film.
- Equivalent Series Resistance (ESR) and self-healing mechanisms are controlled by the electrode properties.

**Wind glass**
- Glass ribbon up to a 100 meters in length has been produced by glass manufacturers, which will need to be coiled into a capacitor configuration.
- Coil diameters of 1 cm have been demonstrated for 50µm thick ribbon. Substantially smaller diameters (<1 cm) are possible with thinner glass.

**Package**
- Packaging includes end termination, lead attachment and encapsulation.
- Thermal, mechanical and electrical performance must be considered in package design.

**Test**
- The capacitance and loss is characterized as a function of frequency, temperature and AC voltage strength.
- Reliability tests to predict capacitor performance under operating conditions.
Coiled Glass Capacitor

- NEG-OA 10 glass ribbon
- 50 µm thick
- 2.9 m long
- 30 mm wide

Coiled glass capacitor fabricated at Penn State by spraying Ag ink on the glass ribbon and then winding the ribbon around a mullite mandrel. Right side: free standing glass ribbon section. Left side: fully packaged coiled glass capacitor.

Fabricated in FY12
Coil Characterization at 23°C

<table>
<thead>
<tr>
<th>Frequency</th>
<th>1 kHz</th>
<th>10 kHz</th>
<th>1 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance</td>
<td>67.1 nF</td>
<td>67.0 nF</td>
<td>67.1 nF</td>
</tr>
<tr>
<td>Loss</td>
<td>0.001</td>
<td>0.002</td>
<td>0.004</td>
</tr>
</tbody>
</table>

- Calculated value of 70 nF

\[
\text{Capacitance} = \frac{\varepsilon_0 \varepsilon_r A}{t} = \frac{\varepsilon_0 \times 5.3 \times 2.9 \times 2 cm}{50 \mu m} = 70 \text{nF}
\]

- Next step is to scale to longer lengths
- Projected ESR for 10 µF capacitor = 3 mΩ

Data obtained in FY12
# High Temperature Properties

<table>
<thead>
<tr>
<th>Temperature</th>
<th>Frequency</th>
<th>Capacitance, nF</th>
<th>Loss</th>
</tr>
</thead>
<tbody>
<tr>
<td>50°C</td>
<td>1 KHz</td>
<td>67.2</td>
<td>0.001</td>
</tr>
<tr>
<td></td>
<td>10 KHz</td>
<td>67.1</td>
<td>0.002</td>
</tr>
<tr>
<td>100°C</td>
<td>1 KHz</td>
<td>67.6</td>
<td>0.004</td>
</tr>
<tr>
<td></td>
<td>10 KHz</td>
<td>67.4</td>
<td>0.003</td>
</tr>
<tr>
<td>150°C</td>
<td>1 KHz</td>
<td>68.2</td>
<td>0.005</td>
</tr>
<tr>
<td></td>
<td>10 KHz</td>
<td>67.9</td>
<td>0.003</td>
</tr>
</tbody>
</table>

Data obtained in FY12

Environmental Chamber

Coiled Capacitor
Collaborators

- Argonne National Laboratory
  - Prime contractor
  - Penn State characterizes Argonne capacitors
- Sandia National Laboratory
  - Collaborate on the defining capacitor specifications for PEEM
- Oak Ridge National Lab
  - Independent validation of capacitor measurements
- Industry
  - SPS (capacitor manufacturer)
  - NEG (glass manufacturer)

Glass sheet supplied by NEG corporation

Glass will be wound into a capacitor at Penn State

Prototype capacitors will be tested at Oak Ridge
Proposed Future Work

• Highly Accelerated Life Test (HALT) of 10 µm thick glass.
  – Temperatures up to 450 C
  – Voltages up to 5 kV
  – Life predictions for DC bus capacitors in electric vehicles
  – Complementary studies of ppm level sodium migration

• Characterization of coiled glass capacitors at high voltage (>1000 V) and high temperature (140°C)

Bend radius is inversely proportional to the glass sheet thickness.

Photo from collaborator T. Murata, NEG
There has been a substantial world-wide expansion in flat panel display glass in the past decade. This plentiful material has excellent high temperature dielectric properties.

In FY12, coiled glass capacitors were fabricated and tested.

Future work for the remainder of FY12 will focus on life testing and long-term aging of flat panel display glass. This is important for capacitor performance over the HEV lifetime.

In FY13, coil capacitors will be tested at high temperature and under high AC voltage.
Technical Back-Up Slides

(Note: please include this “separator” slide if you are including back-up technical slides (maximum of five). These back-up technical slides will be available for your presentation and will be included in the DVD and Web PDF files released to the public.)
Table 1: DOE Vehicle Technologies Program DC Bus Capacitor Targets

<table>
<thead>
<tr>
<th>Typical Capacitor Bank Requirements</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacitance, μF</td>
<td>1000</td>
</tr>
<tr>
<td>Operating voltage, VDC</td>
<td>450</td>
</tr>
<tr>
<td>Peak transient voltage, VDC for 50 ms</td>
<td>650</td>
</tr>
<tr>
<td>Leakage current at operating voltage, mA</td>
<td>≤ 1</td>
</tr>
<tr>
<td>Dissipation factor at 10 kHz(^1), %</td>
<td>&lt; 2</td>
</tr>
<tr>
<td>Equivalent series inductance (ESL), nH</td>
<td>≤ 5</td>
</tr>
<tr>
<td>Ripple current, amps RMS continuous</td>
<td>90</td>
</tr>
<tr>
<td>Temperature range of ambient air, °C</td>
<td>-40 to +140</td>
</tr>
<tr>
<td>Volume requirement, l</td>
<td>≤ 0.6</td>
</tr>
<tr>
<td>Cost</td>
<td>≤ $30</td>
</tr>
<tr>
<td>Failure mode</td>
<td>Benign</td>
</tr>
<tr>
<td>Life @ operating conditions, hr</td>
<td>&gt;13,000</td>
</tr>
</tbody>
</table>
Coil Fabrication

Glass Sheet Side 1
- Spray coated electrode
- Sheet Resistance 10 Ω/

5 mm

Glass Sheet Side 2
- Uncoated margin on opposite sides for voltage isolation

Co-wind glass

2 cm

Glass Sheet
- No electrode

Steve Perini and Amanda Baker
Coil Measurement Procedure

- Glass spacer layer is required to separate + and – sides of glass layer.
- Connections are made at several points along the length of the glass ribbon.
- Excellent frequency response expected in this configuration.