Thermal Evaluation of a High-Voltage Ultracapacitor Module for Vehicle Applications

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Outline

• Objectives
• Cell Testing
  – Calorimeter testing
  – Thermal imaging
• Module thermal testing
• Observed self-cooling
• Summary
Objectives

• Identify thermal issues of ultracapacitor cells and modules over a range of vehicle duty cycles to understand and minimize thermal impacts

• Identify improvements for ultracapacitor thermal management
Cell Description:
Maxwell BOOSTCAP 3000-P

• Voltage Range = 0 V – 2.7 V
• $C_{\text{rated}} = 3000$ F
• $T_{\text{operating}} = -40$ C to +65 C
• $m = 0.55$ kg
• Carbon electrodes
• Aluminum current collectors
• Organic electrolyte (Acetonitrile)
Calorimeter Description

- Large conduction calorimeter that measures heat generation and heat capacity

- Cavity dimensions: 21 x 20 x 39 cm (WxHxL)
- Heat rate detection: 0.015 W to 100 W
- Minimum detectable heat effect: 15 J (at 25°C)
- Baseline stability: ± 10 mW
- Temperature range: -30°C to 60°C
Calorimeter Results: Heat Generation and Efficiency
Current Square Wave, 5 Cycles, $T_{\text{test}} = 30$ C, Single BCAP3000-P Cell

At 200 A, $R_{\text{equiv}} = 0.000350 \ \Omega$

Average Heat Rate: 

$$\dot{q}_{av} = \frac{Q_{\text{calorimeter}}}{\Delta \text{time}}$$

Heat efficiency: 

$\eta_H = 1 - \frac{Q_{\text{calorimeter}}}{|E_{\text{in}}| + |E_{\text{out}}|}$

Heat Equivalent Resistance: 

$$R_{\text{equiv.}} = \frac{\dot{q}_{avg}}{I_{\text{rms}}}$$
Calorimeter Results:
Heat Capacity, $T_{test} = 30^\circ C$, Single BCAP3000-P Cell

$$C_p = \frac{Q_{removed}}{m\Delta T}$$

Starting Cell $T = 43.9^\circ C$
Ending Cell $T = 29.5^\circ C$
Average Cell $T = 36.7^\circ C$
Mass = 0.545 kg
Energy = 8453 J
Heat Capacity = 1079.6 J/kg-K

Three test average results
Heat capacity deviation < 1%
Thermal Imaging
Thermal Imaging: Single BCAP3000-P Cell
200 A, Square Wave Cycle, $T_{ambient} = 24$ C
Thermal Imaging: BCAP3000-P Series String of 5 Cells
200A, Square Wave Cycle, $T_{\text{ambient}} = 22^\circ\text{C}$

Cells coated for uniform emissivity

1. Aborted test, terminal cell heating

2. Switched positive end cells, retorqued

3. Large bus bar on positive terminal

Improved uniformity over aborted case

Improved uniformity over re-torqued case
Thermal Imaging: BCAP3000-P Series String of 5 Cells 200 A, Square Wave Cycle, $T_{ambient} = 22^\circ\text{C}$, Cells Switched
Module Thermal Testing Facility Description

- ABC-1000 bidirectional programmable power supply
  - 420V, 1000A, 125 kW
- Environmental chamber
  - 64 ft³
  - -45 C to 190 C
- Independent data acquisition system
Maxwell Module BMOD0063-125 V

- Early module design
- 48 cells
- $C_{\text{rated}} = 63$ F
- 0 V – 125 V
- $T_{\text{operating}} = -40$ C to +65 C
- $I_{\text{max, cont}} = 150$ A ($T_{\text{rise}} \leq 15$ C)
- $V_{\text{fan}} = 13.8$ V, $I_{\text{fan}} = 6.55$ A
- In chamber air flow
  ~ 244 CFM
- All clearances were greater than specified minimums
Module: Internal Thermocouple Locations

- **Top Face**
- **Bottom Face**
- **Top & Bottom Face**
- **Detailed**

**Cell Detail Instrumentation**

- Heat Sink
- Thermal Pad
- Thermal Nut
- Balance Bar
- Bus Bar

**Air Flow**

- Indicates positive terminal up

**Bus Bar Detail**
- Thermal interface pad bottom
- Thermal interface pad top
Module: Other Instrumentation

- Voltages for every cell (48) attached to bus bars
- Current
- Airflow
  - Mapped flow as a function of pressure drop along fins
  - Used in-chamber pressure drop to estimate flow during chamber tests

External Thermocouple Locations

- Top Face
- Top & Bottom Face
- Side (Halfway down)
Thermal Performance Test Cycles

- 20 A charge to 120 V immediately before cycling
- 120 minutes continuous cycling
- Square wave cycle
  - 60 V to 120 V

- Proprietary Oshkosh Heavy Hybrid cycle: $I_{\text{rms}} \approx 225$ A
- Light-Duty HEV test cycle: $I_{\text{rms}} \approx 90.4$ A
Light-Duty HEV Test Cycle

- NREL analysis shows significant HEV fuel savings are achievable with “low”-energy Ucap energy storage*
- Power profile obtained from simulation to cycle this module:

**Vehicle Assumptions**
- Midsize car
- Parallel HEV configuration
- Vehicle mass = 1675 kg
- Engine = 110 kW
- Motor = 25 kW
- US06 cycle
- 80 Wh operating window
- ~10% improvement in simulated fuel economy over comparable conventional vehicle on same drive cycle

Module: Cell Terminal Temperatures
150 A, Sq Wave, $T_{\text{test}} = 30$ °C

- Offset due to fan heating
- Preheating due to initial charge prior to cycling
- Temperatures close to steady state after 2 hours of cycling

Temperature [°C]

Cycle Time [min]
Module: Selected Temperatures
150 A, Sq Wave, $T_{test} = 30$ C

Positive terminal lug hotter than cell, indicating lead wire heating

Coolest cell at air inlet corner (side cooling effect)
Module: Selected Temperatures
Light-Duty HEV Test Cycle, 12 cycles (120 min), $T_{test} = 30 \, ^\circ C$

- Less than an 8 C rise after 120 minutes of cycling
- $I_{rms} = 90.4 \, A$
Module: Cell Terminal Temperature Rise Over Ambient*

\[ T_{\text{test}} = 0 \text{ or } 30 \text{ } ^\circ\text{C} \]

* Average over last five minutes of cycling, 115-120 min

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- 244 CFM
- Reduced fan, 221 CFM

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- Reduced fan, 221 CFM
- 244 CFM

NREL National Renewable Energy Laboratory
Module: Cell Terminal Temperature Rise Over Ambient*

\[ T_{\text{test}} = 0 \text{ or } 30 \, ^\circ\text{C} \]

* Average over last five minutes of cycling, 115-120 min

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- 244 CFM

**Graph:**
- HEV
- HH
- Max
- Ave
- Min

**Legend:**
- \( \text{SqwWave, } 30^\circ\text{C} \)
- \( \text{SqwWave, } 12\text{V Fan, } 30^\circ\text{C} \)
- \( \text{SqwWave, } 0^\circ\text{C} \)
- \( \text{HH, } 0^\circ\text{C} \)
- \( \text{HEV, } 30^\circ\text{C} \)

**Notes:**
- 244 CFM
- Reduced fan, 221 CFM

*Average over last five minutes of cycling, 115-120 min*
Module: Estimated Temperature Distribution*
150 A, Sq Wave, $T_{test} = 30$ C

- Average over last five minutes of cycling
- Bus bar temperature used when no cell data were available
- Pos and neg cell terminals averaged
- Missing data averaged and/or estimated

* Average over last five minutes of cycling, 115-120 min
Module: Center Line Temperatures*
150 A, Sq Wave, $T_{\text{test}} = 30$ C

* Average over last five minutes of cycling, 115-120 min
Module: Cell 17 Detail, Exit Side Center
150 A, Sq Wave, $T_{test} = 30 \degree C$

- Capacitor midpoint significantly hotter than terminals, may be good place for maximum temperature measurement
- ~40% temperature drop across fin
- ~17% temperature drop from terminal to thermal pad
- ~5% of the temperature drop across thermal pad ($\approx 0.85\degree C$)

* Average over last five minutes of cycling, 115-120 min
Module: Observed Self-Cooling, Cell Temperatures

\( T_{\text{test}} = 30 \, ^{\circ}\text{C} \), Fans Off, Full Discharge

- 5.5 A charge to 125 V, open-circuit rest for 5 hrs, 20 A discharge to 0 V
- Observed cell self-cooling to below ambient temperature
Module: Observed Self-Cooling, Fans Off
Cell 17 Detail (Air Exit Center Cell), $T_{\text{test}} = 30 \ C$

- Cooling trend from cell midpoint to outside environment
- Cell surface midpoint cools $\sim 0.82 \ C$
- Requiring $\sim 483 \ J$
Investigation of Self-Cooling, Endothermic Calorimeter Response on Discharge: BCAP 3000-P Cell, $T_{\text{test}} = 30^\circ C$

- Preliminary data (insufficient rest periods)
- Endothermic response measured
- Lead heating will decrease measured endothermic response for the inner chamber
- On the order of 345 [J] of cooling for a 1.3 V discharge
- If linear with voltage change
  - ~628 [J] of cooling on full discharge
  - giving ~1.06 C of cooling for a cell
- Consider the heat gain from the environment and additional thermal mass in the module (terminal nuts, bus bar, and heat sink)

Test description: charge at 5.5 A to 2.6 V, clamp voltage for 3 hrs, discharge to 1.3 V at $I_{\text{dis}}$, rest 3 hrs
Explanation of Self-Cooling, Reversible Heat Effect: Entropy Theory Compared to Measurement

Reversible heat, entropy model*

Assume
- Entropy model suggested by Schiffer et al.
- A specific capacitance of 6.5-30 μF/cm²
- \( V_o \approx 200 \text{ cm}^3 \)
- \( d_{\text{Helmholtz}} = 0.8 \text{ nm} \)
- T change can be neglected for entropy calculation

Found
- \( Q_{\text{discharge}} = -203 \text{ [J]} \) to -515 [J]
  - For a 1.3 V discharge
    - \( T = 30 \text{ °C} \)
- Agrees reasonably well with the \( Q \sim -345 \text{ [J]} \) measured in the calorimeter

\[
\frac{dQ_{\text{rev, meas}}}{dt} = -T \frac{ds}{dt} = -2T \frac{Ck}{e} \ln \left( \frac{V_H}{V_o} \right) \frac{dU}{dt}
\]

\( C \): Cell capacitance [F]  
\( e \): Elementary Charge [C]  
\( k \): Boltzmann constant [J/K]  
\( Q \): Heat [J]  
\( S \): Entropy [J/K]  
\( t \): time [s]  
\( T \): temperature [K]  
\( U \): Potential [V]  
\( V_H \): Helmholtz Layer Volume [cm³]  
\( V_o \): Total electrolyte Volume [cm³]

Conclusions: Cell

• Thermal efficiency decreased approximately linearly with current
• Heat generation increased approximately with the square of current
• Thermal imaging showed that
  – Positive cell terminals tend to heat faster, possibly because of cell construction
  – Cell terminal connections are important for thermal performance
Conclusions: Module

• With ~80% of rated unrestricted air flow, the tested module was less than 2.8 C above its rated 150 A continuous current temperature.
• Vehicle environmental temperatures (-30 C- 52 C*) and power demands are highly variable, requiring an understanding of ultracapacitor temperatures as a function of these variables.
• The current level must be limited to prevent cells from reaching high temperatures that reduce life and reliability.
• The module had less than an 8 C rise after 120 minutes of continuous cycling on a simulation based HEV US06 drive cycle.
• Peak temperatures occurred near the module center and at the module positive terminal.
• Understanding module temperature distribution is critical to design effective thermal management systems and properly locate sensors.
• Preferential cooling of the module centerline and reduction of lead wire heating would be beneficial.
• Capacitor self-cooling was observed on discharge both at the module level and in the calorimeter.

*USABC FreedomCAR requirement
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