National Renewable Energy Laboratory

Innovation for Our Energy Future

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

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Jason Lustbader
(Jason_Lustbader@nrel.gov)
Charlie King
Jeff Gonder
Matt Keyser
Ahmad Pesaran

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Outline

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

Objectives

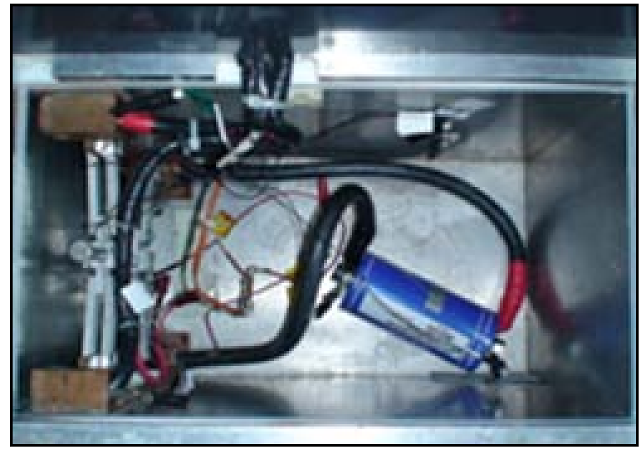
- Identify thermal issues of ultracapacitor cells and modules over a range of vehicle duty cycles to understand and minimize thermal impacts
- Identify improvements for ultracapacitor thermal management

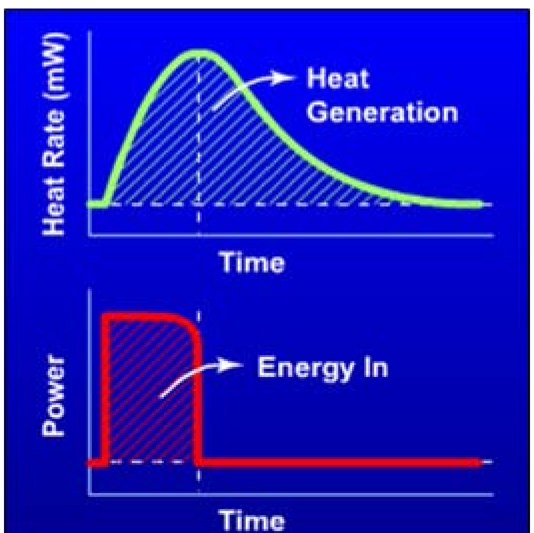
Cell Description:
Maxwell BOOSTCAP 3000-P

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

Calorimeter Description

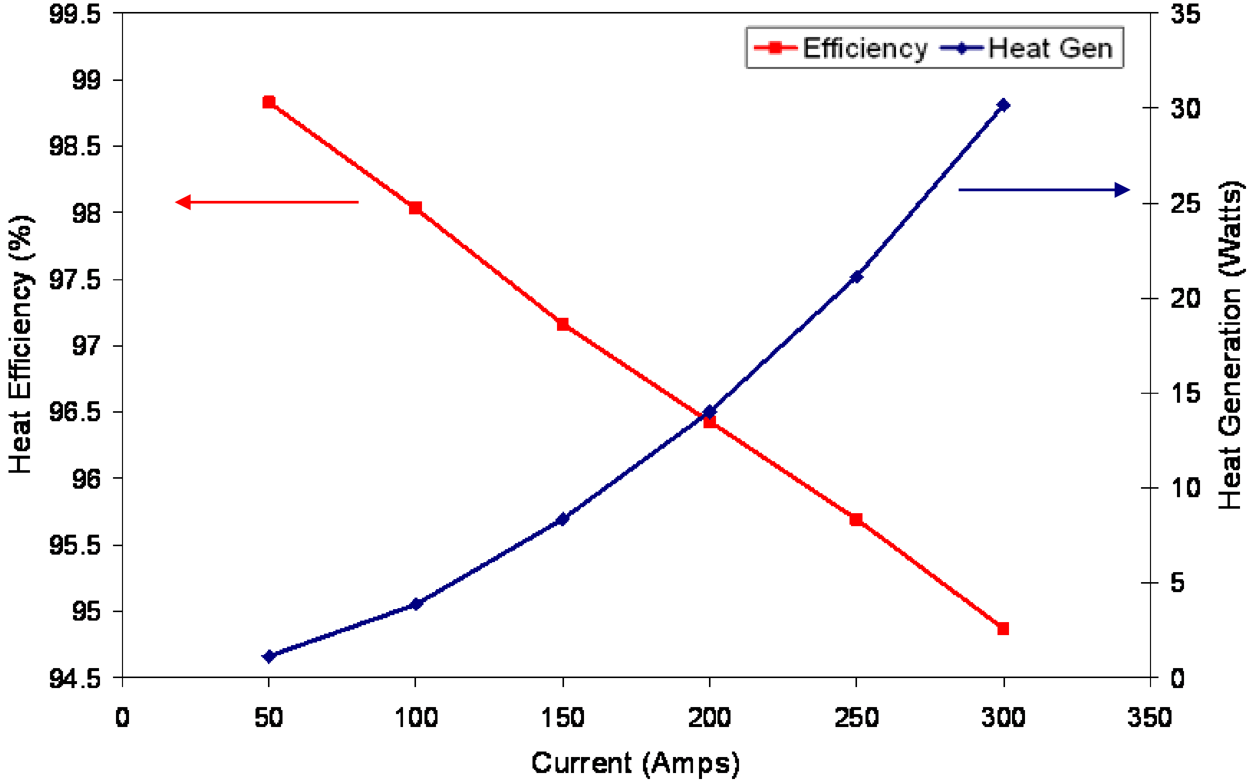
- Large conduction calorimeter that measures heat generation and heat capacity





- 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 25ºC)
- Baseline stability: ± 10 mW
- Temperature range: -30ºC to 60ºC

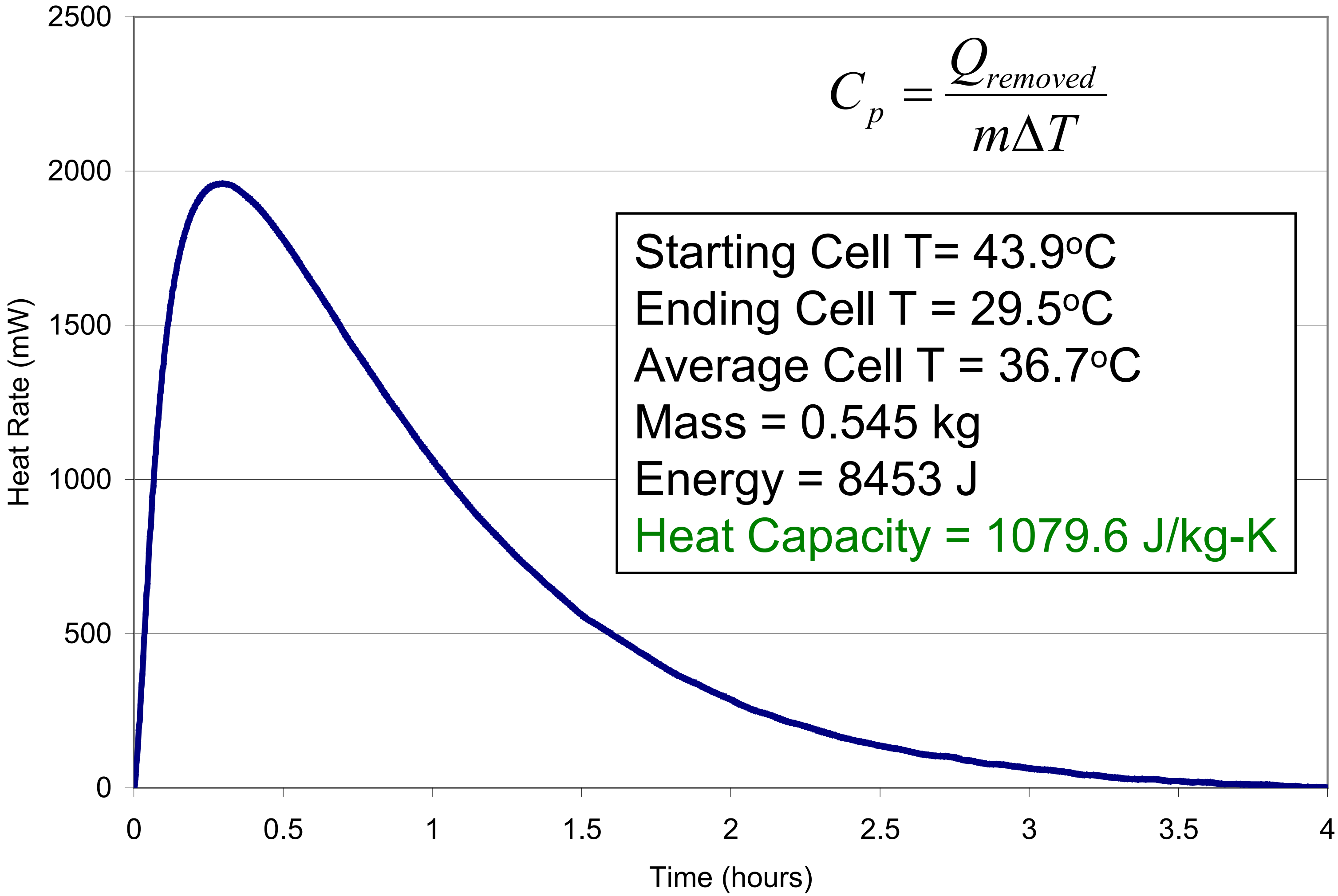
Calorimeter Results: Heat Generation and Efficiency
Current Square Wave, 5 Cycles, T_{test} = 30 C, Single BCAP3000-P Cell



At 200 A, R_{equiv} = 0.000350 Ω

Average Heat Rate:	Heat efficiency: (differs from roundtrip effic.)	Heat Equivalent Resistance:
$\dot{q}_{avg} = \dfrac{Q_{calorimeter}}{\Delta time}$	$\eta_H = 1 - \dfrac{Q_{calorimeter}}{\lvert E_{in} \rvert + \lvert E_{out} \rvert}$	$R_{equiv.} = \dfrac{\dot{q}_{avg}}{I_{rms}^{2}}$

Calorimeter Results: Heat Capacity, T_{test} = 30°C, Single BCAP3000-P Cell

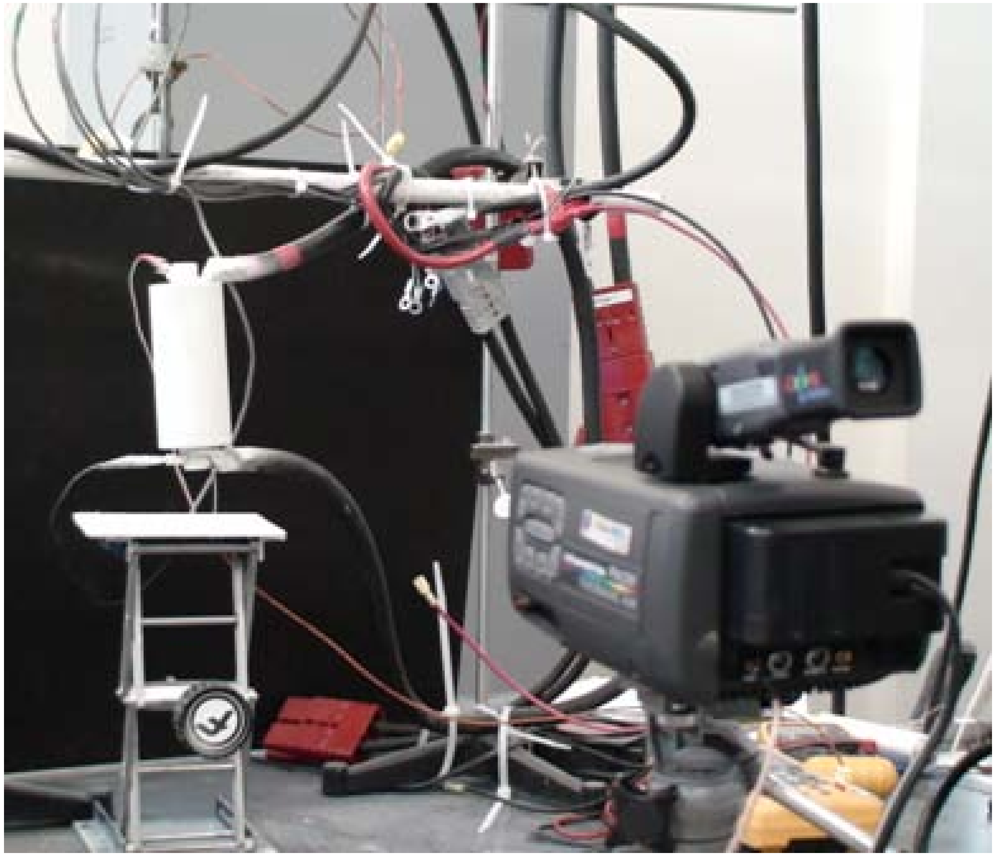


$$C_p = \frac{Q_{removed}}{m\Delta T}$$

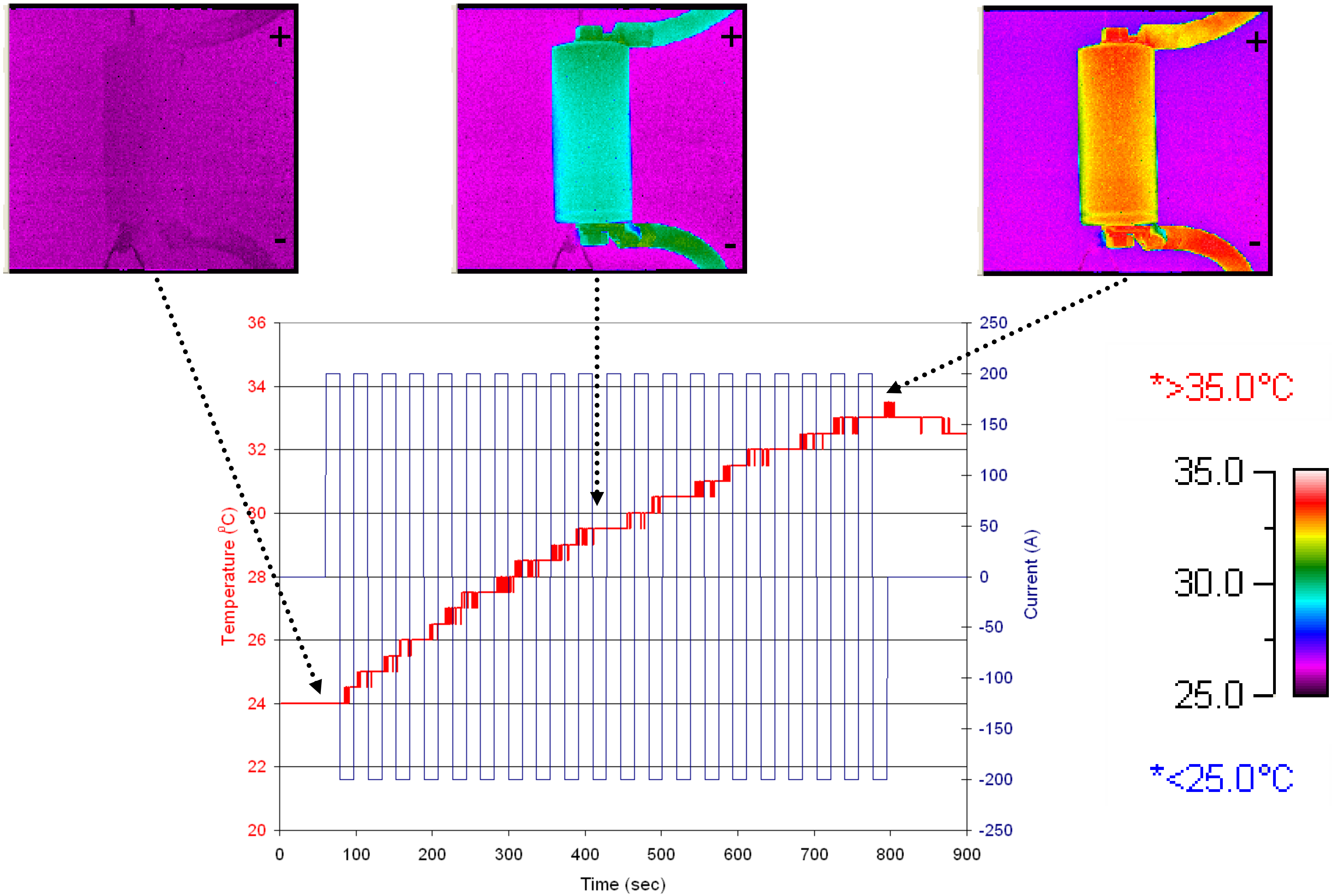
Starting Cell T= 43.9°C
Ending Cell T = 29.5°C
Average Cell T = 36.7°C
Mass = 0.545 kg
Energy = 8453 J
Heat Capacity = 1079.6 J/kg-K

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

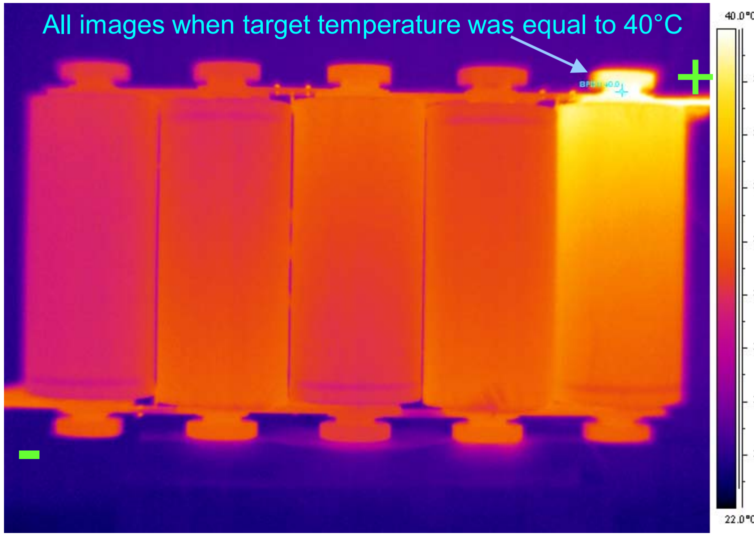


Thermal Imaging: BCAP3000-P Series String of 5 Cells 200A, Square Wave Cycle, $T_{ambient}$ = 22°C

Cells coated for uniform emissivity

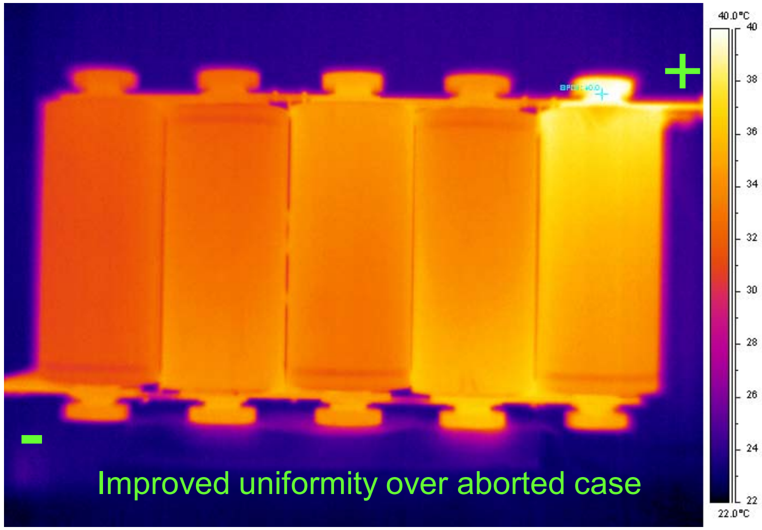
Aborted test, terminal cell heating

1.



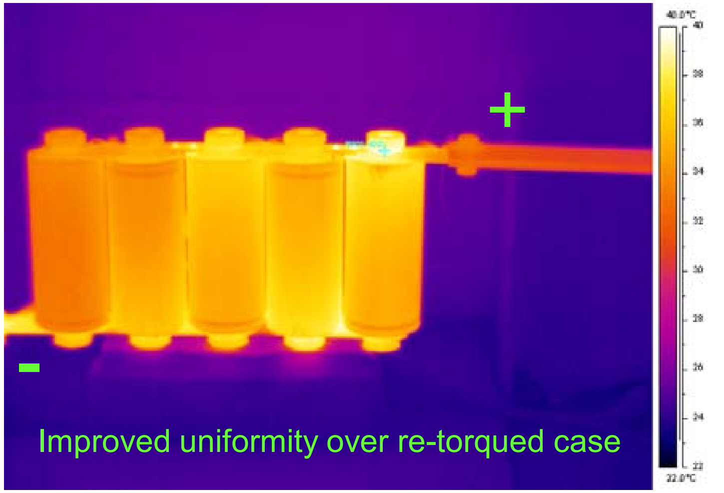
Switched positive end cells, retorqued

2.

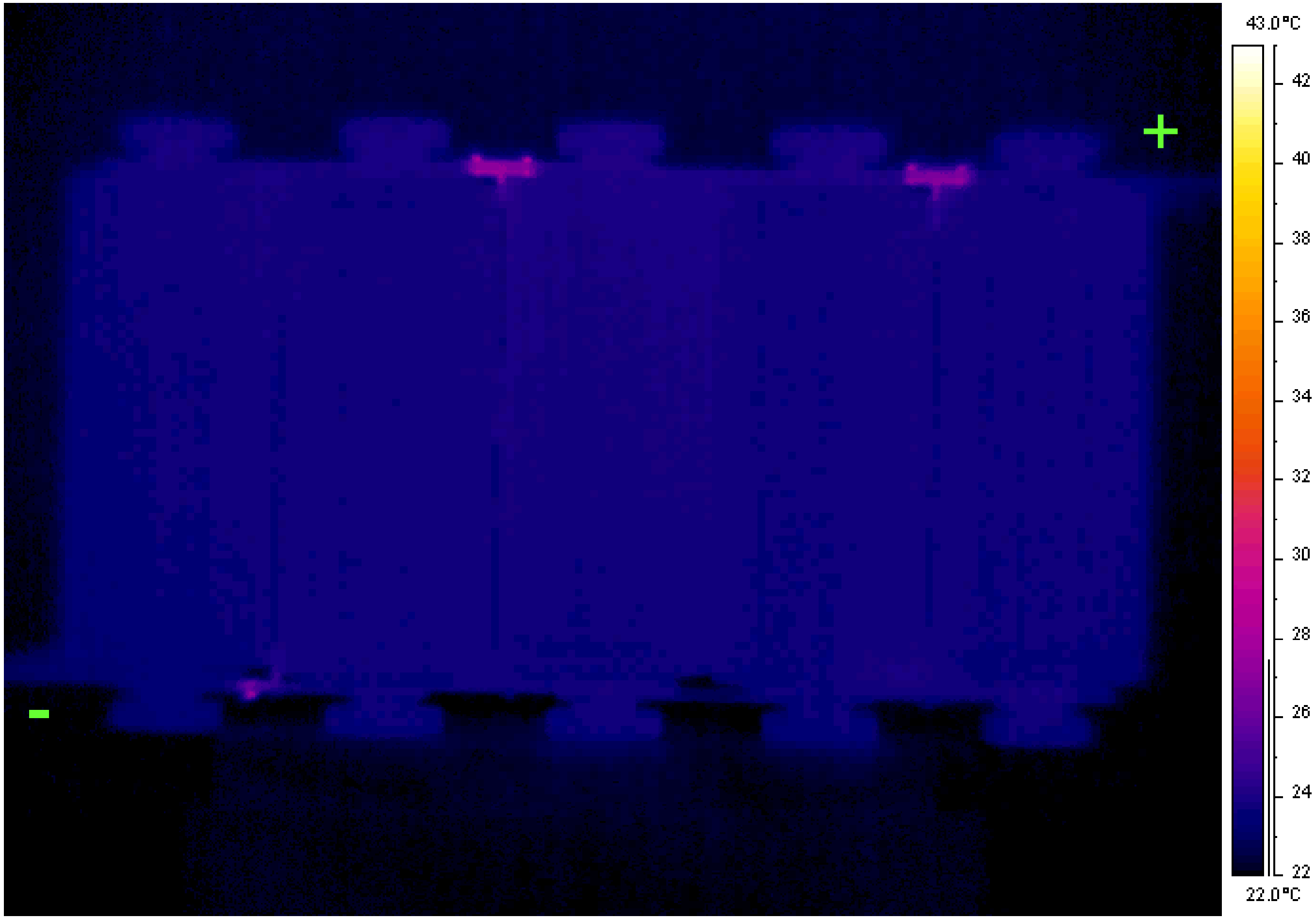


Large bus bar on positive terminal

3.



Thermal Imaging: BCAP3000-P Series String of 5 Cells 200 A, Square Wave Cycle, $T_{ambient}$ = 22°C, Cells Switched



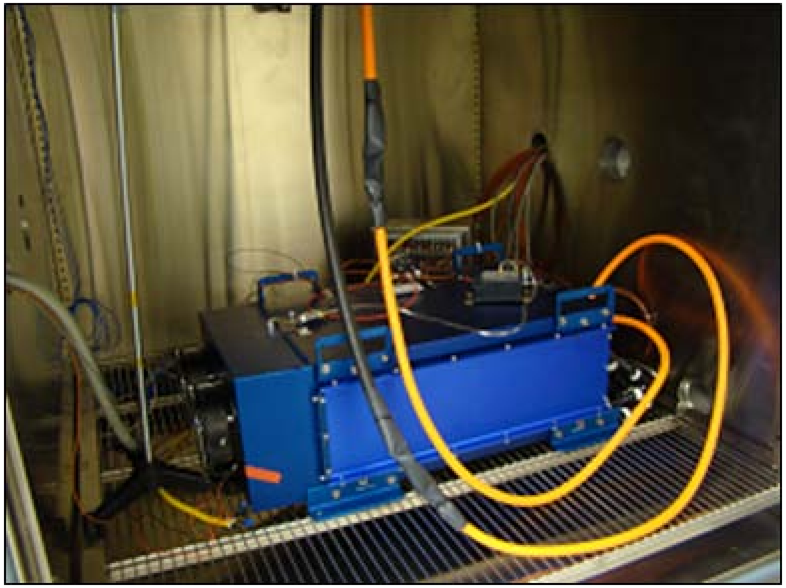
Module Thermal Testing Facility Description

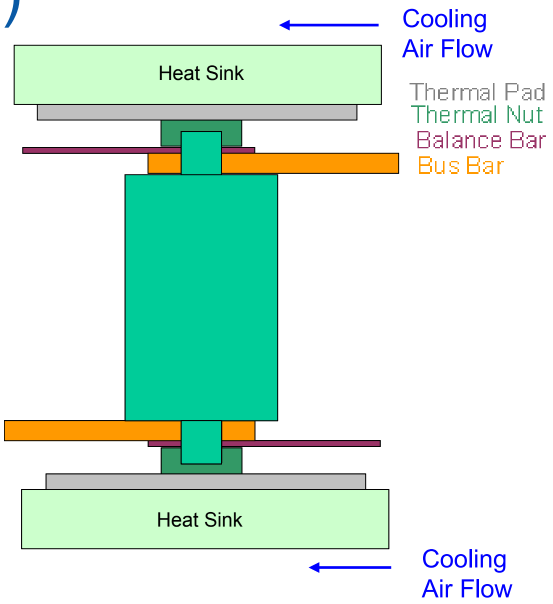
- ABC-1000 bidirectional programmable power supply
  - 420V, 1000A, 125 kW
- Environmental chamber
  - 64 ft^3
  - -45 C to 190 C
- Independent data acquisition system

Maxwell Module BMOD0063-125 V

- Early module design
- 48 cells
- C_{rated} = 63 F
- 0 V – 125 V
- $T_{operating}$ = -40 C to +65 C
- $I_{max, cont}$ = 150 A (T_{rise}<=15 C)
- V_{fan} = 13.8 V, I_{fan} = 6.55 A
- In chamber air flow

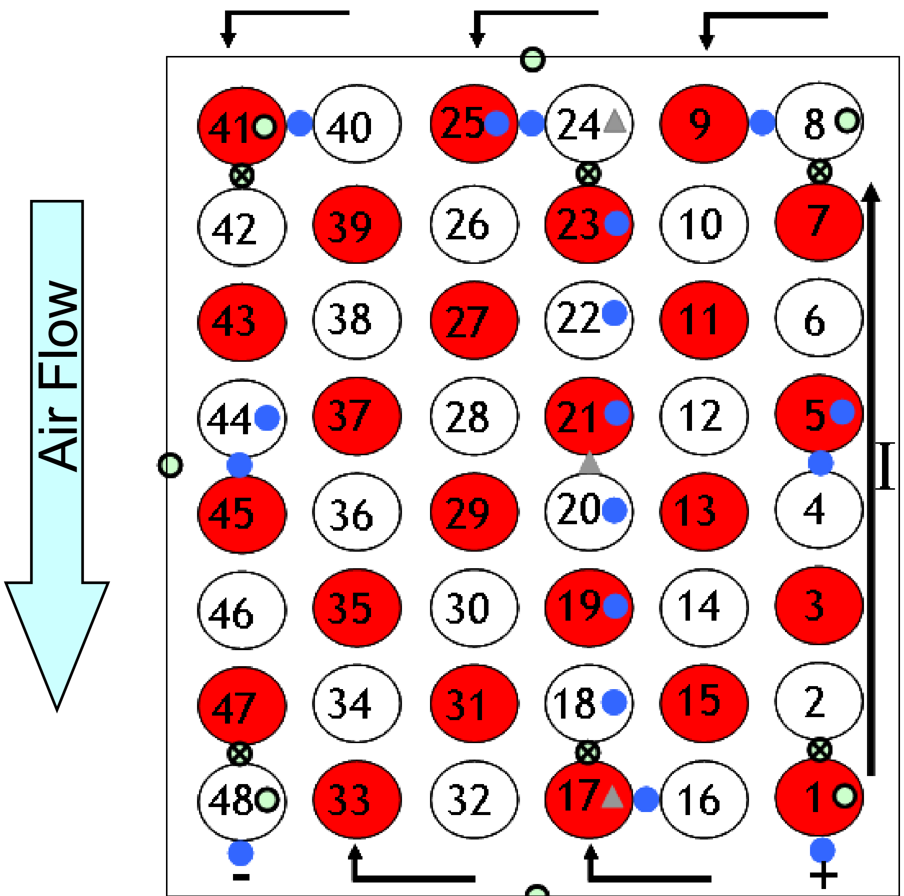
  ~ 244 CFM
- All clearances were greater than specified minimums





Module: Internal Thermocouple Locations

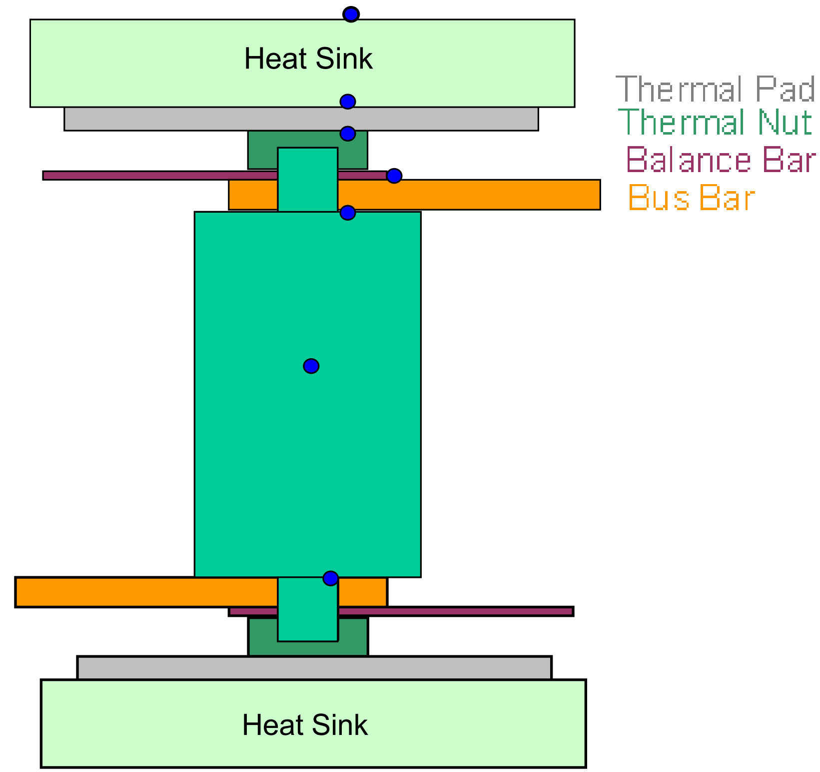
Top Face | Top & Bottom Face
Bottom Face | Detailed



Top View

Indicates positive terminal up

Cell Detail Instrumentation

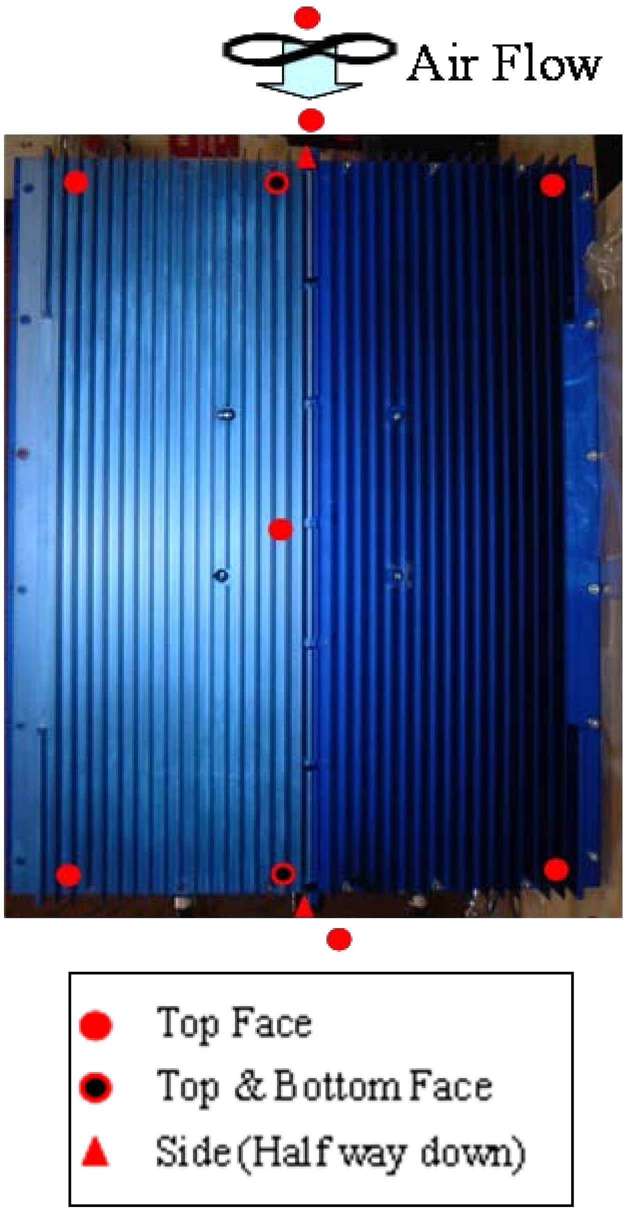


Bus Bar Detail

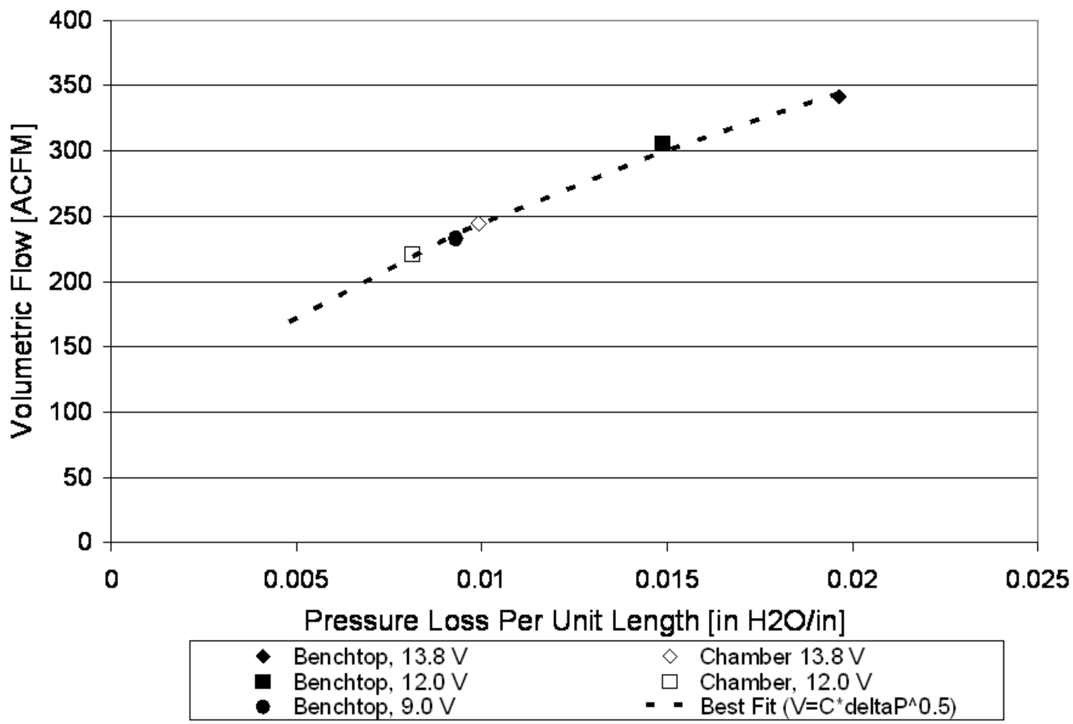
- Thermal interface pad bottom
- Thermal interface pad top

Module: Other Instrumentation

External Thermocouple Locations

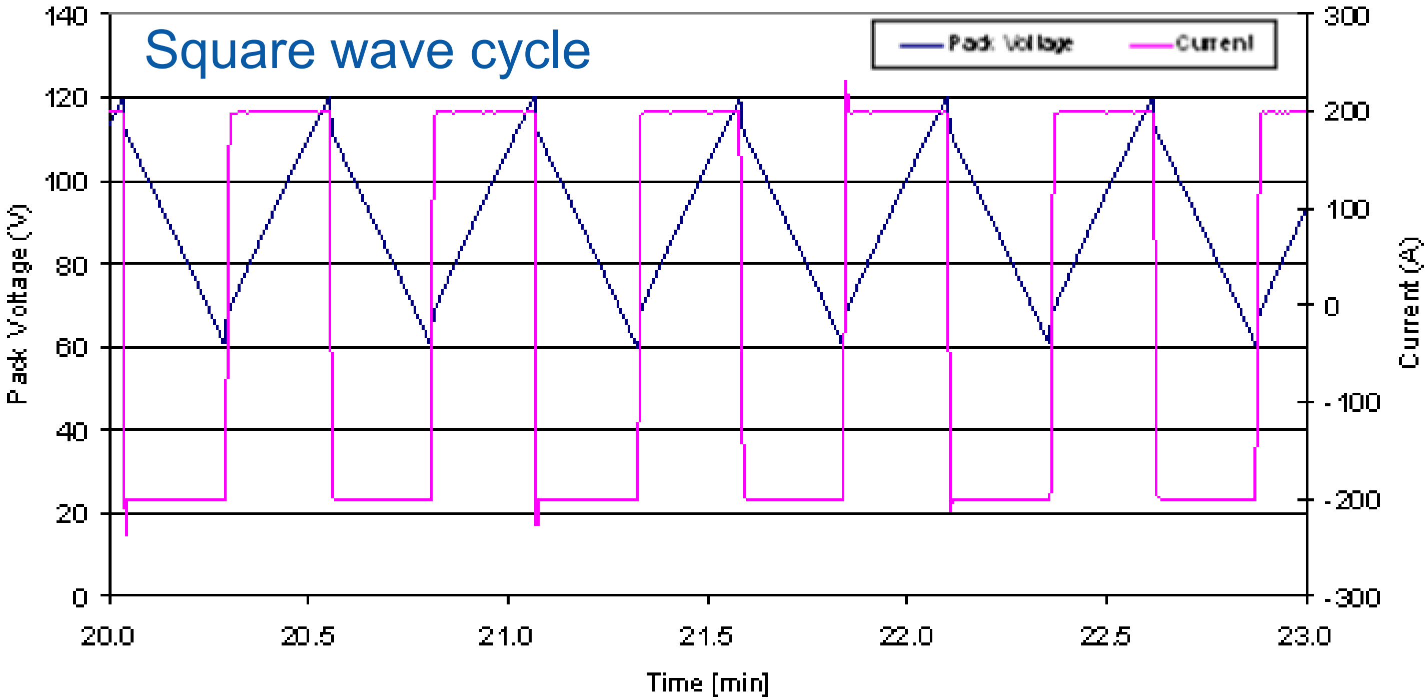


- Voltages for every cell (48) attached to bus bars
- Current
- Airflow
  - Mapped flow as a function of pressure drop along fins
  - Used in-chamber pressure drop to estimate flow during chamber tests



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

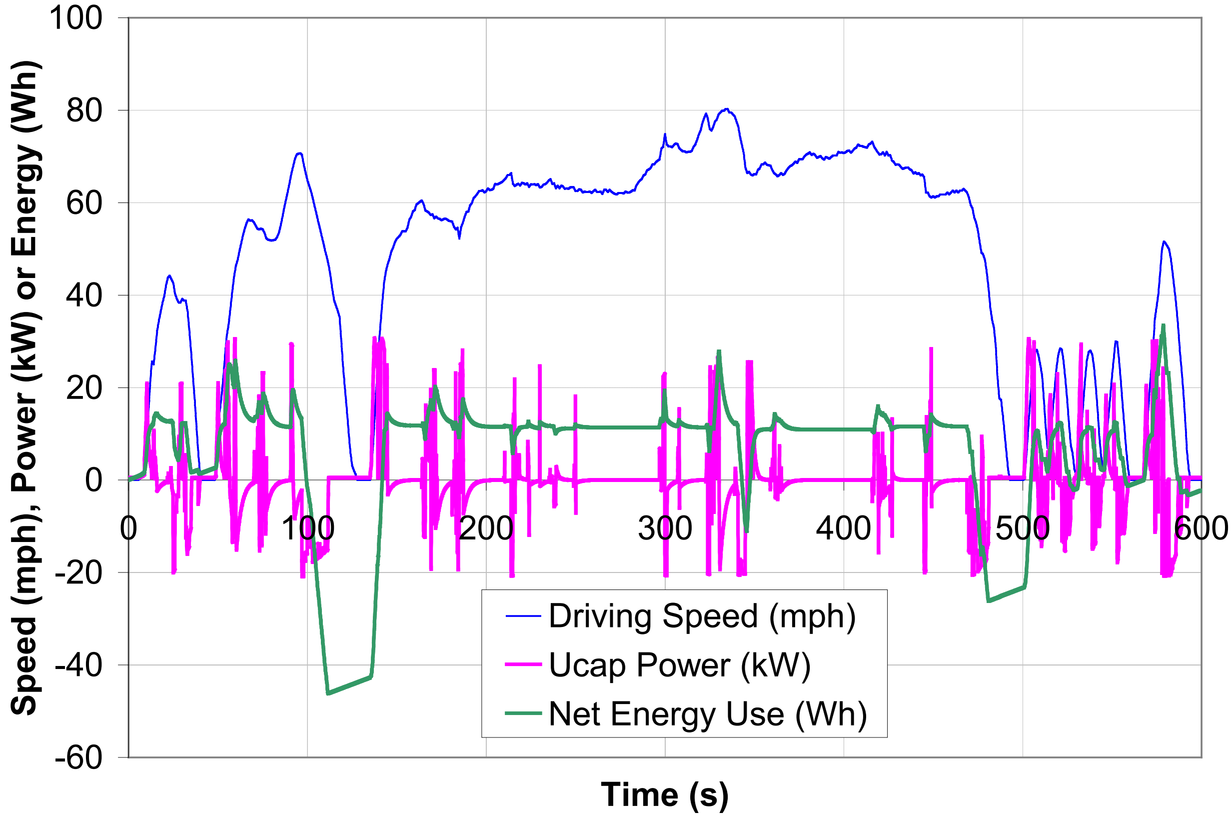


- Proprietary Oshkosh Heavy Hybrid cycle: $I_{rms} \approx 225$ A
- Light-Duty HEV test cycle: $I_{rms} \approx 90.4$ A

Light-Duty HEV Test Cycle

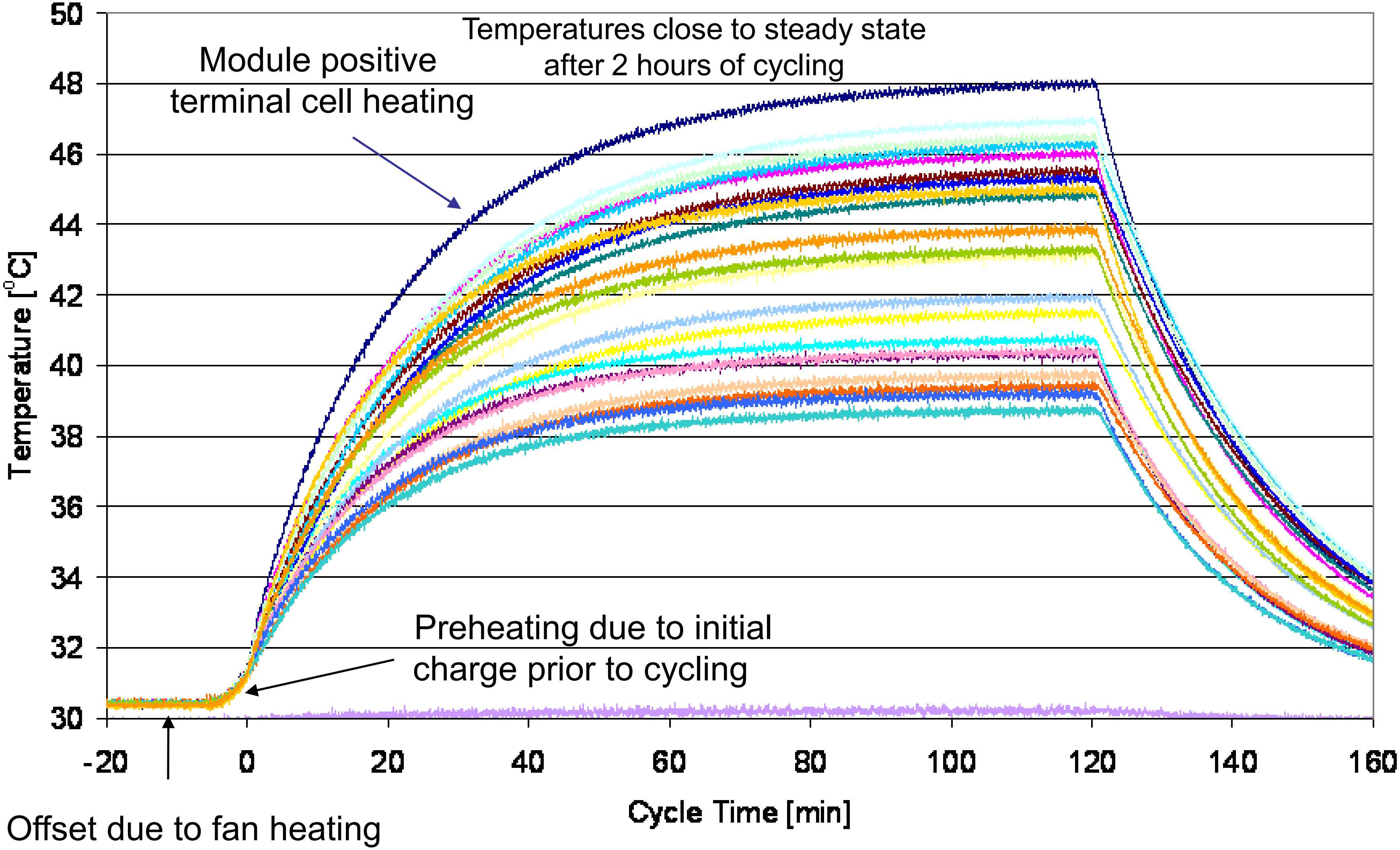
- NREL analysis shows significant HEV fuel savings are achievable with "low"-energy Ucap energy storage*
- Power profile obtained from simulation to cycle this module:

- 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

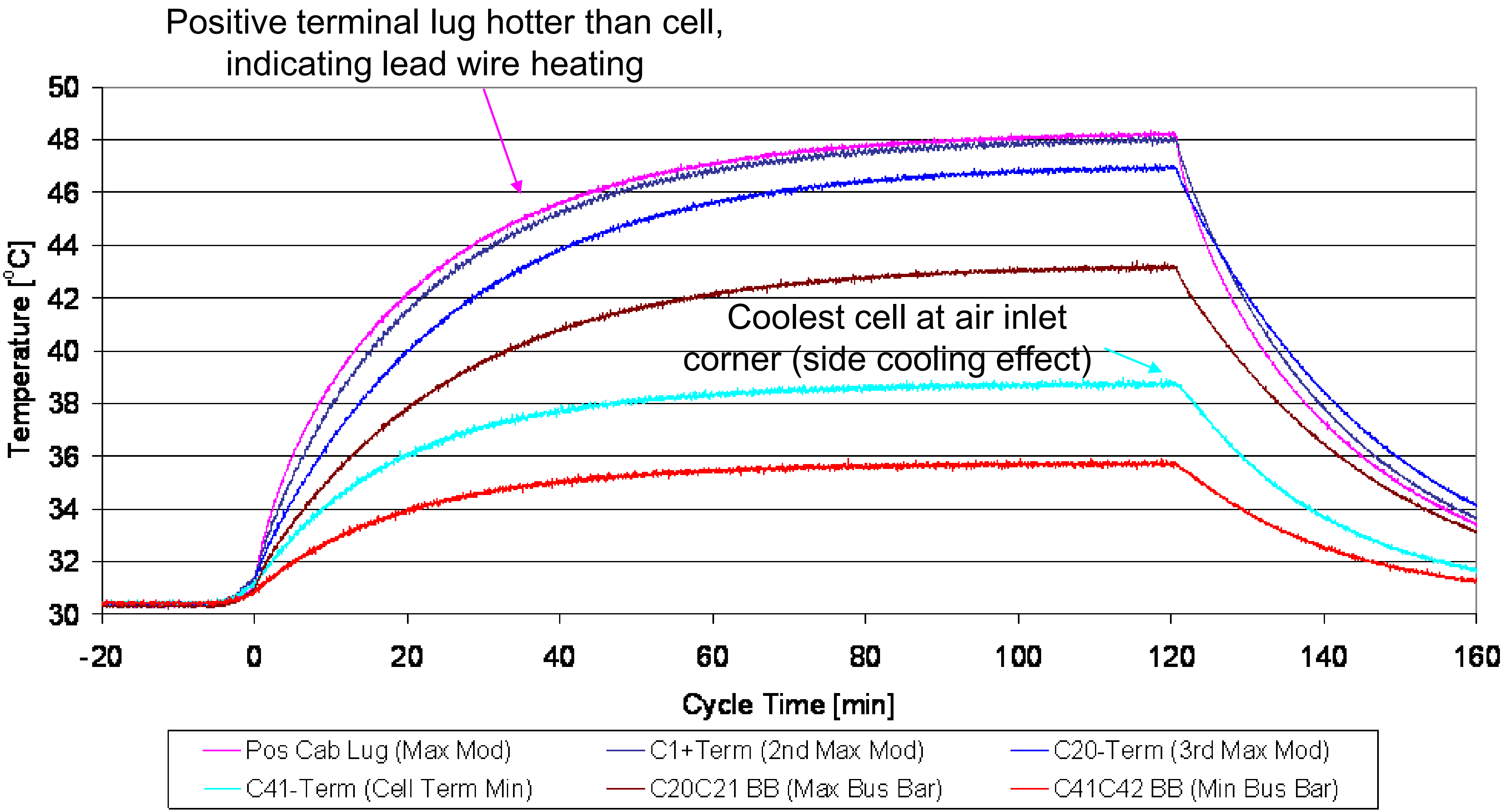


* Pesaran, A.; Gonder, J.; Brooker, A. "Factors & Conditions for Widespread Use of Ultracapacitors in Automotive Applications." Proceedings of Advanced Capacitor World Summit 2007; July 23-25, 2007, San Diego, CA.

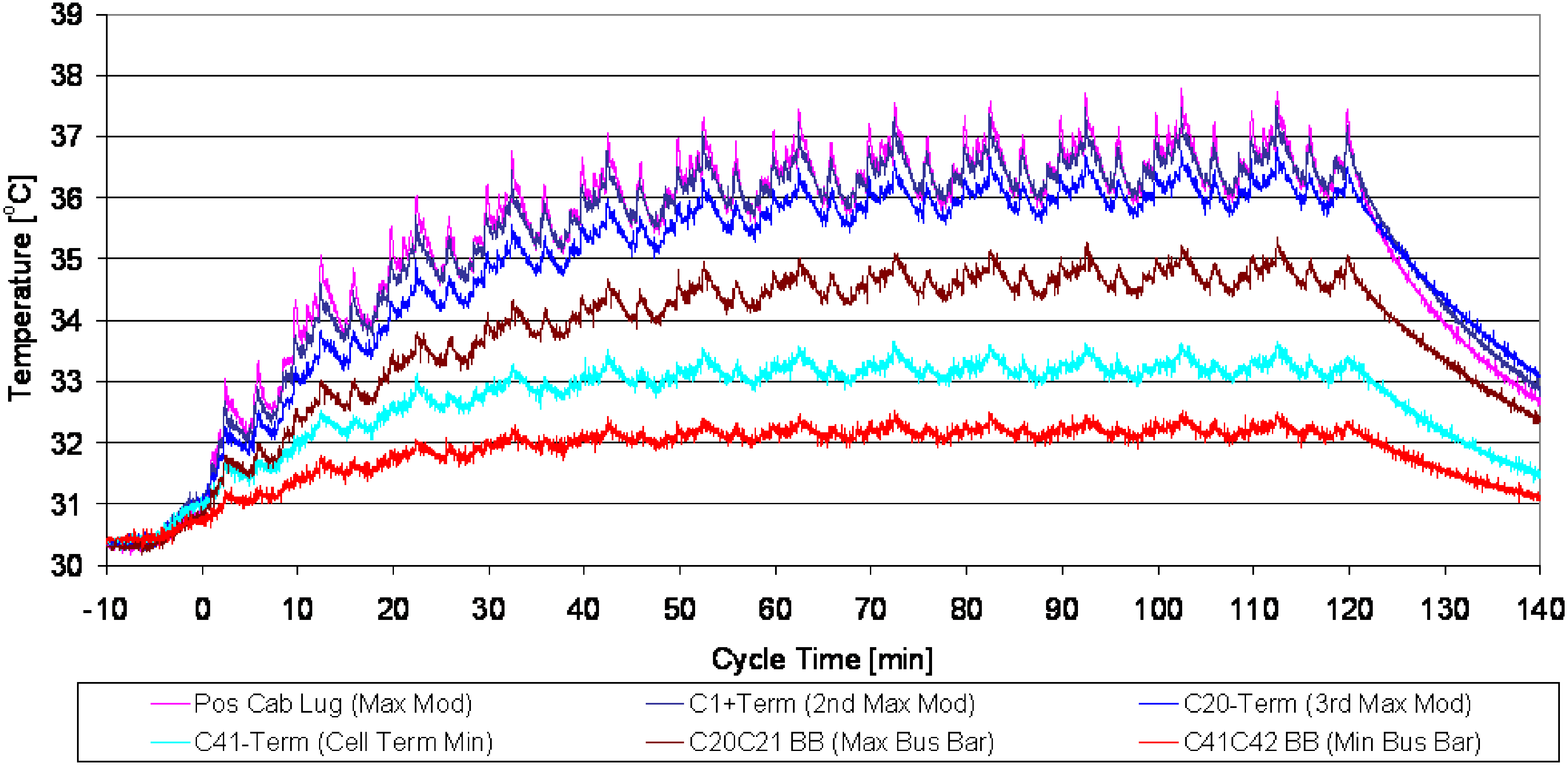
Module: Cell Terminal Temperatures
150 A, Sq Wave, T_{test} = 30 C



Module: Selected Temperatures 150 A, Sq Wave, T_{test} = 30 C

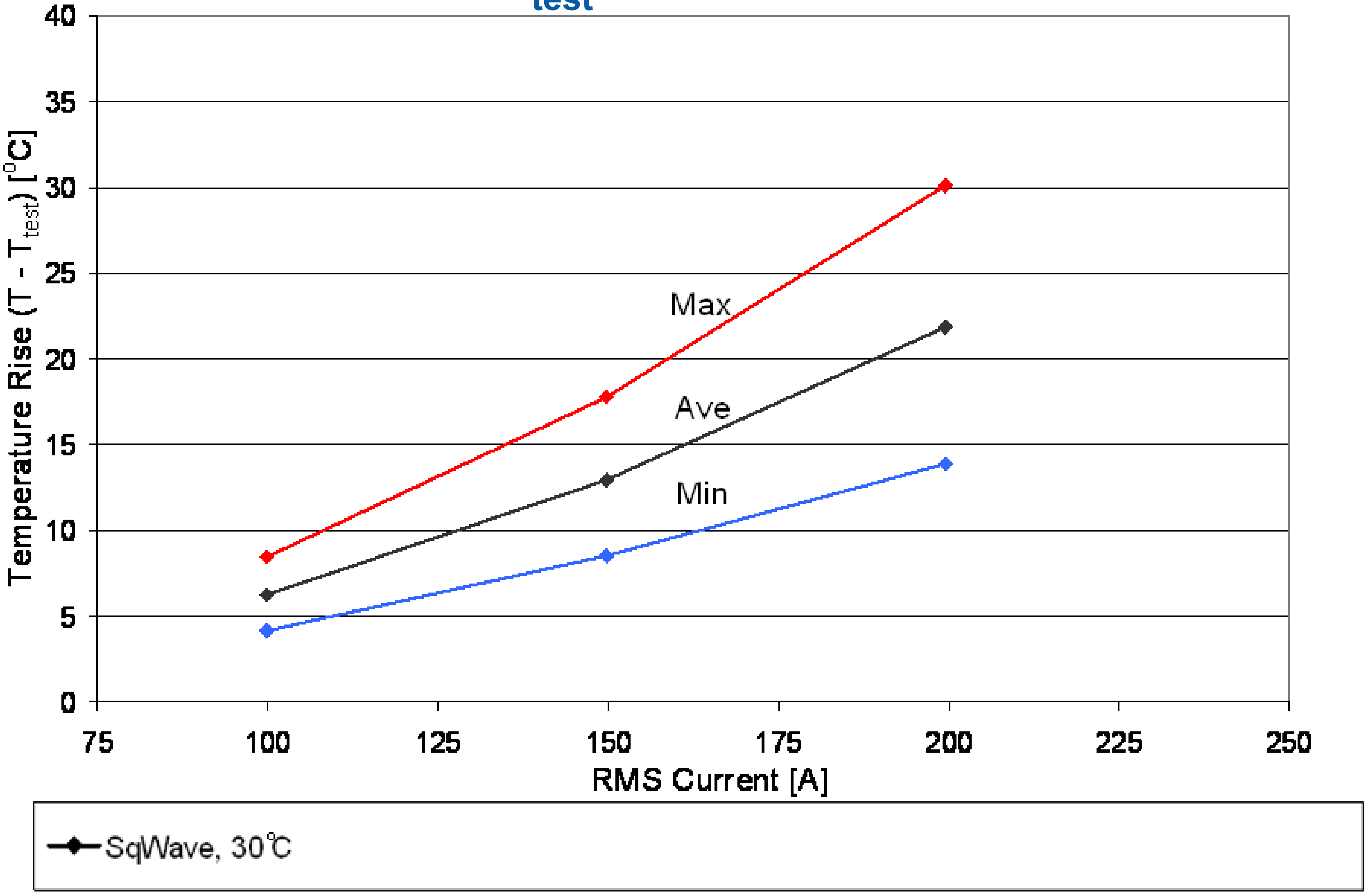


Module: Selected Temperatures
Light-Duty HEV Test Cycle, 12 cycles (120 min), T_{test} = 30 C



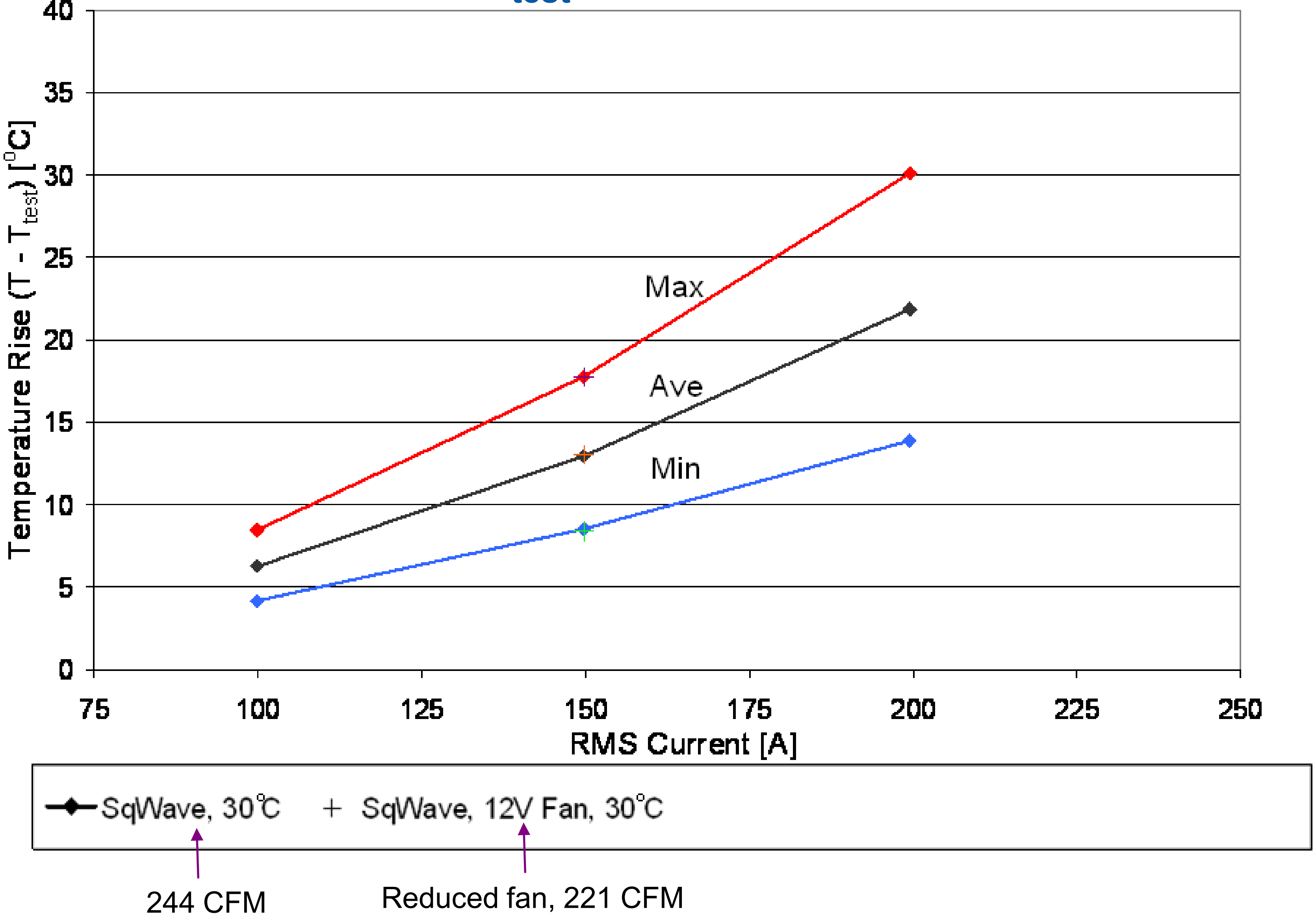
- Less than an 8 C rise after 120 minutes of cycling
- I_{rms} = 90.4 A

Module: Cell Terminal Temperature Rise Over Ambient*
T_{test} = 0 or 30 C



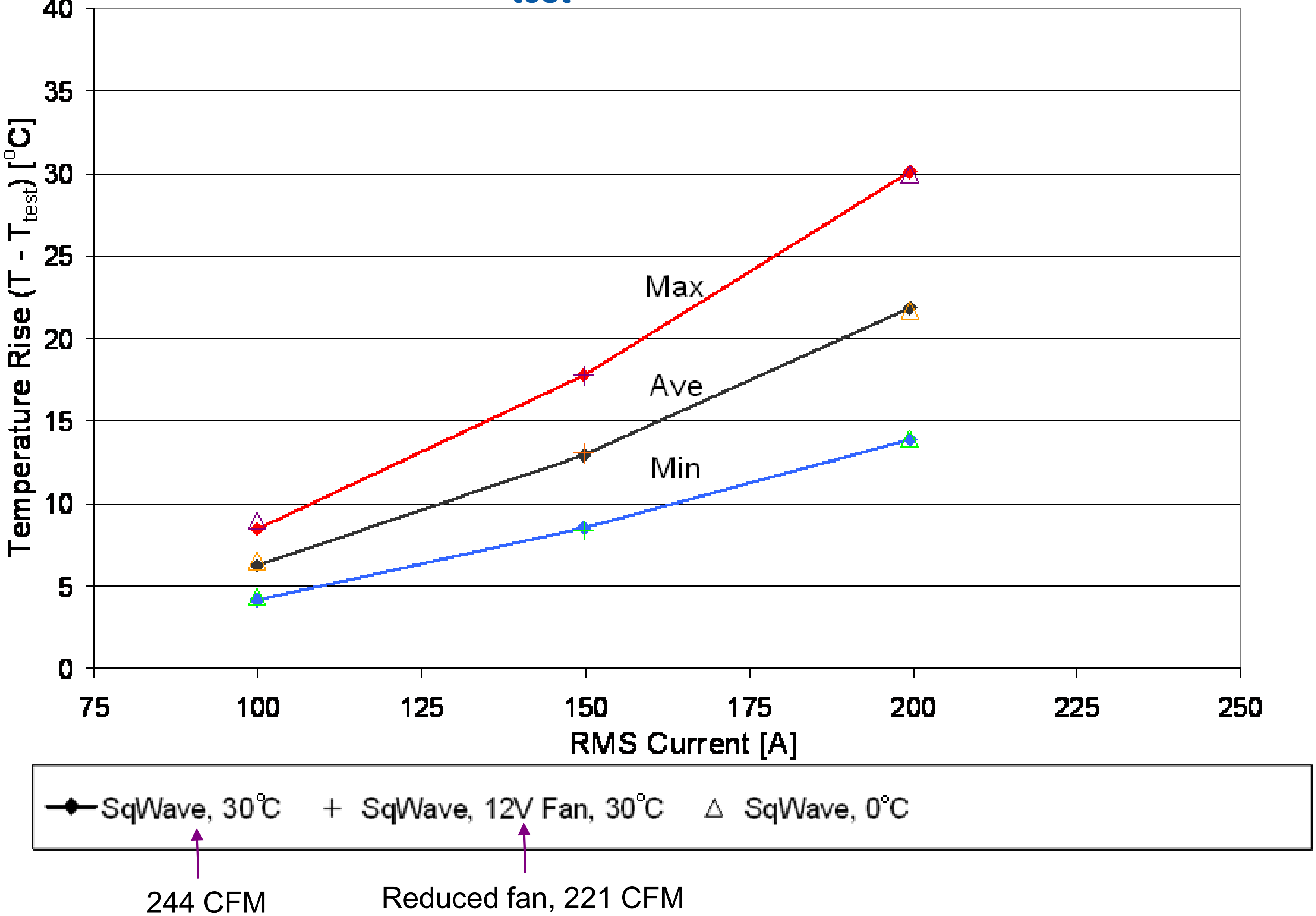
** Average over last five minutes of cycling, 115-120 min*

Module: Cell Terminal Temperature Rise Over Ambient*
T_{test} = 0 or 30 C



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

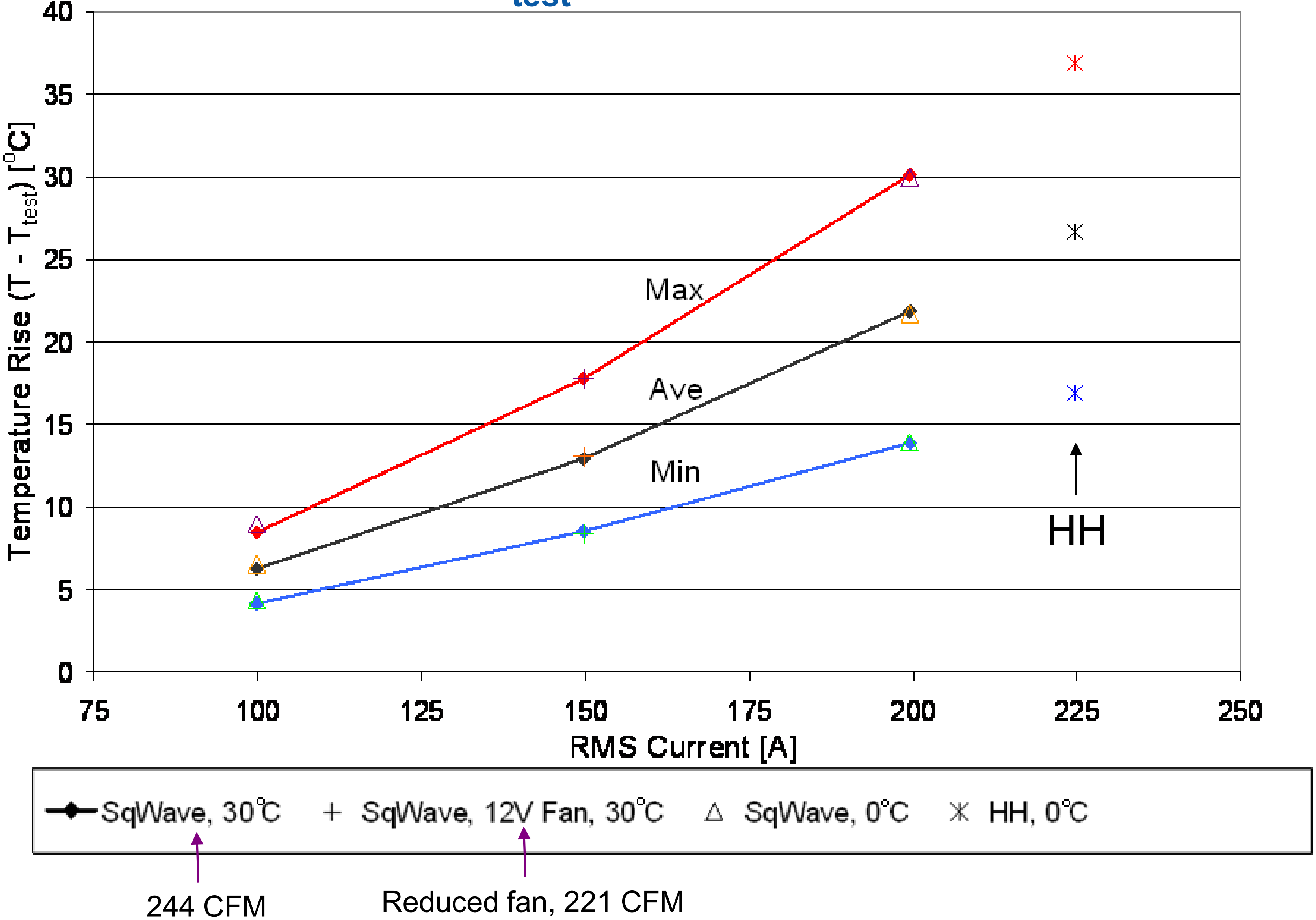
Module: Cell Terminal Temperature Rise Over Ambient*
T_{test} = 0 or 30 C



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

Module: Cell Terminal Temperature Rise Over Ambient*

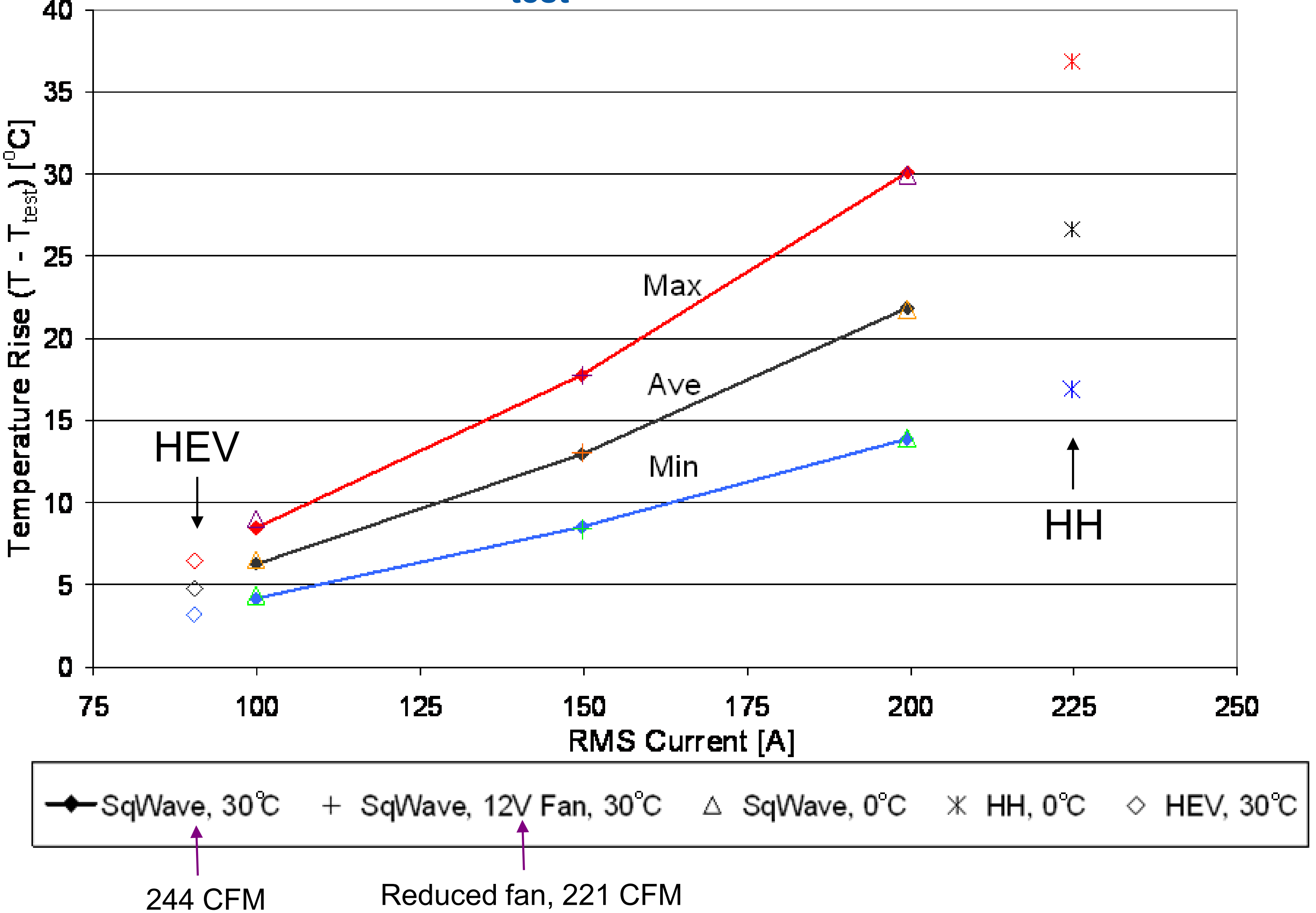
T_{test} = 0 or 30 C



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

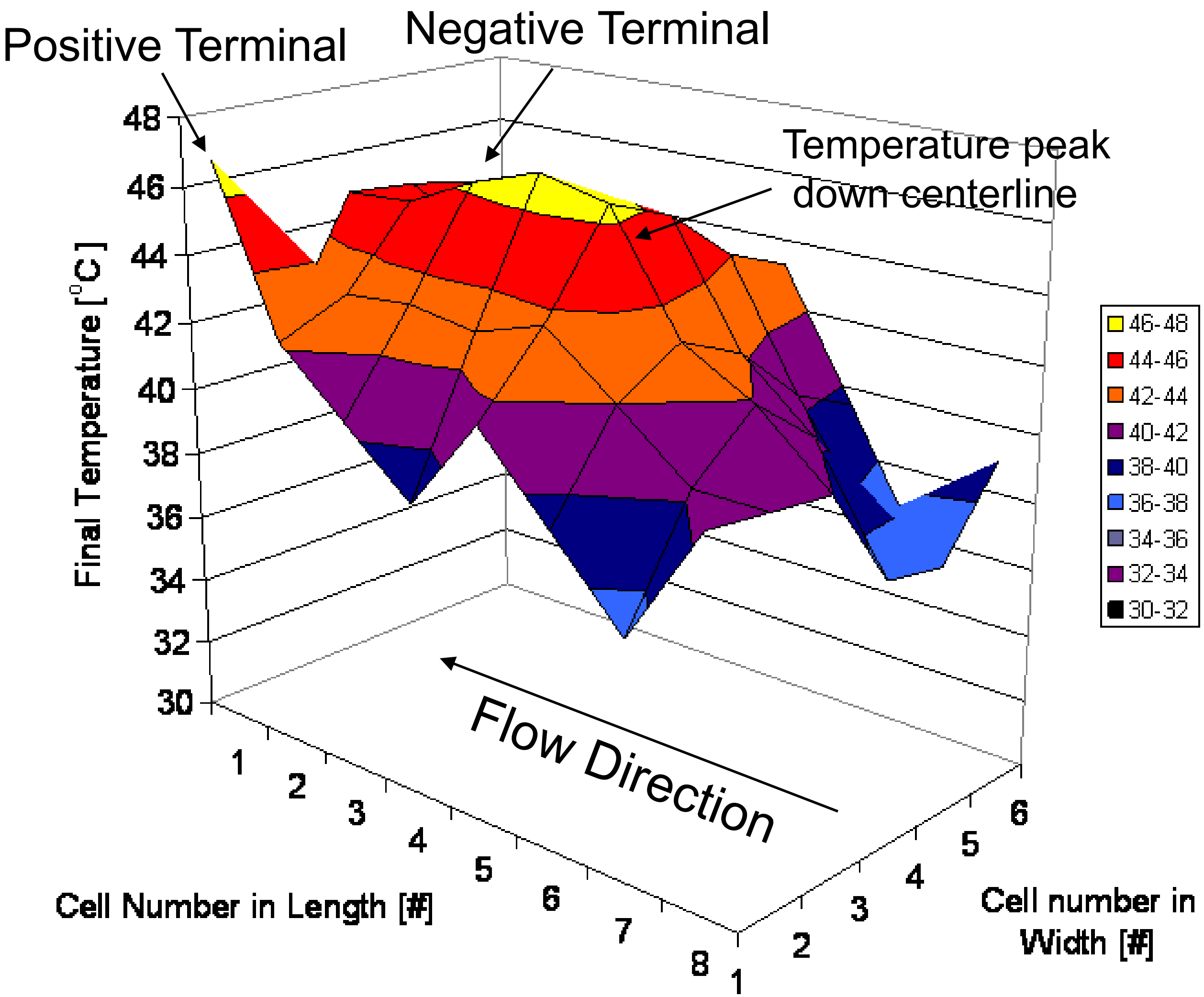
Module: Cell Terminal Temperature Rise Over Ambient*

T_{test} = 0 or 30 C



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

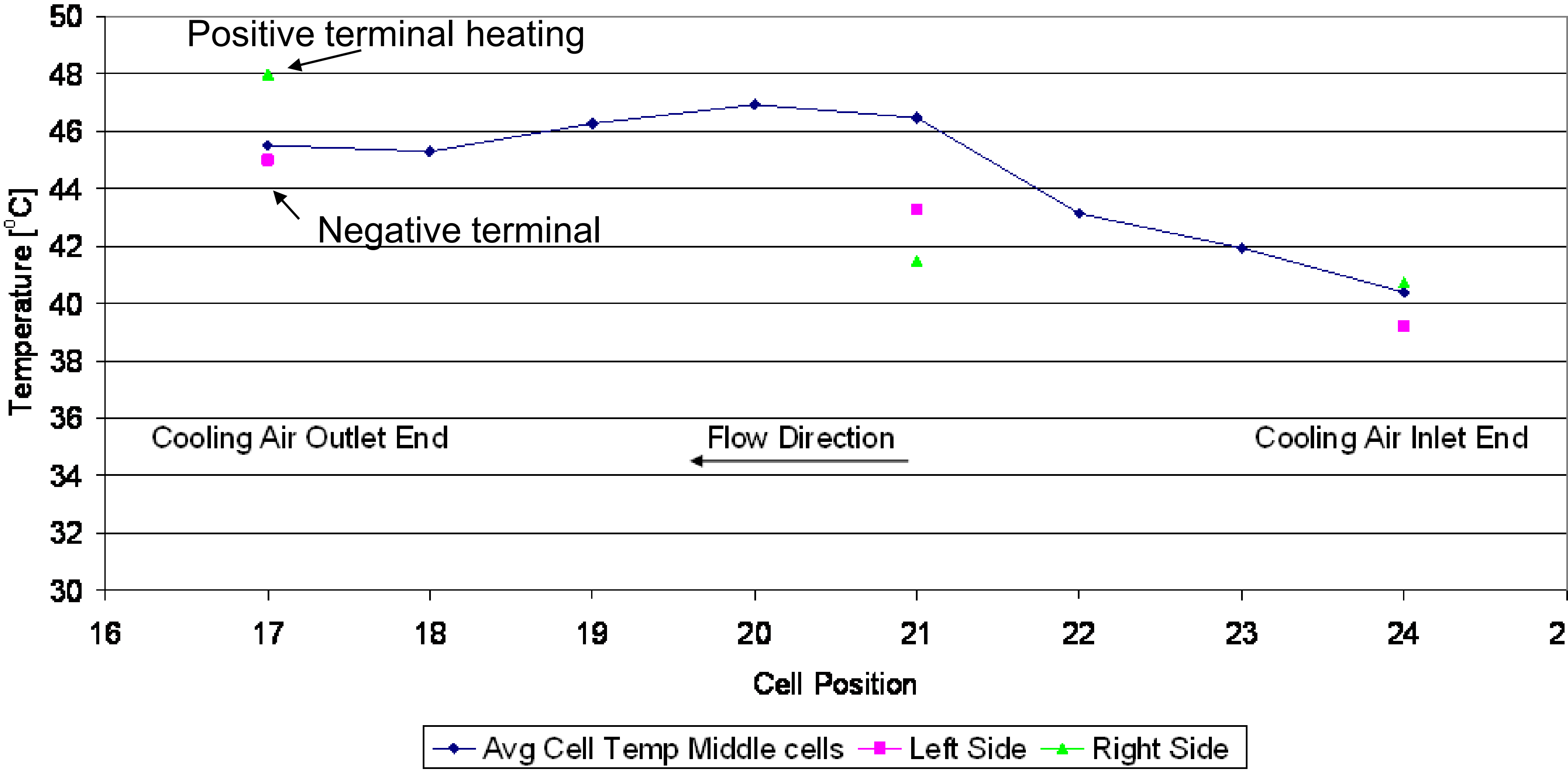
Module: Estimated Temperature Distribution*
150 A, Sq Wave, T_{test} = 30 C



- 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

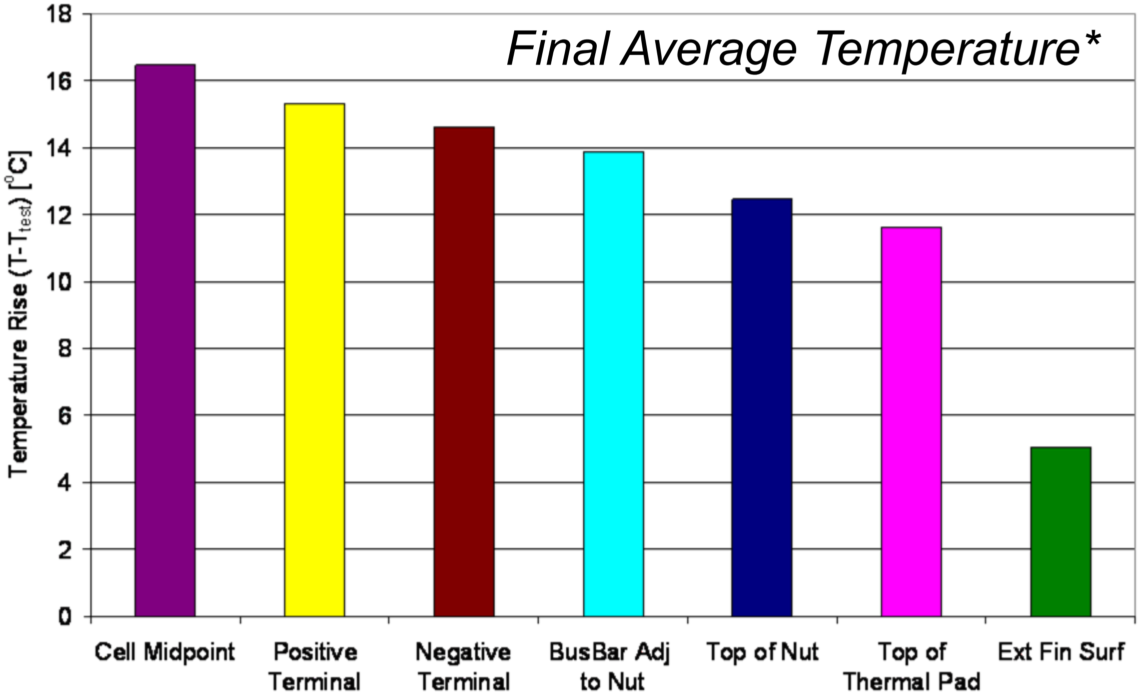
* *Average over last five minutes of cycling, 115-120 min*

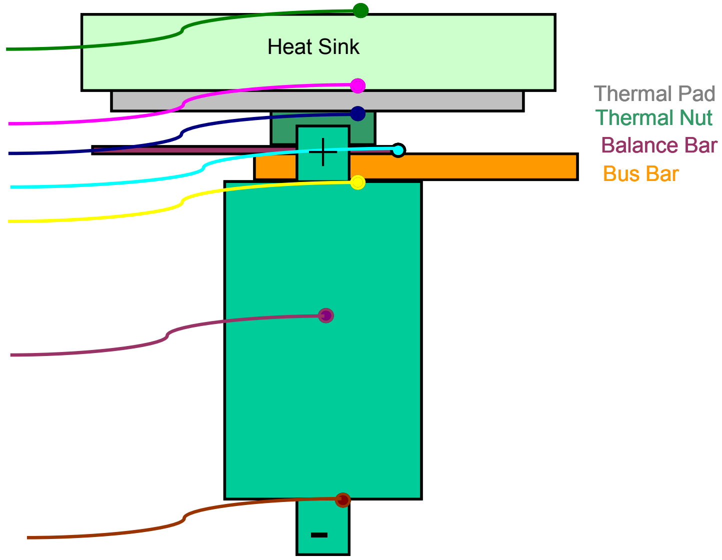
Module: Center Line Temperatures*
150 A, Sq Wave, T_{test} = 30 C



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

Module: Cell 17 Detail, Exit Side Center
150 A, Sq Wave, T_{test} = 30 C

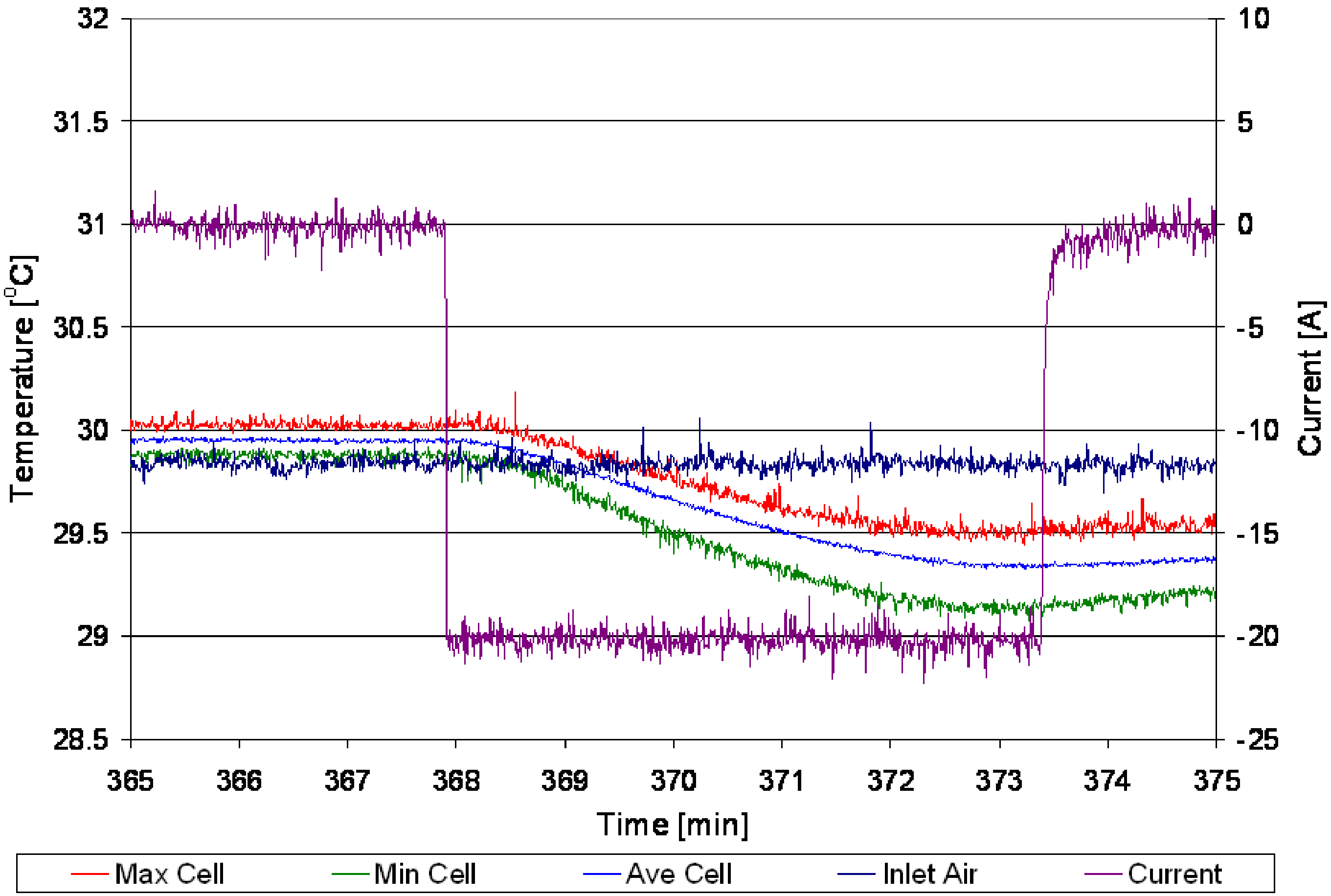




- Capacitor midpoint significantly hotter than terminals, may be good place for maximum temperature measurement
- ~40% temperature drop across fin
- ~17% temperature drop from terminal to thermal pad
- ~ 5% of the temperature drop across thermal pad (≈0.85°C)

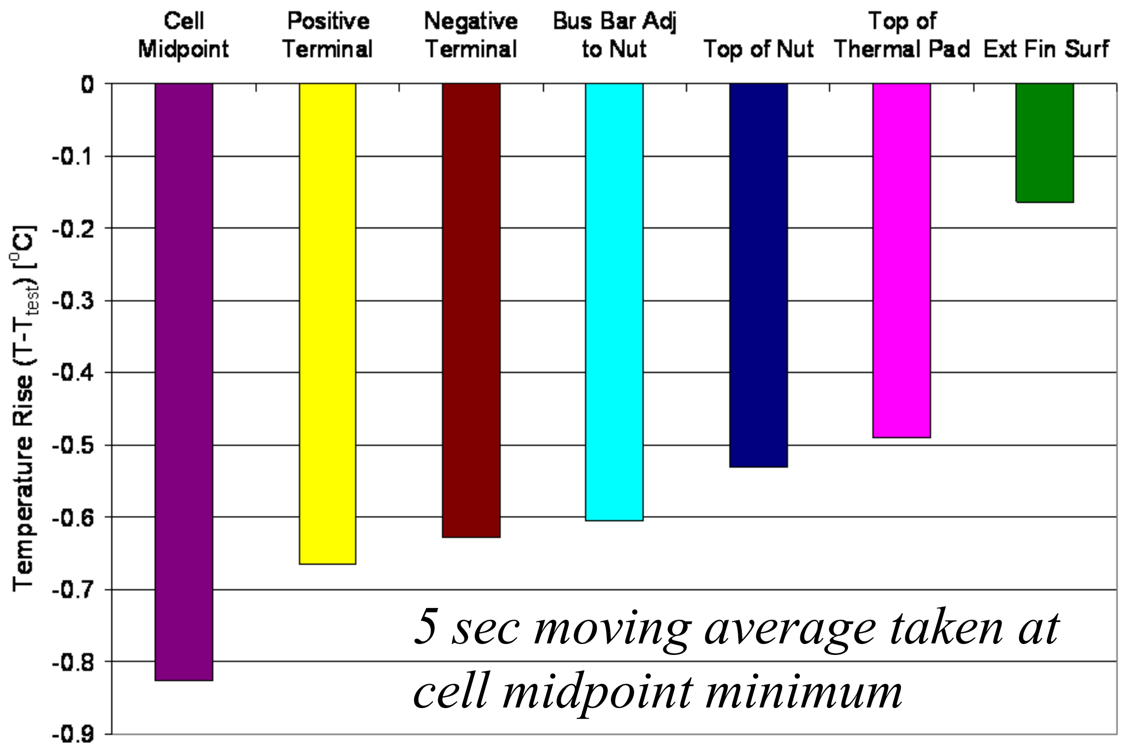
** Average over last five minutes of cycling, 115-120 min*

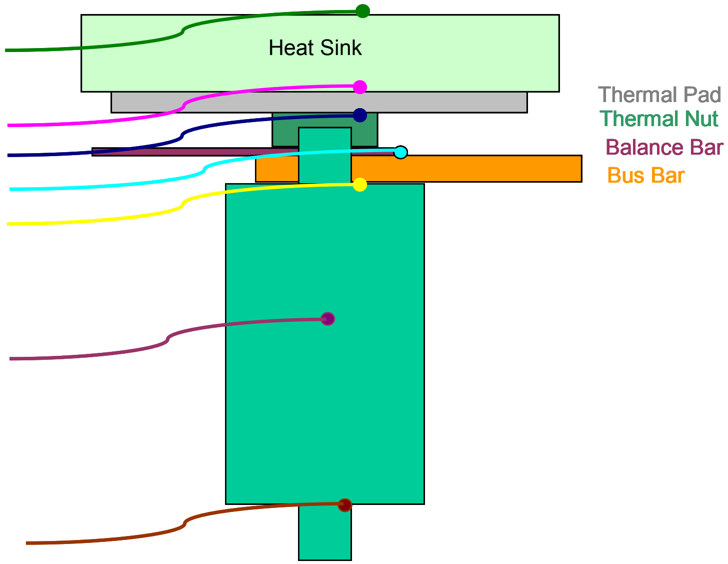
Module: Observed Self-Cooling, Cell Temperatures T_{test} = 30 C, Fans Off, Full Discharge



- 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_{test} = 30 C

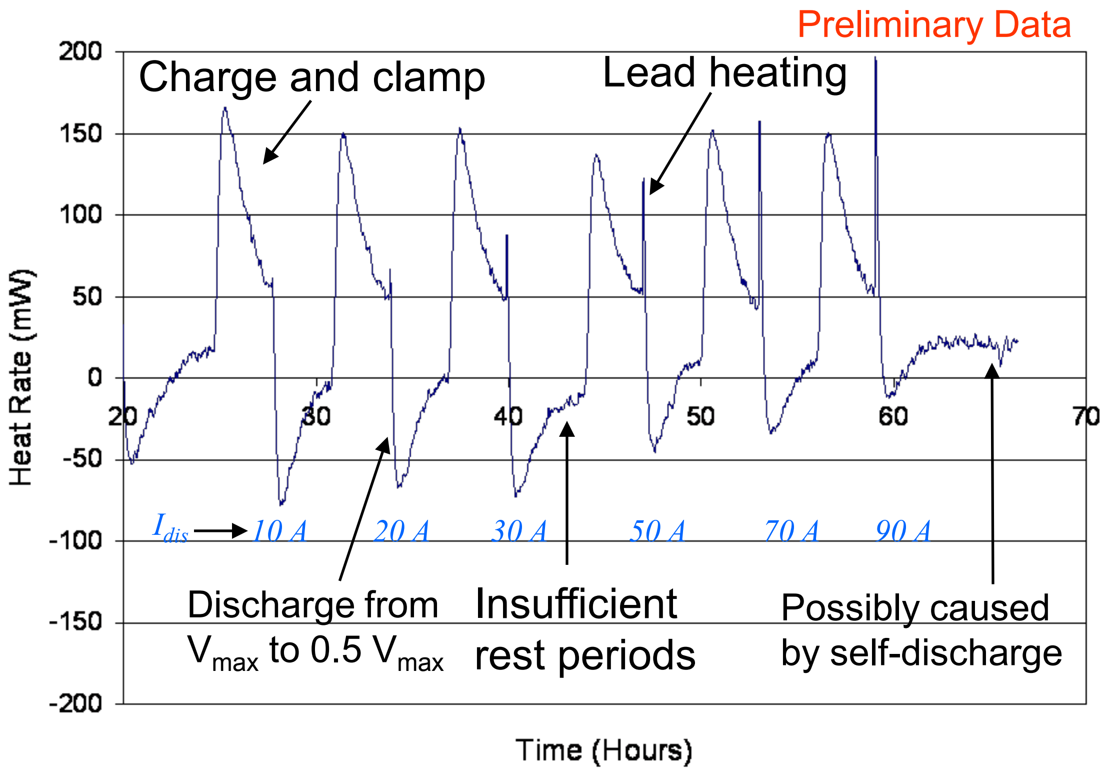




- Cooling trend from cell midpoint to outside environment
- Cell surface midpoint cools ~ 0.82 C
- Requiring ~ 483 J

Investigation of Self-Cooling, Endothermic Calorimeter Response on Discharge: BCAP 3000-P Cell, T_{test} = 30 C

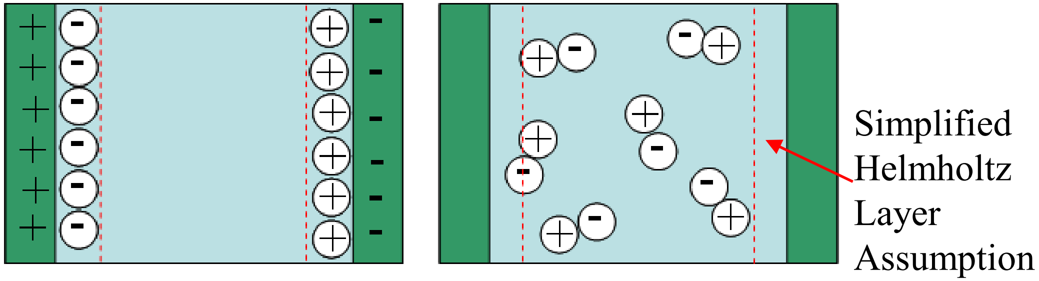
- Preliminary data (insufficient rest periods)
- Endothermic response measured
- Lead heating will decrease measured endothermic response for the inner chamber
- On the order of 345 [J] of cooling for a 1.3 V discharge
- If linear with voltage change
  - ~628 [J] of cooling on full discharge
  - giving ~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_{dis}, rest 3 hrs

Explanation of Self-Cooling, Reversible Heat Effect: Entropy Theory Compared to Measurement

Reversible heat, entropy model*



Charged State   Discharged State

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

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	*[cm^3]*
Vo: Total electrolyte Volume	*[cm^3]*

- Assume
  - Entropy model suggested by Schiffer et al.
  - A specific capacitance of 6.5-30 μF/cm^2
  - $V_o \approx 200$ cm^3
  - $d_{Helmholtz}$ = 0.8 nm
  - T change can be neglected for entropy calculation
- Found
  - $Q_{discharge}$ = -203 [J] to -515 [J]
    - For a 1.3 V discharge
    - T = 30 C
  - Agrees reasonably well with the Q ~ -345 [J] measured in the calorimeter

* Schiffer, J., et al. (2006). "Heat generation in double layer capacitors." *Journal of Power Sources* 160(1): 765-772.

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*

Acknowledgements

- Supported by the Vehicle Technologies Program of the U.S. Department of Energy

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  - Oshkosh Corporation: Michael Bolton, Lorenzo Pisan
  - Maxwell Technologies: John M. Miller, Uday Deshpande, Jeremy Coperthwaite
  - JME: John R. Miller, Arkadiy Klementov
  - NREL: Bob Rehn, Ken Kelly, Rob Farrington, Barb Goodman, Terry Penney